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Performance of Off-the-Shelf Technologies for Spacecraft Cabin Atmospheric Major Constituent Monitoring

J.D. Tatara
Qualis Corporation, Huntsville, Alabama

J.L. Perry
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

October 2004

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National Aeronautics and
Space Administration

Marshall Space Flight Center • MSFC, Alabama 35812

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LIST OF ACRONYMS AND SYMBOLS

c	common
CO_2	carbon dioxide
ECLS	environmental control and life support
GE	General Eastern
H_2O	water
ISS	*International Space Station*
MCA	major constituent analyzer
N_2	nitrogen
O_2	oxygen
SAMe	spacecraft atmospheric monitor-experimental

TECHNICAL MEMORANDUM

PERFORMANCE OF OFF-THE-SHELF TECHNOLOGIES FOR SPACECRAFT CABIN ATMOSPHERIC MAJOR CONSTITUENT MONITORING

1. INTRODUCTION

Monitoring the atmospheric composition of a crewed spacecraft cabin is central to successfully expanding the breadth and depth of first-hand human knowledge and understanding of space. Highly reliable technologies must be identified and developed to monitor atmospheric composition. This will enable crewed space missions that last weeks, months, and eventually years. Atmospheric composition monitoring is a primary component of any environmental control and life support (ECLS) system.[1–3] Instrumentation employed to monitor atmospheric composition must be inexpensive, simple, lightweight, and provide robust performance. Such a system will ensure an environment that promotes human safety and health and that can be maintained with a high degree of confidence. Key to this confidence is the capability for any technology to operate autonomously, with little intervention from the crew or mission control personnel. A study has been conducted using technologies that, with further development, may reach these goals.

Integrated testing was conducted to demonstrate the capability of simple, inexpensive, off-the-shelf instruments to control the composition of a simulated spacecraft cabin atmosphere. Long-duration testing results providing insight into the logistical support required for the instruments under evaluation are also presented. The results build a case for evaluating other off-the-shelf monitoring devices for a variety of spacecraft cabin atmospheric quality monitoring purposes.

2. BACKGROUND

Successfully controlling the atmospheric composition of a crew spacecraft cabin requires robust monitoring technologies. Control and monitoring are dependent on each other. Without reliable instruments to monitor atmospheric composition, controlling that composition cannot be done reliably. As mission duration and complexity increase, the need for reliable monitoring instrumentation becomes more important. Operational autonomy also becomes important as the focus of exploration moves beyond low-Earth orbit.

Spacecraft cabin atmospheric composition monitoring can be divided into two distinct classifications—major atmospheric constituents and trace chemical contaminants. Major constituents include nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), and water (H_2O) vapor, which are typically monitored continuously. Trace chemical contaminants are produced from a variety of sources including equipment offgassing, human metabolism, and myriad onboard operations.[4] These contaminants, if not maintained at low concentrations, can contribute to symptoms associated with sick building syndrome. Studies on sick building syndrome have indicated that a total nonmethane volatile organic compound concentration of 25 mg/m^3 may cause symptoms under certain conditions.[5–7] Analysis of samples collected from crewed spacecraft has reported compounds representing the hydrocarbon, alcohol, aldehyde, ester, ether, aromatic, ketone, organosilicone, and halocarbon functional classes.[8] In addition, inorganic trace contaminants, such as ammonia, carbon monoxide, and hydrogen, are present. Methane accounts for the largest proportion of the typical trace contaminant loading followed by alcohols, hydrogen, organosilicone compounds, and carbon monoxide. In all, these contaminants have accounted for 97 percent of the total trace contaminant concentration in previously monitored space flights. Monitoring trace chemical contaminants is accomplished via a combination of nearly real-time monitors deployed on board the spacecraft and postflight analysis of archive samples collected during the mission.[9] In combination with monitoring cabin pressure and the operation of assorted environmental control equipment that conditions the cabin atmosphere by maintaining a comfortable temperature and removing carbon dioxide, trace contaminants, and excess water vapor, a healthy environment can be maintained for any mission architecture.

2.1 Technological Approach Employed by Past and Present Crewed Spacecraft Programs

The technological solutions employed by NASA to monitor atmospheric major constituents vary according to the spacecraft architecture and mission design. The atmosphere for the earliest crewed spacecraft, Mercury and Gemini, consisted of 100-percent oxygen maintained at a pressure of 34.5 kPa (5 psia). Cabin pressure and carbon dioxide concentration were the most critical parameters to monitor. The Apollo cabin differed from Mercury and Gemini by using a two-gas atmosphere during launch. In this mission phase, the atmospheric composition and pressure were maintained at 60-percent oxygen with the balance nitrogen at 103 kPa (15 psia). During flight, the cabin pressure was allowed to decay to 34.5 kPa. Because oxygen was used as the primary breathing gas, and to compensate for overboard leakage, the atmospheric composition converged on 100-percent oxygen. As with the Mercury and Gemini spacecraft, cabin pressure and carbon dioxide concentration were the primary atmospheric parameters monitored.[9,10]

Beyond basic atmospheric composition monitoring, a gas chromatograph was included in some Apollo Block I spacecraft. It was flown for flight qualification purposes and provided data on 28 trace chemical compounds. The unit consisted of three separate capillary columns and associated detectors. Helium carrier gas stored at 41.4 MPa (6,000 psia) was supplied to the gas chromatograph at 290 kPa (42 psia). Each capillary column/detector set targeted specific chemical compounds. One was used to identify nitrogen, oxygen, carbon monoxide, hydrogen, and methane. Ammonia, carbon dioxide, and water vapor were identified by a second capillary column and detector set. The third capillary column and detector set was used to identify 20 trace chemical contaminants. Sampling and analysis time was 80 min, and samples could be collected from three locations.[10]

Skylab employed a two-gas atmosphere at 34.5 kPa (5 psia). Oxygen partial pressure was maintained at ≈24.8 kPa (3.6 psia) or 72 percent by volume. Nitrogen was used to maintain the cabin's total pressure. The primary atmospheric composition parameters monitored were oxygen partial pressure, carbon dioxide concentration, and total pressure. Redundant oxygen partial pressure control circuits consisting of an oxygen sensor, amplifier, and controller were used to maintain the atmospheric composition. A sensor incorporated into the carbon dioxide removal system monitored the atmospheric carbon dioxide concentration. This sensor was the primary means for monitoring carbon dioxide concentration. A portable carbon dioxide and dewpoint monitor was provided but failed. *Skylab's* experimental payload complement included a mass spectrometer used periodically for evaluating human performance in space. The data from cabin atmospheric samples collected before the crew conducted the experiment were manually transmitted to the ground; the oxygen, carbon dioxide, and water vapor partial pressures were calculated based on the cabin's total pressure. The mass spectrometer was operated only on a periodic basis but did serve to provide a check for the primary oxygen and carbon dioxide sensors. It was used to calibrate the carbon dioxide sensors throughout the series of *Skylab* missions.[10]

The Space Shuttle built upon the use of a two-gas atmosphere by maintaining a more Earth-like condition. The cabin total pressure is maintained at 101 kPa (14.7 psia) with the oxygen and nitrogen partial pressures maintained at 21 percent and 79 percent, respectively. Sensors for monitoring oxygen, carbon dioxide, and cabin total pressure are included. In many respects, the Space Shuttle's atmospheric composition monitoring and control were refinements of the previous crewed spacecraft programs. Trace contaminants are monitored via archival samples that are collected during flight and then analyzed on the ground.[10,11]

The *International Space Station* (*ISS*) also maintains the cabin total pressure at 101 kPa. Like the Space Shuttle, oxygen and nitrogen partial pressures are maintained at ≈21 and ≈79 percent, respectively. Cabin atmospheric composition is monitored using a mass spectrometer. This unit, called the major constituent analyzer (MCA), monitors six atmospheric gases—nitrogen, oxygen, carbon dioxide, methane, hydrogen, and water vapor.[12–15] While the MCA is derived from the U.S. Navy's Central Atmospheric Monitoring System used on board nuclear submarines,[16,17] in many respects it also incorporates features from the Apollo Block I gas chromatograph unit and *Skylab's* mass spectrometer unit. Similar to the Apollo Block I gas chromatograph, stainless steel sample lines extend from the MCA, allowing samples to be collected from various locations within the cabin. The atmospheric gases monitored, however, are similar to those measured by *Skylab's* mass spectrometer.

On board *ISS*, the oxygen partial pressure signal from the MCA is used along with the cabin total pressure measurement to maintain the atmospheric composition. Russian-provided gas monitoring equipment also monitors oxygen, carbon dioxide, and water vapor concentrations. These primary monitors are supplemented by a variety of portable monitors for measuring carbon dioxide, oxygen, carbon monoxide, combustion products, and dewpoint. Many of these portable monitors are commercial off-the-shelf devices modified for spacecraft application.[18,19]

Trace chemical contaminants are monitored via the same archival methods used for the Space Shuttle program. An experimental instrument for monitoring selected trace chemical contaminants in flight has been deployed on board *ISS*; however, it has met with limited success.[20] Likewise, performance issues associated with control and ion pump life limits have restricted the MCA's use. This has resulted in *ISS* cabin atmospheric composition being controlled/managed by redundant instruments.[21]

2.2 Evaluation of Alternate Atmospheric Composition Monitoring Technologies

Since the earliest crewed space exploration missions, NASA has seen a need for monitoring a spacecraft cabin's major atmospheric constituents. For the *ISS* program, these constituents include nitrogen, oxygen, carbon dioxide, methane, hydrogen, and water vapor. Early space exploration programs developed long life electrochemical sensors to monitor oxygen and carbon dioxide partial pressures. However, with increasing exploration mission duration and a desire for long sensor life in reusable craft, a need for simple, reliable, atmospheric composition monitors has emerged.

Building from past experience in crewed space exploration and similar experience gained by the U.S. Navy from its nuclear submarine program, mass spectroscopy was selected for use on board *ISS*. This selection, however, necessitated developing a robust mass spectrometer that could operate autonomously and continuously with minimal logistical needs, and withstand the rigors of launch while being simple to use. Experience with prototype and flight versions of the MCA has been varied. When functioning properly, the units provide good control. However, problems attributed to microgravity on board *ISS*, such as maintenance difficulty with the prototype unit and specifically ion pump life sensitivities, make mass spectrometry a less desirable option for extended space exploration.

Although the selection of technology and equipment design are not trivial tasks, some have discounted the challenge presented by atmospheric monitoring and concluded that it can be ignored when evaluating a mission design concept.[22] From experience, such an approach is a mistake, and atmospheric monitoring must be based on well-defined specifications and included as a major part of system design trade studies.

