EVALUATION OF PORTABLE MULTI-GAS ANALYZERS FOR USE BY SAFETY PERSONNEL

by

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ABSTRACT

During confined space entry operations as well as Shuttle-safing operations, United Space Alliance (USA)/National Aeronautics and Space Administration (NASA) safety personnel use a variety of portable instrumentation to monitor for hazardous levels of compounds such as nitrogen dioxide (NO_2), monomethylhydrazine (MMH), FREON 21, ammonia (NH_3), oxygen (O_2), and combustibles (as hydrogen (H_2)). Except for O_2 and H_2, each compound is monitored using a single analyzer. In many cases these analyzers are 5 to 10 years old and require frequent maintenance. In addition, they are cumbersome to carry and tend to make the job of personnel monitoring physically taxing.

As part of an effort to upgrade the sensor technology background information was requested from a total of 27 manufacturers of portable multi-gas instruments. A set of criteria was established to determine which vendors would be selected for laboratory evaluation. These criteria were based on requests made by USA/NASA Safety personnel in order to meet requirements within their respective areas for confined-space and Shuttle-safing operations. Each of the 27 manufacturers of multi-gas analyzers was sent a copy of the criteria and asked to fill in the appropriate information pertaining to their instrumentation. Based on the results of the sensor criteria worksheets, a total of 9 vendors out of 27 surveyed manufacturers were chosen for evaluation. Each vendor included in the final evaluation process was requested to configure each of two analyzers with NO_2, NH_3, O_2, and combustible sensors.

A set of lab tests was designed in order to determine which of the multi-gas instruments under evaluation was best suited for use in both shuttle and confined space operations. These tests included linearity/repeatability, zero/span drift, response/recovery, humidity, interference, and maintenance. At the conclusion of lab testing three vendors were selected for additional field testing. Based on the results of both the lab and field evaluations a single vendor was recommended for use by NASA/USA Safety personnel.

Vendor selection criteria, as well as the results from both laboratory and field testing of the multi-gas analyzers, are presented as part of this paper.

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INTRODUCTION

BACKGROUND

Many of the portable analyzers used by both USA and NASA safety personnel during both shuttle-safing and confined space entry operations are outdated from a technology standpoint and require frequent maintenance. The monitoring of compounds such as NO_2, MMH, FREON 21, NH_3, O_2, and H_2 is accomplished with analyzers such as those listed in table 1.

Table 1. Portable Analyzers Used by USA/NASA Safety

Compound Monitored	Vendor	Model
O_2	Biosystems	3100
O_2	Gastech	1620,1313
O_2	Industrial Scientific	MX251
O_2	MDA	3300
H_2	MSA	260
H_2	Bacharach	Sentox 2
H_2	Industrial Scientific	MX251
H_2	Gastech	1214
H_2	MSA	Passport 3210L
MMH	Interscan	4000
MMH	Ecolyzer	6000
MMH	GMD	Dosimeters
Organic Vapor	MIRAN	101 (Freon)
NO_2	Ecolyzer	6000
NH_3	National Draeger	Dosimeter tubes

During September 1996, the Toxic Vapor Detection Laboratory (TVDL) was informed by USA safety that an MDA™ Passport had been chosen as a multi-gas instrument for use in confined-space operations. The Passport was designed to be configured with the following sensors: combustibles (as H_2), NO_2, O_2, and NH_3. Upon further investigation, the TVDL located several vendors in addition to MDA™ that might be viable candidates for use as confined-space instruments. The instrumentation from these vendors could potentially also be used during shuttle-safing operations. Background information was requested from a total of 27 manufacturers of portable multi-gas instruments who were present at the National Safety Show held in Orlando, Florida, in early October 1996.

The purpose of the multi-gas sensor evaluation was to survey the marketplace for replacement instrumentation that would combine the analytical capabilities of several analyzers into one small portable unit. The remainder of this paper details the market survey of multi-gas sensors, laboratory evaluations, field results, and the recommendation of a single vendor.

VENDOR CRITERIA

A set of criteria was established (table 2) to be utilized in comparing vendor capabilities in order to determine which vendors would be selected for laboratory evaluation testing. These criteria were based on requests made by USA/NASA Safety personnel in order to meet requirements within their respective areas for confined-space entry and Shuttle-safing operations. Each of the 27 manufacturers of multi-gas analyzers was sent a copy of the criteria and asked to fill in the appropriate information. The columns in table 2 are as follows:

a) Criterion:	A description of each individual criterion
b) R/D:	Each criterion is designated as required (R) or desired (D). The R/D determination was made by the end-user during early project meetings
c) Meets criterion:	This column is YES if the criterion can be met by a designated instrument model number.
d) Does Not Meet Criterion:	This column is NO if the criterion cannot be met by a designated instrument model number.
e) Comments:	Space for comments from the vendor regarding a criterion.

