The JPL Electronic Nose: Monitoring Air in the US Lab on the International Space Station

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Abstract— **An electronic nose with a sensor array of 32 conductometric sensors has been developed at the Jet Propulsion Laboratory (JPL) to monitor breathing air in spacecraft habitat. The Third Generation ENose is designed to operate in the environment of the US Lab on the International Space Station (ISS). It detects a selected group of analytes at target concentrations in the ppm regime at an environmental temperature range of 18 - 30 °C, relative humidity from 25 - 75% and pressure from 530 to 760 torr. The monitoring targets are anomalous events such as leaks and spills of solvents, coolants or other fluids. The JPL ENose operated as a technology demonstration for seven months in the U.S. Laboratory Destiny during 2008-2009. Analysis of ENose monitoring data shows that there was regular, periodic rise and fall of humidity and occasional releases of Freon 218 (perfluoropropane), formaldehyde, methanol and ethanol. There were also several events of unknown origin, half of them from the same source. Each event lasted from 20 to 100 minutes, consistent with the air replacement time in the US Lab.**

I. INTRODUCTION

There is, at present, no continuous monitoring of breathing air in space habitat. An electronic nose has been developed at the Jet Propulsion Laboratory (JPL) to monitor spacecraft cabin air for anomalous events such as leaks and spills of solvents, coolants or other fluids with near-real-time analysis [1-5]. The JPL Electronic Nose (ENose) is designed to fill the gap between an alarm, which does not identify the stimulus, and a full analytical instrument, which cannot run continuously. Use of an electronic nose allows continuous monitoring for 10-30 targeted species which may contaminate air owing to a leak or a spill.

The JPL ENose is an array–based sensing system which is designed to run continuously and to monitor for the presence of selected chemical species in the air at parts-per-million (ppm) to parts-per-billion (ppb) concentrations. It uses an array of 32 semi-selective chemical sensors; sensing materials are primarily polymer-carbon composite films, but also include inorganic and carbon nanotube sensors.

There have been three phases of development of the JPL Electronic Nose. In the first phase, a device capable of detecting, analyzing and quantifying ten analytes at the 1-hour Spacecraft Maximum Allowable Concentration (SMAC) was developed. This device was tested successfully in 1998 on Space Shuttle flight STS-95 [4]. In the second phase, the ENose was miniaturized and the capabilities were significantly expanded to include 21 analytes and detection at varying humidity and temperature. The Second Generation ENose was tested extensively on the ground and was demonstrated to be able to detect, identify and quantify the 21 analytes at or below their 24-hour Spacecraft Maximum Allowable Concentrations (SMACs) [6]. This Third Generation ENose, shown in Fig. 1, was built as a Technology Demonstration instrument and was installed onboard the International Space Station (ISS) in the US Lab Destiny for a seven month technology demonstration.

The Third Generation ENose is designed to detect, identify and quantify eleven chemical species, including seven organic compounds as well as formaldehyde, ammonia, mercury and sulfur dioxide. The chemical species and the concentrations targeted for this Technology Demonstration are shown in Table 1. Analyte quantification targets are listed as parts-per-million (ppm) at a pressure of 1 atmosphere (760 torr) and a temperature of 300 K (27 °C). Tier 1 is chemical species for which there is a requirement to detect, identify and quantify with a 90% success rate. Tier 2 is chemical species for which

Figure 1. The Third Generation ENose. The Sensor Unit developed in the Second Generation, is enclosed in the Interface Unit, which was connected to EXPRESS Rack 2 on ISS.

there is a requirement for detection, identification and quantification with an 80% success rate. Detection of the Tier 3 species, formaldehyde, was a goal in this program. 24-hour SMACs are included in the table for reference. There is no SMAC established for SO_2; for reference, the OSHA Short Term Exposure Limit is 5 ppm. The target for Freon 218 is significantly lower than the SMAC because it can damage the Environmental Control and Life Support System.

