

Toxicology Report 11-02

Combustion Products Monitor: Trade Study Testing

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1. Introduction

Current combustion products monitoring on the International Space Station (ISS) uses a handheld device (Compound Specific Analyzer-Combustion Products, CSA-CP) containing electrochemical sensors used to measure the concentration of carbon monoxide (CO), hydrogen chloride (HCl), hydrogen cyanide (HCN), and oxygen (O₂). The CO sensor in this device accounts for a well-known cross-sensitivity with hydrogen (H₂), which is important, as ISS air can contain up to 100 ppm H₂. Unfortunately, this current device is being discontinued, and due to space constraints, the new model cannot accommodate the size of the current CO sensor. Therefore, a trade study was conducted in order to determine which CO sensors on the market were available with compensation for H₂, and which instruments used these sensors, while also measuring HCN, O₂, and carbon dioxide (CO₂). The addition of CO₂ to the device is helpful, as current monitoring of this gas requires a second hand-held monitor. By providing a device that will monitor both combustion products and CO₂, volume and up-mass can be reduced as these monitors are delivered to ISS.

Approximately 30 companies were contacted and questioned concerning CO sensors that included H₂ compensation. Industrial Hygiene News (gas detection) was the major resource for companies in the trade study. Web searches for sensors were also performed.

City Technologies (the maker of the sensors used in the current CSA-CP) was first contacted to determine if it was possible to reduce the size of their current hydrogen compensated CO sensor for future installations in smaller combustion products analyzers. Their indication was that there was no plan for this effort, as there were not sufficient customer requests. Additionally, they were not able to provide information regarding those companies using their sensors.

Of the companies contacted, three companies fulfilled both requirements for hydrogen-compensated CO sensing and HCN, CO₂, and Oxygen detection in the same portable, battery powered analyzer. These three analyzers are:

- 1) GfG. This analyzer is capable of having all four sensors housed in a small package (approximately 3 x 4 x 2 inches, shown in **Figure 1**). This instrument uses City Technologies electrochemical sensors. While it was thought that a separate pump attached to the main unit would be required for CO₂ measurement, initial testing showed that this was not the case. Initial testing also indicated that there was significant cross-sensitivity between CO and H₂. GfG replaced this sensor prior to the current testing.

- 2) Dräger. This X-am 5600 analyzer uses Dräger's own sensors, with a variety of measuring ranges. All four sensors are included in a single housing with dimensions of 2 x 5 x 2 inches, as shown in **Figure 2**. As advertised, the analyzer does not require a pump.
- 3) YesAir. This analyzer uses Alphasense and City Technologies electrochemical sensors. E Instruments stated that they had formerly used City Technology sensors in some applications but found some of them to be unreliable, leading to their use of Alphasense. The enclosure housing all four sensors had dimensions of 8 x 3 x 4 inches, seen in **Figure 3**.

A fourth monitor, not currently containing an O₂ sensor, was also tested in these studies. The MX6 iBrid multi-gas detector, produced by Industrial Scientific, was already present in the Toxicology laboratories at Johnson Space Center (**Figure 4**). This instrument is the newly developed model that replaces the CSA-CP in the Industrial Scientific (ISC) catalog. While this monitor did not originally possess the ability to compensate for H₂ in the CO channel, the addition of an H₂ sensor and a firmware upgrade allowed for H₂ cross-sensitivity testing and a comparison with the other monitors to be performed.

These monitors were put through a series of tests aimed at determining their accuracy for individual gases as well as the effects of humidity, cross-sensitivity, and response time.