Defining the challenge's scope is the first step. By evaluating the historical aspects of spacecraft cabin atmosphere monitoring and control, it becomes apparent that a limited number of the major atmosphere constituents can be monitored while still providing adequate data indicative of spacecraft health. From this evaluation, only oxygen, carbon dioxide, and water vapor must be monitored, though this represents the minimum compounds necessary for control. This refined major atmospheric constituent monitoring requirement is amenable to applying simple technological solutions, making inexpensive industrial monitors attractive. Therefore, an effort has been undertaken to investigate off-the-shelf monitoring technologies that, with slight modification and certification, may be acceptable for use on board crewed spacecraft. When supplemented by targeted trace chemical contaminant monitoring, and combined with atmospheric conditioning and cabin total pressure monitoring and control, the simplified major atmospheric composition monitor can meet the performance requirements for crewed space exploration.

Numerous off-the-shelf environmental instruments and gas-detection technologies were considered via a literature search and industrial product review, thereby providing the data necessary to choose the test articles. Key considerations of this search were size, weight, minimal need for expendables, and stable, repeatable performance. To simplify and bound the search, performance reference standards were set for the three analyses. Instruments considered the "gold standard" for each analysis were defined as paramagnetic analysis for oxygen monitoring, infrared spectrometry for carbon dioxide monitoring, and chilled mirror detection for water vapor measurement.

It was very likely that an infrared spectrometer for carbon dioxide monitoring could be found; however, the paramagnetic and chilled mirror monitors possess characteristics and limitations that make them undesirable for use on board crewed spacecraft. The paramagnetic analyzers are delicate and very sensitive to vibration. For this reason, they would not survive the launch vibration loads. The chilled mirror water vapor analyzers suffer from significant maintenance requirements associated with dirt buildup on the mirror, and mirror chamber flooding. Also, microgravity considerations associated with nucleate condensation further limited the utility of chilled mirror water vapor measurement. Existing monitoring techniques presently used on board the Shuttle were considered; however, these are electrochemical sensors that have limitations associated with cross interference and drift. As such, they must be calibrated frequently and tested in a variety of complex environments to ensure specified performance.

Three detection technologies emerged from the industry review. The technologies chosen include fast diode laser oxygen analysis, solid-state infrared carbon dioxide detection, and thin-film capacitive detection for water vapor. These technologies were chosen due to their robust performance, size/weight, reported low maintenance needs, and low cost versus competing technologies.

3. TECHNOLOGY PERFORMANCE EVALUATION

Two separate tests were conducted to evaluate the integrated operational and long duration performance of the selected off-the-shelf analyzers. As an integrated assembly, the test article was known as the spacecraft atmospheric monitor-experimental (SAMe). The first test was an integrated operations test to evaluate SAMe versus reference instrumentation and/or standards. The data collected suggested that further studies or extended duration tests were appropriate. The second test was an extended duration test to evaluate the technologies' stability. Results from this testing can be used to define maintenance schedules for flight or other monitoring applications.

3.1 Integrated Operations Test

In the test, the three analytical units were integrated into a single system, and their ability to control the atmospheric composition in a sealed spacecraft cabin simulator was demonstrated. The test bed includes an oxygen injection assembly, a carbon dioxide removal assembly, humidity injection and removal assemblies, and a pressure regulation assembly.[23] The three gas analysis units, serving as test articles, were configured in series. A simple diaphragm sample pump in the oxygen analyzer provided atmospheric samples to all three units. The test articles, from bottom to top as seen in figure 1, are a Sable Systems International, Inc., infrared carbon dioxide analyzer, an Oxigraf, Inc., laser diode oxygen analyzer, and a Sable Systems International, Inc., thin film conductance dewpoint sensor. Each unit was periodically checked for stability and overall operability.

3.2 Endurance Test

During endurance testing, the three test articles were checked for stability and life in a simple test rig. The units were configured as described for the integrated operations test described in section 3.1 and shown in figure 1. Each unit was checked periodically for stability versus reference standards or certified reference hardware.

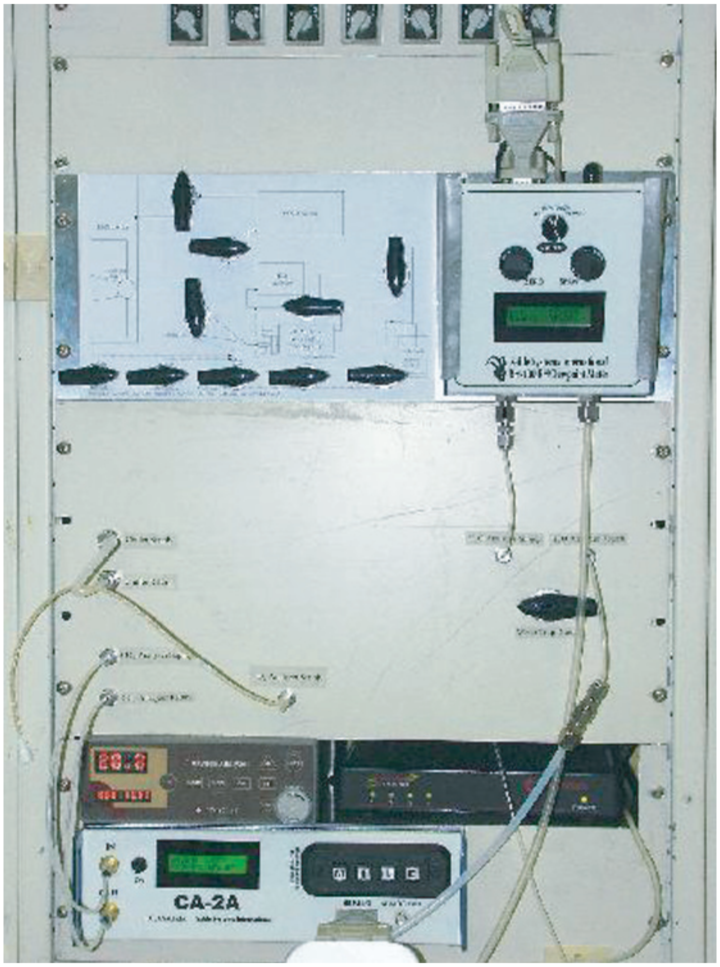


Figure 1. SAMe test rig.

4. TEST ARTICLE CONFIGURATION

A test rig was designed in which the oxygen analyzer, carbon dioxide analyzer, and dewpoint meter are configured in series with a certified reference dewpoint sensor. A manifold assembly allows for the injection of standard gases into each instrument or for the collection of ambient air. Figure 2 shows a diagram of the assembly. The instruments chosen for the test were selected based on perceived ruggedness, ease of use, quoted stability, and price.

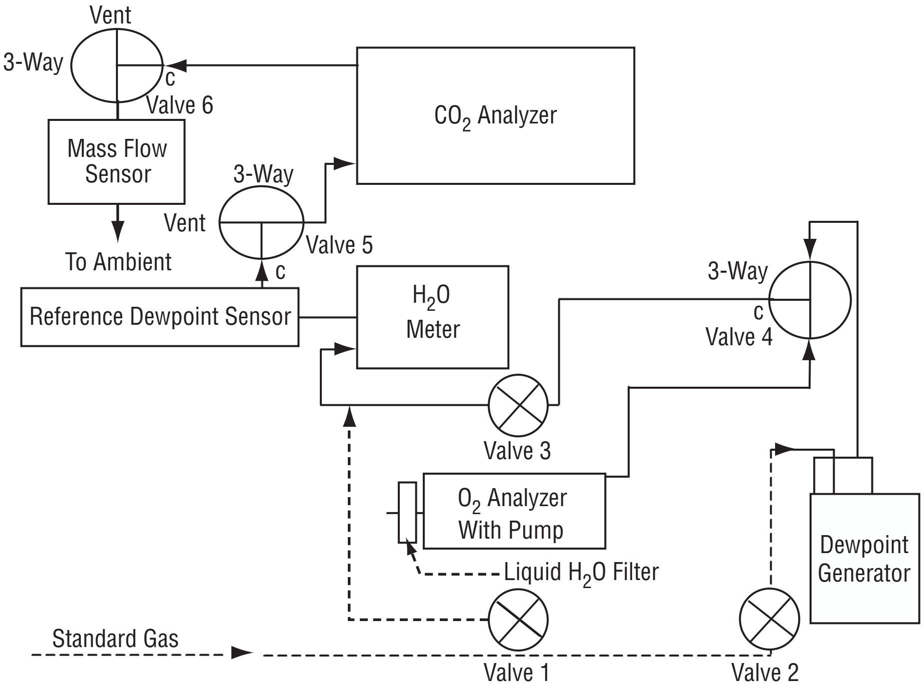


Figure 2. Test configuration line drawing (simplified).

4.1 Oxigraf Model O2 Oxygen Analyzer

The Oxigraf model O2 oxygen analyzer (fig. 3) is an oxygen sensor utilizing solid-state laser diode absorption for the detection of oxygen at concentrations ranging from 0.01 to 100 percent. To remove any aqueous water present at the inlet, a sample is drawn through a hydrophobic filter membrane at a constant rate/pressure using an internal pump. The sample then passes through the analysis cell and out the back of the instrument. The analysis is not dependent on ambient pressure since a pressure sensor within the analysis chamber corrects for pressure variability. In addition, the sample is heated to 45 °C prior to analysis to alleviate any problems associated with condensate buildup in the detection cell.[24]

