# CONTROL OF PARTICULATE MATTER AND MICROORGANISMS IN MANNED SPACECRAFT

<LS-157

October 20, 1965





GARRETT <AIRESEARCH MANUFACTURING DIVISION
Los Angeles, California

52629

# CONTROL OF PARTICULATE MATTER AND MICROORGANISMS IN MANNED SPACECRAFT

LS-157
October 20, 1965

Prepared by

D. K. Edwards

AIRESEARCH MANUFACTURING DIVISION
Los Angeles California

CONTENTS


| Section | | Page |
|---|---|---|
| 1 | INTRODUCTION | 1-1 |
| 2 | PARTICLE REMOVAL AND CONTROL | 2-1 |
| | General | 2-1 |
| | Particles from Human Sources and Related Systems | 2-4 |
| | Conclusions | 2-33 |
| | Recommendations | 2-35 |
| 3 | MICROBE CONTROL | 3-1 |
| | Introduction | 3-1 |
| | Methods and Techniques for Microbe Control | 3-2 |
| | Conclusions | 3-48 |
| | Recommendations | 3-55 |

# SECTION I

## INTRODUCTION

This report considers two major areas of life-support system design that in the past have been treated lightly or naively in the discussion and design of such systems. These areas are the control of contaminant particulate matter and of microorganisms in the spacecraft cabin, atmospheric system, and water supply system. These problems will be of considerable magnitude on long-term missions. Though the discussion presented in this report is fairly detailed, many aspects are mentioned only briefly or not at all, because of a lack of available information in the field; a great deal of important information is lacking simply because the requisite research has not been accomplished. Also, a great many factors, including the nature and design of waste-management, personal-hygiene, and food-preparation systems, interact with the particle- and microbe-control areas. Nevertheless, the discussion here is adequate for at least a preliminary examination of the various problems involved, and of the current thinking on the best methods of control.

The material in this report was originally prepared specifically for the requirements of extended missions in the Apollo vehicle, with a maximum mission length of 120 days. Thus this report is oriented to fairly long-term missions. The conclusions and recommendations presented are specific to the Apollo environmental control system, although much of the material is generally applicable to other closed ecological systems, space vehicles, and extraterrestrial bases and laboratories. The purpose of this report is to provide a fundamental knowledge of the problems involved in these areas and sufficient understanding to enable consideration of other vehicles and missions.

In the discussion of particle control, the author is greatly indebted to Mattoni and Sullivan, Sanitation and Personal Hygiene During Aerospace Missions (Aerospace Medical Research Laboratories MRL-TDR-62-68), and to Dr. Paul Webb's Bioastronautics Handbook (NASA SP-3006). In the discussion of bacterial control, the primary sources were Decker, Buchanan, Hall, and Goddard, Air Filtration of Microbial Particles (P.H.S. Publication No. 953) and the report by C. R. Goucher at Melpar, Inc., Study for Control of Microbial Growth in Manned Spacecraft (NASA Contract NAS 9-3563). These documents contain a great deal of useful information and should be consulted for additional data in their appropriate areas.

# SECTION 2

# PARTICLE REMOVAL AND CONTROL

## GENERAL

It is expected that during normal spacecraft operations a wide variety of particles will be released into the cabin atmosphere. These particles will be solids and liquids, ranging in size from large visible particles to aerosol-range dusts and droplets. Much of this debris will consist of material that will provide an excellent medium for bacterial growth, and almost all of it will be contaminated with viable microorganisms. Even the comparatively inert materials can be very damaging in appreciable amounts by causing equipment malfunctioning, line clogging, potential toxicity, etc. It is therefore necessary to remove this debris from the cabin atmosphere and to prevent its reentry.

In considering the requirements for a system to remove particles from the cabin environment, several factors must be determined and examined, e.g., (1) the nature of the particles, (2) the configuration and type of the environmental control system, (3) power, weight, and volume limitations, (4) maintenance requirements, and (5) the reliability and safety of the particle-removal systems considered. The first of these factors is very important, because it is the least amenable to modification by selection and design; the nature of the particles, especially those produced by the human occupants, may be considered essentially fixed, and thus is the factor that to a great extent governs the others.

There are two basic methods of regulating the particle level: source control and particle removal. Source control should be used to the greatest extent possible, because it is the most economical and offers greater long-term reliability and safety. In general, it is always preferable to prevent the formation of atmospheric contaminants rather than to remove them after they have formed. This prevention can be accomplished by maintaining rigorous specifications for the component materials used in the vehicle. The quantity of debris given off by humans is not amenable to change, however, optimum design of personal-hygiene, waste-management, and food-processing systems should enable most of these materials to be safely contained.

The types of particles that must be handled either by source control or by particle removal are discussed in the following paragraphs. These particles may best be classified by their origin; that is, those particles that arise from the vehicle components and those that arise directly or indirectly from the cabin occupants. Although this classification is arbitrary, it nevertheless reflects the primary method that will be used to control each type of particle.

## PARTICLES FROM SPACECRAFT MATERIALS

It is anticipated that none of the components used in the space vehicle will produce any appreciable particulate contamination. Contamination from this source can be eliminated by proper material selection, implemented by

rigorous specifications and quality control. These specifications can be stated briefly. Plastics, polymers, and elastomers must be compatible with the ambient environments that will be encountered in the prelaunch, launch, and mission conditions. They must not be degraded, cracked, crazed, flaked, etc., by any of the thermal, pressure, gas composition, humidity, and acceleration conditions encountered during the entire mission. Similarly, metals and other materials must be finished and treated to preclude the production of any particles during the mission.

Components containing moving parts or components that may be subjected to wear must either be isolated from the atmospheric system or designed or treated to minimize the generation of abraded materials. Components included in this category are those that will be affected by the movements or activities of the astronauts; e.g., switches, seats, clothing, restraining devices, hinges, fasteners, writing materials, etc. Equipment that contains fluids and other volatile or particle-forming materials must be designed so that not only do their external surfaces remain coherent, but also so that they do not leak or spill the materials they contain. This requirement pertains particularly to fuel and water lines, food containers, waste management components and containers, and the particle removal system itself. Electrical insulation must remain stable from the standpoint of toxicity and with respect to material breakdown under the maximum anticipated electrical overload.

Those systems that are involved with particulate or potentially particulate materials must be designed to function with the minimum release of particles to the cabin atmosphere. The food preparation system should function so that minimum spillage occurs during the complete operation cycle, from the time the food is removed from the storage area to the final disposal of the scraps and container materials. This will involve adequate packaging and food-preparation techniques, and leak-free mating with the water supply and disposal system, as well as the eating technique used by the astronaut. The personal-hygiene system is intended to prevent the release into the atmosphere of a fairly large number of potential contaminating materials excreted by or removed from the human body; these products (described in detail below) include hair, dermal products, fingernail clippings, etc. Proper design and function of this system is required to ensure that these products are not released into the atmosphere during use, also, the materials used in the personal-hygiene system, such as wash water, cleaning agent, and dentifrice, must not be released into the atmosphere. Similarly, the waste-management system must be designed so that its use does not produce atmospheric contamination; this system is particularly critical because of the nature of the particles and gasses involved.

Adequate design of these potentially particle-producing systems should present no large problems; present systems perform the primary physical aspects of their functions quite adequately. However, frequently neglected aspect of design that is of major importance is human engineering. It is recommended that a human engineering staff be involved in all phases of the design and development of these systems. Since none of these systems is amenable to automatic operation during its primary use, it is imperative that the astronauts who are to operate the systems be able to do so in the most efficient manner. With respect to particle control, particularly, the vehicle occupants must be able to carry out their system-related tasks in such a way that the systems

function optimally in preventing particles from being released. Thorough training is also necessary, because even with the best design, particles will be released if the system is used improperly or carelessly. This training must include considerable practice by the specific crew members who will take part in the mission; some dexterity on their part will be required with any system, however well designed. It is much better for this dexterity to be thoroughly learned on the ground, so that the learning process places no high burden on the particle removal system. This training may also indicate final changes in the system that may be required before launch, as well as provide a final system check-out.

System interfaces, particularly the various man-to-machine interfaces, must be designed and constructed so that they present no potential source of particulate matter. Moving parts that may wear or abrade have already been mentioned. Again, components that might interfere with the use of potentially particle-producing tasks or systems must be removed or repositioned; for example components should not be placed where the astronauts are apt to knock against them during personal-hygiene operations, food preparation, etc. This will require human-engineering analyses of the entire cabin. Materials or components that are apt to abrade, scrape, or cut the astronauts must be eliminated, as well as those that could abrade, scrape, or chip other components.

The equipment surfaces and materials, as well as the particles removed from the atmosphere, will also offer a hazard from the growth of microorganisms. Organisms that are permitted to grow on surfaces may be expected to enter the circulating atmosphere and increase both the quantity and the danger of airborne particulate contaminants. In addition to the inherent hazards of microbial contamination, a further danger is presented by the ability of many organisms to degrade their substrate material, thereby weakening the contaminated surface and allowing flaking and aerosolizing of the material itself, besides causing equipment malfunctions, etc. Such microbial growth must be prevented by the bacteria-control provisions, which are discussed later in this report. For many surfaces, treatments to render the surface resistant to bacterial or fungal growth will be used. Such coatings should not only resist bacterial growth but should not permit surface degradation from the ambient atmosphere and environmental conditions. Where such surface treatments cannot be used, the antibacterial technique (washing, for example) should be compatible with the integrity of the surface. Also, the treatment itself, particularly wiping with soap or bactericide, should be designed and carried out to minimumize airborne contaminants.

It is inevitable that, despite the greatest care in component design, material selection, human engineering, testing, and training, some debris from the cabin materials will be introduced into the cabin atmosphere. A listing of these materials will not be attempted here, because all of the materials and components will be chosen and designed to give off no particles at all, and it is difficult to say exactly what materials will fail in this respect. It is expected, however, that the particles may consist of materials from equipment surfaces, including metallic and elastomeric dusts from surface oxidation and volatilization, fabric lint, flakes of coatings, oil residues from machining processes, microorganisms from surface films, escaping lubricants, and perhaps escaping liquids from fuel, water, and refrigerant lines. It is difficult to

estimate the quantity of material produced, especially since the particles themselves cannot be precisely identified. Mattoni and Sullivan (Reference 1) have estimated a maximum of 0.7 gm per man day of materials emanating from cabin sources, assuming optimum source control. This estimate includes gaseous contaminants as well as particulate contamination; the authors suggest that this figure would diminish on a man per day basis with a larger crew. A more meaningful estimate that discounts gasses (which are not considered here) is a maximum of 0.4 gm per man day. Because of the dependence of this figure on undetermined or uncertain items (e.g., the care exercised by the astronauts in using the various systems, the long-term effects of the environment on the cabin materials, components, and inhabitants), this figure should be interpreted as merely an order-of-magnitude estimate as to the maximum quantity that should be encountered from this source.

PARTICLES FROM HUMAN SOURCES AND RELATED SYSTEMS

This category includes all of those particles that are produced by the crew of the space vehicle, as well as those which are produced or encountered in operating the food-preparation, potable-water, waste-management, and personal-hygiene systems. While any of these system components may give off particles (due to material breakdown, leakage, etc.), the only materials considered here are those that would be produced during operation of the system by the crew.

Table I presents a list of the potential particle sources that are either directly human in origin or that might be released by systems in direct contact with the human occupants of the spacecraft. These materials can be expected to appear as particles during the mission, with varying probabilities of occurrence; hair and food particles, for example, will almost certainly be encountered, while blood and vomitus are much less probable. Next to the list of possible particle sources is the generation rate of the physiological materials, where the rate is known or meaningful. This generation rate is not necessarily the same rate at which these materials can be expected to appear in the cabin atmosphere. Hair is a case in point; the growth rate is not generally the same as the rate at which hairs become detached. The rates at which particulate materials enter the cabin atmosphere are for the most part rough estimates based on the generation rates and on data found in the references. Many of these factors are unknown, many are subject to wide individual variations, most are subject to the efficacy of the relevant system, several will be produced only intermittently, and a few are expected very rarely. These factors are also noted in Table I.

Most of these potential particle sources will be controlled by specific systems so designed that they reduce or eliminate the particulate contamination. In these cases, the quantity of particles produced will reflect the adequacy of the system design and the care exercised by the astronauts in the use of the systems. Poor system design could be expected to result in a fairly constant contaminant generation rate, but, with adequate design, this rate should be quite small. Single accidents on the parts of the system users could, however, load the atmosphere with a very large quantity of particulate matter; therefore, training and careful use are extremely important. Since events such as vomiting could create a very large quantity of particulate matter, the particle-control system must be capable of handling large short-term loads;

# TABLE I

## POTENTIAL CREW-PRODUCED PARTICLE SOURCES

| Potential Particle Source | Estimated Production (gm/man-day) | Estimated Loss Into Atmosphere, (gm/man-day) | Reference | Expected Method of Handling or Control | Remarks |
|---|---|---|---|---|---|
| Dermal Materials | | | | | |
| Water | | | | Water-reclamation system (ECS) | Sensible water loss will occur infrequently, but any droplets that do occur, will contain dissolved materials |
| Solids in sweat | 3 00 | 0 30 | 1 | Personal-hygiene system | Estimate based on average concentrations in perspiration under the anticipated perspiration rates |
| Sebum residue | 4 00 | | 1 | Personal-hygiene system | |
| Epithelium | 3 00 | 0 30 | 1 | Personal-hygiene system | |
| Hair | | | | | |
| Facial | 0 035-0 300 | | 2,1 | Personal-hygiene system | Shaving loss, varies widely with individuals. |
| Scalp | 0 17 | | 1 | Personal-hygiene system | Depilation loss from scalp and body may be expected to occur as discrete hairs, hence the generation rate is not too meaningful Approximately 1000 hairs per day will be shed, assuming no radiation loss |
| Body | 0 12 | | | | |
| Fingernails | 0 01 | | 1 | Personal-hygiene system | Encountered as discrete clippings (nails trimmed every 2 to 3 weeks) |
| Toenails | 0 0025 | | 1 | Personal-hygiene system | Encountered as discrete clippings (nails trimmed every 6 to 8 weeks) |
| Tears | 0 86 | | 3 | Personal-hygiene system | Usually wiped and allowed to dry on skin or clothing, blinking may release droplets. |
| Saliva | 846 | 0 01 | 4,1 | | Estimate based on three meals per day Most of this quantity is swallowed, but droplets may be expelled in expiration, sneezing, coughing, talking, etc Droplets may be mixed with food particles. |
| Mucus | 0.04 | 0 005 | 1 | | Production varies widely with individuals Usually swallowed, but may be expelled with coughing or sneezing Production greatly stimulated by respiratory irritants, infections, allergic states, etc |
| Feces | 60-250 | 0 002 | 5, 1 | Waste-management system | Atmospheric particles may be produced during defecation, flatus expulsion, waste handling, and personal hygiene The quantity of particles produced will depend on the system and the care taken in its use |
| Urine | 210-9200 | 0 025 | 6,1 | Waste-management system | Production varies with many factors, including diet, sweat rate, mental and physical state, droplets or solids may be produced by unintentional urination or misuse of the waste-management system |
| Cerumen (ear wax) | | | | Personal-hygiene system | Dried cerumen in the external canal of the ear may flake off into the atmosphere |
| Semen | | 0.003 | 1,5 | | Quantity per emission highly variable even in the same individual range, 0 2 to 6 6 ml, mean, 3 4 ml Droplets may occasionally penetrate clothing in unintentional or nocturnal emissions or be produced in subsequent cleaning |
| Vomitus | | 0.5 | 1 | | Not expected normally, but particles and debris may be expected if vomiting should occur Quantity, 30 to 300 ml per vomiting event |
| Blood, pus, other Unanticipated fluids | | | | | Not expected normally, blood from small cuts would be expected most frequently |
| Wash water | | | | Personal-hygiene system | Would be expected to contain hair, skin secretions, cleaning agents, etc The quantity will depend on the adequacy of the personal-hygiene system and the care taken during its use |
| Drinking water, water for food preparation | | | | Potable-water system food-preparation system | |
| Food | | 0 55 | 1 | Food-preparation system | Quantity released will depend on the adequacy of the systems and the care taken in its use. |
| Dental and oral cleansing agents | | | | Personal-hygiene system | |
| Lint clothing fragments | | | | | Bits of fiber are worn off clothes during wearing, body hair is particularly productive of lint |

estimated daily losses become meaningless in this respect. Nevertheless, such estimates are useful in obtaining an idea of the total load to which the particle-control system will be subjected during a mission. One of the better of these estimates is that given in Reference 1, which provided much of the data in Table 1, the weight and volume per man-day estimates of the major waste products produced in a generalized spacecraft are presented in Table 2. A breakdown of these figures into the estimated quantities that may be expected to be deposited in various places in the cabin is given in Table 3. According to this breakdown, the total quantity of solids, excluding feces, flatus, urine, and insensible water wastes, is 12.363 gm, and the quantity of solids that may be discharged into the atmosphere is 1.891 gm per man-day. These estimates are probably high, especially for a multiman vehicle; thus their use in system selection for such a vehicle will contain a built-in safety factor. It appears that approximately 2 gm of material is a reasonable design figure for the quantity of particles released per man-day.

The following paragraphs describe in some detail the various materials listed in Table 1. The descriptions are necessarily fairly brief and perhaps oversimplified, but should be adequate in most cases for determining the nature of the materials that will be encountered by the particle-control system, and so establish the primary requirements of the system.

Dermal Materials

1. Water

Sensible and insensible water loss from the skin surface will generally take place as evaporation, and the water in the atmosphere will be removed by airconditioning in the spacecraft ECS. However, during periods of sensible water loss, droplets may be formed that can be inadvertently knocked or jarred off the skin surface. The particle-control system may very infrequently encounter such droplets of perspiration. More generally, these droplets will evaporate either in the air or after impingement against some surface, leaving behind a solid residue containing the dissolved materials that were present in the droplet. These materials will then remain to be removed as atmospheric dust or as light coatings on surfaces.

2. Solids in Sweat

Perspiration may be glandular in origin or the result of water diffusion through the epidermis. The glandular perspiration is of greatest interest with respect to particle-control, because it contains various dissolved solids, and because it constitutes the greater quantity of perspiration produced. Glandular perspiration is secreted by two types of glands, the eccrine sweat glands and the apocrine sweat glands. Eccrine glands are distributed with varying surface density over all of the body surface except the lip margins, glans penis, and nipple; apocrine glands are limited to the axilla, areola, genitalia, and circumanal regions. These glands differ in structure and in the composition of their secretions.

TABLE 2

SYNOPSIS OF WEIGHT AND VOLUME OF WASTE PRODUCT GENERATION FROM ALL SOURCES IN THE CLOSED ENVIRONMENT OF A HIGH PERFORMANCE MANNED SPACE VEHICLE*

| | Mass, gm/man-day | Volume, ml/man-day |
|---|---|---|
| Miscellaneous cabin compounds | 0.700 | 0.720 |
| Food spillage | 0.700 | 0.700 |
| Desquamated epithelium | 3.000 | 2.800 |
| Hair, depilation loss | 0.030 | 0.030 |
| Facial, shaving loss | 0.300 | 0.280 |
| Nails | 0.010 | 0.010 |
| Solids in sweat | 3.000 | 3.000 |
| Sebaceous excretion, (residue) | 4.000 | 4.200 |
| Solids in saliva | 0.010 | 0.010 |
| Mucus | 0.400 | 0.400 |
| Seminal fluid, (residue) | 0.003 | 0.003 |
| Urine spillage | 0.025 | 0.025 |
| Fecal particles | 0.025 | 0.023 |
| Flatus as gas | | 2000.0 |
| Microorganisms | 0.160 | 0.140 |
| Solids in feces | 20.0 | 19.0 |
| Water in feces | 100.0 | 100.0 |
| Solids in urine | 70.0 | 66.0 |
| Water in urine | 1400.0 | 1400.0 |
| Insensible water | 1200.0 | 1200.0 |
| Total | 2802.363 | 2807.341 |
| Total excluding urine, feces, flatus, and insensible water | 12.363 | 12.341 |
| Total solids | 102.363 | 97.341 |
| Total water | 3700.000 | 3700.000 |
| Total gas | | 2000.000 |

*Reference 1

TABLE 3

ESTIMATED QUANTITIES OF WASTE PRODUCTS PRIMARILY DEPOSITED IN VARIOUS NICHES OF THE ENVIRONMENT OF A MANNED SPACE VEHICLE IN GRAMS PER MAN PER DAY
(+ INDICATES PROBABLE TRACE)

| Product | Epithelial Surface | | | Clothes[1] | Atmosphere | Surfaces | Containers | Total |
|---|---|---|---|---|---|---|---|---|
| | Face | Body | Mouth | | | | | |
| Misc Equipment Compounds | 0 005 | 0.010 | | 0.015 | 0.650 | 0.020 | | 0 700 |
| Food Spillage - Solids | 0 040 | 0 060 | | 0.050 | 0 550 | 0 050 | | 0.700 |
| Desquamated Epithelium[2] | 0 073 | 2 362 | 0 015 | 0 250 | 0.300 | + | | 3 000 |
| Depilated Hair | | 0.020 | | | 0.010 | + | | 0 030 |
| Shaver Cuttings | | | | | 0.050 | + | 0.250 | 0.300 |
| Fingernail Cuttings | | | | | | | 0 010 | 0.010 |
| Solids of Sweat[2] | 0.073 | 2 362 | 0.015 | 0.250 | 0 300 | + | | 3 000 |
| Sebaceous Residues[2] | 0 078 | 2.406 | 0 016 | 1 500 | | + | | 4.000 |
| Solids of Saliva | 0.004 | | 0.002 | | 0 004 | + | | 0 010 |
| Solids of Mucus | 0.010 | | | 0.385 | 0 005 | + | | 0.400 |
| Solids of Seminal Fluid | | 0 001 | | 0 002 | | | | 0 003 |
| Fecal Particles | | 0.015 | | 0.008 | 0.002 | + | | 0 025 |
| Microorganisms[2] | 0.002 | 0 064 | 0 004 | .060 | 0.020 | 0 010 | | 0.160 |
| Flatus as Gas | | | | | 2000.000 ml | | | 2000.000 ml |
| Solids in Feces | | | | | | | 20.000 | 20 000 |
| Solids in Urine | | 0.010 | | 0.015 | | | 69.975 | 70.000 |
| Water in Feces | | | | | | | 100.000 | 100.000 |
| Water in Urine | | | | | | | 1300 00 | 1330 000 |
| Insensible Water | | | | | 1200.000 | | | 1200 000 |
| | 0.285 | 7 310 | 0.052 | 2.535 | 1.891 - Solids | 0.080 | 1520.235 Solids | 2732 363 102 363 |
| | | | | | 1200.000 - Water | | Water | 2630.000 gr. |
| | | | | | 2000.000 - ml/Gas | | Gas | 2000.000 ml |
| | | | | | | | Solids Not F F.U.[3] | 12 363 gr |

[1] Including wipers

[2] Assuming sufficient bathing to preclude buildups to an extent sufficient to be significantly lost by ablation

[3] Total excluding urine, feces, flatus, and insensible water

The composition of sweat, largely eccrine in origin, is presented in Table 4. The specific gravity of sweat ranges from 1.001 to 1.006. Changes and day-to-day differences in the chemical composition of sweat can be brought about by changes in the demands placed on the thermoregulatory system, the composition of the diet, and individual variations; these factors, as well as the differences in composition caused by sweat collection at different body areas, account for the wide ranges in the values shown in Table 4.

No comprehensive work has been done to elucidate the precise chemical difference between apocrine and eccrine sweat. The primary differences that have been measured are that apocrine sweat is fluorescent and has a higher pH than eccrine sweat (5.0 to 6.5 as opposed to 4.0 to 6.0). Also, most unpleasant body odor seems to be produced by bacterial action on apocrine sweat.

Roughly speaking, the quantity of sweat solids produced is a function of the rate of sweating. One liter per day of sweat would produce a minimum of 0.5 gm per man day of solid residue. According to the data presented in Reference 1, this figure is minimal, and 2 to 3 gm of solids per day is a more realistic estimate; the higher figure is suggested for estimating system requirements. Almost all of this material is soluble, so it will be readily removed by bathing, and no more than an estimated 0.3 gm per man day should reach the atmosphere. However, this material may be released in considerably higher quantities if the personal-hygiene system is used carelessly.

3. Sebum Residue

The surface of the skin is covered by a film consisting of an aqueous-lipid emulsion (Reference 1). The aqueous phase is water from perspiration, while the lipid is contributed by sebum, keratinization, and the apocrine sweat glands; the emulsifiers are cholesterol and wax alcohols. This film, at least the sebaceous components, seems to have a fungicidal effect, and as such serves a protective function. Also, the film seems to prevent excessive drying and exfoliation of the epidermis. The sebum production rate is apparently controlled by the quantity present in the skin film, this quantity, as long as the film is undisturbed, remains constant at the so-called saturation level. This level varies with the particular portion of the body, the temperature, and other factors; the mean level is 0.5 mg per sq cm, with a range of 0.035 to 3.380 mg per sq cm. When this level is reduced (usually by bathing or clothing abrasion), an excretory mechanism is activated that returns the level to saturation. The rate of secretion is such that all lost sebum can be replaced in 3 to 4 hr. The chemical composition of human sebum is presented in Table 5.

The saturation level of the entire body may be calculated to be approximately 9 gm of sebum (Reference 1). Mattoni and Sullivan estimate that the ablating action of clothing, to which sebum adheres, and bathing will result in a daily production of 4 gm per man-day. None of this should be released into the atmosphere if bathing is frequent enough to prevent ablation; however, some may be released from dried material or clothing and from misuse of or accidents with the personal-hygiene system.

TABLE 4

COMPOSITION OF SWEAT

| | Mean | Range |
|---|---|---|
| | mg/100 ml of sweat | |
| Water | - | 99 0-99 5% |
| Solids, total | - | 1 174-1 597% |
| **Electrolytes** | | |
| Calcium | 2 1 | 1-8 |
| Chloride | - | 30-468 |
| Copper | 0 006 | 0 006-7 5 |
| Iodine | 0 0009 | 0005- 0012 |
| Iron | 0 027 | 022-0 2 |
| Magnesium | 0 2 | 001-4 5 |
| Manganese | 0.006 | 002-7 4 |
| Phosphorus | 0 5 | 001-2 0 |
| Potassium | - | 21-126 |
| Sodium | - | 24-312 |
| Sulfur | - | 0 7-7 4 |
| **Nitrogen Compounds** | | |
| Amino Acids | | |
| Arginine | 13 6 | 5 8-21 4 |
| Histidine | 8 | 4 25-14 00 |
| Isoleucine | 2 27 | 1 0-3 73 |
| Leucine | 2 69 | 1 2-4 2 |
| Lysine | 2.26 | 1 1-3 18 |
| Phenylananine | 2 19 | 1 0-3 5 |
| Threonine | 5 38 | 1 7-9 1 |
| Tryptophan | 1 12 | 0 4-1 85 |
| Tryosine | 3 15 | 1 2-5 15 |
| Valine | 2 96 | 1 5-4 5 |
| Creatinine | | 0 1-1 3 |
| Urea | | 12-5 7 |
| Uric Acid | 0 16 | 0-2 5 |
| Nitrogen | | |
| Total N | 33 2 | 27-64 |
| Non-protein N | 31 | 27-64 |
| Amino acid N | 2.8 | 1 1-10 2 |
| Ammonia N | - | 2.5-35 0 |
| Urea N | - | 5-39 |
| **Misc organic compounds** | | |
| Ascorbic acid | - | 0- 002 |
| Carbolic acid (phenol) | - | 2-8 |
| Lactic acid | - | 45-452 |
| Corticoids | - | 004- 008 |
| Sugar (as glucose) | - | 0 1-40 |
| **Vitamins** | | |
| $B_1$ (thiamine) | 00015 | 0- 006 |
| $B_2$ (riboflavin) | .0005 | 0- 0005 |
| $B_6$ (pyridoxine) | - | 0004- 00017 |
| $B_c$ (folic acid) | 0006 | 00053- 00088 |
| $B_x$ (p-aminobenzoic acid) | 00024 | 00008- 00170 |
| C (as dehydro-ascorbic acid) | 0705 | |
| Choline | 0071 | 0003- 0071 |
| Inositol | 021 | 015- 036 |
| Niacin (nicotinic acid) | - | 0017- 022 |
| Pantothenic acid | 0038 | 0015- 0077 |

TABLE 5

CHEMICAL COMPOSITION OF HUMAN SEBUM

| Values are in g/100 g unless otherwise indicated. Those in parentheses are ranges. | |
|---|---|
| Fatty acids, free, straight chain | 28.3 (22.0 - 50.0) |
| Fatty acids, combined, straight chain, total | 34.6 (27.5 - 41.0) |
| Triglycerides | 32.5 |
| Other | 2.1 |
| Unsaponifiable material, total | 30.1 (25.1 - 35.9) |
| Squalene ($C_{30}H_{50}$) | 5.5 (1.0 - 11.2) |
| Other hydrocarbons | 8.1 (5.0 - 20.0) |
| Aliphatic alcohols | 6.2 (4.7 - 6.9) |
| Straight chained | 2.4 |
| Branched | 3.8 |
| Cholesterol | 4.1 (2.7 - 6.9) |
| Vitamin E and tocophenol | 0.0002 |
| Pro vitamin D | 1) |
| Vitamin A precursors | 1) |

1) Biological evidence for presence, not chemical evidence

4. Epithelium

The outer layer of the skin acts as a physical barrier against body damage, bacterial and chemical invasion, etc. This layer is continually shed and replaced by cells from deeper layers, the shed material consists of small particles called desquamated epithelium. The rate of shedding depends on several factors, including the degree of abrasive action, temperature, and individual differences, and is a direct function of the renewal time of the cornified layer. Assuming a 19-day replacement rate, 0.05 mm as the thickness of the cornified layer, and 1.8 sq m as the body surface area, Mattoni and Sullivan (Reference 1) calculated a daily production of 5.0 cu cm per man day of desquamated epithelium. This figure was felt to be high because of the method used in obtaining the replacement rate, so another estimate (32 days) was used, which resulted in a daily production of 2.8 cu cm or 3.0 gm of this material. These authors estimate that 0.3 gm per man day will be released directly into the atmosphere, the remainder, it is hoped, will be trapped in clothes or removed by personal hygiene. The airborne particles may be expected to be composed of proteinaceous material, with sizes of 10 to 15 microns.

Hair

1. General

Hair growth occurs all over the body except the lip margins, glans penis, and the flexor surfaces of hands and feet. There is wide variation in the type and quantity of hair with bodily regions and between individuals. The frequency of hairs per sq cm varies from 300 on the scalp to 0 on the flexor surfaces. According to the estimates in Reference 1, the daily hair loss per man is approximately 1000 hairs, most of which are down hairs (only about 40 crown hairs per day are lost). This estimate assumes an average of 20 hairs per sq cm over the body, a body surface area of 1.8 sq m, and a hair life-span of 12 months. If the hairs have an average volume of 0.025 cu mm and a specific gravity of 1.057, the total weight loss per man per day is 0.03 gm, with a volume of about 0.03 sq cm. Significant increases in this figure may be expected with increased radiation doses. Normal growth rates of human hair are presented in Table 6, while Table 7 shows the chemical composition of hair.

2. Facial Hair

The hairs removed by shaving will be small in size, and will amount to about 0.25 gm per man day, assuming 0.42 mm of growth per day, 100 sq cm of area, 300 hairs per sq cm, and a hair diameter of 0.15 mm (Reference 1). Dr. Mattoni (Reference 1) produced 0.28 gm per day (volume, 0.25 sq cm) in a one-subject test; this author considered himself an average individual with respect to beard growth. However, wide individual variations exist in beard density, growth rate, and beard consistency. The personal-hygiene system should ensure that, during shaving, these facial hairs will not be released into the atmosphere. Any shaved hairs not removed adequately will appear in the cabin atmosphere as particles in length varying with the days between shaving (0.42 mm per day) and with a diameter of approximately 0.15 mm.