TABLE I. ANALYTES TARGETED FOR ENOSE DEMONSTRATION

	ANALYTE	**QUANT. TARGET (ppm)**	**24-Hour SMAC (ppm)**
TIER 1	Ammonia	5.0	20
	Mercury	0.010	.0020
	Sulfur Dioxide	1.0	NA
TIER 2	Acetone	200	200
	Dichloromethane	10	35
	Ethanol	500	2000
	Freon 218	20	11,000
	Methanol	10	10
	2-Propanol	100	100
	Toluene	16	16
TIER 3	Formaldehyde	0.10	0.10

II. ENOSE OPERATION

A. *Ground Testing*

The ENose was tested in the laboratory before it was launched on STS-126 in November, 2008. Success rates for detection, identification and quantification, and requirements on the ENose, have previously been discussed in detail [7]. Results of ground testing showed an overall success rate for detection, identification and quantification of all analytes of 87% under nominal temperature and humidity conditions and 83% over all conditions.

The JPL ENose has been designed to operate in the environment of the US Lab on ISS. It detects targeted analytes at concentrations in the ppm regime at an environmental temperature range of 18 - 30 ^{o}C, relative humidity from 25 - 75% and pressure from 530 to 760 torr. It is designed to run continuously by pulling ambient air over the sensing array. Data analysis is done on-board, in quasi-real time, and results are stored for later review. This paper will discuss the data acquired by the ENose during its period of operation on the EXPRESS Rack on ISS, and results of on-board data analysis and the post-flight laboratory check and.

B. *ENose on ISS*

The JPL ENose was launched on STS-126 on November 14, 2008. It was unstowed, installed on EXPRESS (EXpedite the PRocessing of Experiments to Space Station) Rack 2 in the US Lab and activated at 08:46 GMT, December 9, 2008 and deactivated on July 15, 2009. ENose operated continuously while powered; it was powered down for a total of 10 days in the seven-month operational period. A photo of the ENose installed on EXPRESS Rack 2 is shown in Fig. 2. Instrument health and status data are transmitted from the EXPRESS Rack to ground one time per second; it was possible to design the ENose health and status signal to include raw sensor data, and so real time ENose sensor data as well as instrument health data were transmitted to the ground. The data stream could be read in the ENose lab at JPL using a Graphical User Interface (GUI) designed for the process, whenever there was Ku Band signal from space to ground.

Data acquired through the ENose GUI were saved on a local computer hard drive and full data files were downloaded from ENose to a JPL local computer during weekly command windows, via the Huntsville Operations Support Center (HOSC) at Marshall Space Flight Center; data files downlinked include log files, data files and on-board data analysis.

Shortly after activation, a crew member checked the unit for nominal operation by observing whether LEDs were lighted correctly and the screen was on. A similar status check

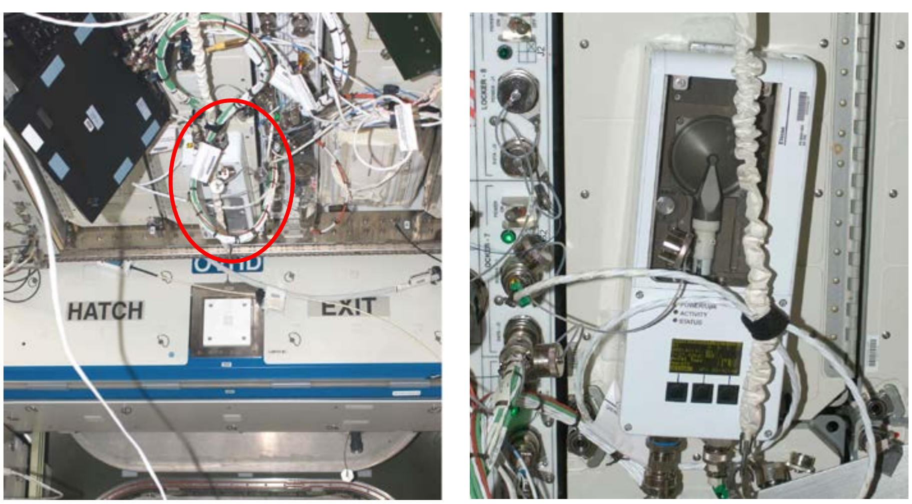

Figure 2. The ENose deployed on ISS; ENose was located on EXPRESS Rack 2, on the “ceiling” above a hatch (circled in red). The picture on the right shows the green power light is on. The screen shows the time, humidity and pressure in this picture. It is generally dimmed and can be “woken up” by pressing one of the front panel keys.

was performed by a crew member weekly. In addition to the weekly status check, a crew member performed a bimonthly confirmational event. The crew member held a disinfectant wipe in front of the ENose inlet for one minute and noted the time. ENose team members at JPL checked the analysis of ENose data to confirm that the event has been detected by ENose and identified correctly.

