AMRL-TDR-64-33

RESEARCH ON A WASTE SYSTEM FOR AEROSPACE STATIONS

TECHNICAL DOCUMENTARY REPORT No. AMRL-TDR-64-33

MAY 1964

BIOMEDICAL LABORATORY
AEROSPACE MEDICAL RESEARCH LABORATORIES
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Contract Monitor: A. Hearld
Project No. 6373, Task No. 637305

(Prepared under Contract No. AF 33(657)-11489 by
John Dodson and Harold Wallman
General Dynamics/Electric Boat, Groton, Connecticut)

NOTICES

Change of Address

Organizations receiving reports via the 6570th Aerospace Medical Research Laboratories automatic mailing lists should submit the addressograph plate stamp on the report envelope or refer to the code number when corresponding about change of address.

700 - July 1964 - 162-44-896

FOREWORD

This report was prepared by General Dynamics/Electric Boat, Groton, Connecticut. The engineering research, process evaluation, and design study on which this report is based were carried out under Contract AF33(657)-11489, Project No. 6373, "Equipment for Life Support in Aircraft," and Task No. 637305, "Analysis and Integration of Life Support Systems." This work was monitored by Mr. A. B. Hearld, Requirements and Evaluation Branch, Biotechnology Division, Biomedical Laboratory, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. Research sponsored by this contract was started in April 1963 and completed in January 1964.

The authors are John Dodson, Chemical Engineer, and Harold Wallman, Head of the Chemical Engineering Section, Research and Development Department, General Dynamics/Electric Boat. This report has been assigned Electric Boat Document No. U413-64-056.

The authors acknowledge the assistance and advice of Dr. E.A. Zuraw, Dr. J. A. Lubitz, and Mr. G. A. Hemerick of General Dynamics/ Electric Boat in the preparation of the sections on biodegradation and sterilization. Acknowledgment is also made to Harold Miner and Victor Speziali for their assistance in preparing the detailed design, to D. Leone for performing the bacterial examinations, and to D. Rosen for editorial assistance.

ABSTRACT

An engineering evaluation was conducted to select an optimum waste management system for collection, storage, and/or disposal of feces and urine in a space station under weightless conditions. Based on this study, a detailed design of an optimum waste management system was prepared for a 7-man, 15-day mission. Tests performed on a breadboard model of the feces collector demonstrated the feasibility of the selected approach.

PUBLICATION REVIEW

This technical documentary report is approved.

Wayne H. McCandless
WAYNE H. McCANDLESS
Technical Director
Biomedical Laboratory

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES (Cont'd)

SECTION 1

INTRODUCTION

This study encompasses the development of techniques and the design of equipment for an optimum waste management system to be used on aerospace stations. It covers the engineering analysis, development of design criteria, and a description of the optimum system as developed; and is based on research conducted in two phases, as follows:

The first phase consisted of an engineering evaluation of applicable methods for handling human wastes (feces and urine) under space station conditions. This evaluation was based on a comprehensive discussion of various techniques and equipment. A description of an optimum waste management system was chosen as a result of the engineering evaluation.

The second phase consisted of the development of design criteria for an optimum waste management system, and the preparation of layouts, drawings, calculations, and other data necessary to fabricate an engineering model of the system.

SECTION 2

DESIGN REQUIREMENTS

In general, design requirements are as follows:

1. The system shall accommodate from 6 to 21 crew members on missions from 14 to 30 days.

2. The system shall be operable under weightless and artificial gravity conditions.

3. The system shall be operable under these environmental conditions:

Cabin Pressure	7.35 to 12 psia
Temperature Range	60° to 75°F
Humidity Levels	30 tc 80% Relative

4. All equipment shall withstand impacts of 25 g axial and 10 g lateral (referred to vehicle axes) and shall be constructed of nontoxic and noncorrosive materials.

5. Except for power, the system shall not be dependent upon other systems of the aerospace station.

6. The system, where practical, shall satisfy all needs of the user relating to the collection, transfer, storage, treatment, and/or disposal of feces and urine. Simplicity of operation and maintenance, and minimum weight, bulk, and power requirements are prime requisites.

SECTION 3

METHOD OF APPROACH

BASIC CONSIDERATIONS

The operation of a body-waste-handling system in an aerospace station will be conducted under "shirt sleeve" conditions, assuming that the crew members will remove their space suits shortly after arrival from earth.

In considering a system to handle the collection, transfer, storage, treatment, and/or disposal of urine and feces, a large number of process and equipment combinations are possible. However, the controlling factor in any such system is the method used for treating the fecal waste. This factor is critical from the points of view of minimum system weight and technical problems involved. The study, therefore, is initially directed towards methods of storing or treating fecal waste, with and without urine.

In all systems studied, urine is collected separately by the use of plastic urinals and then transferred to a storage tank having a one-day capacity for the crew size under consideration. All systems have a common weight and volume penalty factor for collection and storage of urine.

The engineering evaluation is limited to those systems for which prototype apparatus has been built or for which sufficient information is available for an evaluation.

Because crew size will vary in number from 6 to 21 men, it is assumed that living quarters for 6 or 7 men will be contained in one module, and quarters for 21 men will be contained in three modules. This is based on a hexagonal (or similar module) configuration of an orbiting space station (see Ref. 16).

TECHNICAL CONSIDERATIONS

Based on design requirements, the engineering evaluation covered in this report was prepared on the following factors:

1. Except for power, each system studied is independent of other subsystems of the space station.

2. Each system studied is rated quantitatively in regard to:

   (a) Total weight (including penalties for power and heat rejection and cabin air loss)

   (b) Volume (bulk)

3. Each system studied is rated qualitatively in regard to:

   (a) Reliability, safety, and simplicity

   (b) Degree of cabin air contamination

   (c) Crew acceptance (psychological factors)

   (d) Operating, transfer, and maintenance requirements

   (e) Operability in 0-g and low-g fields

   (f) Adaptability to urine-water recovery

4. Each system studied is confined to collection, transfer, storage, treatment, and/or disposal of feces and urine. Recovery systems per se are not compared.

5. Water recovery from feces is not justified for a 30-day mission.

6. The power source consists of solar cells. A weight penalty of 300 lb/kw for power and 0.01 lb/Btu/hr for heat rejection has been adopted for this study.

7. Any material voided to space must be sterile.

8. Average waste production/man/day is considered to be 1500 gm urine containing 5% dry solids, and 150 gm raw feces with 25% dry solids. Ignition residues or ash are 30% of dry-solids weight for urine, and 25% of dry-solids weight for feces.

SECTION 4

PROCESS STUDY

GENERAL

A study of the current literature concerned with the collection, transfer, storage, treatment, and/or disposal of urine and feces in a space vehicle was made. Subsequently, the following processes were selected for consideration:

1. Mixed urine and feces - freeze dried
2. Mixed urine and feces - freeze stored
3. Mixed urine and feces - biodegradation
4. Mixed urine and feces - vacuum distilled with vapor pyrolysis
5. Mixed urine and feces - heat sterilized or disinfected and stored
6. Mixed urine and feces - sterilized and vented
7. Feces collected in bags - sealed storage in cans
8. Feces collected in bags - incinerated
9. Feces combined collection and storage - partial drying by space vacuum

Of these processes, actual prototype apparatus has been built for processes 1, 4, 7 and 8. Process 9 was conceived at General Dynamics/Electric Boat where laboratory experiments were conducted to prove its feasibility. Processes 2, 3, 4, 5, and 6 will be discussed qualitatively and are dismissed from further consideration for the reasons stated. Processes 1, 7, 8, and 9 will be compared quantitatively.

PROCESS DISCUSSION - QUALITATIVE

Freeze Storage of Mixed Waste

The mixed wastes (urine and feces) can be stored at 20°F without decomposition, by removing heat from the mixed wastes by radiation to space or by mechanical refrigeration provided on board the aerospace station. Zeff et al (Ref. 32) considered this method to be impractical because: (a) the radiation panel for heat rejection to space would be quite large, (b) the radiation panel would have to be constantly oriented away from the sun, (c) the bulk storage would become inordinately large for the long missions, and (d) special mixing devices would be necessary to ensure complete mixing of urine and feces under zero-gravity conditions. Other reasons for rejecting this method are: (a) the large storage volume required (in excess of 12 cubic feet and 36 cubic feet for the 7-man crew and 21-man crew, respectively, on a 30-day mission); (b) space radiation freezing has not as yet been simulated, and freezing by mechanical refrigeration would require power and heat rejection that would add weight penalties; and (c) this system would not allow recovery of water from urine.

Biodegradation - Mixed Urine and Feces

Insight to the problems involved in using biological waste treatment methods in space can be obtained by examining conventional practice. In conventional waste treatment, sewage is highly heterogeneous and dilute. It is treated biologically because biological processes are economical. The primary objective is to transform sewage to nonobjectionable solids, liquids, and gases at minimum cost and in minimum time. Liquids from the process are disposed of in bodies of water, and gaseous by-products are eventually released to the atmosphere. Solid by-products are either buried, used as fertilizer, or barged to sea.

In a space station, wastes will be more homogeneous and concentrated, and will have to be treated under severe weight, power, and volume restrictions. In the discussions that follow, biological waste treatment is evaluated for use in a space station. Particular reference is made to the work of Chapman (Ref. 2) and Ingram (Ref. 7).

Minimum Engineering Requirements

Conventional sewage plants are designed on the basis of maximum sewage flow and concentration. Actual sewage flow and concentration varies greatly. Difficulties attributed to biological aspects of the activated sludge process are often sewage-plant design problems, such as poor control over sewage flow and concentration. Since the quantity and composition of wastes in a space station will be more uniform, this design problem should be simplified.

In the biological treatment of concentrated wastes, sufficient data concerning loading rate, detention time, and degree of digestion under continuous-operating conditions are not available for precise design calculations. These factors are important because they determine material balances of the process and the size of the treatment plant required. Nevertheless, minimum engineering requirements can be given, based on known requirements.

In terms of hardware, a blending device is required to disperse and blend feces since bacteria will rapidly degrade soluble and finely dispersed matter only. The process will also require waste storage facilities for treatment of wastes that are reasonably uniform in composition and concentration. Thus, a minimum of two tanks are required for alternate use as a storage system and as a feed system.

A pump is required for feeding the waste to the activated sludge system at some fixed rate. The activated sludge system requires a minimum of one tank with components for providing gas-liquid contact, gas-liquid separation, and liquid-solid separation. Instrumentation must also be provided for controlling and monitoring the process. Additional components are required for adsorbing carbon dioxide, adsorbing gases when storage tanks are vented, and heat rejection. Equipment may also be required for filtration and for drying of solids.

Power will be consumed for blending, pumping, gas-liquid contact, gas-liquid separation, liquid-solid separation, instrumentation, and heat rejection.

Material Balances of Activated Sludge Treatment

On the basis of 1500 gm of urine and 150 gm of feces/man/day, the waste breakdown given in Table I can be used for evaluating biological waste treatment.

TABLE I

ORGANIC AND MINERAL MATTER IN FECES AND URINE

Basis: gm/man/day

1650	H_2O	1537.5				
	Total Solids	112.5	Suspended Solids	37.5	Organic	25
					Mineral	12.5
			Soluble Solids	75	Organic	50
					Mineral	25

This waste can be processed on a continuous basis with a material balance as shown schematically below:

Basis: gm/man/day

Input	gm	Activated Sludge (Standing Crop)	Output	gm
Organic (degradable)	60		Carbon dioxide	51
Oxygen	42	→	Water	21
			Bacterial cells	30
Organic (nondegradable)	15	30	Organic (nondegradable)	15
Minerals	37.5		Minerals	37.5
Water	1,537.5		Water	1,537.5
Total	1,692			1,692

Net Result of process:

1. 30 gm of organic solids converted to CO_2 and water
2. 30 gm of organic solids converted to bacterial cells
3. 42 gm of oxygen consumed

The following assumptions were made in deriving the material balance. (There is little experimental data to support assumptions 1 and 2.)

1. Human organic wastes are degradable microbiologically without dilution with water.
2. The wastes are degraded continuously with a standing culture of 30 gm of activated sludge and a processing rate of 1650 gm of waste/man/day.
3. Sixty gm of the organic matter are degradable within a reasonable time period; 15 gm are not.
4. The bacteria respire with an efficiency of 50%; thus, 30 gm of cells are generated and 30 gm of organic matter are utilized for energy.
5. The production of 1 gm of bacterial cells requires 1.4 gm of O_2.

6. The respiratory quotient* of the sludge culture is 0.9.

7. The bacterial mass is not easily reduced. (A maximum reduction in mass of about 1% per hour can be expected by endogenous respiration.)

The material balance shows that:

1. A reduction in waste organic solids of about 40% can be expected, at best, by the activated sludge process.

2. Nondegradable organic solids will accumulate if not continually removed from the system.

3. The process will produce 51 gm of CO_2 and 21 gm H_2O, and consume 42 gm O_2/man/day.

Reliability

The reliability of an activated sludge process is dependent upon "steady-state" growth of microorganisms. Steady-state growth, in turn, is dependent on genetic integrity and a relatively constant physical and chemical environment. This presupposes a constant feed rate of wastes that are uniform in composition.

The effect of genetic mutations would be minimal in a continuous process with a mixed flora. Since the process is not dependent on any one species, mutants developing more stringent requirements will be overgrown by species growing more rapidly and the mutants will be washed from the system. A continuous process, in fact, will favor microorganisms that can most effectively subsist on the waste.