TABLE 6

GROWTH RATE AND REGENERATION TIME OF HUMAN HAIR

| Hair - Region | Growth Rate (mm/Day) | Regeneration Rate |
|---|---|---|
| Crown | .30 | 4 - 6 years |
| Supraear | .32 | |
| Axilla | .36 | 202 days |
| Thigh | .16 | |
| Chin | .42 (.54 in summer) | 7 - 11 months |
| Cilia | .14 | 150 days |
| Chest | | 124 - 210 days |
| Pubis | | 20 - 35 months |

TABLE 7

COMPOSITION OF HAIR

All data recorded as mg/100 gm of dry, fat-free material.

| | Mean Values | | Range |
|---|---|---|---|
| | Altman and Dittmer, eds. | Spector, ed. | Mattoni and Sullivan |
| Water | 4.2 | 4 1 | |
| Electrolytes | | | |
| Aluminum | $2 \times 10^{-6}$ -3.6 | 3.2 | |
| Arsenic | 0.22 | 0.22 | |
| Boron | - | - | 0 2-0 8 |
| Bromine | - | - | 0 2-0 7 |
| Calcium | - | 20 8 | 18-490 |
| Chromium | 0 2 | 0 2 | - |
| Cobalt | 1.4-1 8 | 1 8 | 1 4-1 8 |
| Copper | - | 10 8 | 0 7-10 8 |
| Iron | - | 14.1 | 0 8-17 0 |
| Lead | - | 4.8 | 1.7-28 4 |
| Magnesium | 1 0-10 1 | - | - |
| Manganese | $10^{-6}$-4 6 | 3.8 | |
| Nickel | - | 0.8 | 0.5-0 8 |
| Phosphorus | - | 80. | 65-90 |
| Silicon | - | - | 15-360 |
| Silver | 00045 | - | - |
| Strontium | - | - | 0000022-.0091 |
| Titanium | - | - | 00320-.0064 |
| Uranium | 0127 | - | - |
| Zinc | - | 21.2 | 0 9-44 4 |
| Organic compounds | | | |
| Pentose | 30 | - | - |
| Protein | - | 91. | 85-91 |
| Sugars | 80. | 80 | - |

From Reference 6

3. Scalp and Body Hair

These hairs will be released as discrete individual hairs, in quantity of about 1000 per day as discussed above. These hairs will be approximately 0.15 mm in diameter, with a length dependent on the time since cutting (for scalp hair). Body hairs very seldom are longer than 7 cm; most will be a great deal smaller than this.

Fingernails

The chemical composition of fingernails is given in Table 8. The growth rate of fingernails is approximately 1 mm per week, so that the ten fingers produce approximately 0.065 cu cm of nails weighing about 0.07 gm (Reference 1). Fingernails should be cut so that any particles encountered will be discrete clippings; files or emery boards should not be used because of the resulting dust. The clippings will weigh approximately 0.007 gm and will be approximately 0.3 to 1.2 cm in length. The personal-hygiene system should prevent these clippings from entering the atmosphere; individuals who bite their nails will be instructed not to release the products of this activity into the cabin atmosphere.

Toenails

Toenails are composed of about the same chemicals as fingernails (Table 8). However, the growth rate is only about 0.25 mm per man week. For a 45-day mission, toenails will not require cutting. For longer missions, they will be trimmed in much the same manner as fingernails, and will be prevented from entering the atmosphere by the personal-hygiene system.

Tears

The secretion rate of tears ranges from 0.031 to 0.041 gm per hr (Reference 3), with a mean of approximately 0.036 gm per hr, or 0.86 gm per man day. As indicated in Table 9, tears contain 1.8 percent solids, which could appear in the atmosphere as particles. The pH of tears ranges from 5.2 to 8.3; alkaline tears are shed after corneal injury. Normally, tear secretions are ducted so that they are released into the nasal area and are subsequently swallowed. During weeping a considerably larger quantity of tears is produced, and these tears may be evolved from the eyes in appreciable quantities. Similar effects may result from the presence of irritants in the atmosphere, or from sneezing, coughing, or vomiting. In such cases, tears will not flow out of the eye, but will tend to pool over the eye because of surface tension in the weightless state. The blinking that would inevitably result would produce airborne droplets unless the eyes were blotted with absorbent material. It is not expected, however, that external tears will be produced very often. Should they occur, airborne droplets may be expected unless blotting takes place in time. Tears wiped on the skin or clothing would dry, and the solid material removed during washing by means of the personal-hygiene system, however, some of the residue might also become airborne.

TABLE 8

CHEMICAL COMPOSITION OF NAILS

| All data recorded as gms/100 gms | | | |
|---|---|---|---|
| | Spector, ed | Silver and Chiego | Rothman |
| Water* | 0.07-0 72 | 7-12 | - |
| Chromium | 0 012 | - | - |
| Zinc | 0 011 | - | - |
| Fat | - | 0 76-1 15 | - |
| Keratin components | | | |
| Ash | - | 0 042 | - |
| Carbon | - | 48 7 | - |
| Hydrogen | - | 6 59 | - |
| Nitrogen | - | 16 55 | 14 9 |
| Sulfur | 3.3-3.5 | 3 92 | 3 8 |
| Amino acids | | | |
| Arginine | - | 10 01 | 8 5 |
| Cystine | - | 2.31 | 12 0 |
| Histidine | - | 0 59 | 0 5 |
| Lysine | - | 3.08 | 2 6 |
| Methionine | - | 2 47 | - |
| Phenylalanine | - | - | 2 5 |
| Tryptophane | - | - | 1.1 |
| Tyrosine | - | - | 3 0 |

* Hygroscopic nature of keratin causes considerable variation in water content

From Reference 6

TABLE 9

COMPOSITION OF TEARS

| | | Mean Values gms/100 ml of tears |
|---|---|---|
| Water | 98.2% | |
| Total Solids | 1.8 | |
| Ammonia | | 5. |
| Ash | | 1050 |
| Chlorides (as NaCl) | | 658. |
| Nitrogen, total | | 158. |
| Nonprotein N | | 51 |
| Potassium as $K_2O$ | | 140. |
| Proteins | | 669. |
| Albumin | | - |
| Globulin | | - |
| Sodium as $Na_2O$ | | 600. |
| Sugar | | 650. |
| Urea | | 30 |
| Vitamin C | | - |

From Reference 6

## Saliva

Saliva is produced both by three pairs of ducted glands and by many small glands in the buccal mucosa. The secretions from the different glands differ in composition, consistency, and quantity of production. Saliva is generated continually to flush the mouth; the normal generation rate has been measured by different investigators, and seems to range from 2.5 to 110 ml per hr (Reference 6). During certain psychic stimuli, particularly the anticipation of eating, and during eating, as much as 288 ml per hr may be produced. Normally this saliva is swallowed. However, droplets may be produced by breathing, sneezing, coughing, and talking; lip wetting may produce deposited solids as well as droplets. Droplets in the air or droplets impinged against surfaces can be expected to dry, leaving a solid residue made up of the materials listed in Table 10. The wide variation shown in the various quantities may be ascribed to the methods of collection, the particular glands that were secreting, and the stimuli used to augment salivary flow. Mattoni and Sullivan (Reference 1) estimated the maximum quantity of solids from saliva to be 10 mg per man day, of which as much as 8 mg might be expelled into the atmosphere. A more reasonable figure, according to Reference 1, is 0.004 gm of solids per man day, this quantity is rather difficult to estimate with any confidence.

## Mucus

Mucus is a viscid fluid secreted by the mucous membranes and glands throughout the nasopharyngeal passages. It is largely a mucoprotein containing mucin, inorganic salts, leukocytes, water, and epithelial cells. It serves several functions; in the gastrointestinal system, for example, it serves as a lubricant over the mucosa, preventing the food from excoriating the mucosa itself. In the respiratory tract, it protects the underlying tissue from noxious chemicals (it is an amphoteric compound) and from potentially infectious bacteria present in inhaled air.

Mucus is secreted continually; variations in the rate of secretion are determined by the quantity of sensitizing or irritating particles encountered. Normally, the production of mucus is not excessive, and the total amount produced is collected by the digestive system. However, infectious states or the presence of irritating materials in the atmosphere may provoke copious discharges, as can such varied stimuli as strong odors, bright lights, cold breathing gas, emotional stresses, etc. The air-purification system should remove atmospheric contaminants that could cause respiratory irritation, and the bacterial-control system should prevent the proliferation of infectious bacteria and virus. Nonetheless, there is always the possibility of latent infectious sources, as well as accidents that could temporarily pollute the atmosphere. Under such conditions, the thick, ropey material called phlegm may be produced, as well as a tendency to sneeze or cough. Even under normal conditions, intermittent sneezing and coughing may produce mucus droplets as well as saliva (which is itself composed partly of mucus). The most frequent production of mucus will probably be as dessicated nasal particles that may be removed and disposed of. The total solids from mucus has been estimated to be 0.4 gm per man day (Reference 1), of which 0.005 gm per man day (dry) would be introduced into the atmosphere.

## TABLE 10

## COMPOSITION OF SALIVA

All data recorded as mg/100 mg of saliva unless otherwise noted

| | Mean Values | | Range |
|---|---|---|---|
| | Diem, ed | Altman and Dittmer, eds | |
| Water | 95 5 | | |
| Total solids | - | 581.0 (P)* | 386-860 (P) |
| Electrolytes | | | |
| Bicarbonate | - | 39 294 | 21 228-65 27 |
| " | - | 96 014 (P) | 49 532-118 767 (P) |
| Bromine | - | | 0 02-0 71 |
| Calcium | - | 5 8 | 4 5-10 |
| " | - | 5 5 (P) | 3 5-9 2 (P) |
| Carbon dioxide | - | 12 | 5-25 (vol %) |
| " | - | 25 (P) | 8-44 (vol %) (P) |
| Chloride | 102 8 | 60 025 | 40 4-165 2 |
| " | - | 41 89 (P) | 11 89-62.835 (P) |
| Cobalt | 00704 | 00244 (P) | 0- 01253 (P) |
| Copper | .0256 | 0063 | 002- 0256 |
| " | - | 0259 (P) | 010- 0475 (P) |
| Fluorine | - | - | .010- 020 |
| Iodine | - | - | 0- 350 |
| Magnesium | - | 1 409 | 3888-2 576 |
| Phosphorus, total | 20 4 | 24 4 | 12 0-28 8 |
| Organic | 5 5 | 5 5 | 0-13 3 |
| Inorganic | 14.9 | 14 9 | 7 4-21 7 |
| Potassium | 77 0 | 80 3 | 46 4-148 |
| " | - | 78 0 (P) | 50-95 |
| Sodium | - | 23 2 | 8-56 |
| " | - | 57 3 (P) | 19-133 |
| Sulfur | 7 6 | - | - |
| Thiocyonate | - | 13 4 | 3 1-33 0 |
| Nitrogen compounds | | | |
| Ammonia | - | 4 42 | 2-10 |
| " | - | 5 95 (P) | 1 56-12 07 |
| Amino acids | | | |
| Alanine | - | 1 2 | 0 5-2 9 |
| Arginine | - | - | 3 3-10 0 (P) |
| Aspartic acid | - | 0 15 | 0 13-0 33 |
| Cystine | - | - | 0 16-0 45 (P) |
| Glutamic acid | - | 1 2 | 0 5-1 3 |
| Glutamic acid | - | - | 3 0-12 6 (P) |
| Glycine | - | 1 4 | 0 5-3 6 |
| " | - | - | 1 9-15 5 (P) |
| Histidine | - | - | 0 35-2 00 (P) |
| Isoleucine | - | - | 0 2-0 9 (P) |
| Leucine | - | - | 0 025-0 300 (P) |
| Lycine | - | 0 77 | 0 15-1 50 (P) |
| " | - | - | 0 4-1 5 (P) |
| Methionine | - | - | 0 005-0 010 (P) |
| Phenylalanine | - | - | 0 6-2 5 (P) |
| Proline | - | - | 0 35-1 50 (P) |
| Serine | - | 0 66 | 0 33-1 20 |
| " | - | - | 1 0-1 8 (P) |

*(P) Paraffin stimulated saliva

(continued on the following page)

TABLE 10 (Continued)

All data recorded as mg/100 mg of saliva unless otherwise noted

| | Mean Values | | Range |
|---|---|---|---|
| | Diem, ed | Altman and Dittmer, eds | |
| Nitrogen compounds (cont ) | | | |
| Threonine | - | - | 0 4-5 6 (P)* |
| Tryptophan | - | - | 0.2-0 9 (P) |
| Tyrosine | - | - | 0 2-1 0 (P) |
| Valine | - | - | 0 7-2 2 (P) |
| Creatinine | - | 0.35 (P) | 0 275-0 455 (P) |
| Histamine | 01456 | - | 01065- 01810 |
| Mucin | - | 250 | 80-600 |
| " | - | 270 | - |
| Nitrogen | | | |
| Total nitrogen | - | 90 0 (P) | 36 1-125 3 (P) |
| Ammonia nitrogen | - | 3 8 | 0 5-9 9 |
| Non protein nitrogen | - | 36.1 | 8.2-62.4 |
| Protein nitrogen | - | 63 0 (P) | 22 9-88 2 (P) |
| Protein, total | 262 | 386 | 0-630 |
| " | - | 242 (P) | 140-527 (P) |
| Urea | - | 12 7 | 8 2-18 1 |
| " | - | 8 8 (P) | 0-14 3 (P) |
| Uric acid | 15. | 1 5 | 0 5-15 |
| " | - | 4 8 (P) | 1 5-8 7 (P) |
| Misc. organic compounds | | | |
| Cholesterol | - | 7.5 | 3-15 |
| Citric acid | - | 1 05 (P) | 0-1.92 |
| " | - | - | 0.20-3 15 (P) |
| Glucose | - | 19 6 | 11 28-28 08 |
| " | - | 20 7 (P) | 14 04-30 00 (P) |
| Lactic acid | - | 1 53 | 1 53-10 |
| Vitamins | | | |
| $B_1$ (thiamine) | - | 0007 | - |
| " | - | - | 0002- 0014 (P) |
| $B_2$ (riboflavin) | - | 0050 | - |
| $B_6$ (pyridoxine) | - | 0006 (P) | 0001- 0017 (P) |
| $B_{12}$ (cyanocobalamine) | - | 00033 (P) | 00014-.0005 (P) |
| $B_c$ (folic acid) | - | 0024 (P) | 0003- 0075 (P) |
| Choline | - | 0 65 | 0 47-0 99 |
| " | - | 1 62 | 0 62-3 64 |
| Niacin (nicotinic acid) | - | 0115 (P) | 00234- 04090 (P) |
| Pantothenic acid | - | 0088 (P) | 0012- 0190 (P) |
| C (ascorbic acid) | 0.218 | 007 (P) | 0 058-0 378 |
| " | - | - | 0-0 372 (P) |
| H (biotin) | - | 0008 | - |
| K | - | 0015 | - |
| Enzymes | | | |
| Ptyalin | - | - | 0-300 |
| Cholinesterase | - | 0 33 (P) | 0 23-0 43 units/liter[4] (P) |
| Esterase, total | - | 0 34 (P) | 0 12-0 65 units/liter[5] (P) |
| B-Glucuronidase | - | - | 170-1750 units/liter[6] (P) |
| Lipase | - | 1 42 (P) | 0 25-2 58 units/liter[7] (P) |
| Lipozyme | - | 670 (P) | 250-1360 units/liter |
| Phosphatase, acid | - | 4 23 (P) | 2 5-7 7 units/liter[8] |

* (P) Paraffin stimulated saliva

From Reference 6

## Feces

Fecal particles could be introduced into the atmosphere during flatus expulsion, during defecation, waste disposal and handling, and during bathing when the appropriate system is not functioning properly or is mishandled. Should diarrhea occur, comparatively large quantities of solids and liquid droplets may be released unintentionally. With proper design and handling, no particles should be released during defecation. Similarly, waste disposal and handling will release no particles with proper design, assuming no leakage or malfunction. The fecal debris that accumulates in the anal area following defecation may be expected to dry with time, and form small, hard pellets adhering to the circumanal skin and hair. These particles must be removed by the personal-hygiene system, malfunction or misuse of which could release them into the atmosphere. In addition, such particles could be inadvertently removed by material in contact with the anal region. Fecal particles in the atmosphere could be particularly dangerous because of their microbial infestation.

The daily production of feces varies with individuals, diet, emotional factors, etc.; generally it ranges between 60 and 250 gm (Reference 6). Table 11 is a list of the materials that are found in feces. Not only are these materials adequate substrates for many microorganisms, but a large number of microorganisms are found in feces before additional contamination takes place. Thus, fecal particles represent a critical aspect of the waste-disposal, personal-hygiene, and particle-control systems. In addition, feces contain several vile-smelling components, which makes their presence unpleasant as well as dangerous.

## Urine

Urine production varies with diet, sweat rate, water consumption, ionic balance, mental stress, individual differences, etc. Depending on all of these interrelated factors, daily urine production may be as high as 9200 gm and as low as 210 gm (Reference 6). The primary control method for urine produced during the mission will be the waste-management system. However a small quantity of urine (0.10 to 0.20 ml) is generally retained in the distal urethra following micturition, and this quantity usually escapes to the exterior. On the basis of this, it is estimated (Reference 1) that about 0.50 ml per man day will be lost, implying about 25 mg of solids (Table 12), which will be deposited in the genital skin and clothing. The removal of this solid material will be a function of the personal-hygiene system; however, there is the possibility that some dried solids or urine droplets will be released into the atmosphere. Accidental micturition could produce a comparatively large quantity of droplets that might enter the atmosphere where they can be removed by the particle-control system or where they will adhere to surfaces where they will dry, leaving a solid substrate that must also be removed to preclude bacterial growth and equipment damage.

## Cerumen

The production of cerumen or ear wax varies considerably between individuals. Cerumen is composed largely of lipids, proteins, and amino acids, as shown in Table 13; the composition is similar to that of sebum. Usually

# TABLE II

## COMPOSITION OF FECES

The water content of feces ranges between 65 and 85%, and the pH from 6 9 to 7 7 The bulk and solid contents shown in the table are recorded in mg/24 hours unless otherwise noted

| | Mean values | | | | | Range** |
|---|---|---|---|---|---|---|
| | Altman and Dittmer, eds | Diem, ed | Sunderman and Boerner | Spector, ed | Goldblith and Wick | |
| Bulk | - | - | - | - | 150 000 | 50 000-350 000 |
| Dry matter | - | - | | - | 27,000 | 23,500-35 000 |
| Electrolytes | | | | | | |
| Aluminum | 0428 | - | - | - | | 0428-2 9 |
| Arsenic | 2 353 | - | - | - | - | 071-8 27 |
| Calcium | 534 0 | 640 | 640 | 548 | 1,180 | 100 0-1,180 |
| Chloride | | 90 | - | - | - | 14 97-35 65 |
| Cobalt | 0005 | - | - | 0005 | 1 400 | 0001-1 400 |
| Copper | 1 925 | - | - | 1 940 | 1 020 | 1 020-2 638 |
| Iron | 8 556 | - | - | 8 640 | 28 80 | 4 6-100 0 |
| Lead | 0 299 | - | - | - | - | 0-400 |
| Lithium | - | - | - | - | 2 600 | - |
| Magnesium | 178 2 | 200 | 200 | 180 | 252 | 107-252 |
| Manganese | | - | - | 4 760 | 3 430 | 1 283-8 556 |
| Mercury | 001 | - | - | - | - | - |
| Molybdenum | | | | | | 2-4 |
| Nickel | | - | - | 0 130 | 2 800 | 0856-10 0 |
| Phosphorus | 703 0 | 510 | - | - | - | 506 2-1700 |
| Potassium | 470 | 470 | 470 | 482 | 291 | 291-1037 |
| Silver | 0570 | - | - | - | - | - |
| Sodium | 121 2 | 120 | 120 | 122 | 116 | 116-122 |
| Strontium | - | - | - | - | 0 580 | - - |
| Sulfur, total | 142 7 | 130 0 | - | - | - | - |
| Tin | - | - | - | - | - | 0 5-32 09 |
| Zinc | 7.130 | - | - | - | - | 4 135-10 27 |
| Nitrogen compounds | | | | | | |
| Arginine | - | - | - | - | - | 1200-2100 |
| Bile pigments | - | - | - | - | 150 | - |
| Histidine | - | - | - | - | - | 600-800 |
| Indole | 90 | - | - | - | - | 60-100 |
| Isoleucine | - | - | - | - | - | 1400-2300 |
| Leucine | - | - | - | - | - | 1800-2900 |
| Lysine | - | - | - | - | - | 1900-2900 |
| Methionine | - | - | - | - | - | 500-800 |
| Nitrogen, total | - | - | - | - | 1500 | 700-2100 |
| Threonine | - | - | - | - | - | 1400-2200 |
| Urobilinogen | - | 10 | - | - | 101 | 10-280 |
| Valine | - | - | - | - | - | 1500-2600 |
| Misc organic compounds | | | | | | |
| Carbohydrates & derivatives | | | | | | |
| Total reducing sugar | - | - | - | - | - | - |
| Fiber* | - | - | - | - | - | 10-30 |
| Fats & derivatives | | | | | | |
| Total fat | - | - | - | - | 4500 | 1000-7000 |
| Total fat* | - | - | - | - | - | 10-25 |
| Total fat (unsaponifiable)* | | | | | | 0-5 |
| Vitamins | | | | | | |
| Vitamin A | - | - | - | - | - | 0 17-0 33 |
| p-Aminobenzoic acid | - | - | - | - | 0 246 | - |
| B vitamins | - | - | - | - | 15 | |
| Vitamin $B_2$ (uroflavin) | 1 029 | - | - | - | - | 0 823-1 313 |
| Vitamin $B_6$ | - | - | - | - | - | 0 5-0 8 |
| Biotin | - | - | - | - | 0 13.5 | 1- 2 |
| B-carotine | - | - | - | - | - | 1 7-3 3 |
| Vitamin E | 21 | - | - | - | - | - |
| Folic acid | - | - | - | - | 0 304 | - |
| Pantothenic acid | - | - | - | - | 2 20 | 1 8-3 8 |
| Pyridoxin | - | - | - | - | 0 38 | 0 1-0 5 |
| 4-pyridoxic acid | - | - | - | - | - | 0 5-0 6 |
| Nicotinic acid | - | - | - | - | 3 63 | 3 5-5 5 |
| Thiamine | - | - | - | - | 0 548 | 0 2-0 8 |
| Riboflavin | - | - | - | - | 1 029 | 0 4-1 20 |

* Per cent of dry weight

** Extreme values include data of Consolazio, et al

TABLE II (Continued)

| Amino Acid in Fecal Protein | | |
|---|---|---|
| Data recorded as grams of amino acid/16 grams of N | | |
| Amino Acids | Determined by Microbiological Assay | Determined by Amino Acid Analyzer |
| Alanine | - | 4 8 |
| Arginine | 5 7, 5 7 | 3 2 |
| Aspartic acid | - | 8 5 |
| Cystine | 0 60, 0 60, 0 64 | - |
| Glycine | - | 3 3 |
| Glutamic acid | - | 4 4 |
| Histidine | 2 5, 2 5 | 1 7 |
| Iso-Leucine | 6 3 6 3 | 3 6 |
| Leucine | 7 9, 7 8, 7 3 | 5 7 |
| Lysine | 8 0, 8 7 | 5 1 |
| Methionine | 2 6, 2 7 | 1 9 |
| Phenylalanine | 4 7, 4 7 | 3 3 |
| Proline | - | 3 7 |
| Serine | - | 2 8 |
| Threonine | 3 7, 3 9 | 3 3 |
| Tryptophan | 0.71, 0 67 | - |
| Tyrosine | 1 9, 1 9 | 3 2 |
| Valine | 8 3, 8 8 | 4 3 |

Comparison of Composition of Bound, Free, and Total Fatty Acids in Fecal Lipid for a Normal Human

| Percentage of Acids in $C_6$ - $C_{20}$ Range | | | | | | | |
|---|---|---|---|---|---|---|---|
| Acid** | Free | Bound | Total | Acid** | Free | Bound | Total |
| 10 0 | 0 6 | 0 | 0 3 | 10-Hydroxy 18 0 | 0 7 | 0 9 | 0 8 |
| 12 0 | 4 3 | 2 2 | 1 3 | 14 1 | 0 | 0 | 0 |
| 14 0 | 8 9 | 4 4 | 6 6 | 16 1 | 1 4 | 2 1 | 1 8 |
| Branched 15 0 | 0 7 | 1 1 | 0 9 | 18 1 | 6 8 | 10 7 | 8 7 |
| 15 0 | 1 4 | 1 1 | 1 2 | Isomer 18.1 | 3 5 | 6 5 | 5 0 |
| 16 0 | 55 2 | 35 3 | 45 2 | 18 2 | 1 3 | 2 8 | 2 0 |
| Branched 17 0 | 0 9 | 1 4 | 1 2 | 18 3 | 0 | 0 | 0 |
| 17 0 | 0 4 | 0 8 | 0 6 | 20 3 | Trace* | Trace* | Trace* |
| 18 0 | 12 9 | 31 8 | 22 3 | 20 4 | Trace* | Trace* | Trace* |
| | | | | Other unsaturated $C_{20}$ acids | Trace* | Trace* | Trace* |

*Trace indicates less than 0 5%

**Number of carbons and double bonds

Source Goldblith and Wick (from Reference 6)

# TABLE 12

## COMPOSITION OF URINE

Urine has a specific gravity of 1 002 to 1 035 and a pH of 4 6 to 8 0 The solid contents shown in the table are recorded as mg/24 hours

| | Mean Values | | | | | Range |
|---|---|---|---|---|---|---|
| | Altman and Dittmer, eds | Long | Sunderman and Boerner | Hawk and Bergheim | Diem, ed | |
| Solids | | | 60,000 | 6),000 | | 55,000-70,000 |
| Electrolytes | | | | | | |
| Aluminum | 077 | 078 | - | - | - | 0 049-0 112 |
| Arsenic | 0231 | - | - | -- | - | 0-0 091 |
| Bicarbonate | 140 0 | - | - | - | - | 35-840 |
| Bromine | - | 2 1 | - | - | - | 0 840-7 70 |
| Calcium | 231 0 | - | - | 200 0 | - | 43 0-581 0 |
| Chloride (as NaCl) | 12,000 | - | - | - | 7,638 | 7,600-15,000 |
| Chlorine | 7,000 | - | - | - | - | 2,800-12,600 |
| Copper | 0 035 | - | - | - | 0 018 | 0-0 049 |
| Fluorine | 1 540 | - | - | - | - | 0 30-7 0 |
| Iodine | - | - | - | - | - | 0 007-0 490 |
| Iron | 0 490 | - | - | - | 0 045 | 0 02-1 1 |
| Lead | 0 028 | 0 035 | - | - | - | 0 004-0 15 |
| Magnesium | 94 5 | - | - | 150 | 103 | 29 4-307 |
| Manganese | - | - | - | - | - | 0 007-0 098 |
| Nickel | - | 0 15 | 0 15 | - | - | 0 140-0 280 |
| Phosphorus (as P) | - | - | - | 1,100 | 1,100 | 700-1 600 |
| Inorganic | 840 | - | - | - | - | 700-1,300 |
| Organic | 9 17 | - | - | - | - | 6 23-13 09 |
| Potassium | 2,380 | - | - | 2,000 | 2,740 | 1,120-3,920 |
| Selenium | 0 035 | - | - | - | - | 0-0 140 |
| Silicon | 9.10 | - | - | - | - | 420-14 0 |
| Sodium | 4,200 | - | -- | 4,000 | 4,615 | 1,750-6,580 |
| Sulfur, total | 1,120 | - | - | 1,000 | - | 357-3,400 |
| Inorganic | 777. | -- | - | 800 | - | 245-2 700 |
| Ethereal | 66 5 | - | - | - | - | 40-300 |
| Natural | 133 | - | - | 120 | - | 73-400 |
| Conjugated | -- | - | - | 80 | - | 80-300 |
| Tin | - | - | - | - | - | 0091- 0175 |
| Zinc | 364 | - | - | - | 0 457 | 110- 500 |
| Nitrogen compounds | | | | | | |
| Adenine | 1.40 | 1 4 | - | - | - | 1 1-1 7 |
| Allantoin | 11 9 | - | - | 40 | - | 2 8-40 |
| Amino Acids, Total | - | - | 1,100 | - | - | 1,100-2,800 |
| Free | - | - | 500 | - | - | 500-1,400 |
| Alanine, Total | 38 5 | 46 | - | - | - | 21-71 |
| Amino-adipic acid | - | 10 | - | - | - | 8-11 |
| Amino-butyric acid | - | 10 | - | | - | Traces-10 |
| Amino-isobutyric acid | - | 20 | - | - | - | 4-180 |
| Anserine | - | - | - | - | - | 5-7 |
| Arginine, Total | 31 5 | <10 | 23 7 | - | 47 0 | <10-56 8 |
| Asparagine | - | 54 | - | - | - | 34-99 |
| Aspartic acid, Total | 119 0 | <10 | 164 5 | - | 113 4 | <10-258 8 |
| Carnosine | - | - | - | - | - | 2-3 |
| Citrulline | 63 0 | 10 | - | - | - | 0-196 0 |
| Cystine, Total | 119 0 | 10 | - | - | 87 7 | 10-200 |
| Glutamic acid, Total | - | <10 | 351 4 | - | 249 9 | <10-484 7 |
| Glutamine | - | 100 | - | - | - | - |
| Glycine, Total | 455 0 | 132 | - | - | 405 0 | 132-670 6 |
| Histidine, Total | 189 0 | 216 | 203 3 | - | 284 0 | 65 4-498 8 |
| Hydroxylysine | - | <10 | - | - | - | <10 |
| Hydroxproline, Total | 1 40 | 0 51 | - | - | 23 05 | 0 26-1 4 |
| Isoleucine, Total | 14 0 | 18 | 20 3 | - | 11 3 | 6 5-33 4 |
| Leucine, Total | 21 0 | 14 | 21 2 | - | 27 9 | 11 9-40 0 |
| Lycine, Total | 56 0 | 19 | 73 2 | - | 102 0 | 7-166 0 |
| Methionine, Total | 9 8 | 10 | 8 6 | - | 6 6 | 3 8-15 0 |
| 1-methylhistidine | - | 180 | - | - | - | 47-384 |
| 3-methylhistidine | - | 50 | - | - | - | - |
| Ornithine | 10 5 | <10 | - | - | - | <10-10 5 |

TABLE 12 (Continued)

| | Mean Values | | | | | Range |
|---|---|---|---|---|---|---|
| | Altman and Dittmer, eds | Long | Sunderman and Boerner | Hawk and Bergheim | Diem, ed | |
| **Amino Acids (cont.)** | | | | | | |
| Phenylalamine, Total | 21 0 | 18 | 23 3 | - | 28 7 | 9-45 4 |
| Proline, Total | 42 7 | <10 | 42 8 | - | 43 3 | <10-63 0 |
| Sarcosine | - | <10. | - | - | - | <10 |
| Serine, Total | 42 0 | 43 | - | - | - | 27-73 |
| Taurine | - | 156. | - | - | 156 | 7 7-294 |
| Threonine, Total | 35 0 | 28 | 53 8 | - | 83.2 | 14 8-182 0 |
| Tryptophan, Total | 28 0 | - | 41.4 | - | 22 9 | 8-86 1 |
| Tyrosine, Total | 49 0 | 35 | 52.5 | - | 55 5 | 15-103 3 |
| Valine, Total | 21 0 | <10 | 19 8 | - | 30 1 | <10-44 7 |
| Ammonia | - | 700 | - | - | - | 300-1,100 |
| Bilirubin | 49.0 | - | - | - | 5 | 5-49 0 |
| Coproporphyrin I & III | - | - | - | - | - | 0168-0 280 |
| Creatine | 56 0 | - | - | - | - | 0-800 |
| Creatinine | 1,610 0 | - | - | 1,200 | 2,145 0 | 1,000-3,219 |
| Ethanolamine | - | 12 2 | - | - | - | 4 8-22 9 |
| Glycocyamine | - | - | - | - | - | 21-67 |
| Guanidine | - | - | - | - | - | 10-20 |
| Guanidinoacetic acid | - | - | - | - | 30 | 14 0-35 0 |
| Guanine | 0 42 | 1 6 | - | - | - | 0 21-2 0 |
| 8-Hydroxy-7-methyl | 1.40 | 1 6 | - | - | - | 1.1-2 0 |
| 7-Methyl | 6 30 | 6 5 | - | - | - | 5 5-7 8 |
| $N^2$-Methyl | 0 490 | 0 5 | - | - | - | 0 4-0 6 |
| Hippuric acid | - | - | - | 700 | 700 | 70-2,500 |
| Histamine | - | - | - | - | - | 0 014-0 070 |
| Hypoxanthine | 9.80 | 9.7 | - | - | - | 5 6-13 3 |
| 1-Methyl | 0 42 | 0.4 | - | - | - | 0 2-0 7 |
| Imidazole derivatives | - | - | - | - | 286 1 | 140 0-300 0 |
| Indoxylsulfuric acid | 70. | 100 | 0 | 10 | - | 5-160 0 |
| Lipoproteins | - | 23.5 | - | - | - | - |
| Methionine sulfoxide | - | - | - | - | - | 0-21 70 |
| Nitrogen | | | | | | |
| Total N | - | - | - | - | 15,300 | 1,000-21,000 |
| Amino Acid N | - | - | - | 200 | 349 | 100-431 |
| Ammonia N | - | - | - | 700 | - | 210-1,000 |
| Protein | - | - | - | - | <50 | 2 10-80 |
| Albumin | | | | | | 10-100 |
| Purine bases | - | - | 10 | - | - | 0 01-70 0 |
| 6-Succinopurine | 0 980 | - | - | - | - | - |
| Urea | - | 22,000 | 30,000 | - | - | 14,000-35,000 |
| Uric acid | 140 0 | 567 0 | - | 700 | 528 | 56-1,000 |
| Urobilin | - | - | - | - | - | 10-130 |
| Urobilinogen | - | - | - | - | - | 0-25 0 |
| Uropepsin(as tryrosine) | - | - | - | - | 417 | 98-835 |
| Xanthine | 6 30 | 6 1 | - | - | - | 4 90-8 6 |
| **Vitamins** | | | | | | |
| $B_1$ (thiamine) | 0 21 | - | - | - | - | 0 042-0 420 |
| $B_2$ (riboflavin) | 0 868 | - | - | - | - | 0 140-1 680 |
| $B_6$ (pyridoxine) | - | - | - | - | - | .0056-.1890 |
| $B_{12}$ (cyanocobalomine) | $30\ 8 \times 10^{-6}$ | 31 | - | - | - | $16\ 1 \times 10^{-6}$-$55\ 3 \times 10^{-6}$ |
| $B_c$ (folic acid) | .00406 | - | - | - | - | .0021-0 238 |
| $B_x$ (p-aminobenzoic acid) | - | - | - | - | - | 0.140-0 210 |
| C (ascorbic acid) | - | - | - | - | - | 5-55 |
| H (biotin) | 0 035 | - | - | - | - | 0 014-0 070 |
| Choline | 5 53 | - | - | - | - | 4 76-9 10 |
| Citrovorum factor | .00259 | - | - | - | - | .00161-.00483 |
| Inositol | 14 0 | - | - | - | - | 8-144 |
| Niacin | 0 238 | - | - | - | - | 0 140-1 40 |
| Niacinamide(niotinamide) | 1 40 | - | - | - | - | 0 70-3 50 |
| Pantothenic acid | 3 15 | - | - | - | - | 1 12-7 0 |
| Dehydroascorbic acid | - | 5 1 | - | - | - | 5 1-20 3 |
| Dehydroascorbic + diketogulonic acid | 16 1 | - | - | - | - | 0-89 6 |