Figure 1: GfG combustion products monitor



Figure 2: Draeger combustion products monitor



Figure 3: YesAir combustion products monitor



Figure 4: MX6 combustion products monitor

2. Experimental Conditions

Testing of the GfG, Dräger, and YesAir combustion products monitors (CPMs) took place in the Toxicology Laboratories of NASA Johnson Space Center from August 22nd – 25th, 2011. Testing of the upgraded ISC CPM was performed on November 23, 2011. Each CPM was placed in a fume hood for all testing. A flow controller was used to mix the test gases to a total flow of 1 L/min using nitrogen (N₂) as a make-up gas and a calibrated flow meter to measure the flow rate. Gas was introduced to each CPM using their individual pumps. The gas flow entering the CPMs was shunted from the main gas line in order to reduce the flow rate over the sensors. A stopwatch was used to monitor the steady state time. This time began when the gas line was introduced to the pump and ended after the reading on the instrument became stable. This stability was determined by waiting 30 seconds after the last change in the reading. Eighty percent response and recovery times were determined for the ISC and Dräger CPMs after initial testing of all instruments. Prior to testing, each instrument was calibrated according to the manufacturer instructions. For testing of humidity effects, a separate gas stream saturated with water vapor was introduced downstream from the flow controller. The flow meter was used to attain the desired relative humidity.

3. Results and Discussion

3.1 Concentration Dependence

3.1.1 CO

Dry CO was introduced to the flow controllers from two standard containers, 100 ppm and 2020 ppm, each balanced in zero air. The results of this addition are shown in **Figure 5**.

At low CO concentration (20 ppm), the MX6 showed a 50% inaccuracy, while the other three CPMs showed better than 15% accuracy, with Dräger being the most accurate. As the concentration of CO was increased, the readings of the MX6 began to improve, the Dräger and YesAir monitors remained accurate, and the GfG monitor began to deviate from ideal behavior. This behavior persisted as the CO concentration continued to increase up to the highest CO concentration to which the monitors were exposed (202 ppm). Upon addition of 404 ppm CO, the Dräger and MX6 monitors were still greater than 95% accurate, while the other two instruments gave no readings.

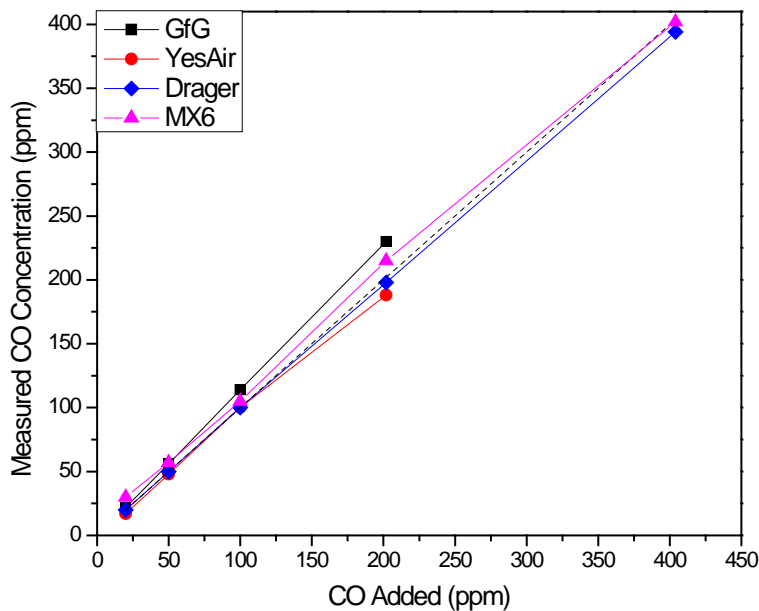


Figure 5: Response of CPMs to dry CO addition. Dotted line indicates 100% accuracy.

3.1.2. HCN

Dry HCN was introduced to the flow controllers from a single standard containing 21.65 ppm HCN with zero air as a balance gas. These results are shown in **Figure 6**.

The accuracy of the monitors towards HCN is much less than that of CO. At the lowest concentration tested (4.33 ppm), the deviations from ideal range from ~ 13% to greater than 200%. Once again, the Dräger analyzer shows the best accuracy, while the GfG analyzer is the least accurate. As the added HCN concentration is increased, the accuracy improves for each of the analyzers, though the value shown by the GfG analyzer is still ~ 150% greater than that added. At the two highest HCN concentrations tested, the MX6, GfG, and YesAir analyzers begin to show increasing inaccuracies.