Bacteriophage conceivably could be a problem to reliability, as sewage is commonly used as a source of bacterial viruses. The mixed flora of activated sludge reduces the probability of process failure, however. A viral attack on a key species involved in waste degradation could affect degradation for a period of time until phage resistance was established. It is more likely that other species competing for similar substrates would quickly supersede the phage-infected species.

Biological waste treatment is considered unsuitable for the mission under study for the following reasons:

1. The process does not eliminate the need for other subsystems; water must still be recovered and solids must still be disposed of at the conclusion of processing.

2. The by-products (CO_2, water, and bacterial cells) are not required for this mission.

*mol CO_2 produced / mol O_2 consumed

3. The process can stabilize only 40% of the organic waste during a reasonable time period.

4. The process imposes additional weight, volume, and power requirements and introduces problems in gas-liquid contacting, gas-liquid separation, and solid-liquid separation under zero-gravity conditions. These problems have no easy solution, nor has hardware been developed to accomplish this on a small scale.

5. The process is relatively inflexible and time-dependent.

6. The state-of-the-art in the biological treatment of concentrated waste is rudimentary.

Disposal of Mixed Wastes by Vacuum Distillation With Vapor Pyrolysis

In this method, urine and feces are collected separately, blended, and fed to a still. The vapors are mixed with cabin air and passed over a catalytic bed at 1000°C. Reynolds and Konikoff (Ref. 20) and Konikoff and Okamoto (Ref. 9) developed and tested an apparatus to perform this operation. This unit has been successfully ground tested and has produced potable water and a dry residue, with approximately 90% water recovery. Unfortunately, these investigations did not give weight and size relationships. A calculation of the energy required to process the average urinary output of 1 man/day, based on the rate of 120 ml of water vapor/hr over a 12-hr period and the method used by Konikoff and Okamoto, gave 3700 Btu or 308 Btu/hr/man. For a 7-man unit this would require 2150 Btu/hr or 0.62 kw of power (weight penalty = 186 lb).

The disadvantages of the system are equipment weight, power penalty, heat-rejection penalty, weight of additional equipment to provide mixing and blending under weightless conditions, messy transfer operations, cabin air loss if vented to space, or CO_2 contamination if vented to cabin. This system is more applicable to longer missions where water recovery is essential.

Sterilization and Storage of Mixed Wastes

Zeff et al. (Ref. 31) discussed separate collection of feces and urine and combined storage under sterile conditions. Sterilization prevents the decomposition of wastes that would present problems of odor removal and cabin air contamination.

Two methods of sterilization have been considered, physical and chemical. In either method, large storage vessels and complicated equipment are necessary for operation under weightless conditions.

Physical Sterilization

Wet heat was considered as a possible method of waste sterilization by Roth et al. (Ref. 21). Waste sterilization by wet heat (steam) is technically feasible, because all living systems are destroyed if the waste is uniformly maintained at 121°C for 30 minutes. The advantages of wet-heat sterilization are:

1. No consumable chemicals are needed.

2. Accidental contamination of cabin atmosphere by chemicals is avoided.

3. The treated waste has no residual toxicity.

The disadvantages are:

1. The process involves heat and requires special containers with means for containing or disposing vented gases and water vapor. If gases are vented, chamber pressure must be at least 30 psia to reach the necessary temperature. If gases are not vented, chamber pressure will be considerably higher. A minimum storage volume of 12 cubic feet is required for a 7-man, 30-day mission.

2. Power failure leaves no means for treatment or disposal of waste.

3. Uniform distribution of heat in the absence of gravity requires an elaborate mixing or stirring device.

Chemical Sterilization

Chemical sterilization of waste is technically feasible for the following reasons:

1. Feces treated with ethylene oxide gas (15%) was regarded as sterile by Sandage (Ref. 22).

2. Agar contaminated with fungus spores and bacteria was sterilized by propylene oxide (5%). (See Thompson and Gerdemann, Ref. 25.)

The advantages of chemical sterilization are:

1. No power required (excluding mixing).

2. No pressure hazard.

3. Residual toxicity prevents growth of microorganisms in event of accidental recontamination of treated waste.

The disadvantages of chemical sterilization depend on the type of chemical sterilant selected. However, by selecting the proper chemical sterilant there is little likelihood of human toxicity or atmospheric contamination.

Oxides of ethylene and propylene are toxic to man, and they are explosive. They require bulk storage and also need special chambers for sterilization. When the gas is removed, the waste has no residual toxicity to microorganisms. Many chemicals are effective sterilants under special conditions, such as in the absence of resistant forms (spores), resistant species, or in the absence of certain substances such as organic matter, soap, or other chemicals which inactivate the sterilant. Thus, some bacterial spores are not killed by mercurials or alcohols. Some bacterial species or isolates are resistant to alkyldimethylbenzyl ammonium chloride; this compound and related compounds are inactivated by soap. The bis-phenols are inactivated by organic matter. (See Reddish, Ref. 19.)

Both physical and chemical methods of sterilization for storage of mixed wastes are technically feasible, but they are not considered practicable because of high volume requirements, weight penalties for power or storage of chemicals, transfer problems, and mixing of wastes in weightless conditions.

Sterilization of Mixed Wastes and Venting to Space

Another concept considered was the collection of mixed wastes on a daily basis and dumping to space after sterilization. Either wet (steam) sterilization or chemical disinfection could be used for this purpose. The same problems of mixing and sterilizing under weightless conditions will be present, but the volume will be considerably less.

There is no general agreement as to the concept of sterility, short of chemical decomposition. One criterion applicable to the question of sterility of waste vented to space is that the total biotic contribution from waste disposal be no more than the biotic contribution from other sources. (See Jaffe, Ref 8.) This criterion can be satisfied by rigorous microbiological assay of both sources.

It is assumed that microorganisms are carried into space by nearly every space vehicle launched. Additional microorganisms are added to space by space vehicle components (solar panels, balloons, etc.) which unfold or deploy after the vehicle leaves the earth's atmosphere, and other microorganisms can be released into space by accidental puncture (meteorite) or rupture of space vehicles. It is also possible that microorganisms have been carried beyond the earth's atmosphere through their own inertia after being accelerated upward by air currents caused by nuclear explosions or weather conditions.

A possible source of nonsterility of vented waste is one of treatment variability. It is well known that sterilization processes on earth sometimes fail due to human error or natural variability of materials. A second cause for incomplete sterilization is that the process is usually carried out near the minimum effective level for reasons of economy or for preservation of substances. For space application, the treatment used would be in excess of established minimum effective levels. Although in a laboratory test, the toxicant is removed to determine death versus inhibition of organisms; in space practice, the toxic residue would remain present indefinitely.

Of the two methods, chemical sterilization appears more feasible because no power is required for heating and no special pressure designed equipment is necessary. Of all the methods of treatment, chemical disinfection and venting to space have the least weight, power, and volume penalties. At the present state of space station technology; however, the venting of sterile mixed wastes may be considered inadvisable because:

1. Intimate mixing is required to ensure sterility.
2. The ejection of mass with velocity will introduce effects on the guidance and speed of the vehicle.
3. Solids, especially ionizable salts, may set up **ionized** fields in space that will interfere with communication.
4. With daily ejection of wastes to space, some cabin air will be lost.
5. The waste must be very finely divided so that particles will not act the same as micrometeorites and penetrate the space vehicle on successive orbits.
6. There is no possibility of water recovery.

PROCESS DISCUSSION - QUANTITATIVE

Freeze Drying of Mixed Wastes

This process is described by Zeff et al. (Ref. 32). Their work included building and testing a prototype vacuum freeze-dry unit for mixed wastes. The wastes consisted of used filters, food tubes, wipes, feces, and urine. The apparatus consisted of an insulated aluminum sphere with a removable, hinged door and seal, with built in filter and filter cartridge on the vapor line for removal of bacteria. The vessel was charged once a day with solid wastes. The daily accumulation of urine was then introduced over a 12-hour period. The vessel was evacuated before urine was fed in. The water in the urine evaporated, removing heat and freezing the solids and remaining water. The ice was gradually sublimed and the contents actually freeze dried. The value of the bulk density of the waste mass was calculated as 10 cc/gm and found to be 11 cc/gm by experiment.

A set of calculations was made using the method of Zeff et al. (Ref. 32) modified for feces, bags, tissue, and urine only. The calculated specific volume of the dried wastes was reduced to 5 cc/gm, because no extraneous waste was included. Based on 1500 gm of urine, 150 gm of feces, and 50 gm of fecal bags/man/day (the 1700 gm is 1530 gm water and 170 gm solids), the volume required to store freeze-dried solids was computed as follows:

Assuming that all water is vaporized daily, the volume required for any mission in terms of man-days is:

$$V = (1530 + 170\ V_s D)M$$

where:

V is volume in cc, V_s is bulk density of solids in cc/gm, D is the length of mission in days, and M is the crew size.

From this relationship it can be readily seen that the primary factor affecting the storage volume is crew size, and the secondary factor is length of mission.

Based on these computations, a weight-and-volume penalty analysis was made as given in Table II. Weight penalties are also shown graphically in Figure 1 for crews of 6, 7, and 21 men, and missions from 14 to 30 days. For sample calculations, see Appendix I, pp 56-58.

Incineration of Feces

This process was described by Nuccio et al. (Ref. 17) and deals with the disposal of feces (collected and bagged) and other solid wastes by thermal decomposition and incineration. From this report, it was concluded that: incineration with cabin air or oxygen with venting of vapors to space is better than thermal decomposition because, in incineration, the products of combustion are water vapor, carbon dioxide, and nitrogen; whereas in thermal decomposition, thermal cracking of the hydrocarbon material to carbon and hydrogen is not complete and tarry vapors tend to condense and stop up vents.

In incineration with stoichiometric quantities of oxygen or air, combustion is not complete, as evidenced by tarry deposit. This should not occur with 20% excess oxygen. Methods of calculating power requirements were not checked by the experimental data. Here again extraneous material, including garbage, food tubes, and sponge wipes were incinerated. Since this study is for the incineration of feces, fecal bags, and tissue only, the calculation process is simplified. To determine power requirements, the same heat balance method was used in this study as was set up by Nuccio et al. (Ref. 17), namely that:

$$Q_{\text{input}} + (Q_c - Q_f)_{\text{net heats of combustion}} = Q_{\text{sensible wastes}} + Q_{\text{sensible system}} + Q_{\text{fusion}} + Q_{\text{latent}} + Q_{\text{sensible gases}} + Q_{\text{losses}}.$$

Of these heat quantities, the net heats of combustion are assumed equal to the sensible heat of the system plus heat losses.

Thus:

The equation becomes:

$$Q_{\text{input}} = Q_{\text{sensible wastes}} + Q_{\text{fusion}} + Q_{\text{latent}} + Q_{\text{sensible gases}}.$$

TABLE II

WEIGHT AND VOLUME PENALTIES - FREEZE-DRY PROCESS - FROZEN STORAGE

Penalty Item	6 men 14 days	6 men 30 days	7 men 14 days	7 men 30 days	21 men 14 days	21 men 30 days
	Weight (lb)					
Bags and Wipes	9.2	19.9	10.8	23.1	32.4	69.3
Spherical Shell	13.8	22.7	15.4	25.4	46.2	76.2
Door and Access.	3.3	3.3	3.3	3.3	9.9	9.9
Insulation	0.9	1.4	1.0	1.5	3.1	4.7
Cabin Air Loss	0.8	3.4	0.9	3.8	2.7	11.6
Collection Seat	3.0	3.0	3.0	3.0	9.0	9.0
TOTAL WEIGHT	31.0	53.7	34.4	60.1	103.3	180.7
	Volume (cubic feet)					
Overall Sphere	3.25	6.48	3.78	7.21	11.35	21.13
Instruments and Access.	0.50	0.50	0.50	0.50	1.50	1.50
Storage Bags and Wipes	0.15	0.32	0.17	0.37	0.52	1.11
Vol. of Collection Seat	0.50	0.50	0.50	0.50	1.50	1.50
TOTAL VOLUME	4.40	7.80	4.95	8.58	14.87	25.24