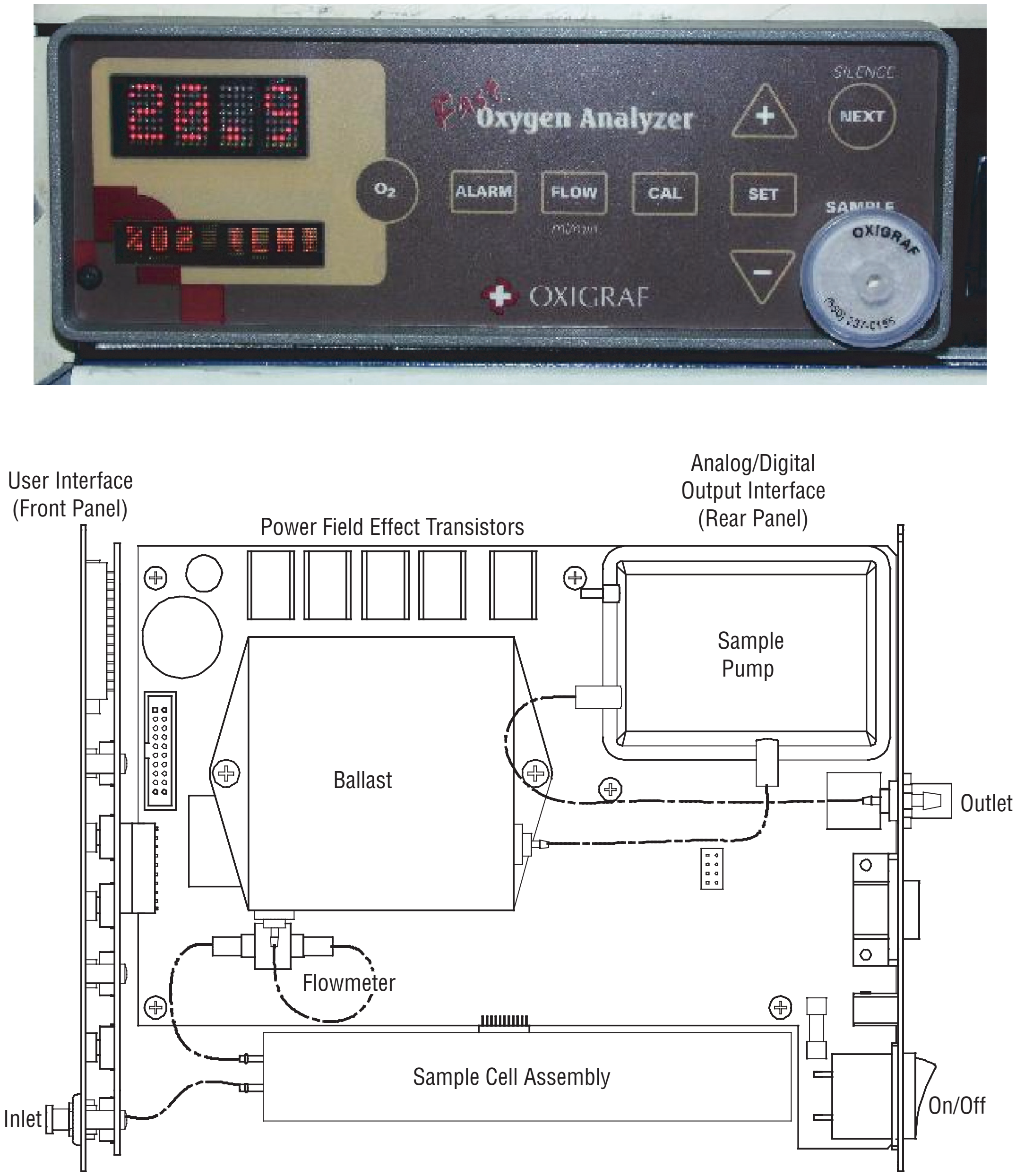


Figure 3. Oxigraf model O2 oxygen analyzer.

The unit does not correct for relative humidity. A typical indoor relative humidity of 50 percent can be expected to yield an error of +0/–1.4 percent at 23 °C. Since this Technical Memorandum covers only life testing of this instrument, since the errors due the humidity are relatively small, and since the fluctu-ations in relative humidity within the test facility are relatively small, no dewpoint adjustments were made to the oxygen determinations.

4.2 Sable Systems Model CA–2A Carbon Dioxide Analyzer

The Sable Systems CA–2A analyzer (fig. 4) is a carbon dioxide sensor utilizing solid-state infrared absorption for the detection of carbon dioxide between 1 ppm and 10 percent. A sample stream is pushed through the unit using an external pump at a constant rate between 100 and 2,000 ppm. The sample then passes through the analysis cell and out the back of the instrument. The analysis is corrected for temperature and pressure variations, and is therefore not affected by changing ambient pressure.[25] The unit is, however, affected by changes in delta pressure from the inlet to the outlet. These pressure changes should not be a problem under normal operating conditions. However, if the outlet pressure changes significantly from that seen during calibration; e.g., if the outlet line is changed in length or some other configuration causes higher back pressure at the outlet, the unit must be recalibrated at the new outlet pressure. The infrared cell has a stated life of 40,000 hr.

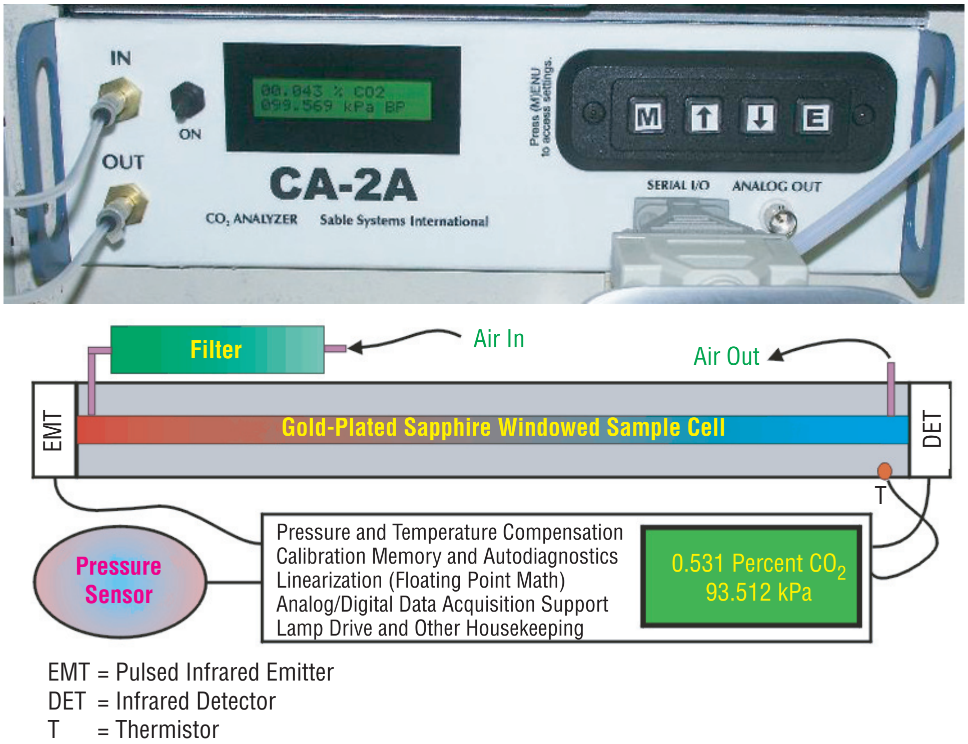


Figure 4. Sable Systems model CA–2A carbon dioxide analyzer.

4.3 Sable Systems Model RH–100 Relative Humidity/Dewpoint Meter

The Sable Systems RH–100 meter (fig. 5) is a relative humidity/dewpoint sensor utilizing solid-state, thin-film capacitance detection between 0.01- and 99-percent relative humidity.[26] A sample stream is pushed through the unit using an external pump at a constant rate between 100 and 2,000 ppm. The sample then passes through the analysis cell and out the back of the instrument. The analysis is temperature corrected and is not affected by ambient pressure variations.

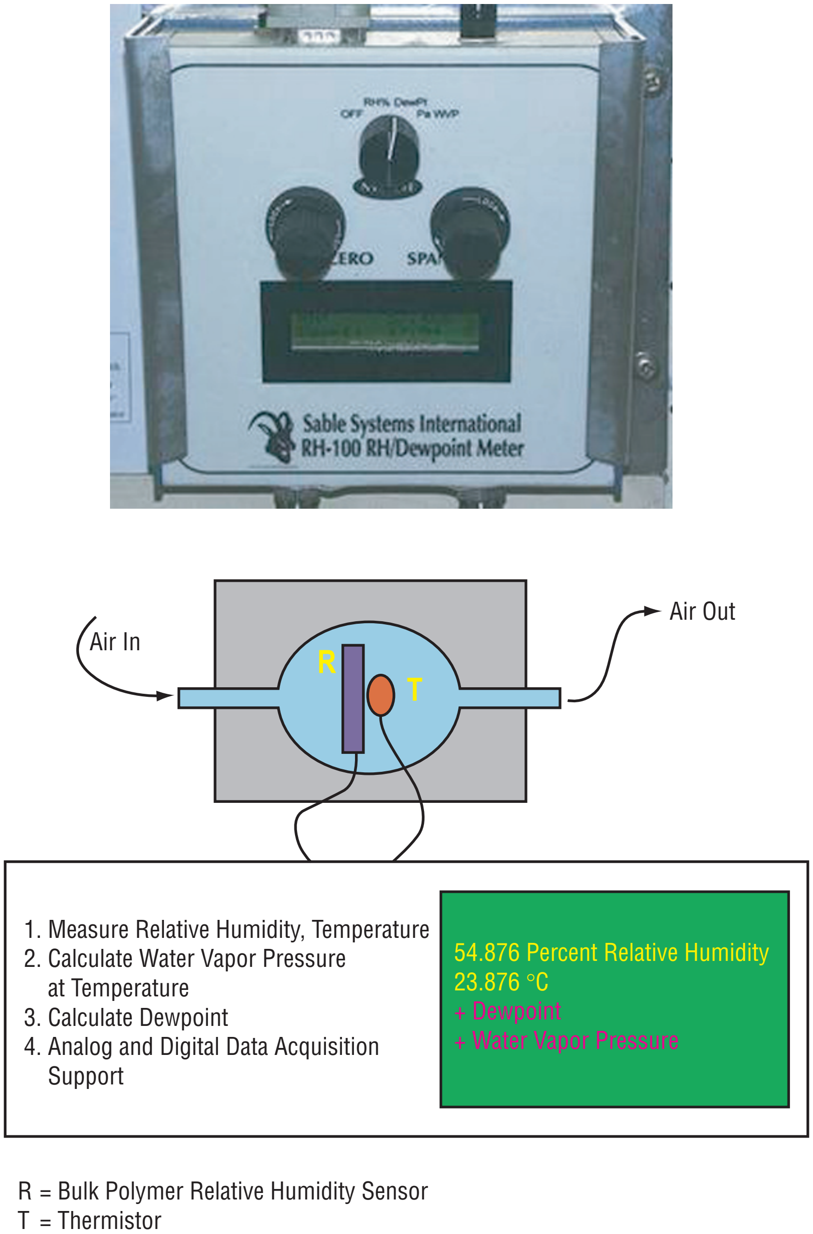


Figure 5. Sable Systems model RH–100 relative humidity/dewpoint meter.

4.4 Integrated Valve Manifold Assembly

Also part of the test bed is the integrated valve manifold assembly (fig. 6). The valve assembly allows for a range of flow setups and for simultaneous configuration with up to six standards or test gases. In addition, the system can be configured to sample directly from a closed environment test chamber if necessary. During calibration, the oxygen analyzer must be isolated from the other units in order to avoid backflow into the oxygen detection sensor and unwanted high pressure within the sensor box. This is also accomplished with the valve assembly.