VENDOR SELECTION

Based on the results of the sensor criteria worksheets received from individual vendors, the nine manufacturers listed in table 3 were selected for inclusion in the laboratory evaluation of multi-gas instrumentation. Most of those vendors who were not included in the evaluation failed to be chosen due to the inability of providing one or more of the requested sensors within an analyzer. Each vendor included in the final evaluation process was requested to configure each of two analyzers with NO_2, NH_3, O_2, and combustible gas sensors. The request for two analyzers from each vendor was made to lessen the chances that a vendor would be disqualified from consideration due to the failure of a single analyzer. Each vendor was also requested to include software for use in downloading stored data, operational manuals, sample tubing, filters to protect the sensors from entrained dust and liquids, and a sample pump as part of their evaluation package. The sensors used by the selected vendors are obtained from a variety of sources including: City Technology (AIM, Biosystems, Crowcon, Gastech, Metrosonics, and RAE), Sensorex (ENMET), and Riken Keiki (RKI). In comparison, National Draeger manufactures all of its own sensors. This breadth of sensor sources allowed for a more comprehensive intercomparison of sensor technology as well as vendor packaging.

LAB EVALUATION TESTS

INTRODUCTION

A set of lab tests was designed to determine which of the multi-gas instruments under evaluation was best suited for use in both shuttle and confined space entry operations. These tests included linearity/repeatability, zero/span drift, response/recovery, humidity, temperature, interferences, and maintenance.

HARDWARE

Humidified air from a primary Miller Nelson Research Model HCS-401 dilution system was delivered to a multi-port round-bottom flask and used as a "zero" air sample during all instrument evaluations. A second Miller Nelson provided an equal flow rate of "zero" air to a tee upstream of a second round-bottom flask and was mixed with a measured flow of bottled gas to produce a "span" sample. The flow conditions of each of the Miller Nelson HCS-401 systems were logged by a TVDL-designed Process Control and Data Acquisition System (PCDAS) and compared to operator-requested setpoints. Adjustments were made by the PCDAS to keep the requested and measured setpoints equivalent. Both the temperature (T) and relative humidity (RH) within the zero and span mixing vessels were continually measured using calibrated Vaisala Model HMP-13 sensors. The output from these sensors was used by the PCDAS and compared to operator-requested T and RH setpoints for the mixing vessels. The PCDAS then controlled the Miller Nelson systems to maintain both mixing vessels at the proper T and RH.

Table 2. Portable Multi-Gas Sensor Criteria

Company: ____________________
Instrument Model #: ____________________

Criterion	R/D	Meets Criterion	Does Not Meet Criterion	Comments
Pump Available	R			
Sample Line [6 feet (ft) +]	R			
Battery Life (8 hour +, rechargeable)	R			
Alarm (audible, 90 decibels (dB) at 12 ft)	R			
Alarm (visible)	R			
Alarm (remote)	D			
Area Class (Class 1 Div 1 Group A,B,C,D)	R			
Electromagnetic Interference (EMI)/Radio Frequency Interference (RFI) Shielded	R			
Calibration Cycle (60 days + desirable, 30 days OK)	D			
Weight (<5 pounds)	D			
Cost (<$3,000)	D			
Temperature Range (5 to 40 degrees Celsius (°C)) Lower Desired	R			
Humidity Range (0 to 100%)	R			
Data Logging	R			
Output [short-term exposure limit(STEL), peak, time-weighted average(TWA)]	R			
Remote Output	D			
Record Keeping Capability	D			
Drop Test (5 ft, minimum)	D			
Digital Display	D			
Backlit Display	D			
Ability to Read Display at 3 ft	D			
Components in one unit (four required, five desirable)	R			
NH_3 [0 to 25 parts per million (ppm), ±5 ppm repeatability]	R			
NO_2 (0 to 20 ppm, ±0.5 ppm repeatability)	R			
O_2 (18 to 23%, ±0.3% repeatability)	R			
Combustibles (as H_2) (1% alarm)	R			
CO (0 to 50 ppm, ±10 ppm repeatability)	D			
Response/Recovery Times (<1 minute to 90% full scale (FS) for any component	R			
ISO 9000/14000 Certified	D			
Tethering Available	D			
Shelf Life of Cells (>=1year)	D			
Evaluation Unit Available?	R			

R = Required feature
D = Desired feature

Table 3. Multi-Gas Vendors Selected For Evaluation

Vendor	Instrument
AIM	4501
Biosystems	PhD Ultra
Crowcon	Triple Plus
ENMET	OMNI 4000
Gastech	STM 2100
Metrosonics	7400
National Draeger	Multiwarn II
RAE	MultiRAE
RKI	Eagle

Unless otherwise stated, the temperature and RH values of all vapor samples used during evaluation tests were 23 °C and 45 percent RH, respectively.

A MIDAC Model G1001 Fourier Transform Infrared (FTIR) was used to display the concentration of NO_2, and NH_3 vapors generated within the span vessel. This FTIR Module was modified by the addition of a gas-driven eductor pump (PIAB Model M32) to draw samples from either the zero or span vessel. The concentration results were sent to a laptop computer running a generic ASCII terminal program for data collection.

A DET_TRONICS Model 400 combustible gas detector was used to monitor the vapor concentrations of H_2 used during lab testing. The output of the detector, in percent lower explosive limit (LEL), was displayed on screen and logged by the PCDAS. The concentration of O_2 in span samples generated for linearity/repeatability studies was measured by a calibrated Panametrics TMO2 oxygen analyzer.

