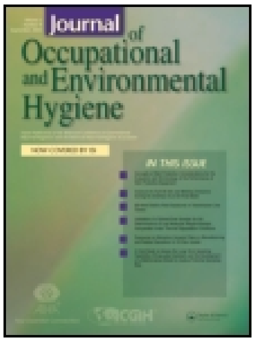

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Measurement Capability of Field Portable Organic Vapor Monitoring Instruments Under Different Experimental Conditions

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The performance of field portable direct-reading organic vapor monitors (DROVMs) was evaluated under a variety of experimental conditions. Four of the DROVMs had photoionization detectors (ppbRAE, IAQRAE, MultiRAE, and Century Toxic Vapor Analyzer), one had a flame ionization detector (Century Toxic Vapor Analyzer), and one was a single-beam infrared spectrophotometer (SapphIRe). Four of each DROVM (two Century Toxic Vapor Analyzers and SapphIRes) were tested. The DROVMs were evaluated at three temperatures (4°C, 21°C, and 38°C), three relative humidities (30%, 60%, and 90%), and two hexane concentrations (5 ppm and 100 ppm). These conditions were selected to provide a range within the operational parameters of all the instruments. At least four replicate trials were performed across the 18 experimental conditions (3 temperatures × 3 relative humidities × 2 concentrations). To evaluate performance, the 4-hr time-weighted average readings from the DROVMs in a given trial were compared with the average of two charcoal tube concentrations using pairwise comparison. The pairwise comparison criterion was ±25% measurement agreement between each individual DROVM and the DROVMs as a group and the average charcoal tube concentration. The ppbRAE group performed the best with 40% of all readings meeting the comparison criterion followed by the SapphIRe group at 39%. Among individual DROVMs, the best performer was a SapphIRe, with 57% of its readings meeting the criterion. The data was further analyzed by temperature, humidity, and concentration. The results indicated the performance of some DROVMs may be affected by temperature, humidity, and/or concentration. The ppbRAE group performed best at 21°C with the percentage of readings meeting the criterion increasing to 63%. At the 5 ppm concentration, 44% of the ppbRAE group readings met the criterion, while at 100 ppm, only 35% did. The results indicate that monitors can be used as survey tools. Based on the data, the inconsistent performance of these DROVMs may not allow them to be used for determining compliance with occupational exposure limits.

Keywords direct-reading organic vapor monitors, gases, performance

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INTRODUCTION

Portable direct-reading organic vapor monitors (DROVMs) have found application as survey tools and as a means of assessing hazards in the areas of confined space entry and emergency response. The advantages of DROVMs are as follows: (1) short lag time between the measurement and the reporting of the result, (2) rapid response and logging of changes in concentration, (3) allowing both peak and time-integrated concentration determinations, (4) providing real-time exposure information to the worker for modifying their work habits during their shift, and (5) allowing more informed decisions on the type of environmental controls and respiratory protection needed.

The specific application for which the DROVM is being used will dictate the appropriate performance requirements. For a DROVM used as a survey tool to detect sources of organic vapor emissions or to assess the overall volatile organic compound (VOC) concentration on site, the requirements may not be as stringent as for a monitor being used to determine compliance with an occupational exposure limit. Monitors for compliance must have greater reliability in terms of accuracy and precision of the measurements, and any bias and/or potential interferences must be identified and characterized.

Accuracy is the degree of agreement between a measured value and the accepted reference value. Precision is the repeatability or reproducibility of individual measurements expressed as standard deviation or relative standard deviation. Bias is the difference between the average measured value and reference value.(1) The most common method for determining an employee's time-weighted exposure average to VOCs is personal sampling using charcoal or thermal desorption tubes followed by chromatographic analysis. Therefore, any DROVM used for compliance assessment must have at least the same level of performance as the conventional method.

Several studies have compared the responses of portable direct-reading photoionization detectors with charcoal tube analysis. Drummond(2) placed a standard charcoal tube on the outlet of a photoionization detector (PID) equipped with a positive displacement sampling pump and tested this system in both the laboratory and field. He found that a consistent response factor could be determined by taking the time-weighted average (TWA) concentration from the charcoal tube and dividing it by the TWA concentration of the PID. For a truck driver loading gasoline, the response factor for benzene was determined to be 0.20.

