EPA/600/R-12/560 | August 2012 | www.epa.gov/ord

United States
Environmental Protection
Agency

Technology Evaluation Report

Testing and Evaluation of Handheld Toxic Industrial Chemical Detectors

Office of Research and Development
National Homeland Security Research Center

EPA 600/R-12/560
August 2012

Technology Evaluation Report

Testing and Evaluation of Handheld Toxic Industrial Chemical Detectors

Notice

The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development's National Homeland Security Research Center, funded and directed this technology evaluation under Work Assignments 1-10 and 2-10 of EPA Contract Number EP-C-10-001 with Battelle. This report has been peer and administratively reviewed and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use of a specific product.

Questions or comments should be addressed to:

Shannon Serre
National Homeland Security Research Center
Office of Research and Development
U.S. Environmental Protection Agency
Mail Code E343-06
Research Triangle Park, NC 27711

Executive Summary

The U.S. Environmental Protection Agency's (EPA's) National Homeland Security Research Center (NHSRC) helps protect human health and the environment from adverse impacts of terrorist acts by carrying out a variety of research activities, including performance tests on homeland security technologies. As part of its mission, NHSRC supports EPA's Regional On-Scene Coordinators and response teams, as well as state and local emergency response agencies, by evaluating technologies to meet the monitoring needs of their organizations. In particular, first responders and emergency management professionals need reliable, sensitive, and portable monitoring devices that can rapidly indicate the presence of hazardous conditions, including air containing reduced levels of oxygen, explosive levels of flammable chemicals in air, or harmful levels of toxic or corrosive chemicals.

This report describes testing to assess the performance of commercially available handheld detectors capable of quantifying oxygen (O_2), flammable mixtures (in terms of the lower explosive limit [LEL] for CH_4), and six toxic industrial compounds (TICs) (i.e., H_2S, SO_2, NH_3, Cl_2, PH_3, and HCN) at concentrations that would present a threat to emergency response personnel. The evaluation reported here used realistically hazardous concentrations of the target species, matched to the detection ranges of each of the detectors. Testing evaluated the following quantitative performance parameters:

- Response and Recovery Time
- Accuracy
- Repeatability
- Response Threshold (i.e., detection limit)
- Effect of Operating Conditions (i.e., temperature and relative humidity [RH])
- Effect of O_2 Deficiency on TIC Response
- Cold/Hot Start Behavior
- Interference Effects
- Battery Life

Operational factors such as size and weight; ease of use; clarity of displays, alarms, and instructions; startup and shutdown procedures; sensor replacement; maintenance issues; and design features affecting handheld operation were also evaluated. The ease of using each detector with personal protective equipment including heavy gloves was also assessed. Testing was conducted over a temperature range of approximately 8 to 35 °C and an RH range from less than 20% to approximately 80%. Interferent testing was conducted using vapors of the following six materials, both in otherwise clean air (to assess false positive responses) and comingled with O_2, CH_4, and each of the six TICs (to assess false negative responses):

- Latex paint
- Gasoline exhaust hydrocarbons
- Diesel exhaust hydrocarbons
- Ammonia cleaner
- Air freshener
- N,N-diethylaminoethanol (DEAE) (a boiler and humidification water additive)

The seven handheld detectors subjected to testing were:

- BW Technologies GasAlert Micro 5
- Dräger X-am 7000
- Environics ChemPro 100i

- Industrial Scientific iBRID MX6
- RAE Systems MultiRAE Pro
- RKI Instruments Eagle 2
- Sperian PHD6

All of the tested detectors except the Environics ChemPro 100i employed a galvanic cell for percent O_2 measurement, a catalytic bead sensor for LEL, and electrochemical (EC) cells for TIC detection. Those six detectors could not incorporate sensors to detect all of the target gases at once, so each detector was purchased with a set of sensors installed and additional sensors were substituted into the detectors as needed to conduct the testing. The ChemPro 100i employed a multi-sensor measurement approach that includes open-loop ion mobility spectrometry along with semiconductor, metal oxide semiconductor, and field effect sensors and temperature, RH, pressure, and flow sensors. The ChemPro 100i was not designed to determine atmospheric O_2 or LEL and, unlike the six other detectors, provided a qualitative reading of signal intensity rather than a measured concentration (e.g., in ppm).

In total, the testing reported here involved seven handheld detectors, eight target gases, six interferents, and six different temperature/RH conditions, as well as specific tests involving three cold start conditions and two levels of reduced O_2. The test results on each performance parameter are summarized below.

ES.1 Response and Recovery Time

Response and recovery time were determined as the elapsed time to achieve a stable detector reading after the start or end, respectively, of a target gas challenge. The response and recovery times of the seven handheld detectors in determination of TICs are summarized in Figures ES-1 and ES-2, respectively. Each figure shows the mean, median, and ±1 standard deviation (SD) range of all the response times recorded for each detector in all testing with the six TICs.

Figure ES-1 shows that the ChemPro 100i exhibited the fastest response overall in testing with the six TICs, and the iBRID MX6 exhibited the slowest response overall with those TICs. Median response times in the TIC testing ranged from approximately 20 seconds with the ChemPro 100i to approximately 100 seconds with the iBRID MX6. The other five detectors exhibited response times in TIC testing that were closely similar and intermediate between those of the ChemPro 100i and the iBRID MX6, e.g., median TIC response times of approximately 40 to 50 seconds. In testing of six detectors with O_2 and CH_4 (not shown in Figure ES-1), relatively faster response was observed as compared to the TIC responses. With O_2, response times for all six detectors were typically less than 30 seconds, and the Eagle 2 often responded in less than 10 seconds. With CH_4, response times for most of the six detectors were less than 30 seconds, with the GasAlert Micro 5

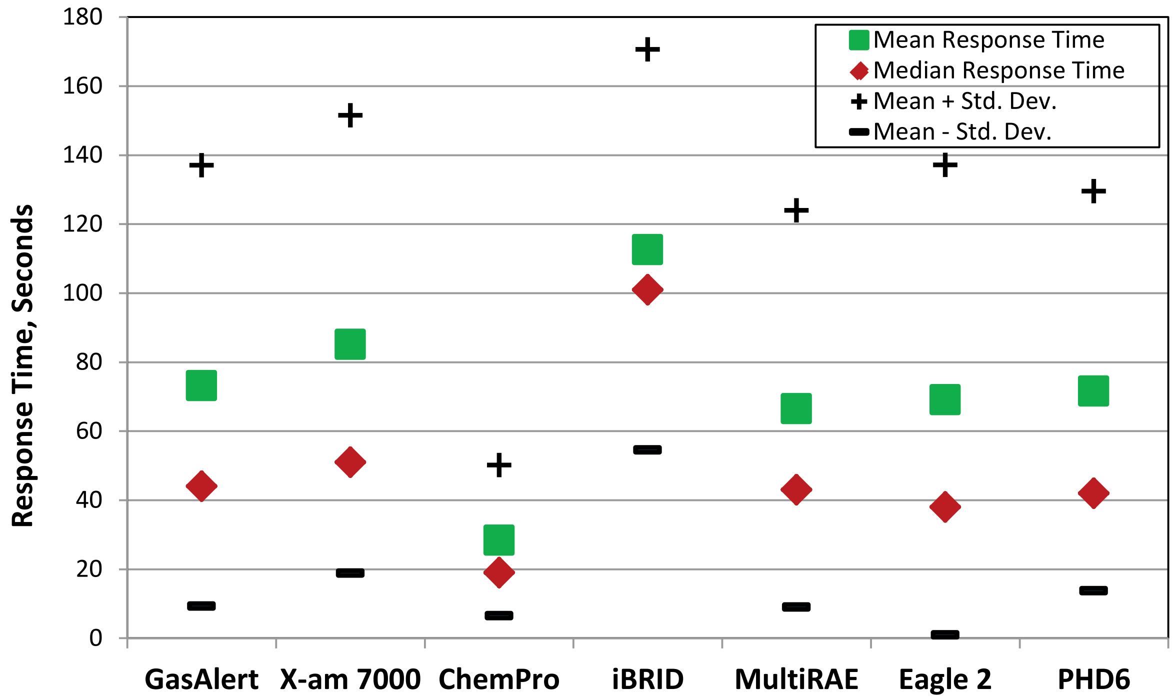

Figure ES-1. Summary of response time results in TIC testing.

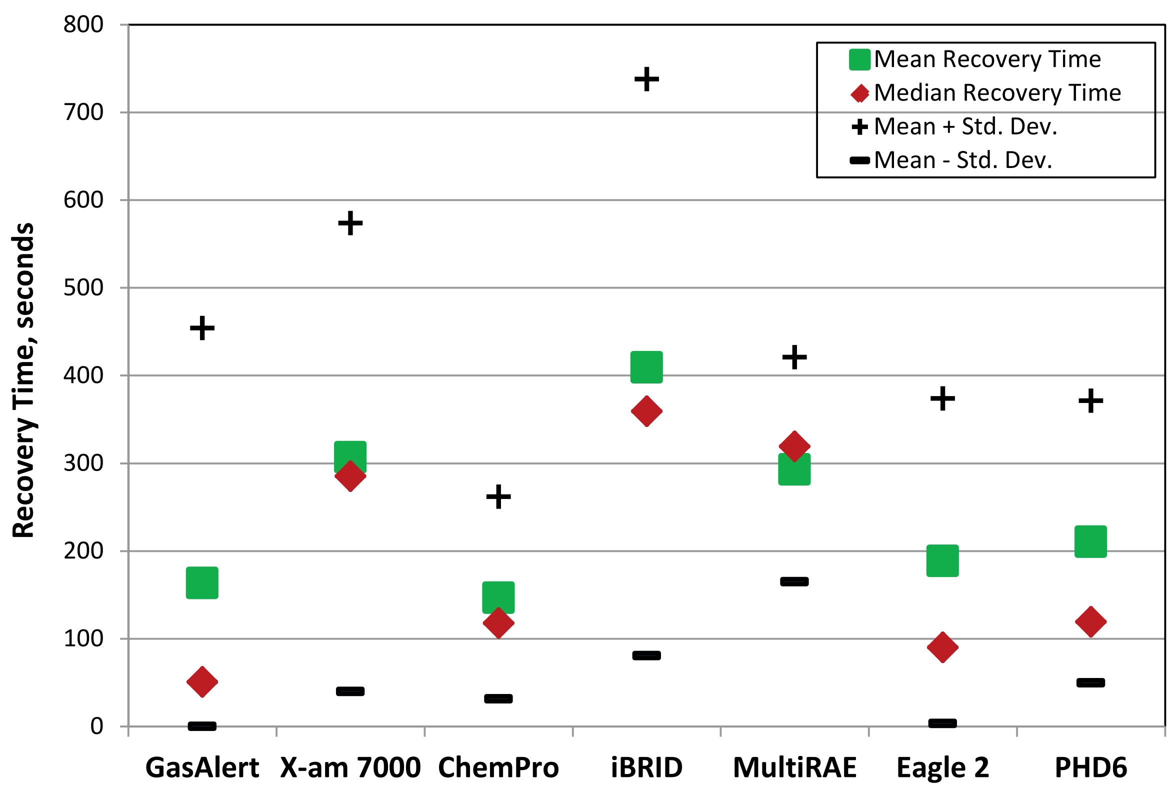

Figure ES-2. Summary of recovery time results in TIC testing.

always responding within 20 seconds and the Eagle 2 often responding in 10 seconds or less. The X-am 7000 response times for CH_4 ranged from about 30 to nearly 50 seconds.

Figure ES-2 shows that the GasAlert Micro 5, ChemPro 100i, Eagle 2, and PHD6 exhibited the fastest recovery overall in testing with the six TICs, and the iBRID MX6 exhibited the slowest recovery overall with those TICs. Median recovery times in the TIC testing ranged from approximately 50 seconds with the GasAlert Micro 5 to approximately 360 seconds with the iBRID MX6. In testing of six detectors with O_2 and CH_4 (not shown in Figure ES-2), relatively faster recovery was observed as compared to the TIC recoveries. With O_2, recovery times for most of the six detectors were typically less than 30 seconds, and the MultiRAE Pro and Eagle 2 often recovered in approximately 10 seconds or less. However, the recovery times for the Sperian PHD6 with O_2 were usually more than 40 seconds and ranged up to more than 250 seconds. With CH_4, recovery times for the six detectors were usually less than 25 seconds, but the GasAlert Micro 5, X-am 7000, iBRID MX6, MultiRAE Pro, and PHD6 all showed recovery times for CH_4 that exceeded 280 seconds in testing conducted at 35 °C.

ES.2 Accuracy

Quantitative accuracy (QUA) was determined for all detectors except the Environics ChemPro 100i, which provided a qualitative indication of response intensity rather than a quantitative concentration reading. Figure ES-3 summarizes the QUA results determined for the other six detectors in all testing with the six TICs, O_2, and CH_4. That figure shows the mean, median, and ±1 SD range of all the QUA values recorded for each detector in all testing, excluding any readings that resulted from a pegged overrange response on a detector. Thus, Figure ES-3 does not include values such as the 111% QUA recorded for the MultiRAE Pro with H_2S, which resulted from the monitor pegging at a reading of 99.9 ppm when challenged with 90 ppm of H_2S.

Figure ES-3 shows that the mean QUA values for the six detectors over all target gases ranged from 91% for the MultiRAE Pro to 125% for the iBRID MX6, and the median QUA values ranged from 95% for the MultiRAE Pro to 113% for the iBRID MX6. However, Figure ES-3 is based on only about two-thirds of the possible QUA results for the X-am 7000 due to non-quantitative overrange indications by that detector in some tests. The same is true for the MultiRAE Pro and Eagle 2 due to exclusion of fixed quantitative readings exhibited during overrange conditions on those detectors. The exclusion of these readings means that QUA values for those three detectors might be significantly higher if quantitative readings above the nominal full-scale value could be obtained from the detectors. In contrast, the iBRID MX6 and Sperian PHD6 never reported an overrange condition in any test. The PHD6 in particular achieved mean and median QUA values near 100% and a relatively narrow range of QUA results around 100%, as indicated by the ±1 SD range in Figure ES-3.

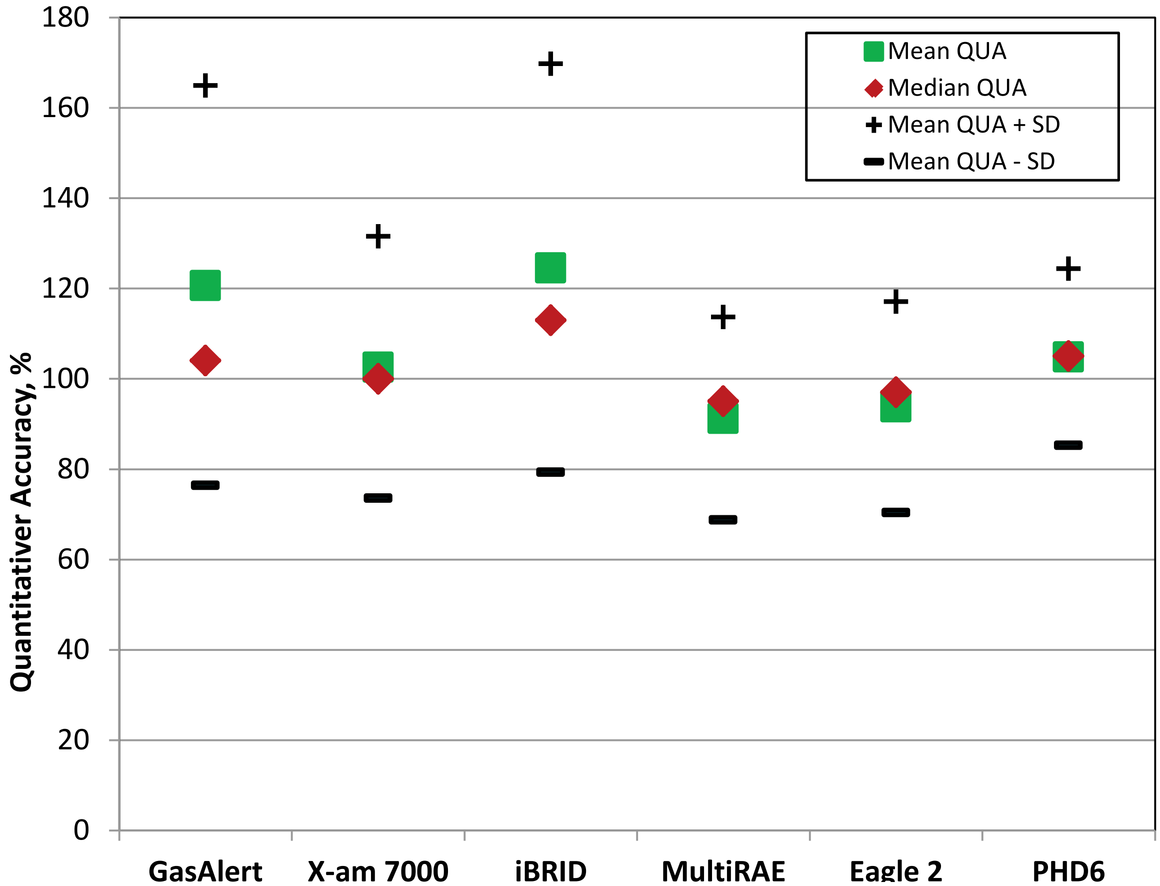

Figure ES-3. Summary of QUA results in TIC, O_2, and CH_4 testing (QUA not determined for ChemPro 100i). Data shown exclude any readings indicating a constant overrange condition of a detector.

Identification accuracy (IA) was 100% (i.e., the detectors correctly identified the gas challenge in all trials) in almost all tests. Other than in tests at the lowest challenge concentrations, the only cases of IA less than 100% were with the ChemPro 100i, which failed to respond in some tests with SO_2, NH_3, Cl_2, and HCN that involved interferent vapors or temperature and RH conditions other than 22°C and 50% RH.

ES.3 Repeatability

For the six detectors other than the ChemPro 100i, repeatability was consistently within 5% relative standard deviation (RSD) in detection of H_2S, SO_2, PH_3, HCN, O_2, and CH_4. A few exceptions of repeatability up to approximately 10% RSD occurred with the Eagle 2 with HCN and with the PHD6 with CH_4. Repeatability results were substantially higher (usually within 10% RSD, with occasional values of 20% or more) for all six detectors with NH_3 and Cl_2. Repeatability for these six detectors was not affected by interferent vapors or by test conditions of temperature and RH. Repeatability values for the ChemPro 100i were constrained by the detector's 1-to-3-bar intensity indication and, in most cases, the ChemPro 100i gave the same intensity response with all five challenges in a test (i.e., repeatability = 0% RSD). However, the presence of interferent vapors and test conditions other than room temperature and 50% RH sometimes degraded the repeatability of ChemPro 100i response.

ES.4 Response Threshold

With few exceptions, all detectors tested exhibited response thresholds of less than 3 ppm for H_2S and NH_3, less than 5 ppm for SO_2 and HCN, less than 1 ppm for Cl_2 and PH_3, and less than 0.2% by volume (i.e., less than 4% of the LEL) for CH_4. The exceptions were that the BW GasAlert Micro 5 showed a response threshold in the range of 1 to 3 ppm for Cl_2, the RAE MultiRAE Pro showed a response threshold in the range of 0.2 to 0.5% for CH_4, and the Environics ChemPro 100i showed response thresholds in the range of 20 to 50 ppm for SO_2, 10 to 50 ppm for NH_3, and 3 to 10 ppm for Cl_2. The observed response thresholds are generally far below the immediately dangerous to life and health (IDLH) levels for the target TICs; even the ChemPro 100i response thresholds for SO_2, NH_3, and Cl_2 are at least a factor of two less than the respective IDLH levels. Except in the case of NH_3, the response threshold testing reported above did not extend to low enough concentrations to prove detection at the acute (i.e., 1 hour) Reference Exposure Level values for these TICs.

ES.5 Effect of Operating Conditions

With all seven detectors the performance factors most affected by variations in temperature and RH conditions were response and recovery times, which were usually lengthened by conditions other than normal room temperature and 50% RH. Effects of temperature and RH on response and recovery times were seen less frequently with the ChemPro 100i than with the other six detectors. The performance factors least affected by variations in temperature and RH were QUA, IA, and repeatability. Effects on QUA occurred with several detectors (this performance parameter was not determined for the ChemPro 100i), whereas the majority of effects on IA and repeatability occurred with the ChemPro 100i.

ES.6 Effect of O_2 Deficiency on TIC Response

The RKI Eagle 2 showed no significant differences in any performance parameter for H_2S with reduced O_2 levels, and none of the detectors showed any significant differences in IA for H_2S at reduced O_2 levels. Significant effects of O_2 level on response time, recovery time, and QUA for H_2S were seen with some detectors. The response time for H_2S was shortened at the 16% O_2 level with both the BW GasAlert Micro 5 and Industrial Scientific iBRID MX6, but was increased (i.e., nearly doubled) with the Dräger X-am 7000 at both 19% and 16% O_2. The recovery time for H_2S was greatly increased at 16% O_2 for the Environics ChemPro 100i and at both 19% and 16% O_2 for the Industrial Scientific iBRID MX6. The QUA for H_2S declined consistently with reduced O_2 levels for the BW GasAlert Micro 5, Dräger X-am 7000, and Industrial Scientific iBRID MX6.

ES.7 Cold/Hot Start Behavior

In most cases, response times, QUA, IA, and repeatability for detection of H_2S were affected only minimally by rapid startup after storage overnight at room, cold, or hot temperature. The delay times between powering up each detector and being ready to begin monitoring similarly showed little impact from the storage condition before startup. However, recovery times were lengthened with several detectors, especially after rapid startup from room temperature or cold conditions. Repeatability was degraded with the ChemPro 100i after cold starts from all three storage conditions.

ES.8 Interference Effects

All of the seven detectors showed false positive (FP) responses in some tests when sampling an interferent vapor in otherwise clean air. Gasoline and diesel exhaust hydrocarbons and paint vapors were the interferents that most frequently caused FP responses. The MultiRAE Pro was the detector most subject to interference effects, showing FP responses with all six interferents in testing with H_2S, O_2, and CH_4, and FP responses with at least one interferent with every target gas. The ChemPro 100i and iBRID MX6 also showed FP responses with at least one interferent with every target gas with which they were tested. The X-am 7000 and GasAlert Micro 5 were the detectors least subject to FP responses. The X-am 7000 showed no FP responses at all in testing with H_2S, PH_3, HCN, and O_2. The GasAlert Micro 5 showed no FP responses at all in testing with H_2S, Cl_2, PH_3, HCN, and CH_4.

The false negative (FN) rates that resulted from the interferents were almost always zero. In fact, for six of the seven detectors (i.e., the GasAlert Micro 5, X-am 7000, iBRID MX6, MultiRAE Pro, Eagle 2, and PHD6) the FN rate was zero with every interferent in every test. FNs were observed with the ChemPro 100i in tests with SO_2, NH_3, Cl_2, and HCN. Gasoline engine exhaust hydrocarbons caused FN with the ChemPro 100i with all four of these TICs, and ammonia cleaner, air freshener, and diesel exhaust also caused FN responses in a few tests with the ChemPro 100i.

ES.9 Battery Life

The battery life of the seven detectors is illustrated in Figure ES-4, and ranged from less than 10 hours for the ChemPro 100i and Dräger X-am 7000 to nearly 46 hours for the RKI Eagle 2 unit E2A505. The two Eagle 2 units exhibited the longest and third-longest periods of battery life, but the battery life of Unit E2A505 was more than twice as long as that of Unit E2A410. This difference is attributed largely to the greater power demand of the LEL sensor in Unit E2A410.

ES.10 Operational Factors

The following are brief summaries of key positive and negative operational factors reported by the test operators for each handheld detector.

BW Technologies GasAlert Micro 5. This detector was small, lightweight, and easy to use, and large font on the display made it easy to read. Operating menus were easy to understand, calibration menus less so.

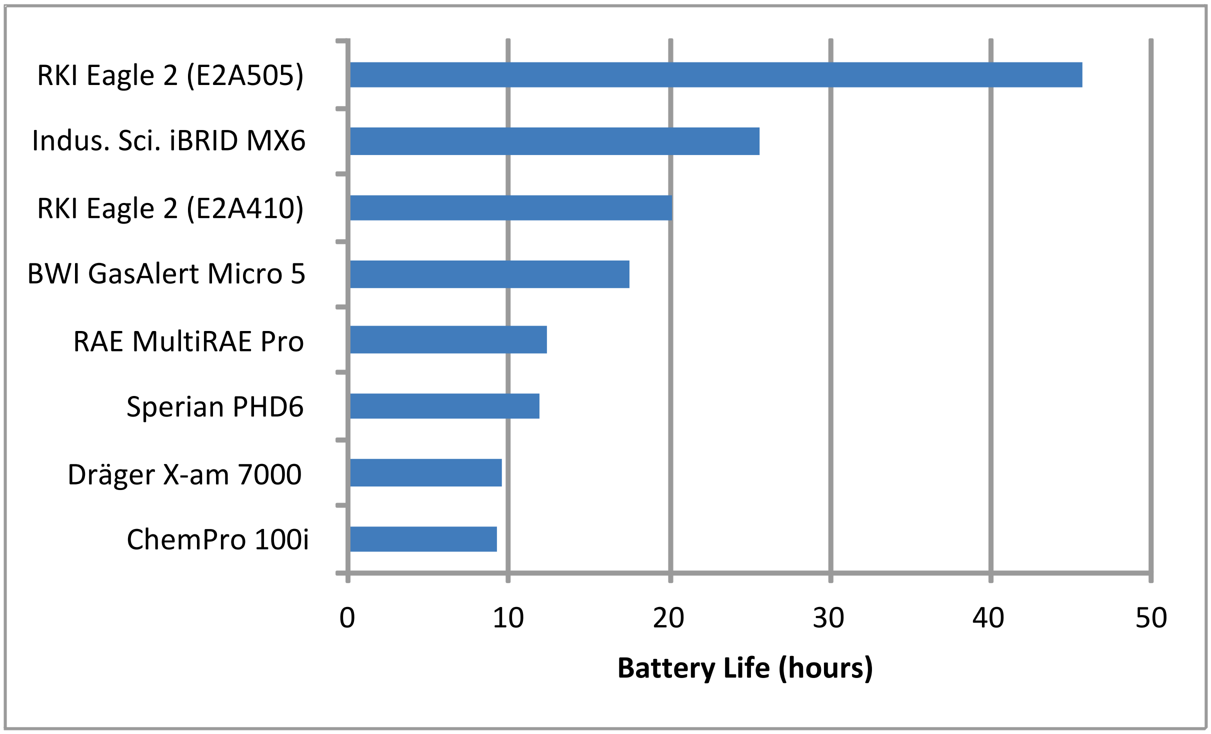

Figure ES-4. Summary of battery life test results.

The operating manual was troublesome because required key sequences were sometimes not located together on the same page.

Dräger X-am 7000. This detector was relatively heavy and boxy in shape, making it uncomfortable to hold in the hand for more than a few minutes. The display area was large and easily readable. Operating menus were easy to understand and the detector was easy to use and had numerous user-defined options. However, the operating manual did not appear to cover all of the features or operations of the unit.

Environics ChemPro 100i. This detector was easy to operate, with intuitive menus, and had large control buttons that could be manipulated correctly even when wearing heavy gloves. The ChemPro 100i required confidence checks with a chemical vapor source provided with the detector. Those checks were simple to perform and the detector responded quickly to the confidence check. The ChemPro 100i was relatively sensitive to the test conditions (temperature and RH) and occasionally had difficulty maintaining its baseline operating condition when moved during testing, causing false alarms and requiring that the operator reset the baseline. The MOS sensor in the first ChemPro 100i unit failed during testing, and a replacement ChemPro 100i unit was provided by the manufacturer.

Industrial Scientific iBRID MX6. This detector had logical and self-explanatory menus, but the menus were difficult to navigate because the buttons on this detector were small and clustered tightly together. This was especially a problem when wearing heavy gloves. The display of the iBRID MX6 was weakly backlit and the display font was small, making readings difficult to discern. This detector also responded relatively slowly to daily bump checks.

RAE Systems MultiRAE Pro. This detector was easy to operate by following the instruction manual, the menus were clearly understandable, and the display was easy to read. However, it was difficult to determine the full-scale ranges of the sensors installed in the MultiRAE Pro without seeking technical support or online information from the manufacturer. The use of heavy gloves made it difficult to feel when the control buttons had been successfully pressed. Multiple EC sensors could fit into the O_2 sensor location of this detector, but would not work in that location. The operator would not know that the sensor was not working until the detector had been reassembled and powered up.

RKI Instruments Eagle 2. Three separate units of this detector had to be purchased to conduct testing because the necessary sensors could not be interchanged within a single unit. The Eagle 2 was relatively large and heavy, but its design and built-in handle made it comfortable to use. The display was clear and legible but did not indicate the status of the batteries. Operation of this detector while wearing heavy gloves was difficult, as it was hard to feel when the control buttons had been successfully pressed.

Sperian PHD6. This detector's display was easy to read, but the detector's alarms would change the display, interfering with concentration readings. Testing staff adjusted the alarm values to avoid this issue during testing. Selection of a particular sensor on the calibration menu required toggling through multiple menu steps. Operation of the detector's control buttons and performance of the pump test were difficult when wearing heavy gloves. The sample inlet tubing of the PHD6 connects at the bottom of the detector, and thus the connection point is directed toward the user when the detector is held in the hand, potentially leading to pinching or snagging of the inlet tubing. The battery charger of the PHD6 makes electrical contact by gravity and sometimes did not make proper contact.

Acknowledgments

Contributions of the following individuals and organizations to the development of this document are gratefully acknowledged.

