

Maintaining and Monitoring the Habitable Environment of the International Space Station

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ABSTRACT

The maintenance of cabin air-quality aboard spacecraft requires a proper balance of contamination generation and removal, and environmental monitoring. Achieving this balance is paramount to a spacecraft's ability to sustain human life and maintain functionality. Spacecraft cabin atmosphere can best be described as an equilibrium. As with other systems in equilibrium, the cabin air-quality of the *International Space Station (ISS)* has a remarkable ability to respond to constantly applied perturbations and restore balance. This is a function of not only design, but also a proficient understanding of the ISS atmosphere. Active air quality control equipment is deployed on board every vehicle to remove carbon dioxide, water vapor, and trace chemical components from the cabin atmosphere. Proper management of various logistics, vehicle construction, and system configuration are applied to ensure that cabin atmospheric quality is preserved. Safeguards, such as design for minimum risk, multiple containment, hazard assessments, rigorous safety reviews, and others, are in place to minimize the probability of any long-term detrimental effects perturbations may have on the ISS environment. In addition to engineering controls, procedural controls and requirements are implemented to address strategies which can mitigate off-nominal situations crew may encounter and a rigorous air-quality monitoring program offers candid snapshots and long-term trending of the ISS environment. The underlying nature of engineering controls is primarily static despite the increases in size and crew of the ISS, and the programmatic changes involved with the ISS Program. This is not necessarily true for the strategies developed for mitigating off-nominal situations, and for monitoring the ISS habitable environment. Environmental health monitoring is addressed as well as why and how the fundamental philosophy of air-quality monitoring may or may not evolve.

INTRODUCTION

The purpose of air monitoring is not simply to collect data but to provide the necessary information required by scientists, management, operations teams, and planners to enable them to make informed decisions on managing the environment. Air monitoring fills a control role in this process, providing the necessary sound scientific basis for management development. However, the limitations of monitoring should also be recognized. It must be understood that, at best, on-orbit monitoring provides an incomplete but useful picture of the environment. Hence, measurements alone may be insufficient for the purpose of air quality management which usually requires assistance from off-gassing measurements, interpolation, interpretation, and adherence to specified rules and regulations. Accordingly, ambient monitoring should be regarded as a component, albeit a key one, in any integrated approach to managing air quality.

AIR MONITORING

The first step in designing or implementing any monitoring system is to define its overall objectives. Moreover, in order for a monitoring program to be effective within the framework of an overall air-quality management system, it is vital that these objectives be clearly stated and understood. Setting diffuse, overly restrictive or unrealistic monitoring objectives will result in a cost-ineffective program with poor data utility. The relationships between the data collected and the information to be derived from it must be taken into account when a monitoring technique is planned, executed and reported. This emphasizes the need for

those involved in analyzing the data to be involved in the planning, not only to ensure that the data are appropriate to their needs, but also to justify the resource commitment. Since there are varying rationale behind any given monitoring plan, it should be noted that each organization is likely to have its own specific objectives for monitoring. These may be influenced by certain requirement constraints, as well as by multilateral obligations. Despite these varying rationale, it is vital that clear, realistic and achievable monitoring objectives be set in order to enable appropriate data quality objectives to be defined. This will allow monitoring instrumentation to be optimally designed, appropriate priority for pollutants and contaminants to be selected, and data management/reporting requirements to be identified.