TEST SETUP

During the evaluation tests, the multi-gas instruments were distributed on three shelves of a roll-around cart in front of a certified fume hood at the TVDL. A 10-ft length of BEV-A-LINE™ IV tubing was attached to each analyzer. This length of tubing was chosen to simulate field conditions where an operator samples vapors from a site that is just out of reach using a sample line attached to an extension pole. The sample lines for the analyzers on each shelf were bundled together in order to make the insertion of these lines into zero and span vessels easier during testing. All of the NH_3 and NO_2 span samples used during the evaluations were prepared by dilution of a measured amount of certified primary standard with humidified air from a Miller Nelson. Both of the certified primary standards were mixed by Scott Specialty Gases. A block diagram of the test setup including Miller Nelson Units, MIDAC FTIR, zero/span vessels, needle valve and Gilmont rotometer is shown in figure 1.

TEST RESULTS

LINEARITY/REPEATABILITY

Response data for each of the NH_3, NO_2, O_2, and combustible gas sensors were collected at several concentrations within the standard operating range of each sensor in order to obtain linearity data. The response of each sensor was logged during three span-zero cycles as a check of repeatability. The total length of each span-zero cycle was 10 minutes. The span and zero portions of each cycle were both 5 minutes in length. All of the sensors for an individual gas (NO_2, O_2, combustible (as H_2), and NH_3) were ranked according to the sum of the absolute differences between input vapor concentrations and the sensor output responses. Using this ranking, the lower the total score, the closer the analyzer came to the known gas concentration being measured. The individual scores for each of the sensors were combined into an overall score for the linearity/repeatability portion of the tests. The overall scores for each analyzer evaluated can be found in table 4. Both of the National Draeger Multiwarn II analyzers performed more consistently than any other vendor. In comparison, the performances of the AIM 4501, and ENMET OMNI 4000 analyzers were in the top three for at least one of the four sensors evaluated. The scores for other sets of analyzers from the same vendor, except Metrosonics, were either widely separated (Crowcon Triple Plus, Biosystems PhD Ultra, RAE MultiRAE) or ranked in the bottom half of linearity results (Gastech STM 2100, RKI Eagle). The Metrosonics 7400 analyzers were not carried through for further testing due to numerous pump and battery failures. Composite vendor scores were obtained by adding together individual sensor results. Each vendor was ranked based on this composite score. These results can be found in table 5.