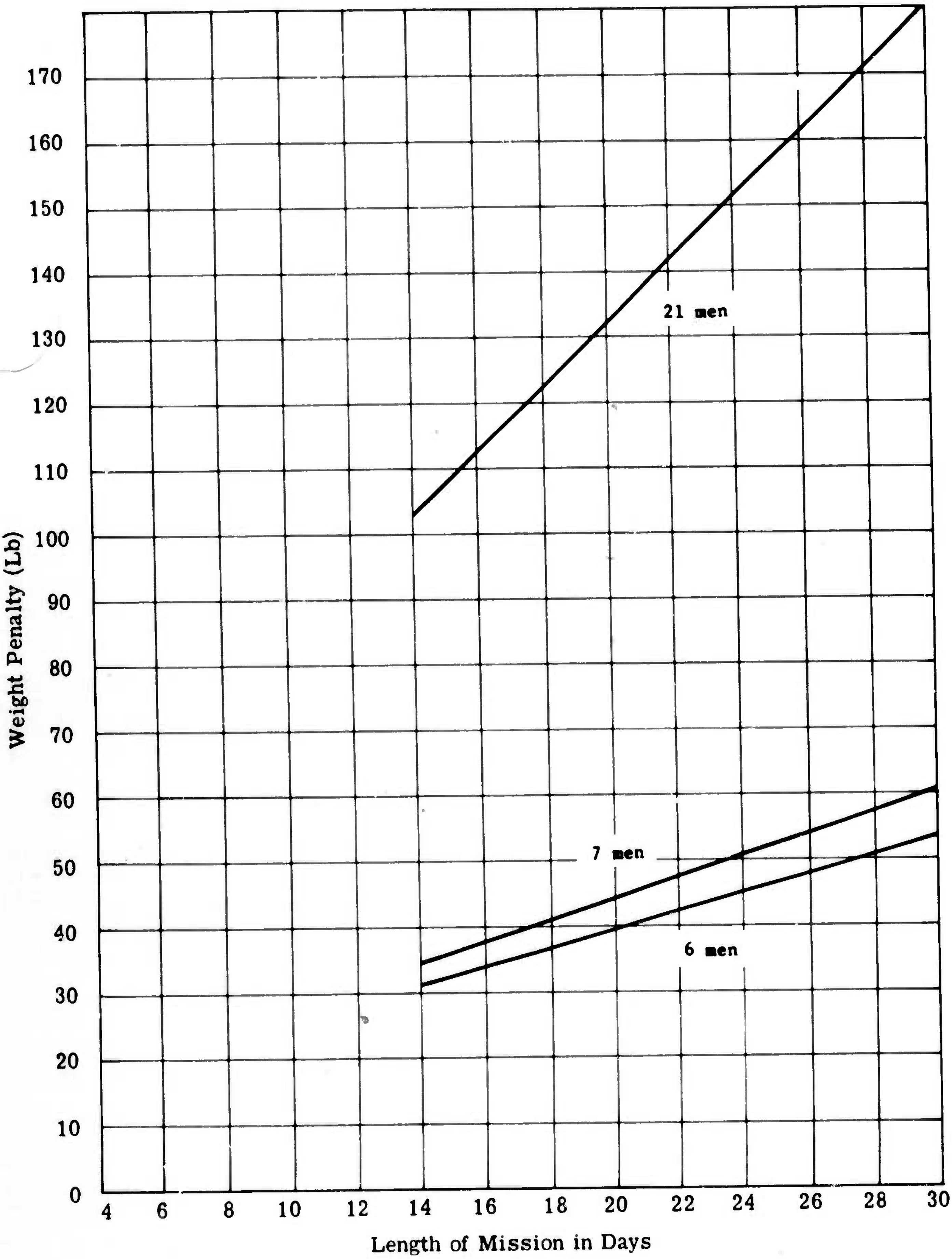


FIGURE 1. WEIGHT PENALTY - FREEZE DRY STORAGE

These quantities can be estimated or calculated for the amounts of wastes considered in this study.

A series of calculations was made (see Appendix I, pp 59-63) and the results listed in Table III and represented graphically in Figure 2. These figures are based on crew sizes of 6, 7 and 21 men for missions from 14 to 30 days.

In these calculations, the wastes were assumed to be incinerated with stored oxygen. Since all the gases are vented to space, incineration with cabin air would result in a tremendous weight penalty, because the nitrogen voided would have to be replaced from storage.

The weight penalties for power and oxygen are the determining factors. For a crew of 7 men, the auxiliaries comprise 60% of the weight penalty.

Sealing and Storing of Feces in Cans

Roth et al. (Ref. 21) recommended the iodophor germicides (particularly West #1443) for food-waste treatment in spacecraft applications. This antiseptic is used in conjunction with a gas-tight can and close-fitting lid as a pressure vessel. Roth et al. state that the principal disadvantage in the use of these germicides lies in the difficulty of mixing liquids and solids under weightless conditions. (Thorough shaking of containers might be an effective way of achieving contact of waste and preservative.)

LaChance* mentioned that when fresh feces were stored in four sealed cans for over two months, 6 psig was the highest recorded pressure in one of the cans, and this gradually returned to 2 psig and remained at this pressure.

Wheaton et al. (Ref. 29) reported that untreated fecal material stored in sealed containers at 30°C produced gases within the containers that reached pressures as high as 33 psia. The gases produced consisted mainly of carbon dioxide, methane, hydrogen, and hydrogen sulfide. The pressure in the containers increased most rapidly during the first four days of storage. The pressure produced by any one sample was dependent on the head space of the container.

Mallman and Chandler (Ref. 12) reported that colloidal iodine was able to penetrate and destroy bacteria embedded in finely divided particles of avian fecal matter, whereas a number of other disinfectants were not successful.

Some qualitative studies on feces storage were performed at General Dynamics/Electric Boat. In one preliminary experiment, feces preserved in sealed plastic bags at 40°F showed no gas production at the end of 48 hours. Feces treated with benzalkonium chloride (BAC) showed no gas production at the end of 72 hours at 40°F and were sterile when cultured for bacteria at the end of 24

*LaChance, P.A., Personal Communication. Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio, October, 1962.

TABLE III

WEIGHT AND VOLUME PENALTIES - INCINERATION OF FECES WITH OXYGEN

Penalty Item	6 men 14 days	6 men 30 days	7 men 14 days	7 men 30 days	21 men 14 days	21 men 30 days
	Weight (lb)					
Bags and Tissue	9.2	19.9	10.8	23.1	32.4	69.3
Cylindrical Shell	24.2	24.2	27.0	27.0	81.0	81.0
Door and Lock	6.0	6.0	6.0	6.0	18.0	18.0
Insulation	40.0	40.0	44.0	44.0	132.0	132.0
Instruments and Accessories	12.0	12.0	12.0	12.0	36.0	36.0
Sub Total	91.4	102.1	99.8	112.1	299.4	336.3
Power Penalty	27.6	27.6	33.0	33.0	99.0	99.0
O_2 Required	23.7	50.7	28.0	60.0	84.0	180.0
O_2 Container	23.7	50.7	28.0	60.0	84.0	180.0
Cabin Air Loss	N E G L I G I B L E					
Collection Seat	3.0	3.0	3.0	3.0	9.0	9.0
TOTAL WEIGHT	169.4	234.1	191.8	268.1	575.4	804.3
	Volume (cubic feet)					
Shell and Insula.	1.87	1.87	2.10	2.10	6.30	6.30
Instruments and Accessories	0.50	0.50	0.50	0.50	1.50	1.50
Storage Bags and Tissue	0.15	0.32	0.17	0.37	0.52	1.11
O_2 and Containers	2.20	4.40	2.20	4.40	6.60	13.20
Volume Collection Seat	0.50	0.50	0.50	0.50	1.50	1.50
TOTAL VOLUME	5.22	7.59	5.47	7.87	16.42	23.61

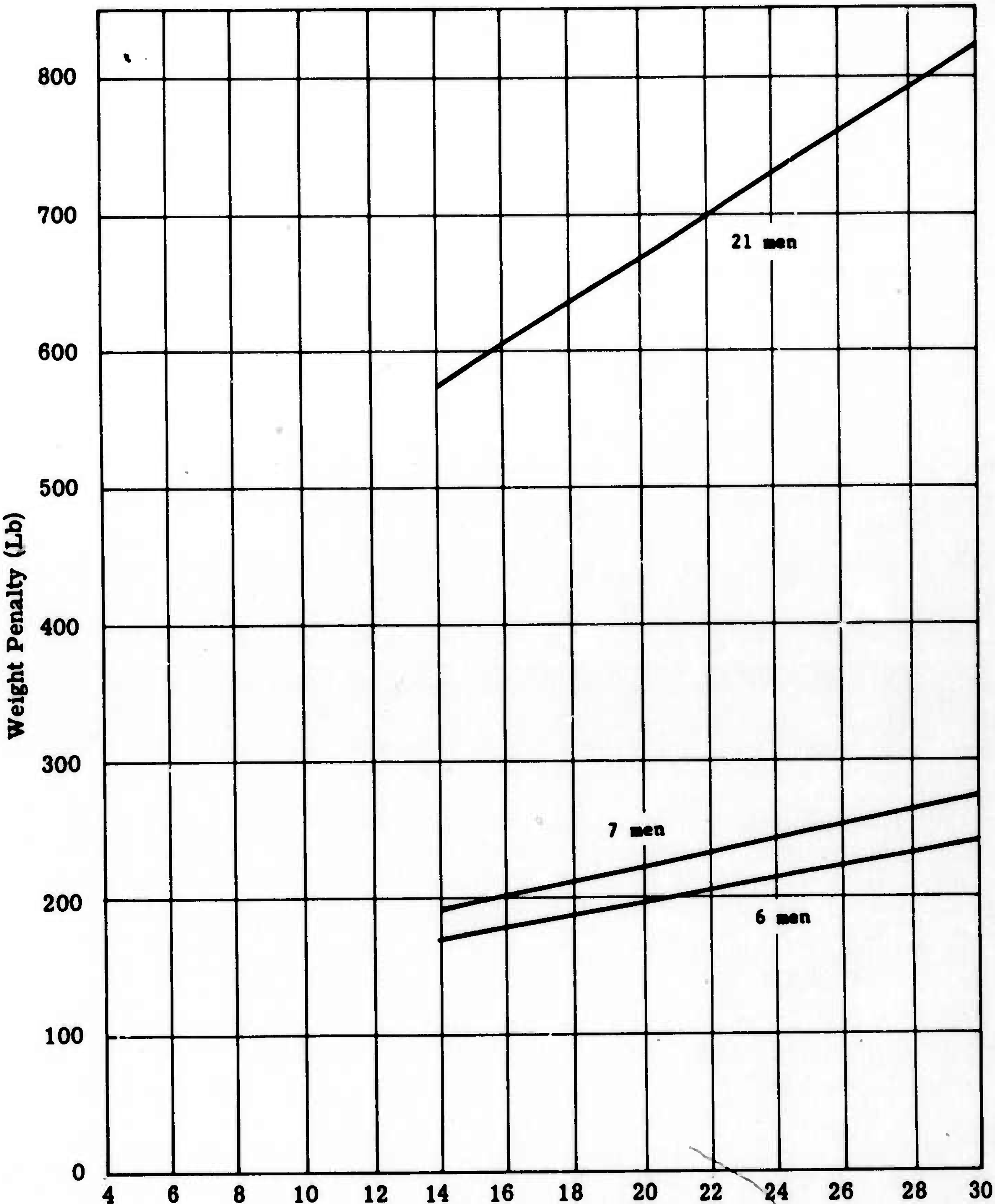


FIGURE 2. WEIGHT PENALTY - INCINERATION OF FECES WITH OXYGEN

hours. In other preliminary experiments, feces were again treated with BAC. These feces were incubated at 98.6°F; the treated feces produced somewhat less gas than the controls. Treated feces samples examined after 48 hours were not sterile. Gas production was measured visually by the amount of inflation of the sealed plastic bags.

In another experiment, three No. 3 sanitary tin cans were used in feces storage tests. To the first can, 111 gm of fresh feces and 30 ml of a solution containing 1% BAC and 1% sodium nitrite were added; to the second can, 71 gm of feces and 30 ml of the same antiseptic antirust solution. One hundred milliliters of water were added to the third can, which was used as a control. The cans were sealed, shaken, and then placed in an incubator at 98.6°F for 23 days. When removed and allowed to cool to room temperature, the first and second cans were slightly bulged and the control can appeared normal. The cans were then stored at room temperature for over 9 months with no apparent change in pressure or leakage.

To check on corrosion, four commercial tin cans were prepared by adding 30 ml of the following:

1. 13% benzalkonium chloride (BAC) solution

2. 5% BAC solution

3. water

4. 1% BAC, 1% sodium nitrite

The first three cans showed signs of rust within 24 hours, the last can showed no rust even at the end of two weeks. The open cans were stored at room temperature for this test.

It therefore appears feasible to store feces in conventional, sanitary, tinned cans using benzalkonium chloride as an antiseptic and sodium nitrite as an anti-rust agent. Although the feces are not sterilized using this agent (as witnessed by the slight swelling of the cans in the above tests), there is sufficient inhibition to prevent rupture of the can when stored for the length of the mission. The feces of 3 to 5 men will fit into one No. 3 can (1-liter capacity) leaving about 50% headspace. About 2 oz. of antiseptic, anti-rust solution (10% BAC for 10 x safety factor, 1% sodium nitrite) should be added to each can before sealing and shaking.

A standard, quart paint can with a special friction lid seems satisfactory for this service. Its use would eliminate the hand-operated, double-seamer required to close a sanitary seal can and would be dependent on laboratory testing.

A quantitative analysis of the weight and volume penalties for various crew sizes and mission lengths is shown in Table IV and is represented graphically in Figure ? For sample calculations, see Appendix I, p 64.