In addition to downlinking data, commands could be sent to change activity or to control parameters on the ENose. For example, the temperature in the ENose sensing chamber was slightly higher than expected, by about 2^{o}C. After noting this higher temperature, new thermal control parameters were established in the laboratory then a new thermal control file was uploaded to ENose during a weekly command window. This new file kept the ENose sensing chamber at a temperature consistent with optimum operation.

C. *Data Analysis Approach*

Data from the ENose are recorded for each individual sensor as resistance versus time. Because the ENose is designed to function as an event monitor, the data are analyzed as change in resistance vs. time. Individual sensor resistances are recorded simultaneously, with a point being taken every twenty seconds. While it would be possible to take data more or less frequently than three times a minute, this data rate has been established as an optimum rate to show fairly rapid changes in the environment without overwhelming computer memory with data. The data analysis approach defines an “event’ as a change in the composition of the environment which lasts longer than ten minutes, or thirty points at the standard data rate, in part because events of duration shorter than ten minutes cannot be addressed practically or mitigated using either breathing apparatus or clean-up techniques. The data analysis algorithm needs about ten points (~ three minutes) to establish that resistance has changed significantly and reports a species and concentration, or classifies a change as unknown, once every five minutes.

The data analysis algorithm is a Levenberg-Marquardt non-linear least squares fitting approach to deconvolution of change in resistance across the sensing array into identification and quantification of the analyte causing response in the sensors. The analysis approach has been discussed in detail previously [8, 9]. Data used to develop the algorithm and provide the coefficients applied to the data were developed in the laboratory through training sets under a range of environmental conditions [7]. The data analysis program was developed and validated in MatLab, then translated to C for use in the ENose on-orbit. Analysis runs on-orbit and results are recorded in a file separate from the sensor resistance file.

On downlinking data, files are processed by converting them to text files of sensor resistance and of operating parameters such as temperature, humidity, pressure, voltage and current. Sensor resistance files are analyzed using the MatLab analysis program, and the results compared with the on-orbit analysis.

Data may be plotted as change in resistance vs. time, as shown in Fig. 3a, for ease of visualization of ENose monitoring, although this step is not necessary, as analysis requires the raw resistances.

III. RESULTS: ENOSE DATA FROM ISS

A. *Initial Data from ISS*

Humidity Cycles Initial data sets acquired by the ENose on ISS showed a periodic rise and fall of about 3 percent relative humidity with a period of 144 minutes. Fig. 3a shows an example of a 24-hour data file; the upper trace is percent relative humidity, as measured by a humidity sensor installed in the same chamber as the ENose sensors (y-axis on right), and the lower traces are normalized change in resistance of eight polymer-carbon black sensors (y-axis on left; dR/R_0 where R_0 is set arbitrarily to the first point in the file.) This plot shows that sensor resistance change follows humidity