U.S. Environmental Protection Agency (EPA)

Michael Boykin
Steven Merritt
Lukas Oudejans
Len Zintak

Battelle Memorial Institute

Contents

NOTICE iii
EXECUTIVE SUMMARY iv
ACKNOWLEDGMENTS xiii
APPENDICES xv
FIGURES xv
TABLES xvi
ABBREVIATIONS/ACRONYMS xviii

1.0 INTRODUCTION 1

2.0 EXPERIMENTAL METHODS 2
2.1 Performance Parameters 2
2.1.1 Response and Recovery Time 2
2.1.2 Accuracy 2
2.1.3 Repeatability 2
2.1.4 Response Threshold 3
2.1.5 Operating Conditions 3
2.1.6 Oxygen Deficiency and TIC Response 3
2.1.7 Cold/Hot Start Behavior 3
2.1.8 Interference Effects 3
2.1.9 Battery Life 3
2.1.10 Operational Characteristics 3
2.2 Target Compounds 4
2.3 Detectors Tested 5
2.4 Testing Parameters 9
2.4.1 Test Conditions 9
2.4.2 Chemical Interferences 9
2.4.3 Test Matrix 11
2.4.4 Test System and Procedures 15
2.5 Data Acquisition 19

3.0 STATISTICAL CALCULATIONS 21
3.1 Response and Recovery Time 21
3.2 Repeatability 21
3.3 Accuracy 21
3.4 Response Threshold 22
3.5 Effect of Operating Conditions 22
3.6 Cold/Hot Start Behavior 22
3.7 Interference Effects 23
3.8 Battery Life 23

4.0 QUALITY ASSURANCE/QUALITY CONTROL 25
4.1 Data Quality Indicators 25
4.2 Audits 26

4.2.1 Performance Evaluation Audit 26
4.2.2 Technical Systems Audit 27
4.2.3 Data Quality Audit 28
4.2.4 QA/QC Reporting 28
4.3 Data Review 28

5.0 RESULTS 29
5.1 Response and Recovery Time 29
5.2 Accuracy 39
5.3 Repeatability 49
5.4 Response Threshold 58
5.5 Effect of Operating Conditions 58
5.6 Effect of Oxygen Deficiency on TIC Response 68
5.7 Cold/Hot Start Behavior 69
5.8 Interference Effects 71
5.9 Battery Life 76
5.10 Operational Factors 76

6.0 SUMMARY 82
6.1 Response and Recovery Time 82
6.2 Accuracy 84
6.3 Repeatability 85
6.4 Response Threshold 86
6.5 Effect of Operating Conditions 86
6.6 Effect of O_2 Deficiency on TIC Response 86
6.7 Cold/Hot Start Behavior 87
6.8 Interference Effects 87
6.9 Battery Life 87
6.10 Operational Factors 87

Appendices

APPENDIX A: NOMINAL UPPER RANGE LIMITS OF THE TESTED DETECTORS
APPENDIX B: EXAMPLE OF LABORATORY DATA RECORDING SHEETS

Figures

Figure ES-1. Summary of Response Time Results in TIC Testing vi
Figure ES-2. Summary of Recovery Time Results in TIC Testing vi
Figure ES-3. Summary of QUA Results in TIC, O_2, and CH_4 Testing (QUA not determined for ChemPro 100i) viii
Figure ES-4. Summary of Battery Life Test Results xi

Figure 2.3-1. Handheld Detectors Tested; a: BW Technologies GasAlert Micro 5, b: Draeger XAM 7000, c: Environics ChemPro 100i, d: Industrial Scientific iBRID MX6, e: RAE Instruments MultiRAE Pro, f: RKI Instruments Eagle 2, g: Sperian PHD6 7
Figure 2.4-1. Schematic of Test System....16
Figure 2.4-2. View of Two Test Systems in Adjacent Laboratory Hoods for Testing of Handheld Detectors....17
Figure 2.4-3. Example of Glass Bell Tube Placed over Inlet Tube of a Detector....18
Figure 5.9-1. Summary of Battery Life Test Results....76
Figure 6.1-1. Summary of Response Time Results in TIC Testing....83
Figure 6.1-2. Summary of Recovery Time Results in TIC Testing....84
Figure 6.2-1. Summary of QUA Results in TIC, O_2, and CH_4 Testing....85
Figure 6.9-1. Summary of Battery Life Test Results....88

Tables

Table 2.2-1. Target Gases Used to Evaluate Handheld Multigas Detectors....4
Table 2.4-1. Summary of Temperature and RH Conditions for Testing....9
Table 2.4-2. Interferences Used in Testing of Handheld Multigas Detectors....11
Table 2.4-3. Summary of Quantitative Evaluations Conducted....12
Table 2.4-4. Summary of Tests Conducted with Each Detector and Target Gas....13
Table 2.4-5. Summary of TIC Challenge Concentrations (ppm) Used with Each Detector....14
Table 2.4-6. Summary of O_2 and CH_4 Concentrations Used in %O_2 and LEL Testing....15
Table 4.1-1. Summary Statistics of Reference Method Results....25
Table 4.2-1. Summary of PE Audit Results....27
Table 5.1-1. Summary of Mean Response and Recovery Times (seconds) with H_2S....31
Table 5.1-2. Summary of Mean Response and Recovery Times (seconds) with SO_2....32
Table 5.1-3. Summary of Mean Response and Recovery Times (seconds) with NH_3....33
Table 5.1-4. Summary of Mean Response and Recovery Times (seconds) with Cl_2....34
Table 5.1-5. Summary of Mean Response and Recovery Times (seconds) with PH_3....35
Table 5.1-6. Summary of Mean Response and Recovery Times (seconds) with HCN....36
Table 5.1-7. Summary of Mean Response and Recovery Times (seconds) with O_2....37
Table 5.1-8. Summary of Mean Response and Recovery Times (seconds) with CH_4....38
Table 5.2-1. Summary of Quantitative Accuracy and Identification Accuracy (percent) with H_2S....41
Table 5.2-2. Summary of Quantitative Accuracy and Identification Accuracy (percent) with SO_2....42
Table 5.2-3. Summary of Quantitative Accuracy and Identification Accuracy (percent) with NH_3....43
Table 5.2-4. Summary of Quantitative Accuracy and Identification Accuracy (percent) with Cl_2....44
Table 5.2-5. Summary of Quantitative Accuracy and Identification Accuracy (percent) with PH_3....45

Table 5.2-6. Summary of Quantitative Accuracy and Identification Accuracy (percent) with HCN 46
Table 5.2-7. Summary of Quantitative Accuracy and Identification Accuracy (percent) with O_2 47
Table 5.2-8. Summary of Quantitative Accuracy and Identification Accuracy (percent) with CH_4....48
Table 5.3-1. Summary of Repeatability (percent RSD) with H_2S 50
Table 5.3-2. Summary of Repeatability (percent RSD) with SO_2 51
Table 5.3-3. Summary of Repeatability (percent RSD) with NH_3 52
Table 5.3-4. Summary of Repeatability (percent RSD) with Cl_2 53
Table 5.3-5. Summary of Repeatability (percent RSD) with PH_3 54
Table 5.3-6. Summary of Repeatability (percent RSD) with HCN 55
Table 5.3-7. Summary of Repeatability (percent RSD) with O_2 56
Table 5.3-8. Summary of Repeatability (percent RSD) with CH_4....57
Table 5.4-1. Summary of Response Threshold Results....58
Table 5.5-1. Performance Parameters under Different Temperature and Relative Humidity Conditions with H_2S 60
Table 5.5-2. Performance Parameters under Different Temperature and Relative Humidity Conditions with SO_2 61
Table 5.5-3. Performance Parameters under Different Temperature and Relative Humidity Conditions with NH_3....62
Table 5.5-4. Performance Parameters under Different Temperature and Relative Humidity Conditions with Cl_2....63
Table 5.5-5. Performance Parameters under Different Temperature and Relative Humidity Conditions with PH_3 64
Table 5.5-6. Performance Parameters under Different Temperature and Relative Humidity Conditions with HCN 65
Table 5.5-7. Performance Parameters under Different Temperature and Relative Humidity Conditions with O_2....66
Table 5.5-8. Performance Parameters under Different Temperature and Relative Humidity Conditions with CH_4....67
Table 5.6-1. Performance Differences Observed in H_2S Detection at Reduced O_2 68
Table 5.7-1. Summary of Performance Parameters under Fully Warmed Up and Cold Start Conditions....70
Table 5.8-1. Summary of False Positive (FP) and False Negative (FN) Rates with H_2S....72
Table 5.8-2. Summary of False Positive (FP) and False Negative (FN) Rates with SO_2....72
Table 5.8-3. Summary of False Positive (FP) and False Negative (FN) Rates with NH_3 73
Table 5.8-4. Summary of False Positive (FP) and False Negative (FN) Rates with Cl_2 73
Table 5.8-5. Summary of False Positive (FP) and False Negative (FN) Rates with PH_3....74
Table 5.8-6. Summary of False Positive (FP) and False Negative (FN) Rates with HCN....74
Table 5.8-7. Summary of False Positive (FP) and False Negative (FN) Rates with O_2 75
Table 5.8-8. Summary of False Positive (FP) and False Negative (FN) Rates with CH_4 75

Abbreviations/Acronyms

CH_4	methane
CI	number of correct identifications
Cl_2	chlorine
CO	carbon monoxide
COR	Contracting Officer's Representative
DEAE	N,N-diethylaminoethanol
DHS	Department of Homeland Security
EC	electrochemical
EPA	U.S. Environmental Protection Agency
FN	false negative
FP	false positive
GC/FID	gas chromatography with flame ionization detection
HCN	hydrogen cyanide
H_2S	hydrogen sulfide
I	number of samples with interferent in air
IA	identification accuracy
IDLH	immediately dangerous to life and health
IMS	ion mobility spectrometry
LEL	lower explosive limit
MOS	metal oxide semiconductor
NH_3	ammonia
NHSRC	National Homeland Security Research Center
NR	number of negative responses
O_2	oxygen
PE	performance evaluation
PH_3	phosphine
PPE	personal protective equipment
PR	number of positive responses
QA	quality assurance
QC	quality control
QMP	quality management plan
QUA	quantitative accuracy
RH	relative humidity
RSD	relative standard deviation
SD	standard deviation
SO_2	sulfur dioxide
STEL	short term exposure limit
T	temperature
TI	number of samples with interferent and target gas
TIC	toxic industrial compound
TSA	technical systems audit
TWA	time-weighted average
VOC	volatile organic compound

1.0 Introduction

The U.S. Environmental Protection Agency's (EPA's) National Homeland Security Research Center (NHSRC) is helping protect human health and the environment from adverse impacts resulting from acts of terror. NHSRC works in partnership with recognized testing organizations, with stakeholder groups (buyers, vendor organizations, scientists, and permitters), and with individual technology developers in carrying out performance tests on homeland security technologies. In response to the needs of stakeholders, NHSRC conducts research and evaluates the performance of innovative homeland security technologies by developing test plans, conducting evaluations, collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance (QA) protocols to ensure the generation of high quality data and defensible results. NHSRC-supported research provides unbiased, third-party information supplementary to vendor-provided information that is useful to decision makers in purchasing or applying the evaluated technologies. Stakeholder involvement ensures that user needs and perspectives are incorporated into the evaluation design to produce useful performance information for each evaluated technology.

Responding to an accident, fire, or deliberately caused chemical release can expose first responders to hazardous conditions, including air containing reduced levels of oxygen, explosive levels of flammable chemicals in air, or harmful levels of toxic or corrosive chemicals. To minimize such exposures, first responders and emergency management professionals need reliable, sensitive, and portable monitoring devices that can rapidly indicate the presence of multiple chemical and environmental hazards at the same time. EPA's NHSRC supports EPA's Regional On-Scene Coordinators and response teams, as well as state and local emergency response agencies, by evaluating technologies to meet this monitoring need. The test results presented in this report are part of NHSRC's efforts to identify and verify the performance of portable hazard detectors for use by such organizations.

The objective of the testing described in this report was to assess the performance of commercially available handheld detectors capable of quantifying oxygen (O_2), flammable mixtures (in terms of the lower explosive limit [LEL]), and multiple toxic industrial compounds (TICs) at concentrations that would present a threat to emergency response personnel. The evaluations used realistically hazardous concentrations of the target species, and assessed response time, accuracy, repeatability, effects of potential interferents, and effects of normal temperature and relative humidity (RH) variations. Operational factors such as battery lifetime, startup time under normal, cold, and hot conditions, and clarity of displays and alarms were evaluated. The ease of using each detector with personal protective equipment (PPE) including heavy gloves was also assessed. In performing this technology evaluation, the procedures specified in the peer-reviewed test/QA plan developed for this test, and complied with quality requirements in the NHSRC Quality Management Plan (QMP) were followed.

2.0 Experimental Methods

Seven commercially available handheld multigas detectors were tested with O_2, a flammable gas (methane, CH_4), and selected TICs under a realistic range of conditions and procedures of use. This section presents the experimental design, test procedures, and test and reference methods.

2.1 Performance Parameters

The following performance parameters were evaluated:

- Response and Recovery Time
- Accuracy
- Repeatability
- Response Threshold (i.e., detection limit)
- Effect of Operating Conditions (temperature and RH)
- Effect of O_2 Deficiency on TIC Response
- Cold/Hot Start Behavior
- Interference Effects
- Battery Life
- Operational Factors.

2.1.1 Response and Recovery Time

Response time (also known as rise time) is the length of time required for a handheld detector to provide a stable quantitative reading after the onset of a challenge with a target gas. The response time was evaluated because response personnel need a rapid indication of chemical hazard and concentration.

Recovery time (also known as fall time) is the length of time required for the detector to return to a stable baseline quantitative reading after a challenge ends. Recovery time was evaluated because it limits how rapidly the detector can provide an accurate reading of a safe (no-hazard) condition or a new response to a hazard condition. This parameter is relevant when, for example, different levels of contamination are present in different places at a response scene, and the detector must clear before it could be used reliably in another place.

Both response and recovery time were recorded in repetitive challenges with each target gas. For both response and recovery time, a stable detector reading was defined as a reading that did not change over approximately 20 seconds, as observed by the test operator.

2.1.2 Accuracy

Accuracy is the degree of quantitative agreement between the target gas concentration indicated by a handheld detector and the known challenge concentration. Quantitative accuracy (QUA) was evaluated by direct comparison of known challenge concentrations and quantitative detector responses. Identification accuracy (IA) was determined by reviewing detector responses to evaluate whether the detector accurately identified the target gas being sampled.

2.1.3 Repeatability

Repeatability is the degree of consistency of the response of a handheld detector to repeated challenges with the same target gas concentration under uniform test conditions. This parameter is important as an indication of the reliability of an individual response from the detector. Repeatability was determined with each target gas by means of the same repetitive challenges used to determine response and recovery time.

2.1.4 Response Threshold

The response threshold is the approximate concentration below which a handheld detector does not detect a target gas (i.e., does not provide a reading different from its baseline reading). It is important to determine whether the response threshold of a detector is low enough that an absence of detector response can be taken to indicate the absence of a hazard. Challenge gas concentrations were stepped downward to estimate the response threshold of each handheld detector. Response threshold was determined at normal conditions of approximately 22°C and 50% RH.

2.1.5 Operating Conditions

Emergency response situations can occur in any weather, so handheld multigas detectors used by responding personnel must be capable of providing correct readings under a wide range of ambient conditions. Consequently, challenge gas mixtures were sampled at selected temperature and RH conditions to investigate the effect of such conditions on detector performance.

2.1.6 Oxygen Deficiency and TIC Response

Some TICs, such as H_2S, are detected by oxidation within the electrochemical (EC) sensors used in many handheld detectors. For such TICs, sensor response may depend on the concentration of O_2 in the air, and detector performance may be degraded in air of lower than normal O_2 content. Consequently, each handheld detector was challenged with H_2S at O_2 levels below the normal 20.9% to test for this behavior.

2.1.7 Cold/Hot Start Behavior

Monitoring instruments may need to provide full operational capabilities on short notice in emergency response situations. Consequently, the handheld multigas detectors were tested for the delay time that is required between turning the instrument on and readiness for hazard detection, and for the accuracy and speed of response under such use. This rapid startup behavior was determined for three separate startup conditions: after overnight startup from room temperature, from cold storage, and from hot storage of the detector.

2.1.8 Interference Effects

In emergency response situations, relatively innocuous chemical compounds or mixtures present in the air may interfere with (i.e., mask or alter) the response of a handheld detector. Examples of such potential interferences may be cleaning supplies, paint fumes, or vehicle exhaust. The effect of potential interferences was assessed because such compounds can potentially produce two types of errors with the handheld detectors: (1) erroneous reporting of the presence of a target gas when none is present (false positives [FPs]) or (2) reduction in sensitivity or masking of response to target gases of interest (false negatives [FNs]). To investigate both types of error, interference effects were evaluated by sampling potential interferences both in otherwise clean air, and in air containing the target gases.

2.1.9 Battery Life

Handheld multigas detectors operate on battery power when in use in the field, and the length of battery life is critical to uninterrupted response operations. Battery life was determined by operating each handheld detector continuously, starting with a fully charged battery, until the battery was fully depleted and the detector stopped operating.

2.1.10 Operational Characteristics

Key operational characteristics of the handheld detectors were evaluated by observations of test personnel and, if necessary, by inquiry to the respective vendors. The operational factors included the readability of displays; ease of operation with and without PPE (i.e., heavy gloves); logic and simplicity of operational functions and software menus; data recording capabilities; and cost. The costs for each handheld detector were assessed based on the purchase price of the detector, any additional sensors needed for testing, and any replaceable or maintenance items.

Testing was not of sufficient duration to test long-term maintenance or operational costs of the technologies.

2.2 Target Compounds

Table 2.2-1 lists the target gases used in testing the handheld multigas detectors. The determination of LEL was addressed by using CH_4 in air at concentrations at or below 25% of its LEL of 5% in air (i.e., concentrations at or below 1.25% methane in air). Six TICs were used to represent a range of gaseous chemical hazards.

Table 2.2-1. Target Gases Used to Evaluate Handheld Multigas Detectors

Hazard Category	Target Gas
Oxygen-Depleted Environment	Oxygen (O_2)
Lower Explosive Limit	Methane (CH_4)
Toxic Industrial Chemicals (TICs)	Hydrogen Sulfide (H_2S) Sulfur Dioxide (SO_2) Ammonia (NH_3) Chlorine (Cl_2) Phosphine (PH_3) Hydrogen Cyanide (HCN)

2.4 Detectors Tested

The seven handheld detectors tested are described below and illustrated in Figure 2.3-1. All seven detectors were purchased from the manufacturers with internal air sampling capability to actively draw the challenge gas mixtures to their sensors. Each detector was operated according to the manufacturer's instructions, as indicated in the operating manuals provided in electronic form for each detector. Operations included daily confidence checks or "bump" tests specified by the vendor to confirm that a detector was operating properly. Positive response to a target or surrogate chemical was required in such checks before testing could start with a given detector.

Six of the seven detectors tested employed a galvanic cell for percent O_2 measurement, a catalytic bead sensor for LEL, and EC cells for TIC detection. Those six detectors could not incorporate sensors to detect all the target gases at once, so each detector was purchased with a set of sensors installed and additional sensors were then substituted into the detectors as needed to conduct the testing. The configuration of each detector (i.e., the set of sensors installed in the detector) was recorded throughout the testing process. The seventh detector employed a completely different measurement principle based on a proprietary open-loop ion mobility spectrometry (IMS) approach. The following descriptions note specific features or requirements of each detector that affected how the detector was used in testing.

BW Technologies GasAlert Micro 5. The GasAlert Micro 5 was 14.5 × 7.4 × 3.8 cm (5.7 × 2.9 × 1.5 in) in size and weighed approximately 370 g (13 oz). This detector (Serial No. M5-XWHS-R-P-D-Y-N-00) was operated on internal rechargeable battery power, which was recharged overnight. The detector was used with the optional pump module, and drew sample in at approximately 0.45 L/min through the pump connector and a 15 cm length of the Teflon®-lined Tygon tubing supplied with the pump module. However, the sample probe and Tygon tubing supplied with the pump module were not used. This detector was capable of holding a maximum of four sensors. The O_2 and LEL sensors were permanently installed. The other sensors installed in the GasAlert Micro 5 were as follows: Cl_2 and SO_2 sensors, during testing with those two TICs; NH_3 and HCN sensors, during testing with those two TICs; and PH_3 and H_2S sensors, during testing with those two TICs, O_2, and CH_4 (LEL). The purchase price of the GasAlert Micro 5 and sensors was approximately $2,600.

Dräger X-am 7000. The X-am 7000 was 15 × 14 × 7.5 cm (5.9 × 5.6 × 3 in) in size and weighed 600 g (21 oz). This detector (Serial No. ARBM-0503) was operated on internal rechargeable battery power, which was recharged overnight. The detector was used with the internal pump and pump adapter, and drew in sample at approximately 0.66 L/min through a 5 cm length of the inlet tubing provided. The sample probe obtained with the detector was not used. This detector was capable of holding a maximum of four sensors. The O_2 and LEL sensors were permanently installed. The other sensors installed in the X-am 7000 were as follows: Cl_2 and SO_2 sensors, during testing with those two TICs; NH_3 and HCN sensors, during testing with those two TICs; a PH_3 sensor during testing with that TIC; and PH_3 and H_2S sensors, during testing with H_2S, O_2, and CH_4 (LEL). The purchase price of the X-am 7000 and sensors was approximately $5,000.

Figure 2.3-1. Handheld detectors tested; a: BW Technologies GasAlert Micro 5, b: Dräger X-am 7000, c: Environics ChemPro 100i, d: Industrial Scientific iBRID MX6, e: RAE Systems MultiRAE Pro, f: RKI Instruments Eagle 2, g: Sperian PHD6.

Environics ChemPro 100i. The ChemPro 100i was 23 × 10 × 5.7 cm (9 × 4 × 2 in) in size and weighed 880 g (31 oz). This detector had internal rechargeable batteries, but at the manufacturer's request was kept in operating mode and connected to line power during all tests except the battery lifetime test. Brief periods of operation on battery power showed no differences in response compared to operation on line power, however this comparison was not a focus of testing. The ChemPro 100i's internal pump drew sample in at approximately 1.3 L/min. The Field Monitoring Cap provided with the instrument was used as the instrument's inlet in all testing. This approach was chosen because the intent of testing was to assess hazard identification in the field, and because of the absence of any physical connection of the detector to the test apparatus (see Section 2.4.4) that would have required use of the detector's Fixed System Monitoring Cap. The ChemPro 100i was designed to detect all six of the target TICs, but did not have capability for O_2 or LEL measurement. The ChemPro 100i uses a multi-sensor measurement technology that includes open-loop IMS; semiconductor, metal oxide semiconductor (MOS), and field effect sensors; and temperature, RH, pressure, and flow sensors. The First Responder library of the ChemPro 100i was used in testing, as this library was most applicable to the intent of the testing and provided identification of the target TICs. Unlike the other six detectors, the ChemPro 100i does not provide quantitative indications of TIC concentration (e.g., ppm values). Instead the ChemPro 100i provided a qualitative indication of response intensity (i.e., one, two, or three bars) when responding to a TIC. The purchase price of the ChemPro 100i was approximately $15,800. Environics representatives required that Contractor personnel take a brief training session in operation and testing of the ChemPro 100i. That training session was conducted by teleconference before any testing took place. The ChemPro 100i was subjected to a confidence check consisting of a sensor test before every test procedure, using the "test tube" source of chemical vapors (1-propanol and diisopropylmethylphosphonate) provided with the detector. No testing of the ChemPro 100i took place unless the detector display indicated "Test Passed" upon completion of the sensor test.

Two units of the ChemPro 100i were used in testing. The first unit (S/N 06CPi103701538) was used throughout testing with SO_2, Cl_2, NH_3, and HCN, but displayed an unrecoverable "functional exception D08:2057" on July 25, 2011, near the end of testing with PH_3. That unit was returned to Environics, and a replacement unit (S/N 06CPi102201497) was promptly received. The replacement unit was then used to complete the final two tests with PH_3, and for all testing with H_2S. The original unit sometimes responded relatively slowly, and occasionally failed a sensor test, giving the error message "No MOS signal detected." This message apparently referred to the metal oxide sensor, and a problem with that sensor may have been the ultimate cause of the first ChemPro 100i unit's failure. The replacement unit never failed the confidence check.

Industrial Scientific iBRID MX6. The iBRID MX6 was 13.5 × 7.7 × 4.3 cm (5.3 × 3 × 1.7 in) in size and weighed approximately 409 g (14.4 oz). This detector (Serial No. 1101397-002) was operated on internal rechargeable battery power, which was recharged overnight. The detector had an internal pump which drew in sample at approximately 0.34 L/min through a 5 cm length of Teflon® tubing. The sample probe obtained with the detector was not used. This detector was capable of holding a maximum of five sensors. The O_2 and LEL sensors, and a carbon monoxide (CO) sensor, were permanently installed. The other sensors installed in the iBRID MX6 were as follows: H_2S and SO_2 sensors, during testing with SO_2; Cl_2 and SO_2 sensors, during testing with Cl_2; NH_3 and HCN sensors, during testing with those two TICs; and PH_3 and H_2S sensors, during testing with those two TICs, O_2, and CH_4 (LEL). The purchase price of the iBRID MX6 and sensors was approximately $4,000.

RAE Systems MultiRAE Pro. The MultiRAE Pro was 19.3 × 9.7 × 6.6 cm (7.6 × 3.8 × 2.6 in) in size and weighed 880 g (31 oz). This detector (Serial No. PGM-6240) was operated on internal rechargeable battery power, which was recharged overnight. The detector had an internal pump which drew in sample at approximately 0.40 L/min through a filter and a 6 cm length of Teflon® tubing. This detector was capable of holding a maximum of five sensors. In almost all tests with the six TICs, sensors for CO, LEL, and volatile organic compounds (VOCs) were installed in the MultiRAE Pro. The other sensors installed in the MultiRAE Pro were as follows: H_2S and SO_2 sensors, during testing with SO_2; H_2S and NH_3 sensors, during testing with NH_3; Cl_2 and HCN sensors, during testing with Cl_2; PH_3 and HCN sensors, during testing with those two TICs; and PH_3 and H_2S sensors, during almost all testing with H_2S. However, during the final tests with H_2S (consisting of the cold start tests, see Table 2.4-4) the MultiRAE Pro held sensors for LEL, VOCs, O_2, PH_3 and H_2S. That same set of sensors was in the MultiRAE Pro in all testing with O_2 and CH_4 (LEL). The MultiRAE Pro gave CH_4 readings in % LEL, rather than in %CH_4 by volume. The %LEL readings were converted to %CH_4 for QUA determination based on the fact that the LEL for CH_4 is 5% by volume in air. The purchase price of the MultiRAE Pro and sensors was approximately $7,300.

RKI Instruments Eagle 2. The Eagle 2 was the largest and heaviest of the detectors tested, measuring 24.1 × 13.5 × 15 cm (9.5 × 5.3 × 5.9 in) in size and weighing 1.73 kg (61 oz). The vendor of the Eagle 2 indicated that the sensors for the various target gases were not all compatible with one another. Consequently, it was necessary to buy three separate units of the detector to achieve detection of all of the target gases for testing. One unit of the Eagle 2 (E2A505 Type 3112) was equipped with sensors for SO_2, PH_3, and HCN. A second unit (E2A504 Type 2011) was equipped with sensors for Cl_2 and NH_3, and the third unit (E2A410 Type 3001) was equipped with sensors for H_2S, O_2, and CH_4. Each Eagle 2 unit had an internal pump which drew in sample at approximately 0.78 L/min through an approximately 30 cm length of the sample hose provided with the unit. That hose was connected by stainless steel quick-disconnect fittings between the sample inlet of the Eagle 2 unit and the hydrophobic probe filter provided with the unit. The Eagle 2 units operated on replaceable batteries (C cells) rather than on rechargeable batteries. The total purchase price of the three units of the Eagle 2 with installed sensors was approximately $6,700.

Sperian PHD6. The PHD6 detector measured 21.6 × 7.9 × 6.1 cm (8.5 × 3.1 × 2.4 in) and weighed 499 g (17.6 ounces). This detector (Serial No. 531104032) was operated on internal rechargeable battery power, which was recharged overnight. The detector had an internal pump which drew in sample at approximately 1.0 to 1.3 L/min through an approximately 30 cm length of Teflon® tubing connected to the detector's inlet port. The sample probe provided with the detector was not used. This detector was capable of holding a maximum of five sensors. The O_2 and LEL sensors were permanently installed. The other sensors installed in the PHD6 were as follows: SO_2, NH_3, and H_2S sensors, during testing with SO_2 and NH_3; Cl_2, PH_3, and HCN sensors, during testing with those three TICs; and Cl_2, PH_3, and H_2S sensors, during testing with H_2S, O_2, and CH_4 (LEL). The PHD6 CH_4 readings were displayed in %LEL, rather than in %CH_4 by volume (the PHD6 manual indicates that either unit can be used). The %LEL readings were converted to %CH_4 for QUA determination based on the fact that the LEL for CH_4 is 5% by volume in air. The purchase price of the PHD6 and sensors was approximately $2,500.

2.4 Testing Parameters

2.4.1 Test Conditions

Table 2.4-1 summarizes the temperature and RH conditions used in testing. The same test procedures were followed with each target gas at each of the test conditions denoted by an "X" in Table 2.4-1. The test gas mixture supplied to the handheld detectors undergoing testing had the indicated RH, and both the challenge gas delivery system and the handheld detectors were maintained at the indicated test temperature. As Table 2.4-1 shows, the test conditions included low, medium, and high RH at room temperature, medium RH at low temperature, and medium and high RH at high temperature.

Table 2.4-1. Summary of Temperature and RH Conditions for Testing

	Temperature (°C)		
RH (%)	**8 (±3)**	**22 (±3)**	**35 (±3)**
≤ 20	--	X	--
50 (±5)	X	X	X
80 (±5)	--	X	X

2.4.2 Chemical Interferences

Table 2.4-2 lists the six chemical mixtures or compounds used to test the interference response of the handheld chemical detectors: latex paint fumes, ammonia cleaner, air freshener, N,N-diethylaminoethanol (DEAE; a boiler water additive found in indoor air via humidification systems), simulated gasoline exhaust, and simulated diesel exhaust. Each of these interferents was delivered to each detector along with each target gas, and also alone in otherwise clean air. Interferent testing used one interferent at a time.

For the latex paint, ammonia cleaner, and air freshener, delivery of the interference involved sweeping saturated vapors from the whole commercial product (obtained at a retail outlet) into an air stream. For the DEAE, delivery of the interference involved sweeping saturated vapors from the neat chemical (i.e., > 95% purity, obtained from a commercial supplier) into an air stream.