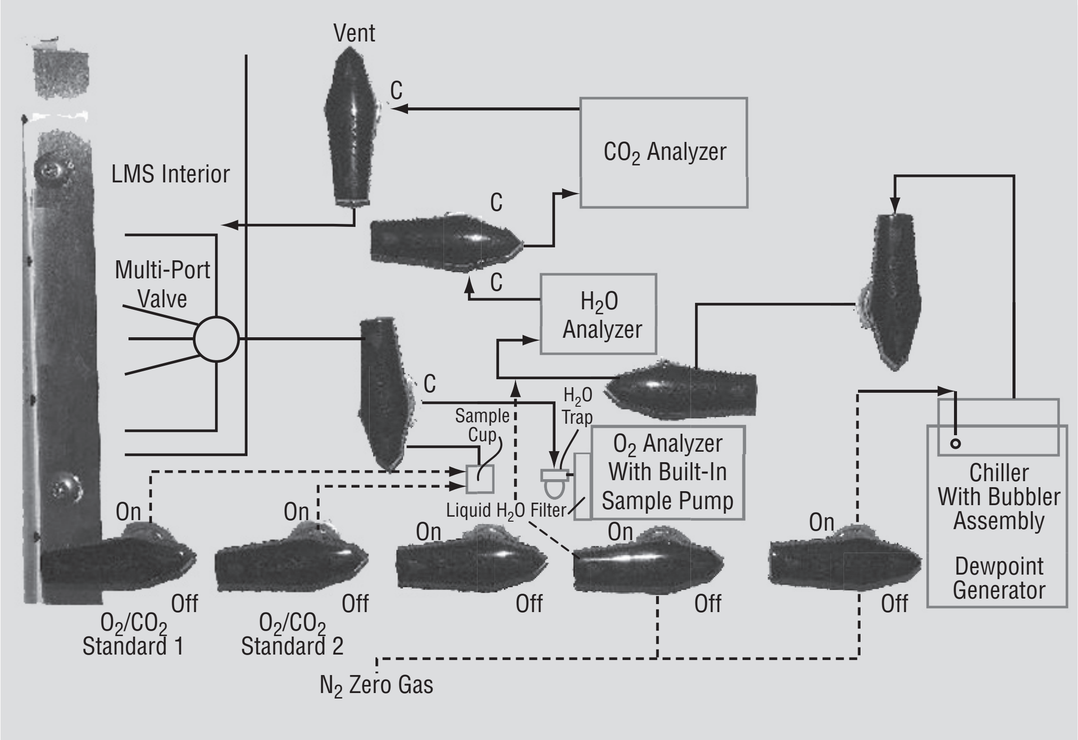


Figure 6. SAMe valve assembly.

5. TEST OPERATIONS SUMMARY

5.1 Integrated Operations Test

The purpose of the integrated operations test is to determine if the instruments that comprise the SAMe are capable of controlling a closed environment maintenance system. The units involved in the testing include the Oxigraf model O2 oxygen analyzer, Sable Systems CA–2A carbon dioxide analyzer, and Sable Systems RH–100 dewpoint/relative humidity meter discussed in sections 4.1–4.3. The test was run for a sufficient period for the oxygen injection to be triggered three times. The chamber doors remained closed during testing, and comparison studies of the oxygen analyzer were carried out following initial testing.

In the test, specific environmental conditions were required to simulate a spacecraft environment. Also summarized in figure 7, the steps taken to accomplish the tasks are as follows:

- Establish initial chamber conditions:

  - Carbon dioxide partial pressure: 0.7±0.3 percent.
  - Total pressure: 133–800 Pa (1–6 mmHg) above prevailing barometric pressure.
  - Nitrogen partial pressure: <80 kPa (<11.6 psia).
  - Oxygen partial pressure: 20.6 percent (20.9 kPa or 3.03 psia).

- Activate oxygen concentrator:

  - Oxygen consumption rate: 0.83 kg/day×6 crewman=5.01 kg/day or 0.21 kg/hr.
  - Oxygen partial pressure to be maintained at 20–20.6 percent (20.3–20.9 kPa); oxygen in bleed should be triggered at 20 percent and shut off at 20.6 percent.

- Data requirements:

  - Carbon dioxide partial pressure: Sable Systems CA–2A instrument.
  - Oxygen partial pressure: Oxigraf model O2 instrument.
  - Chamber dewpoint: Sable Systems model RH–100 instrument.
  - Chamber total pressure.
  - Chamber temperature.

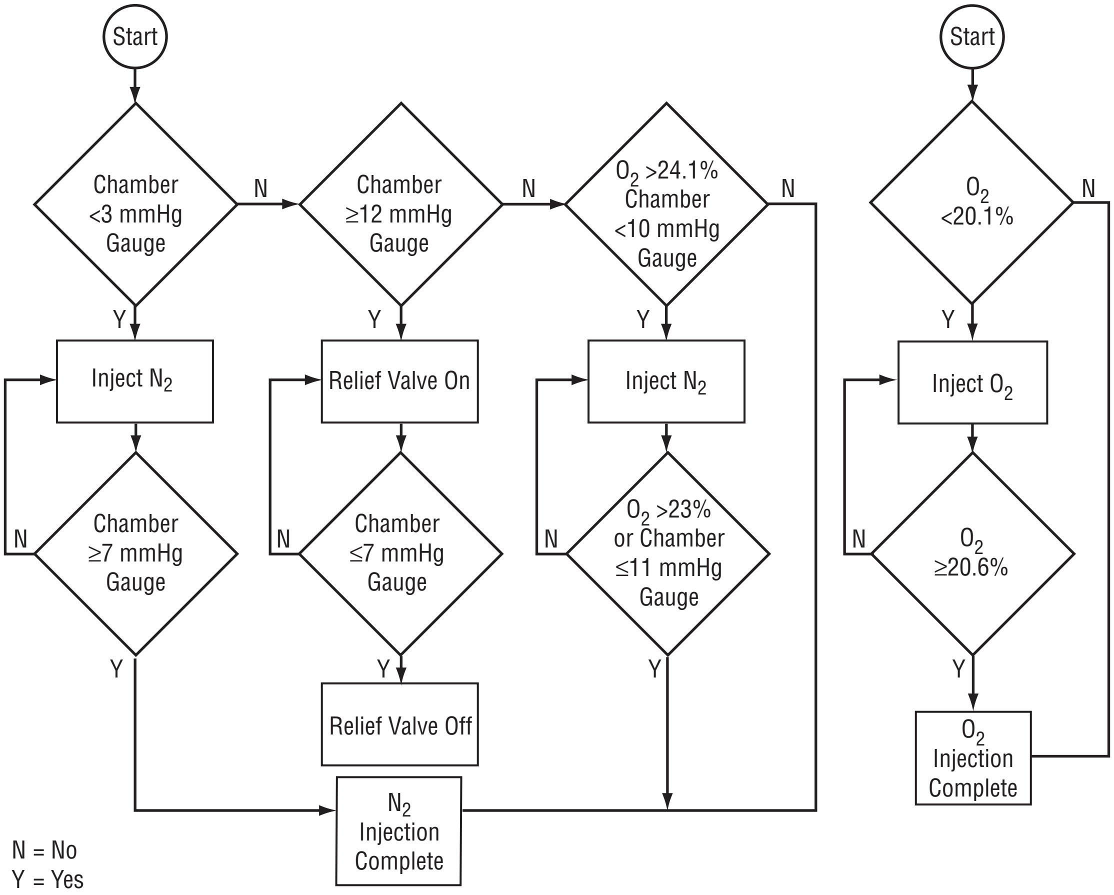


Figure 7. Total pressure and oxygen partial pressure logic control.

5.2 Life Test

The SAMe life test is set up as a life and stability test of the three instruments comprising the SAMe. Checkouts are performed at intervals ranging from 1 to 4 wk. Each instrument is checked individually for drift from the last calibration, and general operability—error codes, malfunctions, failures, etc.

In the test, the oxygen analyzer is compared to air conditioned high bay test facility ambient air at an assumed oxygen concentration of 20.9 percent. Due to the large size of the test facility and the relatively stable humidity in the facility, standard bottled gases are not necessary. During a standard checkout, the display value is recorded and the unit is then recalibrated if necessary to 20.9 percent with high bay air.

The carbon dioxide analyzer is checked for zero (baseline) and span drift. The baseline is checked with zero gas (dry nitrogen) and the span is checked with a standard comprised of 0.5-percent carbon dioxide in air. The variations from the previous calibration are recorded and a calibration is then performed if necessary.

The dewpoint analyzer is checked for zero (baseline) and span drift. The baseline is checked with zero gas (dry nitrogen). The span is checked versus a calibrated and certified reference chilled mirror dewpoint sensor. Since no standardized dewpoint generator is available for testing, this was deemed the best alternative for achieving reliable results. For a portion of the test, the span was checked using a chilled water bubbler assembly and dry nitrogen and analyzed with the chilled mirror dewpoint sensor as the span standard. Later in the test, ambient air was used for adjustment of the span, again versus the certified chilled mirror sensor. All measurements were conducted at 200 ml/min as measured by a mass flow sensor calibrated for air.

During the checkout, several steps are performed as follows; the data are recorded in table 3 in the appendix:

(1) The inlet filter to the oxygen analyzer is checked for obvious signs of contamination, such as low inlet flow or visible obstruction, and is replaced as necessary.

(2) The oxygen value is checked and the oxygen analyzer is recalibrated with ambient air if necessary.

(3) The dewpoint sensor span value is checked versus the certified chilled mirror sensor. If out of calibration, recalibration is performed in steps (7) and (10).

(4) The oxygen analyzer pump is turned off and the oxygen unit is isolated from the carbon dioxide and dewpoint sensors.

(5) The carbon dioxide analyzer is checked for span using the 0.5-percent standard.

(6) Both the carbon dioxide and the dewpoint sensors are checked for zero drift using dry nitrogen gas.

(7) If calibration is necessary, the carbon dioxide analyzer and/or the dewpoint sensor are zeroed versus the dry nitrogen.

(8) The carbon dioxide analyzer is purged with the standard 0.5-percent span gas and recalibrated.

(9) The entire system is brought back to the operation mode (all units in series), and the pump restarted.

(10) Once the dewpoint stabilizes, the dewpoint span is adjusted, if necessary, versus the certified chilled mirror reading.

6. RESULTS

6.1 Spacecraft Atmosphere Monitor-Experimental Integrated Operations Test

Several different subtests were performed in conjunction with the closed-door test. Figure 8 shows data from and an explanation of the SAMe closed-door checkout.[27] The graph in figure 8 shows two different parts of the test—the original test when the oxygen injection set points were inadvertently set wrong (first third of the graph), and the continuation test once the oxygen injection set points were corrected (last two thirds of graph).