TABLE IV

WEIGHT AND VOLUME PENALTIES - STORAGE OF FECES IN CANS

Penalty Item	6 men 14 days	6 men 30 days	7 men 14 days	7 men 30 days	21 men 14 days	21 men 30 days
	Weight (lb)					
Bags and Wipes	9.7	19.9	10.8	23.1	32.4	69.5
Cans, Empty	8.9	19.2	10.6	22.4	31.8	67.0
Sterilant (10% BAC Solution)	3.5	7.5	4.1	8.7	12.3	26.1
Hand Seamer	5.5	5.5	5.5	5.5	16.5	16.5
Cabin Air Loss	NEGLIGIBLE					
Weight of Collection Seat	3.0	3.0	3.0	3.0	9.0	9.0
TOTAL WEIGHT	30.6	55.1	34.0	62.7	102.0	188.1
	Volume (cubic feet)					
Penalty Vol. above Vol. Req'd for Solid Packed Foods -Cans and Racks	0.33	0.70	0.39	0.82	1.15	2.50
Bags and Wipes	0.15	0.32	0.17	0.37	0.52	1.11
Sterilant	0.06	0.12	0.07	0.14	0.21	0.42
Volume of Seat	0.50	0.50	0.50	0.50	1.50	1.50
TOTAL VOLUME	1.04	1.64	1.13	1.83	3.38	5.50

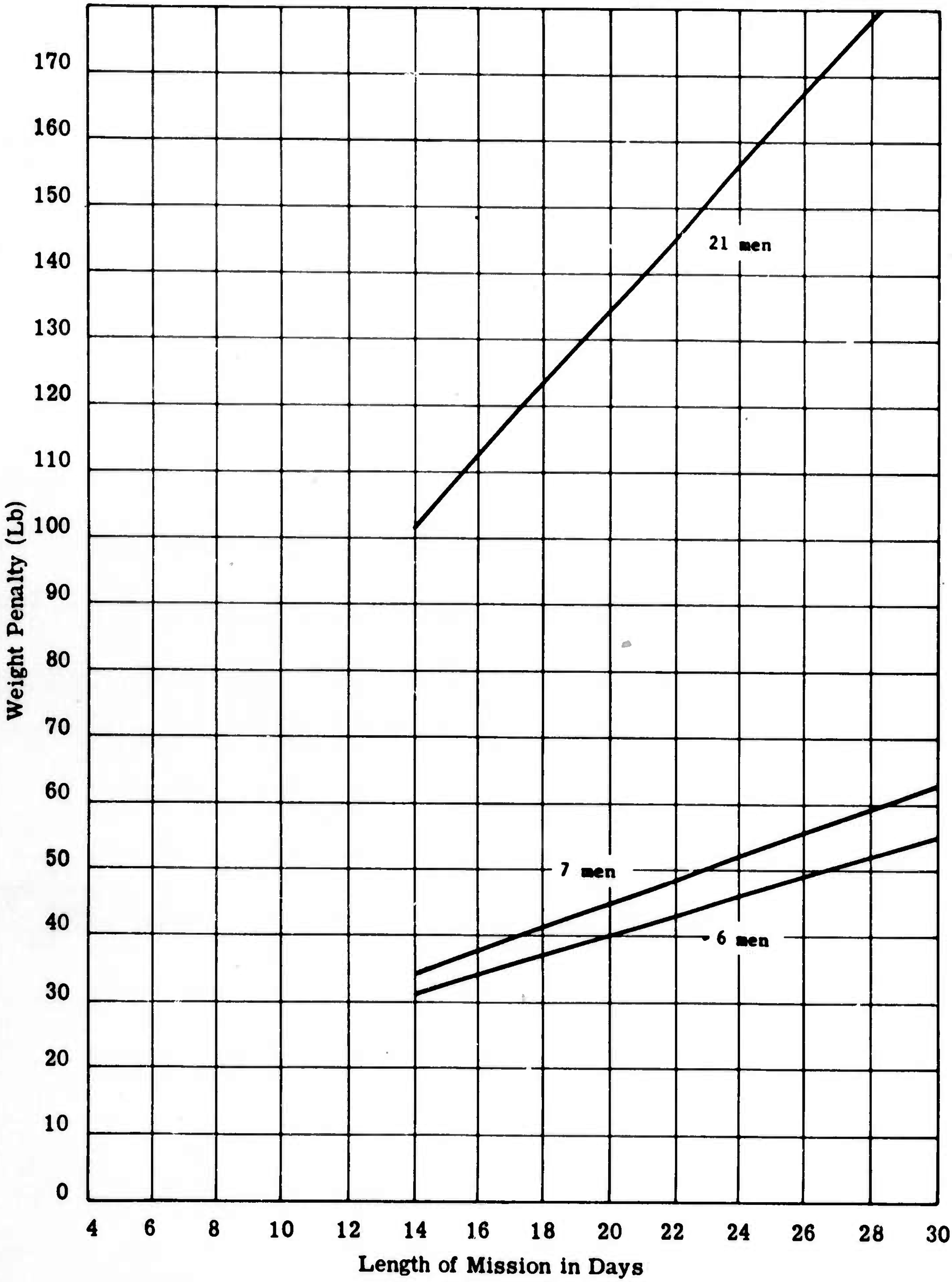


FIGURE 3. WEIGHT PENALTY - STORAGE OF FECES IN CANS

The volume penalty for storage in cans was derived by subtracting the volume of solid-packed, square cross-section food packages from the volume of an equivalent number of cans packed with food in tracked racks. The interstitial voids of tangent cylinders on equal centers (not staggered) make up for most of the additional volume. When the food in the cans is consumed, the feces is placed in these empty cans, sealed, suitably marked, and put in an empty space in the canned food rack.

Combined Collection and Storage of Feces

This system concept was developed at General Dynamics/Electric Boat and is novel in that it integrates fecal collection and storage. This eliminates any transport of fecal collection bags or other devices by the crew member, reduces the amount of necessary hardware, and utilizes a very simple operating procedure. From a psychological standpoint, the appearance and use aspects are similar to those of a conventional toilet.

A complete description of the proposed system is given in Section 8.

Briefly, the fecal storage unit comprises a built-up fiberglass sphere, with a perforated, fiberglass-plastic, inner liner, and a felt impingement liner to act as a filter. There is a 4-inch opening in the top, with a removable pressure-seal cover. There is a bottom outlet which is piped to a 3-port, 2-position valve. This valve allows air to flow from the collection tank, and be pulled by a small blower through a charcoal and bacterial filter, and back to the cabin atmosphere. During defecation, air flow enters through anterior and posterior openings made by the body at such a velocity as to accelerate the fecal stool to the impingement barrier. After defecation and disposal of wipes, the lid is replaced and some of the air pumped by the blower to the cabin through the deodorizing and bacterial filters. The valve is then turned to the overboard position and full vacuum applied for a short period.

A set of calculations was made for weight and volume penalties for this system and the results tabulated in Table V and shown graphically in Figure 4. Sample calculations appear in Appendix I, pp. 65-68.

A breadboard mockup of this system was built and the results of tests conducted are reported in Section 7 of this report.

TABLE V

WEIGHT AND VOLUME PENALTIES
COMBINED COLLECTION AND STORAGE OF FECES

Penalty Item	6 men 14 days	6 men 30 days	7 men 14 days	7 men 30 days	21 men 14 days	21 men 30 days
	Weight (lb)					
Tissue and Wipes	0.32	0.68	0.38	0.80	1.14	2.40
Equipment	6.03	7.53	6.47	8.80	19.41	26.29
Blower	3.50	3.50	3.50	3.50	10.50	10.50
Power Penalty	4.90	4.90	4.90	4.90	14.70	14.70
Cabin Air Loss	1.00	3.50	1.20	4.00	3.60	12.00
TOTAL WEIGHT	15.75	20.11	16.45	22.00	49.35	65.89
	Volume (cubic feet)					
Storage Vol. Wipes	0.01	0.02	0.01	0.02	0.03	0.08
Volume of Sphere	0.67	1.24	0.75	1.45	2.25	4.40
Volume of Access.	0.50	0.50	0.50	0.50	1.50	1.50
TOTAL VOLUME	1.18	1.76	1.26	1.97	3.78	5.98

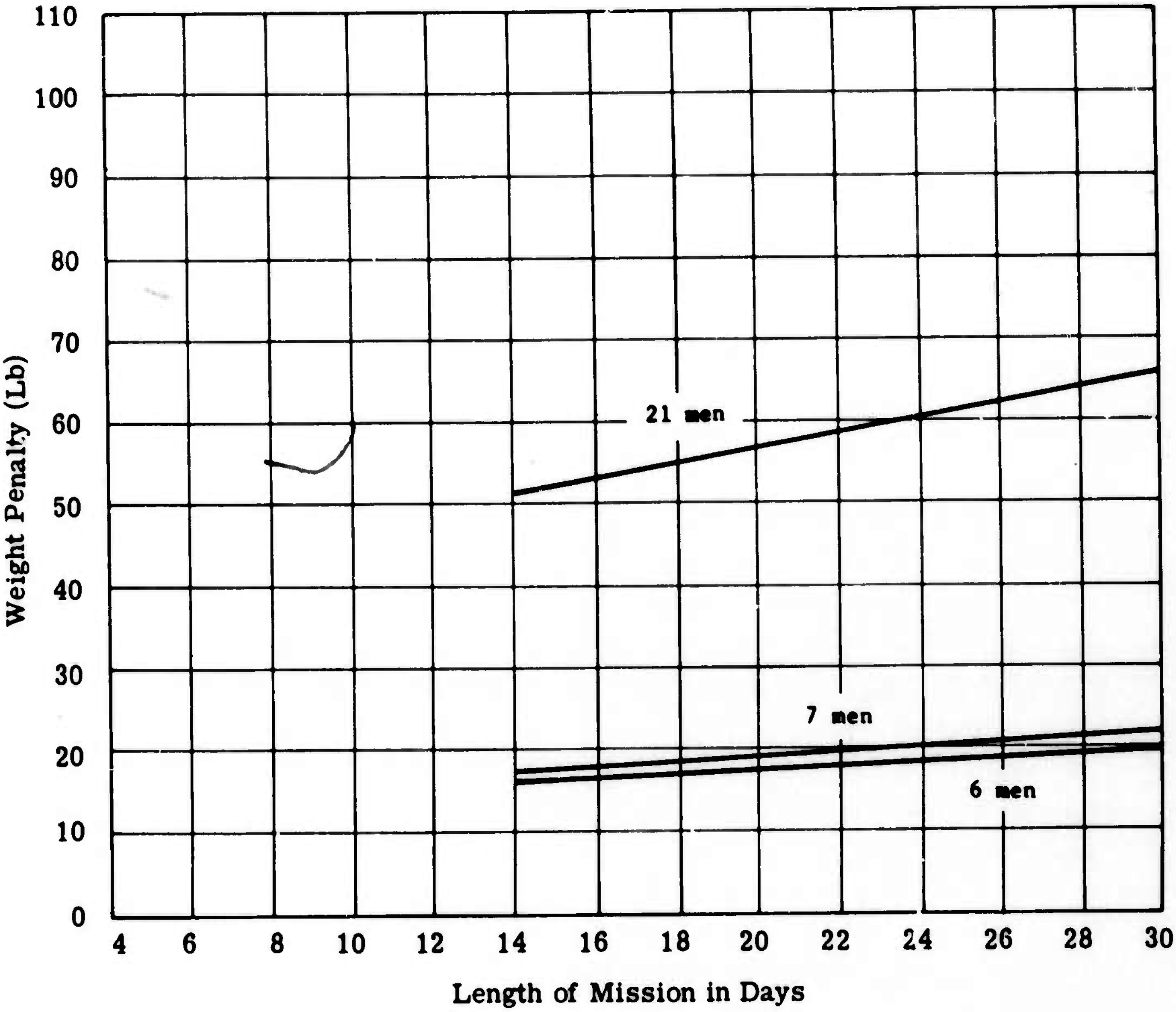


FIGURE 4. COMBINED COLLECTION AND STORAGE OF FECES IN SPHERICAL CONTAINER

SECTION 5

URINE HANDLING

URINE COLLECTION

Most investigators in this field have specified the use of plastic urinals for collection of urine and transfer of the contents to an intermediate storage tank, or, venting to space. Miner et al. (Ref. 14) developed a thin-walled, anti-static latex bag urinal, molded flat and tapered at the closed end. The urinal has a conical section at its open end. The design of the urinal excludes entrapped air and consequent back pressure during urination. The original design has been improved in that the penile adapter is provided with a disposable paper liner treated with a sterilizing agent for prophylaxis. The conical section of the open end of the urinal is designed to fit over an adapter attached to a urine storage tank. Disinfectant tablets are provided to stabilize and sterilize urine; one tablet is placed in the urinal before each urination.

Zeff (Ref. 31) used a semirigid plastic, bellows-type collector, and the Whirlpool Corporation of St. Joseph, Michigan* used a spring-wound, centrifugal collector.

Weight trade-off studies between these three collecting devices are not warranted since their weights are roughly the same and they weigh only a small fraction of the complete waste system.

STERILIZATION AND VENTING OF URINE

General

Urine from normal subjects is sterile when voided. No difficulty is foreseen in the treatment of urine with chemical agents to ensure sterility before venting to space. On the other hand, sediments and precipitates form in urine on standing, and these must be considered in the design of tubing and storage tanks.

Sterilizing agents should be placed in the urinal prior to each use. These serve the dual purpose of (a) preventing odor and bacteria buildup within the urinal, and b) sterilizing its contents prior to disposal overboard. Although normal urine is considered to be bacteria free, it can be readily contaminated by contact with nonsterile surfaces. Therefore, this pretreatment is essential to ensure a sterile condition of the urine prior to venting overboard.

Urine has customarily been preserved for clinical examination by treatment with chemical preservatives when refrigeration was inconvenient. The preservative of choice has been toluene, but camphor, thymol, formaldehyde, and methenamine with salicylic

---

*Verbal communication, May 1963.

acid have also been used. (See Hawk et al., Ref. 6.) Toluene is used by simply overlaying the urine with a thin film of it. Formaldehyde is used in the proportion of 2 drops per 50 ml of urine. This would be a concentration 0.2% of a 37% formaldehyde solution. A bit of camphor or thymol (about 0.1%) sufficient to give a saturated solution is also a satisfactory urine preservative. Methenamine (0.3%) with salicylic acid (0.2%) is used. These substances produce formaldehyde in solution.