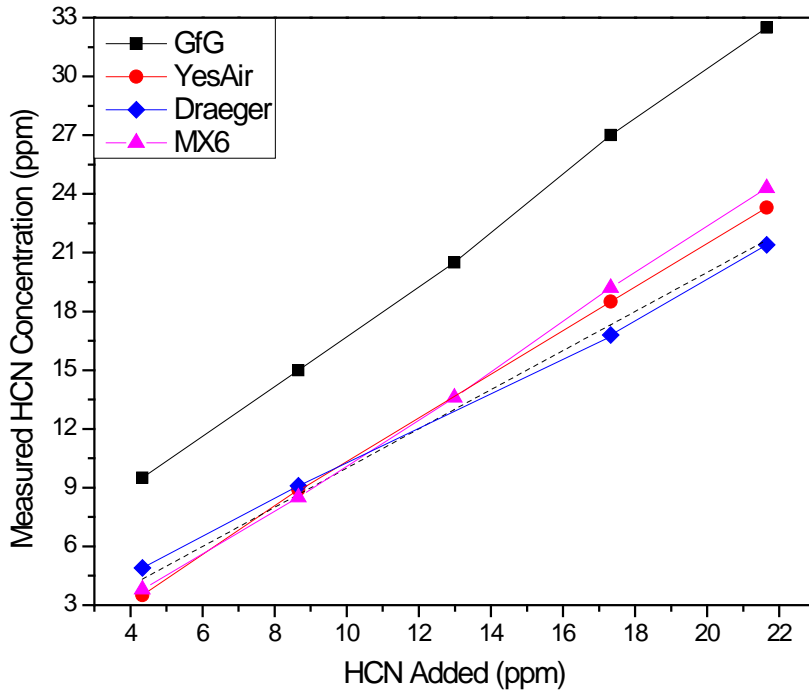


Figure 6: Response of CPMs to dry HCN addition. Dotted line indicates 100% accuracy.

3.1.3. O₂

The responses of the GfG, YesAir, and Dräger CPMs to oxygen were tested by adding dry O₂ from two standard tanks containing 21% and 32% O₂, with the remaining balance gas being N₂. The results of this testing are shown in **Figure 7**.

At low O₂ concentration, the Draeger and YesAir analyzers are both within 93% accuracy, while the GfG analyzer has an inaccuracy of greater than 25%. However, as the added concentration increases, the accuracy of the GfG improves, while that of the other two analyzers remains stable. At 21% O₂, each of the analyzers is very close to 100% accuracy. This might be expected, as this was the concentration used for calibration. At the highest concentration tested (32%), only the YesAir analyzer provided a reading.

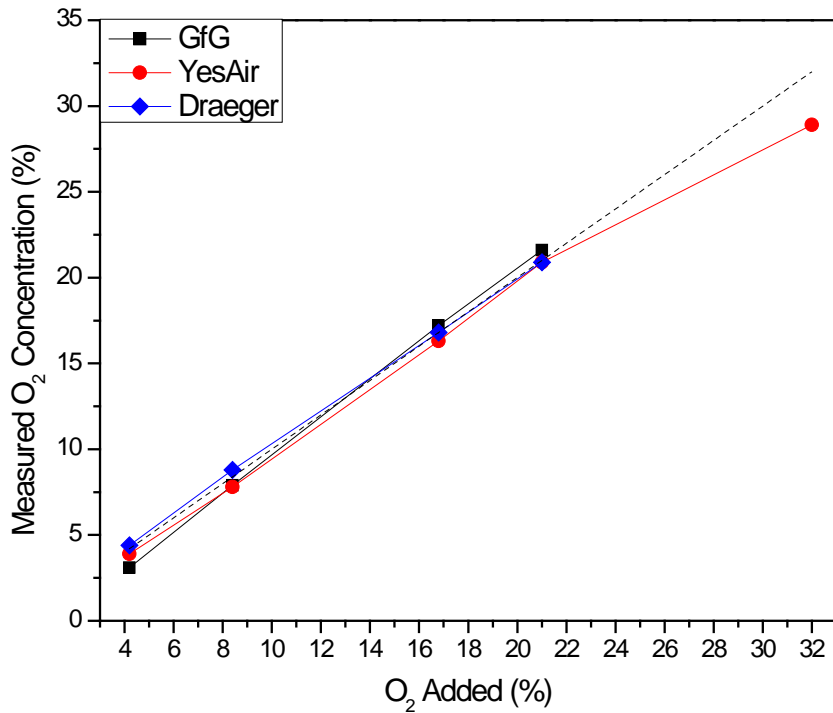


Figure 7: Response of CPMs to dry O₂ addition. Dotted line indicates 100% accuracy.