Poirot et al.(3) compared the response of a PID with charcoal tubes in the laboratory using six different VOCs with sampling times ranging from 5 to 120 min. The same type of comparison was conducted at two different workplaces — during house painting and industrial site reclamation. The workplace sampling was used to determine whether the exposures exceeded either the long-term (8-hr TWA) or short-term (15 min) exposure limits. Good correlation (r^2 close to 1) was found between the PID responses and the charcoal tube concentrations in both the laboratory and in the workplaces. The authors concluded the PID is an excellent means to show possible changes in a worker's exposure.

Coy et al.(4) compared 26 side-by-side TWA personal breathing samples on construction painters using standard charcoal tubes analyzed by gas chromatography and a RAE Systems "Professional PID." The authors suggested the PID response was representative of the TWA total hydrocarbon exposure based on the high correlation ($r^2 = 0.95$). The PID underestimated the exposures in comparison with the charcoal tubes. The authors concluded the use of a PID was appropriate to assess exposures to solvent mixtures. Collectively, these studies show that a PID instruments can over- and underestimate hydrocarbon concentrations depending on numerous factors, such as the ionization potential of the hydrocarbons of interest, the calibration gas/vapor (concentration and composition), the PID lamp emission intensity, interferences between compounds, etc.

The above studies did not evaluate the performance of multiple units of the same DROVM and did not control the environmental conditions. The current study sought to determine the inter- and intra-DROVM performance using multiple units of five different DROVMs. The study also included varying temperature, relative humidity (RH), and concentration to determine the effect on instrument performance.

MATERIALS AND METHODS

Instrumentation

This study evaluated multiple units of five different DROVMs: IAQRAE Indoor Air Quality Monitors with PID (model PGM-5210; RAE Systems, Inc., Sunnyvale, Calif.); PID ppbRAE Parts per Billion VOC Monitors (model PGM-7240; RAE Systems, Inc.); MultiRAE Plus Multiple-Gas Monitors with PID (model PGM-50/5P, RAE Systems, Inc.); MIRANSapphIRe Portable Ambient Air Analyzers with a single-beam infrared spectrophotometer (series 205B, model 100; Thermo Environmental Instruments, Inc., Franklin, Mass.); and Century Portable Toxic Vapor Analyzers (TVAs, model TVA-1000B, Thermo Environmental Instruments, Inc.) with a PID and a flame ionization detector (FID). The testing was conducted using four IAQRAEs, ppbRAEs, and MultiRAEs and two SapphIRes and TVAs.

Instrumentation Calibration

The DROVMs tested were purchased new specifically for this study and were calibrated by their respective manufacturers prior to the beginning of the study. The DROVMs were field calibrated daily (except the SapphIRes) with a two-step process in an adjacent laboratory using compressed zero air and span gas certified to contain 400 ppm hexane in air. The SapphIRes, as per the manufacturer, required only daily zeroing. The hexane calibration data contained in the monitor's fixed library was used to determine the hexane response during testing.

Environmental Conditions

Two concentrations of hexane (95+% HPLC grade n-hexane, catalog number 43, 917-7, Sigma Chemical Company, St. Louis, Mo.) were used to challenge the DROVMs to determine if performance was affected by concentration (5 and 100 ppm). Five ppm was selected as the lowest concentration all the instruments could detect that also provided measurable charcoal tube standard samples using a sampling time of 4 hr. The 100-ppm level was selected because it is the concentration common to all instruments that allowed proper charcoal tube sampling without requiring low flow rates on the sampling pumps. Another reason for using 100 ppm was that it has been demonstrated that FIDs have an inherent non-linear response above 100 ppm.(5) Three temperatures were used: 4°C, 21°C, and 38°C (tolerance ± 2°C). The range represents temperatures found in industrial environments and meets the various DROVM specifications. Three target RH conditions were applied at each of the three temperatures: 30%, 60%, and 90%. The humidities encompass the operational range of the instruments. At least four replicates were performed for each temperature and RH combination. The replicates at each temperature and RH combination were conducted consecutively to minimize the time required for acclimatization of the environmental chamber between environmental conditions.