Sandage (Ref. 22) believes that all physical methods of waste sterilization except filtration have weight, space, or power requirements that eliminate them from consideration or study for purposes of application in a space vehicle; however, calculations are not given. Passing urine through a bacteriological filter as it is vented into space may be suitable for backup use.

During preliminary work at General Dynamics/Electric Boat, the addition of boric acid (1 gm) to urine (100 ml) kept it clear and inhibited odor changes for three days. After this period, slight clouding occurred. At the end of two weeks, there was no change in urine odor (no ammonia odor).

In other experiments to check on urine preservation odor change, production of ammonia was used as a criterion of preservation. Fresh urine samples 125, 200, and 300 ml were each treated with one precrushed tablet of a proprietary quarternary antiseptic (Diaparene) containing 0.1 gm active ingredient. There was no change in odor after two weeks storage in unsealed plastic bottles.

Four urine samples from different subjects were treated with a solution of 1% benzalkonium chloride (BAC) and 1% sodium nitrite. The concentrations used were 1.5, 1.0, 0.35, and 0.15% of the preservative solution. Odor change was used as an index of decomposition. The samples were stored in plastic bottles at room temperature open to air. There was no observable change in odor in any sample after two weeks of storage.

The untreated controls used in the above studies all developed the characteristic ammoniacal urine odor on standing.

Sterilization of Urine

Any number of chemical agents are satisfactory for the sterilization of urine. Benzalkonium chloride (BAC) could be chosen because of its effectiveness in preliminary tests and to avoid duplication since it has been suggested for inhibition of gas production in feces. However, it is felt that since the urine is to be collected and stored separately, an uncrushed Diaparene tablet, or its equivalent, can be added to the plastic urinal just prior to each use. This will ensure sterility and stability for a 24-hour period, and will be satisfactory for short-term storage or venting to space.

Venting

The venting of sterile urine to space has some of the same disadvantages as the venting of mixed wastes; namely, possible effect on vehicle speed and guidance, possible interference with communications, and no possibility of water recovery.

STORAGE AND DISPOSAL OF URINE

Storage

Urine collected in the plastic urinal is discharged to a spherical tank with an internal bladder. The shell side of the bladder has a vacuum and pressure connection. In the transfer cycle from urinal to tank, negative pressure is applied to the shell allowing the bladder to expand and accept the charge from the urinal. After one day's urine waste is collected, an outlet from the bladder is opened and, by applying pressure, the urine is forced out either to an overboard vent or to a water-recovery process.

Disposal

Systems for the recovery of usable products from urine and feces are not included in the scope of this analysis. However, intermediate storage of urine is desirable to allow water recovery.

Most investigators have determined that man will require roughly 5 lb/day of potable water. Of this amount, about 2 lb can be recovered as potable water from the cabin air conditioning system leaving a remainder of 3 lb to be supplied as stored supplies, recovered from urine, or recovered from fuel cells. Since one of the premises upon which this study is based is a solar panel-battery power source, recovery of water from a fuel cell cannot be considered. The amount of urine/man/day has been stated as 1500 cc or 3.3 lb. Of this weight, 5% constitutes solids. Assuming that 95% of the water that could be recovered would be potable, 3 lb of potable water would be provided, eliminating water storage bulk and weight at take off. Thus, a 6-man, 14-day mission would require 252 lb of water, and a 6-man, 30-day mission would require 540 lb of water.

Using power to drive a vapor-compression (VC) water-recovery still, an approximate estimate for 6 men would be an equipment weight of 50 lb and a power requirement of 300 watts or an additional 90 lb.

For this size crew, the equation of Wallman and Barnett (Ref. 28) can be modified to the form:

$$W = 140 + M(6 + 0.2D)$$

Where:

W = total weight penalty
M = crew size
6 lb = two days stored water per man
D = length of mission in days
0.2 = weight of expendables per day

Thus, for a 6-man mission the weight penalties for 14 and 30 days are 193 and 212 lb respectively.

Calculations were also made for a 7-man crew. These weights are compared graphically in Figure 5. The indications are that water recovery from urine with the present stated source of power would be necessary after eight days for a 7-man crew and ten days for a 6-man crew.

The choice of whether to vent urine or to recover water from urine will depend on the development of a fuel cell that will have a low weight penalty per unit of power and that can supply the water lost by overboard venting. Under the present design basis, water recovery from urine is indicated for all missions considered herein.

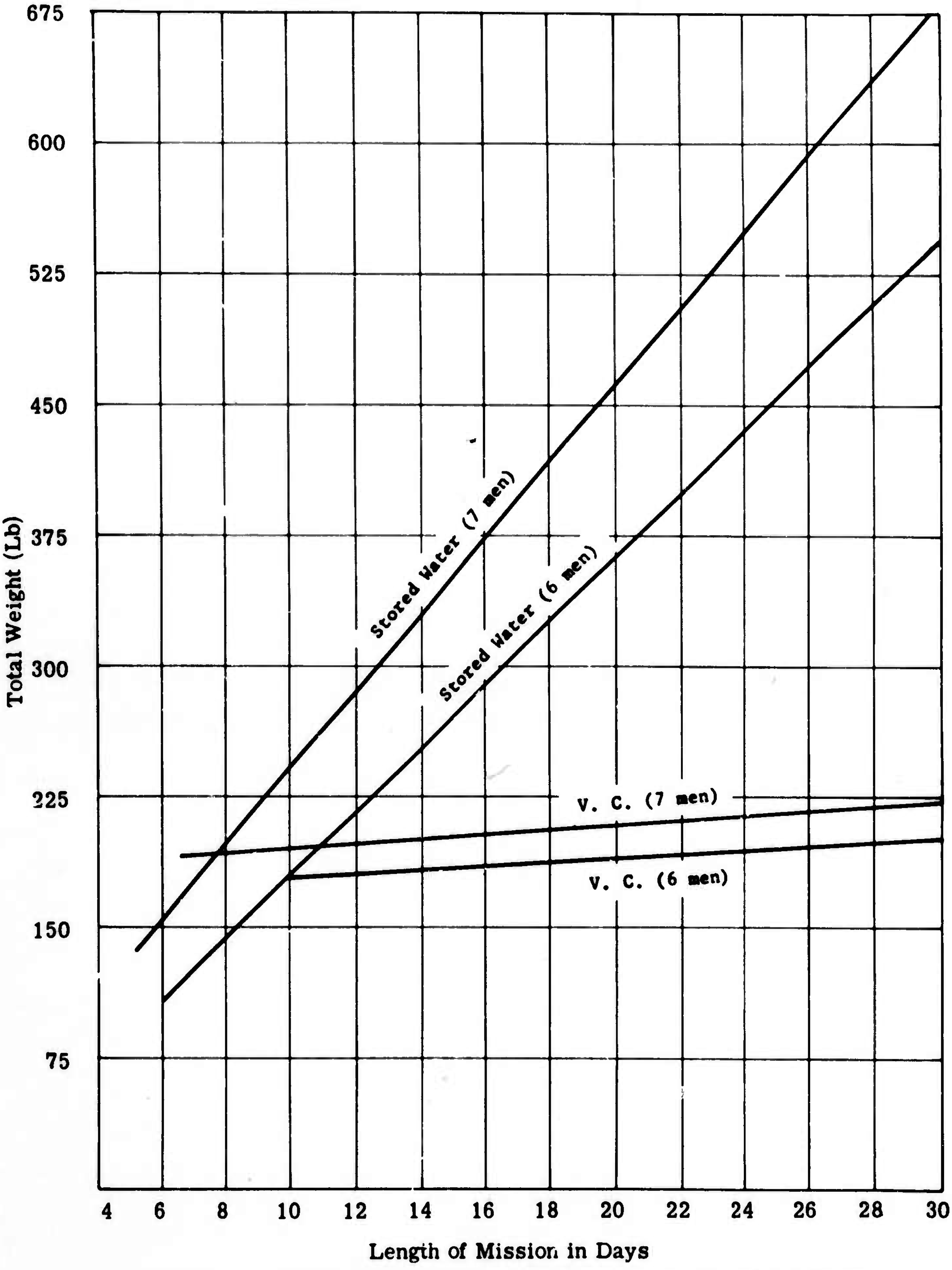


FIGURE 5. STORED WATER VS WATER RECOVERY FROM URINE BY VAPOR COMPRESSION (VC) DISTILLATION

SECTION 6

PROCESS EVALUATION SUMMARY

QUALITATIVE STUDIES

Of the five processes studied qualitatively, all can be disqualified on a weight-volume penalty basis except the sterilization of mixed wastes and jettisoning to space. This process is minimal in weight and volume; however, the problems of space contamination which include indeterminate effects on vehicle speed, guidance and attitude, possibility of communications interruption, and formation of clouds of particulate matter that the vehicle might have to pass through in successive orbits, make this method undesirable. This process also precludes the possibility of any water recovery.

QUANTITATIVE STUDIES

The four processes studied quantitatively were chosen because they appeared to have low weight and volume characteristics, and because they are developed to the point that allows reasonable engineering estimates to be made.

Graphs have been prepared to show weight penalties vs mission time for these four processes for crew sizes of 6, 7, and 21 men. The comparisons are shown in Figures 6, 7, and 8, respectively.

These graphs indicate that the combined collection, storage, and partial drying by space vacuum is the lowest in weight, incineration is the highest in weight, and canned storage and freeze drying of combined wastes are about equal.

The volume relationships are shown in Figures 9, 10, and 11. The canned storage process requires minimum volume for all crew sizes and missions. However, the combined collection and storage system requires next to minimum. Both systems are very low in volume required, and with reference to the module concept, which takes 7 men as a unit basis, the volume for the combined storage concept is about 1.25 cubic feet as compared to 1.13 cubic feet for the canned storage system. Since both remaining systems, incineration and freeze drying, are high in weight as well as volume, the final selection of the optimum process will be made between the storage of canned feces and the combined collection, storage, and partial drying of feces.

Table VI has been prepared rating the two systems. The system having better performance for each heading considered is given a value of 1 and the other a value of 2. The lowest cumulative total denotes the optimum process.

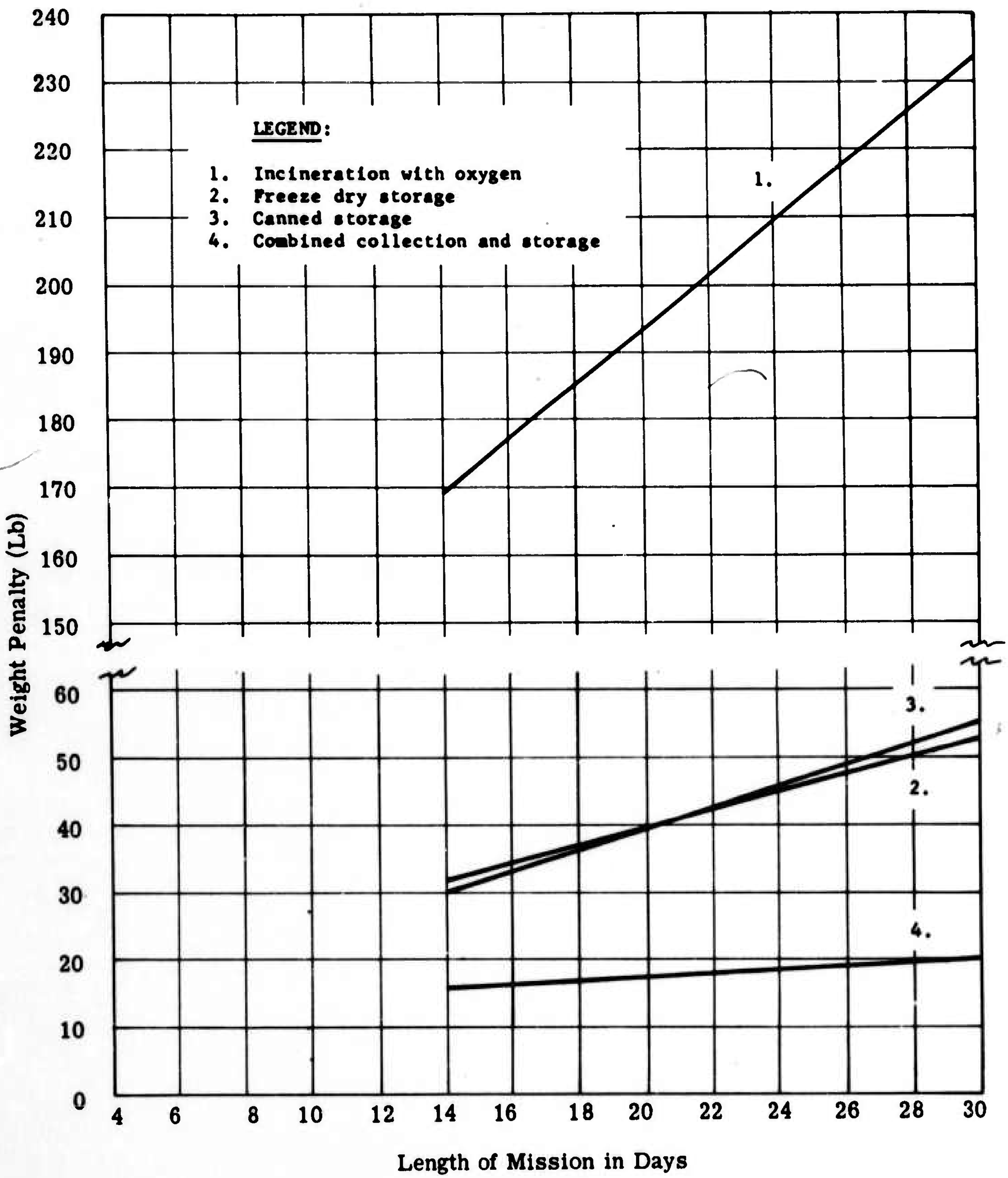


FIGURE 6. WEIGHT COMPARISON OF SYSTEMS (6-MAN CREW)