3.1.4. CO₂

Carbon dioxide response was tested for all four CPMs using a 1.96% CO₂ standard with zero air as the balance gas. The results of this testing are shown in **Figure 8**. Over the range tested, the GfG, MX6, and Dräger analyzers performed very well, while the YesAir monitor was much less accurate at the middle concentrations.

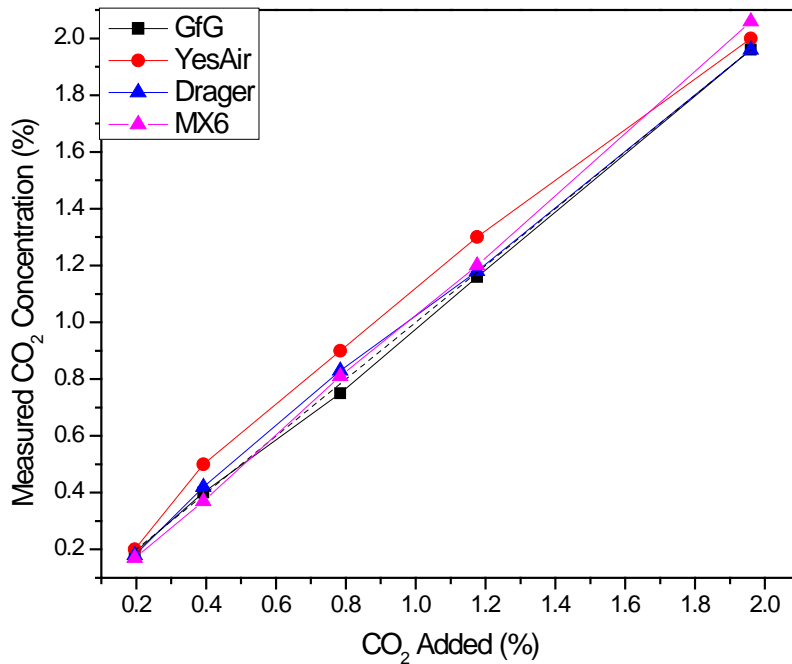


Figure 8: Effect of CO₂ addition on CPM response. Dotted line indicates 100% accuracy.

3.2. Cross-sensitivity

3.2.1. CO/H₂

In order to test for the effects of hydrogen on CO readings, the CPMs were exposed to CO at a fixed concentration while a range of hydrogen concentrations were applied. **Figure 9** shows the results of this testing. At 20 ppm CO, the reading of the Dräger analyzer was very stable and accurate even as the hydrogen concentration approached 400 ppm. At the lowest H₂ concentration, the YesAir analyzer possessed accuracy similar to that of the Dräger analyzer, while the inaccuracy of the GfG and MX6

monitors were already 35% and 65%, respectively. As the H₂ concentration increased, so did the inaccuracy of the GfG and YesAir monitors, with a response of ~ 230% that of ideal at the highest H₂ concentration. Interestingly, the accuracy of the MX6 monitor improved with increasing amounts of H₂. It should be noted that the calibration of the Dräger and MX6 analyzers included a step to calibrate for H₂, while the other two analyzers did not.

As the CO concentration was increased to 202 ppm, the accuracy of the GfG and YesAir analyzers improved across the entire H₂ concentration range, while that of the Dräger unit slightly declined. However, the accuracy of the Dräger was still greater than 93% of ideal. At this concentration, the MX6 showed a CO concentration ~ 20% less than that added.

The response of the YesAir monitor is questionable at this CO concentration. Without H₂, this monitor was found to give no reading above 200 ppm CO. Based on the response seen at 20 ppm CO when H₂ was introduced, it would seem that the reading from the YesAir unit would be greater than the sensor is capable of measuring. Instead, the reading is stable at ~ 10 ppm below ideal across the entire H₂ range. Prior to use of this instrument, further testing would be necessary to determine if these readings are valid.