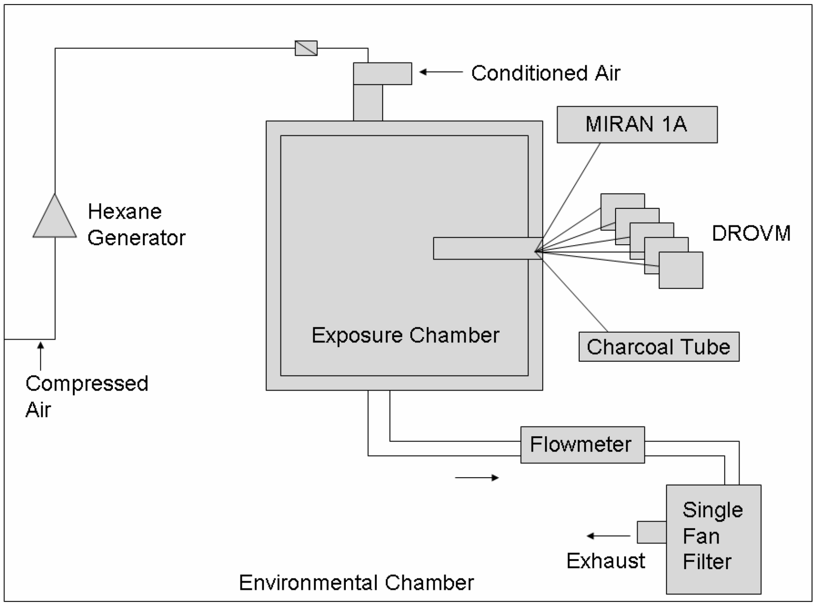

FIGURE 1. Schematic of test setup of environmental and exposure chambers

Instrumentation Testing

All testing was conducted in a 22-m^3 walk-in environmental chamber (Nor-Lake ENVIROLINE; Nor-Lake Scientific, Hudson, Wis.), which provided control of temperature and RH. A 0.4 m^3 Rochester-style (exposure) chamber was placed inside the environmental chamber. The hexane vapor was generated using a bubbler system that was connected to the exposure chamber via a manual airflow control valve (Figure 1).

Exhaust from the exposure chamber was routed through a single fan filter housing (model FS4000; Flow Sciences, Wilmington, N.C.) equipped with an organic solvent bed filter (model FS4251; Flow Sciences) before being returned to the environmental chamber. Total airflow through the exposure chamber was 114 L/min. For each condition, the environmental chamber was programmed with the appropriate temperature and RH. Temperature and RH conditions were monitored in the exposure and environmental chambers by NIST-traceable temperature and humidity reference data loggers (model PRHTEMP 101; MadgeTech, Inc., West Warner, N.H.). Three MadgeTech samplers were used, two in the exposure chamber (at the left lower side and the right upper side) and one to monitor the environmental chamber's temperature and RH (placed on top of the exposure chamber). The conditions were logged at 1-min intervals throughout the test.

For each replicate, two Anasorb coconut shell charcoal sorbent sample tubes (catalog number 226-01; SKC, Eighty Four, Pa.) were placed in the center of the exposure chamber and connected to personal sampling pumps (model SP730; TSI, Incorporated, Shoreview, Minn.) set to a flow rate of 0.1 L min^{-1}. The pumps had been calibrated by the manufacturer prior to the beginning of the study and were also calibrated weekly using a DryCal flow calibrator (model DC-1SC Rev. E; BIOS International, Pompton Plains, N.J.). Both tubes were analyzed by an AIHA-accredited lab for total hydrocarbons using the National Institute for Occupational Safety and Health (NIOSH) Method 1500.(6) Each DROVM, except the SapphIRes, which used the supplied sampling wands, was connected to tubing that ran from the instrument's sensor port to the center of the exposure chamber so that each instrument sampled the same atmosphere. After daily field calibration, the instruments were equilibrated in the exposure chamber for 10 min prior to testing.

To ensure the hexane concentration in the exposure chamber met the target concentration and was stable throughout the test, it was monitored using a Miran 1A general purpose gas analyzer (model 1A-AA1; The Foxboro Company, Bridgewater, Mass.). The Miran 1A was calibrated daily before each test with a 5 ppm or 100 ppm solution of hexane in carbon tetrachloride (reagent grade, 99.9%; catalog number 319961; Sigma-Aldrich Chemical Corp., St. Louis, Mo.).

Data Analysis

Pairwise comparisons were used to determine if the DROVMs and charcoal tube averages were equivalent. Minute-by-minute measurements across the 4-hr experimental duration totaled 240 data points per experimental trial. The average of the 240 measurements for an individual experimental trial was calculated for each unit and used to conduct pairwise comparisons to determine the measurement agreement among and between the five DROVM groups compared with the average concentration measured by the charcoal tubes. A DROVM average was considered to be equivalent if it was within ±25% of the average charcoal tube concentration. The 25% agreement criterion was chosen to coincide with the current Occupational Safety and Health Administration equivalency criterion.(7) Comparisons were made across combined experimental conditions and across separated conditions, by target temperature, humidity, and concentration.