For these four interferences, the interferent vapor generation consisted of a flow of approximately 100 cm^3/min of clean air passing over a stirred aliquot (≤ 0.5 L) of the interferent product or chemical in a glass flask (approximately 2 L volume). The 100 cm^3/min flow became saturated with the interferent vapor, and was then diluted in the approximately 10 L/min clean air flow to the test plenum in the test apparatus described in Section 2.5. The simulated diesel and gasoline exhaust interferences were delivered by dilution of commercially prepared compressed gas standards (Scott Specialty Gases, Plumsteadville, PA) that contain numerous individual hydrocarbon compounds known to be present in the respective exhaust composition. The standards used were Department of Homeland Security (DHS) approved Diesel Exhaust Interferent Standard (part no. MDHS0002-T-30AL) and DHS approved Gasoline Exhaust Interferent Standard (part no. MDHS0003-T-30AL).

Table 2.4-2. Interferences Used in Testing of Handheld Multigas Detectors

Interferent Category	Interferent	Source
Indoor contaminant	Latex paint fumes	Vapor from whole commercial product
Indoor contaminant	Ammonia cleaner	Vapor from whole commercial product
Indoor contaminant	Air freshener	Vapor from whole commercial product
Indoor contaminant	N,N-diethylaminoethanol (DEAE)	Vapor from neat chemical
Vehicle exhaust	Simulated gasoline exhaust	Compressed gas standard
Vehicle exhaust	Simulated diesel exhaust	Compressed gas standard

2.4.3 Test Matrix

Table 2.4-3 summarizes the quantitative evaluations conducted, in terms of the performance parameters, the objective of each parameter, and the basis of evaluating each parameter. The test procedures provided information on several performance parameters simultaneously. Operational factors were evaluated based on qualitative observations that occurred in the test procedures, so no testing specifically to address those factors is included in Table 2.4-3. As the footnote to Table 2.4-3 indicates, the response threshold for the target gas O_2 was not evaluated because the handheld detectors are intended to detect departures of atmospheric O_2 below its normal level of approximately 20.9% by volume; the minimum amount of O_2 that can be detected is unimportant.

The evaluations summarized in Table 2.4-3 were implemented by a series of tests carried out with each detector, and with each of the six TICs, O_2, or CH_4 as the target gas. Table 2.4-4 shows the matrix of tests, briefly describing each of the 20 different tests and indicating the nature of each test in terms of the test conditions and interferent (if any). Tests 1 to 4 involved successively stepping down in target gas concentration to assess response threshold. Tests 8, 9, 11, 12, 14, and 15 involved the interferent vapors described in Section 2.4.2. Tests 16 to 20 involved testing at temperature and RH conditions other than room temperature and involved testing at temperature and RH conditions other than room temperature and 50% RH, as described in Section 2.4.1. Tests 5 and 6 in Table 2.4-4 tested detection of H_2S in a reduced O_2 atmosphere, and Tests 7, 10, and 13 investigated cold start performance with H_2S as the target gas. The seven detectors had widely differing response ranges for the six TICs, as shown by the range values summarized in Appendix A. Consequently, testing with a TIC as the target gas used TIC challenge concentrations adapted to the ranges of each detector. Table 2.4-5 lists the concentration of each TIC that was used in each test with each detector. This table illustrates the downward steps in TIC concentrations in Tests 1 through 4, and reiterates the fact that Tests 5 to 7, 10, and 13 were conducted only with H_2S. In some cases, the upper range limit of a detector for a TIC was lower than the range limits of other detectors, so that detector was not challenged at the highest TIC concentrations. For example, Table 2.4-5 shows that the RKI Instruments Eagle 2 could not be tested with SO_2 at 100, 50, or 20 ppm in Tests 1 to 3, respectively; all testing of that detector with SO_2 used the 5 ppm concentration introduced in Test 4.

Table 2.4-3. Summary of Quantitative Evaluations Conducted[a]

Performance Parameter	Objective	Basis for Comparison
Response Time	Determine rise time of detector response	Elapsed time to stabilization of detector readings after onset of target gas challenge [b]
Recovery Time	Determine fall time of detector response	Elapsed time to stabilization of detector readings after removal of target gas challenge [b]
Accuracy	Characterize agreement of detector readings with reference results Characterize ability of detector to correctly identify the target gas	Compare detector readings to known challenge concentration Compare detector indication to known identity of target gas
Repeatability	Characterize consistency of detector readings with constant target gas concentration	Relative standard deviation of multiple detector readings with constant challenge
Response Threshold	Estimate minimum concentration that produces detector response	Stepping down in target gas concentration until no response occurs[c]
O_2 Deficiency Effects	Evaluate impact of reduced O_2 environment on TIC detection	Challenges with constant H_2S concentration at different O_2 levels
Temperature and RH Effects	Evaluate effect of temperature and RH on detector performance	Conducting target gas challenges at different temperature and RH conditions
Cold/Hot Start Behavior	Evaluate effect of storage temperature on detector performance at startup	Same as above for response/recovery times, repeatability, and accuracy, after startup from storage
Interferent Effects	Evaluate effect of contaminants that may interfere with detector performance	Sample interferents in clean air and along with target gases
Battery Life	Determine useful operating life of detectors on battery power	Continuous operation of detector to depletion of batteries

(a) Testing consisted of five challenges with each target gas concentration at each test condition, alternating with five clean air challenges.
(b) Stable reading defined as no change in detector reading for approximately 20 seconds.
(c) This parameter was not determined for O_2.

(d)

Table 2.4-4. Summary of Tests Conducted with Each Detector and Target Gas

Test Number	Test Conditions T (°C)/RH (%)[a]	Interferent[b]	Additional Description
1	22/50	--	Base test
2	22/50	--	Step down in concentration
3	22/50	--	Step down in concentration
4	22/50	--	Step down in concentration
5	22/50	--	Conducted in 19% O_2 atmosphere (with H_2S only)
6	22/50	--	Conducted in 16% O_2 atmosphere (with H_2S only)
7	22/50	--	Cold start test after room T storage (with H_2S only)
8	22/50	Paint Vapors	Interferent testing
9	22/50	Gasoline Exhaust	Interferent testing
10	22/50	--	Cold start test after low T (approximately 8°C) storage (with H_2S only)
11	22/50	Ammonia Cleaner	Interferent testing[c]
12	22/50	Diesel Exhaust	Interferent testing
13	22/50	--	Cold start test after high T (approximately 40°C) storage (with H_2S only)
14	22/50	Air Freshener	Interferent testing
15	22/50	DEAE	Interferent testing
16	22/20	--	Testing of T/RH effects
17	22/80	--	Testing of T/RH effects
18	8/50	--	Testing of T/RH effects
19	35/50	--	Testing of T/RH effects
20	35/80	--	Testing of T/RH effects

(a) Test temperature controlled ± 3°C, test RH controlled ± 5 %RH.
(b) False positive and false negative responses assessed with interferent in clean air and in challenge with each target gas, respectively.
(c) Interferent testing with ammonia cleaner was not conducted with Cl_2 as the target gas, to avoid formation of particulate matter.

Table 2.4-5. Summary of TIC Challenge Concentrations (ppm) Used with Each Detector

Test Number	TIC	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
1	H_2S	90	90	90	90	90	90	90
	SO_2	100	100	100	100	--	--	--
	NH_3	100	100	100	100	100	--	100
	Cl_2	10	10	10	10	10	--	10
	PH_3	--	50	50	--	--	--	--
	HCN	--	50	--	--	50	--	100
2	H_2S	30	30	30	30	30	30	30
	SO_2	50	50	50	50	--	--	--
	NH_3	50	50	50	50	50	50	50
	Cl_2	3	3	3	3	3	3	3
	PH_3	--	20	20	--	20	--	20
	HCN	15	15	15	15	15	15	15
3	H_2S	10	10	10	10	10	10	10
	SO_2	20	20	20	20	20	--	20
	NH_3	10	10	10	10	10	10	10
	Cl_2	1	1	1	1	1	1	1
	PH_3	5	5	5	5	5	--	5
	HCN	5	5	5	5	5	5	5
4	H_2S	3	3	3	3	3	3	3
	SO_2	5	5	5	5	5	5	5
	NH_3	3	3	3	3	3	3	3
	Cl_2	--	--	--	--	--	--	--
	PH_3	1	1	1	1	1	1	1
	HCN	--	--	--	--	--	--	--
5 to 7, 10, 13	H_2S	90	90	90	90	90	90	90
8, 9, 11,12, 14 to 20[a]	H_2S	90	90	90	90	90	90	90
	SO_2	50	50	50	50	20	5	20
	NH_3	100	100	100	100	50	50	50
	Cl_2	10	10	10	10	10	3	10
	PH_3	5	20	20	5	20	1	20
	HCN	15	50	15	15	50	15	50

(a) With the exception that Test 11 (ammonia cleaner as interferent) was not conducted with Cl_2 as the TIC.

Table 2.4-6 shows the concentrations of O_2 and CH_4 that were used in testing of detectors (except the ChemPro 100i) for $\%O_2$ and %LEL determination. The O_2 concentration was 19% in nearly all of the O_2 tests, and the testing evaluated whether that reduced O_2 content could be accurately determined over the range of T/RH conditions and interferents. An O_2 level of 16% was used in Test 2 to simulate more severe O_2 depletion. Those same O_2 levels were used in Tests 5 and 6 to assess the impact of reduced O_2 on H_2S detection. Methane levels of 1.25%, 0.5%, and 0.2% by volume were used in the LEL testing, corresponding to 25%, 10%, and 4%, respectively, of the LEL for CH_4.

Table 2.4-6. Summary of O_2 and CH_4 Concentrations Used in $\%O_2$ and LEL Testing

Test Number[a]	Target Gas	Concentration (%)
1	O_2 CH_4	19 1.25
2	O_2 CH_4	16 0.5
3	CH_4	0.2
5	O_2	19
6	O_2	16
8, 9, 11,12, 14 to 20	O_2 CH_4	19 1.25

(a) Tests 4, 7, 10, and 13 not conducted with reduced O_2 level or with CH_4 as target gas.

2.4.4 Test System and Procedures

The handheld detectors were tested using test systems represented schematically in Figure 2.4-1. The test system consists of a challenge gas delivery system, a Nafion® humidifier, two challenge plenums, a clean air plenum, RH sensors, thermocouples, and mass flow meters. The appropriate target gas generation system, typically a compressed gas cylinder, was selected for the gas of interest. The target gas was then mixed with a humidified dilution air flow entering the challenge plenums. The test system allows the temperature and RH of the clean air and the challenge gas mixtures to be controlled, multiple challenge concentrations to be delivered, and interferent vapors to be introduced along with the target gases.

Two such test systems were installed in adjacent laboratory hoods and used to conduct testing of all seven handheld detectors simultaneously. Figure 2.4-2 is a photograph of the laboratory showing the two test systems in the adjacent hoods, and the two mass flow control modules (the black boxes at the right center of the figure) that controlled the clean and challenge gas flow rates, the interferent delivery flow rate, the humidifier flow rate, and the plenum temperatures. The laptop computer atop each mass flow control module continually displayed and recorded the temperatures

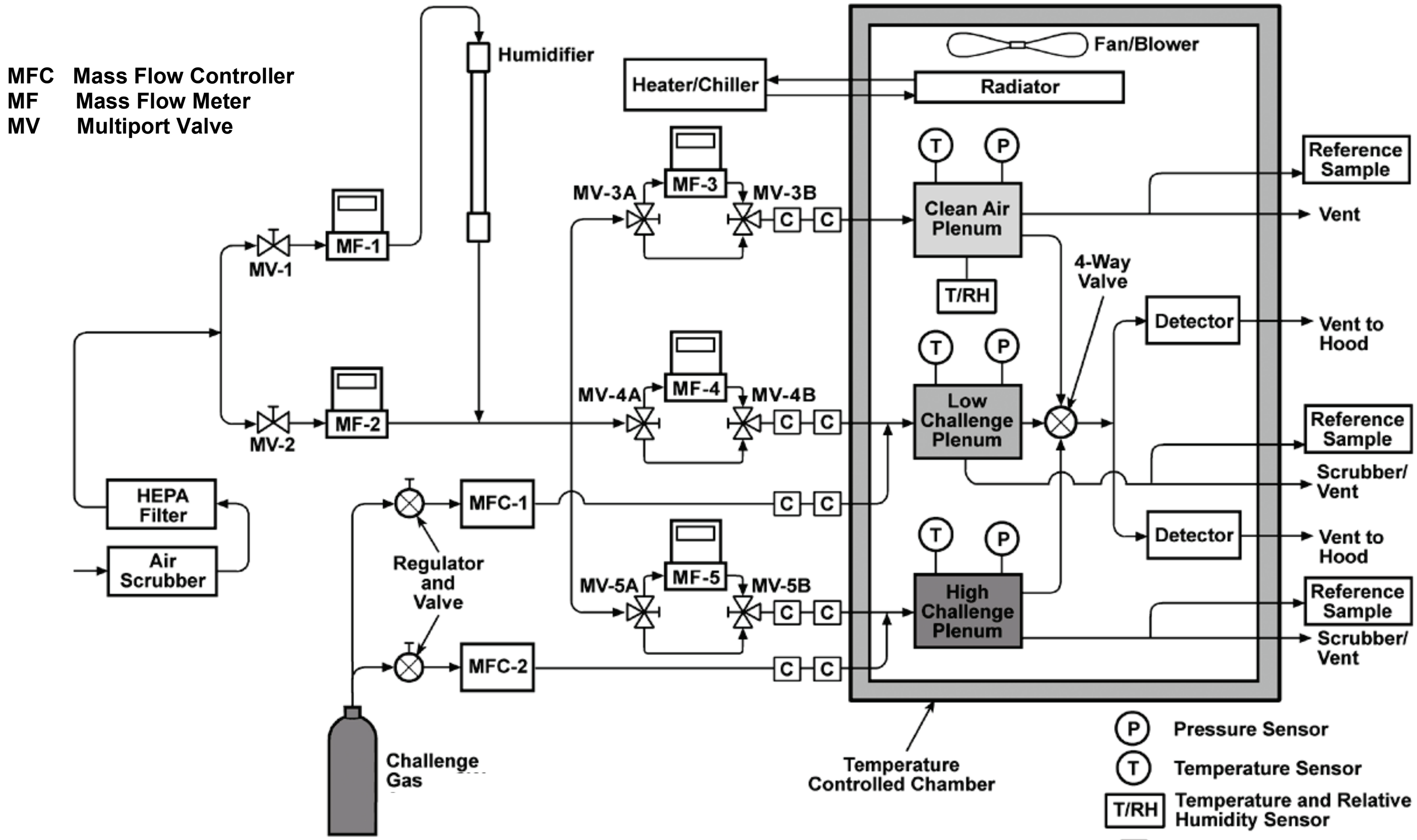

Figure 2.4-1. Schematic of test system.

Figure 2.4-2. View of two test systems in adjacent laboratory hoods for testing of handheld detectors.

and RH readings at multiple points in the test system. The MultiRAE Pro, Eagle 2, and PHD6 were tested in the system in the hood at the left in Figure 2.4-2, and the GasAlert Micro 5, X-am 7000, iBRID MX6, and ChemPro 100i were tested in the system in the hood at the right in Figure 2.4-2.

The seven detectors were not connected directly to the test systems. Instead, clean air or challenge gas mixtures were supplied to each detector through an individual glass bell-shaped tube that surrounded the intake tube of the detector but had an internal diameter much larger than the outer diameter of the intake tube of the detector. These bell tubes thus provided challenge gas flow to each detector in excess of the detector's intake requirement, but without pressurization or flow disturbances. This arrangement is illustrated in Figure 2.4-3, which shows the detail of placement of the Dräger X-am 7000 inlet tube within the glass bell tube connected to the flow system. Each glass bell was connected to a four-way valve, with which the clean air or challenge gas could be selected for delivery to the detector. Flow measurements conducted before any testing took place confirmed that excess sample flow was provided to each detector, and that no detector responses occurred due to the valve switching with only clean air in the system.

Figure 2.4-3. Example of glass bell tube placed over inlet tube of a detector (Dräger X-am 7000).

Each test with a target gas began with all detectors in a test system sampling clean air. The target gas mixture was then delivered to one detector. The length of time needed by that detector to achieve a stable quantitative response was recorded as the response time, and the final quantitative response of the detector was recorded. A maximum of 3 minutes (180 sec) was allowed for the detector to achieve its reading; if an alarm or stable reading was not achieved within 3 minutes, the detector was switched back to sampling clean air, and the response time was recorded as >180 sec. The length of time needed by the detector to return to its baseline reading after switching back to clean air was recorded as the recovery time. No strict limitation was placed on the length of the recovery time, because the challenge gas was delivered to a second detector as the first detector was switched back to clean air. Thus, the second detector was responding to the gas challenge as the first was recovering from it. In some cases, a detector did not completely return to its baseline reading despite a lengthy recovery time after a challenge. In those cases, the recovery time is reported as a "greater than" (>) value in seconds. The sequence of successively challenging one detector at a time was repeated in each test until all detectors in the test system had been subjected to five alternating challenges with clean air and the challenge gas mixture.

In testing with methane and the six TICs, the background readings of the detectors were determined with clean air of the same RH as the challenge mixture. In those cases, the target gas was not present in the sample gas when the background reading was obtained. In testing with O_2 as the target gas, clean humidified air was also used as the background gas, but the target gas was present at its normal atmospheric level (approximately 20.9%).

Reference methods were used to quantify the target gas concentrations in the challenge plenum both before and after delivery of the target gas mixture to the detectors to confirm the challenge concentrations used. For H_2S, SO_2, NH_3, Cl_2, and PH_3, the reference methods were EC detectors made by different manufacturers than the detectors being tested and calibrated independently of the test gas standards. For HCN, the reference method was gas chromatography with flame ionization detection (GC/FID), implemented using an HP 5890 GC in the test laboratory. Challenge gas samples were transferred from the test system to the GC sample loop in Tedlar gas sampling bags. The GC/FID was calibrated with a dedicated HCN gas standard. The reference method for O_2 was a commercial galvanic cell, calibrated with air. The reference method for CH_4 was a commercial LEL sensor made by a different manufacturer than the tested detectors, and calibrated with a dedicated CH_4 standard.

Interferent testing involved only one interferent at a time. The target gas source was independently controlled such that the interferent could be introduced to the flowing gas streams either in the absence or the presence of the target gas. This allowed interference effects to be evaluated with the interferent alone, and with an interferent and target gas together. Testing with the interferent alone allowed evaluation of false positive responses; testing with the interferent and target gas together allowed evaluation of false negatives. False positive testing began with alternating sampling of clean air and the interferent alone in otherwise clean air, for a total of up to five times each, in a procedure analogous to that described above. However, if no false positive response was observed after three such test cycles, the false positive testing was truncated at that point.

2.5 Data Acquisition

Recorded data during testing included the times and conditions of steps in testing; the identities of the test personnel; calibration data and challenge gas results for the reference methods; the responses (or lack thereof) and response and recovery times of the handheld detectors in each portion of the test; and observations about ease of use, cost, etc. These data were recorded by the test personnel in laboratory record books and data forms.

The acquisition of data from the handheld detectors was tailored to the expected use of those instruments as portable rapid-response indicators of hazardous conditions. In such use, the visual display of readings, coupled with an audible or visual alarm, is the primary data output. Consequently, test data including both quantitative readings and the occurrence of alarms were recorded manually by the test personnel, on color-coded data forms for each detector that were prepared before testing began. An example of such a completed data form is shown in Appendix B. The first page of the form records information on the date, time, conditions, and nature of the test, the sensor configuration of the detector in question, and the identities of the testing personnel. The second page records the calibration data for the reference method used, the reference measurement results on the target gas mixture, and other information such as the air flow rate of the interferent vapor source.

The third page of the form documents the challenge mixture, and records the detector responses, response times, and recovery times in successive sampling of clean air and the challenge mixture. The contractor Work Assignment Leader reviewed all such data forms upon completion, and required that any corrections be made promptly by the testing staff.

Test personnel also filled out a test summary form for each test that included the target gas and test number; the identity of the test system and mass flow control module used; the handheld detectors being tested; the results of daily bump tests with individual monitors and of the confidence check of the ChemPro 100i; the start and end times of the test; the test system mass flow rates at the start and end of the test; the name of the datalogger file that recorded all temperature, RH, and flow readings during the test; and the battery life indication of each detector at the end of testing. Those summary forms were filled out by hand, and were pasted into the laboratory record book at the completion of each test by means of their peel-off adhesive backing.

All test data were transferred from the hand-written data forms into a Microsoft® Access database, which organized the test information, detector responses, and reference method results for each test procedure. Organization of the data in this way allowed evaluation of the performance parameters clearly and consistently. The accuracy of entering manually-recorded data into the database was checked at the time the data were entered, and a portion of the data were also checked by the contractor QA Manager as part of the Data Quality Audit (Section 4.2.3).

3.0 Statistical Calculations

The quantitative performance parameters defined in Section 2.1 were evaluated by statistical calculations using the test data. These calculations were built into the Access database compiled from the test data, so that calculations were completed automatically as data were entered into the spreadsheets. The following sections define the calculations that were conducted for each performance parameter.

3.1 Response and Recovery Time

The data collected to evaluate response time were the measured time periods required for each detector to reach a stable reading after initiation of a gas challenge. Response time (in seconds) was measured in each of five replicate test runs at each test condition with each target gas, and the mean, range, and standard deviation (SD) of the five response times in each test were tabulated.

The corresponding data collected to evaluate recovery time were the measured time periods required for each detector to return to a stable baseline reading after removal of a gas challenge. Recovery time (in seconds) was measured in each of five replicate test runs at each test condition with each target gas, and the mean, range, and SD of the five recovery times in each test were tabulated.

When a detector failed to reach a stable reading within 180 seconds after the start of a gas challenge, the response time was recorded as ">180 seconds" and the test procedure was continued with the next clean air sampling period. Detectors were allowed periods of up to 15 minutes to return to baseline after removal of a gas challenge, while challenges were delivered to other detectors. Failure to reach a stable baseline reading was recorded as a ">" recovery time. For statistical analysis, all ">" recovery and response times were assigned their numerical values, i.e., the ">" notation was dropped.

3.2 Repeatability

Repeatability was calculated in terms of the percent relative standard deviation (RSD) of the quantitative readings from five successive test runs with a detector at each test condition and target gas concentration. That is:

$$\text{Repeatability} = (\text{SD}/\text{Mean}) \times 100\% \qquad (1)$$

where SD is the standard deviation of the five quantitative readings and Mean is the arithmetic average of those five readings.

3.3 Accuracy

The QUA of each handheld detector was calculated as a percentage in terms of the ratio of the detector's quantitative reading to the known concentration of the target gas challenge. That is:

$$\text{QUA} = (\text{Detector Reading}/\text{Known Concentration}) \times 100\% \qquad (2)$$

QUA was calculated as the mean of the quantitative detector responses in the five replicate runs at each test condition and target gas concentration. When a detector gave a quantitative reading for a target gas, even though in a constant overrange condition, the QUA was calculated but results were flagged as being underestimates of the true QUA value.

Accuracy was also assessed in terms of the percentage of tests in which each handheld detector properly identified the target gas being delivered. IA was calculated as follows:

$$IA = (CI/\#Tests) \times 100\% \qquad (3)$$

where CI is the number of target gas challenges in which the detector correctly indicated the target gas, and #Tests is the number of target gas challenges. IA was calculated in this way for each handheld detector for each test condition and target gas concentration. That is, #Tests was typically 5, because of the five replicates in each such test scenario. The overall IA was also calculated by applying Equation 3 to all tests conducted with each detector.

3.4 Response Threshold

No statistical calculations were needed to estimate the response threshold of each handheld detector for the target gases. After five replicate tests at approximately 22 °C and 50% RH at an initial gas concentration (see Table 2.4-5), the concentration was reduced and five more replicate gas challenges (interspersed with clean air challenges) were conducted. This process was repeated until a concentration was reached at which the detector failed to respond to the target gas in at least three of the five challenges, or the challenge gas concentration was as low as could reasonably be delivered and confirmed by the test procedures. The response threshold is reported as an upper limit, i.e., less than or equal to the lowest concentration tested.

3.5 Effect of Operating Conditions

The effects of temperature and RH on the performance parameters of response time, recovery time, repeatability, QUA, and IA were determined by comparing the quantitative measures of these parameters in tests conducted at different temperature/RH conditions. For response time, a significant effect of test conditions was inferred when there was no overlap between the mean (± 1 SD) ranges of the response times determined at two different temperature/RH conditions. The same criterion was used to judge temperature/RH effects on recovery time.

For repeatability, QUA, and IA, a significant effect of test conditions was inferred when the metric calculated by means of Equations 1, 2, or 3 above, respectively, differed by more than 20% between two sets of test conditions.

3.6 Cold/Hot Start Behavior

The effects of storage temperature on the performance parameters of response time, recovery time, repeatability, QUA, and IA were determined by comparing the quantitative measures of these parameters in tests conducted with H_2S after overnight storage at different conditions. One test run (i.e., five challenge/clean air replicates) was conducted at the start of a test day immediately after the detector had been removed from cold, hot, or room temperature storage overnight. Storage under these three conditions took place in three successive overnight periods, and the detectors were tested on the corresponding three successive mornings. The time from initial power-up of each detector until the detector was ready to begin monitoring was recorded as the detector delay time. Each detector then received a challenge gas consisting of 90 ppm H_2S in air at 22°C and 50% RH, and the response time and reading of the detector were recorded. The challenge gas was then replaced with clean air and the recovery time of the detector was recorded. Five successive alternating readings of challenge gas and clean air were obtained and used to determine the response time, recovery time, repeatability, QUA, and IA of the detector after startup from the storage condition in question.

The results for response time, recovery time, repeatability, QUA, and IA of the detector after cold, hot, and room temperature overnight storage were compared. For response time, a significant effect of storage conditions was inferred when there was no overlap between the mean (± 1 SD) ranges of the response times determined with two different storage conditions. The same criterion was used to judge storage condition effects on recovery time. For repeatability, QUA, and IA, a significant effect of storage conditions was inferred when the metric calculated by means of Equations 1, 2, or 3 above, respectively, differed by more than 20% between two sets of results obtained after different storage conditions.

3.7 Interference Effects

Interference effects were calculated in terms of the rates of false positive and false negative responses from each handheld detector.

False positive rates were determined based on the response of the handheld detectors to air containing only the interferent vapors. For each detector, the false positive rate (FP) was calculated as:

$$FP = (PR/I) \times 100\%$$

where PR is the number of positive responses observed when sampling air containing the interferent, and I is the total number of such samples (I usually = 5). This calculation was done for each detector with each target gas.

False negative rates were determined based on the absence of handheld detector response to a known concentration of each target gas, when the interferent was present along with the target gas. For each detector, the false negative rate (FN) was calculated as:

$$FN = (NR/TI) \times 100\%$$

where NR is the number of negative responses (i.e., failures to detect a hazardous concentration), and TI is the total number of samples tested containing both the target gas and the interferent (TI = 5). This calculation was done for each detector with each target gas.

3.8 Battery Life

The battery life of each handheld detector was quantified in terms of the hours and minutes of continuous operation achieved before the battery was depleted. Battery life was determined by starting with a fully charged battery or set of batteries and operating the detector until the battery supply was exhausted and the detector shut down.

In addition, in all testing, the battery status indication of each handheld detector was noted on the data recording form at the beginning and end of each set of test runs. In addition to providing information about battery depletion during testing, this requirement helped ensure that testing was always conducted with properly operating detectors. Testing of a detector did not take place unless its batteries showed a sufficient charge indication.

4.0 Quality Assurance/Quality Control

QA/quality control (QC) procedures were performed in accordance with the applicable QMP and the test/QA plan for this evaluation. QA/QC procedures and associated results are summarized below.

4.1 Data Quality Indicators

The testing reported here consisted of more than 800 separate tests, each consisting of five alternate blank and challenge runs with one detector, one challenge gas, and one combination of T/RH conditions, interferent, and startup condition. All of those tests met the requirements for data quality stated in the test/QA plan. Specifically, all temperature and RH conditions in testing were within 3°C and 5% RH, respectively, of the relevant target conditions stated in Table 2.4-1.

The reference methods similarly confirmed that the delivered challenge concentrations closely matched the target concentrations listed in Table 2.4-5. This fact is illustrated in Table 4.1-1, which shows the number, mean, SD, RSD, and median of the reference method results for each target gas at each concentration at which enough testing was done to develop these statistics.

Table 4.1-1. Summary Statistics of Reference Method Results

Gas	Target Concentration	Reference Method Results				
		Number	Mean[a]	SD[a]	RSD (%)	Median[a]
O_2	19 %	88	19.0	0.07	0.4	19.0
CH_4	1.25 %	64	1.22	0.04	3.7	1.22
H_2S	90 ppm	136	89.1	2.29	2.6	89.0
SO_2	50 ppm	44	49.9	2.52	5.1	50.0
	20 ppm	48	18.7	0.94	5.0	18.5
	5 ppm	48	4.63	0.57	12.3	5.0
NH_3	100 ppm	48	99.5	7.32	7.4	98
	50 ppm	48	50.3	3.02	6.0	51
Cl_2	10 ppm	96	9.9	0.51	5.1	9.9
	3 ppm	46	2.83	0.11	4.0	2.80
PH_3	20 ppm	95	19.3	0.74	3.9	19.0
HCN	50 ppm	96	48.5	1.54	3.2	48.7
	15 ppm	96	15.1	0.64	4.2	15.3

(a) Units as indicated in Target Concentration column.

Table 4.1-1 shows that mean and median reference method results for all target gases closely matched the target concentrations. Also the uniformity of concentrations was maintained, as indicated by the RSD values in Table 4.1-1, most of which are less than about 5 percent. The delivered target gas concentrations were well within the target delivery tolerance of 20 percent specified in the test/QA plan. In fact 97.7 percent of the reference measurements for all target gases at all concentrations fell within 10% of the target concentration, and 76.9% fell within 5 percent of the target concentration.

4.2 Audits

4.2.1 Performance Evaluation Audit

A performance evaluation (PE) audit was conducted to assess the quality of the measurements and gas challenges made in this project. The audit addressed only those reference measurements that factored into the data used for evaluation, i.e., the handheld detectors were not the subject of the PE audit. The PE audit was performed by analyzing a standard or comparing to a measurement device that was independent of standards used during the testing. Table 4.2-1 summarizes the PE audits that were done and indicates the PE audit standard or measurement device, the standard or device used in testing, the value or concentration level at which the PE audit comparison was done, the target degree of agreement for the PE audit, and the observed degree of agreement with the PE audit standard. This audit was conducted by the contractor's testing staff.