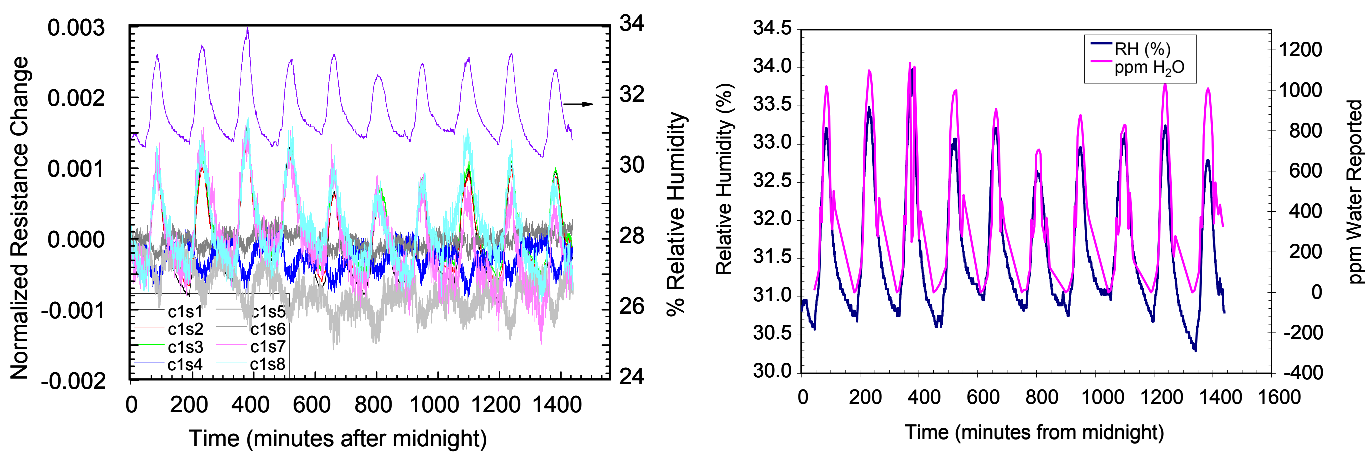

Figure 3. ENose sensor data taken on ISS (A) Eight sensors plotted with change in resistance against the initial point in the trace. The trace on the top is relative humidity as measured by a humidity sensor in the sensing chamber of ENose (right axis). (B) Relative humidity in the sensing chamber varied by about 3% RH with a period of 144 minutes. The analysis program detected a change of about 1000 ppm for each variation. The two axes, Relative Humidity and ppm Water Reported, are scaled to be the same amount of water; i.e. 4.5% RH is 1700 ppm water. Water detection is used as an example because it is the species seen most frequently and repeatedly on ISS.

change with little or no time offset. If the species detected had been one of the targeted species, there might be somewhat more of a time offset, but earlier work has shown that deconvoluted sensor response looks similar to that shown in Fig. 3a.

Fig. 3b shows the results of the automated analysis of sensor data. The analysis program detected a rise and fall of about 1000 ppm water on a 144 minute period, with little or no time delay. This plot shows percent relative humidity on the left y-axis and ppm change in water content on the right y-axis. The two axes are set to span the same range; *i.e.* a change of 4.5 percent relative humidity is equivalent to a change of 1700 ppm water.

Earlier laboratory work on the ability of ENose to detect changes in the environment showed that changes of 5 – 10 percent relative humidity over short periods would interfere with the ability of the ENose analysis program to deconvolute the data and recognize target species; however, the humidity changes detected on ISS occur over 20 – 30 minutes and do not interfere with the data analysis process.

The periodic rise and fall of humidity was present for the first several days of operation on ISS, then stopped, and humidity and temperature were steady. The periodic humidity change observed has been correlated in time with the operation of the Carbon Dioxide Removal Assembly (CDRA), which was under test at the time ENose was activated. The CDRA has a 144 minute half cycle and can expel humidity during the desiccant bed regeneration [10].

*Confirmational Event*s The first confirmational event for ENose was done about two weeks after activation. A crew member held a disinfectant wipe in front of the ENose air inlet for one minute, to provide a stimulus to the sensors of a known species at a recorded time. The first confirmational event was easily seen in the sensor resistance data and was detected by the automated analysis program. The analysis program reported the stimulus as “unknown.” The signature of the disinfectant wipe used in the confirmational event is not included in the ENose data library, as this event gives us the opportunity to confirm that ENose is able to report unknowns. Subsequent to this first confirmational event, a crew member performed one once every two weeks. All confirmational events were detected and classified as “unknown”.

B. Events on ISS Detected and Reported by ENose

In normal operation, very few changes in environment which might be considered to be events are reported. The source of these reports is generally crew observation. There are grab samples taken in the US Lab of ISS about once a month. Analysis of those samples lags considerably in time from when they are taken because they must be transported to the ground and analyzed at Johnson Space Center.

Previous work in testing air quality instruments on ISS has included the Volatile Organics Analyzer (VOA) from NASA and the Analysing Interferometer for Ambient Air (ANITA) from the European Space Agency [11]. VOA measurements are taken up to a few times a day, and so provide a snapshot of the presence (or absence) of some forty chemical species, but does not give insight into air constituent changes lasting less than several hours. ANITA measurements are taken more frequently, and the instrument is designed to run continuously. However, measurements are reported about forty minutes apart, and so would not give insight into changes lasting less than one hour.