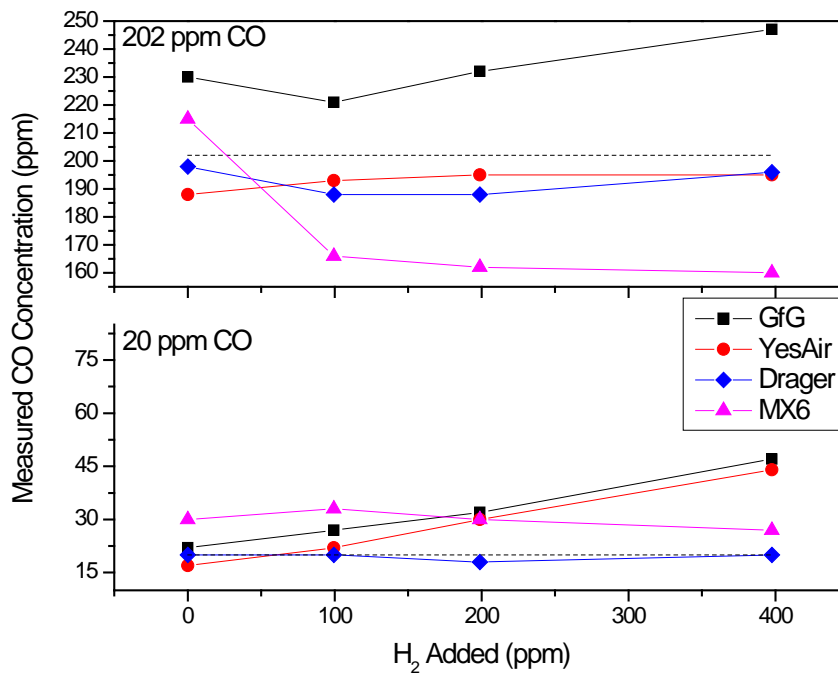


Figure 9: Effects of H₂ addition on CO response.

3.3. Humidity Effects

3.3.1. CO

As the relative humidity levels on ISS are in the range of 30-60%, it is important to test the effects, if any, of humidity on the sensor responses of potential combustion products monitors. Using the method described above, CO was mixed with saturated water vapor to achieve the desired CO concentration and relative humidity. The effects of humidity at two different CO concentrations, 20 ppm and 202 ppm, are shown in **Figure 10**. Over the entire range of humidity and at both CO concentrations, the Dräger CPM again shows the most accurate performance. The GfG and YesAir monitors also show relative stability over the range of humidity, though their overall accuracy is less than that of the Dräger. At the lower CO concentration, the MX6 continues to be the least accurate, even as the humidity is increased. At higher CO concentration, the accuracy of the MX6 is improved, especially at moderate humidity, where it is the most accurate of the monitors tested.