The PE audit standards for methane and the six TICs were gaseous standards of those compounds, obtained from commercial suppliers and distinct from the standards used for reference method calibrations. The PE audits for those gases were conducted by diluting the PE audit standard and the test standard to the same concentration and analyzing both by the reference method. The PE audit standard for O_2 was ambient air, with a known O_2 content of 20.9%. The PE standard for temperature and RH was a calibrated monitoring device for those parameters.

Table 4.2-1 shows that the PE audit results for O_2, CH_4, SO_2, NH_3, PH_3, HCN, temperature, and RH were all well within the respective target range of agreement, and the PE audit result for Cl_2 was only slightly outside the target range. However, the PE audit result for H_2S was substantially greater than the target. The PE audit comparison for H_2S (and for some of the other TICs) was challenging because the PE audit gas standard differed widely in concentration from the test gas standard with which it was compared. This difference required quite different dilution steps to prepare the desired TIC concentration for the PE audit. A comparably large PE audit result (i.e., agreement within about 18%) was originally found for HCN when comparing a 500 ppm PE audit standard to the 1% HCN test standard. However, the agreement shown in Table 4.2-1 (i.e., within 2.7%) was found for HCN when a PE audit gas of 1% HCN concentration was obtained. Similar agreement would be expected in the PE audit results for H_2S had a PE audit standard closer to 1% concentration been available in the course of this project. That is, the relatively high PE audit result for H_2S is believed to be due to the difference in PE and test gas standards, and not to the accuracy of the test gas standard itself. Overall, Table 4.2-1 confirms the validity of the test gas standards and measurement devices used in the test.

Table 4.2-1. Summary of PE Audit Results

Parameter	PE Audit Standard or Device	Test Standard or Device	Test Value or Condition	Target Agreement	Actual Agreement
O_2	Ambient Air	Dräger PAC-III	20.9% O_2	± 1% O_2	0.0% O_2
CH_4	99% CH_4 Cylinder 923103L	10% CH_4 Cylinder ALM035787	1% CH_4	± 10 %	2.3 %
H_2S	1,000 ppm H_2S Cylinder ALM065847	0.999% H_2S Cylinder ALM016184	50 ppm H_2S	± 10 %	17.5 %
SO_2	1,000 ppm SO_2 Cylinder ALM058997	1% SO_2 Cylinder A2316	100 ppm SO_2	± 10 %	4.0 %
NH_3	28% NH_3 Cylinder ALM033321	27.8% NH_3 Cylinder ALM055009	278 ppm NH_3	± 10 %	0.9%
Cl_2	490 ppm Cl_2 Cylinder XA6266	1.00% Cl_2 Cylinder B6237	10 ppm Cl_2	± 10 %	10.5 %
PH_3	500 ppm PH3 Cylinder CC88366	1% PH3 Cylinder A1809	20 ppm PH_3	± 10 %	5.8 %
HCN	0.998% HCN Cylinder D735	1% HCN Cylinder 1A9405	50 ppm HCN	± 10 %	2.7%
Temperature[a]	Vaisala C20972	Vaisala C21552 Vaisala C20749	21 °C	± 2 °C	0.1 °C 0.0 °C
RH[a]	Vaisala C20972	Vaisala C21552 Vaisala C20749	50 % RH	± 5% RH	0.2 % RH 0.2 % RH

(a) Dual entries indicate audit of the temperature/RH monitoring units in the two test systems.

4.2.2 Technical Systems Audit

The contractor QA Manager conducted a technical systems audit (TSA) of the test procedures in the test laboratory on July 26, 2011, to ensure that the evaluation was being conducted in accordance with the test/QA plan and the QMP. As part of the TSA, test procedures were compared to those specified in the test/QA plan, and data acquisition and handling procedures were reviewed. Observations from this TSA were documented in a report which was submitted to the Work Assignment Leader for response. No adverse findings resulted from this TSA. However, two deviations were prepared and approved documenting slight differences between actual test procedures and those stated in the test/QA plan. One deviation addressed the use of Tedlar bags rather than a gas-tight syringe for collection of gas samples for reference analysis. The other deviation addressed the procedure for conducting cold-start tests on the handheld detectors, which was incorrectly described in the test/QA plan. TSA records were permanently stored with the contractor QA Manager.

4.2.3 Data Quality Audit

At least 10% of the data acquired during the evaluation were audited. A contractor QA auditor traced the data from the initial acquisition, through reduction and statistical analysis, to final reporting to ensure the integrity of the reported results. All calculations performed on the data undergoing the audit were checked.

4.2.4 QA/QC Reporting

Each audit was documented in accordance with the QMP. The results of the audits were submitted to EPA (i.e., to the NHSRC Quality Assurance Manager and the EPA Contracting Officer's Representative [COR]).

4.3 Data Review

As described in Section 2.5, all detector test conditions, reference method results, and detector responses were recorded by the testing personnel in laboratory record books, on test summary forms, and on pre-printed data forms that were color-coded for the seven detectors (see example in Appendix B). The testing personnel initialed and dated every page of every data form during the data recording process. All record books, data forms, and summary forms were then subjected to a QC/technical review by the Work Assignment Leader, who clarified and corrected any incomplete or unclear entries through discussions with test personnel and review of other records (e.g., datalogger files). The hard copy data forms were then scanned and converted to electronic (i.e., pdf) format. The data were then entered into a Microsoft® Access database and used in assessing detector performance. All data recording and review were performed by contractor staff. Entry of data from the data sheets into the Access database was performed by subcontractor staff, under the supervision of, and subject to review by, the contractor staff.

5.0 Results

This section summarizes the performance results for each detector with each challenge gas. The following sections address the several performance parameters stated in Section 2.1.

5.1 Response and Recovery Time

Tables 5.1-1 through 5.1-8 summarize the mean response and recovery times observed with each detector in each test with H_2S, SO_2, NH_3, Cl_2, PH_3, HCN, O_2, and CH_4, respectively. For each detector and test condition, the mean response and recovery time are shown in seconds. Note that each detector was given up to 180 seconds to respond to the challenge gas mixture before switching back to the clean air challenge. Consequently, 180 seconds is the maximum value recorded for response time. The testing procedures allowed considerable time for recovery after a challenge, so the maximum recorded recovery times of the detectors were several minutes long.

Table 5.1-1 through 5.1-8 show that the response and recovery times of the detectors varied widely depending on the challenge gas and test conditions, but that response times were generally much shorter than recovery times. Relatively rapid response and recovery were observed with all detectors with O_2 and CH_4 (Tables 5.1-7 and 5.1-8, respectively); relatively slow response and recovery were seen with all detectors with NH_3 (Table 5.1-3).

Table 5.1-1 shows that the ChemPro 100i and RAE MultiRAE Pro responded most rapidly to H_2S (i.e., usually within 20 seconds), but the MultiRAE Pro recovery times were much longer than those of the ChemPro 100i. The iBRID MX6 exhibited relatively long response and recovery times with H_2S.

Table 5.1-2 shows that the Eagle 2 and PHD6 responded most rapidly to SO_2, and the ChemPro 100i responded rapidly in some tests but showed no response in others. Response times with SO_2 were longest with the iBRID MX6, and recovery times were longest with the iBRID MX6, ChemPro 100i, MultiRAE Pro, and Eagle 2.

Table 5.1-4 shows widely varying response and recovery times for Cl_2, with the notable finding that recovery times were shorter than response times in many tests with the GasAlert Micro 5 and iBRID MX6. The ChemPro 100i responded relatively rapidly in some tests but showed no response in others. The longest recovery times after Cl_2 challenges were observed with the X-am 7000, MultiRAE Pro, and Eagle 2.

Table 5.1-5 indicates the shortest response and recovery times (i.e., often less than 15 seconds) with PH_3 were with the GasAlert Micro 5 and Eagle 2 detectors. The detectors generally responded to PH_3 challenges relatively rapidly (compared to response times with other TICs), but some recovery times exceeding 300 seconds were observed, especially with the PHD6 detector.

Table 5.1-6 shows that the X-am 7000 and ChemPro 100i responded most rapidly to HCN, with response times often approximately 20 seconds or less. The iBRID MX6 exhibited the slowest response, often not reaching stable response within 300 seconds. Recovery times with HCN often ranged from about 300 to 500 seconds with the iBRID MX6, MultiRAE Pro, PHD 6, and X-am 7000. Both response and recovery times with HCN were usually less than 100 seconds for the GasAlert Micro 5 and Eagle 2.

Table 5.1-1. Summary of Mean Response and Recovery Times (seconds) with H_2S[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
1	Base test, 90 ppm	50	46	29	95	19	30	121	342	18	319	20	32	30	107
2	Step down, 30 ppm	35	25	101	59	18	50	68	122	19	162	17	20	28	74
3	Step down, 10 ppm	26	14	75	29	19	34	49	69	14	67	15	13	25	50
4	Step down, 3 ppm	19	7	50	19	19	101	44	38	71	29	180	9	42	23
5	H_2S, 19% O_2	49	45	56	119	18	46	82	701	14	279	29	34	34	113
6	H_2S, 16% O_2	38	47	55	106	18	102	70	754	14	281	27	34	32	116
7	H_2S, room T start	43	51	24	139	18	92	88	> 849[b]	18	324	38	33	41	112
8	Paint vapors	45	50	31	99	18	47	68	581	15	328	12	32	26	110
9	Gasoline exhaust	49	62	29	109	18	56	73	565	41	367	62	32	99	117
10	H_2S, low T start	66	55	127	403	19	71	86	> 884[b]	22	420	36	60	37	119
11	Ammonia cleaner	37	55	38	118	18	68	71	635	15	319	13	30	27	110
12	Diesel exhaust	44	63	24	110	18	55	63	655	15	316	14	31	27	108
13	H_2S, high T start	33	62	25	93	19	157	94	892[b]	19	300	51	36	39	115
14	Air freshener	37	51	25	104	19	24	73	695[b]	13	348	11	33	23	113
15	DEAE	43	53	22	94	18	216	70	589	14	323	14	32	28	110
16	Room T, <20% RH	53	50	19	94	18	29	88	353	16	323	16	39	27	117
17	Room T, 80% RH	43	50	91	107	19	34	103	582	14	309	15	33	28	114
18	Low T, 50% RH	41	52	20	100	18	28	105	672	15	317	14	42	25	130
19	High T, 50% RH	36	45	76	190	18	58	84	460	14	351	14	34	28	114
20	High T, 80% RH	35	48	180	340	18	66	81	590	16	359	28	35	29	117

(a) Entries are mean response time and mean recovery time, in seconds, from five replicate challenges in each test.
(b) Response not fully cleared after 15 minutes or more on clean air following one or more TIC challenges.

Table 5.1-2. Summary of Mean Response and Recovery Times (seconds) with SO_2[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
1	Base test, 100 ppm	76	126	64	711	21	165	91	403	NT	NT	NT	NT	NT	NT
2	Step down, 50 ppm	33	71	40	503[b]	28	383	32	254	NT	NT	NT	NT	NT	NT
3	Step down, 20 ppm	36	37	44	287	NR	NR	30	128	37	260	NT	NT	22	117
4	Step down, 5 ppm	11	12	32	130	NR	NR	15	53	35	124	13	342	15	52
8	Paint vapors	180	88	80	582	24	156	165	430	44	315	12	232[c]	27	88
9	Gasoline Exhaust	48	44	134	495	NR	NR	180	455	31	215	12	178	17	75
11	Ammonia cleaner	59	63	52	> 496	17	390[b]	62	289	28	219	12	221	15	80
12	Diesel exhaust	40	44	93	431	17	365[b]	178	466	30	254	11	244	14	74
14	Air freshener	135	86	82	> 585	16	494[b]	106	352	31	230	13	261	16	73
15	DEAE	180	84	98	645	16	356[b]	183	404	27	201	13	206	15	74
16	Room T, <20% RH	29	52	32	> 597	NR	NR	37	240	39	401	12	460	24	117
17	Room T, 80% RH	99	126	134	> 600	33	30	63	359	55	261	23	354	23	134
18	Low T, 50% RH	95	128	45	> 616	20	560[b]	60	> 548	45	345	12	369	28	92
19	High T, 50% RH	85	119	97	> 675	31	79	55	273	55	273	15	265	38	141
20	High T, 80% RH	172	176	150	> 510	19	106	41	248	75	405	33	308	29	95

(a) Entries are mean response time and mean recovery time, in seconds, from five replicate challenges in each test. NR = no response, NT = not tested.
(b) Response not fully cleared after 15 minutes or more on clean air following one or more TIC challenges.
(c) Based on less than five recovery time values.

Table 5.1-3. Summary of Mean Response and Recovery Times (seconds) with NH_3[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
1	Base test, 100 ppm	154	800[b,c]	>180	321	54	118	101	>780[c]	>180	>468	NT	NT	>180	>492[b]
2	Step down, 50 ppm	>180	893	>180	252	120	143	>180	>1152[b]	82	>355	>180	>567	161	>517
3	Step down, 10 ppm	159	198	>180	194	137	52	>180	>810[b,c]	169	274	>180	200	>180	182
4	Step down, 3 ppm	>180	118	>180[c]	66[c]	NR	NR	>180	>917[b]	66	91	>180	99	161	47
8	Paint vapors	>180	>750[c]	>180	390	28	330	>180	>765[c]	>180	>360	>180	>360	>180	>360
9	Gasoline exhaust	>180	> 910[b,c]	>180	283	30	171	>180	>915[b,c]	>180	>504	>180	>468	133	>471
11	Ammonia cleaner	>180	> 810[c]	>180	334	49	158	>180	>825[c]	>180	>420	>180	>408	>180	>384
12	Diesel exhaust	>180	> 672[c]	>180	339	22	168	>180	>630[c]	>180	>408	>180	>384	131	>377
14	Air freshener	>180	> 828[b,c]	>180	321	41	169	>180	>915[b,c]	>180	>420	>180	>396	>180	>432
15	DEAE	>180	> 818[b,c]	>180	243	45	174	>180	>840[b,c]	>180	>420	>180	>348	>180	>360
16	Room T, <20% RH	>180	> 823[b,c]	>180	198	33	98	>180	>825[b,c]	139	>558[b]	>180	>764[b]	155	>590[b]
17	Room T, 80% RH	>180	> 1320[b,c]	>180	>1132[b]	66	381	>180	>1230[b,c]	>180	>450	>180	>420	>180	>366
18	Low T, 50% RH	>180	692	>180	291	36	119	>180	>840[b,c]	>180	>426	>180	>408	>180	>370
19	High T, 50% RH	>180	1049[b]	>180	>1026[b]	59	250	>180	>1112[b,c]	>180	>408	>180	>408	>180	>408
20	High T, 80% RH	>180	>330[c]	>180	>900[b,c]	83	332	>180	>900[b,c]	>180	>426	>180	>396	>180	>372

(a) Entries are mean response time and mean recovery time, in seconds, from five replicate challenges in each test. NR = no response, NT = not tested.
(b) Response not fully cleared after 15 minutes or more on clean air following one or more TIC challenges.
(c) Based on less than five response or recovery time values.

Table 5.1-4. Summary of Mean Response and Recovery Times (seconds) with Cl_2[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
1	Base test, 10 ppm	54	22	>180	>726[b]	24[c]	116[c]	>180	48	63	>320	NT	NT	69	57
2	Step down, 3 ppm	29	5	169	320	17[c,d]	55[c,d]	158	12	105	208	38	>424	118	18
3	Step down, 1ppm	NR	NR	44	16	NR[d]	NR[d]	59	8	> 180	111	34	>396	>180	10
8	Paint vapors	46	21	>180	>600[c]	21	39	111	71	86	>401	68	>574[b]	86	43
9	Gasoline exhaust	36	20	>180	>686[c]	NR	NR	180	86	78	>436	71	>426	95	43
12	Diesel exhaust	87	33	119	122	NR[d]	NR[d]	23	49	33	>328	80	>391	28	27
14	Air freshener	42	19	>180	>600[c]	28	128	107	90	40	>335	>180	>408	22	32
15	DEAE	38	24	>180	>735[b,c]	40	86	133	88	37	410	>180	>390	19	24
16	Room T, <20% RH	180	35	104	>675[c]	24	169	12	29	19	>325	61	>370	18	27
17	Room T, 80% RH	180	27	>180	>702[b,c]	69[c]	43[c]	32	43	71	>417	>180	>324	19	30
18	Low T, 50% RH	51	38	41	124	47	75	>180	168	25	>540	102	>468	>180	41
19	High T, 50% RH	152	25	>180	>888[b]	NR	NR	161	37	43	188	>180	>392	13	26
20	High T, 80% RH	180	14	>180	211	NR	NR	>180	31	>180	191	>180	>348	15	33

(a) Entries are mean response time and mean recovery time, in seconds, from five replicate challenges in each test. NR = no response, NT = not tested.
(b) Response not fully cleared after 15 minutes or more on clean air following one or more TIC challenges.
(c) Based on less than five response or recovery time values.
(d) Alarmed during clean air sampling in at least one challenge.

Table 5.1-5. Summary of Mean Response and Recovery Times (seconds) with PH_3[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
1	Base test, 50 ppm	NT	NT	33	31	17	273	NT	NT	NT	NT	NT	NT	NT	NT
2	Step down, 20 ppm	NT	NT	37	24	78	212	NT	NT	43	220	NT	NT	125	>425
3	Step down, 5 ppm	12	14	32	23	18	55	>180	56	56	59	NT	NT	66	137
4	Step down, 1 ppm	8	3	50	7	18	43	69	16	19	26	10	11	50	41
8	Paint vapors	6	7	29	23	17	231	50	42	24	141	10	12	60	>330
9	Gasoline exhaust	6	8	25	25	18	142	50	38	22	177	10	36	60	>348
11	Ammonia cleaner	5	9	26	25	18	138	57	45	19	256	11	13	65	>320
12	Diesel exhaust	5	7	23	25	18	138	51	37	25	124	11	54	67	>322
14	Air freshener	5	8	28	24	18	151	64	47	16	83	10	90	80	>367
15	DEAE	5	8	27	24	18	147	62	41	23	226	9	12	57	>309
16	Room T, <20% RH	8	10	29	24	17	360	127	45	24	107	9	14	101	>420
17	Room T, 80% RH	6	9	29	24	20	186	>180	134	22	82	10	12	86	>331
18	Low T, 50% RH	8	13	26	25	18	366	59	45	25	104	10	14	106	>300
19	High T, 50% RH	6	7	33	22	16	117	>180	51	19	105	10	14	>180	>372
20	High T, 80% RH	5	5	32	23	18	78	48	78	18	128	10	14	83	>396

(a) Entries are mean response time and mean recovery time, in seconds, from five replicate challenges in each test. NR = no response, NT = not tested.

Table 5.1-6. Summary of Mean Response and Recovery Times (seconds) with HCN[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
1	Base test, 50 ppm	NT	NT	20	>345[c]	NT	NT	NT	NT	117	240	NT	NT	52	>437
2	Step down, 15 ppm	65	79	>180	>765[c]	18	133	>180	>679[c]	53	82	149	102	53	181
3	Step down, 5 ppm	31	24	69	>600[c]	21	120	154	287	77	83	51	17	135	141
8	Paint vapors	26	47	16	>328	30	96	84	342	111	>410	102	52	39	>438
9	Gasoline exhaust	44	63	17	291	NR	NR	>180	>533	115	>502	80	46	41	>485
11	Ammonia cleaner	41	59	17	339	17	123	>180	435	93	>474	83	43	28	>447
12	Diesel exhaust	44	67	17	291	16	73	>180	>545	119	>394	63	41	42	>474
14	Air freshener	24	53	17	305	17	92	89	>392	91	>398	82	97	35	>418
15	DEAE	29	52	17	301	17	91	90	348	86	>396	52	39	37	>405
16	Room T, <20% RH	52	74	16	>340[c]	27	63[c]	>180	>420[c]	54	274	48	62	102	>335
17	Room T, 80% RH	54	66	21	266	26	119	>180	>680[b]	45	296	45	45	93	>342
18	Low T, 50% RH	58	136	15	27	37	78	>180	>570[c]	69	>413	55	113	43	>398
19	High T, 50% RH	31	34	20	291	13[c]	109[c]	>136	225	86	>361	48	36	29	179
20	High T, 80% RH	27	36	41	364	18[c]	163[c]	148	142	119	>352[c]	71	29	97	186

(a) Entries are mean response time and mean recovery time, in seconds, from five replicate challenges in each test. NR = no response, NT = not tested.
(b) Response not fully cleared after 15 minutes or more on clean air following one or more TIC challenges.
(c) Based on less than five response or recovery time values.

Table 5.1-7. Summary of Mean Response and Recovery Times (seconds) with O_2[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
1	Base test, 19% O_2	NT	NT	NT	NT	NT	NT	10	10	9	9	22	63
2	Step down, 16% O_2	NT	NT	NT	NT	NT	NT	9	15	9	10	29	147
8	Paint vapors	21	11	33	19	25	50	16	9	9	8	46	55
9	Gasoline exhaust	21	12	30	20	29	26	8	12	7	9	9	>443
11	Ammonia cleaner	20	10	29	19	25	43	27	11	9	10	43	55
12	Diesel exhaust	NT	NT	NT	NT	NT	NT	17	11	8	8	13	53
14	Air freshener	18	13	28	20	32	30	10	10	8	7	13	24
15	DEAE	21	12	26	20	32	29	6	12	6	8	9	235
16	Room T, <20% RH	16	10	24	24	22	27	13	11	24	7	30	34
17	Room T, 80% RH	21	18	39	22	28	39	11	10	7	9	20	62
18	Low T, 50% RH	23	9	42	19	30	47	12	10	10	8	23	256
19	High T, 50% RH	13	12	28	19	18	26	9	10	7	7	16	19
20	High T, 80% RH	20	28	33	26	29	46	8	17	14	7	27	40

(a) Entries are mean response time and mean recovery time, in seconds, from five replicate challenges in each test. NT = not tested.

Table 5.1-8. Summary of Mean Response and Recovery Times (seconds) with CH_4[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
1	Base test, 1.25%	16	12	35	38	27	19	20	13	10	17	10	18
2	Step down, 0.5%	14	10	35	28	25	21	18	12	9	14	12	14
3	Step down, 0.2%	15	8	31	21	24	15	>180[b]	8	8	14	11	12
8	Paint vapors	16	15	NT	NT	27	20	22	17	21	16	14	20
9	Gasoline exhaust	15	13	NT	NT	26	21	15	12	14	19	19	19
11	Ammonia cleaner	15	16	NT	NT	25	22	21	22	18	15	20	19
12	Diesel exhaust	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
14	Air freshener	13	13	NT	NT	26	22	20	17	15	16	14	20
15	DEAE	15	13	NT	NT	27	21	23	11	11	19	21	19
16	Room T, <20% RH	19	20	41	33	26	20	22	8	10	18	11	19
17	Room T, 80% RH	15	13	46	49	39	26	11	>387	10	382	16	20
18	Low T, 50% RH	15	13	47	37	27	22	24	10	9	19	10	20
19	High T, 50% RH	19	>375[b]	44	>285[b]	28	24	24	>353	10	16	30	16
20	High T, 80% RH	18	>375[b]	NT	NT	30	>345[b]	22	>355	9	23	28	>326

(a) Entries are mean response time and mean recovery time, in seconds, from five replicate challenges in each test. NT = not tested.
(b) Based on less than five response or recovery time values.

5.2 Accuracy

Tables 5.2-1 through 5.2-8 summarize the QUA and IA observed with each detector in each test with H_2S, SO_2, NH_3, Cl_2, PH_3, HCN, O_2, and CH_4, respectively. Both measures of accuracy are shown in percent, as calculated using Equations 1 and 2, with 100% representing ideal performance. QUA was not determined in testing of the ChemPro 100i with the six TICs, as that detector provides a qualitative indicator of the intensity of response (i.e., one to three bars) rather than a concentration measurement. In addition, IA was determined for the ChemPro 100i based on its indication of "Toxic Hazard" because that detector does not identify the specific TIC being detected when operated in the First Responder library as in this test.

Table 5.2-1 shows that the QUA values for the GasAlert Micro 5 and iBRID MX6 for H_2S were high, usually exceeding 150%, whereas QUA for the PHD6 were almost entirely in the range of 100 to 130%. The X-am 7000, MultiRAE Pro, and Eagle 2 gave overrange or pegged full-scale readings in many tests, even though the 90 ppm H_2S challenge concentration was within their nominal detection range.

Table 5.2-2 shows that QUA was near 100% in all tests with SO_2 with the GasAlert Micro 5, X-am 7000, iBird MX6, and PHD6. QUA values were also near 100% with the MultiRAE Pro and Eagle 2, but many of those values resulted from pegged full-scale reading from those detectors.

Table 5.2-3 shows that QUA values for NH_3 were consistently near 100% with the X-am 7000, MultiRAE Pro, Eagle 2, and PHD6. The QUA results for the GasAlert Micro 5 and iBRID MX6 were consistently less than 100%, with some of the iBRID MX6 results falling below 50%.

Table 5.2-4 shows that the QUA values for Cl_2 with the GasAlert Micro 5, MultiRAE Pro, and PHD6 were most consistently near 100%. Some QUA values with the Eagle 2 were near 100%, but values also ranged as low as 25% with air freshener vapor as interferent. QUA values for Cl_2 were variable with the X-am 7000 (i.e., 29 to 148%) and the iBRID MX6 (i.e., 74 to 210%).

Table 5.2-5 shows that QUA values for PH_3 were consistently near 100% with the X-am 7000 and iBRID MX6, and were also near 100% with the MultiRAE Pro and Eagle 2, but many of those values resulted from pegged full-scale readings from those detectors. The QUA values from the PHD6 were often relatively low, and the GasAlert Micro 5 displayed an overrange condition in most tests.

Table 5.2-6 shows that QUA values for HCN were consistently near 100% with the GasAlert Micro 5, iBRID MX6, and PHD6, but were consistently below 100% with the MultiRAE Pro, and more so for the Eagle 2. The X-am 7000 showed an overrange indication in almost all tests with HCN.

Table 5.2-7 shows QUA values near 100% for O_2 with all detectors. Table 5.2-8 shows the Eagle 2 and PHD6 produced QUA results closest to 100% for CH_4, with the GasAlert Micro 5, X-am 7000, and iBIRD MX6 QUA values often over 150%. Most MultiRAE Pro QUA values were well below 100%. The CH_4 tests were done after all other testing was completed, so the LEL sensors in most of the detectors had been previously exposed to all other test challenges. Failure of the LEL sensor caused several tests to be cancelled with the X-am 7000, and LEL sensor failure is suspected as the explanation for the low QUA values with the MultiRAE Pro, as QUA results for CH_4 with that detector declined in chronological order of the tests.

IA was 100% (i.e., the detectors correctly identified the gas challenge in all trials) in almost all tests. Excluding the lowest concentration step-down tests (i.e., Tests 3 and 4), IA was 100% for all challenges under all test conditions with the GasAlert Micro 5, X-am 7000, iBRID MX6, MultiRAE Pro, Eagle 2, and PHD6. Other than in the step-down tests, the only cases of IA less than 100% were with the ChemPro 100i, which failed to indicate a hazard, or to respond at all, in some tests with SO_2, NH_3, Cl_2, and HCN (Tables 5.2-2, 5.2-3, 5.2-4, and 5.2-6, respectively). Those cases with the ChemPro 100i occurred in tests that involved interferent vapors, or temperature and RH conditions other than 22°C and 50% RH.

Table 5.2-1. Summary of Quantitative Accuracy and Identification Accuracy (percent) with H_2S[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA
1	Base test, 90 ppm	179	100	OR	100	NA	100	163	100	111[b]	100	108	100	126	100
2	Step down, 30 ppm	183	100	127	100	NA	100	168	100	135	100	107	100	126	100
3	Step down, 10 ppm	168	100	110	100	NA	100	165	100	139	100	112	100	130	100
4	Step down, 3 ppm	133	100	73	100	NA	100	140	100	97	100	17	100	100	100
5	H_2S, 19% O_2	152	100	108	100	NA	100	129	100	111[b]	100	102	100	117	100
6	H_2S, 16% O_2	126	100	92	100	NA	100	109	100	111[b]	100	102	100	118	100
7	H_2S, room T start	178	100	OR	100	NA	100	148	100	111[b]	100	101	100	113	100
8	Paint vapors	177	100	OR	100	NA	100	152	100	111[b]	100	111[c]	100	133	100
9	Gasoline exhaust	199	100	OR	100	NA	100	171	100	102	100	79	100	94	100
10	H_2S, low T start	172	100	89	100	NA	100	141	100	111[b]	100	101	100	114	100
11	Ammonia cleaner	169	100	OR	100	NA	100	144	100	111[b]	100	111[c]	100	129	100
12	Diesel exhaust	193	100	OR	100	NA	100	166	100	111[b]	100	111[c]	100	131	100
13	H_2S, high T start	170	100	OR	100	NA	100	142	100	111[b]	100	95	100	114	100
14	Air freshener	178	100	OR	100	NA	100	153	100	111[b]	100	111[c]	100	141	100
15	DEAE	200	100	OR	100	NA	100	171	100	111[b]	100	111[c]	100	128	100
16	Room T, <20% RH	202	100	OR	100	NA	100	181	100	111[b]	100	111[c]	100	130	100
17	Room T, 80% RH	203	100	94	100	NA	100	181	100	111[b]	100	111[c]	100	128	100
18	Low T, 50% RH	204	100	OR	100	NA	100	178	100	111[b]	100	111[c]	100	137	100
19	High T, 50% RH	172	100	OR	100	NA	100	158	100	111[b]	100	111[c]	100	129	100
20	High T, 80% RH	173	100	59	100	NA	100	158	100	111[b]	100	104	100	128	100

(a) Entries are mean quantitative accuracy (QUA) and mean Identification Accuracy (IA) from five replicate challenges in each test.
(b) MultiRAE read 99.9 ppm (indicating overrange condition) in all challenges with 90 ppm H_2S.
(c) Eagle 2 read 100.0 ppm (indicating overrange condition) in all challenges with 90 ppm H_2S.
NA Not Applicable. OR overrange (i.e., offscale) indication, no numerical reading.