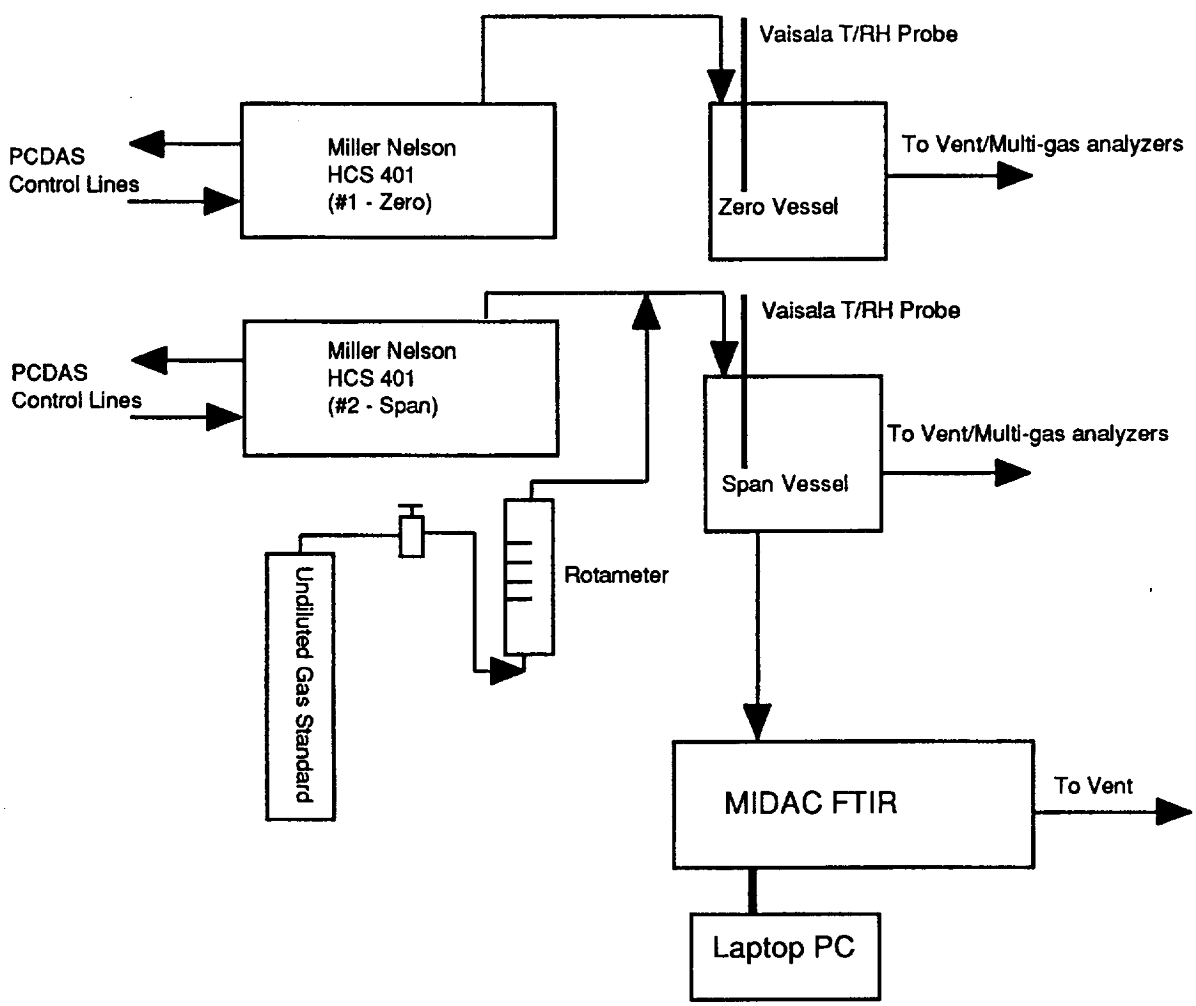

Figure 1. Multi-Gas Test Setup

Table 4. Linearity/Repeatability Ranking by Analyzer (S/N)

Vendor (S/N)	NO2	NH3	H2	O2	Score	Rank
National Draeger Multiwarn II (446)	1	11	4	1	17	1
National Draeger Multiwarn II (470)	2	12	2	2	18	2
Crowcon Triple Plus (363)	5	5	3	9	22	3
AIM 4501(102930)	3	1	15	4	23	4
ENMET OMNI 4000 (1526)	6	4	1	13	24	5
AIM 4501(101295)	4	2	16	7	29	6
RAE MultiRAE (283)	12	7	13	3	35	7
Biosystems PhD Ultra (192)	14	8	6	8	36	8
ENMET OMNI 4000 (1247)	10	3	11	12	36	9
Metrosonics 7400 (1122)	9	13	7	10	39	10
Metrosonics 7400 (1095)	16	15	5	5	41	11
RKI Eagle (72012)	15	16	9	6	46	12
Gastech STM 2100 (99)	13	6	12	17	48	13
RAE MultiRAE (263)	11	16	8	14	49	14
Biosystems PhD Ultra (1823)	7	14	14	15	50	15
Gastech STM 2100 (98)	8	9	18	18	53	16
RKI Eagle (72011)	17	16	10	11	54	17
Crowcon Triple Plus (362)	18	10	17	16	61	18

Table 5. Linearity/Repeatability Ranking by Vendor

Vendor	Composite Analyzer Score	Final Rank
National Draeger Multiwarn II	35	1
AIM 4501	52	2
ENMET OMNI 4000	60	3
Metrosonics 7400	80	4
Crowcon Triple Plus	83	5
RAE MultiRAE	84	6
Biosystems PhD Ultra	86	7
RKI Eagle	100	8
Gastech STM 2100	101	9

ZERO DRIFT TESTS

The purpose of this test was to obtain the zero drift characteristics for each sensor over the range of humidity from 15 to 75 percent RH. The analyzers were zeroed at the lowest humidity and monitored over the entire range of RH values for any changes in the zero value. The analyzers were not turned off or rezeroed during the duration of the testing.

The NO_2 sensor output of the Biosystems PhD Ultra and RAE MultiRAE analyzers exhibited more deviations from baseline when compared to the other tested systems. The response of one of the Biosystems PhD Ultra analyzers drifted downward from 0.1 to -0.3 ppm as the humidity was raised from 55 to 75 percent. During the zero drift testing only the RAE MultiRAE NO_2 sensors displayed values greater than 0.5 ppm. In comparison, the outputs of the remaining analyzers ranged between 0 and 0.2 ppm over the entire humidity range.

While testing NH_3 sensors the Gastech STM 2100 and RAE MultiRAE showed significant deviations from baseline zero across the entire humidity range. In the case of the Gastech sensors some deviations were as high as 20 to 25 ppm on a full scale of 0 to 25 ppm. The responses of the RAE MultiRAE NH_3 sensors increased from 0 to 13 and 14 ppm, respectively, as the humidity increased from 20 to 75 percent. Both of the Biosystems PhD Ultra NH_3 sensors drifted downward from 0 to -2 ppm during the initial testing at 20 percent RH but then showed an upward step change in output to approximately 0.5 ppm during the 40 percent RH cycle. The output of both the Crowcon Triple Plus NH_3 sensors gradually changed from an initial value of -1 ppm to a final value of 1 ppm over the entire humidity ramp. In order, the RKI Eagle, ENMET OMNI and AIM 4501 NH_3 sensors showed the best consistency over the entire humidity range of 20 to 75 percent RH.

During O_2 sensor zero drift testing, both of the Gastech STM 2100 O_2 sensors exhibited the largest baseline deviations compared to all other sensors. The initial baseline value for Gastech (S/N 98) was 21.6 percent O_2 on a full scale of 18 to 23 percent. This value dropped to 20.9 percent O_2 after 5 minutes and remained constant throughout the remainder of the testing. The O_2 response for the second Gastech analyzer started at 23.3 percent, dropped to 21 percent after 5 minutes, and displayed values as low as 20 percent O_2 during the remainder of the humidity ramping. The response of the Crowcon Triple Plus (S/N 21363) showed step changes of $\pm$ 0.2 percent O_2 (absolute) during 75 percent RH level testing but performed adequately at all other humidity levels. The RAE MultiRAE (S/N 500283) displayed a steady baseline at 20, 40, and 55 percent RH but shifted upward by 0.2 percent O_2 (absolute) at the 75 percent RH level and was quite erratic at this humidity. The responses for all other O_2 sensors were within $\pm$ 0.1 percent O_2 (absolute) of a 20.9 percent fresh air calibration value during this portion of the lab evaluation.