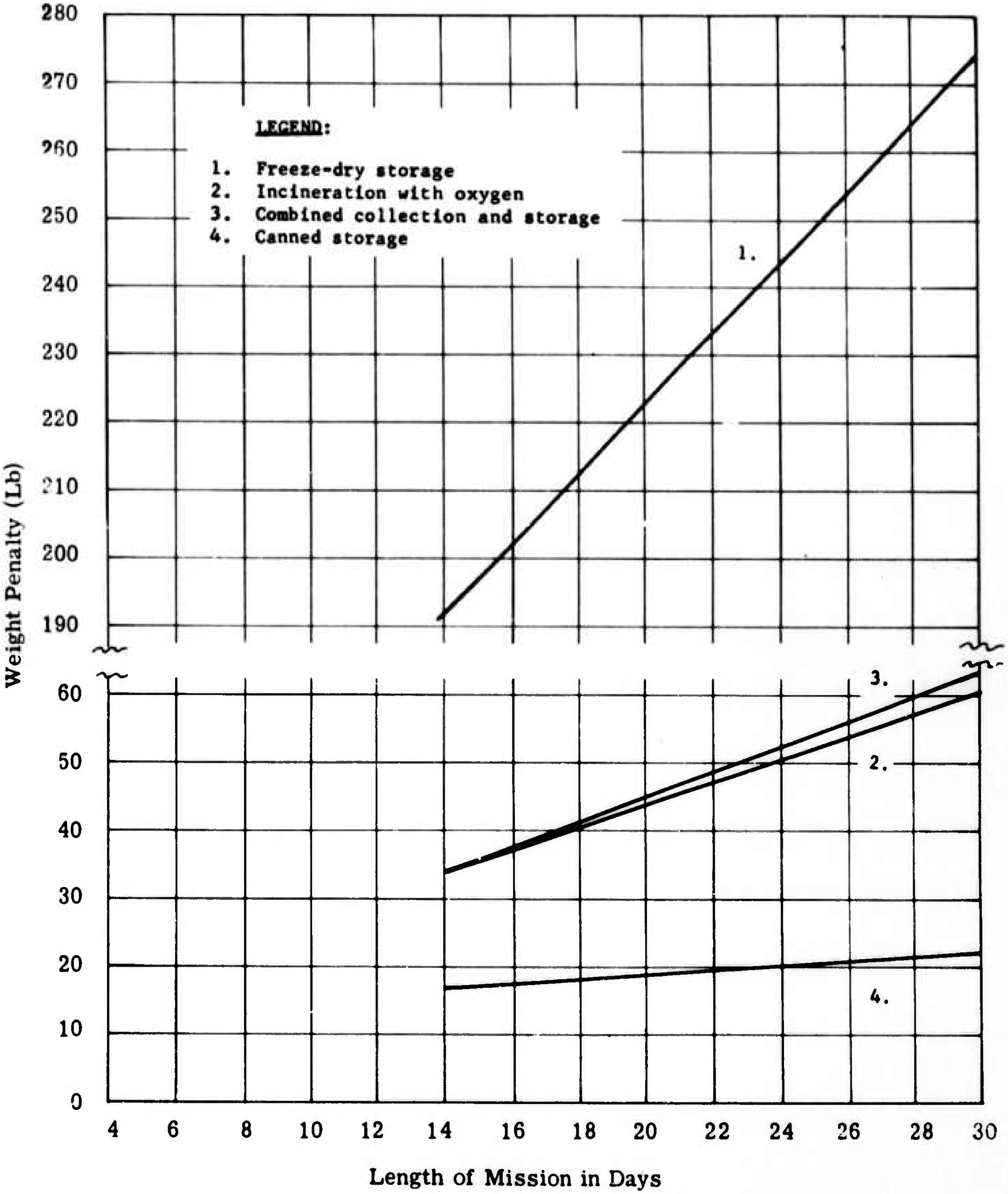


FIGURE 7. WEIGHT COMPARISON OF SYSTEMS (7-MAN CREW)

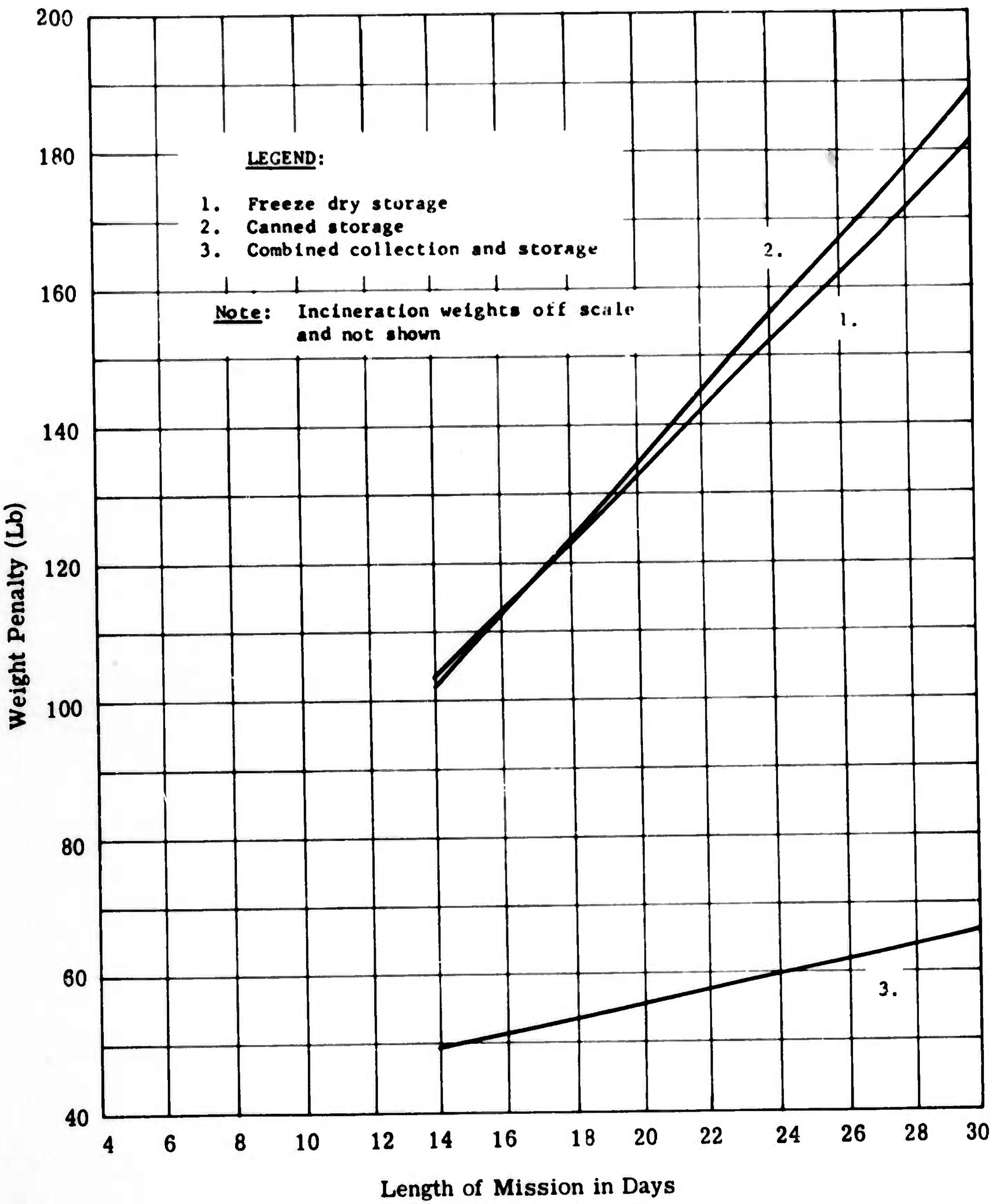


FIGURE 8. WEIGHT COMPARISON OF SYSTEMS (21-MAN CREW)

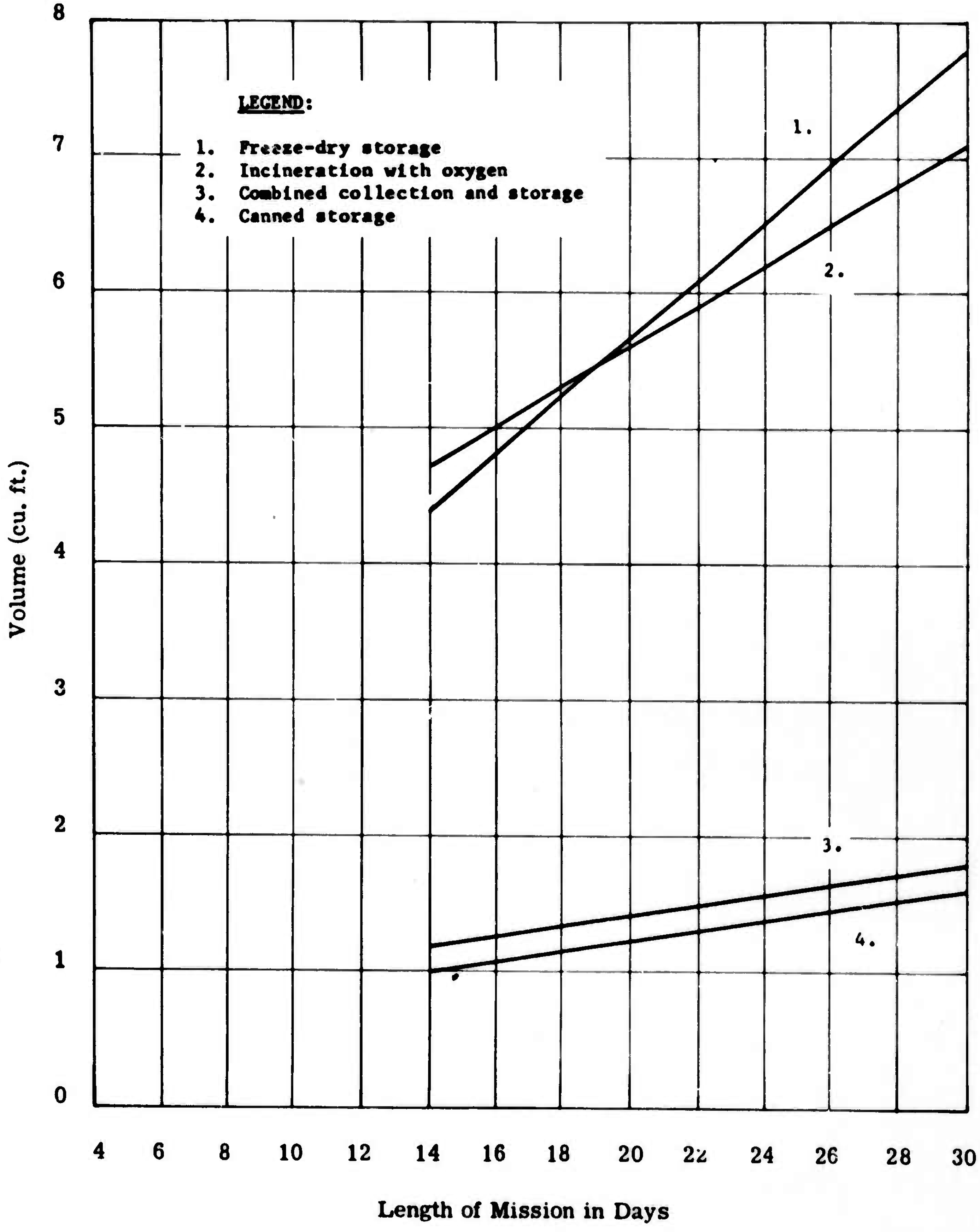


FIGURE 9. VOLUME COMPARISON OF SYSTEMS (6-MAN CREW)