From Reference 6

TABLE 12 (Continued)

| | Mean Values | | | | | Range |
|---|---|---|---|---|---|---|
| | Altman and Dittmer, eds | Long | Sunderman and Boerner | Hawk and Bergheim | Diem, ed | |
| **Vitamins (cont)** | | | | | | |
| Diketogulonic acid | - | - | - | - | - | 9 8-13 30 |
| N'Methylnicotinamide | - | - | - | - | - | 2 80-42 0 |
| Pyridoxal | 0 07 | - | - | - | - | 0 49-0 371 |
| Pyridoxamine | 0 112 | - | - | - | - | 0 028-0 210 |
| 4-Pyridoxic acid | - | - | - | - | - | 0 63-11 20 |
| Trigonelline | - | - | - | - | - | 2 10-21 0 |
| **Acids** | | | | | | |
| Acetoacetic acid | 2 80 | - | - | - | - | 2 10-4 20 |
| Carbolic (phenol) Total | - | - | - | - | - | 14 0-42 0 |
| Free | - | - | - | - | - | 0-3 50 |
| Carbonic acid | 189 0 | - | - | - | - | 147 0-231 0 |
| Citric acid | - | - | - | - | 678 | 128-1 400 |
| Formic acid | 56 0 | - | - | - | - | 28 0-140 0 |
| Glucuronic acid | - | - | - | - | - | 100-1,325 |
| m-Hydroxybenzoic acid | - | - | - | - | - | 10-16 |
| m-Hydroxyhippuric acid | - | 4-6 | - | - | - | 2-150 |
| p-Hydroxyphenyl-hydrocrylic acid | - | 10. | - | - | - | 2-150 |
| Lactic acid | 210 0 | 73 | - | - | - | 50-600 0 |
| Oxalic acid | 35 0 | 22. | - | 20. | - | 1-49 0 |
| Oxoglutaric acid | - | 22 | - | - | - | 20-40 |
| Pyruvic acid | - | - | - | - | 100 | 2 5-100 |
| **Misc organic compounds** | | | | | | |
| Acetone bodies, Total | 14 0 | - | - | - | 19 4 | 2 10-23 5 |
| Amylase (somogyi) | - | - | - | - | - | 260-950 units |
| Cholesterol | - | - | - | - | - | 0-4 998 |
| Glucose (true) | - | - | - | - | 72 | 50-300 |
| Ketones (total) | - | - | - | - | 50 5 | 19 8-81 2 |
| Phenols | - | - | - | 200 | 437. | 200-636 |
| Reducing substances | - | - | - | - | - | 490-1,500 |
| Glucose | - | 4 3 | - | - | - | 1-12 |
| Fructose | - | 5 | - | - | - | 0-5 |
| Arabinose (mgm per 100 ml) | - | 1 5 | - | - | - | 0-3 |
| Ribose | - | 18 7 | - | - | - | - |
| Xylose | - | 1 0 | - | - | - | 0-3 |
| Lactose | - | 7 | - | - | - | 0-10 |
| Sucrose | - | 5 | - | - | - | 0-5 |
| **Hormones** | | | | | | |
| Adrenalin | - | 005 | | | | .0006- 0115 |
| Aldosterone | 0035 | - | - | - | - | .0007-.0091 |
| Androgens | 18 20 | - | | | | 14 0-23 1 |
| Androsterone | 3 5 | - | | | | 2 45-420 |
| Catecholamines (total) | - | .082 | | | | .25- 150 |
| Estradiol | - | .002 | | | | 0- 007 |
| Estriol | - | .006 | | | | .001- 012 |
| Estrone | - | .006 | | | | 0- 011 |
| Etiocholanolone | 3 5 | - | | | | 2 45-4 20 |
| Hydroxysteroids | 5 6 | - | | | | 2 8-11 9 |
| Insulin | - | | | | | (0 16-0 4 units) |
| 17-ketogenic adreno-corticoids | 14 7 | - | | | | 10 5-21 7 |
| α-Ketol-steroids | 18 2 | - | | | | 9 1-32 9 |
| Melanocyte stimulating hormone | - | (27 7 units) | | | | (7 5-47 5 units) |
| Noradrenalin | - | 0 027 | | | | 015- 050 |
| Parathyroid | - | (60 units) | | | | (47-72 units) |
| Pregnanediol | 0 91 | - | | | | 0 35-1 40 |
| Tetrahydrocortisol | 1 68 | - | | | | 0 56-3 50 |
| Tetrahydrocortisone | 3 78 | - | | | | 1 40-8 40 |

From Reference 6

TABLE 13 (from Reference 6)

COMPOSITION OF EAR WAX
(gm/100 gm of wax)

| | Mean | Range |
|---|---|---|
| Total lipids | 4.4 | 13-64 |
| Phospholipids | 0.5 | |
| Non-saponifiable | 3.5 | |
| Saponifiable | 5.1 | |
| Protein | 24. | 15-40 |
| Residue | 32. | |

ear wax is removed from the external canal of the ear during washing; however, there is a possibility that the dry wax in the external canal may produce small particles in the spacecraft atmosphere by flaking of the dried material. It is anticipated, however, that the personal-hygiene system (washing) will remove this material before enough of it is deposited to cause this problem.

Semen

Table 14 indicates the average incidence of unavoidable emission of seminal fluid that may be expected for various individuals. The composition of the fluid is given in Table 15. The quantity per emission varies between 0.2 and 6.6 ml.

Even with the protection of clothing worn during sleep, some of the fluid will dry and be ablated into the atmosphere as both small and fairly large particles; the initial velocity of emission is estimated at 408 cm per sec. Mattoni and Sullivan (Reference 1) estimate the quantity of seminal solids to be disposed of as 3 mg per man-day; they assume that this will be washed off before it enters the cabin atmosphere.

Removal of the fluid from clothing requires extensive washing or the use of a mucoid-albumen precipitant. Problems related to laundering and disposal might be minimized by the use, during sleep, of a genital sheath of a design and material composition compatible with the waste disposal system.

The disposal of seminal fluid might be simplified by voluntary emission, but aside from problems of distastefulness and inconvenience, this would result in a greater total production of fluid than would occur with reliance on nocturnal emissions. In any case it is likely that a small quantity of seminal particles or droplets will emerge into the cabin atmosphere to be removed by the particle-control system.

TABLE 14

FREQUENCY OF NOCTURNAL EMISSIONS PER WEEK,* TOTAL U.S. MALE POPULATION

| Age | Marital Status | |
|---|---|---|
| | Married | Single |
| 21-25 | 0.12 | 0.24 |
| 26-30 | 0.13 | 0.22 |
| 31-35 | 0.11 | 0.17 |
| 36-40 | 0.08 | 0.10 |
| 41-45 | 0.07 | ---- |

* Frequencies may be expected to increase in the absence of other outlet.

(From Kinsey, A.C., Pomeroy, W.B., and Martin, C.E., 1948, Sexual Behavior in the Human Male, W.B. Saunders Co., Philadelphia)

TABLE 15

COMPOSITION OF SEMEN

(All data recorded as mg/100 ml unless otherwise noted)

| | Mean | Range | | Mean | Range |
|---|---|---|---|---|---|
| Water (%) | 91 8 | 89 1-94.4 | Nitrogen Compounds, cont | | |
| pH (standard units) | 7 4 | 7 1-7 5 | Spermine | - | 20-250 |
| Electrolytes | | | Urea | 72 | - |
| Calcium | - | 21-28 | Uric acid | 6 | - |
| Carbon Dioxide | 54. | 43-74 | Misc Organic Compounds | | |
| Chloride | 200. | 100-203 | Cholesterol | 80 | 80-103 |
| Magnesium | 14 0 | - | Citric acid | 480 | 0-2340 |
| Phosphorus | | | Fructose | 290 | 50-600 |
| Total P | 112 | 90-120 | Glucose | - | 203-369 |
| Inorganic P | 11. | - | Lactic acid | 35 | 20-50 |
| Acid soluble | 95 | 67-140 | Phospholipids | 84 | - |
| Lipid P | 6 | - | Vitamin C | 12 8 | 5-14 5 |
| Potassium | - | 66-107 | Enzymes (quantity liberated in 1 hr at 37°C) | | |
| Sodium | - | 240-319 | | | |
| Zinc | 14.0 | 5 0-22 0 | B-N-acetyl glucosaminidase as phenol | 1120 | - |
| Nitrogen Compounds | | | as o- or p-nitrophenol | 1960 | - |
| Ammonia | 2 | - | Galactosidase | | |
| Choline | - | 256-380 | B- (as o- or p-nitrophenol) | 16 | - |
| Creatinine | 20. | - | | | |
| Ergothioneine | 1 5 | 0-1 5 | B-Glucuronidase (as phenolphthalein) | 35 | |
| Glutathione | 30 | - | | | |
| Glycerylphosphorylcholine | 70 | 50-100 | Mannosidase A- as phenol | 10 5 | |
| Inositol | - | 50-70 | as o- or p nitrophenol | 35 5 | |
| Nitrogen | | | | | |
| Total N | 913 | 560-1280 | B- (as phenol) | 20 0 | |
| Non-protein N | 90 | 53-130 | Phosphatase, Acid (units/100 ml) | 370,000 | 50,000-800,000 |
| Phosphorylcholine | - | 70-2000 | | | |
| Protein | 4500 | 1580-7780 | | | |

(From Reference 6)

Vomitus

Vomitus may be expected to contain food particles, saliva, mucus, bile, chyme, and gastric juice. Gastric juice is extremely acid (pH approximately 0.9 to 1.8) and may be damaging to equipment. The quantity of gastric juice is about 40 to 50 ml (Reference 5). The other materials that may be found in vomitus depend on the time since eating, the type of food eaten, and the profundity of the vomiting. It is apparent that vomiting can result in a large quantity of atmospheric particles, in such volume that they can be of considerable danger because of duct blocking and component fouling, as well as bacterial growth. The quantity of regurgitated material generally varies between 30 and 300 ml per event (Reference 1). Mattoni and Sullivan estimate the total vomit production for a 60-day mission to be 30 ml, or 0.5 gm per man day. This figure is highly arbitrary; a vomiting episode may produce considerably more than 30 ml, and the circumstances that cause vomiting in one man are very apt to have the same effect on other men. Also, equipment malfunction or bacterial infection may cause an epidemiological phenomenon, so that some missions may be free from vomiting, while other missions may be plagued with it throughout. This latter situation is not expected, although the long-term effects of weightlessness and the cabin environment are not yet known.

Vomiting must be considered to be a highly unusual event if all of the systems, particularly the food, waste-mangement, bacterial-control, trace-contaminant-control systems, are functioning properly, so that the astronauts remain healthy, and if the long-term effects of the space environment do not cause such effects on the human occupants. However, it cannot be safely assumed that vomiting will never occur, and hence will not be a problem. Fortunately, vomiting is usually preceded by symptoms that are familiar to most adults (nausea, dizziness, salivation, gagging) and preparations can usually be made to catch the ejected material in time so that it is not released into the cabin atmosphere. It has been suggested that the material be ejected into a hand-held bag, placed securely over the mouth, and thence into the waste disposal system. There are several difficulties to this technique, including the fact that a great deal of pulmonary gas is expired during vomiting, the paroxysmal nature of vomiting, which makes careful control difficult, and the effects of weightlessness on the vomitus in the bag. Further study is suggested to devise an adequate technique for handling vomiting; perhaps the fecal disposal technique could be adapted to this purpose.

Blood, Pus, and Other Unanticipated Fluids and Particles

There are many materials that are not normally released from the body, but which under extraordinary conditions could be produced. Blood, for example, could be released from cuts in quantities depending on the location and severity of the cut. Blood would be expected to be released in fairly large droplets unless blood spurting took place, in which case a wide spectrum of droplet sizes could be produced from splattering. Pus could also be produced as the result of a bacterial infection; the probability of pus production is less likely than the production of blood droplets or solids. Scabs from healed or healing wounds are also unlikely and would generally be removed

during bathing. Proper design of the cabin and of its components, as well as the provision of smooth surfaces, the elimination of sharp corners, etc., will minimize the probability of cuts, possible infections, scabs, lymphatic fluid, etc. The bacterial control system should prevent sources of infection and hence the formation of pus. The emergence of any other body tissues or fluids is highly unlikely; any such particles could range in size from cellular (a few microns, e.g. 7 to 20) to quite large (chunks of tissue, etc.). Any of these materials offer great danger of bacterial contamination.

The cadavers of dead astronauts are another potential source of particulate contamination. If cadavers are to be kept in the cabin for more than a few hours, a significant danger exists from bacterial and gaseous contamination. The exact products of a human body decomposing under conditions of reduced pressures are uncertain; however, there is no safe method of keeping a human body in a closed environmental system for any extended length of time without extensive embalming and preservation operations on the part of the remaining astronauts. This in itself can be highly dangerous, because of the toxic nature of most embalming fluids. Also, depending on the cause of death, close contact with the cadaver may endanger the remaining personnel. Furthermore, such an approach would involve a considerable weight-volume penalty from the requisite materials, a penalty that would seem to far outweigh the probability of such an event and the value of returning the cadaver to earth. Other techniques have been suggested for safe-keeping the cadaver, such as sealing in an air-tight bag or in a pressure suit, but none of these is applicable for lengths of time greater than perhaps one week. Gas formation begins almost immediately after death even in an air-tight envelope, because of the action of anaerobic bacteria. This gas contains numerous toxic components, and the odor is highly unpleasant; the length of time until it would cause leakage or bursting of a sealed envelope is uncertain, depending on the physical condition of the cadaver, the ambient temperature, the bacteria flora, etc., but would occur after a few days to at most a month. The particles produced during decomposition are also uncertain, but would be expected to include many bacteria, various fluid droplets, hair, and epithelium, as well as gasses.

Further study should be done on this problem, including laboratory experimentation with decomposing cadavers and methods of preserving them in a closed environment without endangering the living occupants. It is preferable to return the corpses of dead astronauts to earth, both for pathological examination and for reasons of sentiment. However, there is no present method of accomplishing this. The most reasonable method of those proposed is external storage of the cadaver and the return of it to the cabin just prior to reentry. If feasible, this technique is suggested; if it is not feasible then jettisoning is recommended. Both of these have obvious difficulties; the former may be both psychologically unacceptable and damaging to the cadaver, and the latter offers no retrieval of the body for examination, and changes the mass of the system appreciably. Much more study is required on this problem.

Wash Water

Wash water and the remaining possible particulate contaminants listed in Table I are those that are not released directly from human bodies, but that may be released by the actions of the cabin occupants. Wash-water droplets may be expected to be produced during personal-hygiene functions. These droplets may contain not only water but also solids in the form of sweat solids, sebum, epithelial cells, hair, fecal particles, urine solids, semen, etc., as well as any soaps, cleaning agents, or bactericidal agents used in the washing procedure. The quantity of droplets released will depend on the design and efficacy of the personal-hygiene system and components, and the care taken by the astronauts in their use. As discussed previously, this latter factor is expected to be a function of astronaut training in the use of the system. Occasional accidents or misuses may be expected to occur; these spillages will produce a large number of particles to be retrieved and removed. The wash-water droplets would impinge on component surfaces and dry, after which the remaining solids could be reaerosolized and produce particulate contamination, or they could dry in the air, leaving a solid residue, or they could be removed before drying by the particle-removal system.

Drinking Water and Water for Food Preparation

The potable water will be fairly pure and, when uncontaminated by food materials, saliva, etc., may be expected to evaporate completely after droplets are released into the cabin air. The quantity produced will again depend on the design of the potable-water and food-preparation systems, and the care and skill exercised by the astronauts. Although these released droplets will not usually contain appreciable amounts of solids, they will add to the liquid load of the particle-control system and provide moisture for bacterial growth both in various cabin niches and with the particle-control system, as well as add water vapor to the load to be removed by the ECS. Accidents or misuse may occasionally produce large quantities of water to the cabin atmosphere.

Food

Food spillage may be expected to occur fairly frequently; it is reasonable to assume that some spillage will occur during each meal. The spilled material may consist of solid dry particles or wet particles or droplets. Depending on the stage of preparation or consumption at which food is spilled, it may be dry, partly mixed with water, or mixed with saliva. The composition of the food that will be encountered is presently uncertain; but whatever the composition, the particles may be assumed to be contaminated with bacteria and to provide a very adequate bacterial substrate. Unremoved particles may impinge on cabin surfaces where they will dry and decompose.

Food particles may also be produced by breakage of food containers, or by malfunctions of the food-storage and garbage-disposal systems. This source can be eliminated by adequate design and proper handling. Mattoni and Sullivan (Reference 1) estimate that approximately 0.7 gm per man-day of food spillage will take place, with 0.55 gm per man-day being released into the

atmosphere. This figure is quite conservative if the current types of crumbly foods are used; for such foods, this figure should be at least doubled.

Dental and Oral Cleansing Agents

The composition and quantity released of dental and oral cleaning agents will depend on the method used for cleaning the teeth, mouthwashing, etc. Toothbrushing agents generally contain an abrasive, flavored components, and probably a bactericide. These agents are frequently basic in pH to counteract oral acidity, and mild astringents may be employed for removing mucus. One paste that has been suggested for spacecraft use (Reference 1) contains a detergent, 0.5-percent sodium lauryl sulfate, with calcium pyrophosphate suspended in a tragacanth aqueous glycerine base; sodium benzoate (0.25 percent) is added as a preservative, along with a trace of methyl salicylate for flavoring. This compound can be swallowed with no toxic effects for six months or so. Other nontoxic products have been suggested; these range from swallowed mouthwashes to chewing gum to ordinary toothbrushes. In evaluating the various methods, a rule of thumb for particulate-matter production is that, during use, the longer a material is exposed to the cabin atmosphere, the more likely it is that particles will be produced. A technique that can be used with the mouth closed is better than one in which the mouth is open, particularly one that - like a toothbrush - requires agitation. Conventional toothbrushing, despite attempts to hold the mouth closed, almost always produces droplets. These droplets contain cleaning agents, saliva, food particles, and exfoliated epidermal cells. The cleaning agents themselves contain a fairly high percentage of solids. . .

Lint and Clothing Fragements

Because human movement causes abrasion, rubbing, and wear of clothing, small pieces of thread and fabric are produced almost continually. This production can be minimized by use of wear-resistant fabrics, and particularly by eliminating abrasive surfaces that are subject to brushing or rubbing by clothing. The use of proper clothing and treatment of the surfaces the clothing will contact can make a great difference in the quantity of lint and clothing fragments produced. One surface that is not amenable to such treatment is the human body; the action of skin against clothing removes particles from both the skin and the clothing. Body hair is particularly abrasive to clothing, and is thus quite productive of lint. Body hairs often tend to gather and collect fabric materials because of their alignment. Laundry operations, if required, should remove most of the lint from clothing, and bathing should remove that collected in the body hair. However, some release of small threads or lint balls appears inevitable. Lint also may be formed between the astronauts' clothing and the surface of seats; this lint can also be expected to be released into the atmosphere. The lint particles will be small thread fragments or aggregates of these fragments; the aggregates, which may contain various dermal products (body hairs, sweat solids, sebum residue, etc.), should generally be no more than 0.5 cm in size, with a weight of perhaps 0.05 gm. Maximum production should not exceed 0.05 gm per man-day, but much smaller values can be achieved with the proper clothing materials, smooth wearing surfaces, and proper personal-hygiene techniques.

## CONCLUSIONS

The quantity of particles released into the space cabin atmosphere depends on several factors that cannot be specifically defined at present--i.e., the design and treatment of the cabin equipment and surfaces and the design and functioning of the several systems that are related to sources of possible particle production, particularly the cabin occupants. Concerning the latter factor, the systems of primary importance are the personal-hygiene, waste-management, and food-preparation and handling systems. (In this sense, "system" means not only the basic pieces of equipment involved but also any ancillary materials and the techniques for using the equipment.) The human factors involved are a very important consideration regarding these systems--i.e., the adequacy of the human engineering, the adequacy of the training of the astronauts in the system use, and the degree of care shown by the astronauts in using the systems. This latter aspect of system operation is predominantly a psychological function of the men involved, their degree of motivation, and their knowledge of the dangers resulting from misuse.

Because of the many areas of uncertainty, it is very difficult to make an adequate estimate of the quantity of particles that will be discharged into the cabin atmosphere. Also, an estimate on a weight per man per day nature is misleading, in that it implies a continuous generation rate of materials that actually may be produced intermittently or only under special conditions. Furthermore, the particle load may be increased by several orders of magnitude by accidents, equipment malfunctions, etc. With these reservations in mind, an estimate can be made of the normal human particle production, as well as educated guesses about such uncertain quantities as component sources. The estimate made by Mattoni and Sullivan (Reference 1) was 1.891 gm per man day of solids entering the cabin atmosphere. Although it is difficult to have much confidence in the numbers past the decimal point, a figure of 2 gm per man day does appear to be reasonably adequate as an estimate of the atmospheric solids produced from all sources. This estimate probably errs on the high side slightly, but from the standpoint of safety a somewhat high figure is better than a correspondingly low one. Mattoni and Sullivan were not concerned particularly with the liquid components of particles, because these would be expected to evaporate quickly, leaving a solid residue. However, many liquid and semiliquid droplets will be produced, and it is expected that these will also be encountered in the airstream by the particle-control system. The quantity of liquid released will be approximately three times the weight of the solid components, or approximately 6 gm per man-day. Almost all of this liquid will be water. Mattoni and Sullivan also estimated that about 0.080 gm per man day of solids would be deposited on surfaces, 2.535 gm per man day on clothing, and 7.647 gm per man day on the skin of the crew.

These estimates are useful only for computing the total loads to be handled during a total mission and are entirely inadequate for hourly or even daily rates. An incident such as vomiting could easily add 300 gm to the atmospheric particle load in a few minutes. Food spillage, accidental diarrhea, wash-water spillage, leakages in containers or piping, accidents during waste disposal, sudden sneezing, etc., could all cause abrupt high concentrations

of particles. It is expected, then, that a graph of particulate-contaminant concentration vs time since mission initiation would show (1) a base-line particle generation rate that would remain fairly constant throughout the entire mission, (2) a series of slow waves based on circadian rhythm, indicating activity of the subjects, (3) moderate peaks during eating, drinking, and personal-hygiene operations, and (4) occasional high peaks from particle-producing accidents. It is anticipated that the average value of this curve will be approximately the estimated generation rate indicated above. A large number of accidents, or permanent equipment malfunction could cause major increases in this average rate.

Almost all of the materials that are potential producers of particulate contaminants are physiologically active substances, which are either initially contaminated by microorganisms as they are produced or which offer substrates for bacterial proliferation if contamination occurs. It is suggested that all of the products from human sources be considered potentially toxic and infectious.

The composition of most of the predictable kinds of particles is given in the various tables presented with the discussions of the different source materials. Generally, these particles range from those that are almost entirely water (e.g., drinking water) to dry solids (e.g., hair) with many graduations in between. Given time, the particles will almost all evaporate leaving a solid or semi-solid residue. At first, however, several particle types will be almost entirely liquid droplets; e.g., sweat, tears, saliva, urine, blood, and washing and drinking agents. The particles that will be largely viscuous liquids, rather sticky in consistency, are mucus and semen. Sebum, cerumen, and feces will usually be gummy semisolids. Hair, nails, epithelial cells, and lint are fairly dry. The drier a substance, the less apt it is to stick to surfaces upon which it may impinge. Other materials are mixtures of solids and liquids, or lie somewhere in between the above categories.

The size range of the particles spreads over several orders of magnitude. The smallest particles will be viruses and bacteria, which are discussed in Section 3 of this report. The virus size range is approximately 0.01 to 0.10 microns; bacteria may be as much as one thousand times larger than the smaller viruses. The smallest particles of the sort discussed in this section should be approximately 1.0 microns or larger. On the other end of the spectrum, most particles will not be much larger than 1 cm in size, excluding hairs, which may be as long as 8 cm. The smaller particles will be the dusts from abrasion and solid residues from evaporated droplets, while the larger particles will be nail clippings, lint balls, hairs, and various globules of liquids. The latter can be very large when they are the product of spillage; vomit, drinking and wash water, urine, semen emissions, chunks of food, etc., form globules at zero gravity the size of which is limited only by surface tension and the quantity of material available. Generally, however, the size range will be from about 1 micron to 1 cm. A size distribution cannot be prepared with any degree of confidence; however, most particles (by number) will range in size from 15 microns to slightly less than 1 mm.

RECOMMENDATIONS

The particle-control system must remove all of the particles described previously and dispose of them so that they are not released into the atmosphere and do not produce any secondary contamination (i.e., microorganic proliferation with particle release). The system must have a total capacity to remove 2 gm per man-day of solid particles and 6 gm per man-day of liquid material for the entire mission length, preferably with a safety factor of at least 1.5. For liquid materials, removal should enable evaporation of the trapped material or some form of retrieving the water, both because of water-management requirements and to minimize bacterial growth after collection. The system must trap and retain particles in the size range indicated above. It must also handle large quantities of particles such as would be found after accidental spillage. The system must be designed in accordance with human-engineering principles to ensure optimum design and function, and training must be conducted so that the astronauts can operate the components with the maximum ease and efficiency and the minimum particle-producing accidents. In addition, the systems with particle-producing capability must be designed and engineered so that they release a minimum of particles during use; human engineering and training are also required here to ensure optimum function without spillage.

For general atmospheric control, to retain the very small particles that are expected and that will be invisible to the cabin occupants, a fine, permanent filter that will not require replacement during the mission, situated upstream of the ECS and just downstream of the cabin itself, is recommended. This filter should protect the ECS components from particulate contamination and clogging, and also prevent recontamination of the cabin; impinged materials would remain on the filter because of the pressure differential and because of the normal impingement mechanics and electrostatics of small particles. This comparatively fine filter should not be subjected to the entire load of particles produced during the mission; if it were, it would become clogged with larger particles, the results of spillage accidents, heavy bacterial or fungal mats, etc.

To protect the permanent filter so that it can function for the entire mission without developing a prohibitively high pressure drop, a coarse (roughing) filter and a large-debris trap upstream are suggested. The coarse filter should be removable so that it can be changed during the mission. This filter should be changed using the plastic bag technique, so that potentially pathogenic microorganisms will not infect the handler or recontaminate clean areas. This is best done using a bag containing a dry disinfectant to which water may be added. While filter-changing is troublesome and potentially hazardous, it is required by the high particulate load. Because of the possibility of accidents and major spillages, a debris trap is recommended upstream of the coarse filter. Traps of this kind are available that have very small pressure drops and still remove large particles under zero gravity; these traps usually function by air entering a circular chamber circumferentially and exiting axially, so that large particles are deposited in traps along the circumference. The debris trap should be easily opened for cleaning, which should be required only following major unretrieved spillage. These traps have

the capability of removing not only large particles but also fairly large quantities of liquid. Use of such traps for liquids is preferable, because large globules impinged on filter surfaces result in caking, the spread of bacterial contamination, and increased bacterial growth. Such traps hold large droplets of liquids until they evaporate.

Some means must also be provided for the cabin occupants to remove visible particles, particles impinged on equipment, and the large particles from spillage accidents. Several means are suggested for these activities, each of which is appropriate for certain types of particles. For retrieving large dry particles, a folding net is suggested. This net will be useful for retrieving particles that the occupants desire to keep, such as chunks of food, as well as other objects that may be floating loose. Such collapsible nets, similar to insect or fish landing nets, with a net diameter of 12 in., have been devised for this purpose. For retrieving large debris in general, the Apollo vacuum cleaner developed by MRD is recommended. This device, equipped with a hose and blower, contains a gas-permeable bag for immediate collection, and is equipped with storage bags with disinfectant in water-soluble pouches. This cleaner will be used for general maintenance inside the cabin, for retrieving crumbs, lint, etc., and generally whenever it is applicable in removing immediate particulate contamination. Together with the net, it will be used immediately after any spillage to reduce the load of particulate contaminants on the filters. It is anticipated that the cleaner will be used whenever particles are visible in the air, and after personal-hygiene functions, food preparation and eating, and general cleaning, particularly of clothes and seats for lint, body hair, and the like. It should also be useful for large liquid droplets, such as would be encountered after urine, wash water, or drinking water spillage. However, for capture of such globules and droplets, use of sponges or absorbent cloths in addition to the vacuum cleaner is recommended. These may be designed to be attached to extension rods or to the net, so that liquid droplets can be caught and absorbed in the material. The liquid can then be evaporated or removed into the waste disposal system. The large number of liquid materials that are expected will necessitate the use of such devices. In addition, these sponges or cloths will be used for cleaning surfaces. Barring spillages and subsequent deposition, such cleaning should be accomplished about every 5 days.

In summary, the particle-control system should consist of a filter and debris trap upstream of the ECS and just downstream of the cabin, the Apollo vacuum cleaner with blower and hose, a net for retrieving large solid objects and materials, and sponges for retrieving liquid particles and droplets, as well as for cleaning surfaces on which particles impinge. The proper use of these components should result in an entirely adequate system under most conditions. Further study is required for the design and integration of this system, and for integration with other systems, particularly the waste-mangement, personal-hygiene, food-preparation, and bacterial-control systems. The bacterial-control system is particularly important is disposing of the captured particles. It is expected that no bacterial control (except perhaps metallic silver) will be used on the filters <u>in situ</u>; there have not been

adequate bactericidal or bacteriostatic filters developed to date* that are nontoxic and function in other than high humidities. The removable filter must be treated with bactericide after removal, and the debris trap may be washed or swabbed with bactericide. Similar disposal must be made of the material collected in the vacuum cleaner bag.

*Some work that has been done in this field is described in AiResearch Report LS-156.

REFERENCES


1. Mattoni, R.H., and Sullivan, G.H., 1962, Sanitation and Personal Hygiene During Aerospace Missions, Medical Research Laboratories Report TDR-62-68.

2. Hamilton, J.B., 1958, "Factors in the Regulation of Hair Growth in Man," Montagna, W. and Ellis, R.A., eds., Biology of Hair Growth, Academic Press, New York.

3. Sunderman, F.W. and Boerner, F., 1950, Normal Values in Clinical Medicine, W.B. Saunders Co., Philadelphia.

4. Long, C., 1961, Biochemists' Handbook, D. Van Nostrand Co., New York.

5. Diem, K., editor, 1962, Documents Geigy Scientific Tables, 6th Ed., Geigy Pharmaceuticals, Ardsley, New York.

6. Webb, P., ed., 1964, Bioastronautics Handbook, NASA SP-3006.

# SECTION 3

# MICROBE CONTROL

## INTRODUCTION

In the design and development of manned spacecraft, one major objective is to make the space-cabin ecology as nearly ideal for the human occupants as possible. Unfortunately, in doing so, the ecology becomes ideal for normal terrestrial microorganisms as well. In the short flights made to date, the growth of microorganisms has not presented a problem; with more extended missions the danger of microbiological contamination will greatly increase.

The growth of microorganisms is definitely a potential problem in spacecraft, as shown by the importance attached to microbe control by the petroleum industry, the chemical industry, and the military. Microorganisms have seriously impeded the flow of crude oil from wells and have blocked pipelines and processing systems in chemical refining plants. Numerous military aircraft accidents have been caused by the growth of microorganisms in compounds such as RP-1 fuel; molds growing on the surfaces of lenses have impaired optics; in electrical insulators and potting compounds they have caused power leaks and short circuits. They have even been found in the hearts of nuclear reactors, apparently living off the ion exchange. If microorganisms thrive in such rigorous environments and can cause such problems, they may be expected to impair functioning of water supply systems, space suits, waste-management systems, component surfaces, etc., as well as affect food supplies in manned spacecraft.

