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Airborne Particulate Matter in Spacecraft

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SECTION 2

AGENDA

AIRBORNE PARTICULATE MATTER IN SPACECRAFT

Lunar and Planetary Institute

July 23-24, 1987

Thursday, July 23, 1987

8:00	Depart Holiday Inn	
8:30	Crew Flight Experience with Particulates (bldg. 15)	M. Cleave
9:00	Tour Space Station Mockup	
10:00	Tour 1-g Trainer	
11:00	Lunar and Planetary Institute/ Introduction and Welcome	N. Cintron
11:15	Spacecraft/ECLSS-Systems	J. Whalen
11:35	Debris Collected Postflight	J. Goodman
12:00	Lunch	
1:30	Panel Responsibilities	B. Liu
1:45	Panel Discussion: Acceptability Limits	
4:30	Adjourn	

Friday, July 24, 1987

8:30	Resume Panel Discussion/Acceptability Limits	
10:00	Panel Discussion/Sampling Procedures	
12:00	Lunch	
1:30	Resume Discussion/Sampling Procedures	
3:00	Meeting Summary	B. Liu
3:30	Adjourn	

SECTION 3

PANEL REPORT

3.1 SUMMARY

The Panel on Airborne Particulate Matter in Spacecraft met on July 23-24, 1987, in Houston, Texas, to consider acceptability limits and sampling and monitoring strategies for airborne particles in spacecraft. Based on instances of eye and respiratory tract irritation reported by Shuttle flight crews, the Panel recommended the following acceptability limits for airborne particles:

a. For flights of 1 week or less duration: 1 mg/m^3 for particles less than 10 µm in aerodynamic diameter (AD) plus 1 mg/m^3 for particles 10 to 100 µm in AD

b. For flights greater than 1 week and up to 6 months in duration: 0.2 mg/m^3 for particles less than 10 µm in AD plus 0.2 mg/m^3 for particles 10 to 100 µm in AD

These numerical limits were recommended to aid in spacecraft atmosphere design which should aim at particulate levels that are as low as reasonably achievable (ALARA). Sampling of spacecraft atmospheres for particles should include size-fractionated samples of 0-10, 10-100, and >100 µm particles for mass concentration measurement and elementary chemical analysis by nondestructive analysis techniques. Morphological and chemical analyses of single particles should also be made to aid in identifying airborne particulate sources. Air cleaning systems based on inertial collection principles (cyclones and virtual impactors) and fine particle collection devices based on electrostatic precipitation and filtration should be considered for incorporation into spacecraft air circulation systems. The Panel also recommended that research be carried out in space in the areas of health effects and particle characterization. Specific research recommendations included (1) lung function measurement; (2) regional deposition of particles in the respiratory tract; and (3) characterization of aerosols and gases in the space environment and particle generation, transport, and deposition studies.

3.2 INTRODUCTION

The Panel on Airborne Particulate Matter in Spacecraft was sponsored by NASA to review the available information on airborne particles in the Space Shuttle and to recommend acceptability limits and sampling and monitoring strategies both for the Space Shuttle and the Space Station. The Panel included four aerosol physicists with interests and expertise in lung deposition and health effects (Lippmann) and sampling and monitoring strategies (Liu, Lundgren, and Marple); one industrial hygienist (Ettinger); and two medical scientists specializing in toxicology and the health effects of airborne particles (Hobbs and Utell).

The Panel met for 2 days on July 23-24, 1987, at the Lunar and Planetary Institute, Houston, Texas. Panel members were given a tour of the 1-g Trainer and Space Station Mockup and heard presentations from Astronaut Mary Cleave, who related her experiences on the Space Shuttle, and from other NASA personnel (J. Whalen, J. Goodman), who discussed the particulate matter problem. This is a report of the Panel based on information given to the Panel and the workshop deliberations.

3.3 THE PROBLEM

The primary evidence available to the Panel concerning a possible problem relating to particles in spacecraft atmospheres was verbal reports by Space Shuttle flight crews who mentioned instances of eye and respiratory tract irritation associated with the presence of airborne particles and floating debris in the Shuttle cabin. There have also been reported cases of instrument failure caused by airborne particles. The Panel was shown debris collected from rough avionic filters and vacuumed postflight from Shuttle internal surfaces. The debris included metal shavings; paint chips; hair skin flakes; food particles; and glass and fibrous material, including fibers from clothing, Velcro, and fiberglass.