Air monitoring methodologies can cover a wide range of costs and performance levels. The simplest methods that meet air monitoring objectives should be selected. Inappropriate, too complex, or failure-prone equipment will result in limited data utility and, worst of all, a waste of resources and budget. Given the complex nature of the space environment, a focus on proven and generally accepted measurement methods should be considered. Although monitoring objectives are the major factor to consider, resource constraints must also be considered. It should be noted that all conventional, state-of-the-art, ground-based instruments may not be feasible for spacecraft applications. Spacecraft applications have requirements, such as size, weight, power usage, vibration hardened, etc., that may not constrain ground-based applications. Ongoing costs for equipment support, calibration and maintenance in addition to capital purchase expenditure must be considered not only in the budget aspect but also in the performance aspect of the equipment. There is a clear trade between equipment cost, complexity, reliability and performance. More advanced systems can provide increasingly refined data, but are usually more complex. Automatic analyzers can be expensive and not always straightforward to operate successfully. In practice, the combined use of variable sampling capability and automatic analyzers in a hybrid monitoring instrument can be a versatile and cost-effective approach. Such hybrid designs can use passive or active samplers to provide good spatial coverage and resolution of measurements. Automatic analyzers, deployed at carefully selected locations if possible, can provide more detailed time-resolved data for assessing peak concentrations or comparison with archival samples. Instruments with remote sensors or remote sampling capability can provide an integrated picture of the overall environment. This can be very powerful in situations where the lack of natural convection can result in spatially distributed concentration ranges. This can be a very costly air monitoring system, and careful attention needs to be paid to calibration, quality control and data validation procedures if the best use is to be made of this strategy. Any air quality analyzer requires careful selection. Some instrumental parameters are readily

quantified and therefore often quoted by manufacturers; these include specifications such as linearity, response time, accuracy and precision, noise, drift and detection threshold/range. Although these factors are clearly important, other instrumental characteristics, though less readily defined, may be of paramount importance in a practical context. These parameters include reliability and ease of operation, compatibility with existing equipment, maintenance/calibration requirements, and the capability for unattended operation over long periods.

Given the high cost of resupply to the ISS and a continually changing ISS crew, the importance of maintenance procedures for air quality instruments is of paramount importance, especially when considering the limitations of supply and return post-shuttle retirement. It is only through proper instrument support that monitoring systems can be relied on to operate satisfactorily and for extended periods on-orbit. Maintenance schedules for the replacement of consumable parts, diagnostic checks and equipment overhaul should in all cases follow manufacturer's recommendations. This may not be possible for commercial systems not specifically designed and built for spacecraft applications. In this case, sufficient on-ground testing must be performed to ensure that deviations from the manufacturer's recommendation does not jeopardize data quality. Call-out procedures and repair turnaround times need to be specified, in the event of equipment failure on-orbit. It is important to recognize the need for resource commitments well beyond the initial capital investment costs. On-going expenditure are usually required for the lifetime of the equipment to support the monitoring effort, maintain the equipment in an operational state, and ensure that meaningful data are being acquired.

Proper calibration of automatic monitoring instruments is essential for obtaining accurate air quality data. This may involve the use of an internal or external standard, thereby determining the system response to known compounds. An additional determination of the corresponding zero point or system response when no pollutant is present is also very helpful. More often on-orbit, a two-point calibration, zero-point and span calibration is adequate for many purposes. Multipoint calibrations involving several different concentrations may be required in some circumstances, for example, after equipment servicing/repair or if linearity problems are suspected. However, multipoint calibrations of this nature are not always practical on-orbit and careful thought must be made to compensate for this shortcoming. The frequency and type of on-orbit calibrations required for any analyzer should be defined in the operational plan. A clear understanding of the data quality which results from different types of calibrations is important. Rigorously certified gas mixtures should always be used as primary references for the on-orbit standards. Such primary standards must be directly traceable to absolute measurements or to accepted

national or international standards. In practice, it is often desirable to prepare gases with one technique and verify or cross-check with others.