Except for Gastech, Crowcon, and Biosystems, the responses of all other H_2 sensors were no greater than $\pm$0.1 percent LEL over the tested humidity range of 20 to 75 percent RH. The Gastech sensors showed deflections as high as $\pm$4 percent LEL while baseline shifts approximately +1 percent LEL in magnitude were observed for both the Biosystems and Crowcon analyzers.

In summary, all of the RKI Eagle sensors exhibited fewer deviations from baseline during the zero drift testing than all other vendors. The AIM 4501 sensors ranked second to RKI followed closely by the ENMET OMNI 4000 and National Draeger Multiwarn II. The Biosystems PhD Ultra, Gastech STM 2100, Crowcon Triple Plus and RAE MultiRAE sensors showed numerous deviations from baseline across the entire humidity range of 20 to 75 percent RH.

SPAN DRIFT TESTS

This test was used to check the ability of an instrument to maintain the value of a span sample over a 30-minute period. Each analyzer was zeroed in clean air and then allowed to analyze a vapor sample whose input concentration was in the middle of the operating range for a particular sensor. Three span-zero cycles were completed at each of 4 humidities in the range of 15 to 75 percent RH.

The AIM 4501 NO_2 sensors were the most accurate and stable over the entire humidity range of 15 to 75 percent. The responses of these sensors fluctuated by ±3 to 4 percent (relative) from an input of 10.8 ppm during span drift testing. A decrease of approximately 5 percent (relative) in the response of the National Draeger Multiwarn II (S/N 470) sensor was observed between 15 and 30 percent RH. The output of this sensor was higher than the input concentration by 10 percent (relative) at the 15 percent RH level compared with 3 to 5 percent (relative) between 30 and 75 percent RH. The RKI Eagle NO_2 sensors showed the largest changes in span values during testing ranging from a high of 12 to 14 ppm at the 15 percent RH level to a low of 3 to 4 ppm at the 75 percent RH level. No data is presented for the RAE MultiRAE analyzers due to battery failures.

The outputs of both the RKI Eagle and National Draeger Multiwarn II NH_3 sensors were very stable through the span drift testing. No baseline shifts or monotonic increases/decreases were noted. All other NH_3 sensors exhibited baseline shifts or increases in noise as the RH transitioned from 19 to 75 percent. The average response of the RKI sensors decreased by 1 ppm during the transition from 19 to 30 percent RH, but remained constant from 30 to 75 percent RH. In comparison, the average response of the Draeger sensors remained constant during each span cycle over the RH range tested.

The output of the RKI Eagle O_2 sensors steadily decreased over the 15 to 75 percent RH range tested. Although the 2.5 percent (relative) decrease in response is small, no other sensors showed a similar downward trend. The largest error in response, 25 to 30 percent (relative) below the input value of 19.8 percent O_2, was recorded for one of the two Gastech STM 2100 analyzers. This error was consistent across the entire RH range tested. In comparison, the output of the 2nd Gastech analyzer was low by -0.34 percent (relative) over the same RH range. Although the responses for the Crowcon Triple Plus analyzer (S/N 21362) were nearly identical for all humidities, they were always higher than the input concentration by 2 percent (relative). The relative errors in the responses of all of the AIM 4501 and National Draeger Multiwarn II O_2 sensors were the lowest at 1 to 1.2 percent. The errors for other sensors ranged from 1.4 to 2.3 percent.

The responses of the H_2 sensors for the RKI Eagle (S/N 72012), AIM 4501 (S/N 102930), and Crowcon Triple Plus (S/N 21363) did not drift over the 22 to 75 percent RH humidity range tested. These analyzers were also consistent in their responses at each of the four RH values tested (22, 35, 55, and 75 percent RH). Although the second Crowcon analyzer did not drift during testing, the recorded output values were 60 to 75 percent (relative) higher than the input concentration of 8.2 percent LEL. The responses of the Biosystems PhD Ultra and National Draeger Multiwarn II analyzers both increased approximately 10 percent (relative) when the humidity was changed from 15 to 35 percent RH. Between 35 and 75 percent RH the responses of these analyzers remained constant. The second RKI Eagle analyzer decreased in response by 10 to 15 percent (relative) during the transition from 35 to 55 percent RH and remained at this level for the duration of the test. The Gastech STM 2100 (S/N 99) steadily increased its response over the entire humidity range while the second STM 2100 (S/N 98) failed to respond during the span drift test.

Overall, the AIM 4501 and National Draeger Multiwarn II sensors were more consistent than those of any other vendor. This consistency was observed in the responses obtained during the span drift testing across all sensors. In addition, if one compares the responses of two sensors from the same vendor, the AIM and National Draeger sensors were consistently similar, while the sensors from other vendors were widely separated in their responses.

RESPONSE/RECOVERY TIMES

The response and recovery times for each sensor were evaluated using span values in the middle of their respective operating ranges. The experimental response times, as measured to 90 percent of the full scale value for each sensor, were compared to the published values provided by each vendor. Wherever possible, data was obtained in both pump and diffusion modes for each sensor. The RAE MultiRAE and RKI Eagle could not be run in diffusion mode since their respective sample pumps are always energized.