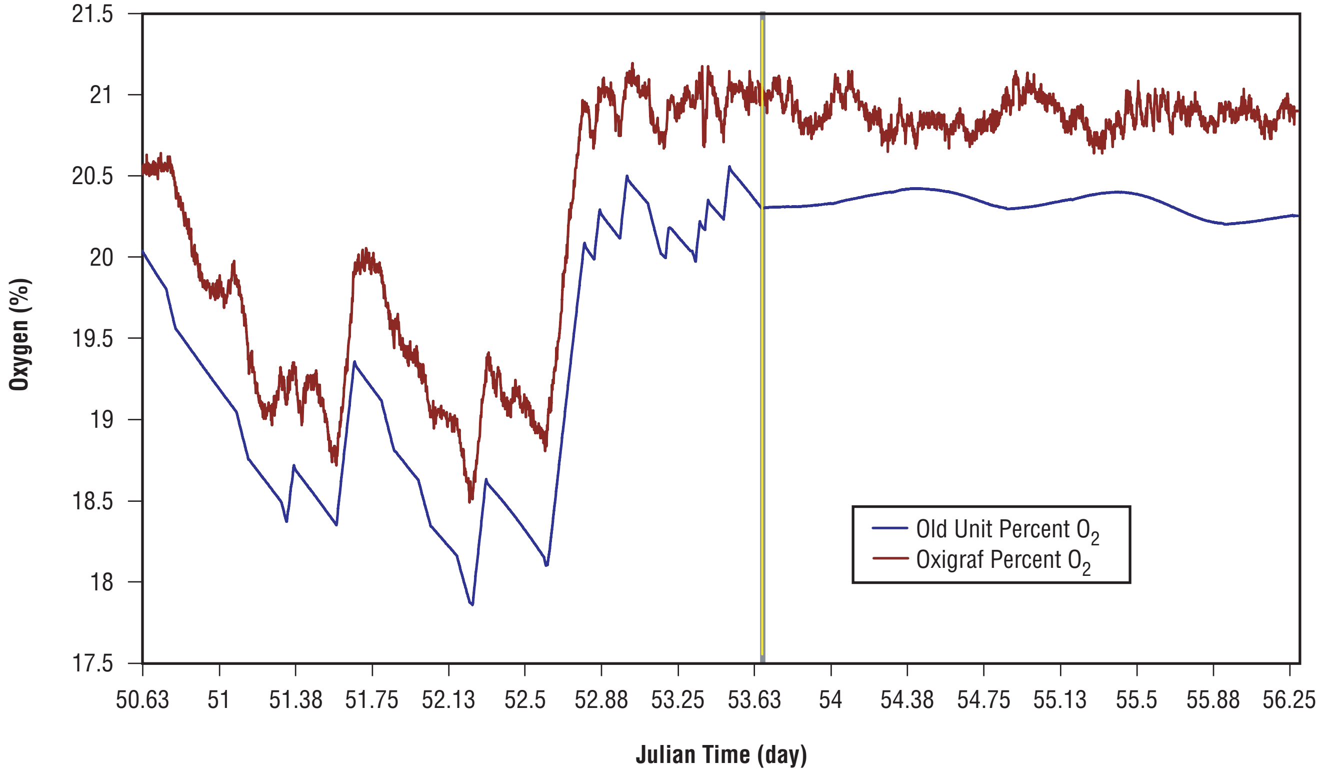


Figure 8. Oxigraf oxygen analyzer (top line) versus uncalibrated paramagnetic analyzer (bottom line).

In the early phase of the test, due to a minor programming error, the high oxygen injection point was ≈1 percent higher than desired and the low set point was ≈1 percent lower. Some unusual things happened, such as hitting the pressure limit before sufficient oxygen could be injected, which required modification to the controller program. The problem was corrected, and a rise in oxygen concentration was then observed, as can be seen in the last two thirds of the graph. Despite the problem, it can be seen that the two oxygen detection units track well. Each point where the oxygen levels abruptly rise is an oxygen injection point. The first test was officially stopped (oxygen, carbon dioxide, and humidity injection) where denoted by the vertical line, but additional data were logged on the stagnant environment to determine how well the two units corresponded. These data show pronounced "noise" in the Oxigraf signal versus the old paramagnetic sensor, but the noise is not great enough to adversely affect the environmental control system.

In this test, the paramagnetic oxygen sensor was not calibrated prior to the test, so actual oxygen concentrations should be ignored. Tracking response was similar, however, and is the basis of the test. The Oxigraf unit is not only noisier than the paramagnetic unit, but also shows some inconsistent tracking versus the paramagnetic unit. Again, the variability is not significant and should not affect the unit's use as an environmental monitor and control sensor.[27]

The graph in figure 9 shows a comparison of the Sable Systems carbon dioxide analyzer and a reference/calibrated Horiba Instruments, Inc., carbon dioxide analyzer. The two units track quite well.[27] It was found during the test that it is important the Sable Systems instrument be calibrated with hard-lined carbon dioxide calibration standard. Calibration was initially carried out by sampling from a purge cup vented to the ambient environment. This lead to inconsistent carbon dioxide values, requiring a modification to the procedure. During the Sable Systems instrument calibration, the pressure of the calibration standard at the monitor inlet should be held between 1 and 5 psig. It has been determined that 2 psig works well with this unit, does not overpressure the system, and provides a steady flow of calibration standard very near the desired 200 mL/min. (Minor adjustments are necessary for exact flow.)

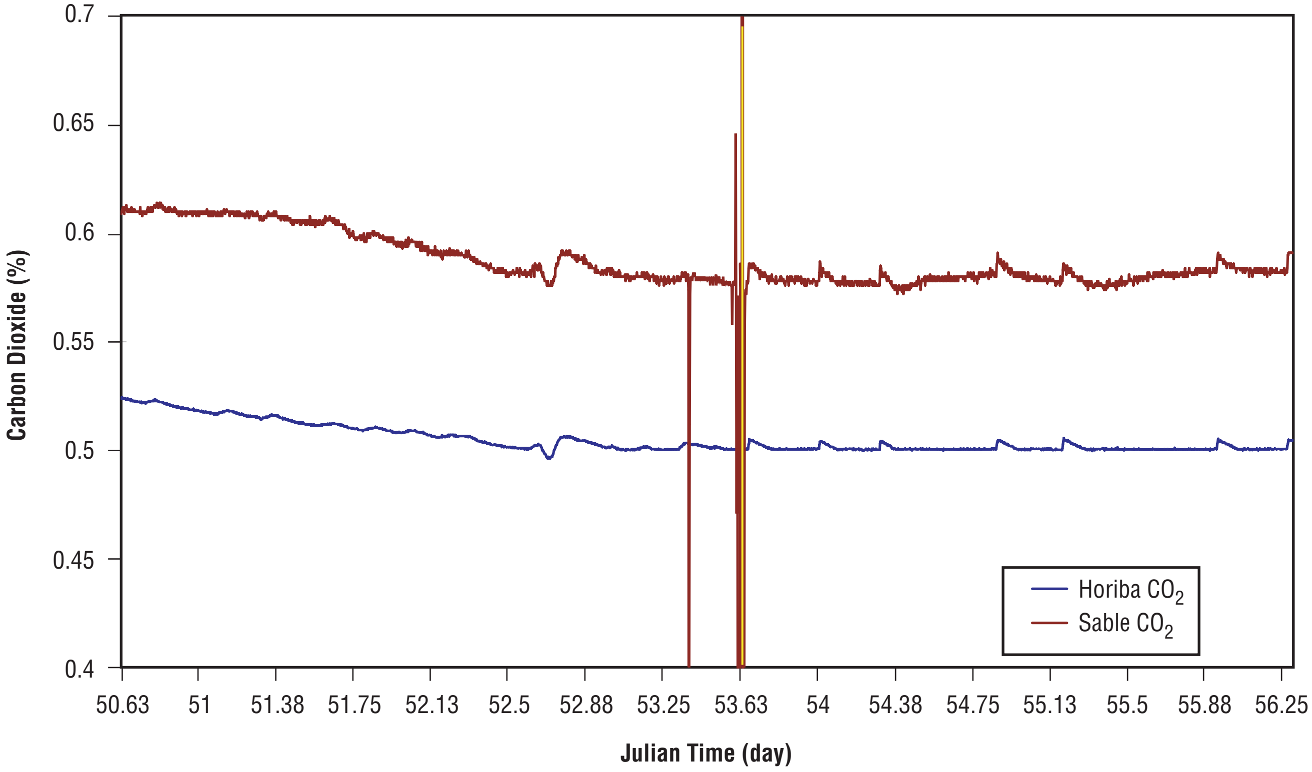


Figure 9. Sable Systems carbon dioxide analyzer versus Horiba Instruments carbon dioxide analyzer.

The graph in figure 10 depicts a follow-on test run with the Oxigraf and the paramagnetic oxygen analyzers. Both units were calibrated prior to this test. As shown in the graph, the instruments are much more closely calibrated than in the first oxygen test and the Oxigraf still shows some signs of variance versus the paramagnetic instrument. There are some unusual data at ≈57.4 days. The cause of this is unknown, but it is very unlikely that the cabin oxygen concentration ever reached 21.5 percent based on pressure monitoring.

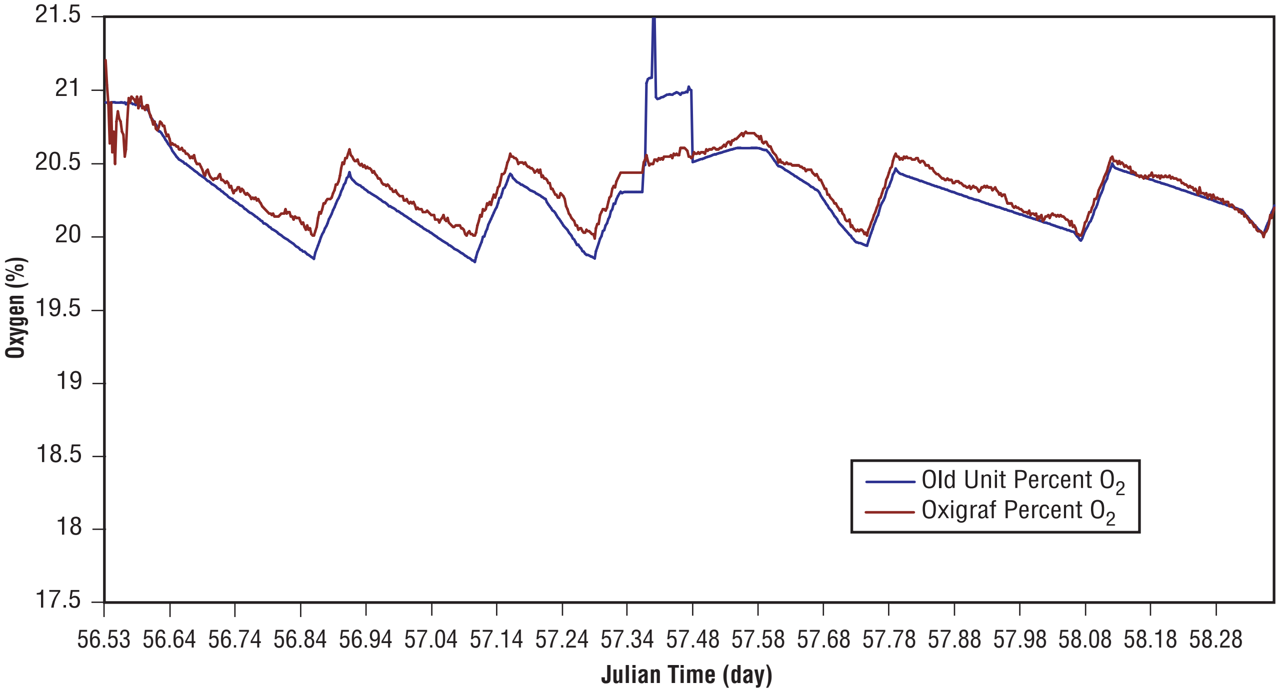


Figure 10. Oxigraf oxygen analyzer versus calibrated paramagnetic analyzer.