RESULTS

All completed tests were considered valid if the instrument field calibrated and logged readings of zero or greater. Two tests at the 4°C/60%/100 ppm condition were invalid: Trial 2 for MultiRAE #4 and Trial 1 for IAQRAE #4. The cause for these invalid tests could not be determined, and the instruments functioned normally after the invalid tests.

The pairwise comparisons indicated that the IAQRAE, the ppbRAE, and the SapphIRe groups had the highest agreement with the charcoal tube average under all conditions (Figure 2). To discern the effect of temperature, RH, and concentration on the comparability of a monitor group to the charcoal tube average, the data was segregated into the target environmental conditions. The IAQRAE, the ppbRAE, and the SapphIRe groups continued the trend to the highest comparability with the charcoal tube average for the individual environmental conditions except at 4°C where the only the SapphIRe group continued comparable performance.

The pairwise comparisons were conducted not only for the groups but also for each individual DROVM to determine if it performed better than its group. The four best performing DROVMs (SapphIRe #1, IAQRAE #1, and ppbRAE #2 and #4) were selected based on the total number of readings meeting the 25% criterion for all the environmental conditions combined (Table I). All four of these individual instruments had at least a 42% agreement with the charcoal tube average (Figure 3) under all environmental conditions. SapphIRe #1 was most comparable to the charcoal tube averages with a 67% agreement (Figure 3 and Table I). Figure 3 demonstrates that both ppbRAEs were equally affected by temperature at 4°C, and overall, these individual DVORMs were more comparable than their group.

Table II provides the mean and standard deviation for the concentrations measured by the charcoal tubes vs. the group and individual DROVM measurements. Most of the group and individual averages were higher than the charcoal tube averages, with the instruments showing greater variability as evidenced by their standard deviations.