The danger presented to components and systems by these organisms is no greater than the danger presented to the human occupants of the spacecraft. Studies under simulated space-cabin conditions have shown that the subject's antibody titer decreases notably, implying an increased susceptibility to infection from microorganisms. Uninhibited microbial growth could spoil the the potable-water supplies and impede waste disposal. Also, microorganisms may add noxious and toxic gases such as methane, ammonia, and hydrogen sulfide to the cabin atmosphere, thereby adding trace contaminants to the system.

It is extremely difficult to sterilize a spacecraft; attempts to do this have resulted generally either in low component reliability or in the presence and spread of residual contamination. The complexities of assembly and prelaunch activities render such attempts almost useless. Similarly, it is impossible to sterilize human occupants. Human beings are normally hosts to numerous microbial species, including several pathogenic forms. Furthermore, attempts to systematically kill all of the organisms that may be expected in manned spacecraft may result in the proliferation of mutant strains that are resistant to the sterilization technique used. Thus, it seems that the most advantageous technique would be one that produces a biostatic condition, under which the population of microorganisms is controlled at an acceptable low level, permitting no ecological niches where resistant strains could grow unchecked.

Any such technique, of course, involves problems of its own. For example, the biostatic method must not introduce any toxicity or similar dangers to the human occupants. The equipment involved must function reliably under the peculiar conditions of a space mission; it must be acceptable from the standpoints of weight, volume, power load, etc. Any study used to arrive at such a technique must examine the microorganisms involved in the environmental conditions under which they will be growing, recognizing that the effects of reduced pressure, increased oxygen level, elevated carbon dioxide level, etc., can greatly affect the microbial flora.

The areas of specific concern at which microbe control is necessary are (1) the ambient cabin atmosphere, (2) the potable-water system, (3) equipment and component surfaces, (4) the inside of space suits, and (5) the bodies of the astronauts. The criteria for evaluating possible techniques and systems for microbe control are:

> Control should be effected at spacecraft temperature, humidity, and gaseous environment.
>
> Control apparatus and components should have minimum weight, volume, and power requirements.
>
> Any apparatus should be simple to operate and maintain.
>
> The control system should not permit or produce adverse conditions, such as the production of resistant strains, materials degradation, water impalatability, trace contamination generation, etc.
>
> The control should be in itself nontoxic and incapable of producing sensitivity reactions in humans.

The basic evaluation criteria were first, the safety and health of the human spacecraft occupants; second, the prevention of microbial degradation of equipment and components; and third, the efficiency of operation in the spacecraft environment.

## METHODS AND TECHNIQUES FOR MICROBE CONTROL

### General

The foundations of modern disinfection methods were developed by a number of researchers during the nineteenth century. As early as 1827, Alcock evaluated hypochlorites as disinfecting agents, although the germ theory of disease was not fully appreciated until the work of Pasteur in 1857, nor proved until the studies of Koch in 1876. During this early period while the microbial etiology of disease was being proved, Lister's concept of antiseptic surgery using carbolic acid was developed.

As with all living cells, the growth and biochemical characteristics of microorganisms are the outcome of a complex series of enzyme activities. The protein nature of enzymes makes them subject to inactivation by any physical or chemical denaturation; this is a probable explanation of much antibacterial action. Any treatment that inactivates one or more of the enzymes or enzyme systems may stop growth (bacteriostasis); if a number of essential enzymes are blocked, killing or bactericidal activity results.

Although it is generally known that various species of microorganisms are variously sensitive to disinfectants, it is not usually recognized that sensitivity to disinfectants depends on the age of the cell and the nature of the growth medium used to determine the rate of kill. In testing any particular disinfectant with cultures of various ages and with suitable growth media of widely different compositions, it is obvious that cells in the initial stationary phase of growth (about 1/2 to 4 hr for some bacteria) have the greatest level of sensitivity in any of the media. There are vast differences between recovery of treated microbes on simple media; media containing few components give the least recovery and complex media containing many components the greatest recovery. This difference in recovery is generally attributable to the fact that, as enzyme systems are blocked, the microorganisms require more and more preformed amino acids, vitamins, etc.; these may not be present in the simple medium but may be available in the complex medium. This is an important consideration, because apparently non-viable microorganisms might still be capable of growth in food supplies or in the human body.

In the following paragraphs, various methods and techniques presently used in microorganism control that may be applicable in spacecraft environments are described. The methods are discussed generally to outline particular techniques that may prove best for any spacecraft biological-control system.

The problem to be considered involves the prevention of microbiological growth in the individual spacesuits, in the water-supply system, and in the general confines of the spacecraft, as listed above. This involves basically the prevention of growth on surfaces, such as spacesuits, hardware, and materials, and the elimination and deactivation of airborne microorganisms that spread spacecraft contamination. Thus, the control techniques may include the treatment of surfaces, decontamination of the water supply with filters, chemicals, irradiation, etc., and removal and control of airborne particles by any of several techniques of particle removal.

Such control techniques offer the distinct possibility of presenting further problems when used in the spacecraft environment. For example, paints and similar materials that are sufficiently resistant to microbiological growth may not meet other performance specifications. Impregnated filters in an airstream may produce aerosols and gases in the spacecraft atmosphere that may be toxic to the occupants over an extended period, or that might induce hypersensitivity either alone or reacting additively or synergistically with other atmospheric components. Treatment of potable water may cause allergic responses, long- or short-term toxicity, or impalatability. The study of prospective methods must, of course, obviate such possibilities.

## Removal of Microbes from the Atmosphere

### 1. General

Microorganisms in the cabin atmosphere will be encountered either as discrete individual organisms, clumps or organisms, or organisms attached to aerosol particles, dust, or liquid droplets. In any case they can be treated as particles to be removed from the air. The laws governing the movements of these particles and the size ranges of exemplary particles are shown in Figure 1. The general categories of particle removal to be considered are mechanical separation and filtration, electrostatic filtration, and electrostatic precipitation.

Mechanical filters include particulate filters and mechanical particle separators. Basically, mechanical filters are devices in which mechanical and inertial forces are used to remove contaminant particles from a fluid stream. The methods used in mechanical filtering include centrifugal separation, gravity settling, washing and scrubbing for sterilization, and filtration through fibrous and porous media.

Electrostatic filters are generally fibrous filters that employ electrostatic forces together with inertial forces to entrain particles in the filter medium. Several approaches have been used to charge filter material. The charged fiber exerts electrostatic forces on the particulate matter, causing it to be displaced from the streamline flow about the fibers and thereby increasing the probability of impingement. Electric field effects also have been used to exert forces on the particles passing through the filter and so improve efficiency.

Electrostatic precipitators have been very satisfactory commercially in removing aerosols and particles. Particles are removed from the gas stream by first charging them and then collecting them on plate electrodes of opposite charge.

### 2. Particle Filters

These filters usually have a fibrous or porous medium for the removal of particles such as microorganisms. Fibrous filter materials include paper, felt, glass, ceramics, and metals, usually in the form of a relatively compact fiber bed. Filtration is accomplished by the mechanical forces of interception, impaction, diffusion, and electrostatic and thermal forces. Generally, it is found that the predominant mechanism is highly dependent on the face velocity and on the size of the particle.

Very few practical air filters depend on screening or sieving action to remove the suspended material. Since the interstices of a screening-type filter must be smaller than the smallest particle to be removed, the resistance to air flow is high. As the surface becomes covered with collected material, resistance rises and ultimately air flow stops as all the interstices become plugged (Reference 7).

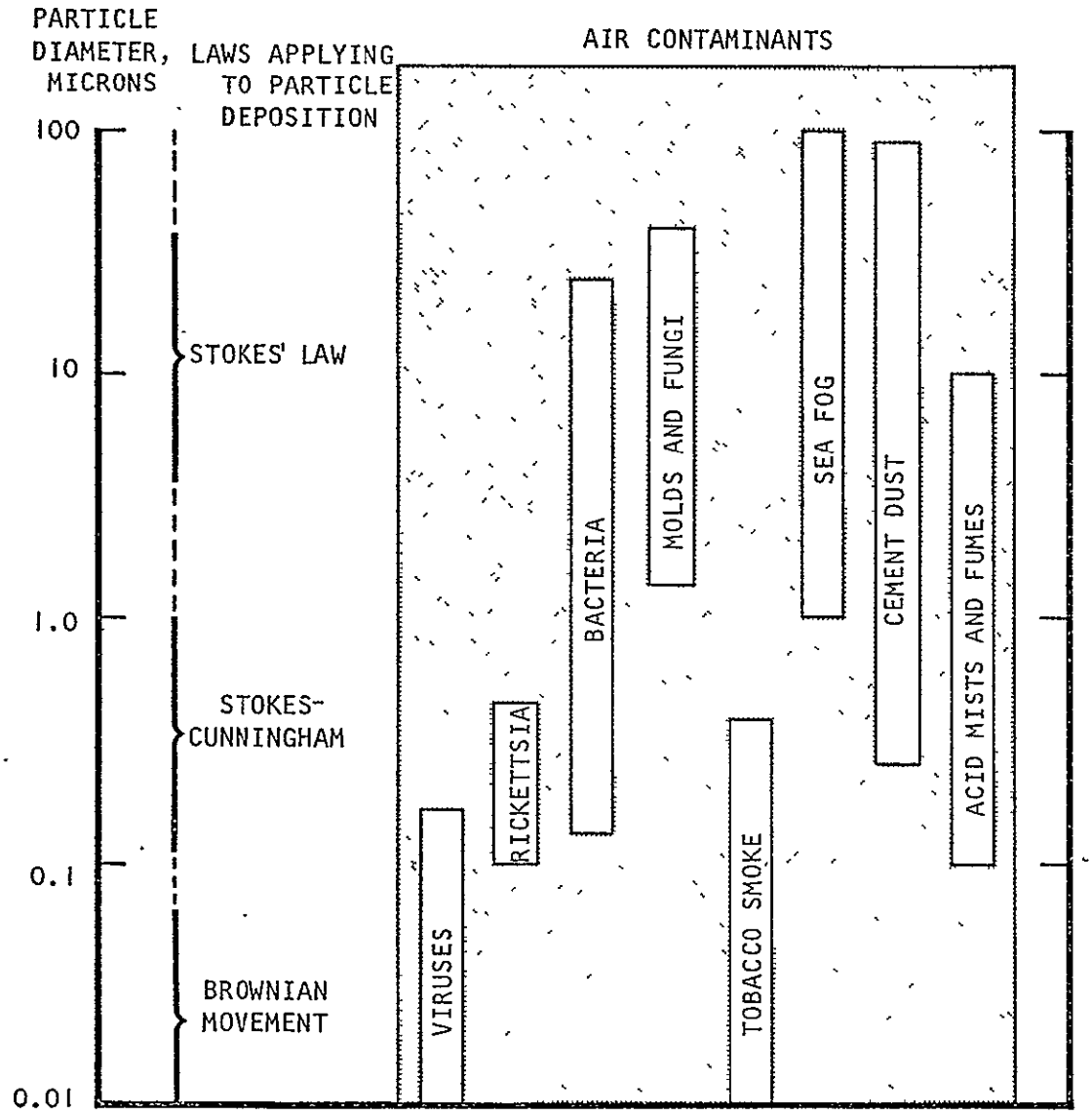



Figure 1. Size Range of Airborne Particles (From Reference 7)

A-15275

All practical aerosol filters consist of randomly oriented fibers of various materials placed so that most of the open spaces or interstices are considerably larger than the mean diameter of the particles to be removed. The filtering action takes place by the particles contacting and adhering to the fibers or collecting surface. The mechanisms that may cause suspended particles to impact on the fibers are (1) direct interception, (2) deposition in accordance with Stokes' Law, (3) inertial effect, (4) diffusion, and (5) electrostatic effects. Of these mechanisms, the last three seem to exert the greatest effect in removing particles (Reference 7).

The first mechanism, direct interception, is applicable only to particles whose centers remain in a given streamline, this occurs when the particles are too large to exhibit appreciable Brownian motion, but are too small to be subject to Stokes' Law. The second method is settling according to Stokes' Law concerning rate of fall. Sufficiently large particles will be deposited on the upper surfaces of filter fibers instead of remaining within the streamline. The deposition rate varies with particle size, concentration, and the total area that the upper surfaces of the fibers project into the horizontal plane. The rate of fall of particles less than 0.3 micron in diameter is so low that this mechanism is probably negligible in removing small particles (Reference 7).

The third mechanism of particle impingement is inertial effect, which is most effective for particles 1 micron in diameter and larger. Air flowing through a fiber must change direction continuously to flow around the randomly oriented fibers; particles with enough mass tend, because of inertia, to continue in their original paths and thus strike the filter fibers instead of following the streamlines around the fibers. Impaction of particles 1 to 5 microns in size increases with increased air velocity through the filter material because the inertial force is directly proportional to the square of the air velocity and inversely proportional to the radius of curvature of the air stream. It has also been shown that decreasing the fiber diameter increases the collection efficiency (Reference 7).

Diffusion, or Brownian motion, pertains primarily to small-particle aerosols, and is responsible for the impaction of almost all particles smaller than 0.3 micron. Particles of this size diffuse in a manner similar to molecular diffusion, and in filters are further subject to the laws governing isotopic turbulence, which occurs with randomly distributed eddying motion. In contrast to large particles, decreased air velocity increases deposition, because the particles remain in the filter material for a longer time, offering a greater opportunity for diffusive impaction and correspondingly less for inertial effects (Reference 7).

Electrostatic effects are most notable with low-humidity air; these effects result from charges on the particles and on the filter material itself. Certain filters may build up areas of both positive and negative charge, which provide strong forces for particle collection (Reference 7).

For maximum filter efficiency, it is desirable to have fiber diameters less than the diameter of the smallest particles that will be encountered. Small-diameter fibers greatly increase the deposition area of the filters and, at the same time, reduce the air flow pressure drop. Because small-diameter fibers tend to pack together, binders are usually required to hold them apart, allowing minimum resistance and increased deposition on the inner filter fibers (Reference 7). Thermal gradients in the air stream tend to move particles from hot to cold regions because of the differential molecular bombardment. This mechanism is probably the least-studied of the mechanisms described here.

After fiber particle interception, particles may be assumed to remain attached to the fiber. The forces holding the particles in place may be electrostatic, van der Waal's, or simple adhesive forces. Adhesive force can be increased by coating fibers with oil, bactericide, etc. The ability of particles to remain in filters depends more on the nature of these adhesive forces than it does on fiber or particle size, until particle agglomerates become large enough to produce enough air resistance for detachment.

For a given particle size and fiber diameter, there will usually be a face velocity at which the collection efficiency is at a minimum. Below this velocity, Brownian motion, thermal and electrostatic effects, and interception are the important mechanisms in operation. At higher velocities, inertia effects, such as impaction, tend to predominate. As particle size decreases (below about 0.2 to 0.3 micron in diameter), the interception effect decreases because of the lessened chance of passing close to a fiber. The diffusion of particles will usually increase, however, to a point where it is more than enough to offset this effect. Experiments have shown that at too high a velocity many particles will be dislodged from the fibers and reenter the airstream. Also, pressure drop increases with velocity; in the case of a spacecraft ECS, this sets an upper limit on the face velocity to be used.

In general, the efficiency of a filter will be a function of particle size, shape, physical and chemical properties, and fiber diameter, physical and chemical properties, and compactness and array of the fibers.

Because of the many variables affecting efficiency, and because of the statistical nature of the collection process, an air filter can usually be designed only so that the probability of penetration by a single size of particle during the period of operation is less than a certain value. Absolute filters, such as a Millipore assay filter, will remove all particles larger than a certain diameter, but this is a screening or sieving action, rather than an impacting or intercepting one. Bulk density and fiber distribution in filter beds are more important in the collection action than is the kind of fibrous material used (Reference 8).

Although extensive theoretical and experimental effort has been devoted to particle filtration, comparatively few studies reported have dealt with particles which were microorganisms. In 1947, it was reported that 3 in. of slag wool was 99.9998+ percent efficient in removing Bacillus subtilis spores from low-velocity airstreams. Tests of from 7 to 10 days duration

made on slag- and glass-wool filters used in industrial penicillin preparation showed from 99.89- to 100-percent efficiency for face velocities of 0.2 to 0.5 ft per sec (Reference 9). In 1951, efficiencies of 99 to 100 percent were obtained in removing Serratia indica and E. coli bacteriophage from air using a combination spun-glass filter and electrostatic precipitator (Reference 10).

In 1951, Ramskill and Anderson (Reference 11) represented the relationship of velocity, particle properties, and mat properties in a general graph (Figure 2). This graph shows changes in collection efficiency with velocity as collection shifts from removal by the diffusion mechanism, through direct interception, to inertial deposition. These relationships and the results of more recent theoretical work must be used in defining each mechanism and its interaction to predict where and to what degree maximum penetration of particles through any selected filter may be expected.

In defining the filtration mechanisms as they are presently used in air purification, it is expected that the particulate media performance will be at or near maximum collection efficiency. It is also expected that fibrous mats for particle filters can be more clearly defined for use in specific designs.

The filters used in the bacterial tests discussed previously may be classified as high- or ultra-high-efficiency filters. Generally, filters may be classified by the percentage of particles 1 to 5 microns in diameter that they remove. Roughing filters remove from 10 to 60 percent of such particles, medium-efficiency filters remove 60 to 90 percent, high-efficiency filters remove 90 to 99 percent, and ultra-high-efficiency filters remove 99.99+ percent of this size range of particles. This nomenclature will be used in the following discussion of filters.

The use of a filter in a closed atmospheric system would result in a logarithmic decay in the initial quantity of particles in the atmosphere, assuming no production of microorganisms. In the Apollo vehicle, however, a fairly constant generation of microorganisms is anticipated, largely from human sources. With a constant generation rate and a given filter efficiency, an equilibrium level of microorganisms will be reached. Appropriate calculations have been made that will serve to indicate the levels of particles reached as a function of time. An exemplary model used in References 7 and 12 assumed a sealed room volume of 5000 cu ft, with the air initially clean. The air is circulated ten times per hour, all of the air is filtered with each circulation, and there is complete mixing. Under these conditions, organisms are assumed to be generated at the rates of $10^3$, $10^4$, and $10^5$ per min. The theoretical results are presented in Table 16 for these conditions. The mathematical treatment of such problems is fairly simple, involving basically the following equation (Reference 7):

$$N = \frac{60b}{aKV}\left[1 - \exp\left(-\frac{aKt}{60}\right)\right]$$

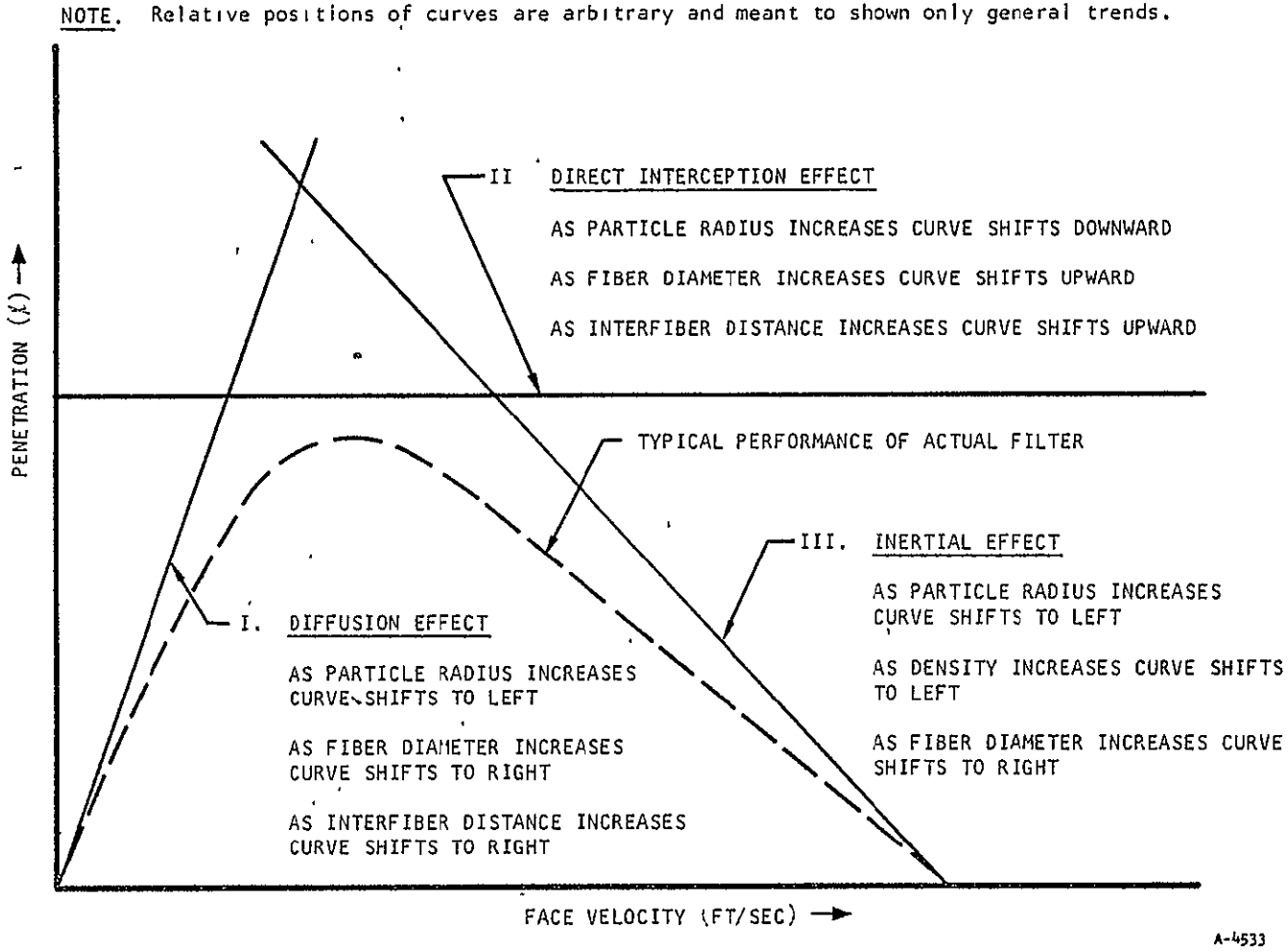



Figure 2. Effect of Face Velocity on Particle Penetration of a Fibrous Filter (after Ramskill and Anderson)

TABLE 16

ROOM CONTAMINATION IN ORGANISMS PER CUBIC FOOT
AT END OF ONE HOUR AND AT STEADY STATE

| Filter Efficiency, % | Organisms being generated per minute | | |
|---|---|---|---|
| | 1,000 | 10,000 | 100,000 |
| 30 | 3.80085* (4.00000)* | 38.00852 (40.00000) | 380.08520 (400.00000) |
| 60 | 1.99504 (2.00000) | 19.95042 (20.00000) | 199.50420 (200.00000) |
| 90 | 1.33316 (1.33333) | 13.33163 (13.33333) | 133.31630 (133.33333) |
| 100 | 1.19994 (1.20000) | 11.99946 (12.00000) | 119.99460 (120.00000) |

Assumptions: 5,000 cubic feet in room; clean at start. Then air changes 10 times per hour through filters. Complete mixing obtained at all times.

* First figure in the body of the table gives concentration in organisms per cubic foot reached at end of one hour. The second figure, in parentheses, gives the equilibrium or steady state concentration.

(From Reference 7)

where N = the number of organisms per cubic foot present at t

t = time in minutes

V = cabin volume in cubic feet

K = number of complete changes of cabin volume per hour

b = total number of organisms per minute entering or released from human occupants

a = efficiency of the filter (or any other such organism-removing device)

Figure 3 shows a graph of these results for the $10^5$ organisms per minute generation conditions, illustrating the comparatively small difference between the levels reached with 90-percent and 30-percent efficiency filters. As indicated by Table 16, the contamination rate has no effect on the choice of filters, because the equilibrium concentration reached is directly proportional to the contamination rate for any particular filter efficiency. The equilibrium level is reached with all filters in approximately 1 hr, with the more efficient filters reaching equilibrium somewhat faster. It will also be noted that there is considerable reduction in the equilibrium level between 30 and 60 percent and 60 and 90 percent, but comparatively little between 90 and 100 percent (Reference 7). Because there is so little difference between high-efficiency and ultra-high-efficiency filters, the high-efficiency 90-percent filters have been recommended for hospital use because of their lower power requirements. Examples of the materials, resistance characteristics, and volume capacities of the four classes of commercial filters for microbial filtration are shown in the Appendix.

### 3. Mechanical Particle Separators

Presently used mechanical particle separators are based on some form of centrifugal cyclone or centrifugal tube separator. Usually, the particle-laden airstream is injected tangentially into a tube at one or more points and leaves through a central opening. Inertial forces cause the heavier particles to move to the outside wall of the tube, from which they are removed to some type of collector. In commonly used cyclones, the separating forces will normally range from 5 to 2500 times the particle weight, depending on the cyclone diameter and entrance velocity. These devices are not usually applicable to the removal of particles smaller than 5 microns in diameter, which, together with the power and weight penalties imposed by even normal cyclone speeds, so limits their use in spacecraft that they will not be considered further.

### 4. Electrostatic Filters

Electrostatic filtration combines the effects of simple mechanical filtration and electrostatic forces to cause a greater incidence of particle collision with the filter medium. To increase filter efficiency without

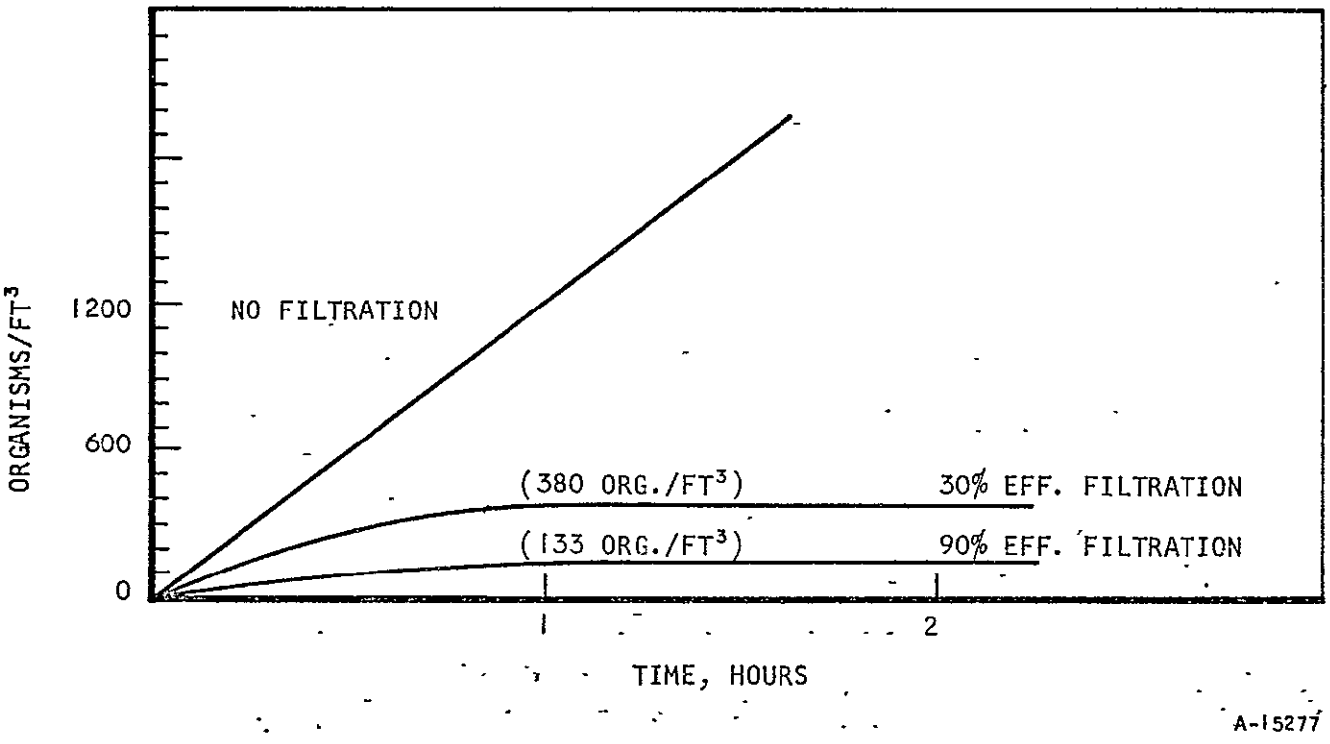



Figure 3. Equilibrium Levels With 30- and 90-Percent Efficient Filters (From Reference 6)

increasing fiber density and flow resistance, forces other than mechanical forces must be applied to the particles. A number of electrostatic phenomena exert forces on charged and uncharged particles relative to filter fiber that is charged or that is in a nonuniform electric field. These include Coulomb attraction of charged particles, dielectrophoretic force, and electrical image force. In the presence of an electric field, a dielectric particle is polarized; when this field is nonuniform, an attractive force results, since one end of the polarized particle is in a region of greater field intensity than the others. For particles suspended in a gas, attraction is always toward the region of greater field intensity, regardless of the direction of the field. The dielectrophoretic force may be expressed as:

$$F_d = 2\pi a^3 K_1 \epsilon_0 \frac{K_2 - K_1}{K_2 + 2K_1} E^2$$

where $F_d$ = dielectric force, Newton

$E$ = field strength, volts per meter

$a$ = radius of particle, meters

$\epsilon_0$ = permitivity of free space, farad meter

$K_2$ = relative dielectric constant of particle

$K_1$ = relative dielectric constant of medium (for air $\cong$ 1)

Electrostatic image force is due to an image charge inducted in a conductor on the dielectric material by a charged particle. The induced image charge is opposite to that of the particle and results in attraction of the particle to the material, regardless of its potential. For a dielectric material, the attractive force on the particle is:

$$F_i = \frac{K_1 - K_2}{K_1 + K_3} \frac{q^2}{16\pi\epsilon_0 r^2}$$

where $F_i$ = image force on particle

$q$ = distance of particle from collecting material

$r$ = distance of particle from collecting material

$K_3$ = dielectric constant of collecting material

Methods to utilize these forces include self-charging electrostatic filters, mechanically charged electrostatic filters, and nonuniform electric fields applied across the filter material and normal to the air flow.

A number of high-dielectric plastics, resins, and waxes become electrostatically charged when subjected to air flow. Materials that exhibit this characteristic to some degree are listed in Table 17.

TABLE 17

SELF-CHARGING MATERIALS

| | | |
|---|---|---|
| Rubber hydrochloride | Vinylidene chloride polymers and copolymers | Fluorinated ethylene |
| Cyclized rubber | Cellulose nitrate | Methyl methacrylate |
| Chlorinated rubber | Cellulose acetate | Ethyl cellulose |
| Polyisobutylene | Regenerated cellulose | Melamine resins |
| Vinyl chloride polymers | Polamide resins | Urea resins |
| Polystyrene | Polyethylene | Phenolic resins |
| | Waxes | Natural resins |

One difficulty involved with such materials in a closed environmental system is that, under increased oxygen and reduced pressure it is uncertain whether or not many of them may give rise to toxic components harmful to the spacecraft occupants.

Since almost all airborne particles are charged to some extent, the particles will have a Coulomb force exerted on them. Even uncharged particles will be affected, since highly nonuniform electric fields are established with the greatest field intensity at the surface of the filter material. These electrical forces tend to alter or displace the particle trajectory from the airflow streamlines around the fibers and increase the probability of the particle contacting the filter fiber, where it is retained. Tests have shown that this type of filter provides a significant increase in efficiency over normal mechanical filters. If proper filter materials are used, even relatively high humidity does not appreciably affect the filter.

Mechanically charged filters perform similarly to the self-charging filters, differing only in the method by which the electrical charge is induced on the filter. Filter fabric made of material on one end of the triboelectric series (see Table 18 ) is rubbed by another material at the opposite end of the triboelectric series to produce an electrical charge on the filter. This can be accomplished with a filter in the form of an endless belt that continuously rubs against a fixed piece of material that charges the belt, or by a windshield wiper effect across the face of the filter fabric. Power consumption by a small motor is comparatively low, yet fairly high electrostatic charges result. The magnitude of charge is, however, dependent on humidity; the charge completely disappears above 120 gr of moisture per pound of dry air.