During diffusion-mode testing of the H_2 sensors only the Gastech STM 2100 (S/N 98) analyzer failed. There was not response from this sensor. All other H_2 sensors passed. There were no failures of any O_2 sensors in either pump or diffusion mode. Failures of the NO_2 sensors in the pump mode included: Biosystems PhD Ultra (2 analyzers) , Crowcon Triple Plus (S/N 21363), and ENMET (S/N 1247). In the diffusion mode the following NO_2 sensors failed: AIM 4501 (S/N 101930), Biosystems PhD Ultra (2 analyzers), Gastech STM 2100 (S/N 99), and National Draeger Multiwarn II (S/N 470). Finally, the NH_3 sensors used by the Crowcon Triple Plus and Gastech STM 2100 analyzers failed both pump and diffusion mode testing. All other NH_3 sensors passed.

The response/recovery time requested by the customer (table 2) for each sensor is <1 min to 90 percent of full scale reading. Except for the failed sensors noted in the previous paragraph, this requirement was met by all H_2, O_2, and NO_2 sensors. In the case of the NH_3 sensors, only the RKI Eagle was able to meet the criterion requested by the customer.

INTERFERENCES

Cross interference data was collected on each of the sensors for a number of compounds including acetone, isopropyl alcohol (IPA), hydrazine (HZ), and MMH. In addition to these compounds, data obtained for each sensor during the linearity/repeatability testing was analyzed for sensor cross-talk. The purpose of this testing was to determine if any problem areas existed that would lead to false positive or negative readings for an individual sensor. The largest cross interference was found when the NH_3 sensors were exposed to H_2. Values for this interference ranged from a low of 0 ppm (RKI sensor) to a high of 120 ppm (ENMET sensor) for a 7.3 percent LEL H_2 input concentration. This large cross interference will dramatically shorten the life of the NH_3 sensors. Users of the multi-gas sensors should be aware of the potential for large false positive values for the NH_3 sensors in the presence of H_2. Additional responses were noted for most of the NH_3 sensors in the presence of NO_2, acetone, and IPA. The RKI Eagle NH_3 sensors showed no positive response to any of the interferents tested. The National Draeger Multiwarn II NH_3 sensors showed no response to HZ, MMH, or NO_2. The corresponding responses to acetone, IPA, and H_2 were all less than 5 ppm. This compares favorably to the current alarm level of 10 ppm. In the case of the H_2 and NO_2 sensors cross interferences were only noted for acetone and IPA. The levels of acetone and IPA tested, 7 and 12 times above their respective TWA values, are not typical of what might be present under normal operating conditions. Further testing of the sensors at lower levels may indicate that the responses are well below the allowable alarm levels. In addition, if it is known that solvents such as acetone or IPA have been used in areas to be surveyed, it is recommended that the sensors not be activated until potential solvent interferent vapors have dissipated. Changes in procedures to include drying of potential contaminated surfaces prior to sensor testing could be proposed.

MAINTENANCE

The battery packs for the National Draeger Multiwarn II, Gastech STM 2100, Metrosonics 7400 and Biosystems PhD Ultra are all very easy to remove and change in the field, if necessary. The Multiwarn II battery pack slides away from the electronics section, while the Gastech STM 2100 and Biosystems PhD Ultra use self-contained packs with locking screws that attach to the body of the analyzer. The Metrosonics 7400 battery pack, although easily changed out, was not reliable and tended to need frequent recharging. Access to the batteries for the RKI Eagle is obtained by unscrewing two knurled nuts to separate the electronics section from the battery/pump/sensor section. The ENMET OMNI 4000 has a set of three Phillips-head screws that attach the battery pack to the analyzer and allow for a relatively easy changeout. Changing out the batteries for either the Crowcon Triple Plus, RAE MultiRAE, or AIM 4501 analyzers requires the analyzer to be physically taken apart and is more time consuming.

The ENMET OMNI 4000 sensors are the easiest to change out. The Sensorex and City Technology sensors used by ENMET have been repackaged into a physical size that is easy to take out of the analyzer and replace. The sensors for the National Draeger Multiwarn II, Biosystem PhD Ultra, Gastech STM 2100, and RAE MultiRAE analyzers are slightly more difficult to take out and replace due to their smaller size and closer packing within an individual analyzer. The AIM 4501 sensors are removed using a set of small tongs that grip the sides of the sensors during changeout. If the tongs are bent, the sensors are more difficult to remove. Sensor changeout for both the Crowcon Triple Plus and RKI Eagle is very time consuming. The Crowcon analyzer housing must be disassembled in order to access an individual sensor. In addition, the sensor and its electronic package are held together in place by screws and ribbon cables. In order to change out either the NO_2 or NH_3 sensor for the RKI Eagle, the inlet and outlet lines from the pumping system must be disconnected along with several hold-down brackets. Removal and replacement of the sensors for the Metrosonics 7400 require the use of a plastic tool that fits over the top of the sensor and locks into place. The close packing of the sensors within the analyzer makes removal and replacement of these sensors somewhat difficult. The sensors used by most manufactures are keyed and/or color coded so they cannot be incorrectly socketed into an analyzer. The NO_2, O_2, and NH_3 sensors for the National Draeger Multiwarn II, Biosystems PhD Ultra, Gastech STM 2100, Metrosonics 7400, and RAE MultiRAE can be moved around within the analyzer housing, since the software deciphers the sensor type based on information obtained from the attached electronics board.