On one Skylab mission, a limited amount of aerosol measurement was done with a light-scattering instrument. All data were collected in particle counts and were considered to be of limited value. No data on chemical characterization of either individual particles or bulk material were available to the Panel. Apparently, there has been little done to characterize the Shuttle cabin atmosphere for particles.

It is obvious that large particles accumulate in spacecraft atmospheres due to the absence of gravitational fallout mechanisms. Normal gravity on Earth would cause many of these particles to fall out quickly. In the absence of gravity, particles remain airborne for long periods, leading to the buildup of high concentrations in the cabin air.

Although no chemical analysis has been made of the airborne particulate material, it can reasonably be assumed that the material is not highly toxic. The reported instances of eye and respiratory tract irritation by Shuttle crews, however, indicate that the particulate concentration is probably too high to be acceptable. High levels of particulate matter in the cabin air, even of material that is not highly toxic, can lead to severe problems for the Shuttle crew. The Shuttle crew is subject to a great deal of environmental stress: during the prelaunch period, they spend hours in cramped quarters; during launch, they are subjected to high-g forces and vibration; and finally, during flight, they must adjust to the weightlessness of outer space. The existence of additional environmental stress in the form of particulate irritants is certainly undesirable and should be avoided. Such irritants may also impair the crew's ability to perform tasks during critical periods with potentially severe health and/or safety consequences.

3.4 ACCEPTABILITY LIMITS

Aerosols deposit in the respiratory tract of humans by the processes of sedimentation, impaction, diffusion, and interception. Interception is important only for fibers. Sedimentation due to gravity is an important mechanism of deposition of particles in the respiratory tract, especially for particles greater than 0.5 µm in aerodynamic diameter. Under zero-g conditions, sedimentation is not a mechanism of deposition. Thus, deposition of particles in the respiratory tract will be less in zero g, especially for larger particles. However, entry of large particles into the nose and mouth may be easier, and large particles may also come into direct physical contact with the eyes much more easily under zero-g conditions.

The Panel was unanimous in the opinion that the level of particles in spacecraft atmospheres should be ALARA. It was felt that relatively simple aerosol cleaning technology could be used in the Space Shuttle to markedly decrease the level of particles in its atmosphere. Certainly, adequate attention should be given to techniques for particle removal in design of the Space Station.

Because of the lack of information on particle levels, size characteristics, and chemical composition, the Panel was at first reluctant to recommend any numerical acceptability limits for particles in spacecraft atmospheres. However, upon consideration, it was felt that maintenance of concentrations below a specified target level would protect the crew from acute toxic effects, provide relief from discomfort, and be of value in establishing design criteria for particle removal from spacecraft atmospheres. In considering what a numerical limit should be, the Panel considered that the recommended limits would be for a population of very healthy astronauts already engaged in an occupation with a relatively high degree of risk involved. Thus, for example, application of the current EPA standard for <10 µm particulates of 50 µg/m^3 would not be appropriate because this standard is designed to adequately protect the most sensitive individuals in the U.S. population from continuous, long-term exposure.

While, as discussed above, there is currently little information available on the characteristics of the aerosols in the spacecraft atmospheres, the Panel felt that the particles were likely to have many characteristics of nuisance dusts as defined by the American Conference of Governmental Industrial Hygienists. However, there are at least anecdotal reports from Shuttle crews of symptoms of eye and respiratory tract irritation. The Panel also felt that the carcinogenic risk associated with inhaled particles would be relatively small, especially in comparison to the carcinogenic risk from ionizing radiation during space travel. Thus, carcinogenic potential was not specifically considered in the recommendations. The Panel recognized that these views might have to be modified when adequate characterization of spacecraft particles has been completed.

The Panel also questioned if the reported symptoms of irritation were really due to particles. Many felt that the symptoms could also have been due to gases such as ozone, nitrogen dioxide, or formaldehyde directly present in the air or sorbed on particles. Unfortunately, no data were available on measurement of these gases, so no conclusions could be reached.

The Panel recommended that the levels of particles in spacecraft atmospheres be ALARA. To allow for design of appropriate particle control technology for use in the current Space Shuttle vehicles and in the future Space Station, the Panel recommended the following numerical limits:

a. For flights of 1 week or less duration: 1 mg/m^3 for particles less than 10 µm in AD plus 1 mg/m^3 for particles 10 to 100 µm in AD

b. For flights greater than 1 week and up to 6 months in duration: 0.2 mg/m^3 for particles less than 10 µm in AD plus 0.2 mg/m^3 for particles 10 to 100 µm in AD

No specific limit for particles >100 µm in AD was recommended as it was felt that adequate particle cleanup technology to meet the above values would result in acceptable levels of larger particles.