The Sable Systems dewpoint meter was calibrated against a certified General Eastern (GE) chilled mirror dewpoint sensor at 15 °C on March 6, 2002. The meter was then checked to see how well it held calibration and corresponded to the reference dewpoint sensor over several days (table 1).

Table 1. Sable Systems dewpoint meter versus GE reference dewpoint sensor.

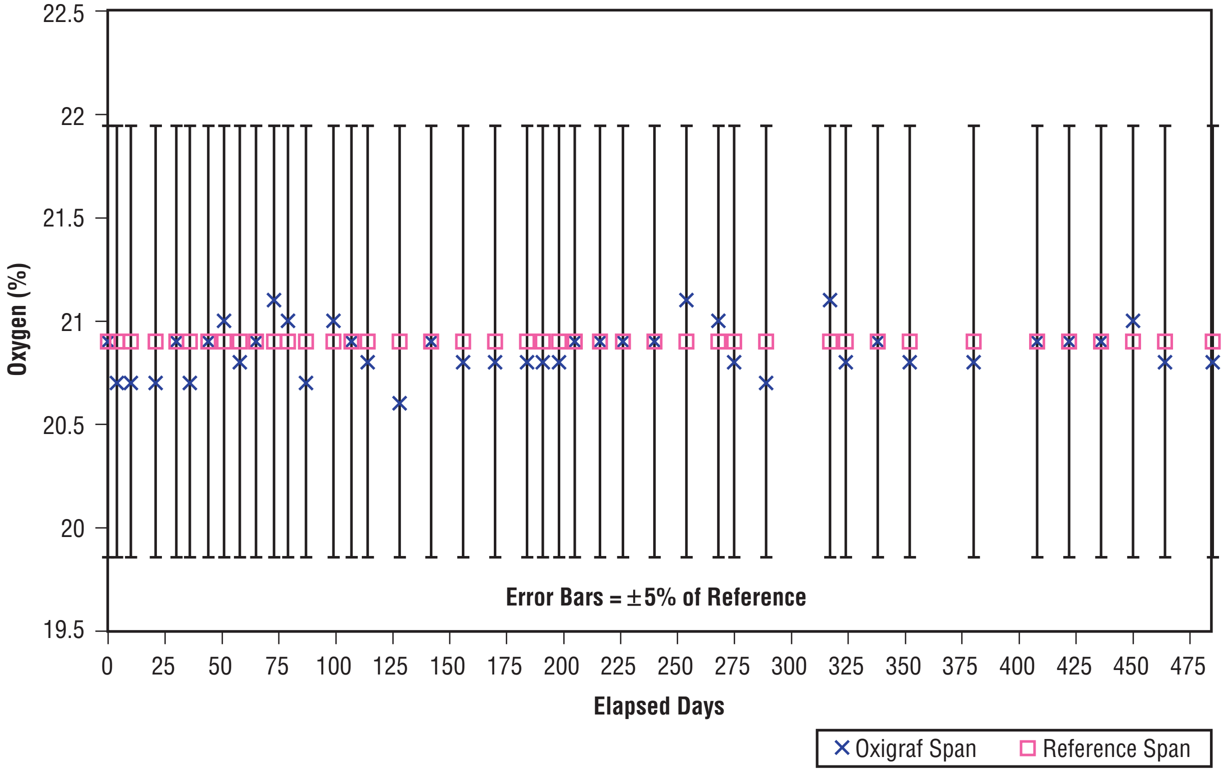
	3/6/02	**3/7/02**	**3/8/02**	**3/14/02**	**Calibration Check 3/14/02**
Sable	–2.6	–1.61	3.21	6.81	–39.1 and 24.77
GE	–3.7	–2.3	3.2	7.2	–35.2 and 24.7

It should be noted that the response of the Sable Systems instrument is not as quick as the GE instrument. While the GE instrument becomes stable within 60 s, it takes ≈5 min for the Sable Systems instrument to become stable. The Sable Systems instrument does, however, reach 95 percent of the stable value within 30 s of contact with the reference gas.

6.2 Spacecraft Atmospheric Monitor-Experimental Extended Duration Test

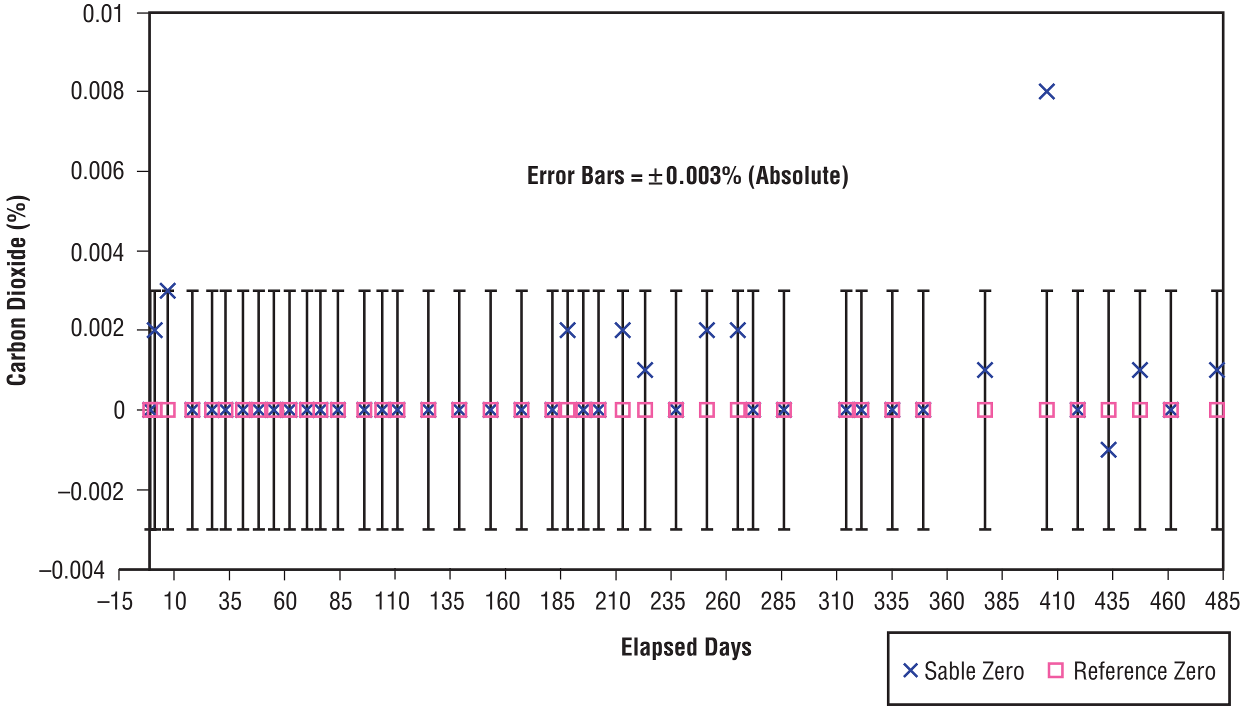
The SAMe extended duration test lasted for over 11,500 hr without interruption. During this time, no anomalies were observed and typical calibration drift suggests that recalibration will be required every 7 to 10 days.

In the graphs shown in figures 11–15, the statistical data shown are for the delta between a reference value and an actual value; i.e., for both the high and low reference values. For oxygen, only one data set is evaluated since the unit is calibrated at one data point.



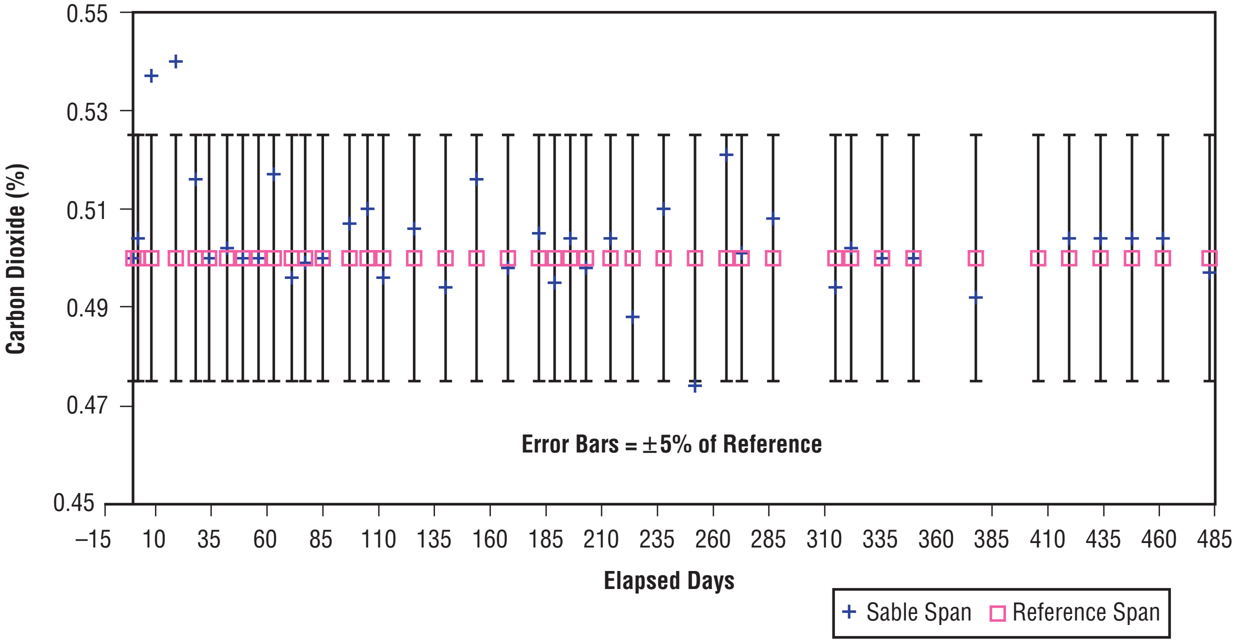
Oxygen Delta	
Mean	–0.04047619
Standard Error	0.018052551
Standard Deviation	0.1169939
Sample Variance	0.013687573
Count	42

Figure 11. Oxigraf oxygen analyzer test data (span data).