The Biosystems PhD Ultra, Gastech STM 2100, and Metrosonics 7400 sample pumps can be easily removed and replaced if necessary. The sample pumps for the AIM 4501, Crowcon Triple Plus, RAE MultiRAE and RKI Eagle, and National Draeger Multiwarn II all require some disassembling of the analyzer housing in order to be replaced. The Crowcon sample pump is the most difficult to remove since the analyzer housing must be disassembled and internal sensors must be removed before it can be replaced.

MISCELLANEOUS INSTRUMENT FEATURES

During operations in the field, the multi-gas analyzers may remain ON for an extended period of time. The customer requested criterion (table 2) for battery lifetime is 8 hrs. The lifetime of the analyzer battery packs were compared to this criterion by turning on each analyzer, performing a fresh air zero, and allowing the analyzer to operate unattanded until the battery failed. A battery check was done every 2 hours over the lifetime of the test. Both of the Metrosonics 7400 and RAE MultiRAE analyzers failed the battery lifetime test. During earlier testing the Metrosonics 7400 analyzers continuously needed battery pack recharging/replacement and are very unreliable in their ability to remain operational for long periods of time. Additionally, the battery pack for one of the Gastech STM 2100 analyzers was only operational for 6 hours and barely meets the manufacturer's specifications. All other analyzers used during this test could be turned on and continuously operated in pump mode for nearly 8 hours. Although battery lifetimes were not measured with analyzers operating in the diffusion mode, each vendor stated that a minimum of 4 to 6 additional hours of running time should be present in this mode compared to the pump mode.

Except for the AIM 4501, all other multi-gas analyzers come with software for downloading, viewing, and exporting data for further processing by spreadsheet programs such as EXCEL. In the case of the AIM 4501 analyzers, data is simply downloaded as an ASCII file without the inclusion of any graphical interface. The best overall software package is included with the National Draeger Multiwarn II analyzers. An added feature of this software is a tutorial that leads the user through both operation and troubleshooting of the analyzer. No other vendor includes a tutorial as part of a software package. The Biosystems PhD Ultra software simultaneously displays separate graphical data from up to four sensors on screen at the same time. This feature allows quicker intercomparison between sensor responses. All other vendors display either overlayed sensor responses on one graph or allow the user to choose an individual sensor for display. The data collection rate for the ENMET analyzer is fixed at one per minute, while all other systems can acquire information as fast as one point every 10 seconds. The National Draeger and RAE analyzers can also acquire data at the rate of one point each second, if neccessary. The faster data rates are useful if peak profile information is required rather than an average or maximum data point over a longer data acquisition period.

All of the multi-gas analyzers were evaluated for their user interface characteristics including instruction manuals, screen display, and overall ease of use. The instruction manuals for the AIM 4501, Biosystems PhD Ultra, Gastech STM 2100, and RAE MultiRAE units were all well written and included numerous examples and flowcharts to assist the user in proper operation of the analyzers. In comparison, the National Draeger Multiwarn II manual was not as easy to follow and did not include as much user help in the form of flowcharts and examples. The user manuals for RKI, Crowcon, ENMET, and Metrosonics analyzers were adequate.

The screen display for the RKI Eagle was the largest in physical size, and the bright characters were easily read from a distance of 2 to 3 ft. Concentration and sensor identification are contained on one line for both the RKI and National Draeger analyzers. Most other vendors place this information on two separate lines. The AIM single-sensor displays have an added feature that illuminates a sensor if an alarm condition exists and makes it easy for the user to identify. All other vendors have the sensor information on one screen and employ "flashing sensor" information to indicate an alarm condition. The screen display for the Metrosonics is quite small and difficult to read unless it is approximately 1 ft from a user.

The menu structure of the National Draeger Multiwarn II makes it very easy to access all of the available user functions. Operations that are repeated often, such as fresh air zeroing, automatic display of STEL, TWA, alarm and battery lifetime values, can be placed on a top-level menu and easily chosen through activation of a single button. Secondary menus are easily accessible and the scrolling properties of each menu make finding a user function simple. The RKI Eagle user menus, like the Multiwarn II, are displayed on a single screen and include easy to follow prompts. Although access to many of the user functions of both the AIM 4501 and RAE MultiRAE are "button intensive" the sequences required are well documented in the user manuals. The user functions available when operating the Gastech STM 2100 are accessible by means of a set of buttons located behind an access panel on the side of the analyzer. The user functions are quite extensive, but simultaneously using these buttons while viewing the front panel is difficult. The user functions for the ENMET, Biosystems, Crowcon, and Metrosonics analyzers are much more extensive, both in scope and use, when compared to other vendors.