In recommending these limits, the Panel considered acute and chronic irritation of the respiratory tract and eyes to be the primary concerns. In selecting the 1 mg/m^3 limit for short flights, the Panel considered that if the irritation reported was due to the particles and not gases, this limit should protect from irritation of the respiratory tract. This was based on data from exposure of healthy humans to submicrometer-sized aerosols of sulfuric acid at concentrations as high as 1 mg/m^3 with no signs of respiratory tract or eye irritation. The limit for flights of longer duration was lowered by a factor of five to allow for the uncertainties about the toxicity of the particles. The Panel also noted that the 0.2 mg/m^3 limit is the same as that for a U.S. submarine where conditions are somewhat similar to spaceflight.

The Panel recommended a separate limit for particles of 10 to 100 µm in AD, recognizing that these particles are likely to deposit primarily in the upper respiratory tract, while particles <10 µm AD are more likely to be deposited in the lower respiratory tract including the pulmonary region.

It is emphasized that these numerical limits were recommended primarily to aid in design criteria for adequate particulate control for spacecraft atmospheres. In fact, the Panel felt that the use of adequate particle removal technology to remove the large particles, now apparent in spacecraft atmospheres, might result in atmospheres with particle concentrations well below the numerical limits recommended. This is consistent with the ALARA recommendation.

It is also emphasized that levels of particles above these limits probably do not represent a serious immediate health hazard to space crews. Thus, measurement of higher levels should result in actions to correct the situation, but there should be no need to terminate a flight.

3.5 SAMPLING AND MONITORING STRATEGY

Although some recommendations for aerosol concentration limits are discussed and proposed, it is very important to obtain actual measurement of the spacecraft aerosol concentrations, composition, and size distribution. After appropriate aerosol measurements have been obtained, it will then be possible to properly assess the potential hazards which these aerosols may present to humans.

Of greatest concern from a health basis are the <10 µm particles because they are the most likely to be deposited and retained for long periods in the pulmonary region of the respiratory tract. Both the mass concentration and chemical composition of these particles are important and should be measured. This basic measurement requires the precollection or separation of the >10 µm particles, preferably into 10 to 100 µm and >100 µm size fractions. All sizes refer to particle aerodynamic diameter (equivalent to the diameter of a spherical particle of one gram per cubic centimeter density having the same settling velocity). Although these size fractions are based upon human health considerations, they are also consistent with aerosol generation principles and aerosol collection and analysis considerations.

Instrumentation exists to monitor, collect, and analyze airborne particles of almost any type, concentration, and/or size. This type of equipment is reliable and available, but the large size, weight, and power consumption make it unsuitable for direct spacecraft use. However, certain compromises can be made, and a simple and reliable aerosol monitoring and sampling system can be constructed to adequately meet the above requirements.

An educated guess of spacecraft aerosol concentrations may be 0.01 to 1 mg/m^3 for particles <10 µm. For analysis purposes, a minimum sample size for particulate analysis may be 1 mg. This lower concentration estimate would require a sampling rate of 10 L/m for a 7-day mission ($10{,}000 \text{ min} \times 10 \text{ L/min} \times 10^{-3} \text{ m}^3\text{/L} \times 0.01 \text{ mg/m}^3 = 1 \text{ mg}$). Sampler operation need not be continuous if higher concentrations are encountered or multiple samples could be obtained. Operation, in series, with a near real-time aerosol concentration monitor would provide adquate indication of high or increasing aerosol concentrations and would allow for obtaining time-fractionated samples.

A simple aerosol monitoring-particle collection system would consist of the following components:

a. An inlet covered with a wire screen to capture and later analyze the very large (>100 µm) particles (which may otherwise interfere with the sampler operation)

b. An inertial fractionation stage (a virtual impactor or cyclone) which would fractionate out and retain all particles >10 µm in AD

c. An aerosol total light-scattering photometer which would continuously monitor the total light scattered by the <10 µm in AD aerosol

d. An efficient filter which would collect the <10 µm in AD particles for later analysis

e. A simple pump and flowmeter

Such an aerosol sampler could be a few liters in volume, weigh about one kilogram, and operate on several watts of power. Samples of all three particle size fractions would be available for later analysis. The known flowrate and sampling time would produce particle concentration data.