TABLE 18

TRIBOELECTRIC SERIES OF COMMON FIBERS

Positive End

↑

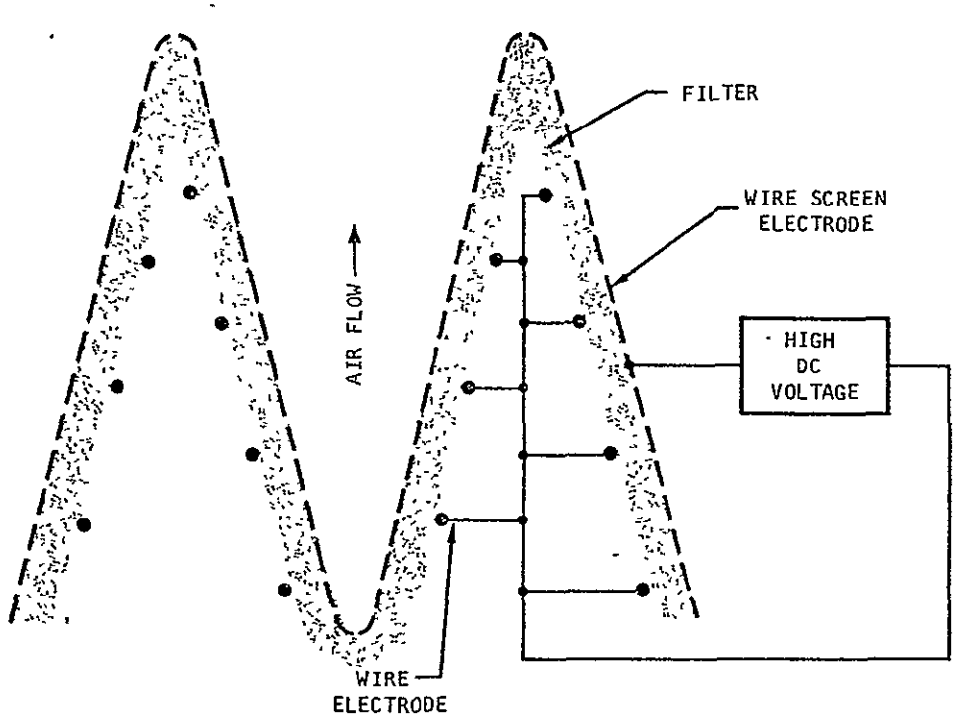
Glass
Nylon yarn
Wool
Silk
Viscose rayon
Cotton
Steel
Acetate rayon
Orlon
Saran
Polythene

↓

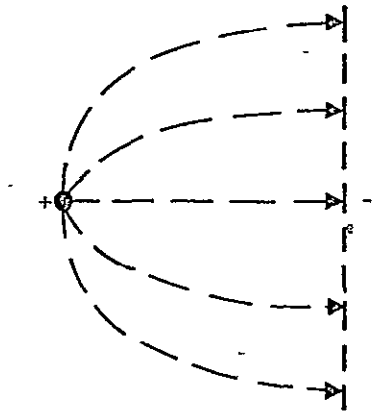
Negative End

Application of a nonuniform electric field normal to the airflow exerts Coulomb and dielectrophoretic forces on charged and neutral particles, respectively. These forces are normal to the airflow, causing displacement of the particle trajectory perpendicular to the streamline flow and thereby increasing the chance of impingement on the filter fiber. The filter fiber is necessarily a dielectric material with low moisture absorption, since an electric field cannot exist in a conducting medium. Filter efficiencies have been shown to increase considerably, especially for particle sizes below 3 microns. This is understandable, since the smaller particles have lower inertias and tend to stay in the streamline when no electric field is present. Figure 4 illustrates the overall configuration of the filter arrangement, electric field, distortion of the electric field, and resulting behavior of charged and neutral particles.

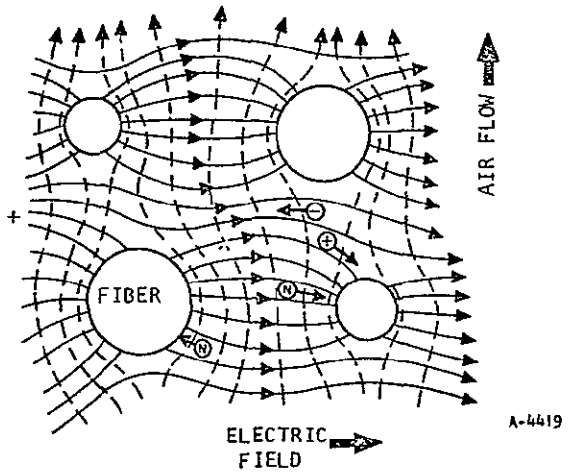
In general, electrostatic forces applied in fibrous filter media increase efficiency for a given fiber density and filter thickness. Thus the advantage in using electrostatic filters is mainly one of size reduction as compared to normal fibrous filters. The disadvantages of self-charging materials are that most of the materials required are inflammable to some extent, and are of uncertain toxicity. In addition, the use of such filters has not been adequately studied; the bacterial reactions with such fibers could be very hazardous, should it prove that bacteria degrade these materials. Induced charges on fiber material increase the power requirements, and the humidity limitations of electrostatic filters could be critical.




a. General Configuration of Filter



b. General Configuration of Nonuniform Field Between Wire Electrode and Screen




c. Distortion of Electric Field by Filter Fiber and Motion of Charged and Neutral Particles

Figure 4. Electrostatic Filter

## 5. Electrostatic Precipitation

Electrical or electrostatic precipitation differs from mechanical filtration in that an electrical force is exerted directly on the entrained particles, rather than on the whole gas stream. Particles ranging down to submicron size may be effectively removed from the gas stream through the relatively large electric forces acting upon the particles. All particulate matter, including almost all microorganisms, can be charged and thus can be removed by electrostatic precipitation. The inherent advantages of this type of particle removal include (1) low resistance to gas flow through the apparatus, regardless of the size of the contaminant and (2) continuous, long-term operation, which is possible since the equipment does not become clogged with particulate matter.

In current commercial applications, power requirements for electrostatic precipitators are 10 percent or less than for the cyclone type of separator used for industrial gas cleaning. Very high power efficiencies are presently being attained in two-stage air-conditioning separators.

Three basic steps are involved in electrostatic precipitation: (1) electrical charging of the particles; (2) collection of the particles in an electric field; (3) removal of the collected particulate matter from the collecting electrodes into an external receptacle. Since the natural electrical charge carried by most particulate matter is usually insufficient to be removed by electrical field forces, it is necessary to further charge the particle. This is usually accomplished by high-voltage d-c corona discharge. A high potential is applied between a fine wire and a ground cylindrical or plate electrode to create a region of high electrical field intensity around the wire. In this region, a visible corona glow occurs, and large numbers of positive and negative ions are formed. A negative corona is the most efficient, since a greater potential may be applied before sparkover or arcing occurs; this results in greater ion intensity. For air conditioning, however, a positive corona is generally used, because 8 to 10 times less ozone is formed by the corona discharge. In the latter case, the negative ions are attracted to the positive wire electrode; thus, the space between the corona wire and the grounded plate contains only positive ions. The particulate matter flowing through the corona field becomes highly charged as it is bombarded by the positive ions.

During operation, either the presence of fairly large particles or of high humidity may cause arcing, which can be harmful to the plates and can cause permanent damage. Also, high collection efficiencies with small particles are hard to attain without very precise temperature and humidity control; very small particles frequently do not reach the collecting electrodes, and large particles are prone to reentrainment. A corona discharge is disadvantageous in a space vehicle because it gives rise to a high production of ozone, which adds to the trace contamination load and which could quickly become dangerous with malfunction of the trace-contaminant control system. Electrostatic precipitators, largely because of the high voltages involved, require a fairly high power loss. Further, ionization elements can be dangerous in a spacecraft. Finally, theoretical predictions of electrostatic precipitator

efficiencies and requirements are very difficult to make, and applicable models for spacecraft application have not been constructed and tested. These disadvantages seem to outweigh the advantages of electrostatic precipitators (i.e., wide range of particle sizes, low pressure drop, and the capability of handling large flows).

6. Heating and Thermal Destruction

Heating has long been used as a primary method for killing bacteria and all other microorganisms. It is extremely effective and is the method of choice where ultra-high-filtration is not sufficient--e.g., where very high airborne concentrations of pathogens are encountered. Various factors affect the efficiency of heat-killing, including (1) the water content of the medium, (2) the water content of the organisms, (3) the hydrogen-ion content of the medium, (4) the age of the cells, and (5) the presence or absence of spore forms. The efficacy of heat-killing is generally a function of the temperature and the time that the organisms spend at the high temperature. For example, in relatively dry air, exposure to a temperature of 212°F (100°C) for 10 min kills all but the most resistant spores. AiResearch studies have shown that thermal sterilization using high temperatures can provide biological decontamination ratios of greater than $10^5$:1. These studies included aerosol-propagated spores of B.subtilis var. niger (B.globigii)(which was chosen because of its resistance) and a sterilization temperature up to 900°F. The time-temperature relationship for a 99.999- to 99.9999-percent kill of this organism is shown in Figure 5.

To use high-temperature sterilization as a method of controlling airborne microorganisms in a spacecraft, it would be most practical to use either (1) waste heat from other spacecraft components, (2) high-temperature devices in the spacecraft that are intended for other purposes, or (3) collected solar heat. In several cases, a catalytic burner will be used to oxidize trace contaminant gases in the vehicle. Such a device offers three major advantages as a means of microbe control: (1) it is already useful in the spacecraft as a means of removing gaseous trace contaminants, (2) its use as a microbe control would require no major modification of the catalytic burner, and (3) it would incinerate the organisms, so that the problems associated with removal from the air would not be encountered. There are also, however, certain disadvantages, particularly if the catalytic burner were used as the sole method of microbe control. These are, first, that if only a portion of the circulated air were ducted through the catalytic burner, the unducted air would be free to present large quantities of contamination to the downstream portion of the ECS. Second, with large quantities of organisms in the air, breakdown products from the incinerated cells could provoke toxic or sensitization reactions in the astronauts. Third, there is the effect of incinerated organisms tending to clog the burner with their residues, thus spoiling the catalyst and thereby reducing the burner's capability to oxidize gaseous trace contaminants.

All in all, the catalytic burner would appear to be an excellent back-up device for microbe control. With a temperature of 600°F and a residence time of 0.2 sec or greater, the burner will kill essentially all of the

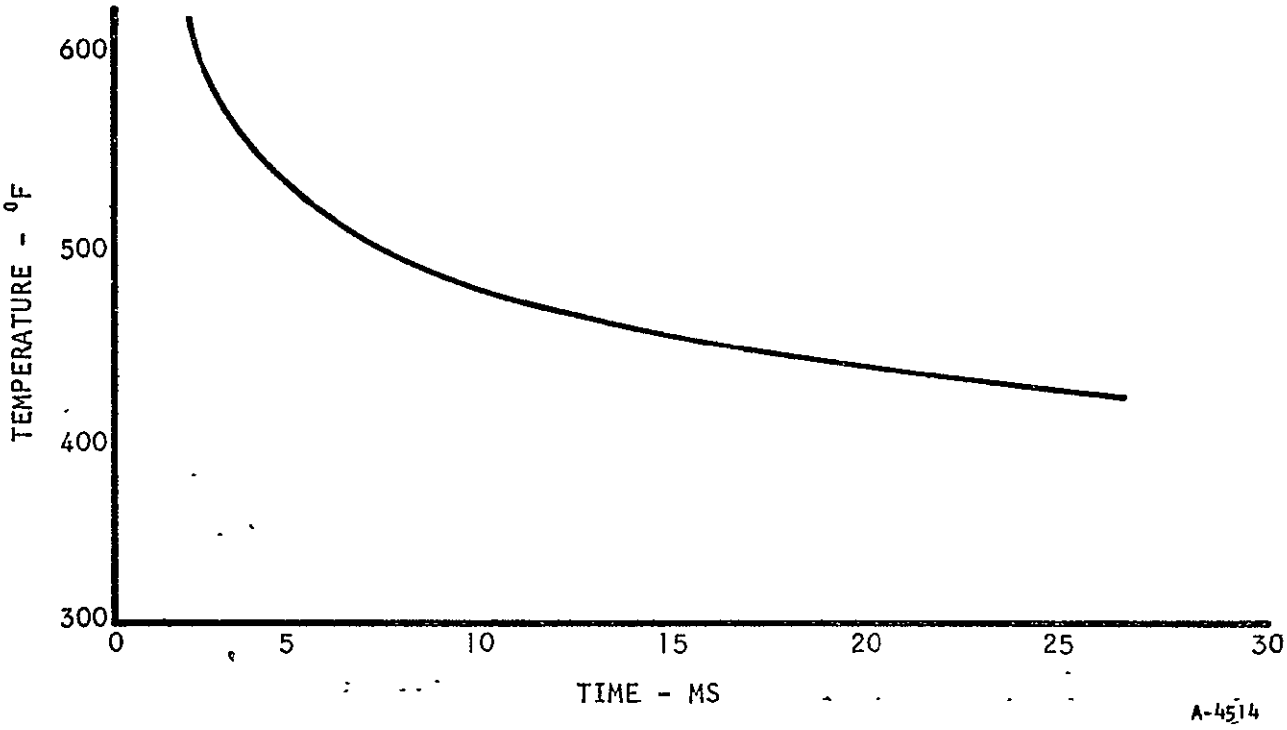



Figure 5. Time-Temperature Dry Sterilization Curve for B. globigii

organisms entering it. Therefore, any burner and bypass system may be thought of as a filter system with an efficiency equal to the fraction of the air ducted through the burner. As a back-up system, the catalytic burner would add to the total system efficiency.

7. Radiation

Various types of radiative energy are effective in controlling microbiological growth. The effectiveness depends on the radiation used, the intensity of radiation, the duration of exposure, and the environmental conditions present during irradiation. Two general types of radiation can be considered: particulate radiation and electromagnetic radiation. Particulate radiation would require either a small nuclear pile or an isotope radiation source. While these latter have been considered for decontamination of air, food, and waste products in spacecraft, it is felt for the purpose of this discussion that this is impractical because of the shielding requirements. Therefore particulate radiation will not be considered as a means of microbe control in this discussion.

Electromagnetic radiations in the wavelengths between $10^{-14}$ and $10^{-7}$ meters presently appear to be the most promising for bacteria control. These wavelengths approximate the X-ray, gamma ray, and ultraviolet segments of the electromagnetic spectrum. Both X-rays and ultraviolet irradiation are proven methods for effectively killing microorganisms. The biological effects of both these rays are similar in that they excite electrons or ionize atoms within the cells of the organisms, causing changes in various chemical substances. New compounds may be formed, such as hydrogen peroxide, which in turn react with existing cell components. The effect may be direct, destroying essential enzyme systems and necessary chemical building blocks. Either of these reactions causes death, but the X-ray is more damaging and penetrating because it is higher in energy and shorter in wavelength than the ultraviolet. When X-rays are used, however, large amounts of shielding are necessary to protect humans from adverse effects. Therefore, since only minimal shielding is required for ultraviolet light, it is considered superior to X-ray and gamma rays for spacecraft applications.

The effect of ultraviolet radiation on bacteria has been thoroughly investigated, so that the relationship between germicidal effectiveness and wavelength is well known. Figure 6 shows this idealized relationship, and Figure 7 (Reference 12) shows similar data for two species of microorganisms. This curve is fairly independent of the nature of the bacteria tested, within experimental accuracy, and it shows a well-defined maximum at 2600 Å. It is obvious that since low-pressure mercury vapor lamps have a high output at 2537 Å (90 percent), they may be used very effectively as bactericidal agents.

Of course, the dose level of ultraviolet radiation varies with different microbial species, and these levels may vary over several orders of magnitude, as shown in Table 19 (Reference 12).

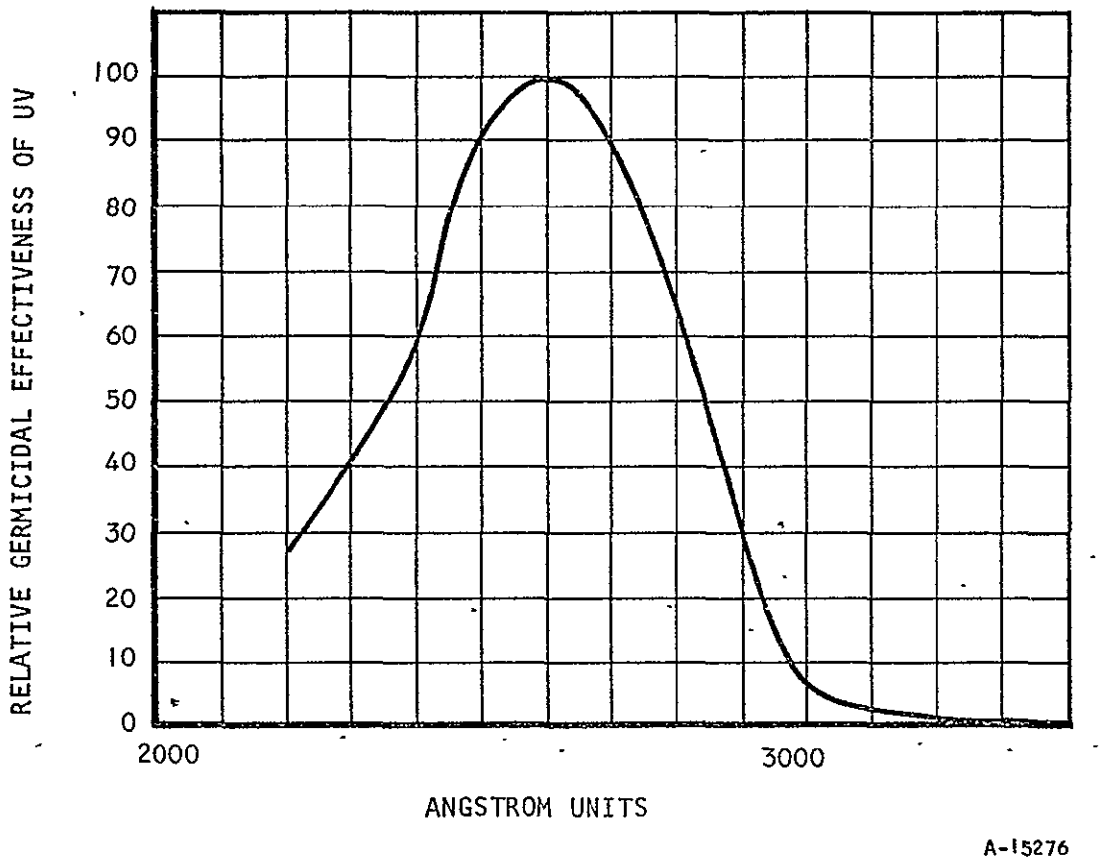



Figure 6. Curve Showing the Relative Bactericidal Effectiveness of Radiant Energy (From General Electric Lamp Bulletin TP-122)

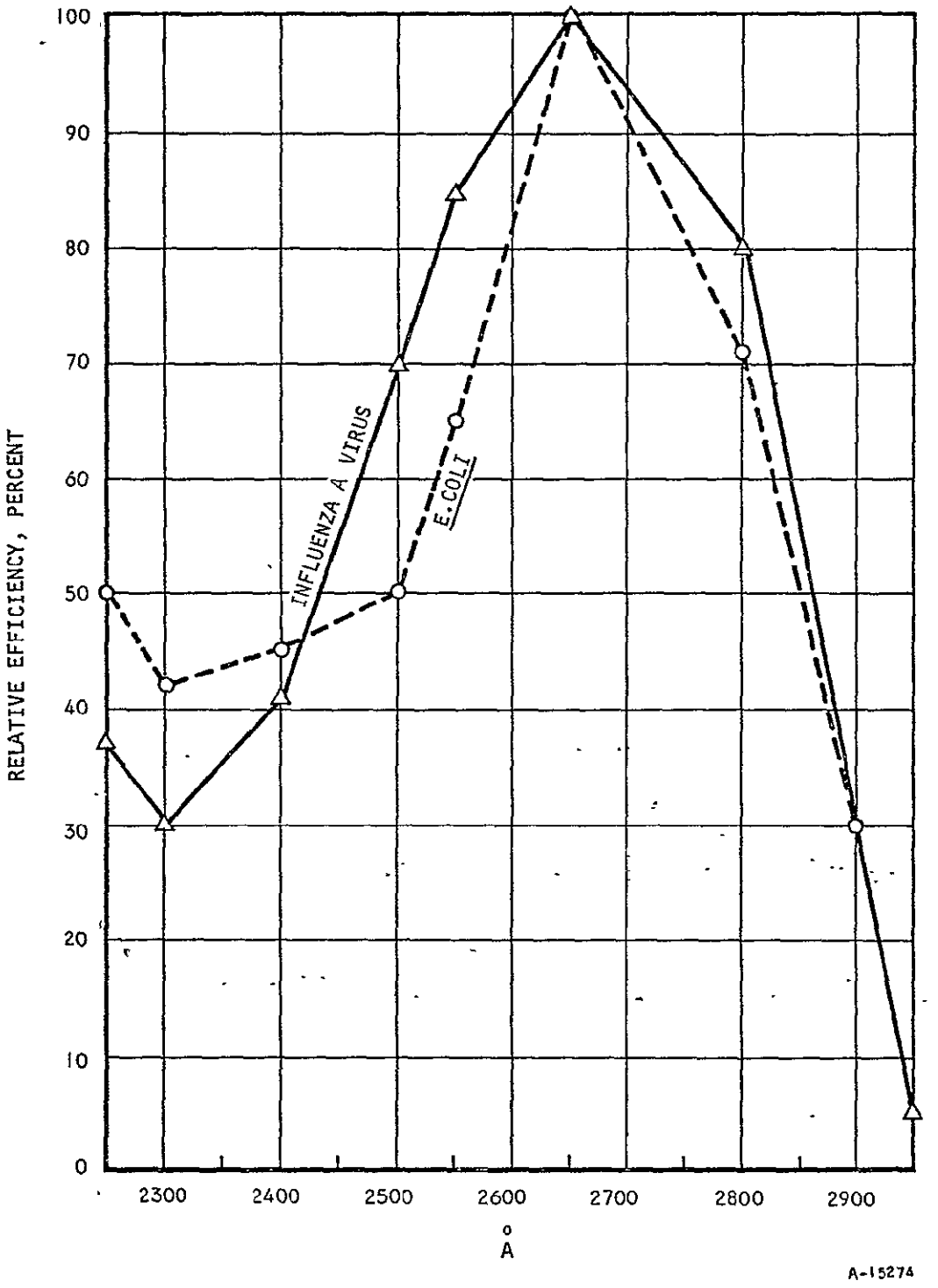



Figure 7. Sensitivity to Ultraviolet Radiation as a Function of Wavelength (From Reference 12)

TABLE 19

EXPOSURE TO 2537Å TO KILL 50 PERCENT IN 1 MIN

| Organism | Watts/sq cm |
|---|---|
| α - Streptococcus sp. and Staphylococcus aureus | 0.75 |
| β - hemolytic Streptococcus sp. and E. Coli | 3.4 |
| Mold Spores (typical) | 19.0 |
| Aspergillus niger spores | 250.0 |

The Bunsen-Roscoe reciprocity relationship holds for ultraviolet radiation, so these figures can be multiplied by 60 to convert them to 1-sec exposures, which are more meaningful for spacecraft ECS (Reference 12).

The power required for ultraviolet is relatively low, as is the exposure time necessary for killing. For example, the use of a 5-w ultraviolet lamp in a 1-cu-ft air duct kills 99 percent of the viruses present in 0.5 sec, and 99 percent of the resistant fungi in 30 sec. It should be mentioned that intermittent radiation doses over a short period of time are cumulative in effect; thus, in a closed system where air is being circulated continuously, all biological organisms suspended in the air should eventually receive a lethal dose. Power requirements for various percentages of kill can be computed roughly for air-conditioning ducts, knowing flows and the sizes of the ducts. Figure 8 shows the relationships which hold for 90-percent kill, these wattages must be converted to actual power requirements by using the specifications of actual lamps. Figure 9 may be used for calculations when other percentage kills are required. These relationships are shown as volume flows per watt of germicidal ultraviolet in Figure 10.

The high effectiveness and low power required for ultraviolet radiation make it reasonably attractive for spacecraft application. Ultraviolet lamps could be mounted directly in vents of the environmental system. The exact number or placement of the ultraviolet lamps depends upon the volume of air to be circulated and the configuration of the ECS.

The effectiveness of bactericidal agents is often measured in terms of the survival ratio, which introduces the following general concept: micro-organisms subjected to a lethal agent do not all die immediately, rather, a constant fraction of those present dies in each increment of time according to the equation

$$N/N_0 = e^{-kIt}$$

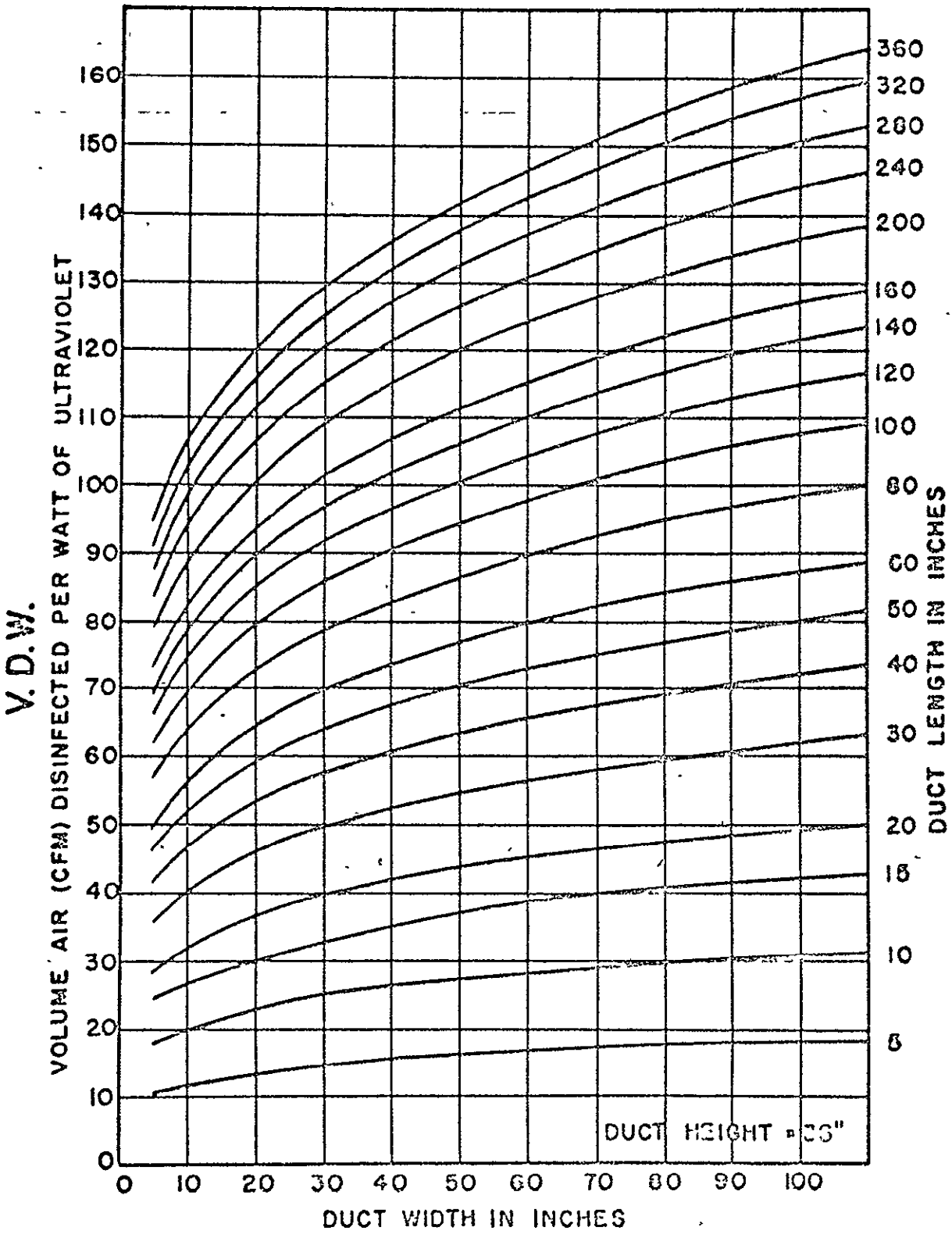



Figure 8. Ultraviolet Watts (Output) for 90-Percent Bacterial Kill (From Westinghouse Bulletin ASC-170 Rev.)

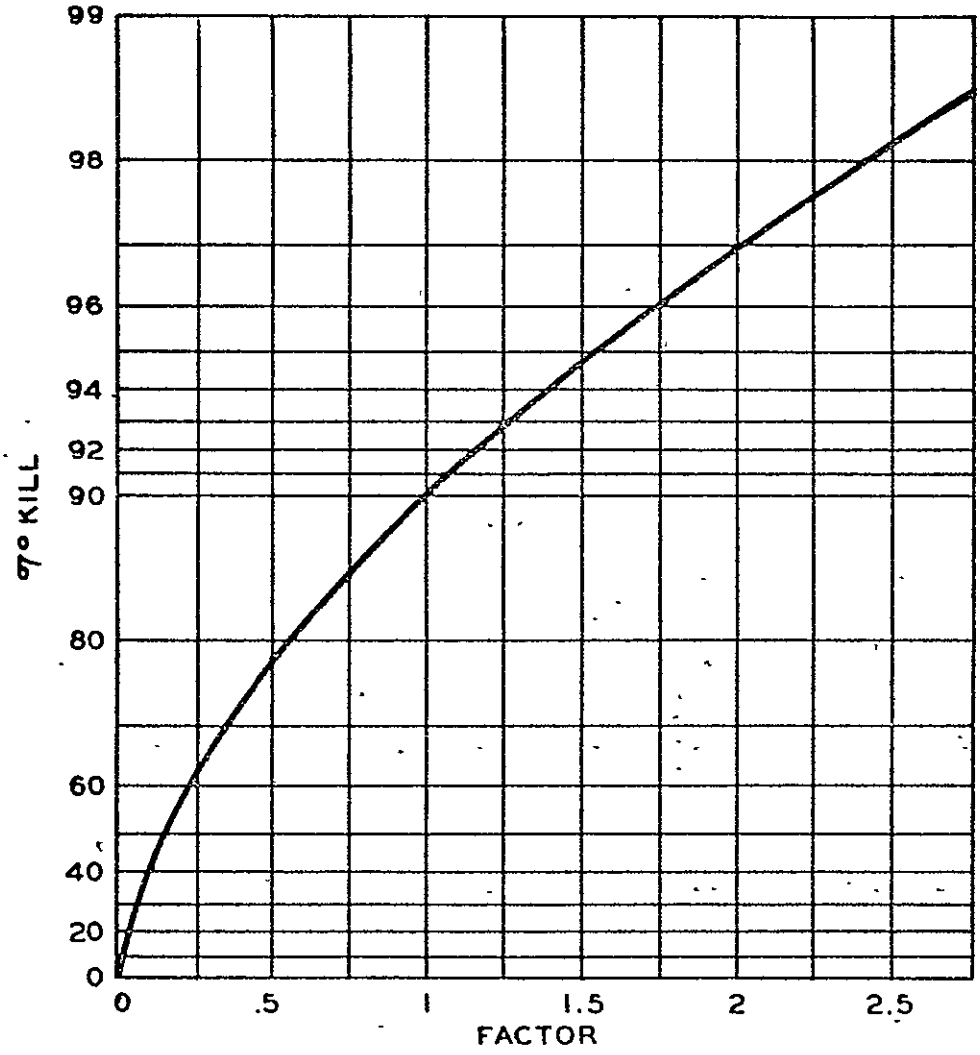



Figure 9. To Determine the Number of Lamps for Various Percentage Kills, First Calculate for 90% Kill (10% Survival) and Multiply by Factor (From Westinghouse Bulletin ASC-170 Rev.)