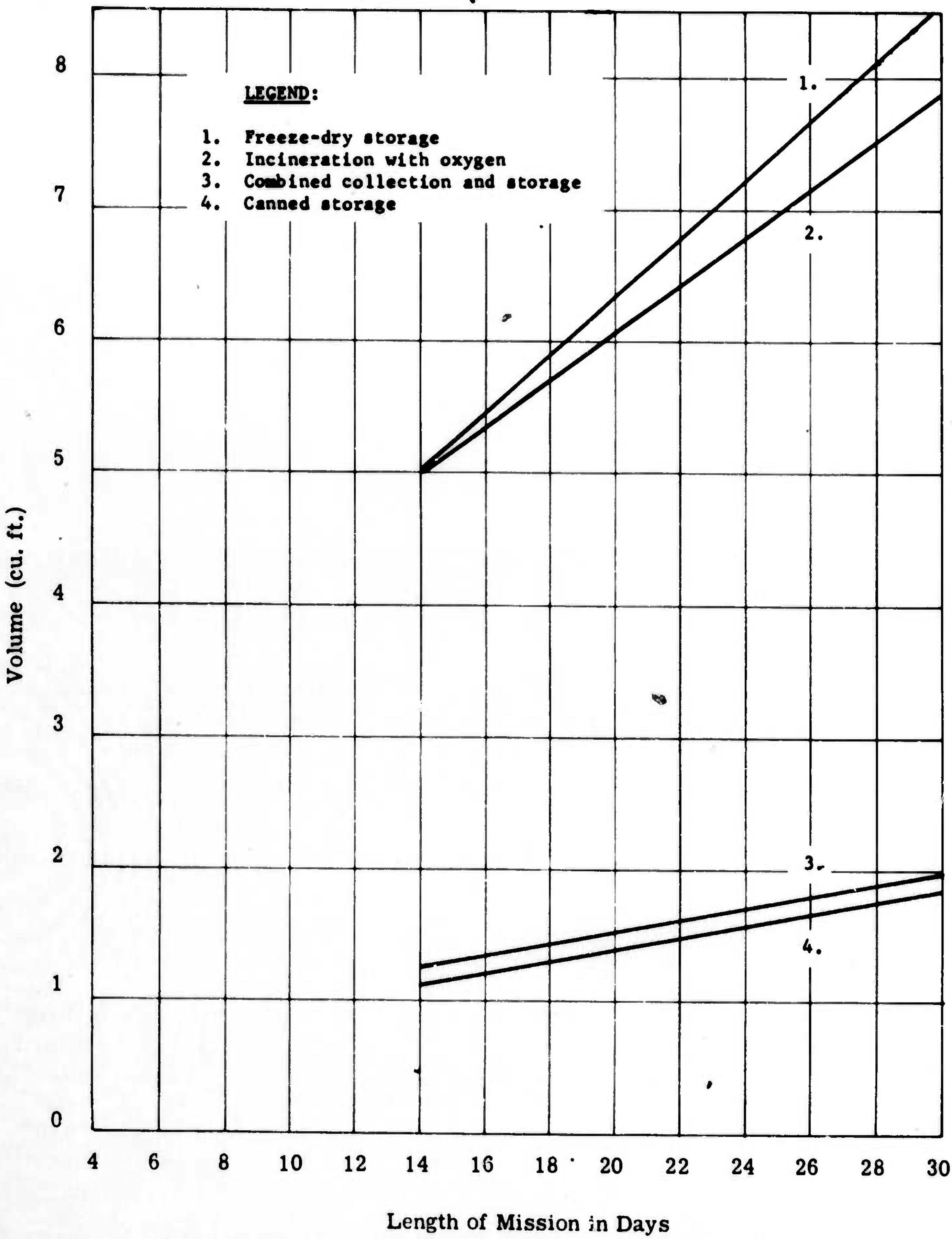


FIGURE 10. VOLUME COMPARISON OF SYSTEMS (7-MAN CREW)

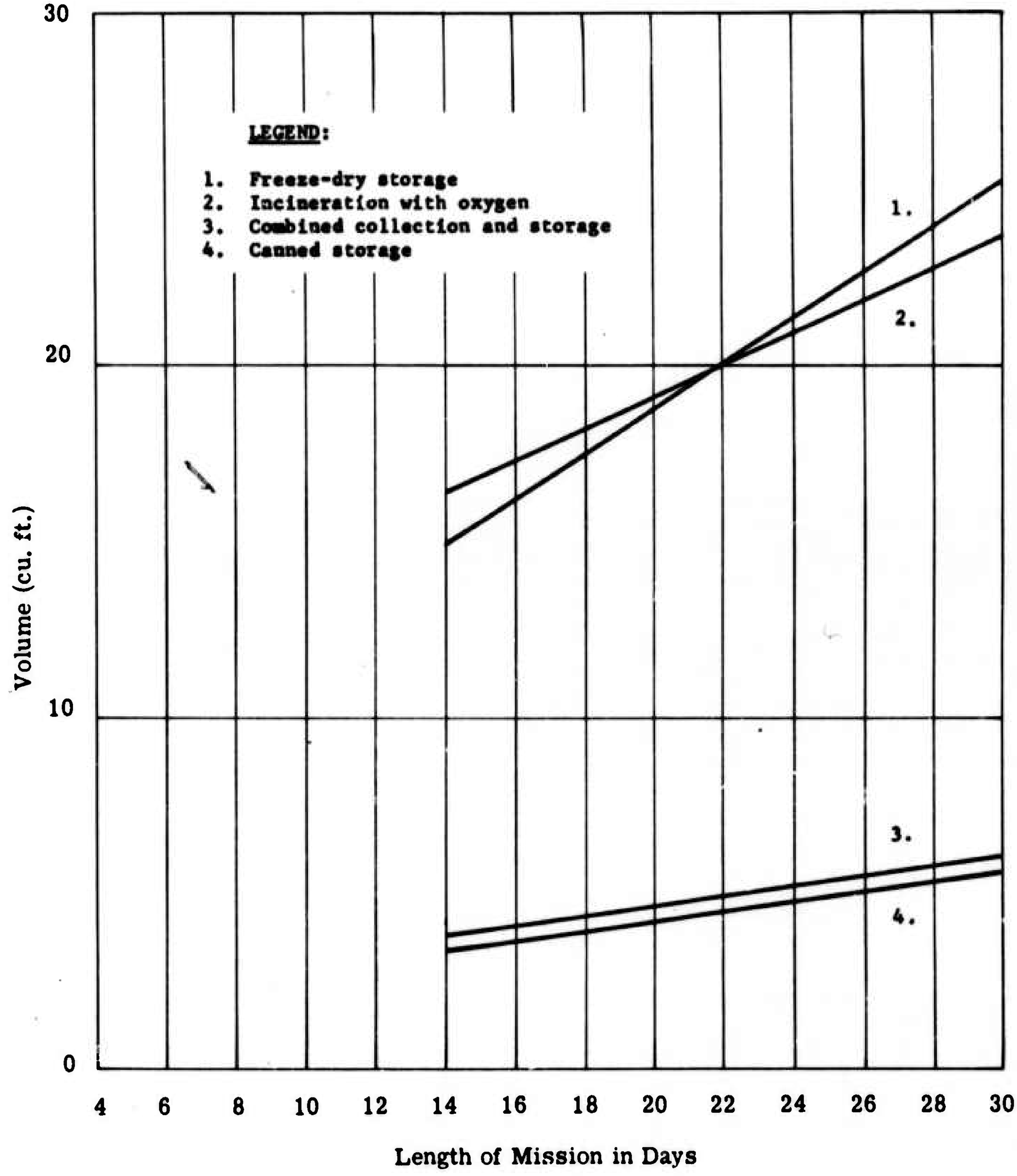


FIGURE 11. VOLUME COMPARISON OF SYSTEMS (21-MAN CREW)

TABLE VI

COMBINED COLLECTION AND STORAGE VS CANNED STORAGE
(Feces)

ITEM	COMBINED COLLECTION AND STORAGE	STORAGE IN CANS
Total Weight (including power penalty)	1	2
Volume	2	1
Reliability, Safety, and Simplicity	1-1/2	1-1/2
Degree of Cabin Air Contamination	1	2
Operating, Transfer, and Maintenance Requirements	1	2
Operability in 0 g field	1-1/2	1-1/2
	8	10

The approach having the optimum potential for use in a space station waste management system is obviously one based on combined collection, storage, and partial drying of feces. This system has a real advantage in that once defecation is accomplished, the feces arenot handled in any manner. During defecation and in initial draw-down of vessel pressure, odor control is readily accomplished by the activated carbon filter. Evacuation of some of the cabin air in the collector back to the cabin reduces cabin air loss to a minimum. The collection unit assembly is light and small and, if missions longer than 30 days are necessary, spare units can be furnished along with food on resupply trips; and the filled containers can be ferried back to earth. Another advantage of the collection sphere is that the decomposition rate would be lowered because of partial drying, and maximum pressure buildup in the sealed sphere would be reduced.

The power required to operate the blower would be less than 0.05 hp and would be required only during and immediately after defecation. For a 7-man crew, this would average about 1 hour per day or less.

SECTION 7

EXPERIMENTAL WORK - BREADBOARD MOCKUP STUDIES

OBJECTIVE

The objective of the breadboard study was to demonstrate the feasibility of the selected approach by testing: (a) pressure buildup in partially dried feces over a 30-day period, (b) the ability of activated charcoal to remove odors, and (c) the removal of bacteria from the air stream by a Millipore filter.

DESCRIPTION OF EQUIPMENT

A 2-gallon pressure tank was modified by inserting an inner cylindrical liner of 16-mesh, aluminum wire screen covered with 4 oz. nylon felt on sides and bottom. The cylinder was sized to allow a 1/2-inch annular space between the screen and the pressure vessel wall. One connection in the lid was connected to an internal 1/4-inch OD copper tube leading to the bottom of the inter-cylinder space. This line was valved to isolate the collection device after evacuation. Another connection, with two external needle valves, led to the feces side of the collecting cylinder. One valve controlled a line to a 40-inch mercury manometer, the other controlled an air bleed line from the ambient air. This air passed through a bacterial filter and rotometer. The top annular space was sealed with a sponge rubber gasket. The removable cover was held in place by six swivel bolts and wing nuts locking to cast-notched lugs in the cover.

Two test setups were used as shown in Figures 12 and 13. Figure 12 shows two (0.5μ) Millipore filter elements in series in the vacuum line followed by an activated carbon column, a cold-trap (vacuum filter flask immersed in dry ice and acetone) and a Gelman high-volume,low head, oil-free compressor, modified to serve as an exhauster.

Figure 13 shows the two Millipore filters removed and the Gelman pump replaced with a Welsh Duoseal laboratory vacuum pump for maintaining 5 mm Hg absolute.

METHOD OF TESTING

The collection vessel with valves open and cover in place was weighed. The cover was removed and the vessel placed under a space toilet seat arrangement. After defecation and deposition of soiled toilet tissue, the cover was replaced and the vessel reweighed.

The collection vessel was then connected into the laboratory set-up as shown in Figure 12. Air was pulled through the collector for 10 minutes with the Gelman pump. The outlet of the pump was sniffed to detect odor and results recorded. The coldtrap condensate was also checked for odor. The pump was shut off and