The size fraction of primary interest is the <10 µm sample. It would be weighed to determine particle mass concentration and then analyzed by nondestructive techniques such as x-ray fluorescence or neutron activation for elemental composition. A fraction would be archived for future use and a fraction analyzed by ion chromatography for water soluble ions. A small sample would be viewed in an optical microscope and in an electron microscope for morphology and elemental analysis.

The 10 to 100 µm size fraction would be weighed and carefully analyzed in an optical microscope for particle morphology and, where possible, specific identification. Some elemental and ion chromatographic analysis may also be performed. The >100 µm particles would be analyzed in an optical microscope and identified further.

The Panel also recommended that in addition to the chemical and physical characterization of spacecraft particles, as discussed above, immediate attention be given to measuring levels of irritant gases in spacecraft atmospheres. The gas considered to be of highest priority to measure is ozone, due to the likelihood of it being formed in a spacecraft and its highly irritating properties at low concentrations. The measurement of ozone in the spacecraft can best be accomplished with an onboard, commercially available instrument. Measurement of ozone should be given higher priority than the measurement of other gases that have been measured in the past.

The Panel also recommended that commercially available, passive personal monitors be used during flight to monitor nitrogen dioxide and aldehydes such as formaldehyde. This should be done at the next available opportunity. The monitors can be exposed during flight and analyzed upon return. Following the return of the next Space Shuttle, its duct work should also be swabbed and cultured for fungi and other biologically active materials.

3.6 AIR CLEANING

3.6.1 Rationale

As previously indicated in this report, allowable particle concentrations in the Shuttle or Space Station air should be reduced to levels which are ALARA even though specific criteria are identified for the <10 µm and 10 to 100 µm size fractions. This ALARA concept is desirable, since without detailed knowledge of the chemical composition and size distribution of the contaminant particles present in the space vehicle it is not clear what health effects can occur. Because this information will not be available for some time, the design of the Space Station must be initiated in the absence of such data. ALARA levels can be attained by a combination of administrative procedures to limit the source terms and by using properly designed and maintained engineering air cleaning systems to remove particulates which inevitably will be produced due to operations in the Space Station.

Briefings presented during the workshop indicate that NASA is implementing administrative procedures to reduce sources of particulate contamination during ground activities. However, these procedures alone cannot provide a particle-free environment, due to the complexity of operations on the ground and the activities which must occur during flight. Therefore, an air cleaning system should be provided for the Space Station, and modified versions for the Shuttle should be developed in the future. Retrofitting an air cleaning system to existing Shuttles would also be desirable and highly recommended. The following guidance is provided to assist the current NASA efforts in this area and is consistent with the air quality levels previously noted in this report.

In designing the air cleaner, two facts must be considered:

a. A high level of performance (high degree of cleanup of cabin air) must be provided for both large particles (>10 µm) and small particles (<10 µm) to control the eye/respiratory tract irritation reported by astronauts on previous flights (assuming this irritation is due to particles and not gases/vapors).

b. Dust loadings which exist in the spacecraft would present a continually increasing pressure drop for most high collection efficiency air cleaners.

For these reasons a multistage design is recommended. The first stage would be a system which has a high collection efficiency for relatively large particles (>10 µm) without the potential for increasing pressure drop over long operating time periods. Such systems (described below) are commercially available in several different designs with modest energy requirements. These systems have a high holding capacity for collected particles, are simple to maintain, and have a low collection efficiency for small particles. The second stage of the air cleaning system would compensate for this deficiency (low efficiency for particles <10 µm) and would be protected against the increasing pressure drop problem by the first stage of the air cleaning system. Such systems are also commercially available in several different designs.

There are a number of devices that can be used to remove particles from the air if the air is transported through these devices with a blower or other appropriate air mover. At the entrance to the large/small particle removal devices, there should be some type of coarse screen or webbing to prevent large objects from entering and clogging the cleaning devices. There is essentially no pressure drop in passing air through such a screen, and the screen should be placed so that particles collected on it can be easily removed by the astronauts.

The air cleaning problem can also be modeled by assuming that air is removed from a space, the particles are removed from the airstream, and the clean air is returned into the space and thoroughly mixed with the ambient air already present.