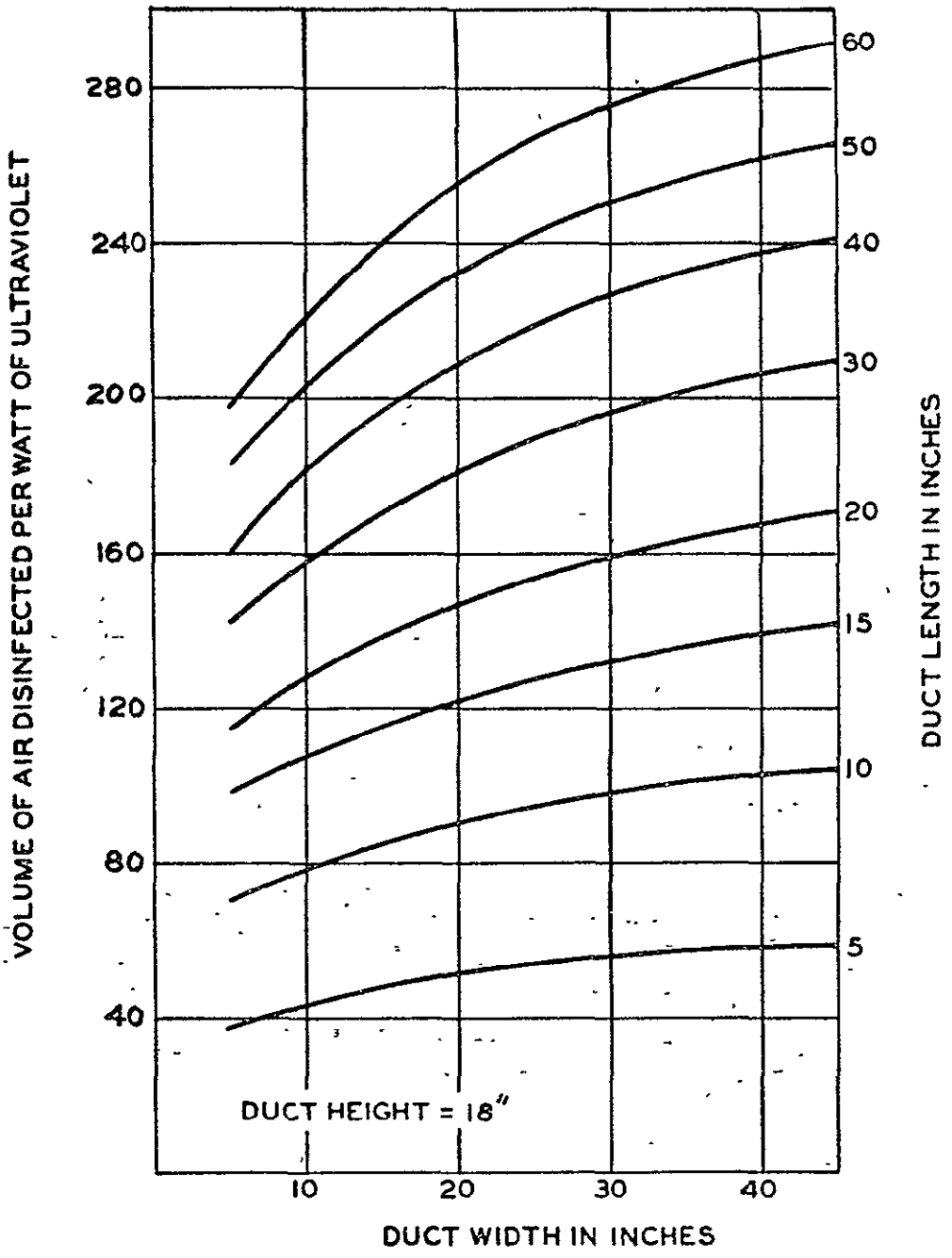



Figure 10. Volume of Air Disinfected Per Watt of Ultraviolet (From Westinghouse Bulletin ASC-170 Rev.)

where $N_0$ = the number initially present

$N$ = the number surviving at time t

$t$ = the time of exposure to the lethal agent

$k$ = a constant depending on the nature of the organism (and, in the case of ultraviolet radiation, on the wavelength of the radiation)

$I$ = the intensity of the lethal agent

The exposure (the product of the intensity of radiation and the time) necessary to produce a given survival ratio is a measure of the resistance of an organism to ultraviolet radiaton. Within wide limits, the exposure survial ratio relation is independent of the intensity of radiation and the exposure time, as discussed above. This relation has been found to hold over a thousandfold range in intensity for both bacteria and mold spores. The failure of this law at very low radiation intensities can be attributed to the reproduction of bacteria during the time of exposure, which would obscure the effect on any individual organism. Ultraviolet intensity and exposure time required to give various values of survival ratios for bacteria and molds are shown in Figure 11. Spore-forming bacteria are much more resistant than nonspore-formers, as evidenced by the difference in B.subtilis and B.coli; molds and yeast are even more resistant, exceeding bacteria in resistivity by a factor of 100 to 1000. The resistance of many viruses is comparable to that of bacteria, so that ultraviolet radiation, within certain practical limits, is a universally effective germicidal agent.

Between about $40^0$F and $99^0$F, temperature has little or no effect on the germicidal effect of radiation, but humidity exerts a very marked effect. When bacteria are suspended in air, an increase in relative humidity results in a greatly decreased death rate, especially at humidities greater than 50 percent. For example, one investigator reported that increasing the relative humidity from 23 to 75 percent increased the survival from 6.5 to 24 percent. This factor may be of considerably importance in a spacecraft ECS system. Lamp output, however, may be affected by dry-bulb temperature and air flow, as shown in Figure 12.

The design of any system for air disinfection depends upon the protection required, the type of organisms providing the contamination, the type of enclosure, and the kind of occupancy for the enclosure. Air circulated through an enclosure can be sterilized by properly placing lamps in the ventilating duct; it has been shown that the size and shape of the duct, the ultraviolet reflection of the walls, the number and arrangement of the lamps, etc., determine the efficiency of the sterilization.

Current applications of ultraviolet radiation in enclosures involve suitably placed lamps which irradiate the air in a particular portion of the enclosure, in such a manner that the occupants are not directly in the path of the radiation. Such systems generally depend on free convection to carry

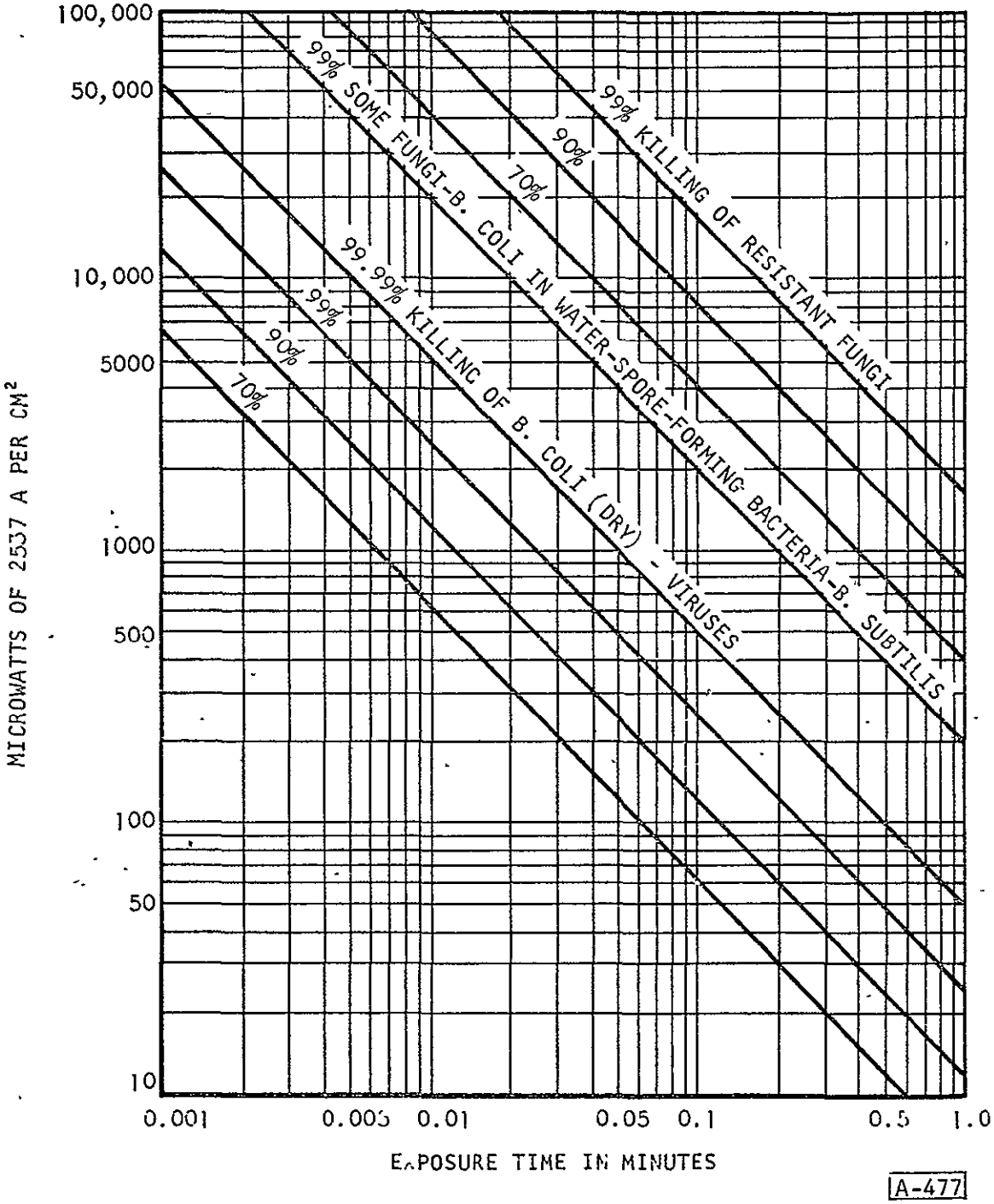



Figure 11. Ultraviolet Intensity and Exposure Time Required to Give Various Values of Survival Ratios for Bacteria and Molds. (Gen. Elec. Lamp Bulletin LD-14.)

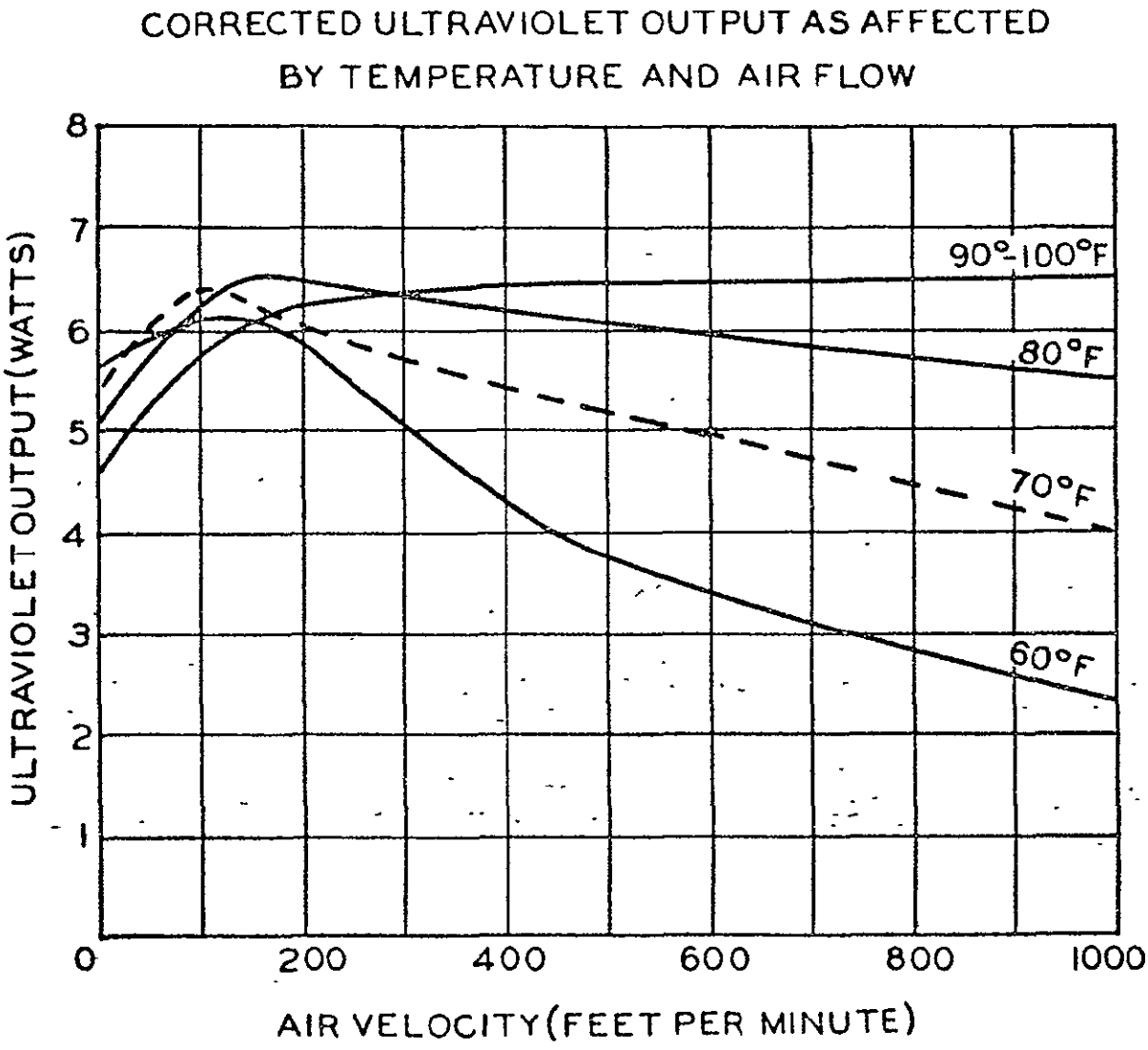



Figure 12. Corrected Ultraviolet Output for a Lamp as Affected by Temperature and Airflow (From Westinghouse Bulletin ASC-170 Rev.)

contaminated air in paths of the lamps. In a spacecraft, such systems would require forced convection because of the absence of free-convective mechanisms in the weightless environment. With forced convection, lamps must be used in such a way that airborne organisms will spend a maximum of time in the ultraviolet beam. The distribution of radiation from such fixtures is shown in Figure 13. As much as possible of the energy should be thrown in a nearly planar beam, and little of it as reflected radiation in ECS ducts. Diffuse radiation may be more efficient in a small enclosure such as a space vehicle, but considerable shielding is required. It is general practice to consider 0.5 microwatts per square centimeter of 2537-Å energy in a 7-hr period to be the maximum safe exposure without protection (clothing, gloves, etc.)

Numerous small ultraviolet tubes are available commercially; three of these tubes (General Electric) are described in Table 20. These small tubes are about 20-percent efficient. The surface area of the G4T4/1 tube is approximately 7 $cm^2$, and the ultraviolet flux at the surface is about $10^5$ $\mu W/cm^2$. This diminishes with distance and with passage through air or water, especially if absorbing material - usually organic - is present. Loss of power at impingement surfaces is almost complete unless the surface is specially treated to enhance reflection. Chromium and aluminum plating have been used for this purpose, these give about 50-percent reflectance. Comparing the calculated output of $10^5$ $\mu W/cm^2$ with the LD-50 figures of 45 to 15,000 $\mu W/cm^2$ second indicates that disinfection should be excellent with a dwell time of 1 sec in an air duct (Reference 12).

TABLE 20

POWER REQUIREMENT AND OUTPUT AND USE-LIFE OF LOW-PRESSURE MERCURY ARCS

| G.E. Lamp Type | Input, watts | Output, watts | Approx. life, hr |
|---|---|---|---|
| G4T4/1 | 4 | 0.7 | 5000 |
| G8T5 | 8 | 1.5 | 7500 |
| G15T8 | 15 | 3.3 | 7500 |

A typical air duct disinfecting intensity for exposures of 1/8 to 1/2 sec is 10,000 $\mu W/cm^2$, which is well within the capacity of the tubes listed in Table 5, provided the linear velocity is appropriate. For a tube length of 6 in., a dwell time of 1/2 sec corresponds to a linear velocity of 1 ft/sec. If the enclosure diameter is 6 in., the flow rate is about 12 cfm (Reference 12). Thus, a limiting factor at substantial flow rates would seem to be the volume of enclosure space.

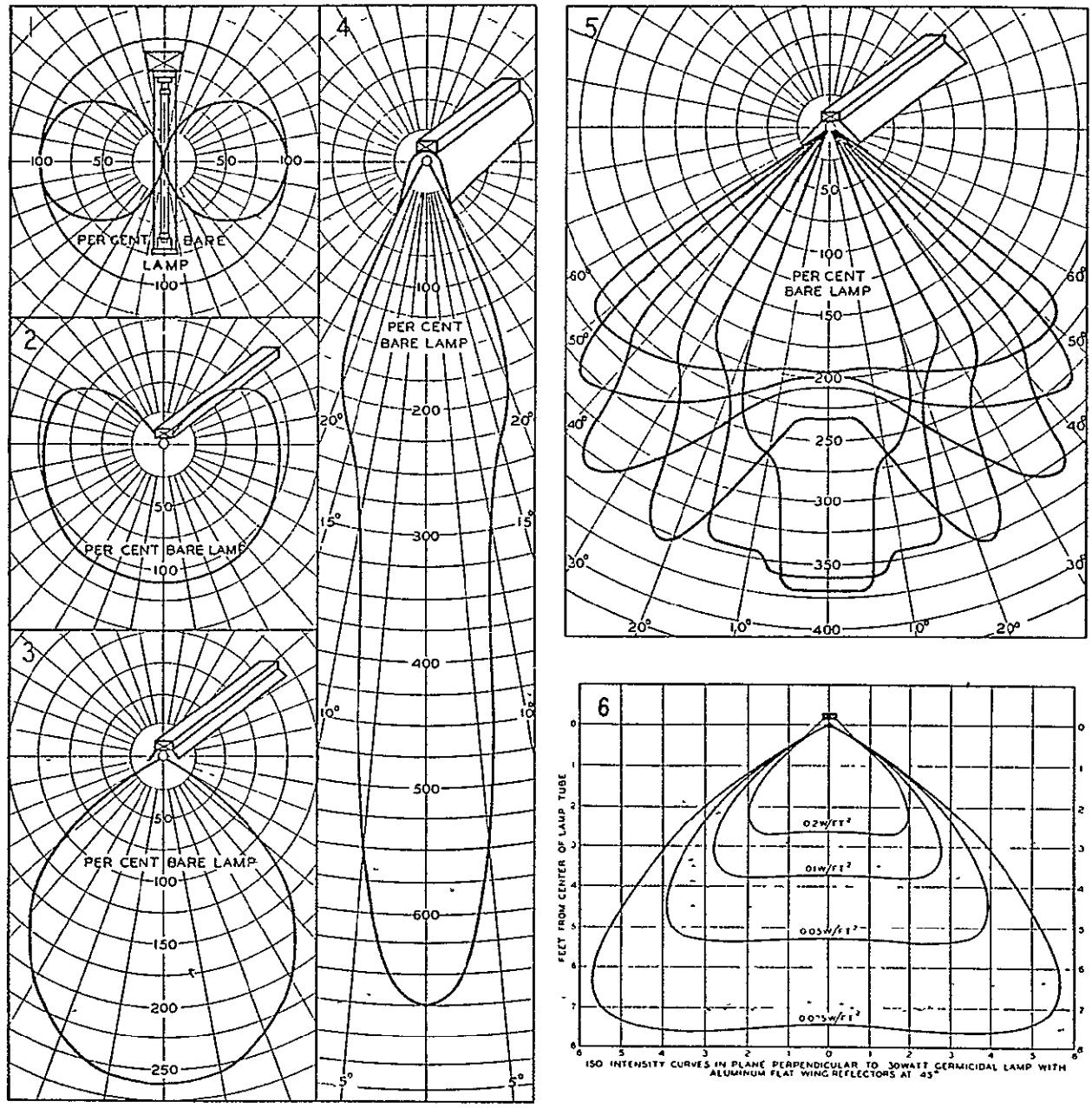



Figure 13. Spatial Distributions and Isointensity Patterns of Various Typical Germicidal Devices (From General Electric Lamp Bulletin TP-122)

There are several difficulties which must be considered in the selection of ultraviolet for a microbe control system for EMA. One of these is the production of ozone by the absorption of atmospheric oxygen of 1840 Å radiation generated in the immediate vicinity of the lamps by the following reactions:

$$O_2 \xrightarrow{1849\ \text{Å}} 2O$$

$$2O + 2\,O_2 \longrightarrow 2O_3$$

Ozone is toxic and highly degrading to rubbers and certain plastics. Under normal conditions, the half-life of atmospheric ozone is several minutes, depending on the presence of factors which promote the reduction of ozone: humidity in excess of 50 percent, visible and ultraviolet light, and surface absorption (Reference 6). A catalytic burner would be expected to degrade ozone, but even with normal and catalytic reduction, the ultraviolet source would be expected to maintain an equilibrium level of ozone.

Other problems include the shielding requirements described above, which demand that the human occupants be protected from direct or reflected ultraviolet. This requirement practically limits the use of ultraviolet lamps to air conditioning ducts, although lamps in the open cabin area would be more efficient. Use in the open cabin would also require forced convection to ensure that a large percentage of the ambient environment was exposed. Ultraviolet sterilizers have the further disadvantage that they must be cleaned and tested frequently. Maintenance and operational monitoring are even more severe and critical for ultraviolet installations than for electrostatic precipitation systems (Reference 7). Furthermore, ultraviolet has limited penetrating ability, and those organisms protected by dust particles may not be killed. Ultraviolet treatment is therefore probably more useful against droplet nuclei than against dust-borne organisms (Reference 7). Another objection is the comparative fragility of the glass lamps themselves, whose breakage would not only seriously compromise the microbe control system but would also contaminate the atmosphere with toxic mercury vapor.

Finally, it must be recalled that ultraviolet radiation is highly mutagenic to microorganisms. This effect may be exerted directly or indirectly by modifying substrate substances in aqueous contact with the organisms. The mutations thus formed are frequently resistant not only to ultraviolet but also to other disinfectants. Resistant mutants of this sort would be very difficult to remove from a closed system, and their presence and proliferation could constitute a major hazard to the mission.

8. Electrical Discharge

Microorganisms can be killed in small ducts or chambers when exposed to electrical discharge. Three considerations make this a rather unattractive solution for the decontamination of spacecraft atmospheres: (1) the lack of knowledge in this area, particularly with respect to its use in air conditioning systems, (2) the very high power requirements, and (3) the large amount of

ozone produced. Because of these factors, electrical discharge will not be considered as a method of atmospheric bacteria control for spacecraft at this time.

9. Air Washing, Scrubbing, and Impaction

Air washing is usually employed for removing dusts and other particulate matter from air. Its use has not been developed extensively for bacteria removal. The most efficient air washers are those which impinge suspended material on a wet surface, where it is then washed off. Only small amounts of particulate matter are removed by direct contact of the particles with liquid droplets. The efficiency of washing alone in removing bacteria is fairly low (20 to 80 percent of the bacteria sizes from 1 to 5 microns). In some instances which require recirculation of the washing fluid, the air bacterial count may be increased by reaerosolization of the bacteria in the fluid (Reference 7). Thus such fluids should be bactericidal in nature.

Scrubbers are used frequently in chemical processes to bring a gas into close association with a liquid. Such devices are used in ventilating systems for humidity control. These scrubbers generally use a hygroscopic solution which flows over rows of multifin coils for temperature control of the absorbent. Such units remove about 40 to 90 percent of the 1- to 5-micron particles, with somewhat higher efficiencies with larger particles. There is less reaerosolization of viable organisms with scrubbers, but again, the liquid used should preferably be bactericidal. Many organisms are killed when the liquid is heated to drive off the water in solution. These scrubbers function automatically and require minimal maintenance.

Cascade impingers and impactors have also been devised for air sterilization. These function by air pumping through series of high-velocity jets and onto impaction surfaces of liquids, glass, and other media. Particulate impaction arises largely from inertial effects. A unit employing four stages of impaction is shown in Figure 14. This unit was analyzed by Goucher (Reference 12), who concluded that for efficient spacecraft operation, this unit required 180 to 200 watts and a pressure drop of 14 in. of water of 45 cfm. Goucher concluded that these devices were not applicable for spacecraft use because of the high power requirements of these devices. Also, small flow rates (2-28 l/min), small orifices, and near-sonic particle velocities are required for efficient collection of particles of less than 10-micron diameter.

The disadvantages of washers and scrubbers are largely the lack of available information and designs for these devices for spacecraft. Washers appear far too inefficient and complex for spacecraft microbe control, as well as offering potential toxicity hazards. Further, no adequate washers have been studied for zero-gravity use. The same is true with scrubbers; although these offer somewhat more promise than washers, they are so unreliable under varied conditions that backup systems are required (Reference 7). The disadvantages of impingement jet scrubbers were discussed above.

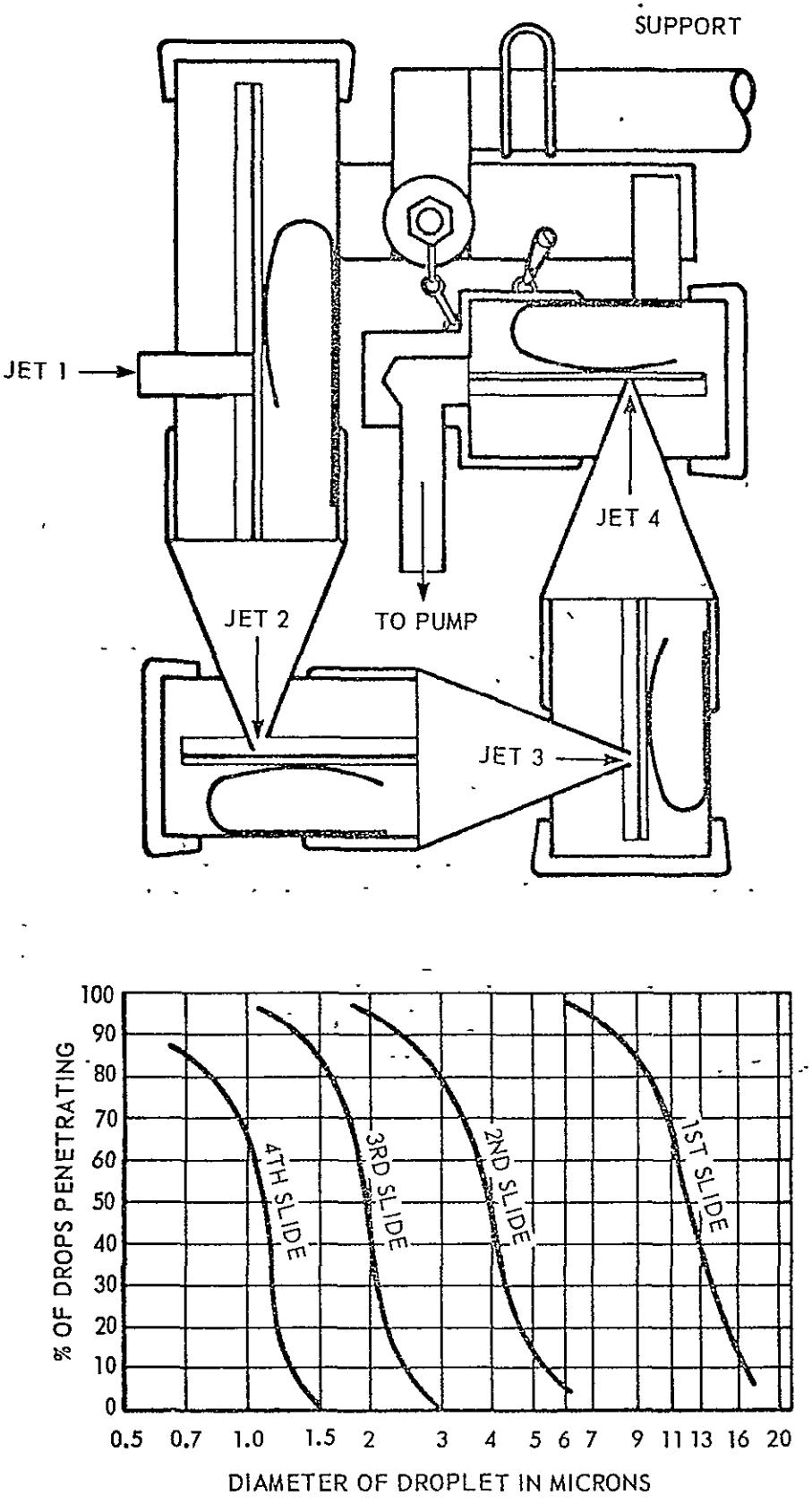



Figure 14. Diagram of Cascade Impactor and Efficiency Curves of the Four Stages (From Reference 12)

## Microbe Control of Surfaces

The surfaces upon which microorganisms can grow and proliferate are numerous in the spacecraft. They include primarily the surfaces of the cabin interior and the associated hardware, the heat exchangers and other components of the ECS, the interior surfaces of the potable water lines and containers, and, of course, the space suit and the skin of its occupant. Such surface growths can lead to surface degradation, buildup of high pressure-drop mats, system malfunction, and disease in the occupants.

The methods described for atmospheric microbe control will help decrease the build-up and growth of microbiological colonies on material surfaces by greatly reducing the airborne spread of microorganisms, and by keeping the overall microbiologic population at a minimum. Ultraviolet radiation, for example, would prevent the growth of microorganisms on any surface on which it impinged, and filters remove airborne contaminants which otherwise might settle on a surface and proliferate. It is inevitable, however, that some microorganisms will escape the atmospheric purging and will settle to a surface where they will be removed from the atmospheric screening. Thus, all surfaces which could harbor growth, particularly those in isolated areas of high humidity and warm temperature, must be treated to retard such growth.

Surfaces apt to undergo great microbial contamination are those which are in frequent contact with the astronauts' bodies, particularly surfaces of spacesuits, clothing, seats, and equipment controls. These areas present unique control problems because they are contaminated by the viable and non-viable exudates of the crew members, and because their proxmity imposes special toxicity restrictions with respect to potential toxicity. Moreover, control in these areas is of particular importance because it is here that the largest concentration of organism production may be expected, and hence the source of the major portion of the ship's contaminants. The primary applicable methods of control in these areas include frequent washing and frequent changing of clothing, the use of disinfectants (which must be free of toxicity or sensitivity reactions), and the use of bactericide impregnation.

Numerous paints and coatings inhibit the growth of microorganisms on equipment surfaces in varying degrees. These paints and coatings must be examined first to ensure that they meet the specifications for the materials and components upon which they will be used. They must then be examined to determine the degree to which they inhibit microbiological growth under given spacecraft conditions. Particular areas of concern involving interior surfaces of the components of the water system are. (1) that no toxic or noxious substance be evolved into the water, and (2) that the coating not adversely affect the operation of the system. It is similarly imperative that coatings in the atmospheric sytem present no toxicity or dysfunction. Coatings used in the space suit must, in addition, permit no contact dermal irritation or induced hypersensitivity.

In addition to any coatings which may be used in the space suits, adequate microbiological protection may also be provided to some degree by skin cleaning. More than 110 compounds are currently available for use as skin antibacterials and antibiotics alone. Although each of these compounds is general in effect, each is more efficient against one or several specific groups of bacteria. Consequently, skin biostat selection depends on which contaminatory microorganisms will likely be found in the spacesuit. In general, however, optimal cleaning of the skin would employ one or more biostatic compounds such as furacin, ilosone, mycostatin, resulin, neomycin, or achromycin in solution in a highly detergent vehicle. Phisohex is an example of commercial bactericide in a desirable solution. Phisohex is a sudsing emulsion containing entsufon, lanolin cholesterols, petrolatum, and hexachlorophene. Another commercially available antimicrobial compound is furacin or nitrofurazone (5- nitro-2 fural-dehyd semi-carbazine). Furacin is bactericidal to most pathogenic bacteria, gram-negative as well as gram-positive. In solution, it can be employed in various concentrations in a water-miscible liquid-polyethylene glycols, octylphenoxy polyethoxyethanol N.F., and water. Quaternary ammonium compounds such as hyamine and benzalkonium chloride such as used in pre-wet cleaning packs are also acceptable.

Biocidal and biostatic compounds developed for dermal decontamination can generally be employed to disinfect clothing as well. If such spacesuit cleaning proves necessary to eliminate microbiological growth in spacesuits, it may be possible to use the same compound as that used for dermal hygiene, provided the compound was compatible with the suit lining and resulted in no degradation, etc. However, spacesuit cleaning is a long and arduous task, and one which may be highly productive of aerosol particles, droplets of cleaner, and microbial contamination. Therefore suit material impregnation with a bactericidal material would appear to be preferable if such a technique were tested and found applicable. The same is true for the ordinary clothing worn by the astronauts, impregnation would result in a much longer time between washing and clothing changes, and should decrease the total dermal production of contamination.

Organic compounds containing copper are currently used frequently in preservation of cotton fabrics. Such compounds include copper naphthenate, copper-8-hydroxy quinoline, and copper salts of organic acids. These compounds are somewhat soluble in water and may therefore be leached from fabrics. Some of these may be toxic, and several have a distinctive odor (Ref. 12). These disadvantages are not found with silver impregnation compounds. Silver compounds show considerable promise in very many bactericidal applications, these compounds, in clothing, exert their effects not only in their matrix but also in their immediate environments; methods now exist for impregnating cotton, wool, silk, nylon, plastic, and latex with silver compounds. These materials may be washed repeatedly without loss of germicidal properties and without discoloration, and they do not cause skin irritation or toxic manifestations in man (Ref. 12).

To summarize, the applicable methods of surface microbial control are surface coatings, surface washing and disinfection, and materials impregnation.

Microbe Control of the Water Supply

The water supply system presents considerable microbiological contamination problems. Water provides an excellent medium for the growth of organisms under almost all conditions; these growths are often extremely tenacious and can be quite damaging. If uncontrolled, these microorganisms form first a film, then a sludge, and then a mat that obstructs orifices, fouls heat exchangers, degrades wicking, blocks valves, etc. In the potable water supply, they could not only cause system malfunction, but could also foul the water to the extent that its ingestion would be difficult and perhaps dangerous. Cloudy water, or water containing sludge or scum, would be unpleasant to drink; furthermore, the taste of the water could be affected, and toxic products from the microorganisms' metabolism could be present, as well as the potentially pathogenic organisms themselves. It is thus imperative that minimal microbiological growth in the water supply be permitted.