Results from ANITA experiments showed that there was much greater fluctuation in the composition of air in the US Lab than had previously been thought [11]. In particular, the ANITA experiment showed a persistent presence of low-concentration Freon 218 (octafluoropropane) with occasional spikes in concentration. [11]

ENose detected several events during the seven month period of operation. The majority of events lasted less than one hour, and several are less than 30 minutes. A summary of events detected by ENose is shown in Table 2. As expected, based on ANITA results, there were several events related to changes in Freon 218 concentration in the environment, along with other small organic molecules previously measured in the ISS atmosphere, such as alcohols and formaldehyde.

TABLE II. SUMMARY OF EVENTS DETECTED ON ISS

Species	Number of Events	Min Con detected (ppm)	Max Con detected (ppm)	One Hour SMAC (ppm)
Ethanol	1	450	800	5000
Methanol	24	3	40	200
Formaldehyde	57	0.18	0.22	0.8
Freon 218	19	6	91	11,000
Conf. Event	13			
Unknown	22	-	-	-

IV. DISCUSSION: ENOSE DATA FROM ISS

A. Identification of Sources of Events

As shown in Table II, several short, non-hazardous events were detected during ENose’s 7 month Technology Demonstration period. Although it is not within the scope of this project to identify the source of each event, an attempt has been made to find broad areas of correlation with activities and to assign possible sources for detected species.

Four target species and one unknown were detected. It has not been possible to correlate the events with crew or other activities because we do not have access to enough information about as-performed time lines on ISS to make correlations. There were no reports by the crew of spills or odors which could be related to the appearance of any of the targeted chemical species.

Freon 218 (alternate names: octafluoropropane, perfluoropropane) is a coolant used in the Russian module. Freon 218 is not a toxic species; its 24-hour SMAC is 11,000 ppm, and the maximum concentration seen by ENose is 90 ppm. The ANITA experiment, a European Space Agency Technology (ESA) Technology Demonstration done in 2008, but not overlapping in time with ENose, was also connected to the EXPRESS Rack in the US Lab [11]. That experiment was not operated continuously, as was ENose, and small molecules such as formaldehyde and methanol were not on their detection target list. However, Freon 218 was on ANITA's target list, and that species was seen frequently as a background trace gas and in "burps" such as might be seen by ENose. ENose would not detect a species always in the background, as it is designed to detect the sudden appearance as in a leak or a spill, but it would detect a species that occasionally occurs as releases. That ANITA detected the unexpected presence of Freon 218 in the US Lab supports the validity of ENose's detection of the same compound.

Formaldehyde was not detectable by ANITA, nor is it detectable by any other instrument currently operating on ISS. ENose detected formaldehyde frequently, at a concentration of about 0.2 ppm. The appearance of formaldehyde cannot easily be correlated with activities as it appeared at several times of day, and was not seen for the first month of operation. If there is equipment or activity that began on or slightly before January 13, 2009 the appearance of formaldehyde may be related to that equipment or activity, but there is no information available to indicate that such activity began. There are periods of quiet, where there were not events of formaldehyde. To some extent, the periods of quiet correspond to periods of Shuttle or Soyuz docking, when there is an increased crew complement, and, presumably, additional volume. After the ISS crew increased to six members on May 27, the number of formaldehyde events was similarly low. Formaldehyde may be produced by operating equipment which heats up polymeric seals or o-rings, and the heated polymer off-gasses formaldehyde. We do not have enough information on the operation of equipment to draw a conclusion regarding the cause of formaldehyde events.

Similarly, methanol is not detected by other instruments now operating on ISS. As with formaldehyde, there are no activities that could be correlated to the presence of methanol.

There are several reports of an unknown species causing a stimulus to the ENose sensors. Using sensor response models based on Quantitative Structure-Activity Relationships (QSAR) [12, 13] and on Hansen Solubility Parameters [14, 15], this unknown species has been identified as sulfur hexafluoride (SF_6) [16]. This identification is not unequivocal, but is supported by post-flight testing which showed that the ENose sensor array response to SF_6 was consistent with the array response to the unknown species.

B. Polymer-Carbon Composite Sensors Lifetime

The polymer-carbon sensors used in the ENose on ISS were well past their lifetime at the end of the Technology Demonstration period. Lifetime was established during the Second Generation ENose research effort as being approximately 15-18 months, where lifetime is the period during which overall array response to a single stimulus does not change more than 10%. When ENose was returned from ISS, more than 18 months had elapsed since the coefficients used in analysis were established. That three species were identified correctly in post-flight verification shows that a lifetime of some 18 months is possible. It is possible that lifetime is extended somewhat by microgravity, as the mechanism for sensor change is mechanical relaxation of the polymer chains. Microgravity may slow the rate of relaxation, thus extending the lifetime.