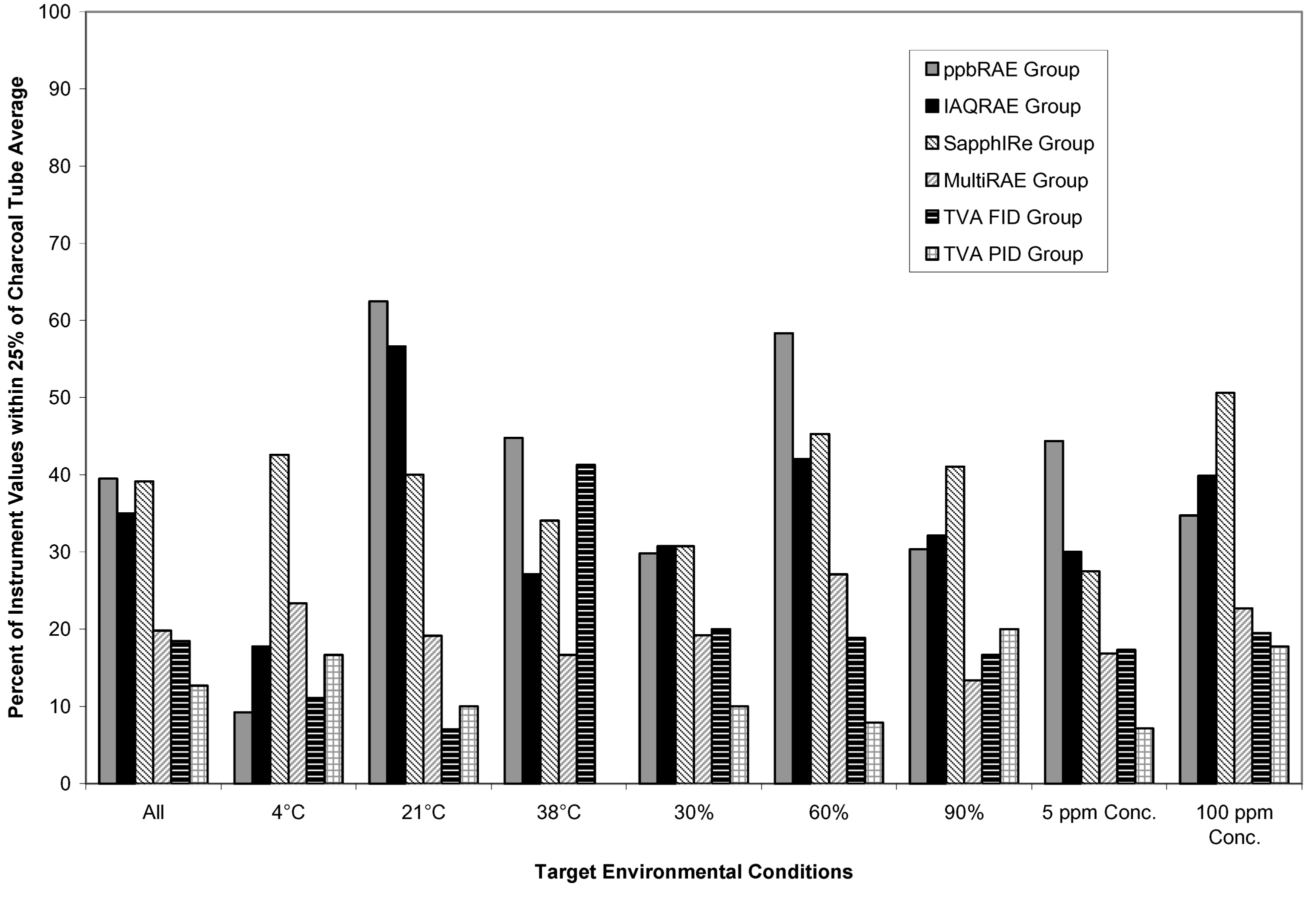

FIGURE 2. Pairwise comparison of DROVMs to charcoal tubes using 25% criterion

TABLE I. Number of DROVM of Readings Within ±25% of Average Tube Values

	Target Environmental Condition							
	All		4°C		21°C		38°C	
Instrument	Tests Within Criterion	Total Tests Completed	Tests Within Criterion	Total Tests Completed	Tests Within Criterion	Total Tests Completed	Tests Within Criterion	Total Tests Completed
ppbRAE group	128	324	10	108	75	120	43	96
ppbRAE #1	29	81	0	27	19	30	10	24
ppbRAE #2	38	81	5	27	24	30	9	24
ppbRAE #3	25	81	0	27	14	30	11	24
ppbRAE #4	36	81	5	27	18	30	13	24
IAQRAE group	113	323	19	107	68	120	26	96
IAQRAE #1	34	81	11	27	15	30	8	24
IAQRAE #2	27	81	7	27	16	30	4	24
IAQRAE #3	29	81	0	27	20	30	9	24
IAQRAE #4	23	80	1	26	17	30	5	24
SapphIRe group	63	161	23	54	24	60	16	47
SapphIRe #1	54	81	23	27	17	30	14	24
SapphIRe #2	9	80	0	27	7	30	2	23
MultiRAE group	64	323	25	107	23	120	16	96
MultiRAE #1	14	81	9	27	3	30	2	24
MultiRAE #2	18	81	1	27	7	30	10	24
MultiRAE #3	17	81	10	27	6	30	1	24
MultiRAE #4	15	80	5	26	7	30	3	24
TVA-FID group	29	157	6	54	4	57	19	46
TVA-FID #1	10	78	0	27	1	27	9	24
TVA-FID #2	19	79	6	27	3	30	10	22
TVA-PID group	15	118	9	54	6	60	0	4
TVA-PID #1	7	59	5	27	2	30	0	2
TVA-PID #2	8	76	4	27	4	30	0	2

	Environmental Condition									
	30%		60%		90%		5 ppm		100 ppm	
Instrument	Tests Within Criterion	Total Tests Completed	Tests Within Criterion	Total Tests Completed	Tests Within Criterion	Total Tests Completed	Tests Within Criterion	Total Tests Completed	Tests Within Criterion	Total Tests Completed
ppbRAE group	31	104	63	108	34	112	71	160	57	164
ppbRAE #1	8	26	15	27	6	28	15	40	14	41
ppbRAE #2	12	26	15	27	11	28	20	40	18	41
ppbRAE #3	4	26	14	27	7	28	13	40	12	41
ppbRAE #4	7	26	19	27	10	28	23	40	13	41
IAQRAE group	32	104	45	107	36	112	48	160	65	163
IAQRAE #1	10	26	11	27	13	28	15	40	19	41
IAQRAE #2	8	26	9	27	10	28	11	40	16	41
IAQRAE #3	8	26	14	27	7	28	12	40	17	41
IAQRAE #4	6	26	11	26	6	28	10	40	13	40
SapphIRe group	16	52	24	53	23	56	22	80	41	81
SapphIRe #1	15	26	19	27	20	28	13	40	41	41
SapphIRe #2	1	26	5	26	3	28	9	40	0	40
MultiRAE group	20	104	29	107	15	112	27	160	37	163
MultiRAE #1	4	26	8	27	2	28	6	40	8	41
MultiRAE #2	5	26	9	27	4	28	8	40	10	41
MultiRAE #3	8	26	6	27	3	28	5	40	12	41
MultiRAE #4	3	26	6	26	6	28	8	40	7	40
TVA-FID group	10	50	10	53	9	54	13	75	16	82
TVA-FID #1	5	24	3	26	2	28	4	37	6	41
TVA-FID #2	5	26	7	27	7	26	9	38	10	41
TVA-PID group	4	40	3	38	8	40	4	56	11	62
TVA-PID #1	3	20	2	19	2	20	0	28	7	31
TVA-PID #2	1	20	1	19	6	20	4	28	4	31