In addition to surface coating techniques involving the inside of the water supply system hardware, there are several other general methods of treatment to retard microbiological growth in the water medium itself. Such methods include distillation, freezing, filtration, and the addition of biocidal or biostatic chemicals. Each of these techniques, of course, presents certain difficulties which may or may not preclude their use in a space vehicle. The addition of chemicals, for example, must not effect the potability and palatability of the water. Because it is anticipated that this water will be mixed with food for eating, the chemical must present no anomalous taste or any reaction with the food itself. Thus, the chemical must either be completely innocuous to human beings, or must be removed from the water before consumption or denatured to the extent that its products are innocuous. It must also be so reliable that accidents or other contingencies do not permit it to endanger system function or spacecraft occupants. Chemicals which meet these requirements and which are still effective against microbiological growth are relatively rare.

The following paragraphs discuss several methods of protecting the water supply system from microorganisms, outlining the difficulties and advantages of each. Several of these may be discarded immediately because of power requirements, practical difficulties, or because insufficient work has been done on them.

1. Freezing

Freezing is not an efficient means of killing microorganisms, since it is necessary to freeze the culture at least three times at 24-hr intervals. Growth can be reduced by exposing organisms to different extremes of temperature at rapid intervals; this is obviously an impractical method, since it involves an excessive power requirement and adds greatly to the thermal load of the spacecraft ECS.

2. High Temperature

As discussed previously, high-temperature sterilization is a highly effective means of killing microorganisms. Two general techniques exist, the first of which involves keeping the stored water at a continually high temperature; the second involves periodic heating of the stored water. The first technique obviously has numerous disadvantages, e.g., redesign of portions of the water supply system, high power cost of continually heating the condensate and fuel-cell water, and the necessity of cooling part of the water for use. The second technique (involving periodic heating of the water) includes distillation, so that the stored water is, for example, passed through heated lines to destroy the microorganisms, cooled, and delivered for use. Unfortunately, such a method allows considerable cool storage area which would permit microbiological growth. Intermittent distillation requires considerable apparatus for 0-g distillation; also, if growth is permitted intermittently, by-products and decomposition products from the microorganisms may be carried over with the water during distillation. The power cost for intermittent heating is, of course, less than for continual heating and also is less with lower temperatures of sterilization than with higher temperatures. Vapor-compression distillation removes a large portion of microorganisms, but by no means all of them because of the comparatively low temperatures involved.

One major advantage of heating water is that it is a method guaranteeing complete freedom from viable microorganisms. Heating water to 250°F for 20 min will assure approximately 100-percent sterilization, it is probably the only applicable method which will assure a zero-viable microorganism count in the potable water supply. This will require pumps to overcome an operating head of 24 psi, with water heated in a recuperator to conserve heat and hence power. However, such a system still presents the possibility of water contamination from the dead bodies resulting from heavy microbial growth upstream; a heater merely kills the organisms; it does not remove them or their metabolic products, and it permits growth in certain areas with concomitant metabolic product excretion. Thus such a system should be backed up with means of controlling microbial growth.

3. High Pressures, Osmotic Changes, and Extreme pH

When most microorganisms are exposed to pressures in excess of 600 psia, their growth is stopped. In the space vehicle water system, however, such pressures would be rather impractical.

Both rapid osmotic change and dehydration are relatively effective in reducing the growth of vegetative bacteria; these methods are less attractive when used to destroy viruses or spores, however, because their effectiveness depends upon the amount of water present in the cell. Again, such techniques appear rather impractical. With pH extremes, the pH must be lowered below 3 or raised above 11 to achieve the desired effect, to a lesser extent, this method also is affected by the amount of water in the cell. Use of pH extremes poses problems of returning the water to a palatable state and of materials compatibility.

4. Agitation

Either mechanical or ultrasonic methods can be employed to combat microorganisms. Mechanical agitation requires that regions of the water supply system contain abrasives such as glass beads, sand, or carborundum, and that these portions be shaken to break the cells into fragments. Large decreases in viability counts have been noted with this technique. A somewhat more practical method of agitation employs the use of ultrasonics, a technique used successfully in commercial sterilization. When bacteria are exposed to sonic vibrations of 400 kc for 1 min, a 99.9-percent kill may be achieved; this result is due primarily to the vibration and secondarily to the heat produced by particulate friction within the cell. Few data are available on the effectiveness of kill of viruses and spores by this method, but it is probably somewhat less than for other organisms. The ultrasonic method is another expensive power consumer, and both techniques of agitation appear impracticable for spacecraft application.

5. Chemical Disinfection*

In general, one usually refers to removal of microorganisms from inanimate objects as disinfection and removal from the animate as antisepsis. We will refer to the general consideration of both types as disinfection, and will discuss here various compounds which may be of use for microbe control not only of the water supply system, but also of the atmosphere material surfaces, including those in contact with man's skin and the skin itself.

Many chemical disinfecting agents are known, as described in Sykes, 1958 (Reference 13), and Reddish, 1957 (Reference 14). Some agents of interest include formaldehyde, ozone, ethylene oxide, hypochlorites, quaternary ammonium compounds, beta propolactone, hexachlorophene, propanediol diacetate, and various antibiotics.

Formaldehyde is certainly a good disinfectant but has the disadvantages of polymerizing on exposed surfaces in confined areas, poor diffusibility, and extreme pungency. Ozone is quite irritating, toxic, and unstable in the presence of moisture. It has been used for water purification, since it leaves no toxic residue and acts as a deodorant. Ethylene oxide, besides being explosive in air mixture, is toxic, produces skin eruptions and other allergy reactions in allergic exposed individuals within three weeks after contact. It has been used to sterilize water, and requires warming to 37°C for volatilization and removal. Hypochlorites are active against many microbes, including viruses, while they are irritant, they have been used successfully in occupied rooms and air raid shelters. One of the most useful groups of agents would appear to be quaternary ammonium compounds, which show good activity against bacterial spores and viruses. Studies with cetyl pyridinium chloride have shown no toxicity at useful concentrations, no pathology in rabbits after large daily dosages for a month, and good activity over a wide range of pH. The compound also is well tolerated in drinking water, odorless, nonstaining, and practically tasteless. Friedman, Sylk,

*See also note at the end of this section (Page 3-61)

and Laumann (Reference 15) evaluated a spray-fog disinfection technique with several quaternary ammonium compounds and found marked control of Staphylococcus sp., Escherichia coli, Pseudomonas sp., Shigella sp., and yeast, with little or no irritation.

Beta propiolactone is another good disinfectant candidate, since it has been reported to be active against viruses, bacteria, bacterial spores, yeasts, and molds. While it is toxic, it will hydrolyze to nontoxic beta hydroxy propionic acid, which can be metabolized. Materials sterilized are also free of allergic reactions. It does not react with many construction materials, including aluminum, stainless steel, polyethylene, or glass and has been reported to be more efficient and easier to handle than ethylene or propylene oxide. It has been used for the sterilization of collagen sutures, bacteriological media, and various surfaces. Hexachlorophene is another compound of considerable interest, since it is reasonably effective against some gram-positive and gram-negative bacteria. Some studies have shown that no resistant strains of Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus or Bacillus subtilis developed during its use, and rare instances of allergic responses and irritation were noticed. Animal studies have been variable with regard to oral toxicity. Another interesting disinfecting agent is 1,2-propanediol diacetate, which has been shown to be effective in low doses against Klebsiella pneumoniae, Proteus vulgaris, Escherichia coli, Staphylococcus aureus, Nocardia, Candida, Trichophyton, and Cryptococcus. It has been shown to be free of side effects and does not induce hypersensitivity.

While the indiscriminate use of antibiotics is not advised because of the usual development of microbial resistance and some toxicity, reports indicate that during long-term, low-level antibiotics therapy (16 months) with oxytetracycline, only a slight transitory resistance developed in the indigenous flora, without toxic effects or hypersensitivity. In some cases of toxic side effects, it was learned that the daily administration of vitamin $B_{12}$, folic acid, and gamma globulin prevented toxicity. Another recent report of significant importance, is the prevention of drug-resistant populations of Staphylococcus aureus, Aerobacter aerogenes, and Escherichia coli in media containing spermine or spermidine, along with the antibiotic streptomycin, penicillin, or erythromycin.

The use of chemical treatment for the water supply system appears fairly promising. Despite the objections described elsewhere in this section, this technique presently appears more feasible than many of the other methods described. Germicides and similar agents have proved effective in microbiological control and are in general usage. Their effectiveness against viruses and spores, however, is variable, depending upon the germicide employed and the length of exposure. Care must be exercised when using this type of disinfectant to assure 100-percent kill. This is necessary to decrease the possibility of mutant strains developing a germicide resistance. Most commercially available germicides are capable of providing a 100-percent kill with sufficient exposure time; however, some are considerably more applicable to spacecraft use than others.

One primary problem with a germicide is its application, many of these substances are toxic in themselves. If such compounds were used, allowance would have to be made for their removal or denaturation. The same is true for compounds which affect taste and palatability of the water. Each of these problems, including the addition of the compounds to the water as well as their removal, must be considered with respect to incorporation into the spacecraft water supply system.

One chemical technique which shows considerable promise -- more promise, at least, than those described above -- is the use of silver salts and/or metallic silver. Silver ion has been investigated by Goucher (Reference 12), who designed a silver-saturated cation exchange column for Apollo application. The results of his work using silver ion in the form of silver nitrate are shown in Table 21. It is apparent that the silver ion is very toxic to microorganisms; essentially all of a very concentrated suspension of

TABLE 21 (Reference 12)

SURVIVAL OF E. COLI IN $AgNO_3$ SOLUTIONS

| Incubation Time (Hours) | Molarity of $AgNO_3$ Solutions | | | |
|---|---|---|---|---|
| | 0 % Survival | $10^{-6}$ % Survival | $10^{-4}$ % Survival | $10^{-2}$ % Survival |
| 0 | 100 | 100.00 | 0.004 | 0.004 |
| 1 | 160 | 0.090 | 0.004 | 0.004 |
| 4 | 125 | 0.004 | 0.004 | 0.004 |

microorganisms was killed by silver ion at 37°C in less than one hour. The molar concentration of silver represents only 0.108 mg of silver per liter of water. The daily silver intake from foods and cooking and eating utensils is estimated to be 0.06 to 0.08 mg of silver per man per day (Reference 12). No acute toxic dose of silver has been established; however, it has been estimated that 0.01 to 2.5 gm of silver salts may be ingested at one time without causing acute symptoms. Chronic silver poisoning results in the disease called argyria, which is a cosmetic anomaly caused by deposition of silver in the skin. Argyria results from silver ingestion over many years; it is accompanied by no known impairment of physiological activity (Reference 12).

To examine the reported bactericidal activity of metallic silver, Goucher (Reference 12) plated the bottom and sides of erlenmeyer flasks with silver and placed suspensions of microorganisms in various media in the flasks. The

TABLE 22

SURVIVAL OF *E. COLI* SUSPENDED IN VARIOUS SOLUTIONS IN FLASKS WITH AND WITHOUT SILVER MIRROR INTERIORS

| Suspending Solution | Container | Incubation Time (Hr) 0 %S | 2 %S | 4 %S | 5 1/2 %S | Silver Concentration (ppm) |
|---|---|---|---|---|---|---|
| $H_2O$ | Mirror | 100 | 0 | 0 | 0 | 1 |
| | Glass | 100 | 52 | 21 | 11 | 0 |
| 0.01% Glucose | Mirror | 100 | 0 | 0 | 0 | 2 |
| | Glass | 100 | 48 | 16 | 7 | 0 |
| 0.1% Egg Albumin | Mirror | 100 | 0 | 0 | 0 | 3 |
| | Glass | 100 | 53 | 24 | 11 | 1 |
| $10^{-2}$ M NaCl | Mirror | 100 | 0.01 | 0 | 0 | 0 |
| | Glass | 100 | 87 | 87 | 75 | 1 |

(Incubation was at 37°C and initial cell count was $\sim 10^7$ cells per ml. The cells were grown in TGY agar and washed with water before use in this determination.) (Reference 12)

TABLE 23

SURVIVAL OF THREE SPECIES OF BACTERIA IN WATER CONTAINED IN FLASK WITH AND WITHOUT SILVER MIRROR INTERIORS

| Organism | Incubation Time (Min) 0 %S | 45 %S | 90 %S | 300 %S | Silver Concentration (ppm) |
|---|---|---|---|---|---|
| *E. coli* | | | | | |
| Silver mirror | 100 | 0 | 0 | 0 | 1 |
| Control | 100 | 90 | 64 | 24 | 1 |
| *S. aureus* | | | | | |
| Silver mirror | 100 | 0.5 | 0 | 0 | 1 |
| Control | 100 | 98 | 78 | 68 | 1 |
| *Ps. aeruginosa* | | | | | |
| Silver mirror | 100 | 0 | 0 | 0 | 1 1/2 |
| Control | 100 | 96 | 70 | 65 | 1 |

(Reference 12)

data in Tables 22 and 23 show the results of these experiments. From these tables it is apparent that metallic silver can act as a bactericide in water storage systems; it is effective in different media and against different species. Again the silver in the water could be ingested directly or removed by an ion-exchange column (Reference 12). Goucher also investigated a resin system which itself contained silver, and this system was also very effective in killing E. coli, Pseudomonas, and Staphylococcus. However, such resin exchange columns are not currently applicable for long-term missions; an ion-exchange column, on the other hand, for removing silver ion from water exposed to metallic silver does appear feasible, although perhaps unnecessary in view of the small amounts involved and the low toxicity of silver.

6. Filtration

The basic aspects of filtration involved in atmospheric control generally hold true with filtration in the water supply system, except that the medium being filtered is water, with its much greater density, and that microorganisms usually grow much better in aqueous than gaseous medium. The latter consideration implies that in the water supply system the chance of mats and sludges growing on the filters is much greater, and must be avoided in system design. Filters in the water supply system are advantageous in areas where fluid is in motion, as opposed to chemical techniques, which are most applicable to stationary water supply system areas. Filtration has the great advantage that dead microorganisms and debris are removed from the aqueous stream. Disadvantages include the pressure-drop over the filter and the possibility of filter clogging from particulate matter.

Generally, filtration has the major advantage that commercially supplied filter material can remove all microbial contamination extending in size down to viral-size particles. The efficiency of one such filter (Pall Trincor Corporation) with lightly and heavily contaminated water is shown in Tables 24 and 25 (Reference 12). This filter material has been shown to be nontoxic to rats.

TABLE 24

BACTERIA REMOVAL EFFICIENCY OF ULTIPOR .15 FILTERS

| Organism | Non-Filtered Water Bacteria/ml | Filtered Water Bacterial/ml | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Escherichia coli | 490 | 0 | 0 | 0 |
| Staphylococcus aureus | 540 | 0 | 0 | 0 |
| Shigella dysenteriae | 580 | 0 | 0 | 0 |
| Streptococcus pyogenes | 490 | 0 | 0 | 0 |
| Diplococcus pneumoniae | 620 | 0 | 0 | 0 |
| Vibria comma | 560 | 0 | 0 | 0 |
| Salmonella typhosa | 490 | 0 | 0 | 0 |
| Mycobacterium tuberculosis | 518 | 0 | 0 | 0 |

TABLE 25

BACTERIA REMOVAL EFFICIENCY OF ULTIPOR .15 FILTERS
ON HEAVILY CONTAMINATED WATER

| Organism | Non-Filtered Water Bacteria/ml | Filtered Water Bacteria/ml |
|---|---|---|
| Bacillus subtilis | 10,000,000 | 0 |
| Serratia marcescens | 27,000,000 | 0 |
| Escherichia coli | 3,730,000 | 0 |

The capacity of this filter is shown in Figure 15; the power requirements are reasonably low, representing a pressure drop of about 0.1 psi at 0.5 gal/min flow (measured using turbid water with algae present; Reference 12). With a roughing filter, the filter should function with a small energy differential at up to about 5 gm of material over 1 $ft^2$ of filter area.

To prevent build-up of sludges and mats on the surface of filters, some form of biocidal impregnation of the filter is recommended. Such filters have not been investigated extensively to date, at least not for the application to the water supply system of a spacecraft. However, a commercial filter with a coating of a silver salt has been developed by the Pall Trincor Corporation, for use in home water purification. The biocidal coating produces a low silver-ion concentration of 15 to 25 parts per billion. This concentration meets PHS 1962 Drinking Water Standards that are concerned with long-term (30 years) toxicity effects (Reference 12). For filters which will be exposed to contaminated surfaces, such treatments are very advisable after suitable testing.

7. Radiation

Two uses of radiation may be considered here: ultraviolet radiation and the use of radiation in conjunction with pigments in the water supply. Particulate radiation will not be considered for reasons described earlier, largely because of the shielding requirements.

Goucher (Reference 12) investigated aqueous microbe control using the dye acridine orange, which absorbes radiation and kills microorganisms after photoactivation. Only very small quantities of this dye are required (0.4 gm for 1000 liters of water) for bactericidal effect, with a power requirement of less than 5 watts continuously. The results of a test run using this dye are shown in Table 26 (Reference 12). The dye is a cation, and would require removal by a cation exchange resin to eliminate possible problems of toxicity and impalatibility. However, the amount of resin required would be fairly small, using the minute quantities of dye possible with photoactivation.

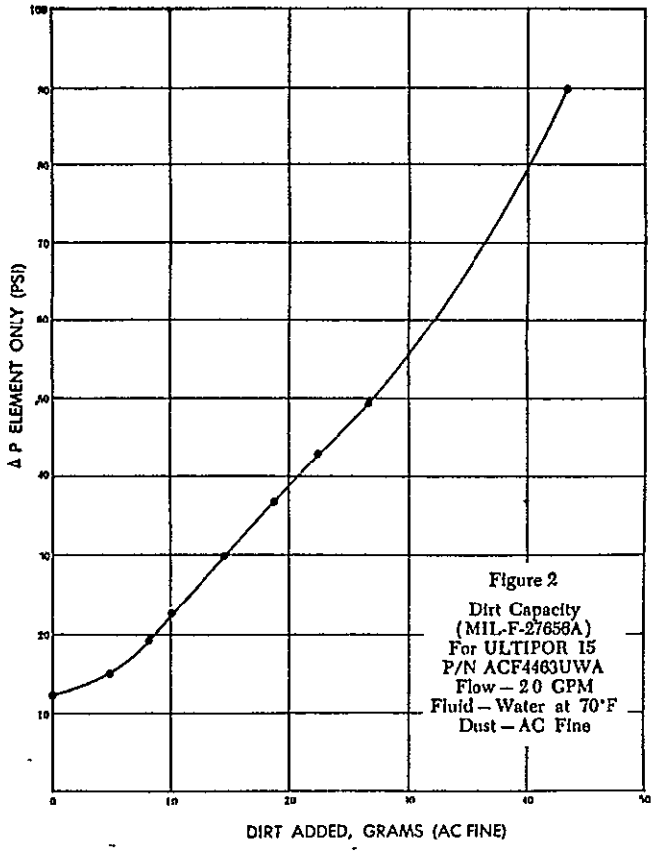



Figure 15. Capacity of Ultipor .15 Filter (from Parentral Drug Assoc. Bulletin, Oct. 30; 1963)

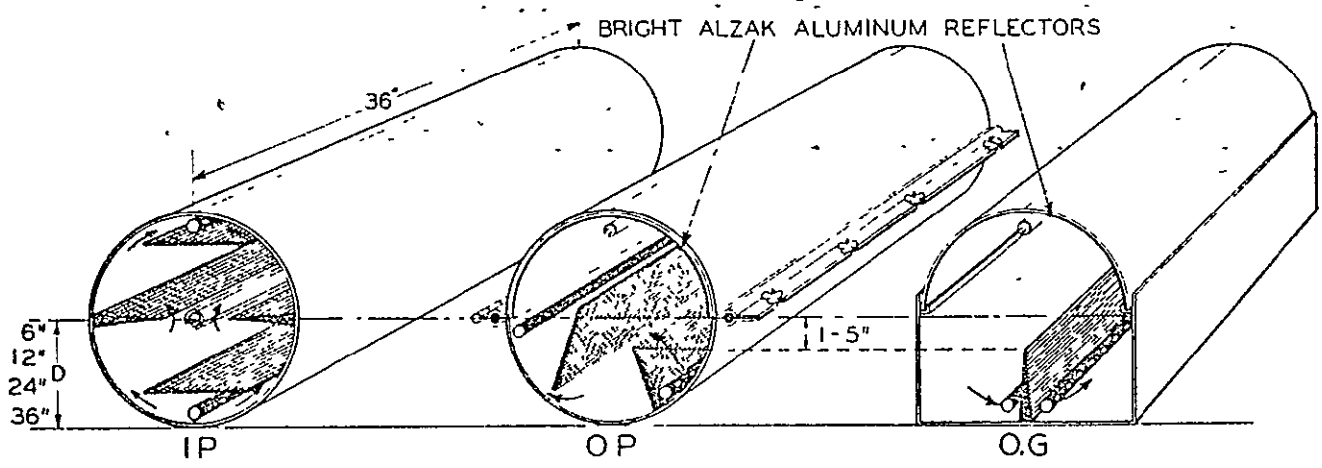



Figure 16. Piping and Baffle Arrangements for Ultraviolet Sterilization of Liquids (from General Electric Lamp Bulletin TP-122)

TABLE 26

THE SURVIVAL OF E. COLI IN ACRIDINE ORANGE SOLUTIONS AND IN WATER IN THE PRESENCE OF VISIBLE RADIATION*

| Time | $H_2O$ Control S(%) | $10^{-5}$ S(%) | $10^{-7}$ M (%) | $10^{-9}$ M (%) |
|---|---|---|---|---|
| 0 Time | 100 | 100 | 100 | 100 |
| 1 Hour | 550 | 0.06 | 150 | 620 |
| 3 Hours | 900 | 0.00001 | 450 | 880 |
| pH after 3 Hours | 5.8 | 6.0 | 5.9 | 5.9 |

*Irradiation was by a 100-watt incandescent bulb 16 in. from the surface surface of a 50-ml solution 1/2 in. deep

NOTE: Acridine orange at $10^{-5}$ M in the absence of light did not cause appreciable loss in viability.

Ultraviolet radiation has been discussed earlier as a method of microbe control in the atmosphere, and most of the problems mentioned there hold for water decontamination. An additional problem, however, is the much greater absorption of the ultraviolet radiation in water. The ultraviolet intensity through absorptive liquids decreases logarithmically with distance from the lamp; the presence of organic and ferric compounds increases the absorption considerably. The effective depth of penetration (distance at which 90 percent of the radiation has been absorbed) of ultraviolet radiation ranges from a few thousandths of an inch in milk and serums, or one-tenth of an inch in wines and syrups, to five inches through potable water of low transmission. It may be as high as 50 in. in drinkable water of high transmission, and up to 10 ft for very pure distilled water. Table 27 shows the General Electric lamps required for 90-percent disinfection of varying quantities water. These lamps draw 4, 8, 15, and 30 watts respectively.

In water streams or piping, ultraviolet is best used with a series of baffles to permit sufficient contact of the ultraviolet radiation with the water. Such baffles are usually installed parallel to the direction of water flow, and should be as thin as structurally possible to minimize radiant absorption. An example of such disinfecting devices installed in a pipe is shown in Figure 16.

The heavy possible contamination of certain areas of the water supply system, combined with the absorbance characterisitcs of ultraviolet radiation, constitutes one major difficulty with ultraviolet sterilization. Contaminated water, because of these factors, becomes self-protecting, in that the more

## TABLE 27

### 90 PERCENT DISINFECTION OF LIQUIDS - GALLONS PER HOUR*

| No. of G4T4+ | | 2 | 3 | 7 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. of G8T5+ | | | 2 | 3 | | | | | | | | |
| No. of G15T8+ | | | | 2 | | | | | | | | |
| No. of G30T8+ | | | | | 2 | 3 | 5 | 7 | 8 | 10 | 13 | 16 |
| Effective Depth of Penetration Inches | 1 | 21 | 42 | 83 | 200 | 400 | 600 | 800 | 1000 | 1200 | 1600 | 2000 |
| | 2 | 42 | 84 | 167 | 400 | 800 | 1200 | 1600 | 2000 | 2400 | 3200 | 4000 |
| | 3 | 63 | 125 | 250 | 600 | 1200 | 1800 | 2400 | 3000 | 3600 | 4800 | 6000 |
| | 4 | 84 | 167 | 334 | 800 | 1600 | 2400 | 3200 | 4000 | 4800 | 6400 | 8000 |
| | 5 | 104 | 208 | 416 | 1000 | 2000 | 3000 | 4000 | 5000 | 6000 | 8000 | 10000 |
| | 6 | 125 | 250 | 500 | 1200 | 2400 | 3600 | 4800 | 6000 | 7200 | 9600 | 12000 |
| | 7 | 146 | 292 | 584 | 1400 | 2800 | 4200 | 5600 | 7000 | 8400 | 11200 | 14000 |
| | 8 | 167 | 333 | 666 | 1600 | 3200 | 4800 | 6400 | 8000 | 9600 | 12800 | 16000 |
| | 9 | 188 | 375 | 750 | 1800 | 3600 | 5400 | 7200 | 9000 | 10800 | 14400 | 18000 |
| | 10 | 209 | 417 | 834 | 2000 | 4000 | 6000 | 8000 | 10000 | 12000 | 16000 | 20000 |
| | 12 | 250 | 500 | 1000 | 2400 | 4800 | 7200 | 9600 | 12000 | 14400 | 19200 | 24000 |
| | 15 | 313 | 625 | 1250 | 3000 | 6000 | 9000 | 12000 | 15000 | 19000 | 24000 | 30000 |
| | 18 | 375 | 750 | 1500 | 3600 | 7200 | 10800 | 14400 | 18000 | 21600 | 28800 | 36000 |
| | 24 | 500 | 1000 | 2000 | 4800 | 9600 | 14400 | 19200 | 24000 | 28800 | 38400 | 48000 |

For cu ft per hr, multiply above by 0.13368, for cu in. per hr, by 231.0; for cu in. per min, by 3.85.
+Allows for 65 percent of bare lamp efficiency for lamp and reflector combination.
*Based on standard microorganism, E. coli
From: General Electric Lamp Bulletin TP-122.

contamination is present, the less ultraviolet penetration occurs and hence less disinfection occurs. Thus a vicious cycle occurs, by which more and more contamination results in less and less disinfection from the ultraviolet lamps. To prevent this situation from occurring, it is necessary that no growth be permitted upstream of the ultraviolet system, which is very difficult when a fuel cell water supply assumed to be contaminated is employed. However, the probability of such an occurrence is greatly reduced if the depth of channel or pipe employed is sufficiently small (e.g., below 3 cm).

## CONCLUSIONS

### General

Before a selection is made of a method of microbe control for a spacecraft, it is useful to examine the various types of microorganisms which may be expected in the spacecraft. These organisms will arise from two sources: the cabin occupants and from residual contamination left over from spacecraft component fabrication and assembly. Because these latter most generally are of human origin, they may be expected to be the hardier varieties of those same types which will be produced by the cabin occupants. The microorganisms generally associated with the human body may be of two forms. The first of these forms are the transient forms, which are pathogenic generally and which come and go, and which may or may not become situated in a part of the body where they can cause infection. The second type of microorganism contains those species which occur as more or less stable populations in various ecological niches of the human body. These range in virulence from nonpathogenic organisms to small numbers of pathogens which may under certain circumstances invade the body. The former type is not expected, because the astronauts should be clean and disease-free at the start of the mission, although latent infectious processes are always possible.

The microorganisms normally found in various areas of the human body are shown in Table 28, which is taken from Mattoni and Sullivan (1962, Reference 1). The most conspicuous members of the dermal organisms are Staphylococcus albus and Proprioni - bacterium, on all mucous membranes the most conspicuous members are Staphylococcus, Streptococcus, and Candida; on the nasopharyngeal area Neisseria and Coryne bacterium, in the mouth and throat Treponema, Endameba gingivalis, and Actinomycetes; and in the intestinal tract are the enteric bacilli Psuedomonas and Clostridium. Several fungi and yeast-like organisms may also be associated with humans in addition to Candida. These may produce superficial infections; they include predominantly forms of the genus Trichophyton, which cause athlete's foot and severe dandruff (Reference 1).

In addition to these organisms, several viruses may be present, although the quantity of these should be fairly low with noninfected individuals. Other somewhat less common organisms may also be present, but those which are possible are far too numerous to list. Also, it is highly questionable whether any attempt to predict the bacterial contaminants of the space vehicle is valid. No adequate studies have been done to determine the long-term

TABLE 28

LIST OF TYPES OF MICROORGANISMS INDIGENOUS TO THE HUMAN BODY. RELATIVE ABUNDANCE BY REGION INDICATED BY (1) IRREGULAR, (2) COMMON OR CONSTANT, (3) MOST NUMEROUS. UNDERLINED TYPES UNIVERSAL TO REGION.

| | Skin | Eye | Nose | Pharynx | Mouth | Intestine | External Genitalia |
|---|---|---|---|---|---|---|---|
| Micrococcus | 1 | | 1 | 1 | 1 | 1 | 1 |
| Staphylococcus | 2 | 1 | 1 | 2 | 1 | 1 | 1 |
| Aerobic micrococcus | 2 | | | 1 | 2 | | 1 |
| Alpha, gamma streptococcus | 1 | | 1 | 3 | 3 | 2 | 1 |
| Beta streptococcus | 1 | | 1 | 1 | 1 | 2 | |
| Anaerobic streptococcus | | | | 1 | 2 | 1 | 1 |
| Pneumococcus | | | 1 | 1 | 1 | | |
| Neisseria | | | 1 | 3 | 1 | | |
| Bacillus | 1 | | | 1 | 1 | 1 | |
| Clostridium | | | | | | 2 | |
| Corynebacterium | | 1 | 2 | 1 | 1 | | 2 |
| Lactobacillus | | | | | 2 | 2 | |
| Proprionibacterium | 3 | | | | | | |
| Actinomycetes | | | | 2 | 2 | 1 | |
| Leptotrichia | | | | | 2 | | |
| Mycobacterium | | | | | | | 2 |
| Escherichia | 1 | | | | 1 | 3 | 2 |
| Aerobacter | | | | | | 1 | |
| Klebsiella | | | | | | 1 | |
| Proteus | | | | | 1 | 1 | |
| Pseudomonas | | | | | 1 | | |
| Hemophilus | | | 1 | 1 | | | |
| Dialister | | | | 1 | | | |
| Bacteriodes | | | | 1 | 1 | 3 | |
| Fusobacterium | | | | 1 | 2 | 1 | |
| Anaerobic vibrio | | | | 1 | 2 | 1 | |
| Spirochaetes | | | | 1 | 3 | 2 | 2 |
| Fungi | 1 | | | | 2 | 1 | 1 |
| Protozoa | | | | | 1 | 1 | 1 |
| Pleuro-pneumonia like organisms | | | | 1 | 1 | | 1 |

From Mattoni R. H. and Sullivan, G H , 1962, Sanitation and Personal Hygiene During Aerospace Missions, Medical Research Laboratories Report No MRL-TDR-62-68

effects of reduced atmospheric pressure and unusual gas compositions on the human microbial flora. Similarly, no studies have been accomplished to learn which species are most apt to flourish in various niches of the cabin, the equipment surfaces, and the water supply system. It is expected that the low pressure and anomalous atmospheric composition will have some effects on the microecology, and that these effects may be small or very large. The weightless state may also exert some effects, but these are not expected to be very large. The organisms of the water system should also be affected somewhat less by the spacecraft environment than those exposed to the gaseous environment, but this too is uncertain. It is entirely possible that the environment of the spacecraft may greatly encourage the proliferation of particular species at the expense of others, and it is possible that these preferred species may be pathogenic to the astronauts. Relevant experimentation is required before any estimate of quantities or identification of proliferative species can be made. However, the function of the microbe control system will be to prevent any species from multiplying to a dangerous extent.

Removal of Microbes from the Atmosphere

Almost all of the systems discussed for removal of microbial growth from the atmosphere have particular advantages and disadvantages. The following paragraphs discuss these aspects, particularly those which are most important for spacecraft application. These advantages and disadvantages form the bases for the recommendations for atmospheric bacteria control presented here; they are summarized from the more detailed discussions preceding.

High-efficiency filters which can remove 90 to 99 percent of 1- to 5-micron particles from the air appear to constitute a very adequate method for bacteria control. Such filters are capable of high-efficiency removal of bacterial aerosols from the air with a pressure drop in the neighborhood of 1.0 in of $H_2O$ at 35 cfm over 0.5-$ft^2$ area, with an estimated power requirement of less than 1 watt, a weight of less than 0.03 oz of filter material, and a size of approximately 20 $in^3$. These filters offer the advantage that, using glass or similar material, they introduce no toxicity, they are simple and reliable, with no moving parts, their useful life with low pressure drop is sufficient if adequately protected, and they remove an adequate quantity of materials from the air. They have the disadvantage that they must be protected from larger particles by roughing filters, their pressure drop increases with loading, and without impregnation there is a possibility of microbial growth on their surface, which could be caused by nutrient material impinged on the filter. Also, most filters are not bactericidal, and thus offer the possibility of recontamination should considerable flow reversal occur. High-efficiency filters are preferable to ultra-high-efficiency filters in that they offer lower pressure drops and greater time to saturation without appreciable difference in equilibrium level.