Table 5.2-2. Summary of Quantitative Accuracy and Identification Accuracy (percent) with SO_2[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA
1	Base test, 100 ppm	99	100	100	100	NA	100	100	100	NT	NT	NT	NT	NT	NT
2	Step down, 50 ppm	104	100	107	100	NA	100	107	100	NT	NT	NT	NT	NT	NT
3	Step down, 20 ppm	104	100	106	100	NA	0	108	100	100[b]	100	NT	NT	109	100
4	Step down, 5 ppm	120	100	117	100	NA	0	140	100	116	100	120[c]	100	118	100
8	Paint vapors	97	100	102	100	NA	100	100	100	100[b]	100	120[c]	100	105	100
9	Gasoline exhaust	88	100	97	100	NA	0	92	100	100[b]	100	120[c]	100	108	100
11	Ammonia cleaner	99	100	104	100	NA	80	103	100	100[b]	100	120[c]	100	115	100
12	Diesel exhaust	92	100	101	100	NA	100	96	100	100[b]	100	120[c]	100	113	100
14	Air freshener	98	100	103	100	NA	60	101	100	100[b]	100	116	100	113	100
15	DEAE	96	100	101	100	NA	100	99	100	100[b]	100	114	100	113	100
16	Room T, <20% RH	103	100	109	100	NA	0	104	100	100[b]	100	120[c]	100	105	100
17	Room T, 80% RH	100	100	100	100	NA	80	103	100	100[b]	100	118	100	108	100
18	Low T, 50% RH	101	100	109	100	NA	80	105	100	100[b]	100	120[c]	100	105	100
19	High T, 50% RH	100	100	105	100	NA	80	105	100	100[b]	100	113	100	103	100
20	High T, 80% RH	98	100	99	100	NA	100	105	100	100[b]	100	117	100	108	100

(a) Entries are mean quantitative accuracy (QUA) and mean Identification Accuracy (IA) from five replicate challenges in each test.
(b) MultiRAE read 19.9 ppm (indicating overrange condition) in all challenges with 20 ppm SO_2.
(c) Eagle 2 read 6.0 ppm (indicating overrange condition) in all challenges with 5 ppm SO_2.
NA Not Applicable. NT Not Tested.

Table 5.2-3. Summary of Quantitative Accuracy and Identification Accuracy (percent) with NH_3[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA
1	Base test, 100 ppm	80	100	109	100	NA	100	OR	100	97	100	NT	NT	92	100
2	Step down, 50 ppm	79	100	80	100	NA	100	104	100	105	100	96	100	98	100
3	Step down, 10 ppm	100	100	80	100	NA	20	136	100	92	100	69	100	74	100
4	Step down, 3 ppm	147	100	78	60	NA	0	167	100	100	100	83	100	87	100
8	Paint vapors	66	100	88	100	NA	100	54	100	83	100	88	100	88	100
9	Gasoline exhaust	62	100	89	100	NA	60	38	100	86	100	95	100	102	100
11	Ammonia cleaner	68	100	97	100	NA	100	47	100	90	100	91	100	90	100
12	Diesel exhaust	61	100	85	100	NA	100	39	100	82	100	91	100	104	100
14	Air freshener	54	100	94	100	NA	100	48	100	80	100	76	100	76	100
15	DEAE	60	100	90	100	NA	100	36	100	83	100	89	100	92	100
16	Room T, <20% RH	70	100	96	100	NA	100	76	100	97	100	87	100	92	100
17	Room T, 80% RH	67	100	66	100	NA	100	81	100	93	100	85	100	88	100
18	Low T, 50% RH	69	100	89	100	NA	100	53	100	86	100	84	100	88	100
19	High T, 50% RH	73	100	92	100	NA	100	88	100	95	100	82	100	94	100
20	High T, 80% RH	77	100	87	100	NA	100	88	100	94	100	76	100	86	100

(a) Entries are mean quantitative accuracy (QUA) and mean Identification Accuracy (IA) from five replicate challenges in each test.
NA Not Applicable. NT Not Tested. OR overrange (i.e., offscale) indication, no numerical reading.

Table 5.2-4. Summary of Quantitative Accuracy and Identification Accuracy (percent) with Cl_2[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA
1	Base test, 10 ppm	74	100	76	100	NA	80	117	100	109	100	NT	NT	104	100
2	Step down, 3 ppm	33	100	43	100	NA	20	107	100	100	100	100[b]	100	99	100
3	Step down, 1ppm	NR	NR	15	100	NA	NR	84	100	84	100	130	100	92	100
8	Paint vapors	102	100	123	100	NA	100	121	100	102	100	100[b]	100	101	100
9	Gasoline exhaust	98	100	121	100	NA	NR	119	100	104	100	100[b]	100	101	100
12	Diesel exhaust	96	100	77	100	NA	NR	147	100	114	100	100[b]	100	106	100
14	Air freshener	96	100	118	100	NA	100	120	100	113	100	25	100	109	100
15	DEAE	114	100	148	100	NA	100	139	100	115	100	91	100	112	100
16	Room T, <20% RH	90	100	100	100	NA	100	140	100	123	100	100[b]	100	112	100
17	Room T, 80% RH	82	100	58	100	NA	20	119	100	107	100	57	100	113	100
18	Low T, 50% RH	106	100	OR	100	NA	100	210	100	115	100	100[b]	100	85	100
19	High T, 50% RH	70	100	64	100	NA	NR	74	100	111	100	79	100	140	100
20	High T, 80% RH	64	100	29	100	NA	NR	61	100	90	100	47	100	128	100

(a) Entries are mean quantitative accuracy (QUA) and mean Identification Accuracy (IA) from five replicate challenges in each test.
(b) Eagle 2 read 3.0 ppm (indicating ovverrange condition) on all challenges at 3 ppm Cl_2.
NA Not Applicable. NT Not Tested. NR No Response. OR overrange (i.e., offscale) indication, no numerical reading.

Table 5.2-5. Summary of Quantitative Accuracy and Identification Accuracy (percent) with PH_3[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA
1	Base test, 50 ppm	NT	NT	92	100	NA	100	NT	NT	NT	NT	NT	NT	NT	NT
2	Step down, 20 ppm	NT	NT	108	100	NA	100	NT	NT	100[b]	100	NT	NT	66	100
3	Step down, 5 ppm	OR	100	100	100	NA	100	94	100	101	100	NT	NT	60	100
4	Step down, 1 ppm	100	100	100	100	NA	100	133	100	130	100	100[c]	100	94	100
8	Paint vapors	OR	100	105	100	NA	100	105	100	100[b]	100	100[c]	100	78	100
9	Gasoline exhaust	OR	100	104	100	NA	100	101	100	100[b]	100	100[c]	100	80	100
11	Ammonia cleaner	OR	100	115	100	NA	100	114	100	100[b]	100	96	100	89	100
12	Diesel exhaust	OR	100	106	100	NA	100	98	100	100[b]	100	100[c]	100	65	100
14	Air freshener	OR	100	115	100	NA	100	107	100	100[b]	100	100[c]	100	90	100
15	DEAE	OR	100	104	100	NA	100	99	100	100[b]	100	98	100	80	100
16	Room T, <20% RH	OR	100	100	100	NA	100	98	100	100[b]	100	100[c]	100	62	100
17	Room T, 80% RH	OR	100	100	100	NA	100	103	100	100[b]	100	100[c]	100	62	100
18	Low T, 50% RH	OR	100	95	100	NA	100	98	100	100[b]	100	100[c]	100	65	100
19	High T, 50% RH	OR	100	100	100	NA	100	98	100	100[b]	100	100[c]	100	64	100
20	High T, 80% RH	OR	100	100	100	NA	100	114	100	100[b]	100	100[c]	100	61	100

(a) Entries are mean quantitative accuracy (QUA) and mean Identification Accuracy (IA) from five replicate challenges in each test.
(b) MultiRAE Pro read 19.9 ppm (indicating overrange condition) in all challenges with 20 ppm PH_3.
(c) Eagle 2 read 1.0 ppm (indicating overrange condition) in all challenges with 1 ppm PH_3.
NA Not Applicable. NT Not Tested. OR overrange (i.e.,offscale) indication, no numerical reading.

Table 5.2-6. Summary of Quantitative Accuracy and Identification Accuracy (percent) with HCN[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA
1	Base test, 50 ppm	NT	NT	OR	100	NT	NT	NT	NT	90	100	NT	NT	100[b]	100
2	Step down, 15 ppm	109	100	141	100	NA	100	117	100	93	100	87	100	112	100
3	Step down, 5 ppm	108	100	162	100	NA	100	129	100	118	100	92	100	140	100
8	Paint vapors	107	100	OR	100	NA	100	116	100	86	100	68	100	109	100
9	Gasoline exhaust	107	100	OR	100	NA	0	114	100	85	100	65	100	108	100
11	Ammonia cleaner	112	100	OR	100	NA	100	115	100	92	100	63	100	116	100
12	Diesel exhaust	107	100	OR	100	NA	100	125	100	87	100	66	100	110	100
14	Air freshener	109	100	OR	100	NA	100	115	100	85	100	73	100	111	100
15	DEAE	104	100	OR	100	NA	100	107	100	84	100	66	100	109	100
16	Room T, <20% RH	109	100	OR	100	NA	100	112	100	82	100	79	100	107	100
17	Room T, 80% RH	100	100	OR	100	NA	100	109	100	86	100	73	100	116	100
18	Low T, 50% RH	107	100	OR	100	NA	100	115	100	63	100	50	100	111	100
19	High T, 50% RH	99	100	OR	100	NA	60	105	100	97	100	91	100	110	100
20	High T, 80% RH	117	100	OR	100	NA	80	113	100	98	100	73	100	98	100

(a) Entries are mean quantitative accuracy (QUA) and mean Identification Accuracy (IA) from five replicate challenges in each test.
(b) PHD6 read 100 ppm (indicating overrange condition) on all challenges at 100 ppm HCN in Test 1. Tests 8 to 20 conducted with 50 ppm HCN with this detector.
NA Not Applicable. NT Not Tested. OR Overrange (i.e.,offscale) indication, no numerical reading.

Table 5.2-7. Summary of Quantitative Accuracy and Identification Accuracy (percent) with O_2[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA	QUA	IA
1	Base test, 19% O_2	NT	NT	NT	NT	NT	NT	99	100	99	100	100	100
2	Step down, 16% O_2	NT	NT	NT	NT	NT	NT	95	100	98	100	99	100
8	Paint vapors	98	100	100	100	98	100	100	100	100	100	100	100
9	Gasoline exhaust	97	100	99	100	98	100	92	100	92	100	94	100
11	Ammonia cleaner	98	100	100	100	98	100	100	100	99	100	101	100
12	Diesel exhaust	NT	NT	NT	NT	NT	NT	97[b]	100[b]	97	100	98	100
14	Air freshener	98	100	99	100	98	100	98	100	98	100	99	100
15	DEAE	97	100	99	100	98	100	92	100	91	100	93	100
16	Room T, <20% RH	99	100	101	100	99	100	99	100	101	100	100	100
17	Room T, 80% RH	98	100	100	100	98	100	99	100	97	100	100	100
18	Low T, 50% RH	99	100	100	100	97	100	99	100	99	100	100	100
19	High T, 50% RH	98	100	100	100	98	100	99	100	98	100	100	100
20	High T, 80% RH	97	100	100	100	98	100	98	100	100	100	100	100

(a) Entries are mean quantitative accuracy (QUA) and mean Identification Accuracy (IA) from five replicate challenges in each test.
(b) Based on four challenges due to depletion of interferent supply before last challenge.
NT Not Tested.

Table 5.2-8. Summary of Quantitative Accuracy and Identification Accuracy (percent) with CH_4[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		QUA	IA	QUA	IA	QUA	IA	QUA[b]	IA	QUA	IA	QUA	IA
1	Base test, 1.25%	136	100	164	100	163	100	34	100	112	100	106	100
2	Step down, 0.5%	180	100	167	100	218	100	60	100	141	100	132	100
3	Step down, 0.2%	250	100	190	100	320	100	20	20	184	100	140	100
8	Paint vapors	171	100	NT	NT	203	100	52	100	92	100	117	100
9	Gasoline exhaust	174	100	NT	NT	204	100	48	100	106	100	127	100
11	Ammonia cleaner	171	100	NT	NT	203	100	56	100	92	100	116	100
12	Diesel exhaust	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
14	Air freshener	176	100	NT	NT	212	100	56	100	100	100	122	100
15	DEAE	173	100	NT	NT	203	100	40	100	96	100	110	100
16	Room T, <20% RH	152	100	165	100	188	100	23	100	118	100	147	100
17	Room T, 80% RH	160	100	177	100	181	100	110	100	128	100	110	100
18	Low T, 50% RH	168	100	124	100	220	100	77	100	128	100	154	100
19	High T, 50% RH	176	100	176	100	184	100	95	100	126	100	98	100
20	High T, 80% RH	195	100	NT	NT	191	100	88	100	120	100	78	100

(a) Entries are mean quantitative accuracy (QUA) and mean Identification Accuracy (IA) from five replicate challenges in each test.
(b) Inspection of results shows MultiRAE Pro QUA values decline in chronological order of tests with CH_4; possible sensor failure.
NT Not Tested.

5.3 Repeatability

Tables 5.3-1 through 5.3-8 summarize the repeatability observed with each detector in each test with H_2S, SO_2, NH_3, Cl_2, PH_3, HCN, O_2, and CH_4, respectively. Repeatability was calculated as percent RSD of the five replicate responses in each test, according to Equation 3. It should be noted that for most of the handheld detectors repeatability was determined from concentration readings provided by the detectors, but for the ChemPro 100i repeatability was determined from the 1-to-3-bar intensity indications provided by that detector. Thus, the repeatability results for the ChemPro 100i are not directly comparable to those of the other detectors.

The BW GasAlert Micro 5 and the Dräger X-am 7000 gave no quantitative values for offscale (i.e., overrange) readings, however other detectors continued to indicate a quantitative numerical reading even when in an overrange condition. Such occurrences are flagged by means of footnotes in Tables 5.3-1 through 5.3-8 to distinguish them from instances in which a detector gave five identical on-scale readings (both occurrences result in a calculated repeatability value of 0.0% RSD).

For the detectors other than the ChemPro 100i, Tables 5.3-1 through 5.3-8 show repeatability values that were consistently less than 5% RSD with most detectors in detection of H_2S, SO_2, PH_3, HCN, O_2, and CH_4. A few exceptions of relatively higher repeatability results (i.e., up to approximately 10% RSD) occurred with the Eagle 2 with HCN (Table 5.3-6), and with the PHD6 with CH_4 (Table 5.3-8). On the other hand, repeatability results were substantially higher (usually below 10% RSD, with occasional values of 20% or more) for all detectors with NH_3 and Cl_2 (Tables 5.3-3 and 5.3-4). Repeatability was not affected by interferent vapors or by test conditions other than room temperature and 50% RH.

Repeatability values for the ChemPro 100i were constrained by the detector's 1-to-3-bar intensity indication and, in most cases, the ChemPro 100i gave the same intensity response with all five challenges in a test (i.e., repeatability = 0% RSD). However, the presence of interferent vapors, and test conditions other than room temperature and 50% RH, sometimes reduced the repeatability of ChemPro 100i response. This observation was most evident with H_2S (Table 5.3-1), NH_3 (Table 5.3-3), and PH_3 (Table 5.3-5).

Table 5.3-1. Summary of Repeatability (percent RSD) with H_2S[a]

Test Number	Test Description	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i[b]	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
1	Base test, 90 ppm	0.0	OR	0.0	0.6	0.0[c]	0.8	1.1
2	Step down, 30 ppm	0.8	2.8	0.0	1.0	2.6	1.4	1.2
3	Step down, 10 ppm	2.7	3.3	0.0	6.1	2.3	2.4	0.0
4	Step down, 3 ppm	0.0	1.8	0.0	1.7	0.0[c]	0.0	0.0
5	H_2S, 19% O_2	0.7	1.1	0.0	0.7	0.0[c]	0.5	0.8
6	H_2S, 16% O_2	0.8	0.7	0.0	1.0	0.0[c]	0.2	0.9
7	H_2S, room T start	0.5	OR	50	0.8	0.0[c]	1.1	0.5
8	Paint vapors	0.3	OR	34.2	0.4	0.0[c]	0.0[d]	0.7
9	Gasoline exhaust	0.7	OR	0.0	0.7	0.4	0.4	0.7
10	H_2S, low T start	0.6	22.9	34.2	0.8	0.0[c]	2.2	0.0
11	Ammonia cleaner	0.6	OR	0.0	0.9	0.0[c]	0.0[d]	0.8
12	Diesel exhaust	0.7	OR	0.0	0.7	0.0[c]	0.0[d]	0.4
13	H_2S, high T start	1.3	OR	63.6	0.2	0.0[c]	0.5	0.9
14	Air freshener	1.3	OR	0.0	1.5	0.0[c]	0.0[d]	1.9
15	DEAE	0.6	OR	63.6	0.5	0.0[c]	0.2	0.4
16	Room T, <20% RH	0.2	OR	0.0	1.0	0.0[c]	0.0[d]	0.7
17	Room T, 80% RH	0.8	OR	63.6	0.7	0.0[c]	0.7	0.5
18	Low T, 50% RH	0.0	OR	0.0	0.1	0.0[c]	0.0[(d)]	1.1
19	High T, 50% RH	0.4	OR	34.2	0.3	0.0[c]	0.0[(d)]	0.8
20	High T, 80% RH	0.0	19	0.0	0.2	0.0[c]	0.0	0.5

(a) Entries are percent relative standard deviation (RSD) of quantitative responses from five replicate challenges in each test. NT Not Tested.
(b) ChemPro 100i reports intensity (1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
(c) MultiRAE Pro read 99.9 ppm (indicating overrange condition) on all challenges at 90 ppm H_2S.
(d) Eagle 2 read 100 ppm (indicating overrange condition) on all challenges at 90 ppm H_2S.
OR overrange (i.e.,offscale) indication, no numerical reading.

Table 5.3-2. Summary of Repeatability (percent RSD) with SO_2[a]

Test Number	Test Description	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i[b]	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
1	Base test, 100 ppm	1.1	0.5	0.0	0.2	NT	NT	NT
2	Step down, 50 ppm	0.9	0.8	0.0	0.5	NT	NT	NT
3	Step down, 20 ppm	2.2	0.9	NR	0.7	0.0[c]	NT	0.4
4	Step down, 5 ppm	0.0	0.9	NR	0.6	2.9	0.0[d]	1.4
8	Paint vapors	1.1	0.5	39.3	0.5	0.0[c]	0.0[d]	0.4
9	Gasoline exhaust	1.9	0.8	NR	1.0	0.0[c]	0.0[d]	0.4
11	Ammonia cleaner	1.8	0.9	0.0	0.5	0.0[c]	0.0[d]	2.6
12	Diesel exhaust	1.0	0.8	0.0	0.6	0.0[c]	0.0[d]	1.1
14	Air freshener	2.2	1.6	0.0	1.4	0.0[c]	1.7	1.9
15	DEAE	1.5	0.4	0.0	0.8	0.0[c]	1.9	1.0
16	Room T, <20% RH	1.1	0.8	NR	0.5	0.0[c]	0.0[d]	0.9
17	Room T, 80% RH	0.0	1.9	0.0	0.4	0.0[c]	2.9	2.3
18	Low T, 50% RH	1.8	0.5	0.0	0.5	0.0[c]	0.0	0.8
19	High T, 50% RH	0.0	1.5	0.0	1.2	0.0[c]	3.7	0.6
20	High T, 80% RH	2.5	3.8	0.0	0.5	0.0[c]	3.8	1.2

(a) Entries are percent relative standard deviation (RSD) of quantitative responses from five replicate challenges in each test.
(b) ChemPro 100i reports intensity (1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
(c) MultiRAE Pro read 19.9 ppm (indicating overrange condition) on all challenges at 20 ppm SO_2.
(d) Eagle 2 read 6.0 ppm (indicating overrange condition) on all challenges at 5 ppm SO_2.
NR No Response. NT Not Tested.

Table 5.3-3. Summary of Repeatability (percent RSD) with NH_3[a]

Test Number	Test Description	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i[b]	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
1	Base test, 100 ppm	20.2	20.6	0.0	OR	0.9	NT	3.3
2	Step down, 50 ppm	3.9	8.7	0.0	3.7	1.7	4.5	6.2
3	Step down, 10 ppm	10.0	25	NR	8.4	4.9	9.4	12
4	Step down, 3 ppm	12.5	24.9	NR	0.0	0.0	0.0	21.2
8	Paint vapors	4.8	10.6	0.0	0.8	2.1	2.2	5.3
9	Gasoline exhaust	4.9	4.7	34.8	1.2	2.0	1.4	2.6
11	Ammonia cleaner	5.8	6.4	34.4	1.0	3.8	5.1	6.9
12	Diesel exhaust	6.6	6.5	0.0	3.3	0.0	1.7	1.7
14	Air freshener	45.1	9.8	39.3	3.8	1.8	2.5	6.1
15	DEAE	5.3	5.6	34.4	2.5	1.3	1.8	5.1
16	Room T, <20% RH	3.1	4.9	0.0	8.6	1.8	2.8	4.2
17	Room T, 80% RH	7.8	20.4	0.0	5.6	1.9	2.5	5.0
18	Low T, 50% RH	3.3	7.4	34.4	1.6	4.0	2.5	7.7
19	High T, 50% RH	3.2	6.1	0.0	1.7	1.2	0.7	3.3
20	High T, 80% RH	4.8	15	0.0	1.0	2.8	5.8	4.8

(a) Entries are percent relative standard deviation (RSD) of quantitative responses from five replicate challenges in each test.
(b) ChemPro 100i reports intensity (1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
NR No Response. NT Not Tested. OR overrange (i.e., offscale) indication, no numerical reading.

Table 5.3-4. Summary of Repeatability (percent RSD) with Cl_2[a]

Test Number	Test Description	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i[b]	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
1	Base test, 10 ppm	7.4	15.1	0.0	13.5	3.7	NT	2.3
2	Step down, 3 ppm	0.0	18.5	NC	5.3	6.3	0.0[c]	5.1
3	Step down, 1ppm	NR	0.0	NR	6.0	10.7	2.3	4.3
8	Paint vapors	8.2	14.3	0.0	8.7	3.7	0.0[c]	1.1
9	Gasoline exhaust	8.6	10.1	NR	7.0	5.0	0.0[c]	2.8
12	Diesel exhaust	5.7	OR	NR	6.5	3.9	0.0[c]	1.5
14	Air freshener	5.7	12.3	0.0	5.9	4.1	8.1	2.6
15	DEAE	7.8	6.4	0.0	6.0	4.6	3.7	2.2
16	Room T, <20% RH	0.0	4.2	0.0	2.9	4.0	0.0[c]	2.0
17	Room T, 80% RH	5.5	25.0	NC	6.6	8.0	2.9	2.0
18	Low T, 50% RH	10.8	OR	0.0	10.8	3.0	0.0[c]	0.6
19	High T, 50% RH	0.0	15.2	NR	4.7	2.7	2.5	2.7
20	High T, 80% RH	8.6	23.9	NR	7.7	11.4	5.0	2.6

(a) Entries are percent relative standard deviation (RSD) of quantitative responses from five replicate challenges in each test.
(b) ChemPro 100i reports intensity (1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
(c) Eagle 2 read 3.0 ppm (indicating overrange condition) on all challenges at 3 ppm Cl_2.
NC Not Calculated (response in only one challenge). NR No Response. NT Not Tested. OR overrange (i.e.,offscale) indication, no numerical reading.

Table 5.3-5. Summary of Repeatability (percent RSD) with PH_3[a]

Test Number	Test Description	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i[b]	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
1	Base test, 50 ppm	NT	0.0	0.0	NT	NT	NT	NT
2	Step down, 20 ppm	NT	2.5	0.0	NT	0.0[c]	NT	1.1
3	Step down, 5 ppm	OR	0.0	0.0	5.7	1.0	NT	0.0
4	Step down, 1 ppm	0.0	0.0	0.0	0.8	0.0	0.0[d]	5.3
8	Paint vapors	OR	0.0	0.0	2.7	0.0[c]	0.0[d]	0.4
9	Gasoline exhaust	OR	2.2	0.0	2.0	0.0[c]	0.0[d]	0.3
11	Ammonia cleaner	OR	0.0	0.0	3.0	0.0[c]	5.2	0.9
12	Diesel exhaust	OR	2.1	0.0	1.8	0.0[c]	0.0[d]	0.3
14	Air freshener	OR	3.1	21.2	2.1	0.0[c]	0.0[d]	0.7
15	DEAE	OR	2.2	0.0	2.6	0.0[c]	3.1	1.2
16	Room T, <20% RH	OR	0.0	34.2	14.0	0.0[c]	0.0[d]	2.9
17	Room T, 80% RH	OR	0.0	34.2	5.0	0.0[c]	0.0[d]	0.7
18	Low T, 50% RH	OR	0.0	0.0	3.1	0.0[c]	0.0[d]	5.3
19	High T, 50% RH	OR	0.0	34.2	6.1	0.0[c]	0.0[d]	2.0
20	High T, 80% RH	OR	0.0	0.0	1.2	0.0[c]	0.0[d]	1.3

(a) Entries are percent relative standard deviation (RSD) of quantitative responses from five replicate challenges in each test.
(b) ChemPro 100i reports intensity (1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
(c) MultiRAE Pro read 19.9 ppm (indicating overrange condition) on all challenges with 20 ppm PH_3.
(d) Eagle 2 read 1.0 ppm (indicating overrange condition) on all challenges at 1 ppm PH_3.
NT Not Tested. OR overrange (i.e., offscale) indication, no numerical reading.

Table 5.3-6. Summary of Repeatability (percent RSD) with HCN[a]

Test Number	Test Description	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i[b]	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
1	Base test, 50 ppm	NT	OR	NT	NT	2.6	NT	0.0[c]
2	Step down, 15 ppm	3.4	2.4	0.0	1.8	0.0	2.7	2.0
3	Step down, 5 ppm	10.2	2.4	0.0	1.4	3.7	5.4	2.3
8	Paint vapors	0.0	OR	0.0	1.4	2.1	6.1	1.0
9	Gasoline exhaust	0.0	OR	NR	0.6	1.8	5.8	0.6
11	Ammonia cleaner	2.7	OR	0.0	1.5	2.3	7.2	0.8
12	Diesel exhaust	0.0	OR	0.0	0.8	3.0	7.1	0.8
14	Air freshener	3.4	OR	0.0	1.3	2.1	9.2	1.9
15	DEAE	3.5	OR	0.0	1.6	1.4	6.9	0.3
16	Room T, <20% RH	3.4	OR	0.0	1.0	0.7	6.6	0.4
17	Room T, 80% RH	0.0	OR	0.0	0.5	1.3	7.5	0.3
18	Low T, 50% RH	0.0	OR	0.0	1.3	1.4	16.6	1.0
19	High T, 50% RH	3.0	OR	0.0	1.3	0.9	6.7	0.8
20	High T, 80% RH	3.1	OR	0.0	0.5	3.0	7.2	2.4

(a) Entries are percent relative standard deviation (RSD) of quantitative responses from five replicate challenges in each test.
(b) ChemPro 100i reports intensity (1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
(c) PHD6 read 100 ppm (indicating overrange condition) on all challenges at 100 ppm HCN in Test 1. Tests 8 to 20 conducted with 50 ppm HCN with this detector.
NR No Response. NT Not Tested. OR overrange (i.e.,offscale) indication, no numerical reading.

Table 5.3-7. Summary of Repeatability (percent RSD) with O_2[a]

Test Number	Test Description	BW GasAlert Micro 5	Dräger X-am 7000	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
1	Base test, 19% O_2	NT	NT	NT	0.0	0.2	0.0
2	Step down, 16% O_2	NT	NT	NT	0.3	0.0	0.7
8	Paint vapors	0.0	0.0	0.2	0.2	0.0	0.2
9	Gasoline exhaust	0.2	0.0	0.0	0.0	0.0	0.0
11	Ammonia cleaner	0.0	0.3	0.2	0.2	0.0	0.0
12	Diesel exhaust	NT	NT	NT	0.3	0.0	0.0
14	Air freshener	0.0	0.0	0.0	0.2	0.3	0.3
15	DEAE	0.0	0.0	0.0	0.0	0.0	0.0
16	Room T, <20% RH	0.0	0.0	0.0	0.0	0.0	0.2
17	Room T, 80% RH	0.0	0.0	0.3	0.3	0.0	0.2
18	Low T, 50% RH	0.2	0.0	0.0	0.0	0.0	0.0
19	High T, 50% RH	0.0	0.0	0.3	0.0	0.2	0.0
20	High T, 80% RH	0.2	0.2	0.0	0.0	1.6	0.2

(a) Entries are percent relative standard deviation (RSD) of quantitative responses from five replicate challenges in each test.
NT Not Tested.

Table 5.3-8. Summary of Repeatability (percent RSD) with CH_4[a]

Test Number	Test Description	BW GasAlert Micro 5	Dräger X-am 7000	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
1	Base test, 1.25%	0.0	0.5	0.5	6.5	0.0	5.8
2	Step down, 0.5%	0.0	1.2	0.0	0.0	4.3	6.4
3	Step down, 0.2%	0.0	0.0	0.0	NC	1.2	9.8
8	Paint vapors	2.3	NT	0.4	0.0	0.0	2.9
9	Gasoline exhaust	1.8	NT	0.4	0.0	2.3	2.6
11	Ammonia cleaner	2.3	NT	0.4	0.0	0.0	2.4
12	Diesel exhaust	NT	NT	NT	NT	NT	NT
14	Air freshener	0.0	NT	0.4	0.0	0.0	1.8
15	DEAE	2.3	NT	0.4	0.0	0.0	2.0
16	Room T, <20% RH	0.0	0.0	0.4	7.8	2.0	2.3
17	Room T, 80% RH	0.0	0.5	0.4	2.0	0.0	4.2
18	Low T, 50% RH	0.0	0.6	0.7	6.8	3.1	3.0
19	High T, 50% RH	0.0	0.5	0.0	1.9	1.9	9.9
20	High T, 80% RH	2.0	NT	0.0	0.0	0.0	10.6

(a) Entries are percent relative standard deviation (RSD) of quantitative responses from five replicate challenges in each test.
NC Not calculated; MultiRAE Pro responded in only one of five challenges. NT Not Tested.

5.4 Response Threshold

Table 5.4-1 summarizes the results of the response threshold tests for all seven detectors with the six TICs and with CH_4. Note that response threshold was not determined for O_2, as the purpose of O_2 measurement is to determine departures below normal atmospheric O_2 content. Also, the CH_4 response threshold was not determined for the ChemPro 100i, as that detector does not provide an indication of LEL.