3.6.2 Large Particle Cleaning Device

Large particles (>10 µm) can be removed very easily from the airstream by employing some type of inertial separator such as a cyclone or virtual impactor system. Using cyclones would be the most conventional since these devices have been used for gas cleaning for several decades. They are known for their reliability (no moving parts), high capacity of particle retention before overloading, and moderate-to-low pressure drops. In spacecraft operation it may be advantageous to consider using a multicyclone assembly which will have a lower pressure drop than a single cyclone with the same total flowrate and collection efficiency.

The virtual impactor is another simple inertial classifier which operates much like a high-capacity impactor since it consists of a jet of air impinging into a cavity. The large particles penetrate into the cavity with a small amount of air and are removed by a filter. Again, multiple virtual impactors used in tandem can reduce pressure drop.

3.6.3 Small Particle Cleaning Device

After the large particles have been removed from the airstream, the air can be passed through a device to remove the small particles (<10 µm). Devices which should be considered are filters or electrostatic precipitators.

Filters are available in a wide range of pressure drops and collection efficiencies with pressure drops increasing as the particle collection efficiency increases. It may not be necessary to use high-efficiency particulate air (HEPA) filters because the same results can be obtained by moving more air through a lower efficiency filter which produces a lower pressure drop. The lower efficiency filter is also less likely to become plugged. High-efficiency filter materials such as electrets should also be considered.

Another device which can remove small particles efficiently at low pressure drop is the electrostatic precipitator (ESP). However, caution must be taken with use of an ESP to ensure that excessive ozone is not generated. These devices are currently used in submarines for air cleaning.

3.6.4 System Design

The previous sections have outlined the type of engineering air cleaning controls which can provide a significant reduction in the particulate contamination level in spacecraft. While the components for such a system are commercially available, in designing the system careful attention should be paid to details, especially for the high-efficiency second stage. For example, it is pointless to install a 99.97 percent HEPA filter in a manner which permits significant quantities of particulate contamination to bypass the filter through poorly designed gasket seals or filter-holding mechanisms which loosen as a result of vibration or cabin pressure changes. Examples of such poor designs have been found in some installations where attention to detail is lacking. One means of assuring a high-level system performance is the inclusion of the capability for routine in-place testing of the high-efficiency air cleaner. Probably the best examples of such systems and test methods are found in the nuclear industry.

System designs should also have airflow distribution within the spacecraft to avoid the buildup of particles in any areas where air movement is limited. This will represent a relatively unique design consideration for the zero-g situation. NASA is already considering this question in its plans to provide air cleaning for the Shuttle. To fully evaluate this problem, theoretical modeling of the airflow patterns within the cabin using alternate methods for creating mixing would be desirable. An experimental evaluation of the many options available would be difficult to perform.

Another design option which should be considered is the use of only the large particle air cleaner for air supplied to the avionics equipment, while a smaller volume of air is treated by both the large and small particle air cleaners. Over time, the cabin air would be cleaned up by this smaller volume of clean airflow, provided the rate of particle removal of the air cleaner is higher than the rate of particle generation in the cabin.

3.7 RESEARCH RECOMMENDATIONS

Because long-duration spaceflight by humans involves unknown health effects and risks, it would be advantageous for NASA to initiate basic research programs to examine these effects and to address in a fundamental way questions about particulate contamination in spacecraft. The following areas of research were recommended by the Panel for investigation by NASA.

3.7.1 Lung Function Measurements

The physiological effects of prolonged weightlessness include important changes in lung function. The lung is extremely sensitive to gravity which normally causes the apex-to-base differences of ventilation, bloodflow, and gas exchange. However, pulmonary function has had minimal study in weightlessness, and additional measurements should be made on lung function in space. A variety of approaches could be used ranging from simple but repeated measurements of flowrate with peak-flow meters or simple spirometry to more sophisticated measurements of gas distribution, capillary blood, et cetera, by rebreathing soluble gases. Furthermore, it is important to point out that repeated measurements of lung function would also provide important diagnostic information. This would especially be the case in evaluating lung function changes after accidental inhalation of toxic vapor, gases, or particles.