Mechanical particle separators are not effective for the removal of small particles. Pump-driven cyclones, using fairly high speeds, can remove some bacteria, but they are too inefficient for spacecraft purposes. Also, for high-speed cyclones, the power and weight penalties are not competitive

with other systems of greater efficiency. A mechanical separator is suggested for use in removing large-size particles from the air, as a part of the particulate control system, but this device will remove little or no bacterial particles, or dust-borne bacteria.

Electrostatic filters increase efficiency by using electrostatic particle-fiber attractions; their advantages are much the same as those of ordinary filters, except that somewhat less pressure drop is required. Their disadvantages are that self-charging materials have been insufficiently studied, so that they offer the possibility of toxin production and chemical and physical reactions with atmospheric compounds and the spacecraft environment. Also, most of them are flammable. Their reactions to bacterial deposition are unknown; this may be an critical factor, because bacterial degradation of filter material could present a considerable hazard. A belt electrostatic charging system requires comparatively little power, but it does not appear sufficiently reliable. Also, such systems may generate sparks and arcing, which could be hazardous. Ordinary filters generally exhibit electrostatic effects to a limited extent.

Electrostatic precipitators offer the advantages of negligible pressure drop and easy disposal of collected particles. The disadvantages are numerous, the major disadvantage being the high power, weight, and size penalties. Other disadvantages include the inefficiency of electrostatic precipitators in collection of small (microbial) particles at reasonable flow rates, the production of ozone from the corona discharge, and the possibility of dangerous arcing. Further, very precise humidity control is required because of the danger of arcing. These devices may be considered, at best, the equivalent of medium-efficiency filters.

Heating, particularly heating to incineration of microorganisms, is an excellent method of control, although there is a considerable power penalty for heating and recooling the air. However, when the use of a catalytic burner is anticipated, this device presents a candidate method of microbe control by heating. A temperature of $600^{0}$F and a dwell-time of 0.2 sec in the catalytic burner would assure the destruction of all organisms passing through it. The use of this device as the sole means of bacteria control offers several disadvantages, however. One of these is that frequently only a portion of the atmosphere is ducted through the burner, so that the downstream ECS areas are subject to massive contamination. In addition, large numbers of microorganisms passing through the catalytic burner would result in the production of organic breakdown products, as well as possible spoiling of the catalyst, so that the primary function of the catalytic burner would be impaired.

Particulate radiation is not considered for bacterial control. Ultraviolet radiation, however, offers several advantages as a candidate air-sterilization technique, predominantly low pressure drop and moderately effective killing capacity. The disadvantages of mercury arc lamps are numerous, however, including mutagenicity and a continual power requirement (15 watts) as major factors. In addition, ozone may be evolved from a part of the lamp's spectrum. Ultraviolet is readily absorbed by organic materials,

and humidity also offers a shielding effect, so the atmosphere must be fairly well controlled. Microorganisms on aerosol particles may be shielded from the ultraviolet by the particle itself. The maintenance requirements of ultraviolet lamps are quite high, because it is imperative that the lamps be kept clean. The lamps are fragile, also, and must be equipped with indicators to show their function; lamps may lose their ultraviolet production and still produce visible light which is innocuous to microorganisms. Finally, the ultraviolet is hazardous to the skin and eyes of humans, and so the astronauts must be shielded from direct radiation.

Electric discharge is known to kill microorganisms in small chambers. However, relatively little is known about this process with respect to space vehicles. Furthermore, the high power requirements and the large ozone productions present further major difficulties with this technique. Air-washing is a technique of only moderate efficiency (20 to 80 percent bacterial removal); its use without bactericides presents the danger of re-entrainment of particles, and with use of a bactericide a toxic hazard may appear. Air scrubbing is also fairly inefficient, and presents major difficulties in integration with the ECS. However, the maintenance requirements for scrubbers are low. Impaction-impingement scrubbers require as much as 150 watts for 0.5 cfm flow, and thus have high power as well as weight penalties. All of these methods suffer from lack of adequate designs for spacecraft systems, and their selection would require considerable design and development.

Removal of Microbes from Surfaces

The most critical surfaces are those which are in contact with or in close proximity to the cabin occupants. These include seats, clothes, various personnel systems, surfaces of equipment which is handled, niches in equipment where bacterial growth conditions are favorable, and the spacesuits. The interior surfaces of the air-conditioning and circulation system may also be considered. The basic methods for bacterial control of these surfaces include: (1) the use of bactericidal or bacteriostatic coatings, (2) washing and chemical disinfection, and (3) materials impregnation for fabrics. It should be recalled that the control system used for atmospheric microbe control will serve to keep the quantity of viable materials on surfaces at a minimum.

Coatings and paints which retard bacterial growth are advisable for hard component surfaces; such coatings are available commercially and appear to function adequately in preventing surface growth. Such coatings may, however, impair component function, be degraded or damaged by the atmosphere or by particulate impingement, and present a toxic hazard in the spacecraft. Thus before use of such coatings, a screening should be accomplished to ensure that such actions will not take place. A coating which appears to be of considerable promise, particularly of the interior surfaces of the ECS, is metallic silver. However, fairly little is known yet about the toxicity of this material and the effects of the oxide layer which is prone to form on metallic silver.

Washing, using simply soap and water, is an excellent method of protecting surfaces from microbial growth. If such washing is accompanied by the use of chemical bactericides, then the efficacy of this technique is enhanced. Disinfectant sprays are particularly effacious in this application. Washing and liquid disinfection are also applicable to surfaces not amenable to paints and coatings, such as clothing, seats, and the interior of the spacesuits. The problems presented by these techniques are the particulate contamination which would result from washing procedures, the physical effort such housecleaning tasks would involve, and the possible toxic hazards implicit in the use of bactericidal chemicals and spray. Another potential difficulty is the degradation of the components and surfaces which are washed by the washing action and/or the chemicals involved.

Materials impregnation is a technique applicable predominantly to fabrics, these fabrics being predominantly those of the seats, clothing, and the spacesuit. Bactericidal impregnating materials which are applicable for spacecraft are primarily compounds of heavy metals, predominantly copper and silver. Copper has been used frequently in the past for commercial use, but it has the disadvantages that the impregnating material is water-soluble and is thus leached out of fabrics with washing. Also, these compounds have a high vapor pressure, producing an odor and possible respiratory-rate toxicity. Silver compounds, or fibers of metallic silver, show more promise from the standpoint not only of stability with washing but also with toxicity (respiratory or dermal pathways) and in bactericidal efficacy.

The use of direct radiation of ultraviolet on surfaces is not generally applicable because the critical areas on which surface growth is most probable are those occupied by the astronauts, to whom such radiation would be harmful. However, this technique is applicable for regions which are shielded from direct line-of-sight of the astronauts, in which surface growth appears likely. Such areas include humid, warm areas which cannot be reached for washing. With such radiation, all of the advantages and disadvantages of ultraviolet sterilization hold, with the addition that the surfaces themselves may be degraded by the radiation. In such areas, though, intermittent illumination should be adequate.

Control of Microbial Growth in the Water System

The requirement for zero viable microorganisms from the potable water supply demands stringent control of microbial growth in the entire water supply system. In addition, is it requires that the potable water not be polluted by dead microorganisms or by the various chemical products released by heavy microbial growth or the killing of large number of microorganisms. Thus it is advantangeous not only to kill viable microorganisms in the water supply system but also to prevent microbial growth to the greatest extent possible and to remove the debris left after killing those which do grow. These considerations greatly influence the choice to be made for a microbe control system in the water supply. Many of the same techniques which apply to atmospheric bacteria control apply to the water system control, and so many of the same conclusions apply.

It should be borne in mind that many factors of concern with the water supply system microbial aspects are unknown or uncertain. The sources of water-borne microbial contamination cannot be identified without experiments on a functioning water supply system, preferably under accurately simulated conditions. The fuel-cell water offers the possibility of contamination, as does the suit heat exchanger system, possibly to an even greater extent. The human cabin occupants may also add directly and indirectly to the aqueous contaminant load by unexpected contingencies. The quantity of contamination and the organisms which are preferred for growth from fuel cell and condensate sources are unknown, and the final microbial control system selection may well depend on such findings. The following conclusions should still apply generally, however.

Freezing is not an advantageous method of killing microorganisms because of the great resistance exhibited by several forms. To be effacious, the freezing must be done repeatedly. Also, the power requirements for such a system would be prohibitively high, and no applicable designs for such systems have been devised. High temperatures, on the other hand, are excellent for providing sterility in that heating to 250°F for 20 min provides almost complete certainty of 100-percent kill. This technique requires considerable power, and a gauge pressure of 24 psi, which a pump must be able to overcome. Another difficulty is that the bacteria are killed but not removed from the medium, so that their bodies and denatured components may be present in the water.

The use of high pressures per se, osmotic gradients, and extremes of pH are all methods of killing microorganisms, but they all appear impractical for use in spacecrafts. Such systems would be of considerable complexity, and adequate designs and studies have not been conducted for their spacecraft application. Furthermore, they offer considerable hazards to the equipment in many cases. These same difficulties are encountered with agitation; ultrasonic agitation of the microbial particles is required for adequate and practical killing. This would require a chamber for exposure to the ultrasound and an abrasive medium, and would also require a fairly large amount of power. Thus agitation too appears impractical.

The use of chemicals for disinfection of the water supply system appears to be a fairly attractive method of bacterial control in the water supply system. Cetyl pyridinium appears to be a good candidate chemical, as do other quaternary ammonium compounds and beta propiolactone. One excellent chemical which has recently been investigated is acridine orange, a dye which with visible light irradiation is very bactericidal. Another chemical which appears to have considerable application to the water supply system is metallic silver or silver ion. Most of these compounds, with the possible exception of the metallic silver, have the disadvantages of possible toxicity to the astronauts, as well as offering possible palatability problems. Acridine orange requires an additional source of power (less than 5 watts continually). Usually, toxicity and palatability problems must be overcome by the use of appropriate ion-exchange resins, and these, in turn, together with expendable chemicals, introduce the problem of resupply.

Filters capable of removing bacteria from water exhibit a finite pressure drop which increases with filter loading. The concomitant power loss is approximately 0.2 watts for 0.1 psi for 0.5 gal/min, with very little increase in power requirement even with appreciable filter loading. Such filters remove a nominal 98 percent of particles less than 0.15 micron and 100 percent of particles greater in size than 0.35 micron. Filters, of course, merely remove microorganisms from the water stream; they do not kill them. Therefore the possibility exists of growth taking place in the filter material--growth which could cause formation of mats and sluges which could hamper filter operation. It is, however, potentially feasible to incorporate in the filter material a bacteriostatic compound to prevent such growth. A commercial filter which accomplishes this using a silver salt has been very successful, although a certain amount of silver is present in the effluent water. Filters using metallic silver impregnation should similarly inhibit microbial growth, with less silver in the effluent stream. The toxicity of silver is apparently very low, but its removal could be accomplished, if required, by an ion-exchange resin.

Ultraviolet radiation in water exhibits many of the same effects as ultraviolet radiation in the air. However, additional problems include the fact that ultraviolet is much less effective against bacteria in water, so that a considerably larger residence or exposure time is required. Baffles are frequently used for this purpose, and baffles create a pressure drop depending in their configuration. Ultraviolet radiation is absorbed in much less distance in water than in air, particularly if the water contains absorbing organic materials such as microorganisms, limiting the safe distance for water disinfection to less than 3 cm. With heavy contamination, the biocidal effects may be attenuated by absorption. The problem of mutagenicity is, of course, present with ultraviolet wherever it is used. The ultraviolet lamp would require approximately 15 watts of power continuously, and adequate cleaning and maintenance. The maintenance requirements would be rather difficult to satisfy with the lamps in the water supply system. Again, some monitoring should be required to ensure that the lamp was functioning properly.

## RECOMMENDATIONS

The recommendations presented below are based largely on the preceding conclusions. It is difficult to make concrete recommendations on the basis of the little knowledge that is presently available about the effects of various spacecraft environments on microbial flora. The various niches, both physical and ecological, cannot presently be identified with any assurance. The effects of the cabin pressure, gas content, and temperature may have major effects on the human microbial flora and they may not, microorganisms may be prone to flourish in the confines of the cabin and in the various systems and they may not. Until more space flights have taken place, or until adequate simulation studies have been accomplished and evaluated, these factors must remain uncertain. Because of this, the recommendations presented here tend to be conservative, and it is hoped that any erroneous assumptions err on the side of superfluous rather than inadequate microbe control. However, it is possible that even these techniques will prove inadequate. The techniques recommended for bacterial control are discussed

under the three general classifications of atmospheric, surface, and water system control, although it should be recalled that considerable overlap exists between these three areas. Recommended techniques for control in other areas are also suggested.

Removal of Microbes from the Atmosphere

The recommended basic method of controlling microbial growth in the atmosphere is the use of a high-efficiency filter located in the air-circulating system downstream of the cabin and the particulate control filters. This filter should be of a canister type, preferably using glass-fiber filter medium, and it should retain 90 to 99 percent of the 1- to 5-micron particles which enter it. This filter should, for 45-day missions, have before it the equivalent of two roughing filters which should each remove 10 to 60 percent of the 1- to 5-micron particles. Roughing filters have a maximum pressure drop (clean) of about 0.1 in. of water. Probably this configuration will serve for a mission length of up to 60 days, although for longer missions filter changing will probably required, depending on the quantity of microbial particles produced. The use of such a filter will keep the atmosphere microbial concentration at a very low level sufficient for safety. The filters suggested earlier for particulate control are expected to provide the equivalent of two roughing filters.

Both the high-efficiency filter and the roughing filters will provide atmospheric control by removing microorganisms from the gas stream, not by killing them. It is expected that living, and conceivably, reproducing, microorganisms will be trapped in these filters. Bacterial growth is not expected to any great extent on the filter surfaces; however, in view of the physiologically active substances which are expected to be encountered, at least by the roughing filters, it would be advisable to incorporate a bacteriostatic or bactericidal substance in the filter medium to prevent such growth, should conditions of high humidity, water droplets, etc., occur which could permit bacterial multiplication. While good filter bactericides which function well at low humidities have not been devised, several exist which work well under high humidity conditions, and these conditions are precisely those which could permit bacterial multiplication. All of these are uncertain as to toxicity, but metallic siliver seems to be the safest compound. Most reports indicate that metallic silver fibers in a filter would prevent serious (clogging) growth under environmental conditions which would permit growth. The use of silver as an impregnating material appears to be very advantageous, after suitable testing.

The use of a catalytic burner for trace-contaminant control will function as a back-up system to the high-efficiency filter. Depending on the fraction of air ducted through the burner, the entire system will act as a filter with a higher efficiency than the total of the filters employed. Under normal conditions, however, the catalytic burner should be exposed to very few microorganisms, by placing the filters upstream of the burner. In the event of filter changing, removal, or breakdown, the catalytic burner would be very useful in keeping the atmospheric level of microorganisms low; in fact, the burner would act as an adequate bacterial control system by itself, except for the problems of breakdown products and catalyst contamination.

Further bacteria control should be exercised by control of bacteria sources. This implies a minimum of particles should be produced by waste management, personal hygiene, food preparation, etc., operations and activities. Contamination from these sources should be minimized by adequate system design and by thorough training of the astronauts. The Apollo vacuum cleaner which will be used for particulate control will be of considerable use in bacterial control with proper use, if the cleaner bags are removed and disposed in such a way that the contaminated material which they contain is either safely stored or treated with bactericide. In general, adequate particle control will greatly help atmospheric bacteria control, both by removing media on which bacteria can flourish and by reducing the load on the filters.

Removal of Microbes from Surfaces

Several methods are recommended for control of microbial growth on surfaces, with certain methods being specific to certain particular types of surface. Most surfaces, surfaces of the components, walls, instruments, etc, of the interior of the cabin, should be coated with a nontoxic finish which will retard bacterial and fungal growth. One such coating which may prove advisable from the standpoint of off-gassing toxicity is silver plating. All reasonable precautions will be made during construction and assembly to maintain the integrity of these surfaces and to minimize organic and microbial contamination. Prior to launch, all of these interior surfaces should be thoroughly cleaned with soap and water and treated with a disinfectant. The disinfectant should be fairly nontoxic, such as the commercial spray SBT-12, although most of this material should have volatilized before launch.

During flight, the interior surfaces should be cleaned at least every five days, this cleaning should involve all of the surfaces within reach of the astronauts which will not be harmed by this treatment. This cleaning may employ any of several agents, simple soap and water, applied with a cloth or sponge, would be adequate. However, the use of a nontoxic bactericide would be recommended. This bactericide could be incorporated into the soap or cleaning solution. One technique of surface cleaning which would require further study is the incorporation of a cleaning agent-bactericide spray with the vacuum cleaner, by which the vacuum cleaner would be equipped with fixed rubber blades (squeegee type) to remove the impinged agent after it was sprayed on. This would require design and subsequent testing, however. This periodic cleaning of the cabin interior should be standardized and human-engineered so that a regular procedure is used. The astronauts should be practiced and familiar with the procedure before launch; in the devising of this procedure, certain types of cleaning instruments may be seen to be necessary and subsequently should be devised and tested.

The fabrics and cloth-type surfaces should also be cleaned, specifically, the seats, clothing, and interior of the space suit should be cleaned. Clothing cleaning is generally considered to be an aspect of personal hygiene. The same agents used for surface cleaning should also be applicable to the seats, etc., as to the other component surfaces. However, for these critical areas which are in close contact with the astronauts' bodies, impregnation

with bactericidal material is suggested. Silver salts deposited in the cloth and silver filters or threads can be tentatively recommended for this purpose. The use of such impregnating materials should greatly reduce the production of viable organisms from the humans, and hence the total production in the cabin.

The interior surfaces of the air conditioning and water supply systems should be treated with care during construction to minimize the deposition of active materials. Before final assembly and, if possible, after final assembly, these components should be sterilized, by heat or by whatever method is applicable from the standpoint of material compatibility and possible toxic residues. In addition, all of these interior surfaces should be coated with metallic silver to retard surface growth, or, if silver is not applicable, other such coatings should be employed to prevent slime and mat growths on these surfaces, and to minimize growth in the fluid itself. The use of such coatings may produce a prohibitively high silver concentration in the water system, in which case use of an ion-exchange resin (such as Dowex-50) will be required.

Certain surfaces which would not be reached by washing may become contaminated by microorganisms; such areas should be treated with special consideration during assembly. Silver coatings or other such coatings should minimize growth in these areas. Electrical insulation on wiring may be particularly vulnerable to microbial attack if it is not protected, whenever possible, such materials should be inert and bacteriostatic, so that at least they do not act as a growth medium for impinged microorganisms. In certain areas (e.g., behind panels, etc.) where cleaning is not advisable and yet which are ventilated by the ambient atmosphere so contamination could occur, the use of ultraviolet lamps may be required. It is thought that adequate germicidal treatment beforehand, and use of appropriate materials and finishes, will obviate the need for this precaution. If ultraviolet is required, however, care must be taken to ensure that the occupants are properly shielded and that the materials themselves are not harmed or degraded by the radiation. In such case, intermittent illumination should suffice.

The astronauts should be thoroughly clean at the beginning of the flight. In addition, a quarantine period under approximate flight conditions should be observed before flight to disclose any latent pathogens. The period should be long enough to permit incubation and manifestation of symptoms. This is desirable so that the contamination at launch is more or less known, and the preflight washing should serve to reduce the number of removable dermal contaminants. This latter is advisable because the suggested microbial control system will function best with a minimum of secondary (nonhuman) contaminant sources, and initial cleanliness will provide a longer period before secondary contamination becomes manifest.

Control of Microbial Growth in the Water System

Because of the stringent requirements for potable water, two primary methods are suggested in addition to the interior surface treatment mentioned above. These methods are heating and filtration. The heating sterilization

loop should include primarily the potable water tank, a pump, a heater and recuperator hot and cold outlets, and a return line to the potable water tank. This loop, basically, should heat the water to 250°F with a stay time of at least 20 min. The use of such a heater upstream of the delivered potable water is the only method by which complete sterility of the water (zero viable organisms) can be assured.

The filter will serve both as a redundant control and to minimize the quantity of particles to be killed by the heating. The filter type of choice was described above, it should remove 98 percent of particles smaller than 0.15 micron and 100 percent of those larger than 0.35 micron, with a pressure drop of 0.1 psig initially. Were it not for the zero-viable-organism requirement, then such a filter would be applicable as the sole method of control. With the heater, the filter will serve to remove the debris from the killed organisms, so that no turbid water, through it might render microbial growth nonviable, will be delivered to the astronauts.

The filter may be situated upstream or downstream of the heater. The downstream location will remove most of the debris, with the disadvantage that the breakdown chemicals from the possibly large number of killed organisms will be passed into the water. However, this location is preferable for a nonbacteriostatic or nonbactericidal filter, because the organisms will be dead and will not present the problem of possible growth and subsequent clogging. It is preferred to place the filter upstream of the heater so that the large mass of organisms is prevented from being cooked; however, upstream growth may occur because the impinged organisms are viable. Hence the filter should if possible be bactericidal. For this application, again, silver salt or silver fabric impregnation seems preferable.

As noted above, silver impregnation is suggested both for filter impregnation and for coatings inside the water system. The coating inside the system should be as ubiquitous as possible, to minimize growth in all parts of the system. If possible, this metal should also be used in the fuel cell, and on all heat-exchanger surfaces and all ducting. Further study is required to determine whether or not an ion-exchange resin is required in the water supply system; presently, it appears that the toxicity of silver is low enough that its use here would not be physiologically harmful. Study should be undertaken, however, to provide assurance for this hypothesis. In addition, it is obvious that silver should not be used where its presence would interfere with the primary function of the particular component or system. In the case of the water supply system, this does not appear to be a problem except with areas whose construction is not amenable to metal plating.

Control of Microbial Growth in Other Areas

The particle-control system filters, which may serve for roughing bacterial filters, will be subjected to the impingement of microorganisms and nutrient materials. Even though these filters are normally washed with air, some growth may be possible because of aerosol droplets which may impinge on these filters. Such growth should not be expected, because of the anticipated rapid drying, but the possibility exists, and provisions

should be made to prevent it. For these filters, impregnation with silver metal fibers appears most applicable. The particulate debris trap is amenable to metallic silver plating; in addition, it should be cleaned with soap and water or the selected cleaning agent periodically and immediately after any event which would introduce a large quantity of materials to it.

For body cleaning, a nontoxic bactericide is recommended. This aspect of bacterial control is an adjunct of the personal hygiene system; the use of one of the quaternary ammonium compounds such as hyamine or benzalkonium chloride would seem to be applicable. Adequate personal hygiene provides a major contribution to effective microbe control. Thus it is also necessary to ensure the bacteriological adequacy of wash water disposal and the treatment of clothing. Either hermetic removal from the environment or use of bactericides is desirable for these applications.

The food and waste management systems should be designed for innate bacterial control as one major aspect of their function, in addition, hygienic procedures are required with the use of these systems. Generally, any items touched by human skins or clothing should be cleaned as soon as possible after contact. This is particularly applicable to the waste management system, where the products may be assumed to be contaminated. Adequate design, human engineering, and testing of these systems should ensure that they offer minimum possibility of microbial contamination.

Microbe control of corpses presents a considerable problem, particularly if any bodies are kept in the confines of the cabin. No adequate information exists on protecting the remaining astronauts from the microorganism contamination which would be produced by this occurrence. Short of complete embalming and disinfecting procedures, there is no way of keeping a corpse in the cabin area without great microbial hazards.

The techniques recommended in this discussion should result in complete bacteriological safety to the astronauts and to the cabin equipment. It is suggested, however, that medical provisions be included to combat any infection which may take place despite these precautions. These provisions should include broad-spectrum antibiotics such as tetracycline, and perhaps oral penicillin, and other drugs useful in combating infectious processes. It is not recommended that use of antibiotics be contemplated under normal conditions.

Finally, as this report suggests, considerably more research should be accomplished to determine the changes brough about in the microbial flora by the specified environmental conditions. Floral changes may be expected in both the humans involved and in the cabin ecology due to the peculiar atmospheric conditions. Further changes will be brought about by the microbe control precautions. The nature of these changes is almost entirely unknown, and experimentation should be undertaken to determine and evaluate these changes and their degree before the missions are begun.

In addition, it is highly desirable to monitor the bacteria levels in the spacecraft. There are numerous obvious reasons why this is advisable, and there are many potential methods of monitoring, but they will not be discussed here. Nevertheless, their use is strongly recommended.

NOTE: Just before publication of this document, AiResearch pilot studies showed that metallic silver retards bacterial growth in urine by a factor of from 10 to 100; the same effect is produced in urine concentrated by heat to half its initial volume. The study periodically assayed bacterial growth over an eight-day period in bottles of human urine and urine concentrate incubated at 37°C; the silver metal used was in the form of U.S. twenty-five-cent pieces. Total aerobic counts were made after 48-hr culture of aliquots spread on nutrient agar. When the coins were removed from the bottles, they were tarnished and coated. This work indicates that metallic silver may provide some degree of control of bacteria in water-reclamation systems.

REFERENCES


7. Decker, H. M., Buchanan, L. M., Hall, L. B., and Goddard, K. R., 1962, Air Filtration of Microbial Particles, Public Health Service Publication No. 953, U. S. Government Printing Office, Washington, D.C.

8. Humphrey, A. E., and Gaden, E. L., 1955, Ind. and Eng. Chem., 47: 5, 924.

9. Terjesen, S. J., and Cherry, G. B., 1947, Trans. Inst., Chem Engrs. (London), 25: 89.

10. Decker, H. M., Geile, F. A., Mooreman, H. E., and Glick, C. A., 1951, Heating Piping, Air Conditioning, 23:125.

11. Ramskill and Anderson, 1951, J. Col. Sci., 6:416.

12. Goucher, C. R., 1965, Study for Control of Microbial Growth in Manned Spacecraft, Phase I Report, Melpar, Inc., NASA Contract No. NAS 9-3563.

13. Sykes, G., 1958, Disinfection and Sterilization, D. Van Nostrand Co., Inc., Princeton, New Jersey.

14. Reddish, G. F., 1957, Antiseptics, Disinfectants, Fungicides and Chemical and Physical Sterilization, Lea--and Febiger Co., Philadelphia, Pa.

15. Friedman, H. S., Sylk., and Laumann, D., 1962, pp.66-75 in Antimicrobial Agents and Chemotheraphy, Sylvester, J. C., ed., Braun-Brumfield, Ann Arbor, Michigan.

# APPENDIX

## CHARACTERISTICS OF COMMERCIAL FILTERS
(From Reference 7)

TABLE A-I

ROUGHING FILTERS
PARTICLE RETENTION* 10 TO 60 PERCENT**
(REFERENCE 7)

| Nomenclature | Manufacturer | Media | Capacity cfm/ft$^2$ of face A | Face velocity ft/min | Press. drop In. of $H_2O$ | Max. oprn. temp. |
|---|---|---|---|---|---|---|
| AAF type HV 2 | American Air Filter Corp. Louisville, Ky. | Adhesive-coated V-crimped wire screen mesh | 250 to 430 | 300 to 500 | 0.04 to 0.10 | 110°F |
| AAF PL24 w/type G media | American Air Filter Corp. | Glass filament | up to 250 | 250 | 0.06 | 250°F |
| Drico puffglass | Drico Industrial Corp. Passaic, N. J. | Spun glass fiber | 32 to 1,000 | 300 | 0.08 to 0.11 | 175°F |
| Far-Air HP-2 | Farr Filter Co. Los Angeles, Calif. | Pleated cotton fabric | 250 to 435 | 250 to 435 | 0.045 to 0.115 | 225°F |
| Farr 44-68 | Farr Filter Co. | Crimped screen and wire mesh | 250 to 435 | 250 to 435 | 0.040 | 275°F |

* One to five microns.
** Inclusion of any particular filter in this table does not constitute endorsement by the United States Government or by the authors.

TABLE A-2

MEDIUM-EFFICIENCY FILTERS
PARTICLE RETENTION* 60 TO 90 PERCENT**
(REFERENCE 7)

| Nomenclature | Manufacturer | Media | Capacity cfm/ft² of face A | Face velocity ft/min | Press. drop In. of $H_2O$ | Max. oprn. temp. |
|---|---|---|---|---|---|---|
| AAF deep bed Type 100 FG | American Air Filter Corp. Louisville, Ky. | Fiberglass | 50 to 250 | 250 | 0.24 | 700°F |
| AAF PL 24 frame Type 25 FG | American Air Filter Corp. | Fiberglass | 50 to 250 | 200 | 0.09 | 400°F |
| Aerosolve 45 | Cambridge Filter Corp. Syracuse, N. Y. | Glass fibers | up to 500 | 250 to 500 | 0.16 to 0.25 | 400°F |
| Expandure | Flanders Filters Riverhead, N. Y. | Fiberglass | 250 | 250 | 0.38 | 200°F |
| Type CA | Microtron Corp. Charlotte, N. C. | Polyester/acetate adhesive coated | 200 to 250 | 200 to 250 | 0.08 to 0.13 | 350°F |
| U-LOK | Union Carbide Development Co. New York, N. Y. | Dynel fibers | 200 to 500 | 300 | 0.10 | 180°F |

* One to five microns.
** Inclusion of any particular filter in this table does not constitute endorsement by the United States Government or by the authors.

TABLE A-3

HIGH-EFFICIENCY FILTERS
PARTICLE RETENTION* 90 TO 99 PERCENT**
(REFERENCE 7)

| Nomenclature | Manufacturer | Media | Capacity $cfm/ft^2$ of face A | Face velocity ft/min | Press. drop In. of $H_2O$ | Max. oprn. temp. |
|---|---|---|---|---|---|---|
| Multi-Pak w/*** 50 FG | American Air Filter Corp. Louisville, Ky. | Glass fiber | 125 to 250 | 250 | 0.42 | 400°F |
| Deep bed w/ 50 FG | American Air Filter Corp. | Glass fiber | 40 to 200 | 200 | 0.42 | 400°F |
| Micretain | Cambridge Filter Corp. Syracuse, N. Y. | Glass-asbestos pleated | 50 to 250 | Up to 250 | 0.4 | 220°F to 800°F |
| Aerosolve 85 | Cambridge Filter Corp. | Glass fibers pleated | 125 to 500 | 250 to 500 | 0.22 to 0.32 | 400°F |
| Aerosolve 95 | Cambridge Filter Corp. | Glass fiber pleated | 125 to 500 | 250 to 500 | 0.35 to 0.45 | 400°F |
| HP-100 | Farr Filter Co. Los Angeles, Calif. | Glass fiber pleated | 250 | 250 | 0.20 | 275°F |
| HP-200 | Farr Filter Co. | Glass fiber | 250 | 250 | 0.38 | 275°F |

* One to five microns.
** Inclusion of any particular filter in this table does not constitute endorsement by the United States Government or by the authors.
*** These filters made to accommodate double thickness of media.

TABLE A-4

ULTRA-HIGH-EFFICIENCY FILTERS
PARTICLE RETENTION* MORE THAN 99.99 PERCENT
(REFERENCE 7)

| Nomenclature | Manufacturer | Media | Capacity cfm/ft² of face A | Face velocity ft/min | Press. drop In. of $H_2O$ | Max. oprn. temp. |
|---|---|---|---|---|---|---|
| AAF Type F (glass) | American Air Filter Corp. Louisville, Ky. | Glass fiber and kraft paper or alum sep. | 30 to 400 | 68 to 325 | 1.0 | 250°F to 1000°F |
| AAF Type F (ceramic) | American Air Filter Corp. | Ceramic asbestos fiber and alum sep. | 30 to 250 | 250 | 1.0 | 1600°F to 2300°F |
| Cambridge Absolute | Cambridge Filter Corp. Syracuse, N. Y. | Glass fiber asbestos paper sep. | 30 to 345 | Up to 275 | 1.0 | 800°F |
| Magnamedia | Farr Filter Co. Los Angeles, Calif. | Glass fiber | 30 to 400 | Up to 250 | 1.0 | Up to 1000°F |
| Airpure absolute glass F 600 | Flanders Filters Riverhead, N. Y. | Glass fiber (F600) | 30 to 400 | Up to 320 | 1.0 | 850°F |
| Airpure absolute ceramic-asbestos | Flanders Filters | Ceramic-asbestos | 50 to 250 | Up to 250 | 1.0 | 1600°F |
| Ultra-Aire | Mine Safety App. Co. Pittsburgh, Pa. | Glass fiber | 35 to 250 | Up to 250 | 0.9 | 500°F |

NOTE: 1. Capacities are in cfm per sq ft of face area, not total area of filter.
2. Face velocities are fpm for 1 sq ft of face area, not media velocity.

* One to five microns.

** Inclusion of any particular filter in this table does not constitute endorsement by the United States Government or by the authors.