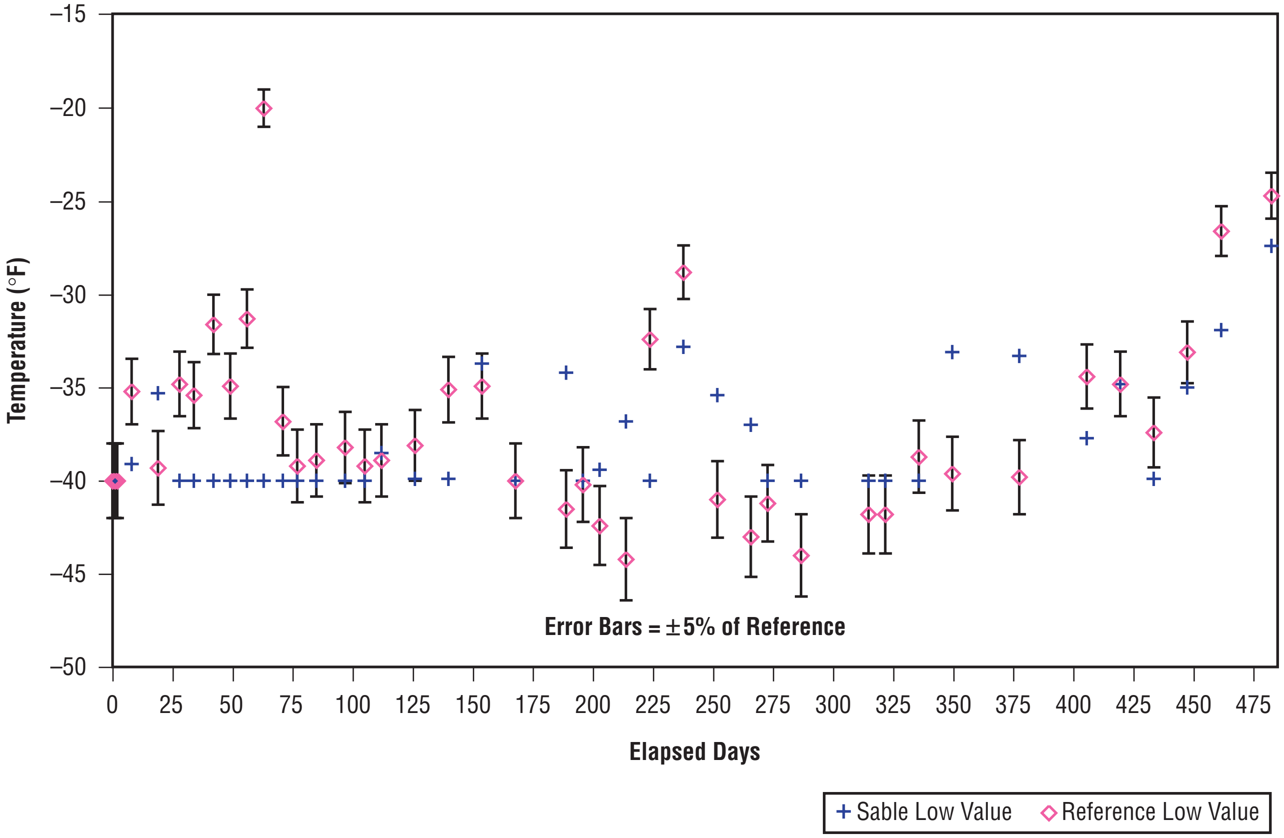
Low Carbon Dioxide Delta	
Mean	0.000571429
Standard Error	0.000221238
Standard Deviation	0.001433788
Sample Variance	2.05575×10^{-6}
Count	42

Figure 12. Sable Systems carbon dioxide analyzer (zero data).



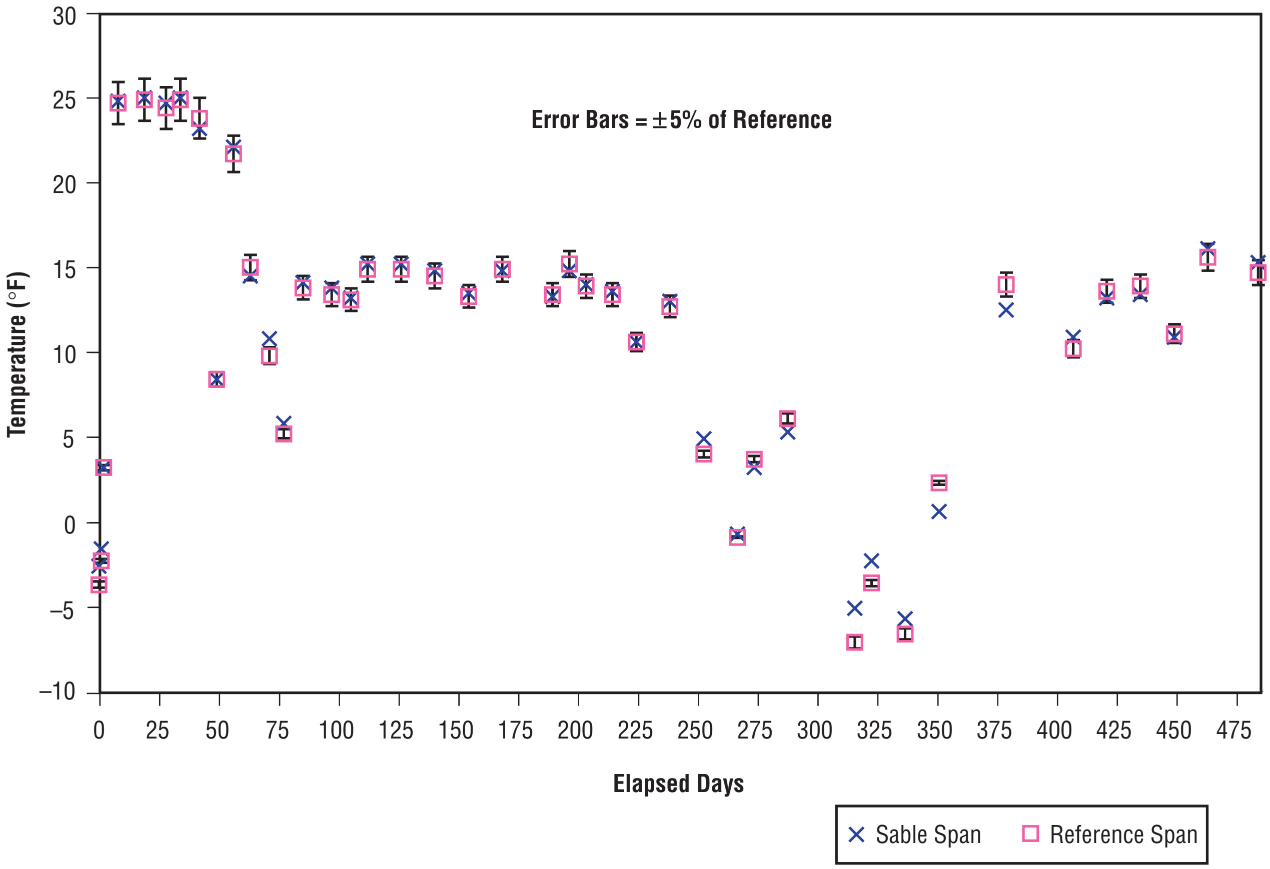
High Carbon Dioxide Delta	
Mean	0.006190476
Standard Error	0.003132431
Standard Deviation	0.020300472
Sample Variance	0.000412109
Count	42

Figure 13. Sable Systems carbon dioxide analyzer (span data).



Dewpoint Delta Low	
Mean	0.15952381
Standard Error	0.104212077
Standard Deviation	0.675371451
Sample Variance	0.456126597
Count	42

Figure 14. Sable Systems dewpoint meter (zero data).



Dewpoint Delta High	
Mean	–0.997619048
Standard Error	0.79127419
Standard Deviation	5.128042849
Sample Variance	26.29682346
Count	42

Figure 15. Sable Systems dewpoint meter (span data).

7. CONCLUSIONS

In these tests, the units performed well with no failures observed. To be flight qualified, additional testing will be needed. Package design as well as electrical certification must also be addressed. Before performing this work, it is inappropriate to suggest any of the technologies are truly flight ready. The positive results observed, however, show that further testing and development is warranted.

7.1 Oxigraf Model O2 Oxygen Analyzer

The Oxigraf model O2 oxygen analyzer was the most stable instrument in the test group. As shown in figure 11, the data fell well within the allowed ±5 percent range, and in fact, fell well within 1 percent of the expected value in all but one instance. This shows that the unit will be a low maintenance item, requiring calibration only once every 2 to 3 wk. The only maintenance performed on the unit was the replacement of the hydrophobic filter membrane found at the inlet (fig. 3). This cartridge required replacement approximately once every 3 mo as shown in the appendix.

7.2 Sable Systems Model CA–2A Carbon Dioxide Analyzer

The Sable Systems CA–2A carbon dioxide analyzer was also a very reliable and stable instrument. As shown in figure 12, zero data regularly fell within a value of ±0.003 percent of zero on the low side and was typically within ±5 percent of the certified value on the high side; i.e., span level. While not as stable as the oxygen analyzer, the unit is still an excellent performer and will require calibration every 1 to 2 wk. There are no regular maintenance items or expendables for this unit other than the infrared cell, which has an estimated life of 40,000 hr (4.5 yr continuous use).

7.3 Sable Systems Model RH–100 Relative Humidity/Dewpoint Meter

The Sable Systems dewpoint meter, while moderately accurate at low-level dewpoints (–25 °F and lower) was extremely accurate versus our reference chilled mirror dewpoint sensor at ambient dewpoint levels (between –10 and –30 °F). As shown in figure 14, there were only four instances out of a set of 42 data points where the value exceeded ±5 percent of the reference dewpoint value. Given this performance and the solid-state nature of the solid polymer electrode, this technology is an excellent candidate for further investigation.