RECOMMENDATIONS FOR FIELD TESTING

The following instrument features were evaluated and used to rank each vendor in order to choose the top three analyzers for further field testing: (1) Linearity/Repeatability, (2) Zero Drift, (3) Span Drift, (4) Sensor Response, (5) User Interface, (6) Software, and (7) Maintenance. An individual ranking was assigned to each one of these features along with a corresponding vendor ranking for each selected feature. The product of the feature ranking and vendor ranking intercompares each vendor. Both the feature and vendor ranking range from a low of 1 to a high of 7. The linearity/repeatability feature was ranked highest since end-users are most interested in whether an analyzer is correctly quantifying vapors. The zero drift feature was judged to be next in importance to assist in preventing false positives due to sensor drift. The sensor response time was ranked as third in importance since worker safety depends how quickly a sensor responds to potential hazardous vapors. The overall rankings for each vendor are summarized in table 6. Based on the laboratory results presented in table 6, the ENMET OMNI 4000, National Draeger Multiwarn II, and AIM 4501 were recommended for further field testing. The data presented in table 7 intercompares the laboratory results obtained for AIM, National Draeger, and ENMET for each of the four sensors that were tested (NO_2, O_2, H_2, and NH_3)

Table 6. Overall Vendor Ranking

Feature (Rank)	National Draeger	AIM	ENMET	RKI	Biosystems	Crowcon	RAE	Gastech	Metrosonics
Linearity/Repeatability (7)	9	8	7	2	3	5	4	1	6
Zero Drift (6)	7	8	6	9	4	5	2	3	1
Sensor Response (5)	8	7	9	6	4	5	3	2	1
User Interface (4)	7	9	3	8	4	2	5	6	1
Maintenance (3)	5	4	7	3	8	2	6	9	1
Software (2)	9	1	3	2	8	5	6	7	4
Span Drift (1)	8	9	5	7	3	6	2	5	1
TOTALS	214	198	174	150	124	120	107	105	69

Table 7. Lab Evaluation Summary

Sensor	Range Tested	Range Claimed by Vendor	Observed Repeatability	Observed Response Time (90 % FS)
NO_2	0 to 20 ppm	0 to 20 ppm	± 5 percent of reading or ± 0.2 ppm (whichever is greater)	< 1 minute
NH_3	0 to 25 ppm	D 0 to 300 ppm A 0 to 250 ppm E 0 to 100 ppm	D ± 5 ppm A ± 2 ppm E ± 2 ppm	< 150 seconds
O_2	18 to 21 percent	17 to 25 percent	D ± 0.2 percent A ± 0.4 percent E ± 0.6 percent	<1 min
H_2	0 to 25 percent LEL	0 to 25 percent LEL	± 3 percent of reading or ± 0.3 percent (whichever is greater)	< 1 min

Notes: 1. D = National Draeger, A = AIM, E = Enmet

FIELD EVALUATION TESTS

INTRODUCTION

The purpose of testing several multi-gas analyzers in the field was to obtain user feedback under normal operating conditions. Prior to releasing analyzers for field testing, all of the sensors were recalibrated and checked for their basic response. Additionally, all data was downloaded and processed prior to clearing the data memory for each analyzer. Finally, a separate procedure was written for each vendor detailing the steps needed to perform basic operations such as turning the analyzer ON or OFF, initiating a fresh air zero, and battery charging. Features, such as changing of any calibration parameters, alarm settings, or other maintenance items of all of the multi-gas analyzers were locked out through the use of security codes.

User feedback on the operation of the ENMET, AIM, and National Draeger multi-gas analyzers was obtained from four separate groups: (1) USA Safety Orbiter Processing Facility (OPF), (2) Launch Pad A Safety, (3) Wiltech Calibration Facility, and (4) EG&G Environmental Health. Operation of the analyzers was explained to each of these groups. Both the OPF and Pad A groups were given first priority in terms of using the analyzers. As they became available, analyzers were given to Wiltech and EG&G for additional testing and evaluation.

SUMMARY

The ENMET OMNI 4000 was discarded from consideration early in the field testing due to the potential for leaving the external sample pump de-energized. This pump must be manually turned on by an operator. In comparison, the software for the AIM 4501 can be configured to automatically turn on the sample pump when power is applied to the analyzer. The sample pump for the National Draeger Multiwarn II analyzer is activated automatically if a pump mode attachment is in place. Personnel evaluating the National Draeger analyzer felt that proper use of the pump mode attachment would not be a problem.

The backlight capabilities of the Multiwarn II analyzer are cumbersome since one of the small front panel buttons must be depressed in order to activate the backlight. Once activated, the screen only stays illuminated for 15 seconds. In comparison, the AIM 4501 automatically backlights the display for any sensor if an alarm condition exists. The AIM 4501 analyzer can also be configured to continuously backlight all sensors. This feature would be advantageous during night landings at the Shuttle Landing Facility (SLF).

Each sensor for the AIM 4501 has an individual large display which can easily be read beyond the 3-ft minimum desired by end-users. A brightly colored name plate above the sensor display identifies the sensor. In comparison, all of the sensor outputs on the National Draeger Multiwarn II are displayed on one screen. This display does not lend itself to ease of visual use by operators.

RECOMMENDATION

Based on the results from laboratory testing and field evaluations it is recommended that the AIM 4501 be used for USA/NASA Safety confined space and Shuttle safing operations. During laboratory testing both the AIM and National Draeger analyzers were comparable in linearity/repeatability, zero drift and span drift characteristics. Although the data analysis software package for the National Draeger Multiwarn II is superior to that of the AIM 4501, end users felt that this was not a major drawback and that the AIM analyzer was more suited for field use.

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