C. Event Duration

Most events detected by ENose on ISS lasted 30-60 minutes; the longest lasting event was less than two hours. That events did not last longer than two hours indicates that most events detected by ENose were truly chemical release events, where a chemical species was released and concentration rose, then concentration fell as the air in the US Lab was taken up by the ECLS system, cleaned and returned to the environment. The air flow rate within the US Lab is 663 m^3/hour; with a volume of 122 m^3, US Lab air will be replaced one time in about 11 minutes. This replacement rate may explain the short duration of chemical events observed by ENose. The airflow rate into and out of the US Lab from other modules is about 1/3 the flow rate within the lab (230 m^3/hour), so chemical species entering the lab from other modules would have to be at a rather high concentration in order to travel to a single point monitor to be detected.

V. POST FLIGHT VERIFICATION

The ENose flight unit was returned to JPL in October, 2009, after returning to earth on shuttle flight 17A (STS-128). On receipt, the ENose was inspected. It had no nicks or scratches, no bent pins, and all caps and covers were in place. It looked as it did when delivered.

The ENose was installed on the laboratory bench at the main gas handling system, where training sets were developed. ENose was exposed to three concentrations of each of three of the four species detected on orbit. The exposures were ethanol 450 and 800 ppm, methanol 3 and 10 ppm, formaldehyde 0.21 and 0.25 ppm. These exposures were selected based on the quantities of each of these three analytes detected on orbit, the target detection range, and the quantities which could be delivered without modifying the vapor delivery system. The quantities detected on orbit were ethanol 800 ppm, methanol 3 – 40 ppm (detection range 1 – 10 ppm), and formaldehyde 0.17 to 0.23 ppm (detection range 0.1 – 0.3 ppm.)

Each of the analytes delivered by the vapor delivery system was detected, identified and quantified correctly by ENose. Ethanol was quantified as 350 and 630 ppm for 400 and 800 ppm delivered. Methanol was quantified as 3 and 8 ppm. Formaldehyde was quantified as 0.19 and 0.23 ppm. In each case, the quantification is accurate to better than +/- 50%, as required.

Freon 218 was not tested in post-flight verification because to do so would have required modifying the vapor delivery system. We concluded that if three of the four analytes were identified and quantified correctly, that post-flight operation is verified.

VI. CONCLUSION

The overall vision for development of air quality monitoring using a sensing array such as ENose goes further than developing the instrument. With the completion of this on-orbit technology demonstration, we have shown that ENose can run autonomously and continuously, and that it detects events without being overwhelmed by “nuisance alarms” from standard crew activities such as preparing food. The short duration of events detected indicates that air replenishment is rapid and keeps the breathing environment fairly clean. Thus, for a technology such as ENose to be useful, it would be necessary to distribute several around the crew habitat. In this way, the differences among various locations could be monitored, and the development of an event could also be monitored and pinpointed in space as well as time. Finally, a truly autonomous system would integrate environmental control functions with the monitoring functions provided by a distributed network of sensing arrays. In this way, crew habitat would include a system in which deviations from healthy air detected by the monitor would initiate environmental control measures such as closing off areas and triggering additional clean-up functions.

Because ENose is conceived as and designed to be an event monitor, it does not perform the functions of trace gas monitoring, which detects vapors at lower concentration than ENose is designed to detect, or of major constituent monitoring. These functions are performed by other, more complex instruments, which are generally not designed for continuous operation. Because those instruments are not designed for continuous operation, it is possible that they would miss an event which might build to a hazardous level. Thus, linking a continuous monitor such as ENose as a trigger to an analytical instrument such as ANITA, the Vehicle Cabin Air Monitor (VCAM) or the Volatile Organics Analyzer (VOA) would allow both cross-validated analysis and improved understanding of changes in spacecraft air quality.

As NASA moves toward long-duration spaceflight, the need for air quality monitoring will become more evident, and so development of technologies which can provide that monitoring will proceed. ENose is a technology which has now been demonstrated on-orbit and can fill some of the needs for real-time monitoring in crew habitat.

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