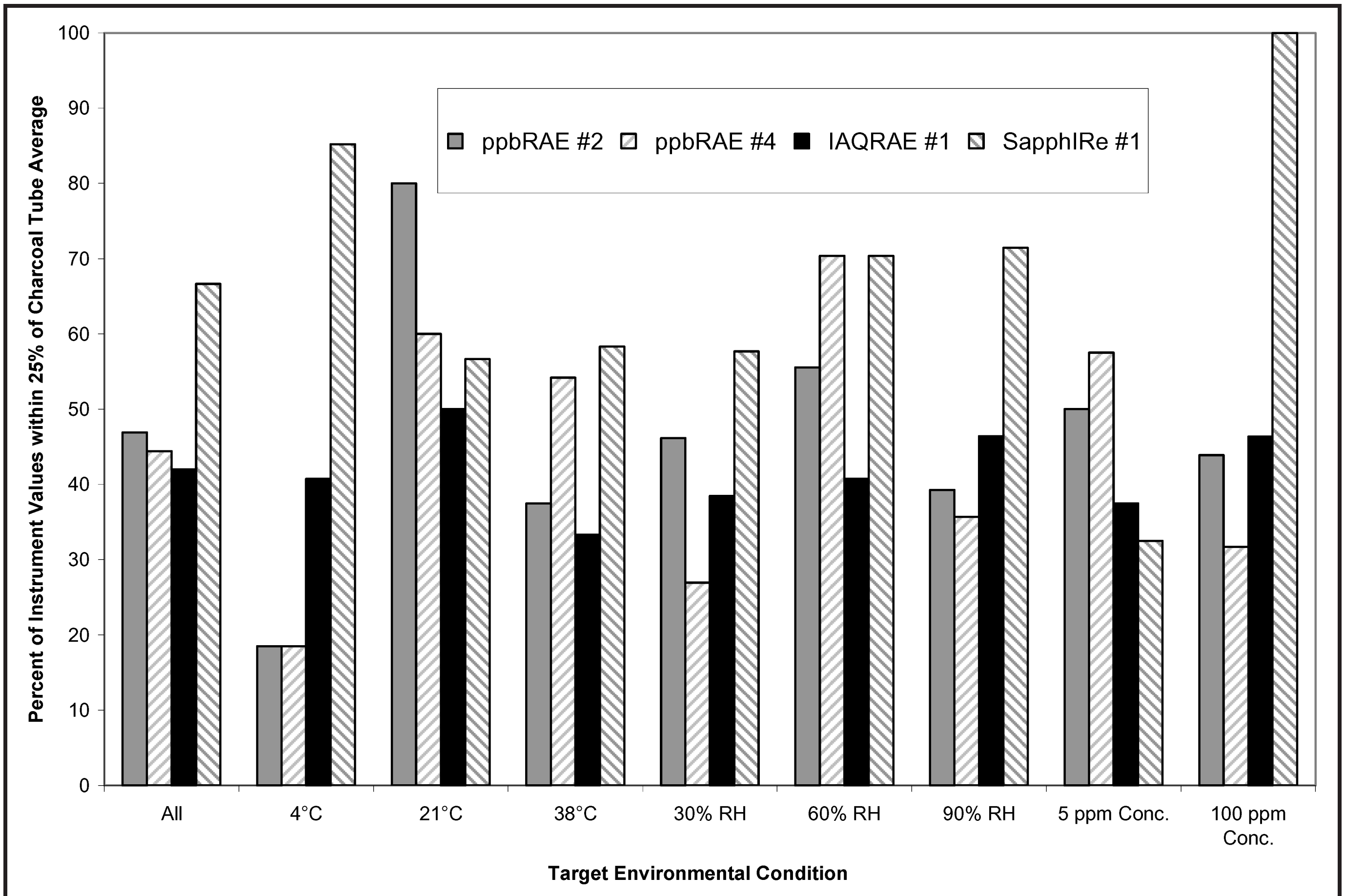

FIGURE 3. Pairwise comparison of four best performing DROVM units to charcoal tubes using 25% criterion