Table 5.4-1. Summary of Response Threshold Results

Challenge Gas	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
H_2S	<3 ppm	< 3 ppm	<3 ppm	< 3 ppm	< 3 ppm	< 3 ppm	< 3 ppm
SO_2	< 5 ppm	< 5 ppm	20-50 ppm	< 5 ppm	< 5 ppm	< 5 ppm	< 5 ppm
NH_3	< 3 ppm	< 3 ppm	10-50 ppm	< 3 ppm	< 3 ppm	< 3 ppm	< 3 ppm
Cl_2	1 - 3 ppm	< 1 ppm	3 -10 ppm	< 1 ppm	< 1 ppm	< 1 ppm	< 1 ppm
PH_3	< 1 ppm	< 1 ppm	< 1 ppm	< 1 ppm	< 1 ppm	< 1 ppm	< 1 ppm
HCN	< 5 ppm	< 5 pm	< 5 ppm	< 5 ppm	< 5 ppm	< 5 ppm	< 5 ppm
CH_4	< 0.2%	< 0.2%	NA	< 0.2%	0.2-0.5%	< 0.2%	< 0.2%

NA Not Applicable.

Table 5.4-1 shows (by means of entries indicated as < values) that most of the detectors had response thresholds below the lowest challenge concentration for most of the challenge gases. The Dräger X-am 7000, Industrial Scientific iBRID MX6, RKI Eagle 2, and Sperian PHD6 exhibited response thresholds that were below the lowest challenge concentration for all gases listed. Response thresholds that differ from those of the other detectors are highlighted by shaded cells in Table 5.4-1. The BW GasAlert Micro 5 and RAE MultiRAE Plus responded in only one of five challenges at the lowest challenge concentration for Cl_2 and for CH_4, respectively. The MultiRAE's response threshold for CH_4 may have been affected by the sensor issue with that detector that is noted in Section 5.2. The Environics ChemPro 100i exhibited response thresholds for SO_2, NH_3, and Cl_2 that were substantially higher than those of the other detectors for those TICs. The great majority of the observed response thresholds are far below the immediately dangerous to life and health (IDLH) levels for the target TICs, and even the ChemPro 100i response thresholds for SO_2, NH_3, and CL_2 are at least a factor of 2 less than the respective IDLH levels. Except in the case of NH_3, the response threshold testing reported above did not extend to low enough concentrations to prove detection at the acute (i.e., 1 hour) Reference Exposure Level values for these TICs.

5.5 Effect of Operating Conditions

Tables 5.5-1 through 5.5-8 summarize the effects of temperature and RH on the performance parameters of each detector in each test with H_2S, SO_2, NH_3, Cl_2, PH_3, HCN, O_2, and CH_4, respectively. The performance parameters included in this comparison are the response and recovery time, QUA, IA, and repeatability. Shaded cells in Tables 5.5-1 through 5.5-8 highlight results that were significantly different in Tests 16 through 20 (conducted over a range of temperature and RH conditions) from the corresponding results in Test 1 (conducted at room temperature and 50% RH). In this comparison, response and recovery times were judged to be significantly different if their mean (±1 SD) ranges did not overlap. Accuracy and repeatability results were judged significantly different if they differed by 20% or more.

Tables 5.5-1 through 5.5-8 show that with all the detectors response and recovery times were the performance factors most frequently affected by variations in temperature and RH conditions. Most often response and recovery times were lengthened by conditions other than normal room temperature and 50% RH, but reductions in response and recovery times were also observed, e.g., in a few cases with PH_3 and HCN (Tables 5.5-5 and 5.5-6). Significant effects of temperature and RH on response and recovery times occurred less frequently with the ChemPro 100i than with the other detectors. QUA, IA, and repeatability were less frequently affected by variations in temperature and RH. The effects on QUA occurred with several detectors (QUA was not calculated for the ChemPro 100i), whereas most effects on IA and repeatability occurred with the ChemPro 100i, consistent with the observations noted in Section 5.3 regarding the repeatability of that detector.

The overall indication from Tables 5.5-1 through 5.5-8 is that varying conditions of temperature and RH are unlikely to adversely affect the detectors' identification of a hazard, or the accuracy and repeatability of quantifying hazard concentrations. However, the detectors are likely to respond more slowly and take longer to clear after a positive response when the temperature and RH differ widely from normal room conditions (approximately 22 °C and 50% RH).

Table 5.5-1. Performance Parameters under Different Temperature and Relative Humidity Conditions with H_2S

Performance Parameter	Condition	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
Response Time (seconds)	22 C/50 % RH	50	29	19	121	18	20	30
	22 C/< 20 % RH	53	19	18	88	16	16	27
	22 C/80 % RH	43	91	19	103	14	15	28
	8 C/50 % RH	41	20	18	105	15	14	25
	35 C/50 % RH	36	76	18	84	14	14	28
	35 C/80 % RH	35	180	18	81	16	28	29
Recovery Time (seconds)	22 C/50 % RH	46	95	30	342	319	32	107
	22 C/< 20 % RH	50	94	29	353	323	39	117
	22 C/80 % RH	50	107	34	582	309	33	114
	8 C/50 % RH	52	100	28	672	317	42	130
	35 C/50 % RH	45	190	58	460	351	34	114
	35 C/80 % RH	48	340	66	590	359	35	117
QUA (%)	22 C/50 % RH	179	OR	NA	163	111[a]	108	126
	22 C/< 20 % RH	202	OR	NA	181	111[a]	111[c]	130
	22 C/80 % RH	203	94	NA	181	111[a]	111	128
	8 C/50 % RH	204	OR	NA	178	111[a]	111[c]	137
	35 C/50 % RH	172	OR	NA	158	111[a]	111[c]	129
	35 C/80 % RH	173	59	NA	158	111[a]	104	128
IA (%)	22 C/50 % RH	100	100	100	100	100	100	100
	22 C/< 20 % RH	100	100	100	100	100	100	100
	22 C/80 % RH	100	100	100	100	100	100	100
	8 C/50 % RH	100	100	100	100	100	100	100
	35 C/50 % RH	100	100	100	100	100	100	100
	35 C/80 % RH	100	100	100	100	100	100	100
Repeatability[b] (%RSD)	22 C/50 % RH	0.0	OR	0.0	0.6	0.0	0.8	1.1
	22 C/< 20 % RH	0.2	OR	0.0	1.0	0.0	0.0	0.7
	22 C/80 % RH	0.8	OR	63.6	0.7	0.0	0.7	0.5
	8 C/50 % RH	0.0	OR	0.0	0.1	0.0	0.0	1.1
	35 C/50 % RH	0.4	OR	34.2	0.3	0.0	0.0	0.8
	35 C/80 % RH	0.0	19	0.0	0.2	0.0	0.0	0.5

(a) MultiRAE Pro read 99.9 ppm (indicating overrange condition) on all challenges.
(b) ChemPro 100i reported intensity readings (i.e., 1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
(c) Eagle 2 read 100.0 ppm (indicating overrange condition) in all challenges with 90 ppm H_2S.
OR overrange (i.e., offscale) indication, no numerical reading. NA Not Applicable.

Table 5.5-2. Performance Parameters under Different Temperature and Relative Humidity Conditions with SO_2

Performance Parameter	Condition	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
Response Time (seconds)	22 C/50 % RH	33	40	228	32	37	13	22
	22 C/< 20 % RH	29	32	NR	37	39	12	24
	22 C/80 % RH	99	134	33	63	55	23	23
	8 C/50 % RH	95	45	20	60	45	12	28
	35 C/50 % RH	85	97	31	55	55	15	38
	35 C/80 % RH	172	150	19	41	75	33	29
Recovery Time (seconds)	22 C/50 % RH	71	503	383	254	260	342	117
	22 C/< 20 % RH	52	>597	NR	240	401	460	117
	22 C/80 % RH	126	>600	30	359	261	354	134
	8 C/50 % RH	128	>616	560	>548	345	369	92
	35 C/50 % RH	119	>675	79	273	273	265	141
	35 C/80 % RH	176	>510	106	248	405	308	95
QUA (%)	22 C/50 % RH	99	100	NA	100	100[a]	120[c]	109
	22 C/< 20 % RH	103	109	NA	104	100[a]	120[c]	105
	22 C/80 % RH	100	100	NA	103	100[a]	118	108
	8 C/50 % RH	101	109	NA	105	100[a]	120[c]	105
	35 C/50 % RH	100	105	NA	105	100[a]	113	103
	35 C/80 % RH	98	99	NA	105	100[a]	117	108
IA (%)	22 C/50 % RH	100	100	100	100	100	100	100
	22 C/< 20 % RH	100	100	0	100	100	100	100
	22 C/80 % RH	100	100	80	100	100	100	100
	8 C/50 % RH	100	100	80	100	100	100	100
	35 C/50 % RH	100	100	80	100	100	100	100
	35 C/80 % RH	100	100	100	100	100	100	100
Repeatability[b] (%RSD)	22 C/50 % RH	1.1	0.5	0.0	0.2	0.0	0.0	0.4
	22 C/< 20 % RH	1.1	0.8	NR	0.5	0.0	0.0	0.9
	22 C/80 % RH	0.0	1.9	0.0	0.4	0.0	2.9	2.3
	8 C/50 % RH	1.8	0.5	0.0	0.5	0.0	0.0	0.8
	35 C/50 % RH	0.0	1.5	0.0	1.2	0.0	3.7	0.6
	35 C/80 % RH	2.5	3.8	0.0	0.5	0.0	3.8	1.2

(a) MultiRAE Pro read 19.9 ppm (indicating overrange condition) on all five challenges.
(b) ChemPro 100i reported intensity readings (i.e., 1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
(c) Eagle 2 read 6.0 ppm (indicating overrange condition) in all challenges with 5 ppm SO_2.
NA Not Applicable. NR No Response.

Table 5.5-3. Performance Parameters under Different Temperature and Relative Humidity Conditions with NH_3

Performance Parameter	Condition	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
Response Time (seconds)	22 C/50 % RH	154	>180	54	101	82	>180	>180
	22 C/< 20 % RH	>180	>180	33	>180	139	>180	155
	22 C/80 % RH	>180	>180	66	>180	>180	>180	>180
	8 C/50 % RH	>180	>180	36	>180	>180	>180	>180
	35 C/50 % RH	>180	>180	59	>180	>180	>180	>180
	35 C/80 % RH	>180	>180	83	>180	>180	>180	>180
Recovery Time (seconds)	22 C/50 % RH	800	321	118	>780	>355	>567	>492
	22 C/< 20 % RH	>823	198	98	>825	>558	>764	>590
	22 C/80 % RH	>1320	>1132	381	>1230	>450	>420	>366
	8 C/50 % RH	692	291	119	>840	>426	>408	>370
	35 C/50 % RH	1049	>1026	250	>1112	>408	>408	>408
	35 C/80 % RH	>330	>900	332	>900	>426	>396	>372
QUA (%)	22 C/50 % RH	80	109	NA	OR	105	96	92
	22 C/< 20 % RH	70	96	NA	76	97	87	92
	22 C/80 % RH	67	66	NA	81	93	85	88
	8 C/50 % RH	69	89	NA	53	86	84	88
	35 C/50 % RH	73	92	NA	88	95	82	94
	35 C/80 % RH	77	87	NA	88	94	76	86
IA (%)	22 C/50 % RH	100	100	100	100	100	100	100
	22 C/< 20 % RH	100	100	100	100	100	100	100
	22 C/80 % RH	100	100	100	100	100	100	100
	8 C/50 % RH	100	100	100	100	100	100	100
	35 C/50 % RH	100	100	100	100	100	100	100
	35 C/80 % RH	100	100	100	100	100	100	100
Repeatability[a] (%RSD)	22 C/50 % RH	20.2	20.6	0.0	OR	1.7	4.5	3.3
	22 C/< 20 % RH	3.1	4.9	0.0	8.6	1.8	2.8	4.2
	22 C/80 % RH	7.8	20.4	0.0	5.6	1.9	2.5	5.0
	8 C/50 % RH	3.3	7.4	34.4	1.6	4.0	2.5	7.7
	35 C/50 % RH	3.2	6.1	0.0	1.7	1.2	0.7	3.3
	35 C/80 % RH	4.8	15.0	0.0	1.0	2.8	5.8	4.8

(a) ChemPro 100i reported intensity readings (i.e., 1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
NA Not Applicable. OR overrange (i.e., offscale) indication, no numerical reading.

Table 5.5-4. Performance Parameters under Different Temperature and Relative Humidity Conditions with Cl_2

Performance Parameter	Condition	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
Response Time (seconds)	22 C/50 % RH	54	>180	24	>180	63	38	69
	22 C/< 20 % RH	180	104	24	12	19	61	18
	22 C/80 % RH	180	>180	69	32	71	>180	19
	8 C/50 % RH	51	41	47	>180	25	102	>180
	35 C/50 % RH	152	>180	NR	161	43	>180	13
	35 C/80 % RH	180	>180	NR	>180	>180	>180	15
Recovery Time (seconds)	22 C/50 % RH	22	>726	116	48	>320	>424	57
	22 C/< 20 % RH	35	>675	169	29	>325	>370	27
	22 C/80 % RH	27	>702	43	43	>417	>324	30
	8 C/50 % RH	38	124	75	168	>540	>468	41
	35 C/50 % RH	25	>888	NR	37	188	>392	26
	35 C/80 % RH	14	211	NR	31	191	>348	33
QUA (%)	22 C/50 % RH	74	76	NA	117	109	100	104
	22 C/< 20 % RH	90	100	NA	140	123	100	112
	22 C/80 % RH	82	58	NA	119	107	57	113
	8 C/50 % RH	106	OR	NA	210	115	100	85
	35 C/50 % RH	70	64	NA	74	111	79	140
	35 C/80 % RH	64	29	NA	61	90	47	128
IA (%)	22 C/50 % RH	100	100	80	100	100	100	100
	22 C/< 20 % RH	100	100	100	100	100	100	100
	22 C/80 % RH	100	100	20	100	100	100	100
	8 C/50 % RH	100	100	100	100	100	100	100
	35 C/50 % RH	100	100	0	100	100	100	100
	35 C/80 % RH	100	100	0	100	100	100	100
Repeatability[a] (%RSD)	22 C/50 % RH	7.4	15.1	0.0	13.5	3.7	0.0	2.3
	22 C/< 20 % RH	0	4.2	0.0	2.9	4.0	0.0	2.0
	22 C/80 % RH	5.5	25	NC	6.6	8.0	2.9	2.0
	8 C/50 % RH	10.8	OR	0	10.8	3.0	0.0	0.6
	35 C/50 % RH	0.0	15.2	NR	4.7	2.7	2.5	2.7
	35 C/80 % RH	8.6	23.9	NR	7.7	11.4	5.0	2.6

(a) ChemPro 100i reported intensity readings (i.e., 1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
OR overrange (i.e., offscale) indication, no numerical reading. NA Not Applicable. NR No Response. NC Not Calculated (response in only one challenge).

Table 5.5-5. Performance Parameters under Different Temperature and Relative Humidity Conditions with PH_3

Performance Parameter	Condition	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
Response Time (seconds)	22 C/50 % RH	12	33	17	>180	43	10	125
	22 C/< 20 % RH	8	29	17	127	24	9	101
	22 C/80 % RH	6	29	20	>180	22	10	86
	8 C/50 % RH	8	26	18	59	25	10	106
	35 C/50 % RH	6	33	16	>180	19	10	>180
	35 C/80 % RH	5	32	18	48	18	10	83
Recovery Time (seconds)	22 C/50 % RH	14	31	273	56	220	11	>425
	22 C/< 20 % RH	10	24	360	45	107	14	>420
	22 C/80 % RH	9	24	186	134	82	12	>331
	8 C/50 % RH	13	25	366	45	104	14	>300
	35 C/50 % RH	7	22	117	51	105	14	>372
	35 C/80 % RH	5	23	78	78	128	14	>396
QUA (%)	22 C/50 % RH	OR	92	NA	94	100[a]	100[c]	66
	22 C/< 20 % RH	OR	100	NA	98	100[a]	100[c]	62
	22 C/80 % RH	OR	100	NA	103	100[a]	100[c]	62
	8 C/50 % RH	OR	95	NA	98	100[a]	100[c]	65
	35 C/50 % RH	OR	100	NA	98	100[a]	100[c]	64
	35 C/80 % RH	OR	100	NA	114	100[a]	100[c]	61
IA (%)	22 C/50 % RH	100	100	100	100	100	100	100
	22 C/< 20 % RH	100	100	100	100	100	100	100
	22 C/80 % RH	100	100	100	100	100	100	100
	8 C/50 % RH	100	100	100	100	100	100	100
	35 C/50 % RH	100	100	100	100	100	100	100
	35 C/80 % RH	100	100	100	100	100	100	100
Repeatability[b] (%RSD)	22 C/50 % RH	OR	0.0	0.0	5.7	0.0	0.0	1.1
	22 C/< 20 % RH	OR	0.0	34.2	14	0.0	0.0	2.9
	22 C/80 % RH	OR	0.0	34.2	5.0	0.0	0.0	0.7
	8 C/50 % RH	OR	0.0	0.0	3.1	0.0	0.0	5.3
	35 C/50 % RH	OR	0.0	34.2	6.1	0.0	0.0	2.0
	35 C/80 % RH	OR	0.0	0.0	1.2	0.0	0.0	1.3

(a) MultiRAE Pro read 19.9 ppm (indicating overrange condition) on all challenges.
(b) ChemPro 100i reported intensity readings (i.e., 1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
(c) Eagle 2 read 1.0 ppm (indicating overrange condition) in all challenges with 1 ppm PH_3.
OR overrange (i.e., offscale) indication, no numerical reading. NA Not Applicable.

Table 5.5-6. Performance Parameters under Different Temperature and Relative Humidity Conditions with HCN

Performance Parameter	Condition	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
Response Time (seconds)	22 C/50 % RH	65	20	18	>180	117	149	52
	22 C/< 20 % RH	52	16	27	>180	54	48	102
	22 C/80 % RH	54	21	26	>180	45	45	93
	8 C/50 % RH	58	15	37	>180	69	55	43
	35 C/50 % RH	31	20	13	>136	86	48	29
	35 C/80 % RH	27	41	18	148	119	71	97
Recovery Time (seconds)	22 C/50 % RH	79	>765	133	>679	240	102	>437
	22 C/< 20 % RH	74	>340	63	>420	274	62	>335
	22 C/80 % RH	66	266	119	>680	296	45	>342
	8 C/50 % RH	136	27	78	>570	>413	113	>398
	35 C/50 % RH	34	291	109	225	>361	36	179
	35 C/80 % RH	36	364	163	142	>352	29	186
QUA (%)	22 C/50 % RH	109	OR	NA	117	90	87	100
	22 C/< 20 % RH	109	OR	NA	112	82	79	107
	22 C/80 % RH	100	OR	NA	109	86	73	116
	8 C/50 % RH	107	OR	NA	115	63	50	111
	35 C/50 % RH	99	OR	NA	105	97	91	110
	35 C/80 % RH	117	OR	NA	113	98	73	98
IA (%)	22 C/50 % RH	100	100	100	100	100	100	100
	22 C/< 20 % RH	100	100	100	100	100	100	100
	22 C/80 % RH	100	100	100	100	100	100	100
	8 C/50 % RH	100	100	100	100	100	100	100
	35 C/50 % RH	100	100	60	100	100	100	100
	35 C/80 % RH	100	100	80	100	100	100	100
Repeatability[a] (%RSD)	22 C/50 % RH	3.4	OR	0.0	1.8	2.6	2.7	0.0
	22 C/< 20 % RH	3.4	OR	0.0	1.0	0.7	6.6	0.4
	22 C/80 % RH	0.0	OR	0.0	0.5	1.3	7.5	0.3
	8 C/50 % RH	0.0	OR	0.0	1.3	1.4	16.6	1.0
	35 C/50 % RH	3.0	OR	0.0	1.3	0.9	6.7	0.8
	35 C/80 % RH	3.1	OR	0.0	0.5	3.0	7.2	2.4

(a) ChemPro 100i reported intensity readings (i.e., 1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
OR overrange (i.e., offscale) indication, no numerical reading. NA Not Applicable.

Table 5.5-7. Performance Parameters under Different Temperature and Relative Humidity Conditions with O_2

Performance Parameter	Condition	BW GasAlert Micro 5	Dräger X-am 7000	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
Response Time (seconds)	22 C/50 % RH	NT	NT	NT	10	9	22
	22 C/< 20 % RH	16	24	22	13	24	30
	22 C/80 % RH	21	39	28	11	7	20
	8 C/50 % RH	23	42	30	12	10	23
	35 C/50 % RH	13	28	18	9	7	16
	35 C/80 % RH	20	33	29	8	14	27
Recovery Time (seconds)	22 C/50 % RH	NT	NT	NT	10	9	63
	22 C/< 20 % RH	10	24	27	11	7	34
	22 C/80 % RH	18	22	39	10	9	62
	8 C/50 % RH	9	19	47	10	8	256
	35 C/50 % RH	12	19	26	10	7	19
	35 C/80 % RH	28	26	46	17	7	40
QUA (%)	22 C/50 % RH	NT	NT	NT	99	99	100
	22 C/< 20 % RH	99	101	99	99	101	100
	22 C/80 % RH	98	100	98	99	97	100
	8 C/50 % RH	99	100	97	99	99	100
	35 C/50 % RH	98	100	98	99	98	100
	35 C/80 % RH	97	100	98	98	100	100
IA (%)	22 C/50 % RH	NT	NT	NT	100	100	100
	22 C/< 20 % RH	100	100	100	100	100	100
	22 C/80 % RH	100	100	100	100	100	100
	8 C/50 % RH	100	100	100	100	100	100
	35 C/50 % RH	100	100	100	100	100	100
	35 C/80 % RH	100	100	100	100	100	100
Repeatability (%RSD)	22 C/50 % RH	NT	NT	NT	0.0	0.2	0.0
	22 C/< 20 % RH	0.0	0.0	0.0	0.0	0.0	0.2
	22 C/80 % RH	0.0	0.0	0.3	0.3	0.0	0.2
	8 C/50 % RH	0.2	0.0	0.0	0.0	0.0	0.0
	35 C/50 % RH	0.0	0.0	0.3	0.0	0.2	0.0
	35 C/80 % RH	0.2	0.2	0.0	0.0	1.6	0.2

NT Not Tested.

Table 5.5-8. Performance Parameters under Different Temperature and Relative Humidity Conditions with CH_4

Performance Parameter	Condition	BW GasAlert Micro 5	Dräger X-am 7000	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
Response Time (seconds)	22 C/50 % RH	16	35	27	20	10	10
	22 C/< 20 % RH	19	41	26	22	10	11
	22 C/80 % RH	15	46	39	11	10	16
	8 C/50 % RH	15	47	27	24	9	10
	35 C/50 % RH	19	44	28	24	10	30
	35 C/80 % RH	18	NT	30	22	9	28
Recovery Time (seconds)	22 C/50 % RH	12	38	19	13	17	18
	22 C/< 20 % RH	20	33	20	8	18	19
	22 C/80 % RH	13	49	26	>387	382	20
	8 C/50 % RH	13	37	22	10	19	20
	35 C/50 % RH	>375	>285	24	>353	16	16
	35 C/80 % RH	>375	NT	>345	>355	23	>326
QUA (%)	22 C/50 % RH	136	164	163	34[a]	112	106
	22 C/< 20 % RH	152	165	188	23[a]	118	147
	22 C/80 % RH	160	177	181	110[a]	128	110
	8 C/50 % RH	168	124	220	77[a]	128	154
	35 C/50 % RH	176	176	184	95[a]	126	98
	35 C/80 % RH	195	NT	191	88[a]	120	78
IA (%)	22 C/50 % RH	100	100	100	100	100	100
	22 C/< 20 % RH	100	100	100	100	100	100
	22 C/80 % RH	100	100	100	100	100	100
	8 C/50 % RH	100	100	100	100	100	100
	35 C/50 % RH	100	100	100	100	100	100
	35 C/80 % RH	100	NT	100	100	100	100
Repeatability (%RSD)	22 C/50 % RH	0.0	0.5	0.5	6.5	0.0	5.8
	22 C/< 20 % RH	0.0	0.0	0.4	7.8	2.0	2.3
	22 C/80 % RH	0.0	0.5	0.4	2.0	0.0	4.2
	8 C/50 % RH	0.0	0.6	0.7	6.8	3.1	3.0
	35 C/50 % RH	0.0	0.5	0.0	1.9	1.9	9.9
	35 C/80 % RH	2.0	NT	0.0	0.0	0.0	10.6

(a) Inspection of results shows MultiRAE Pro QUA values decline in chronological order of tests with CH_4; possible sensor failure.
NT Not Tested.

5.6 Effect of Oxygen Deficiency on TIC Response

In Tests 5 and 6 with H_2S, the detectors were challenged with 90 ppm of H_2S at O_2 levels of 19% and 16% in air, respectively (see Table 2.4-4). The purpose of these tests was to evaluate whether the response to H_2S was changed by the reduced oxygen level, relative to the response to the same H_2S concentration delivered in normal air in Test 1. In this comparison, response and recovery times were judged to be significantly different if their mean ±1 SD ranges did not overlap. Accuracy and repeatability results were judged to be significantly different if they differed by 20% or more.

The test results show relatively little impact of the reduced O_2 levels on the detector performance parameters for H_2S. The RKI Eagle 2 showed no significant differences in any performance parameter for H_2S with reduced O_2 levels. Similarly the other six detectors showed no significant differences in IA (all detectors identified H_2S in all five replicates in all of tests 1, 5, and 6), or in repeatability. The few differences found for different detectors in response time, recovery time, and QUA are summarized in Table 5.6-1, where shaded entries indicate performance in Tests 5 and 6 that differs significantly from that obtained with H_2S in normal air (Test1).

Table 5.6-1 shows that response time for H_2S was reduced at the 16% O_2 level with both the BW GasAlert Micro 5 and Industrial Scientific iBRID MX6, but was increased (i.e., nearly doubled) with the Dräger X-am 7000 at both 19% and 16% O_2. The small differences in response time shown for the RAE MultiRAE Pro and Sperian PHD6 are significant by the criteria noted above but of little practical significance.

Table 5.6-1 also shows that the recovery time for H_2S was greatly increased at 16% O_2 for the Environics ChemPro 100i and at both 19% and 16% O_2 for the Industrial Scientific iBRID MX6. Only small effects on recovery time were observed for the Dräger X-am 7000 and Sperian PHD6. Finally, Table 5.6-1 shows that QUA for H_2S declined consistently with reduced O_2 levels for the BW GasAlert Micro 5, Dräger X-am 7000, and Industrial Scientific iBRID MX6.

Table 5.6-1. Performance Differences Observed in H_2S Detection at Reduced O_2

Performance Factor	Detector	O_2 Level 20.9%[a]	19%[b]	16%[c]
Response Time (sec)	BW GasAlert Micro 5	50 ± 4.1	49 ± 13.1	38 ± 4.4
	Dräger X-am 7000	29 ± 4.1	56 ± 9.0	55 ± 2.9
	Indus. Sci. iBRID MX6	121 ± 36.9	82 ± 15.7	70 ± 5.7
	RAE MultiRAE Pro	18 ± 1.1	14 ± 1.1	14 ± 0.7
	Sperian PHD6	30 ± 2.1	34 ± 0.9	32 ± 3.1
Recovery Time (sec)	Dräger X-am 7000	95 ± 8.2	119 ± 10.8	106 ± 6.0
	Environics ChemPro 100i	30 ± 1.3	46 ± 3.7	102 ± 6.0
	Indus. Sci. iBRID MX6	342 ± 23	701 ± 83	754 ± 111
	Sperian PHD6	107 ± 2.9	113 ± 2.4	116 ± 3.4
Quantitative Accuracy (%)	BW GasAlert Micro 5	179 ± 0.0	152 ± 1.0	126 ± 1.0
	Dräger X-am 7000	127 ± 1.2[d]	108 ± 1.2	92 ± 0.7
	Indus. Sci. iBRID MX6	163 ± 0.9	129 ± 1.0	109 ± 1.2

(a) Test 1
(b) Test 5
(c) Test 6
(d) Dräger X-am 7000 responses to 90 ppm H_2S in Test 1 were off scale; quantitative response comparison based on responses to 30 ppm H_2S in Test 2.

5.7 Cold/Hot Start Behavior

The performance of the seven detectors was tested with H_2S immediately after starting up from room temperature, cold (8 °C), and hot (40 °C) overnight storage in Tests 7, 10, and 13, respectively (see Table 2.4-4). All such tests were conducted with 90 ppm of H_2S, delivered in air at 20°C and 50% RH, and the results were compared to the corresponding results obtained in the same test conditions with each detector in a fully warmed-up state in Test 1. Table 5.7-1 summarizes the results of these tests for response time, recovery time, QUA, IA, and repeatability. Shaded cells in Table 5.7-1 indicate results that differ from those obtained in the corresponding fully warmed-up test at the same conditions. For response and recovery time differences were judged significant if the ±1 SD ranges of the response or recovery times did not overlap. For QUA, IA, and repeatability, differences were judged significant if these metrics differed by 20% or more.

Table 5.7-1 shows that for most detectors the delay time between powering up the detector and being ready to begin monitoring was not dependent on the storage condition before startup. For the GasAlert Micro 5 the delay time increased from 1 minute after room temperature storage to 2 minutes after hot storage, and for the ChemPro 100, which had the longest delay times in general, the corresponding increase was from 4 minutes to 7 minutes delay time. The delay time of the X-am 7000 was longer after room temperature storage than after cold or hot storage.

Table 5.7-1 also shows that response times for H_2S were affected minimally if at all by cold or hot startup, regardless of storage conditions, but that recovery times were lengthened with several detectors, especially after a cold start from room temperature or cold conditions. The parameters of QUA, IA, and repeatability for H_2S were largely unaffected, although the QUA and repeatability comparisons were limited by the overrange readings of the X-am 7000 and the MultiRAE Pro. Repeatability effects were observed with the ChemPro 100i after cold starts from all three storage conditions.