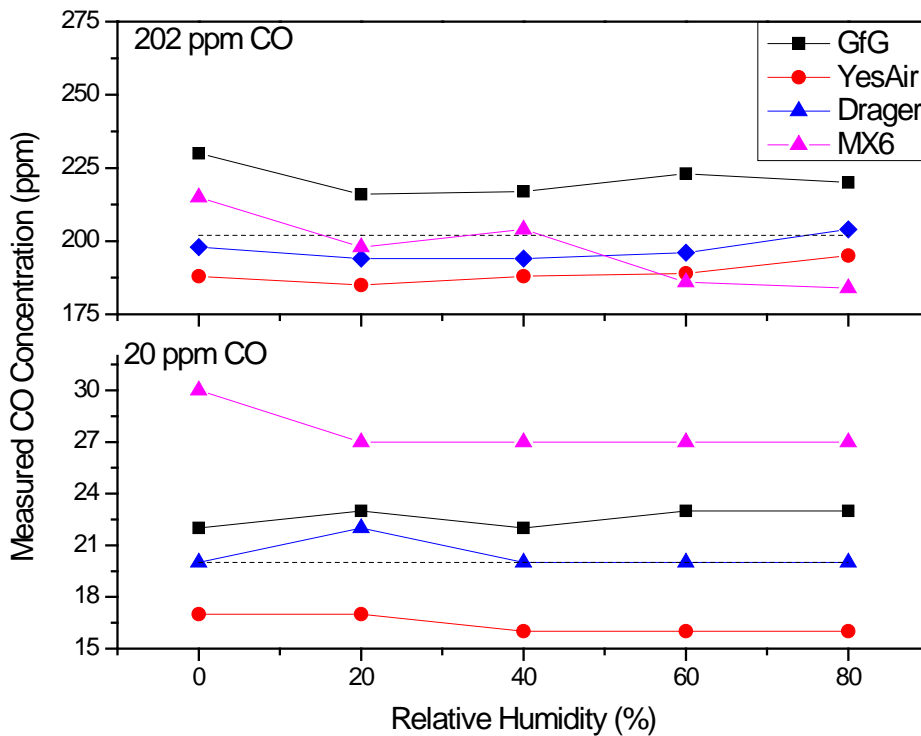


Figure 10: Humidity effects on CO sensor response. Dotted line indicates 100% response.

3.3.2. HCN

Figure 11 shows the effects of humidity on HCN response for the CPMs. At low HCN, both the Dräger and YesAir monitors show changes as the humidity is increased, with the Dräger changing by 30% and the YesAir changing by 28%. These changes are not consistently high or low; the readings of the Dräger unit start high at low humidity and end low at higher humidity, while the readings of the YesAir monitor are the opposite. The GfG monitor shows consistently higher readings than ideal over the full range of humidity. However, as the humidity increases, the readings fall from 220% greater than ideal to 4% greater. At this HCN concentration, the MX6 shows stable results as the humidity is increased, and the results are relatively accurate, staying around 90% of the ideal concentration.

Fewer humidity points were available for testing at higher HCN concentration. However, at the two humidity points tested, the Dräger, YesAir, and MX6 units were stable and had inaccuracies of less than 12%. Again, the GfG monitor began much more inaccurately, but, as seen at the lower HCN concentration, an increase in humidity increased the accuracy.

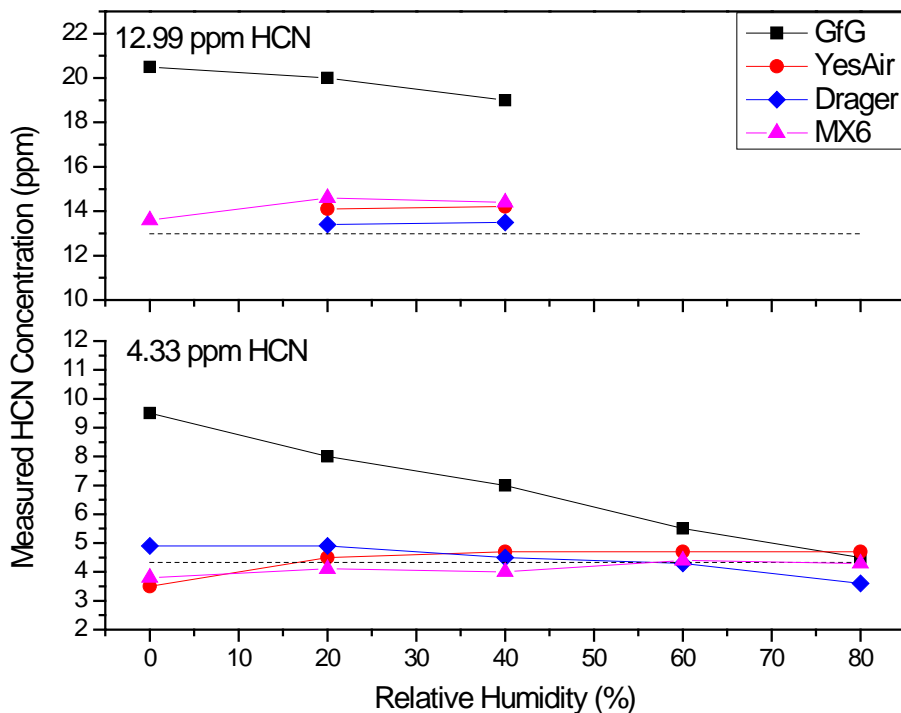


Figure 11: Effects of humidity on HCN sensor response. Dotted line indicates 100% response.