7.4 Consumables

In long-term space flight, resupply and, thus, logistics are a primary concern. The items tested have a limited lifespan, though that lifespan is not known at this time. The test articles will continue to be tested until they fail, but prior to that time, the usable life of any one component can only be estimated. Table 2 denotes each instrument, consumable items for that sensor, and the estimated life of each.

Table 2. Estimated life of testing instruments and corresponding consumable items.

Item Tested	Replacement Part	Estimated Life
Oxigraf model O2	Sensor	45,000 hr
	Hydrophobic inlet filter	2,000 hr
Sable Systems CA–2A	Sensor	45,000 hr
	Infrared light source	30,000 hr
Sable Systems RH–100	Sensor	45,000 hr
Calibration standards	80-ft^3 zero gas	2 yr*
	80-ft^3 mixed span gas	2 yr*

* >48 calibration events using biweekly frequency

APPENDIX—SPACECRAFT ATMOSPHERIC MONITOR-EXPERIMENTAL TEST DATA SUMMARY

Tables 3–5 are the SAMe test data summaries for the dewpoint, carbon dioxide, and oxygen sensors, respectively.

Table 3. SAMe test data summary for Sable Systems model RH–100 meter.

Date	**3/6/02**	**3/7/02**	**3/8/02**	**3/14/02**	**3/25/02**	**4/3/02**	**4/9/02**
Sable (wet) (°C)	–2.6	–1.6	3.2	24.8	25	24.7	25
Sable (dry) (°C)	na	na	na	–39.1	–35.3	<–40	<–40
GE (wet) (°C)	–3.7	–2.3	3.2	24.7	24.9	24.4	24.9
GE (dry) (°C)	na	na	na	–35.2	–39.3	–34.8	–35.4
Note	Calibrated	No cal.	No cal.	No cal.	Cal.	No cal.	Cal.
Date	**4/17/02**	**4/24/02**	**5/1/02**	**5/8/02**	**5/16/02**	**5/22/02**	**5/30/02**
Sable (wet) (°C)	23.2	8.4	22.1	14.5	10.8	5.8	14.1
Sable (dry) (°C)	<–40	<–40	<–40	<–40	<–40	<–40	<–40
GE (wet) (°C)	23.8	8.4	21.7	15	9.8	5.2	13.8
GE (dry) (°C)	–31.6	–34.9	–31.3	–20	–36.8	–39.2	–38.9
Note	Cal.	Cal.	Cal.	Cal.	Cal.	No cal.	Cal.
Date	**6/11/02**	**6/19/02**	**6/26/02**	**7/10/02**	**7/24/02**	**8/7/02**	**8/21/02**
Sable (wet) (°C)	13.8	13.2	15.2	15.2	14.8	13.5	14.8
Sable (dry) (°C)	<–40	<–40	–38.5	–39.9	–39.9	–33.7	NA
GE (wet) (°C)	13.4	13.1	14.9	14.9	14.5	13.3	14.9
GE (dry) (°C)	–38.2	–39.2	–38.9	–38.1	–35.1	–34.9	NA
Note	Cal.	Cal.	No cal.	Cal.	Cal.	Cal.	No cal.
Date	**9/11/02**	**9/18/02**	**9/25/02**	**10/6/02**	**10/16/02**	**10/30/02**	**11/13/02**
Sable (wet) (°C)	13.3	14.8	14	13.6	10.6	13.0	4.9
Sable (dry) (°C)	–34.2	–40	–39.4	–36.8	–40	–32.8	–35.4
GE (wet) (°C)	13.4	15.2	13.9	13.4	10.6	12.7	4
GE (dry) (°C)	–41.5	–40.2	–42.4	–44.2	–32.4	–28.8	–41
Note	No cal.	Cal.	Cal.	Cal.	Cal.	Cal.	Cal.
Date	**11/27/02**	**12/4/02**	**12/18/02**	**1/15/03**	**1/22/03**	**2/5/03**	**2/19/03**
Sable (wet) (°C)	–0.7	3.2	5.3	–5.1	–2.3	–5.7	0.6
Sable (dry) (°C)	–37	–40	–40	<–40	–40	–40	–33.1
GE (wet) (°C)	–0.9	3.7	6.1	–7.1	–3.6	–6.6	2.3
GE (dry) (°C)	–43	–41.2	–44	–41.8	–41.8	–38.7	–39.6
Note	Cal.	No cal.	Cal.	Cal.	Cal.	Cal.	Cal.

Table 3. SAMe test data summary for Sable Systems model RH–100 meter (Continued).

Date	3/19/03	4/16/03	4/30/03	5/14/03	5/28/03	6/11/03	7/2/03
Sable (wet) (°C)	12.5	10.9	13.2	13.4	10.9	16.1	15.3
Sable (dry) (°C)	–33.3	–37.7	–34.8	–39.9	–35	–31.9	–27.4
GE (wet) (°C)	14	10.2	13.6	13.9	11.1	15.6	14.7
GE (dry) (°C)	–39.8	–34.4	–34.8	–37.4	–33.1	–26.6	–24.7
Note	Cal.	Cal.	No cal.	Cal.	Cal.	Cal.	Cal.

* Note: The Sable is incapable of determining dewpoint below –40 °C. At this point and below, relative humidity readings are used. The unit is calibrated to 0.05% relative humidity for the dry reading using dry nitrogen.

** Switched over to monitoring dewpoint in slightly wet air rather than relative humidity in bone-dry air. This makes correlation between units easier.

Table 4. SAMe test data summary for Sable Systems CA–2A carbon dioxide analyzer.

Date	3/4/02	3/8/02	3/14/02	3/25/02	4/3/02	4/9/02	4/17/02
Zero	NA	NA	0.002	0.003	0	0	0
Span (0.5% CO_2)	0.5	0.504	0.537	0.54	0.516	0.5	0.502
Note	Calibrated	No cal.	Cal.	Cal.	Cal.	No cal.	No cal.
Date	**4/24/02**	**5/1/02**	**5/8/02**	**5/16/02**	**5/22/02**	**5/30/02**	**6/11/02**
Zero	0	0	0	0	0	0	0
Span (0.5% CO_2)	0.5	0.5	0.517	0.496	0.499	0.5	0.507
Note	No cal.	No cal.	Cal.	Cal.	No cal.	No cal.	Cal.
Date	**6/19/02**	**6/26/02**	**7/10/02**	**7/24/02**	**8/7/02**	**8/21/02**	**9/4/02**
Zero	0	0	0	0	0	0	0
Span (0.5% CO_2)	0.51	0.496	0.506	0.494	0.516	0.498	0.505
Note	Cal	No cal.	Cal.	Cal.	Cal.	No cal.	Cal.
Date	**9/11/02**	**9/18/02**	**9/25/02**	**10/6/02**	**10/16/02**	**10/30/02**	**11/13/02**
Zero	0.002	0	0	0.002	0.001	0	0.002
Span (0.5% CO_2)	0.495	0.504	0.498	0.504	0.488	0.51	0.474
Note	Cal.	Cal.	Cal.	Cal.	Cal.	Cal.	Cal.
Date	**11/27/02**	**12/4/02**	**12/18/02**	**1/15/03**	**1/22/03**	**2/5/03**	**2/19/03**
Zero	0.002	0	0	0	0	0	0
Span (0.5% CO_2)	0.521	0.501	0.508	0.494	0.502	0.5	0.5
Note	Cal.	No cal.	Cal.	Cal.	No cal.	No cal.	No cal.
Date	**3/19/03**	**4/16/03**	**4/30/03**	**5/14/03**	**5/28/03**	**6/11/03**	**7/2/03**
Zero	0.001	0.008	0	–0.001	0	0	0.001
Span (0.5% CO_2)	0.492	0.613	0.504	0.504	0.504	0.504	0.497
Note	Cal.	Cal. Outlet mod. Higher back pressure	Cal.	Cal.	Cal.	Cal.	Cal.

Table 5. SAMe test data summary for Oxigraf model O2 oxygen analyzer.

Date	**3/4/02**	**3/8/02**	**3/14/02**	**3/25/02**	**4/3/02**	**4/9/02**	**4/17/02**
Value (20.9% Std)	20.9	20.7	20.7	20.7	20.9	20.7	20.9
Note	Calibrated	Cal.	Cal.	Cal.	No cal.	cal.	No cal.
Date	**4/24/02**	**5/1/02**	**5/8/02**	**5/16/02**	**5/22/02**	**5/30/02**	**6/11/02**
Value (20.9% Std)	21	20.8	20.9	21.1	21	20.7	21
Note	Cal.	Cal.	No cal.	No cal.	Cal.	Cal.	Cal.
Date	**6/19/02**	**6/26/02**	**7/10/02**	**7/24/02**	**8/7/02**	**8/21/02**	**9/4/02**
Value (20.9% Std)	20.9	20.8	20.6	20.9	20.8	20.8	20.8
Note	No cal.	No cal.	Cal. Swap Filter	No cal.	No cal.	No cal.	No cal.
Date	**9/11/02**	**9/18/02**	**9/25/02**	**10/6/02**	**10/16/02**	**10/30/02**	**11/13/02**
Value (20.9% Std)	20.8	20.8	20.9	20.9	20.9	20.9	21.1
Note	No cal.	No cal.	No cal.	No cal. Swap filter	No cal.	No cal.	Cal.
Date	**11/27/02**	**12/4/02**	**12/18/02**	**1/15/03**	**1/22/03**	**2/5/03**	**2/19/03**
Value (20.9% Std)	21	20.8	20.7	21.1	20.8	20.9	20.8
Note	No cal.	No cal.	Cal.	Cal. Swap filter	No cal.	No cal.	No cal.
Date	**3/19/03**	**4/16/03**	**4/30/03**	**5/14/03**	**5/28/03**	**6/11/03**	**7/2/03**
Value (20.9% Std)	20.8	20.9	20.9	20.9	21	20.8	20.8
Note	No cal.	No cal.	No cal.	No cal.	Cal.	No cal.	No cal.

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13. ABSTRACT *(Maximum 200 words)*

Monitoring the atmospheric composition of a crewed spacecraft cabin is central to successfully expanding the breadth and depth of first-hand human knowledge and understanding of space. Highly reliable technologies must be identified and developed to monitor atmospheric composition. This will enable crewed space missions that last weeks, months, and eventually years. Atmospheric composition monitoring is a primary component of any environmental control and life support system. Instrumentation employed to monitor atmospheric composition must be inexpensive, simple, and lightweight and provide robust performance. Such a system will ensure an environment that promotes human safety and health, and that the environment can be maintained with a high degree of confidence. Key to this confidence is the capability for any technology to operate autonomously, with little intervention from the crew or mission control personnel. A study has been conducted using technologies that, with further development, may reach these goals.

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