Table 5.7-1. Summary of Performance Parameters under Fully Warmed Up and Cold Start Conditions

Performance Parameter	Start Condition	BW GasAlert Micro 5	Dräger X-am 7000	Environics ChemPro 100i	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instruments Eagle 2	Sperian PHD6
Startup Delay (seconds)	Room T Cold Start	60	120	240	<60	120	60	60
	5°C Cold Start	60	60	300	<60	120	60	60
	40°C Cold Start	120	60	420	60	120	60	60
Response Time (seconds)	Warmed Up	50 ±4	29 ±4	19 ±1	121 ±37	18 ±1	20 ±7	30 ±2
	Room T Cold Start	43 ±1	24 ±2	18 ±1	88 ±7	18 ±1	38 ±11	41 ±3
	5°C Cold Start	66 ±16	127 ±72	19 ±2	86 ±14	22 ±3	36 ±8	37 ±0.5
	40°C Cold Start	33 ±7	25 ±2	19 ±2	94 ±25	19 ±3	51 ±6	39 ±2
Recovery Time (seconds)	Warmed Up	46 ±2	95 ±8	30 ±1	342 ±23	319 ±43	32 ±3	107 ±3
	Room T Cold Start	51 ±2	139 ±14	92 ±76	> 849	324 ±48	33 ±10	112 ±3
	5°C Cold Start	55 ±2	403 ±118	71 ±49	> 884	420 ±189	60 ±23	119 ±2
	40°C Cold Start	62 ±35	93 ±8	157 ±71	892 ±683	300 ±23	36 ±1	115 ±6
QUA (%)	Warmed Up	179	OR	NA	163	111[a]	108	126
	Room T Cold Start	178	OR	NA	148	111[a]	101	113
	5°C Cold Start	172	89	NA	141	111[a]	101	114
	40°C Cold Start	170	OR	NA	142	111[a]	95	114
IA (%)	Warmed Up	100	100	100	100	100	100	100
	Room T Cold Start	100	100	100	100	100	100	100
	8°C Cold Start	100	100	100	100	100	100	100
	40°C Cold Start	100	100	100	100	100	100	100
Repeatability[b] (%RSD)	Warmed Up	0.0	OR	0.0[b]	0.6	0.0	0.8	1.1
	Room T Cold Start	0.5	OR	50.0[b]	0.8	0.0	1.1	0.5
	5°C Cold Start	0.6	22.9	34.2[b]	0.8	0.0	2.2	0.0
	40°C Cold Start	1.3	OR	63.6[b]	0.2	0.0	0.5	0.9

(a) MultiRAE Pro read 99.9 ppm (indicating overrange condition) on all challenges.
(b) ChemPro 100i reported intensity readings (i.e., 1, 2, or 3 bars) rather than TIC concentrations. Therefore repeatability not comparable to that indicated for other detectors.
OR overrange (i.e., offscale) indication, no numerical reading. NA Not Applicable.

5.8 Interference Effects

Each of the six interferents (latex paint vapors, gasoline exhaust, ammonia cleaner vapors, diesel exhaust, air freshener vapors, and DEAE) were supplied to each detector both in clean air and in air containing one of the target analytes. When the sensor configuration of a detector was changed by replacement of sensors, the sampling of interferent vapors in otherwise clean air was repeated, so that FP responses were assessed in all detector configurations. Tables 5.8- 1 through 5.8-8 summarize the effects of these interferents on detector response by showing the FP and FN rates for each interferent with each detector, in testing with each target analyte.

Tables 5.8-1 through 5.8-8 show that each of the seven detectors showed FP responses in some tests, when sampling one of the interferent vapors in otherwise clean air. Gasoline and diesel exhaust hydrocarbons and paint vapors were the interferents that most frequently resulted in FP responses, with ammonia cleaner, air freshener, and DEAE causing relatively few FP responses. False positive responses occurred most frequently when NH_3 was the target gas, i.e., FP responses for NH_3 occurred at least twice as often as for any other target gas.

The MultiRAE Pro was the detector most subject to interference effects. The MultiRAE Pro showed FP responses with all six interferents in testing with H_2S, O_2, and CH_4, and FP responses with at least one interferent with every target gas. The ChemPro 100i and iBRID MX6 also showed FP responses with at least one interferent with every target gas with which they were tested (the ChemPro 100i was not tested with O_2 or CH_4). On the other hand, the X-am 7000 and GasAlert Micro 5 were the detectors least subject to FP responses. The X-am 7000 showed only a few FP responses in testing with SO_2, NH_3, and Cl_2, and no FP responses at all in testing with H_2S, PH_3, HCN, and O_2 (that detector could not tested for interferent effects with CH_4). The GasAlert Micro 5 showed FP responses with all six interferents in testing with NH_3, only a few FP responses in testing with SO_2 and O_2, and no FP responses at all in testing with H_2S, Cl_2, PH_3, HCN, and CH_4.

An important result shown in Tables 5.8-1 through 5.8-8 is that the FN rates that resulted from the interferents were almost always zero. In fact, for six of the seven detectors (i.e., the GasAlert Micro 5, X-am 7000, iBRID MX6, MultiRAE Pro, Eagle 2, and PHD6) the FN rate was zero with every interferent in every test. This result means that the interferents never prevented those six detectors from properly identifying the appropriate hazard. False negatives were observed with the ChemPro 100i in tests with SO_2, NH_3, Cl_2, and HCN (Tables 5.8-2 through 5.8-4, and 5.8-6, respectively). Gasoline engine exhaust hydrocarbons were a cause of FN with the ChemPro 100i with all four of these TICs. Ammonia cleaner, air freshener, and diesel exhaust also caused FN responses in a few tests with the ChemPro 100i.

Table 5.8-1. Summary of False Positive (FP) and False Negative (FN) Rates with H_2S[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		FP	FN	FP	FN	FP	FN	FP	FN	FP	FN	FP	FN	FP	FN
8	Paint vapors	0	0	0	0	100	0	0	0	100	0	0	0	0	0
9	Gasoline exhaust	0	0	0	0	0	0	100	0	100	0	0	0	100	0
11	Ammonia cleaner	0	0	0	0	100	0	0	0	100	0	0	0	0	0
12	Diesel exhaust	0	0	0	0	0	0	0	0	100	0	0	0	80	0
14	Air freshener	0	0	0	0	0	0	0	0	100	0	0	0	0	0
15	DEAE	0	0	0	0	0	0	0	0	100	0	0	0	0	0

(a) Entries are FP and FN rates in percent in each test with H_2S and an interferent.

Table 5.8-2. Summary of False Positive (FP) and False Negative (FN) Rates with SO_2[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		FP	FN	FP	FN	FP	FN	FP	FN	FP	FN	FP	FN	FP	FN
8	Paint vapors	0	0	0	0	100	0	0	0	100	0	0	0	50	0
9	Gasoline exhaust	0	0	100	0	0	100	100	0	33	0	100	0	0	0
11	Ammonia cleaner	0	0	0	0	0	20	0	0	0	0	0	0	0	0
12	Diesel exhaust	0	0	100	0	0	0	0	0	33	0	100	0	0	0
14	Air freshener	25	0	0	0	0	40	0	0	33	0	100	0	0	0
15	DEAE	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(a) Entries are FP and FN rates in percent in each test with SO_2 and an interferent.

Table 5.8-3. Summary of False Positive (FP) and False Negative (FN) Rates with NH_3[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		FP	FN	FP	FN	FP	FN	FP	FN	FP	FN	FP	FN	FP	FN
8	Paint vapors	100	0	20	0	100	0	60	0	0	0	0	0	50	0
9	Gasoline exhaust	100	0	0	0	0	40	40	0	33	0	0	0	0	0
11	Ammonia cleaner	100	0	20	0	20	0	100	0	0	0	0	0	0	0
12	Diesel exhaust	100	0	0	0	100	0	20	0	100	0	33	0	0	0
14	Air freshener	100	0	0	0	20	0	60	0	33	0	0	0	0	0
15	DEAE	100	0	60	0	20	0	40	0	0	0	0	0	0	0

(a) Entries are FP and FN rates in percent in each test with NH_3 and an interferent.

Table 5.8-4. Summary of False Positive (FP) and False Negative (FN) Rates with Cl_2[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		FP	FN	FP	FN	FP	FN	FP	FN	FP	FN	FP	FN	FP	FN
8	Paint vapors	0	0	0	0	100	0	0	0	100	0	0	0	0	0
9	Gasoline exhaust	0	0	100	0	0	100	100	0	0	0	0	0	0	0
12	Diesel exhaust	0	0	60	0	0	100	0	0	0	0	33	0	0	0
14	Air freshener	0	0	0	0	40	0	0	0	0	0	0	0	0	0
15	DEAE	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(a) Entries are FP and FN rates in percent in each test with Cl_2 and an interferent. Ammonia cleaner not used as an interferent with this TIC.

Table 5.8-5. Summary of False Positive (FP) and False Negative (FN) Rates with PH_3[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		FP	**FN**	**FP**	**FN**	**FP**	**FN**	**FP**	**FN**	**FP**	**FN**	**FP**	**FN**	**FP**	**FN**
8	Paint vapors	0	0	0	0	100	0	0	0	100	0	0	0	0	0
9	Gasoline exhaust	0	0	0	0	0	0	100	0	100	0	100	0	100	0
11	Ammonia cleaner	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Diesel exhaust	0	0	0	0	0	0	100	0	20	0	100	0	80	0
14	Air freshener	0	0	0	0	0	0	0	0	0	0	100	0	0	0
15	DEAE	0	0	0	0	20	0	0	0	0	0	0	0	0	0

(a) Entries are FP and FN rates in percent in each test with PH_3 and an interferent.

Table 5.8-6. Summary of False Positive (FP) and False Negative (FN) Rates with HCN[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Environics ChemPro 100i		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		FP	**FN**	**FP**	**FN**	**FP**	**FN**	**FP**	**FN**	**FP**	**FN**	**FP**	**FN**	**FP**	**FN**
8	Paint vapors	0	0	0	0	100	0	0	0	100	0	0	0	0	0
9	Gasoline exhaust	0	0	0	0	0	100	0	0	100	0	100	0	100	0
11	Ammonia cleaner	0	0	0	0	0	0	20	0	0	0	0	0	0	0
12	Diesel exhaust	0	0	0	0	0	0	0	0	20	0	100	0	80	0
14	Air freshener	0	0	0	0	0	0	0	0	0	0	100	0	0	0
15	DEAE	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(a) Entries are FP and FN rates in percent in each test with HCN and an interferent.

Table 5.8-7. Summary of False Positive (FP) and False Negative (FN) Rates with O_2[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		FP	FN	FP	FN	FP	FN	FP	FN	FP	FN	FP	FN
8	Paint vapors	0	0	0	0	0	0	100	0	0	0	0	0
9	Gasoline exhaust	100	0	0	0	100	0	100	0	0	0	100	0
11	Ammonia cleaner	0	0	0	0	0	0	100	0	0	0	0	0
12	Diesel exhaust	NT	NT	NT	NT	NT	NT	100	0	0	0	80	0
14	Air freshener	0	0	0	0	0	0	100	0	0	0	0	0
15	DEAE	100	0	0	0	100	0	100	0	0	0	0	0

(a) Entries are FP and FN rates in percent in each test with O_2 and an interferent.
NT Not Tested

Table 5.8-8. Summary of False Positive (FP) and False Negative (FN) Rates with CH_4[a]

Test Number	Test Description	BW GasAlert Micro 5		Dräger X-am 7000		Industrial Scientific iBRID MX6		RAE Systems MultiRAE Pro		RKI Instruments Eagle 2		Sperian PHD6	
		FP	FN	FP	FN	FP	FN	FP	FN	FP	FN	FP	FN
8	Paint vapors	0	0	NT	NT	0	0	100	0	0	0	0	0
9	Gasoline exhaust	0	0	NT	NT	100	0	100	0	0	0	100	0
11	Ammonia cleaner	0	0	NT	NT	0	0	100	0	0	0	0	0
12	Diesel exhaust	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
14	Air freshener	0	0	NT	NT	0	0	100	0	0	0	0	0
15	DEAE	0	0	NT	NT	0	0	100	0	0	0	0	0

(a) Entries are FP and FN rates in percent in each test with CH_4 and an interferent.
NT Not Tested.

5.9 Battery Life

The battery life of all seven detectors was tested by operating them continuously starting from a fully charged state and monitoring them until operation stopped due to battery depletion. For this test fresh batteries were installed in two units of the RKI Instruments Eagle 2: Unit E2A505, which contained sensors for SO_2, PH_3, and HCN, and Unit E2A410, which contained sensors for O_2, H_2S, and CH_4 (i.e., LEL). These two units were tested because test operators noted substantially shorter battery life when using Unit E2A410, presumably due to the power needs of the sensors in that unit. The rechargeable batteries in the other six detectors were fully charged before the start of the battery life test. All the detectors were started from room temperature and placed into normal operation (including use of their internal air sampling pumps) between 5:57 and 6:03 am on August 31, 2011. Figure 5.9-1 shows the results of the battery life test.

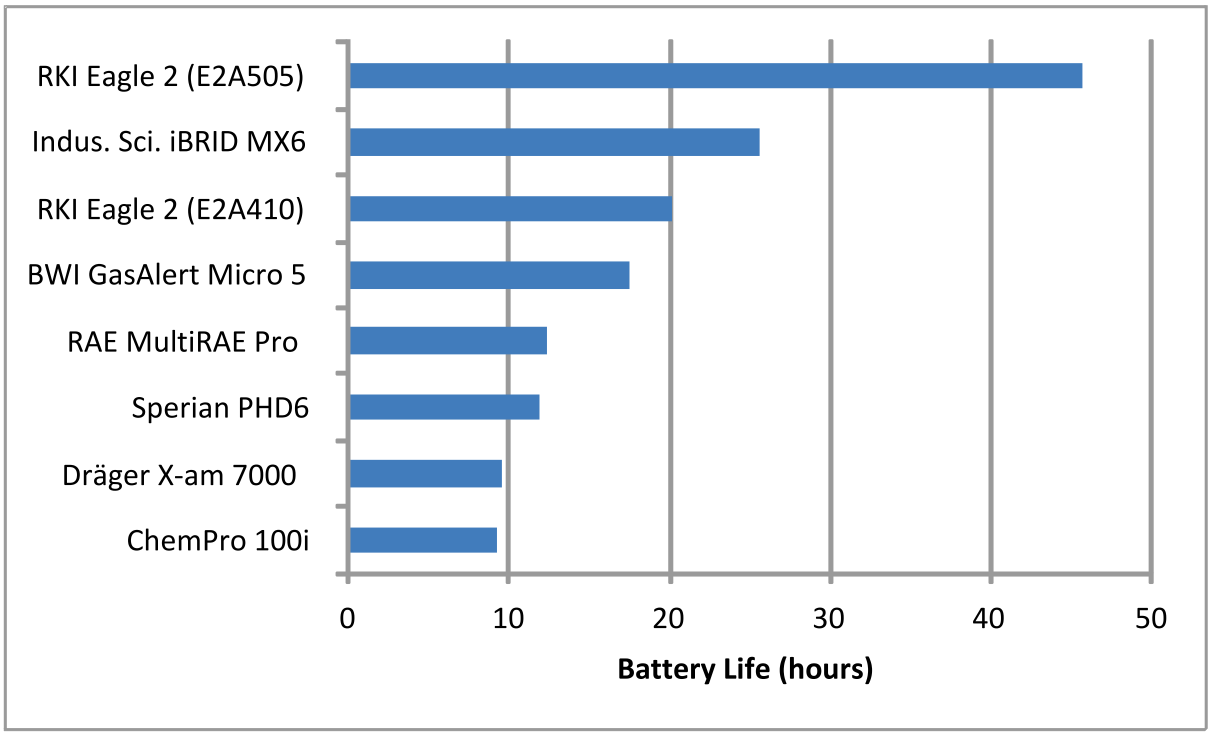

Figure 5.9-1. Summary of battery life test results.

The battery life of the seven detectors ranged from less than 10 hours for the ChemPro 100i and Dräger X-am 7000 to nearly 46 hours for the RKI Eagle 2 unit E2A505. The two Eagle 2 units exhibited the longest and third-longest periods of battery life, but the battery life of Unit E2A505 was more than twice as long as that Unit E2A410. This difference is attributed largely to the greater power demand of the LEL sensor in Unit E2A410.

5.10 Operational Factors

The following summaries of operational factors for each detector were drawn from the observations and records of test operators during the test.

BW Technologies GasAlert Micro 5. Contractor testing personnel found the GasAlert Micro 5 to be small and lightweight, and easy to operate. While the overall size and the area of the display were relatively small, the large numbers and type on the display made it easy to read during testing. Both audible and visual alarms were clear and distinctive. The operating menus were simple to follow, but the calibration menus were not as clear due to the requirement to scroll through three screens to define the calibration options. The startup/shutdown procedures were straightforward, and this detector responded quickly to the daily bump check (within approximately 30 seconds), although the bump check readings of the detector were often relatively higher than the concentration used for the bump test. There were no maintenance issues with this detector during testing. When test personnel operated the GasAlert Micro 5 while wearing heavy protective gloves, they had no difficulties turning the detector on or off. However, those personnel found it difficult to access the detector's menus because of the need to press and hold more than one button at the same time. Multiple attempts were needed to successfully access the menus.

The written documentation provided for the GasAlert Micro 5 contained the necessary information, however staff reported that it was difficult to read because the required key sequences for most operations were not located together on the same page or within the same section. Testing staff also found it necessary to consult the documentation every time for some routine activities such as calibration because the key sequences to access the menus were not intuitive and were difficult to recall. Overall testing staff found the GasAlertMicro 5 to be one of the most user-friendly of the detectors evaluated and it survived the entire test matrix with no sensor failures.

Dräger X-am 7000. Testing personnel found that the relatively heavy, boxy shape of the X-am 7000 was uncomfortable to hold by hand for more than a few minutes at a time. The display area of the detector was relatively large and included a feature that would enlarge the readings of any sensor giving an alarm. Testing personnel found the visual alarms to be quite bright and the audible alarm to be relatively loud and immediately noticeable. Testing personnel also reported that this detector was reasonably easy to operate and had the most available user-defined options. The menus on this detector were easy to understand, and the startup/shutdown procedures were easy to follow. However, the manual provided with the detector had omissions regarding certain operations that are possible on the unit. For example, the manual did not define all of the options available on the menus. This detector took relatively long to stabilize during the daily bump checks (on the order of three to four minutes), but usually gave readings in agreement with the bump check concentration. When operating the X-am 7000 while wearing heavy protective gloves, test personnel found no difficulty in turning the detector on or off, accessing all menus, or selecting settings. One unexplained alarm was triggered in this exercise, apparently when the operator's gloved hand inadvertently depressed two keys at once.

One maintenance issue was encountered with the X-am 7000. When testing was about to begin with CH_4, it was found that the CAT-CH_4 sensor of the X-am 7000 could not be calibrated and the detector then locked out that sensor. Since the CH_4 sensor would no longer display, it was necessary to obtain a new CH_4 sensor from the manufacturer in order to conduct the CH_4 tests. Although the manufacturer responded promptly with a new sensor, several tests with CH_4 were not completed before the testing schedule came to an end. The failure of the CH4 sensor is likely due to its exposure to the several TICs during the testing that preceded the CH_4 tests.

Environics ChemPro 100i. Testing personnel found the ChemPro 100i detector relatively easy to use. Its large control buttons made it easy to operate even when wearing heavy HAZMAT gloves. The display had a strong backlight which made it easy to read. The startup/shutdown procedures for this detector were simple but did take several minutes to complete. Documentation provided for the ChemPro 100i detector did not need to be used, as the menus were quite intuitive. This was the only detector which did not require the sensors to be calibrated (which was the primary reason documentation was necessary for other detectors). The ChemPro 100i was the only detector among those tested which had a dedicated confidence check. The confidence check vial (a "test tube" source of 1-propanol and diisopropylmethylphosphonate) was relatively easy to use and the detector generally responded quickly to the confidence check. Both audible and visual alarms for this detector were clear and sharp. When operating the ChemPro 100i while wearing heavy protective gloves, test personnel had no trouble powering the instrument on, or accessing menus and entering selections. However, the gloves inhibited the action of turning the detector off. Three trials were needed before the detector was successfully turned off, rather than reentering its scrolling menu.

The ChemPro 100i was the only detector among those tested that responded based on built-in gas libraries. Testing was performed using the First Responder library, which indicated the presence of TICs with responses such as "Toxic" or "Chemical Hazard". To identify the TIC present with this detector, the user must perform a narrowing search by using additional libraries in sequence. While Environics recommended using the "Trend" mode, this mode did not provide a distinguishable alarm and the unit often would not clear after a challenge. The "First Responder" mode was also not always consistent in terms of alarms on successive challenges with the same gas under the same conditions. For example during a series of challenges its response would change from "Chemical Hazard" to "Toxic." This detector also showed the greatest variability in response to environmental conditions. For example, during the high temperature test with H_2S it alarmed "Blister."

One complication with testing the ChemPro 100i was that the two different units used during testing behaved quite differently. The original unit (S/N 06CPi103701538) had an unrecoverable "functional exception D08:2057" on July 25, 2011, and was returned to the manufacturer. The replacement unit (S/N 06CPi102201497) was then used from July 29, 2011 until the end of testing on August 31, 2011. The original unit periodically continued alarming for long periods on clean air, and usually had to be cleared with the "Recalculate Baseline" function. The replacement unit did not show this behavior. The original unit also sometimes exhibited a long response time, and periodically required multiple attempts to pass the confidence check, giving the error message "No MOS signal detected." This message may have been referring to the detector's metal oxide sensor, and failure of that sensor may have been the ultimate cause of the detector's failure. The replacement unit always passed the confidence check on the first attempt. Testing personnel did note that the original detector came with a five year warranty, but that the replacement had only a one year warranty, with no explanation provided.

Maintenance issues with the ChemPro 100i during testing included the detector having difficulty maintaining its baseline operation condition, causing false alarms upon the slightest movement such as being picked up or moved from one location to another. Environics recommended that the unit never be turned off, so the detector ran continuously on line power (except during data transfer). This was the only detector in which data transfer capability was evaluated. However, the manufacturer initially failed to supply a working data transfer cable. The provided cable used a serial port which most modern computers do not support and failed to work through a USB-serial converter. It was necessary for the testing crew to find an older laptop computer with a serial port to connect to the detector. The Environics UIP software required to download data did not run properly on this computer and assistance was required from a Contractor Information Management technician. Changing the screen size enabled the software enough to perform the data download, but all operational windows remained nonfunctional. There is a single interface socket on the ChemPro 100i for both power and data download and testing personnel found it inconvenient and cumbersome to switch between those uses. The manufacturer responded promptly to that issue by sending an adapter designed to interface both data and power cables to the single port. Unfortunately, that adaptor did not work, i.e. the adapter allowed data transfer but did not transmit power to the unit. The original ChemPro 100i unit required 30 minutes to download a single nine hour interval of testing data , and the file size was inordinately large, approximately 12 Megabytes. The replacement unit used a different software version, which reduced download time to about 10 minutes, and the file size was more manageable at roughly 1 Megabyte. Testing staff found that Environics staff was both helpful and proactive in assisting with these issues.

Industrial Scientific iBRID MX6. Testing personnel found the iBRID MX6 generally easy to use. The written documentation provided sufficient instructions, but rarely was needed since the menus on the detector display were self-explanatory. Overall, the menus needed for operation were logical and easy to understand, but were difficult to navigate because the control buttons on the iBRID MX6 were so small. Those control buttons consisted of a single small oval arrangement of four keys (up, down, left and right arrows) surrounding a central “enter” button. Because of the close proximity of the buttons, testing staff found it difficult to press only one intended button, especially while wearing HAZMAT gloves. Testing staff also found that the detector display was difficult to read. The backlight on the display was insufficient so a flashlight was needed to view the display during testing. Furthermore, the font size on the display was very small, and the display alternated between reading the concentration and the time-weighted average (TWA), which was confusing to the operators. The audible and visual alarms were sufficient. While the startup/shutdown procedures were relatively easy, testing personnel reported that this detector took a long time to stabilize during the daily bump checks, and often read relatively higher than the concentration used for the bump test. Test personnel found this detector relatively difficult to operate when wearing heavy protective gloves because of the placement of all five of its control buttons in a single close arrangement. Multiple efforts were needed to navigate the control menus because of the operator’s gloved hands repeatedly contacting more than one button at a time.

The only maintenance issue encountered with the iBRID MX6 during testing was that the original PH_3 sensor could not be calibrated. This sensor was replaced early and quickly enough that all testing could be completed. Industrial Scientific supplied the replacement sensor under the warranty agreement.

RAE Systems MultiRAE Pro. Testing personnel found the MultiRAE Pro relatively easy to operate by following the instructions provided in the manual. However, a common problem with this detector was that the sensor concentration range information was not in the manual and was otherwise not easy to locate without seeking technical support or product information online. The display was easy to read and the menus were easy to follow. When wearing HAZMAT gloves, staff noted that it was difficult to tell by feel if the detector buttons had been depressed. In all instances, the button was successfully depressed, but it was difficult for staff to tell this. All alarms were understandable and were easy to adjust within the detector menu. Startup and shutdown procedures were uncomplicated. The MultiRAE Pro had a quick, simple calibration procedure, but it did not display a reason for not passing any failed span calibrations. The sensors were generally easy to change out. The sensors and sensor locations were slotted in order to match up the correct sensor with the correct location, however multiple sensors could fit into the O_2 sensor location but would not work in that location. If this misplacement happened, the operator would not know that a sensor was in the wrong location until the detector was reassembled and powered back up. When operating the MultiRAE Pro while wearing heavy protective gloves, test personnel turned the instrument on and off and accessed all menus successfully. However, these operations were awkward because it was difficult to feel when a button had been depressed.

Testing personnel noted that the quantitative response of the MultiRAE Pro to CH_4 seemed to decrease as the series of tests with that gas progressed (this observation is noted in Section 5.2). It is possible that the performance of the CH_4 sensor in the MultiRAE Pro was affected by exposure to the TICs during the testing that preceded the CH_4 tests. However, since testing was completed no effort was made to obtain a new CH_4 sensor to investigate this possibility.

RKI Instruments Eagle 2. A limitation of the Eagle 2 in this testing was that the needed sensors could not all be substituted into a single unit, and consequently three different units of the detector had to be purchased to carry out the testing with all target analytes. The Eagle 2 was relatively large in size and relatively heavy, but its design (including the built-in handle) made it relatively easy to use. Use of this detector with HAZMAT gloves was manageable, but it was often difficult to tell by feel whether detector buttons had actually been depressed. All alarms were easy to understand and easy to adjust within the detector menus. Startup and shutdown procedures were simple and easy to follow. Testing personnel reported that overall the Eagle 2 detector was easy to operate by following the instruction manual. Those personnel noted that the manual gave good instructions on how to enter the main menu on the unit, but that those instructions were listed only once in the manual and took a bit of time to locate. Many other instructions required the use of the main menu and testing personnel felt that it would have been useful to reference the page number where the main menu information was located. The detector's display was easy to view and understand, but did not display the remaining battery status in the normal display. The battery status could only be viewed by toggling through a series of displays. The Eagle 2 was unique among the detectors tested in using replaceable rather than rechargeable batteries. Testing staff noticed during testing that the battery life of the Eagle 2 unit used for H_2S, CH_4, and O_2 tests was noticeably shorter than it had been for the Eagle 2 units used for other testing (see Section 5.9). This difference was attributed to greater power consumption of the sensors used in that unit (likely specifically the CH_4 sensor). Test personnel found operating the Eagle 2 while wearing heavy protective gloves to be awkward, as it was difficult to feel when a button had been properly engaged. This was especially an issue for actions such as accessing a menu that required a button to be engaged twice in rapid succession.

Sperian PHD6. Testing personnel reported that the PHD6 detector display was easy to view and understand. The alarms were easy to understand; however, the unit's Short Term Exposure Limit (STEL) and TWA alarms would change the unit's display and then the current concentrations could not be viewed. Testing staff could not locate how to disable the STEL and TWA alarms through the menu and were only able to get around this problem by adjusting the alarm values so that they would not be triggered. Testing staff also reported that selecting the sensor of interest on the span menu was a little complicated. Multiple choices had to be toggled through to get to the desired sensor and then any remaining sensors would have to be toggled through to escape the span menu. Otherwise, startup/shutdown operations were easy and menus were easy to navigate. The instruction manual was complete and easy to follow. When wearing HAZMAT gloves, staff noted that it was difficult to tell by feel if the detector buttons had been depressed. In all instances, the intended button was successfully depressed, but it was difficult for staff to tell this. Additionally, this detector requires a pump test by requesting the operator to block the pump port. With gloves on, this process became more difficult and time-consuming, but could be accomplished with a little extra effort.

Testing personnel also noted that it was somewhat difficult to align the PHD6's inner cover after installing the sensors, and it was not initially clear whether access to the sensors needed to be obtained through the front or the back of the detector. A feature peculiar to the PHD6 was that when using its internal sample pump, as in this testing, its sample intake port was at the bottom of the unit, i.e., pointing toward the operator when held in the hand. This arrangement would seem to risk accidentally tangling or pinching off the sample intake line while using the detector. Staff also had difficulty with the detector's charging system, which makes an electrical connection solely by gravity. On at least three occasions the PHD6 detector failed to charge due to poor contact between the unit and the charging system.

6.0 Summary

The testing reported here involved seven handheld detectors, eight target gases, six interferents, and six different temperature/RH conditions, as well as specific tests involving three cold start conditions and two levels of reduced O_2. That testing showed a wide range of performance of the handheld detectors, with each detector performing well in some tests and less well in others. This section provides a summary of the test results on each performance parameter. It should be noted that the Environics ChemPro 100i used a different detection principle than the BW Technologies GasAlert Micro 5, Dräger X-am 7000, Industrial Scientific iBRID MX6, RAE Systems MultiRAE Pro, RKI Instruments Eagle 2, and Sperian PHD6, which used similar detection technology. The ChemPro 100i also differed from the other six detectors in that it did not provide quantitative concentration readings for the TICs, and was not equipped to indicate O_2 or LEL. Consequently, certain performance parameters were not determined for the ChemPro 100i, or are summarized separately from the results for the other six detectors.

6.1 Response and Recovery Time

The response and recovery times of the seven handheld detectors in determination of TICs are summarized in Figures 6.1-1 and 6.1-2, respectively. Each figure shows the mean, median, and ±1 SD range of all the response times recorded for each detector in all testing with the six TICs. In compiling these figures, response and recovery times that were recorded as "greater than" (>) values (see Tables 5.1-1 to 5.1-8) were assigned their numerical value (i.e., the > sign was dropped). Thus, the calculated means, medians, and standard deviations shown in Figures 6.1-1 and 6.1-2 must be recognized as underestimates of these parameters.