3.3.3. O_2

When testing for humidity effects on the response of the sensors to oxygen, it is necessary to account for the O_2 present in the zero air used to produce the saturated water vapor. Therefore, increased humidity will lead to increased oxygen. The trends seen in **Figure 12** appear very similar to the low-concentration trends in **Figure 7**, indicating that the presence of water vapor does not have a significant effect on the O_2 sensor response for any of the monitors.

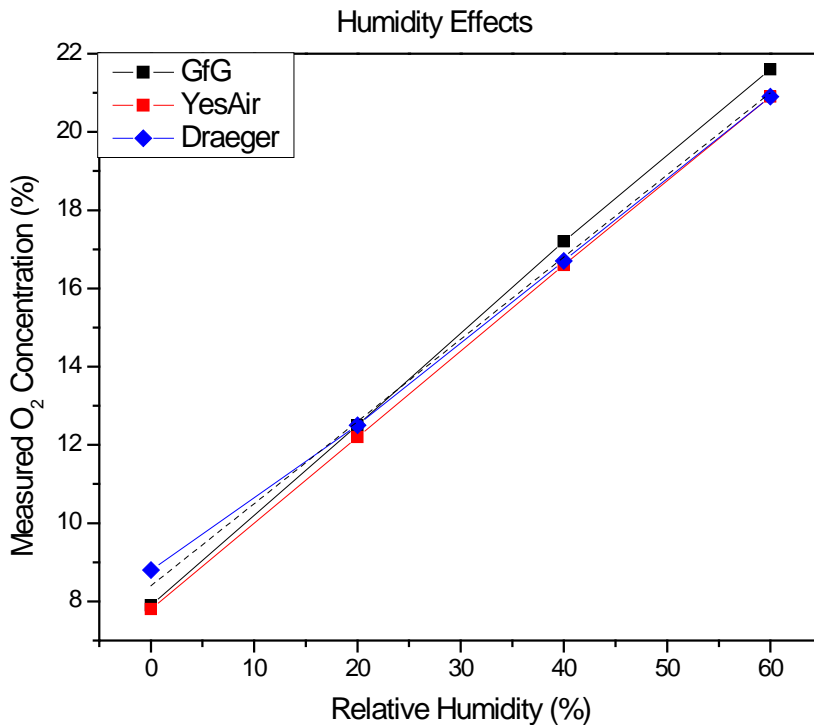


Figure 12: Effects of added humidity on O_2 sensor response.

3.3.4. CO_2

The effects of humidity on CO_2 sensor response were tested at three CO_2 concentrations (**Figure 13**). Of the four monitors, the YesAir unit was the most stable with respect to humidity, showing no change with added humidity at the two lowest CO_2 concentrations and only a slight change at the highest concentration. The remaining monitors were stable at the two highest CO_2 concentrations as humidity was added, but each showed the effects of added humidity at the lowest CO_2 concentration tested.