DISCUSSION

The variability among the DROVMs used in this study demonstrated the need for using multiple monitors of the same type to evaluate performance as previously undocumented differences were found. The inherent variability impeded the determination of temperature, RH, and concentration effects on DROVM performance although analysis of the data from individual DROVMs indicated that at least the ppbRAEs were affected by temperature. Temperature effects varied across the various DROVM groups even among those using the same type of sensor.

For example, four of the DROVM groups (TVA, IAQRAE, MultiRAE, and ppbRAE) all used a PID to detect VOCs but demonstrated differing effects in response to changes in temperature. The IAQRAE and ppbRAE groups performed best at 21°C, while the TVA-PID group performed the best at 4°C. The MultiRAE group performed approximately the same at all three temperatures. The PIDs performed differently in response to concentration. The IAQRAE group performed better at the high concentration, while the ppbRAE group performed better at the low concentration. This might be due to the inherent design of the ppbRAE instrument to detect concentrations as low as 1 ppb.

Others have also attempted to assess temperature and RH effects on inter-DROVM comparability. Barsky et al.(5) compared the response of a PID with a 10.2 eV lamp and a second PID having an 11.8 eV lamp to a portable FID organic vapor analyzer. Eight different VOCs were measured in air at two humidities (0% and 90%). The authors concluded that the FID was practically unaffected at the high humidity condition (≤10% decrease as compared with the 0% condition) at concentrations below 100 ppm. The effects noted above this concentration were caused by the inherent nonlinearity of the FID response. The 10.8 eV PID response was found to be sensitive to humidity despite water vapor having an ionization potential of 12.6 eV. The responses to benzene and toluene (similarly structured compounds) at 90% humidity were only 27% and 78%, respectively, of the responses in dry air. The 11.8 eV PID appeared to have equal responses among the different VOCs. It was shown to detect water vapor, rendering it unsuitable for use in high humidity environments. Barsky et al.(8) conducted another study of multi-DROVM comparability when monitoring VOCs. When used in high humidity conditions (approximately 90%), the PID response was dependent on the compound. The response appeared to decrease by a factor of 2 for all classes of compounds except for saturated halogenated alkanes. The current study

TABLE II. Individual Monitor Means and Standard Deviations (SD) Hexane Concentration Readings

	5 ppm		100 ppm	
Monitor	Mean (ppm)	SD	Mean (ppm)	SD
Charcoal tube average	5.8	2.0	89.8	10.8
Charcoal Tube 1	5.7	2.1	89.9	11.7
Charcoal Tube 2	5.9	2.0	91.7	10.0
ppbRAE group	8.8	13.1	119.8	33.4
ppbRAE #1	9.4	12.6	123.8	30.9
ppbRAE #2	7.4	10.3	113.1	30.6
ppbRAE #3	9.1	17.4	123.5	36.8
ppbRAE #4	9.2	10.7	118.7	33.6
IAQRAE group	16.1	51.6	104.3	41.6
IAQRAE #1	11.3	22.7	97.4	36.0
IAQRAE #2	31.2	91.3	103.3	47.5
IAQRAE #3	7.6	4.9	106.0	35.4
IAQRAE #4	14.5	38.1	110.6	45.1
SapphIRe group	8.5	24.3	122.0	45.8
SapphIRe #1	6.8	16.4	87.4	18.4
SapphIRe #2	10.1	30.0	156.6	38.2
MultiRAE group	11.1	54.5	94.5	51.6
MultiRAE #1	6.2	12.1	72.5	44.9
MultiRAE #2	9.0	11.9	109.2	37.5
MultiRAE #3	7.3	10.3	86.0	58.5
MultiRAE #4	21.9	106.4	110.7	52.7
TVA-FID group	4.5	4.8	64.3	50.3
TVA-FID #1	3.6	2.5	63.6	51.7
TVA-FID #2	5.2	5.8	64.9	49.2
TVA-PID group	85.1	187.9	143.9	146.7
TVA-PID #1	45.6	23.6	130.5	130.1
TVA-PID #2	111.9	239.1	152.2	155.6

agreed with Barsky et al. in that the TVA-FID comparability was not affected by RH. The finding for the PIDs (TVA, IAQRAE, MultiRAE, and ppbRAE) differed across RH, but no discernible differences were detected.