Quality control/assurance measures are necessary in order to maximize data integrity. Unfortunately, however well implemented or operated, equipment malfunction, human error, power failures, interference and a wide variety of other disturbances can result in the acquisition of spurious or incorrect data. This data must be recognized and, if possible, filtered out before final data can be generated or used. The data review process is often regarded as a two-stage process, of data validation followed by reporting. Data validation involves a rapid front-end screening process to identify or remove clearly spurious data prior to reporting. Instruments for on-orbit use rely on software specifically designed for this task. Although this occurs in the background, verification of the efficacy of this process must be performed on the ground prior to implementation. Many commercially available monitoring systems allow for the identification of out-of-range or suspect data and calibration factors. However, adherence to rigid data acceptance criteria and the automatic rejection of flagged data do not necessarily guarantee high data quality. For instance, a potential consequence of following such pre-established data rejection routines is the invalidation of extreme, but at times valid, contaminant measurements simply because they lie outside pre-set or accepted limit values. Active examination of data throughput by knowledgeable personnel can provide a more flexible approach to data validation. This review process can identify possibly erroneous or invalid data and provide quick notification of any equipment malfunction or problem requiring attention. Typically, ground instrumentation rely on both daily data summaries and regular weekly or monthly compilations of graphical data and calibration control charts to assist data review relying on the experience, common-sense and initiative of personnel for the review process to be implemented successfully. This level of data validation is not always practical or even possible for on-orbit instrumentation and should be accounted for prior to final implementation.

ISS CABIN ATMOSPHERE

The ISS cabin atmosphere is very dynamic, constantly responding to changes in crew activities, payloads, equipment, and continuous scrubbing. Although the constituents of the ISS atmosphere are generally believed to be well characterized based on years of archival sampling and, to some extent, real-time monitoring, the behavior of the ISS atmosphere is still very complex and not necessarily well understood. The presence of inter-modular ventilation (IMV) typically allows the assumption that the cabin atmosphere is well mixed between the various modules. However, point sources of specific contaminants are present, and as such, it is not unusual to find higher concentrations in those modules locations. In addition, air quality data

and crew observations have shown that homogeneous mixing may not be a valid assumption. With the lack of gravity, natural convection is absent and diffusional mixing can be quite slow. Payload and stowage issues can be very disruptive to air-flow on-board ISS creating small pockets or areas with minimal or no air-flow. Virtually all aspects of the ISS will affect the quality of the ISS cabin atmosphere. For example, it is well known that areas within a single module can have varying concentrations of carbon dioxide.[1] Similarly, a simple blockage of a screen in the inter-modular ducting with dust and debris has been shown to have a profound effect on the concentration dynamics of formaldehyde.[2] The affect of these ventilation variants can also have a measurable affect on system functionality, inter-modular ventilation, and humidity condensate collection.

Nevertheless, the ISS atmosphere can be considered a relatively homogeneous mixture of chemicals. These chemicals can be categorized as one of two types of constituents – trace contaminants and major constituents. Major constituents include oxygen, nitrogen, methane, hydrogen, water vapor, and carbon dioxide. These major constituents are monitored in real time by the Major Constituents Analyzer (MCA) in the Atmosphere Revitalization rack of the US Lab, the Compound Specific Analyzer – Oxygen (CSA-O₂), and the Carbon Dioxide Monitoring Kit (CDM). Of the six major constituents listed, three, methane, hydrogen and carbon dioxide, are generated by human metabolism. The bulk of the ISS atmosphere contains oxygen, nitrogen, carbon dioxide, and methane. Other contributors include carbon monoxide, hydrogen, and various volatile organic compounds (VOC). Because methane is a major constituent relative to the other VOCs found in the ISS atmosphere, it is more meaningful to separate methane from other compounds classified as a VOC. This, in turn, provides a more realistic picture of the classes of compounds that contribute to the VOC levels. Figure 1 illustrates the organic chemical groups that contribute to the total non-methane VOCs (NMVOC).

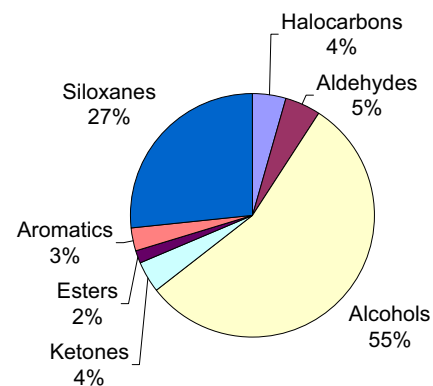


Figure 1. Classes of non-methane volatile organic compounds typically present on ISS