Figure 6.1-1 shows that the ChemPro 100i exhibited the fastest response overall in testing with the six TICs, and the iBRID MX6 exhibited the slowest response overall with those TICs. Median response times in the TIC testing ranged from approximately 20 seconds with the ChemPro 100i to approximately 100 seconds with the iBRID MX6. The other five detectors exhibited response times in TIC testing that were closely similar and intermediate between those of the ChemPro 100i and the iBRID MX6, e.g., median TIC response times of approximately 40 to 50 seconds. In testing of six detectors with O_2 and CH_4 (not shown in Figure 6.1-1), relatively faster response was observed as compared to the TIC responses. With O_2, response times for all six detectors were typically < 30 seconds, and the Eagle 2 often responded in less than 10 seconds. With CH_4, response times for most of the six detectors were < 30 seconds, with the GasAlert Micro 5 always responding within 20 seconds and the Eagle 2 often responding in 10 seconds or less. The X-am 7000 response times for CH_4 ranged from about 30 to nearly 50 seconds.

Figure 6.1-2 shows that the GasAlert Micro 5, ChemPro 100i, Eagle 2, and PHD6 exhibited the fastest recovery overall in testing with the six TICs, and the iBRID MX6 exhibited the slowest recovery overall with those TICs. Median recovery times in the TIC testing ranged from approximately 50 seconds with the GasAlert Micro 5 to approximately 360 seconds with the iBRID MX6. In testing of six detectors with O_2 and CH_4 (not shown in Figure 6.1-2), relatively faster recovery was observed as compared to the TIC recoveries. With O_2, recovery times for most of the six detectors were typically <

30 seconds, and the MultiRAE Pro and Eagle 2 often recovered in approximately 10 seconds or less. However, the recovery times for the Sperian PHD6 with O_2 were usually > 40 seconds and ranged up to more than 250 seconds. With CH_4, recovery times for the six detectors were usually < 25 seconds, but the GasAlert Micro 5, X-am 7000, iBRID MX6, MultiRAE Pro, and PHD6 all showed recovery times for CH_4 that exceeded 280 seconds in testing conducted at 35 °C.

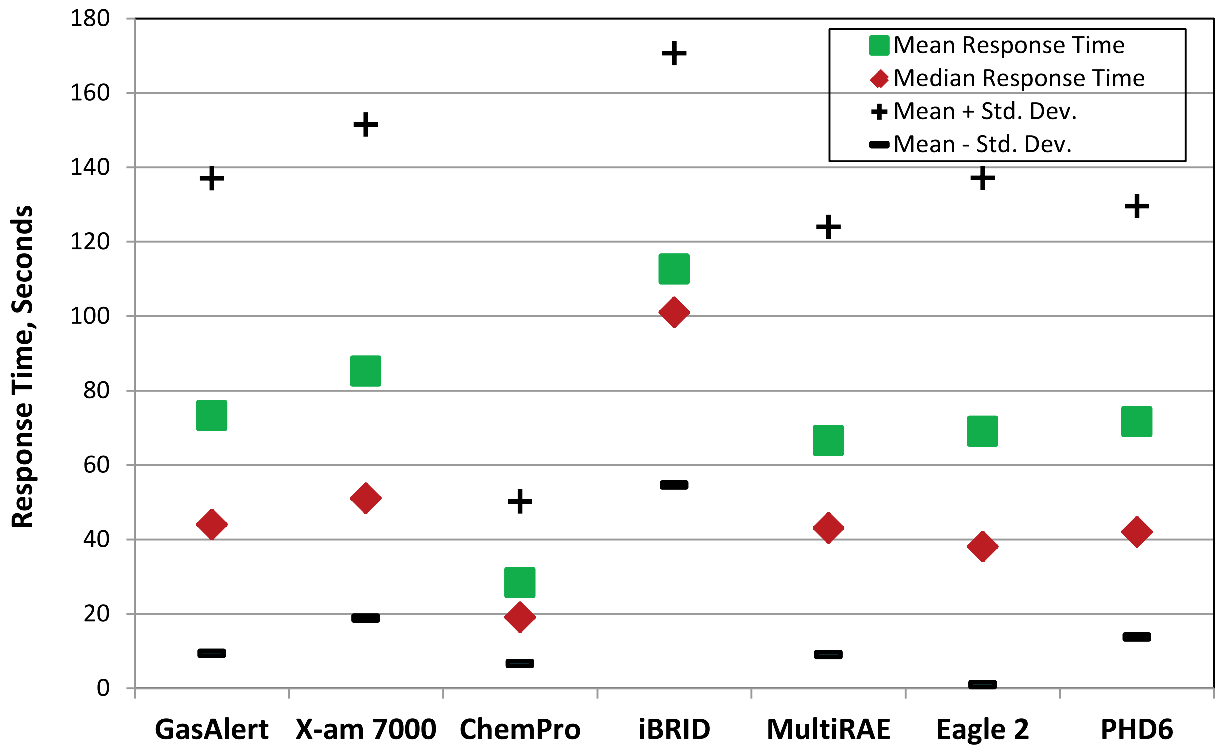

Figure 6.1-1. Summary of response time results in TIC testing.

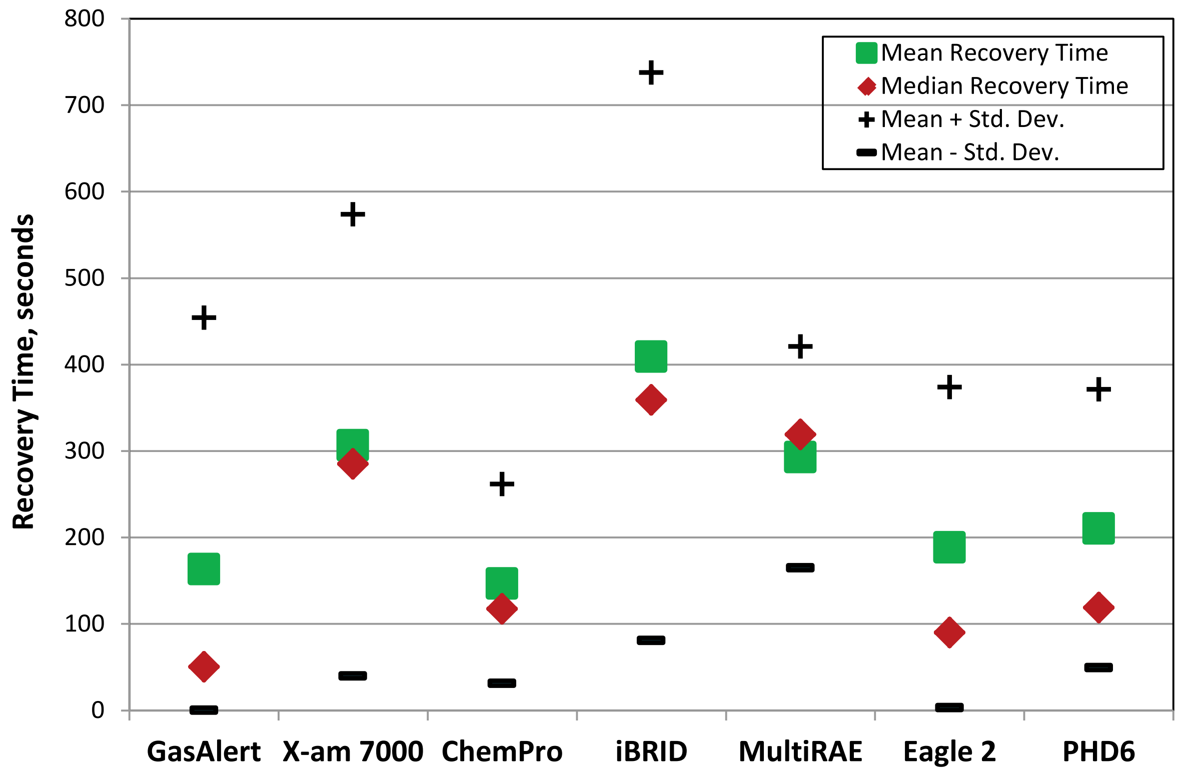

Figure 6.1-2. Summary of recovery time results in TIC testing.

6.2 Accuracy

Quantitative accuracy was determined for all detectors except the Environics ChemPro 100i. Figure 6.2-1 summarizes the QUA results determined for the other six detectors in all testing with the six TICs, O_2, and CH_4. That figure shows the mean, median, and ±1 SD range of all the QUA values recorded for each detector in all testing, excluding any readings that resulted from a pegged (i.e., quantitative but unvarying) overrange response on a detector. Thus, for example, Figure 6.2-1 does not include values such as the 111 percent QUA recorded for the MultiRAE Pro with H_2S in Table 5.2-1, which resulted from the monitor pegging at a reading of 99.9 ppm when challenged with 90 ppm of H_2S.

Figure 6.2-1 shows that over all the target gases the mean QUA values for the six detectors ranged from 91% for the MultiRAE Pro to 125% for the iBRID MX6, and the median QUA values ranged from 95% for the MultiRAE Pro to 113% for the iBRID MX6. However, Figure ES-3 is based on only about two-thirds of the possible QUA results for the X-am 7000 due to non-quantitative overrange indications by that detector in some tests. The same is true for the MultiRAE Pro and Eagle 2 due to exclusion of fixed quantitative readings exhibited during overrange conditions on those detectors. The exclusion of these results indicates that QUA values for those three detectors might be significantly higher if quantitative readings above the

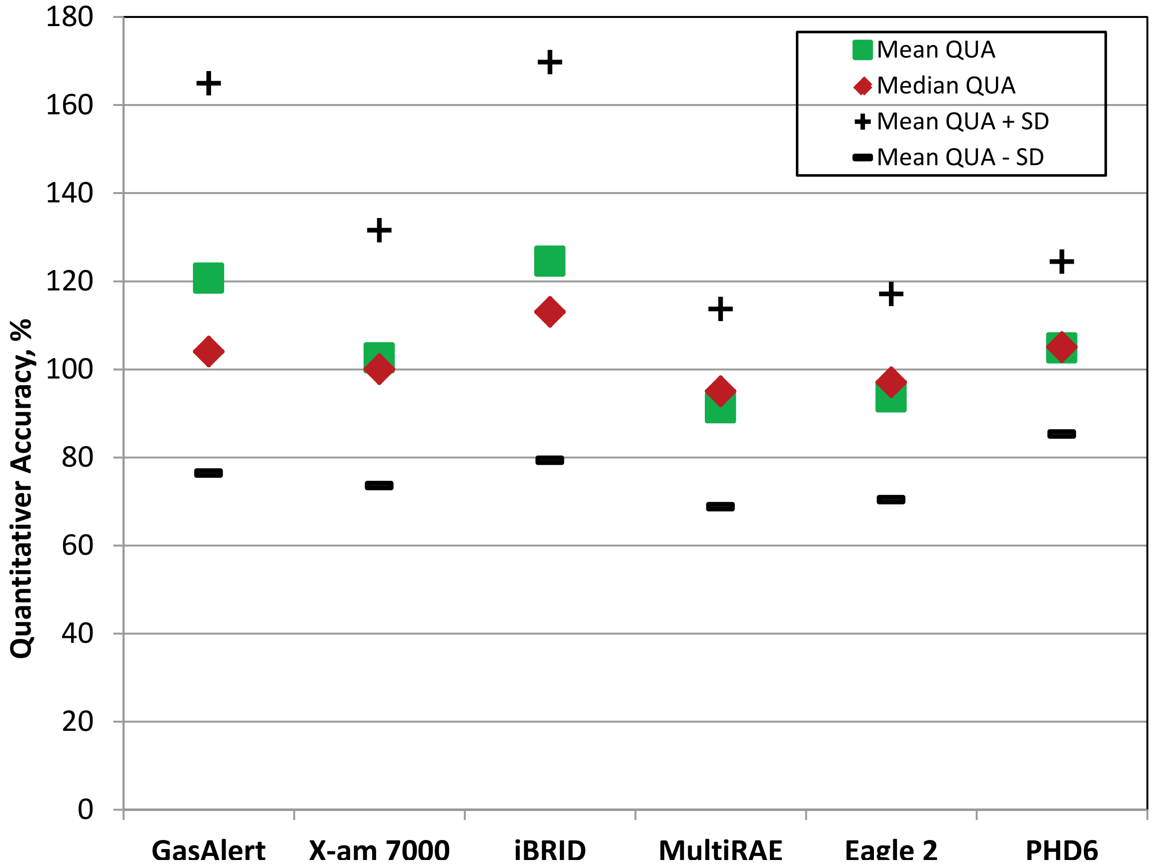

Figure 6.2-1. Summary of QUA results in TIC, O_2, and CH_4 testing (QUA not determined for ChemPro 100i). Data shown exclude any readings indicating a constant overrange condition of a detector.

nominal full scale value could be obtained from the detectors. In contrast, the iBRID MX6 and Sperian PHD6 never reported an overrange condition in any test. The PHD6 in particular achieved mean and median QUA values near 100% and a relatively narrow range of QUA results around 100%, as indicated by the ±1 SD range in Figure 6.2-1.

Identification accuracy was 100% (i.e., the detectors correctly identified the gas challenge in all trials) in almost all tests. Other than in tests at the lowest challenge concentrations, the only cases of IA less than 100% were with the ChemPro 100i, which failed to respond in some tests with SO_2, NH_3, Cl_2, and HCN that involved interferent vapors or temperature and RH conditions other than 22°C and 50% RH.

6.3 Repeatability

For the six detectors other than the ChemPro 100i, repeatability was consistently within 5% RSD in detection of H_2S, SO_2, PH_3, HCN, O_2, and CH_4. A few exceptions of repeatability up to approximately 10% RSD occurred with the Eagle 2 with HCN and with the PHD6 with CH_4. Repeatability results were substantially higher (usually within 10% RSD, with occasional values of 20% or more) for all six detectors with NH_3 and Cl_2. Repeatability for these six detectors was not affected by interferent vapors or by test conditions of temperature and RH.

Repeatability values for the ChemPro 100i were constrained by the detector's 1-to-3-bar intensity indication, and in most cases the ChemPro 100i gave the same intensity response with all five challenges in a test (i.e., repeatability = 0% RSD). However, the presence of interferent vapors and test conditions other than room temperature and 50% RH sometimes degraded the repeatability of ChemPro 100i response.

6.4 Response Threshold

With few exceptions, all detectors tested exhibited response thresholds of < 3 ppm for H_2S and NH_3, < 5 ppm for SO_2 and HCN, < 1 ppm for Cl_2 and PH_3, and < 0.2% by volume (i.e., < 4% of the LEL) for CH_4. The exceptions were that the BW GasAlert Micro 5 showed a response threshold in the range of 1 to 3 ppm for Cl_2, the RAE MultiRAE Pro showed a response threshold in the range of 0.2 to 0.5% for CH_4, and the Environics ChemPro 100i showed response thresholds in the range of 20 to 50 ppm for SO_2, 10 to 50 ppm for NH_3, and 3 to 10 ppm for Cl_2. It is possible that the response threshold of the RAE MultiRAE Pro for CH_4 was affected by the suspected progressive failure of the LEL sensor in that detector, which was noted in Section 5.2.

6.5 Effect of Operating Conditions

With all seven detectors the performance factors most affected by variations in temperature and RH conditions were response and recovery times, which were usually lengthened by conditions other than normal room temperature and 50% RH. Effects of temperature and RH on response and recovery times were seen less frequently with the ChemPro 100i than with the other six detectors. The performance factors least affected by variations in temperature and RH were QUA, IA, and repeatability. Effects on QUA occurred with several detectors (this performance parameter was not determined for the ChemPro 100i), whereas the majority of effects on IA and repeatability occurred with the ChemPro 100i.

6.6 Effect of O_2 Deficiency on TIC Response

The RKI Eagle 2 showed no significant differences in any performance parameter for H_2S with reduced O_2 levels, and none of the detectors showed any significant differences in IA for H_2S at reduced O_2 levels. Significant effects of O_2 level on response time, recovery time, and QUA for H_2S were seen with some detectors. The response time for H_2S was shortened at the 16% O_2 level with both the BW GasAlert Micro 5 and Industrial Scientific iBRID MX6, but was increased (i.e., nearly doubled) with the Dräger X-am 7000 at both 19% and 16% O_2. The recovery time for H_2S was greatly increased at 16% O_2 for the Environics ChemPro 100i and at both 19% and 16% O_2 for the Industrial Scientific iBRID MX6. The QUA for H_2S declined consistently with reduced O_2 levels for the BW GasAlert Micro 5, Dräger X-am 7000, and Industrial Scientific iBRID MX6.

6.7 Cold/Hot Start Behavior

In most cases, response times, QUA, IA, and repeatability for detection of H_2S were affected only minimally by rapid startup after storage overnight at room, cold, or hot temperature. The delay times between powering up each detector and being ready to begin monitoring similarly showed little impact from the storage condition before startup. However, recovery times were lengthened with several detectors, especially after rapid startup from room temperature or cold conditions. Repeatability was degraded with the ChemPro 100i after cold starts from all three storage conditions.

6.8 Interference Effects

All of the seven detectors showed FP responses in some tests when sampling an interferent vapor in otherwise clean air. Gasoline and diesel exhaust hydrocarbons and paint vapors were the interferents that most frequently caused FP responses. The MultiRAE Pro was the detector most subject to interference effects, showing FP responses with all six interferents in testing with H_2S, O_2, and CH_4, and FP responses with at least one interferent with every target gas. The ChemPro 100i and iBRID MX6 also showed FP responses with at least one interferent with every target gas with which they were tested. The X-am 7000 and GasAlert Micro 5 were the detectors least subject to FP responses. The X-am 7000 showed no FP responses at all in testing with H_2S, PH_3, HCN, and O_2. The GasAlert Micro 5 showed no FP responses at all in testing with H_2S, Cl_2, PH_3, HCN, and CH_4.

The FN rates that resulted from the interferents were almost always zero. In fact, for six of the seven detectors (i.e., the GasAlert Micro 5, X-am 7000, iBRID MX6, MultiRAE Pro, Eagle 2, and PHD6) the FN rate was zero with every interferent in every test. False negatives were observed with the ChemPro 100i in tests with SO_2, NH_3, Cl_2, and HCN. Gasoline engine exhaust hydrocarbons caused FN with the ChemPro 100i with all four of these TICs, and ammonia cleaner, air freshener, and diesel exhaust also caused FN responses in a few tests with the ChemPro 100i.

6.9 Battery Life

The battery life of the seven detectors is illustrated in Figure 6.9-1, and ranged from less than 10 hours for the ChemPro 100i and Dräger X-am 7000 to nearly 46 hours for the RKI Eagle 2 unit E2A505. The two Eagle 2 units exhibited the longest and third-longest periods of battery life, but the battery life of Unit E2A505 was more than twice as long as that Unit E2A410. This difference is attributed largely to the greater power demand of the LEL sensor in Unit E2A410.

6.10 Operational Factors

The following are brief summaries of key positive and negative operational factors reported by the test operators for each handheld detector.

BW Technologies GasAlert Micro 5. This detector was small, lightweight, and easy to use, and large font on the display made it easy to read. Operating menus were easy to understand, calibration menus less so. The operating manual was troublesome because required key sequences were sometimes not located together on the same page.

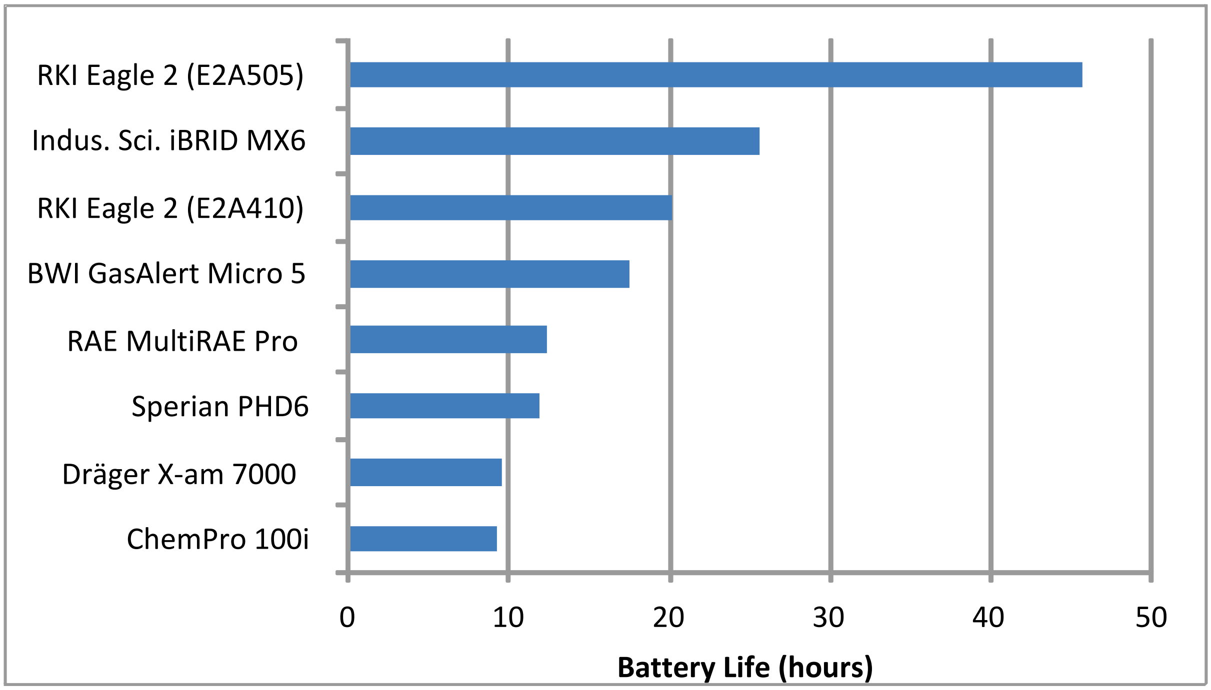

Figure 6.9-1. Summary of battery life test results.

Dräger X-am 7000. This detector was relatively heavy and boxy in shape, making it uncomfortable to hold in the hand for more than a few minutes. The display area was large and easily readable. Operating menus were easy to understand and the detector was easy to use and had numerous user-defined options. However, the operating manual did not appear to cover all of the features or operations of the unit.

Environics ChemPro 100i. This detector was easy to operate, with intuitive menus, and had large control buttons that could be manipulated correctly even when wearing heavy gloves. The ChemPro 100i required confidence checks with a chemical vapor source provided with the detector. Those checks were simple to perform and the detector responded quickly to the confidence check. The ChemPro 100i was relatively sensitive to the test conditions (temperature and RH) and occasionally had difficulty maintaining its baseline operating condition when moved during testing, causing false alarms and requiring that the operator reset the baseline. The MOS sensor in the first ChemPro 100i unit failed during testing, and a replacement ChemPro 100i unit was provided by the manufacturer.

Industrial Scientific iBRID MX6. This detector had logical and self-explanatory menus, but the menus were difficult to navigate because the buttons on this detector were small and clustered tightly together. This was especially a problem when wearing heavy gloves. The display of the iBRID MX6 was weakly backlit and the display font was small, making readings difficult to discern. This detector also responded relatively slowly to daily bump checks.

RAE Systems MultiRAE Pro. This detector was easy to operate by following the instruction manual, the menus were clearly understandable, and the display was easy to read. However, it was difficult to determine the full-scale ranges of the sensors installed in the MultiRAE Pro without seeking technical support or online information from the manufacturer. The use of heavy gloves made it difficult to feel when the control buttons had been successfully pressed. Multiple EC sensors could fit into the O_2 sensor location of this detector, but would not work in that location. The operator would not know that the sensor was not working until the detector had been reassembled and powered up.

RKI Instruments Eagle 2. Three separate units of this detector had to be purchased to conduct testing, because the needed sensors could not be interchanged within a single unit. The Eagle 2 was relatively large and heavy, but its design and built-in handle made it comfortable to use. The display was clear and legible but did not indicate the status of the batteries. Operation of this detector while wearing heavy gloves was difficult, as it was hard to feel when the control buttons had been successfully pressed.

Sperian PHD6. This detector's display was easy to read, but the detector's alarms would change the display, interfering with concentration readings. Testing staff adjusted the alarm values to avoid this issue during testing. Selection of a particular sensor on the calibration menu required toggling through multiple menu steps. Operation of the detector's control buttons and performance of the pump test were difficult when wearing heavy gloves. The sample inlet tubing of the PHD6 connects at the bottom of the detector, and thus the connection point is directed toward the user when the detector is held in the hand, potentially leading to pinching or snagging of the inlet tubing. The battery charger of the PHD6 makes electrical contact by gravity and sometimes did not make proper contact.

APPENDIX A

NOMINAL UPPER RANGE LIMITS OF THE TESTED DETECTORS FOR EACH TARGET GAS

Gas	BW Technol. Micro 5	Dräger X-am 7000	Environics ChemPro 100i	Industrial Scientific iBRID MX6	RAE Systems MultiRAE Pro	RKI Instrum. Eagle 2	Sperian PHD6
O_2	30 %	25 %	NA	30 %	30 %	40 %	30 %
LEL	100 %	100 %	NA	100 %	100 %	100 %	100 %
H_2S	500 ppm	100 ppm	100 ppm	500 ppm	100 ppm	100 ppm	200 ppm
SO_2	150 ppm	100 ppm	100 ppm	100 ppm	20 ppm	6 ppm	25 ppm
NH_3	100 ppm	300 ppm	100 ppm	100 ppm	100 ppm	75 ppm	100 ppm
Cl_2	50 ppm	20 ppm	10 ppm	100 ppm	10 ppm	3 ppm	50 ppm
PH_3	5 ppm	1000 ppm	50 ppm	5 ppm	20 ppm	1 ppm	20 ppm
HCN	30 ppm	50 ppm	20 ppm	30 ppm	100 ppm	15 ppm	100 ppm

NA: Not applicable.

APPENDIX B

EXAMPLE OF LABORATORY DATA RECORDING SHEETS

DATA SHEETS FROM TESTING OF BW TECHNOLOGIES GAS ALERT MICRO 5 WITH HYDROGEN CYANIDE AT TARGET CONDITIONS OF 35 °C AND 80% RH (i.e., Test #20 with HCN)

EPA TESTING DATA SHEET – **Detector Testing_100000638-03TESTING**

Date: 07-12-11 Sheet ID# AC-2Ø-1 Time: Start 1300 Finish 1448

Staff: DBD, MML

Test Chamber ID: TC-2 Environmental Chamber ID: EC-2

Detector being tested: **Gas Alert** Sensor Configuration: AC, NH_3, O_2, LEL

Test being conducted: AC-2Ø 15 PPM

TEMP (35 ± 3°C) RH (80 ± 5%)

Stopwatch ID: Z Stopwatch Calibration Expiration Date: ~~10/25/2013~~ WO DBD 11-19-2012 07-12-11

Actual Test Conditions at Start of Testing:

Temperature: 33.1°C Relative Humidity: 78.7% % O_2 N/A

Data Logger file name: 7121Ø854.MXD LRB: 53338-66

Notes/Comments:

Verified Datalogger Temp, RH, and O_2 are within tolerances: (initial/date/time) DBD/ 07-12-11/ 1637

Continued on Sheet ID # AC-2Ø-2

Signature David B. Davis Date 07-12-11

Data Sheet Reviewed by Tom Kelly Date 7/25/11

Valid ✓	Invalid
Comment	Comment
Reported ☑ Not Reported ☐	

Version 1.0 5/03/2011

EPA TESTING DATA SHEET – **Detector Testing_100000638-03TESTING**

Date 07-12-11 Sheet ID# AC-20-2

Detector being tested: **Gas Alert** Reference Method GC-FID

Method Zeroed (HHMM): N/A	**Zero Reading (ppm):** N/A
Calibration Standard: AC (HCN) 1.00% SCOTT 1A 021622 EXP 07-26-11	**Calibration Formulation:** 15cc of 1% AC into 3L zero air

Time	ID	TIC	Target Conc. (ppm)	Actual Conc. (ppm)	File Name/Comment
08:08	CAL 1	AC	50	50.54	AC0712 00
08:16	2	↓	↓	50.56	01
08:27	↓ 3	↓	↓	50.61	↓ 02
— : —	—	—	—	—	—

Time	ID	TIC/I*	Conc. (ppm)	File Name/Comment
13:23	BLANK 1	AC	0.46	AC0712 20
13:31	REF 1		15.15	21
13:37	REF 2		15.41	22
14:33	BLANK 2		0.53	26
14:40	REF 3		15.49	27
14:48	REF 4	↓	15.68	↓ 28
:				
:				
:				
:				
:				
:				

* I = Interferent

Continued on Sheet ID # AC-20-3

Other Notes/Comments

Signature David B. Davis Date 07-12-11

Data Sheet Reviewed by TJK Date 7/25/11

Version 1.0 5/03/2011

EPA TESTING DATA SHEET – **Detector Testing_100000638-03TESTING**

Date ∅7-12-11 Sheet ID# AC-20-3

Detector being tested: **Gas Alert**

	Challenge Start Time	Challenge and Challenge Concentration	TIC	Conc. ppm/ %LEL	Time to Alarm	Time to Clear	Notes / Observations (switch to clean air, false positives, etc.)
1	13:47	AC/15 PPM	AC	17	–:22	–:–	—
	13:47	CLEAN AIR	AC	CLEAR	–:–	–:33	SWITCH AT 0:52
2	13:56	AC/15 PPM	AC	17	–:3∅	–:–	—
	13:57	CLEAN AIR	AC	CLEAR	–:–	–:35	SWITCH AT 1:00
3	14:∅5	AC/15PPM	AC	18	–:27	–:–	—
	14:∅5	CLEAN AIR	AC	CLEAR	–:–	–:36	SWITCH AT 0:57
4	14:13	AC/15PPM	AC	18	–:28	–:–	—
	14:13	CLEAN AIR	AC	CLEAR	–:–	–:37	SWITCH AT 0:58
5	14:21	AC/15 PPM	AC	18	–:3∅	–:–	—
	14:22	CLEAN AIR	AC	CLEAR	–:–	–:37	SWITCH AT 1:00
	:				:	:	
	:				:	:	
	:				:	:	
	:				:	:	
	:				:	:	
	:				:	:	
	:				:	:	
	:				:	:	
	:				:	:	

DBD 07-12-11

NR= no response

Continued on Sheet ID # NONE

Other Notes/Comments

Signature David B. Davis Date 07-12-11

Data Sheet Reviewed by TJK Date 7/25/11

Version 1.0 5/03/2011

SC
IEN
CE

EPA
United States
Environmental Protection
Agency

Office of Research and Development (8101R)
Washington, DC 20460