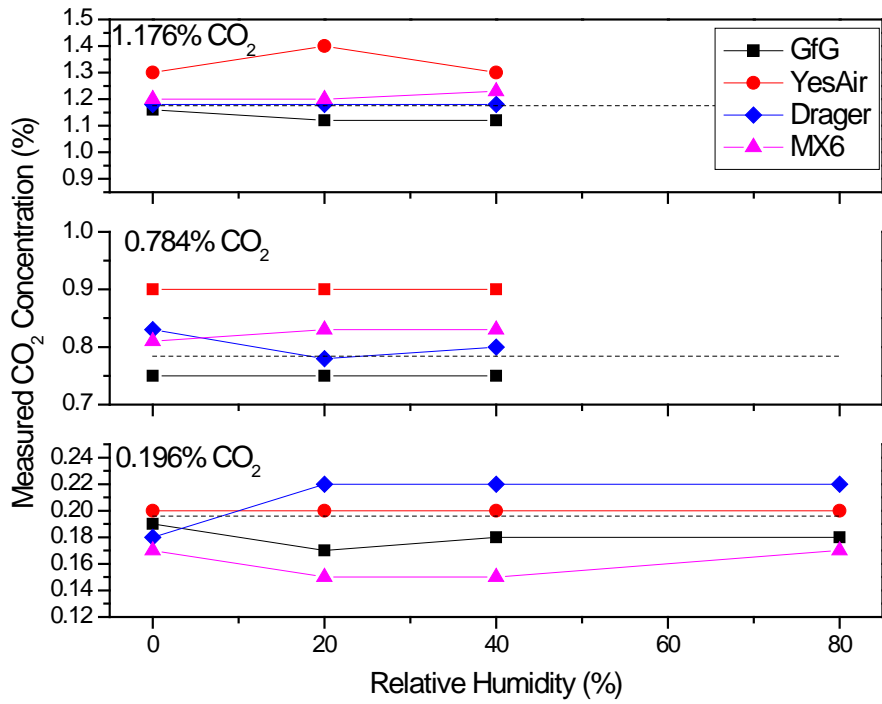


Figure 13: Effects of humidity on CO₂ sensor response

3.4 Response Times

The time required for an individual sensor to stabilize at a steady state value for a particular gas was measured in each unit. The average times and standard deviations for each gas or gas combination (i.e. CO/H₂) are shown in **Table 1**. For all gases other than HCN, the Dräger monitor stabilizes more quickly than the other units. For that gas, the GfG monitor has the quickest response.

Table 1: Average steady-state stabilization times (in seconds) for individual sensors

	GfG		YesAir		Dräger		ISC MX6	
	<i>Average</i>	<i>StDev</i>	<i>Average</i>	<i>StDev</i>	<i>Average</i>	<i>StDev</i>	<i>Average</i>	<i>StDev</i>
CO	46.5	16.4	96	30.1	25	7.0	37.3	12.5
CO/H ₂ O	58.5	23.3	86.4	23.7	20.9	4.8	32.8	10.2
CO/H ₂	78.3	36.1	78	26.8	21.5	5.4	94.7	13.2
HCN	25.8	8.2	149.3	36.4	67.3	44.6	191	45.2
HCN/H ₂ O	44.1	18.7	114.7	38.2	87.9	29.1	138.6	30.6
O ₂	62.7	11.6	47.8	22.9	14	7.9		
O ₂ /H ₂ O	51	18.4	44.3	24.6	17.5	7.8		
CO ₂	57.4	9.3	42.2	17.6	17.2	4.8	46.8	13.3
CO ₂ /H ₂ O	55.8	17.1	39.5	21.4	26.6	5.1	37.6	13.7

In situations where time is of the essence, it is not desirable to wait for steady-state values to be obtained. For these cases, 80% response and recovery times can provide a much quicker “snapshot” of the conditions. The Dräger and MX6 CPMs were tested at some mid-point concentrations for their ability to respond and recover quickly in the presence of HCN, CO, and CO₂. The Dräger monitor was also tested for its response to falling O₂ levels. The results are collected in **Table 2**. Here, the Dräger continues to respond more quickly to changes in gas concentrations, but the differences are much less pronounced.

Table 2: Approximate 80% response and recovery times for individual sensors

	Dräger		MX6	
	<i>Response (s)</i>	<i>Recovery (s)</i>	<i>Response (s)</i>	<i>Recovery (s)</i>
HCN - 4.33 ppm	9	10	46	45
CO - 100 ppm	12	14	12	16
CO ₂ - 1.176%	9	12	16	15
O ₂ - 16.8%	4	4		

4.0 Summary

Combustion products monitors from four different companies were tested in the JSC Toxicology Laboratory as NASA plans to select a new monitor to replace the discontinued model from Industrial Scientific. These tests aimed to determine the accuracy in concentration measurements, the effects of humidity, the effects of hydrogen gas on the individual carbon monoxide sensors, and the response times of the monitors. For the gases tested, the Dräger monitor was consistently more accurate than the GfG, YesAir, and MX6 monitors and performed well in the presence of H₂ and humidity. With the exception of HCN response, in which it was slower than the GfG monitor, the Dräger monitor also responded more quickly in the gas testing. The other monitors performed well in specific tests, with the YesAir and MX6 monitors performing in a relatively similar fashion and generally more accurate than the GfG monitor.