A number of factors in the experimental design of the current study could have contributed to the observed variability. All possible precautions were taken to allow tight control of the environmental conditions, although not all tests were equally controlled. Control of chamber humidity was difficult, with the actual humidity values for the higher humidity tests generally lower than what was desired. This was the result of poor humidity control by the environmental chamber and the increased recovery time whenever the door was opened at higher humidity levels. There is some overlap between actual humidity levels during tests conducted at what was termed 60% and tests at what was termed 90%.

Another issue is that this study used only one vapor, hexane. Except for the SapphIRes, the DROVMs tested cannot resolve multiple gases/vapors in the same environment. The inability to differentiate among a mixture of gases is another key limitation in using DROVMs for compliance or in efforts to quantify specific gases or vapors, since there are very few environments that contain only a single gas or vapor. Multiple gases/vapors may impact the DROVM's performance, since the instrument's sensitivity may vary by gas/vapor.

The manufacturers state their DROVMs should not be used in condensing humidity conditions. Space limitations required charging and calibrating instruments outside the environmental chamber. Bringing the DROVMs from normal laboratory conditions (approximately 22°C and 40% RH) into the environmental chamber at the extremes of temperature and humidity might have caused condensation in the DROVMs. However, this was not substantiated by the data.

All other experimental practices were conducted to conform to manufacturer's recommendations, and yet, unexpected differences in instrument performance were experienced. Both TVA-PIDs exhibited abnormal performance, most notably the 4°C and 21C° conditions. TVA-PID #2 began each test with readings around ∼100 ppm with the values gradually increasing throughout the 4-hr test until the readings were in the 100 ppm range even for tests conducted at the 5 ppm hexane concentration. Within four weeks, TVA-PID #1 started exhibiting the reverse. The readings at the beginning of each test were in the 100-ppm range and decreased steadily until at the end of the test they were in the −100 ppm range. The number of negative values logged during a test ranged from 10 to over 200.

The two TVA-PIDs were not the only instruments to record negative values. For 14 of the 81 tests, the two SapphIRes registered negative values. The maximum number for a test was 166 for SapphIRE #2. IAQRAE #2 and #3 had five and four tests, respectively, where negative values were logged. In about half of these tests, the total number of negative values was less than 25. For the other tests, the values ranged between 156 and 208. The reason for negative readings is unknown, although an issue with the electronics is a possible explanation.

Future developments to the instrument electronics and software should not allow for data logging of negative values. Rather, the user should be alerted with an error message, and those readings should be discontinued or at least flagged by the software. During the statistical analyses for this study, all negative values were set to missing so that these values would not affect the performance determinations.

The number of zero values logged by each instrument was also investigated. All the MultiRAE units had tests with zero values even at a concentration of 100 ppm. The number of zero values ranged from 60 to 194. Because these zero values were treated as valid data points, they are a possible cause of the MultiRAE group values not having a large agreement with the charcoal tube average. The lack of a high degree of agreement between the DROVM groups and the charcoal tubes indicates the wide variations in instrument response were apparently random and followed no pattern.

Every DROVM unit did not complete every test. For example, the threads on TVA-FID #1 became damaged with almost 4 weeks left in the testing scheme. A week later the TVA-PID #1 became inoperable. Neither SapphIRe battery was able to last the full 4 hours of testing with both instruments sampling for about 3 hours in a test. Decisions about performance of these two DROVM groups were also affected by the use of only two units, but the expense of these DROVMs prohibited the purchase of more than two.

CONCLUSIONS

The five different types of DROVMs used in this study did not provide accurate and precise measurements in comparison with charcoal tube samples of hexane. The DROVM variability prevented conclusive determinations about the effects of temperature, RH, and concentration on instrument performance. A high degree of variability was seen between units of the same DROVM group sampling the same atmosphere as well as between groups. Because the DROVMs were not consistent with the charcoal tubes, they may not be suitable for compliance monitoring. Although the DROVMs' performance was poor in quantifying hexane to within 25% of the average charcoal tube concentration, their utility as survey meters to identify exposure sources or concentration profiles seems to be appropriate. Whatever their use, DROVMs should not be relied on without frequent and careful calibration checks and, where necessary, additional validation using a reference standard.

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