3.7.2 Regional Deposition of Particles in the Respiratory Tract

The deposition pattern and efficiency of inhaled particles in the respiratory tract will differ in a zero-g environment from those on Earth because of the absence of sedimentation as a deposition mechanism. The effect becomes increasingly important as particle size increases above 0.5 μm as sedimentation displacement becomes significant in relation to the size of small airways. For particles of >10 μm, sedimentation will become increasingly important because it greatly affects the persistence of the particles in air and, hence, the likelihood that they will be aspirated into the nose or mouth. It is expected that large particles will tend to dominate the aerosol concentration at zero g to a much greater extent that at one g. The toxic dose potential of airborne particles can therefore be quite different at zero g, and the current lack of knowledge about airborne levels and the effects of zero g on deposition efficiencies at various levels of the respiratory tract may preclude accurate modeling of these differences. On the other hand, direct measurements of deposition efficiency could be performed in spacecraft, providing applicable data for toxicant dosimetry.

The Panel recommended that deposition experiments be performed in future spacecraft missions using relatively simple monodisperse aerosol generators and continuous photometric particle detectors for the purpose of determining deposition efficiencies in the human respiratory tract as a function of particle size, tidal volume, and ventilation rate.

3.7.3 Characterization of Aerosols and Gases in Spacecraft and Particle Generation, Transport, and Deposition Studies

Maintaining a suitable environment for long-term occupancy and for instrument and equipment operation requires characterization and control of the airborne contaminants generated in the spacecraft. This will require the following:

a. Determination of the concentration, chemical compositions, and biological nature of airborne particles as a function of particle size

b. The quantitative mesurement of selected gases and vapors (e.g., formaldehyde, ozone, oxides of nitrogen, et cetera)

c. Determination of the surface sorption or reaction of selected gases and vapors with particles--as a function of particle size

d. Deposition or removal of these pollutants

e. Knowledge of generation rates

Having this information will provide an estimate of the potentially adverse health effects on the astronauts due to inhalation or sorption of toxic or biologically active chemicals. It will identify sources of spacecraft contaminants, providing information which is needed to develop procedures for controlling the release of these contaminants through the use of engineering controls or material substitution. Physical, chemical, and biological analysis should be performed on the samples after they are returned to Earth. In addition, fundamental studies should also be made to determine the mechanisms of particle generation, transport, and eventual deposition on surfaces in order to provide the basic knowledge needed for the design of future-generation spacecrafts. This may become critical if clean laboratory or manufacturing space must be provided for scientific research or for material or device production in space.

As emphasized in this report, symptoms of eye and respiratory tract irritation have been reported by Shuttle crews. They have associated these symptoms with the presence of aerosols including large debris in the Shuttle atmosphere. The Panel had concerns that the observation and association of the symptoms with particles could be incidental. In the opinion of several Panel members, this irritation could be due to irritant gases. As emphasized in the body of this report, ozone, nitrogen dioxide, and aldehydes should be measured in the near future. Additional research on the levels and sources of irritant gases is also warranted.

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15. Supplementary Notes

Benjamin Y. H. Liu, Ph.D., an aerosol physicist at the University of Minnesota, served as chairman of this panel. Dane M. Russo, Ph.D., organized the panel.

16. Abstract

The Panel on Airborne Particulate Matter in Spacecraft met on July 23-24, 1987, in Houston, Texas to consider acceptability limits and sampling and monitoring strategies for airborne particles in spacecraft. Based on instances of eye and respiratory tract irritation reported by Shuttle flight crews, the Panel recommended the following acceptability limits for airborne particles: (1) for flights of 1 week or less duration - 1 mg/m^3 for particles less than 10 µm in aerodynamic diameter (AD) plus 1 mg/m^3 for particles 10 to 100 µm in AD; and (2) for flights greater than 1 week and up to 6 months in duration - 0.2 mg/m^3 for particles less than 10 µm in AD plus 0.2 mg/m^3 for particles 10 to 100 µm in AD.

These numerical limits were recommended to aid in spacecraft atmosphere design which should aim at particulate levels that are as low as reasonably achievable (ALARA). Sampling of spacecraft atmospheres for particles should include size-fractionated samples of 0-10, 10-100, and >100 µm particles for mass concentration measurement and elementary chemical analysis by nondestructive analysis techniques. Morphological and chemical analyses of single particles should also be made to aid in identifying airborne particulate sources. Air cleaning systems based on inertial collection principles (cyclones and virtual impactors) and fine particle collection devices based on electrostatic precipitation and filtration should be considered for incorporation into spacecraft air circulation systems. The Panel also recommended that research be carried out in space in the areas of health effects and particle characterization. Specific research recommendations included (1) lung function measurement; (2) regional deposition of particles in the respiratory tract; and (3) characterization of aerosols and gases in the space environment and particle generation, transport, and deposition studies.

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