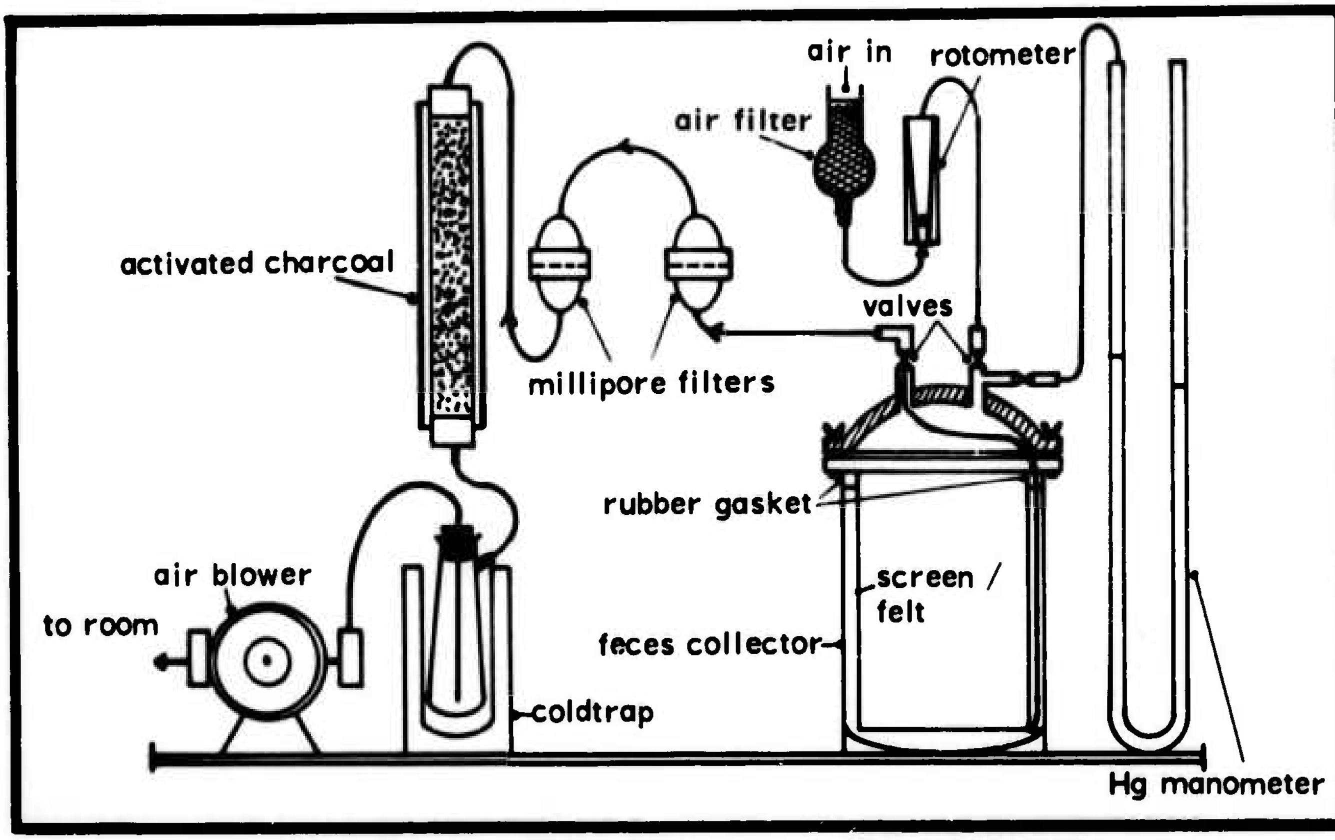


FIGURE 12. TEST EQUIPMENT ARRANGEMENT
ODOR AND BACTERIAL REMOVAL

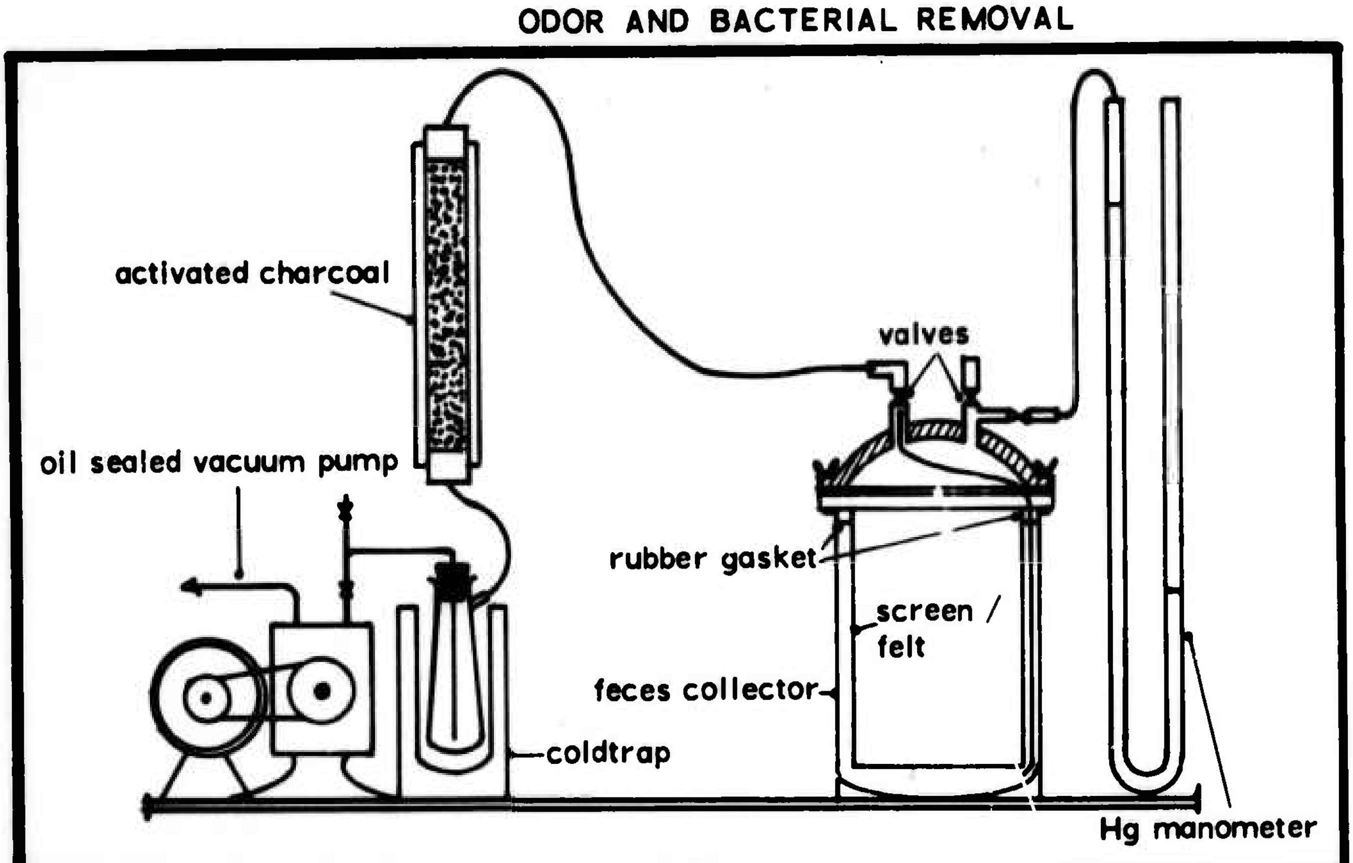


FIGURE 13. TEST EQUIPMENT ARRANGEMENT
PARTIAL DEHYDRATION AND PRESSURE BUILDUP

the Millipore filters removed. The filter discs were cultured in petri dishes for 18 hours and examined for coliforms, using the standard Millipore filter technique.

The equipment setup was then rearranged as shown in Figure 13, the air bleed valve was closed, and the vessel evacuated for 3 hours. Manometer pressure, barometer readings and temperature were recorded. The vessel was sealed and left overnight. Prior to use the next morning, temperature, manometer, and barometer were read. The vacuum was then broken by opening the air bleed line, and the vessel was weighed. The bacteria tests were continued for 15 days and the odor tests for 30 days. At the end of the 30-day period, the vessel, then half full, was filled to 80% by addition of inert plastic chips. The vessel was evacuated and absolute pressures recorded every 24 hours for another 30-day period.

TEST RESULTS

The results of the bacteria, odor, and weight loss tests during the collection period are listed in Table VII. The pressure buildup over the subsequent 30-day storage period is shown graphically in Figure 14.

In considering the removal of bacteria results, only once were colonies of E. coli detected on the first filter and never on the second filter. This would indicate that the nylon felt liner is a good bacterial filter.

A total weight loss of 889 grams from a total waste weight of 2270 grams indicated considerable drying of the feces.

Pressure buildup in the device after use and evacuation are just slightly more than the loss in vacuum from in-leakage into the empty system.

CONCLUSIONS

From the indicated weight loss, it is apparent that partial dehydration of the fecal matter occurs. This is sufficient to inhibit decomposition and pressure buildup between uses. The increase in pressure in 24 hours was negligible; vessel pressure was less than cabin pressure even after 30 days of storage.

Test results show that bacteria present in the circulating air over stored feces can be effectively removed by a properly designed filter cartridge.

The absence of odor either in the cold-trap condensate or at the pump discharge indicates the capability of a properly designed activated carbon filter to remove objectionable odors from the recirculated cabin air.

TABLE VII
FECES COLLECTION AND STORAGE-PRESSURE TEST AND WEIGHT LOSS
(Ten Minute Air Circulation)

Usage	Wt. Feces & Tissue (gm)	Loss in Wt. (gm)	Press. Start (in. HgAbs)	Press. End (in. HgAbs)	ΔP (in. Hg)	Time (Hr.)	Rate** of leak (in. Hg/hr)	Coliforms		
								No. 1 Filter	No. 2 Filter	Odor
1	81	4	0.31	3.54	3.23	20.5	0.157	Neg.	Neg.	None
2	92	13	0.23	3.67	3.44	19.0	0.182	Neg.	Neg.	None
3	120	24	0.30	3.92	3.62	19.0	0.190	Neg.	Neg.	None
4	126	20	0.28	3.70	3.42	19.5	0.176	Neg.	Neg.	None
5	37	25	0.32	3.33	3.01	17.5	0.173	Neg.	Neg.	None
6	40	26	0.26	9.36	9.10	67.0*	0.136	Neg.	Neg.	None
7	25	31	0.34	3.53	3.19	21.0	0.152	Neg.	Neg.	None
8	70	36	0.33	3.44	3.11	18.0	0.174	Neg.	Neg.	None
9	156	35	0.32	4.16	3.84	21.0	0.183	Neg.	Neg.	None
10	21	21	0.54	12.89	12.35	68.0*	0.181	Neg.	Neg.	None
11	60	35	0.33	3.57	3.24	19.0	0.170	Neg.	Neg.	None
12	25	32	0.48	3.60	3.12	19.0	0.164	3 cols.	Neg.	None
13	207	46	0.30	4.60	4.30	17.0	0.250	Neg.	Neg.	None
14	29	28	0.48	3.39	2.91	17.0	0.171	Neg.	Neg.	None
15	20	24	0.47	12.85	12.38	90.5*	0.137	END OF TEST		
16	45	30	0.49	3.85	3.36	18.0	0.208			
17	73	31	0.49	3.83	3.34	19.0	0.175			
18	38	24	0.52	3.74	3.22	20.5	0.157			
19	60	33	0.38	11.16	10.78	67.0*	0.161			
20	217	33	0.50	5.22	4.72	21.0	0.225			
21	61	32	0.43	4.02	3.59	17.0	0.210			
22	44	26	0.12	4.37	4.25	19.5	0.217			
23	35	34	0.45	4.57	4.12	20.5	0.200			
24	71	36	0.46	13.50	13.04	92.5*	0.158			
25	---	31	0.40	4.70	4.30	20.0	0.218			
26	116	34	0.50	8.29	7.79	44.5	0.175			
27	11	34	0.51	11.38	10.87	65.5*	0.169			
28	110	37	0.47	4.75	4.38	20.0	0.219			
29	270	40	0.43	6.13	5.70	19.5	0.292			
30	---	44	0.49	1.47	0.98	19.5	0.05			
TOTAL	2270	889								

*Test continued over weekend.
**10 days tests on empty collector varying from 24 to 120 hours gave an average in-leak rate of 0.130 inches of Hg per hour.

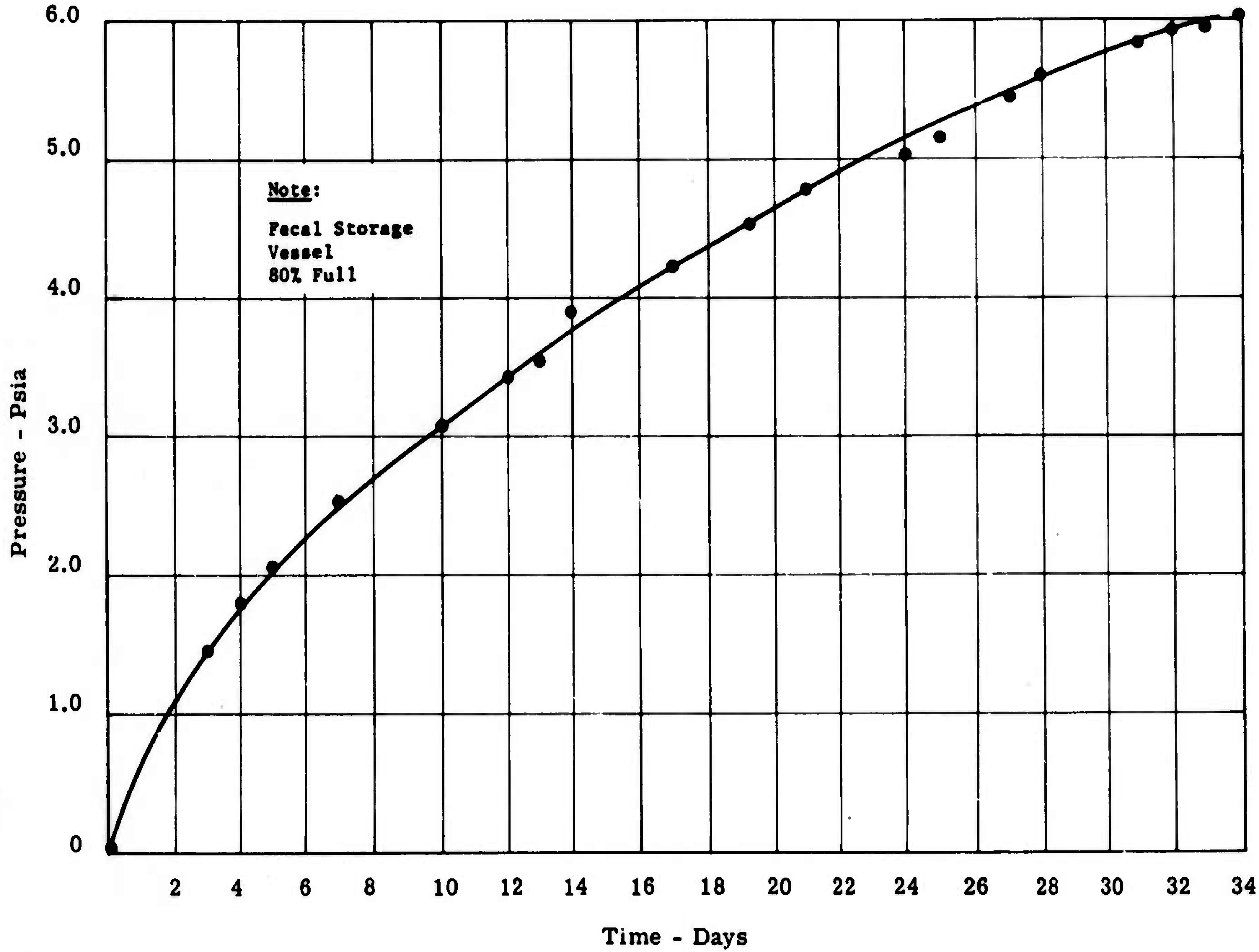


FIGURE 14. PRESSURE TEST RESULTS - ABSOLUTE PRESSURE VS TIME

SECTION 8

SYSTEM DESCRIPTION - FINAL DESIGN

GENERAL

The final design is based on separate collection of urine and feces. Urine is collected in a latex urinal and transferred immediately by the individual to an intermediate urine storage tank, consisting of a sphere with rubber, inner bladder. Feces are collected in a spherical collection tank with foam cushions around the top opening to allow the astronaut to take the normal sitting position during defecation. Feces and wipes are directed against the false inner sphere by airflow and, after the sealing lid has been replaced, the collection vessel is evacuated to space. A cutaway drawing of the assembled unit with major components is shown in Figure 15.

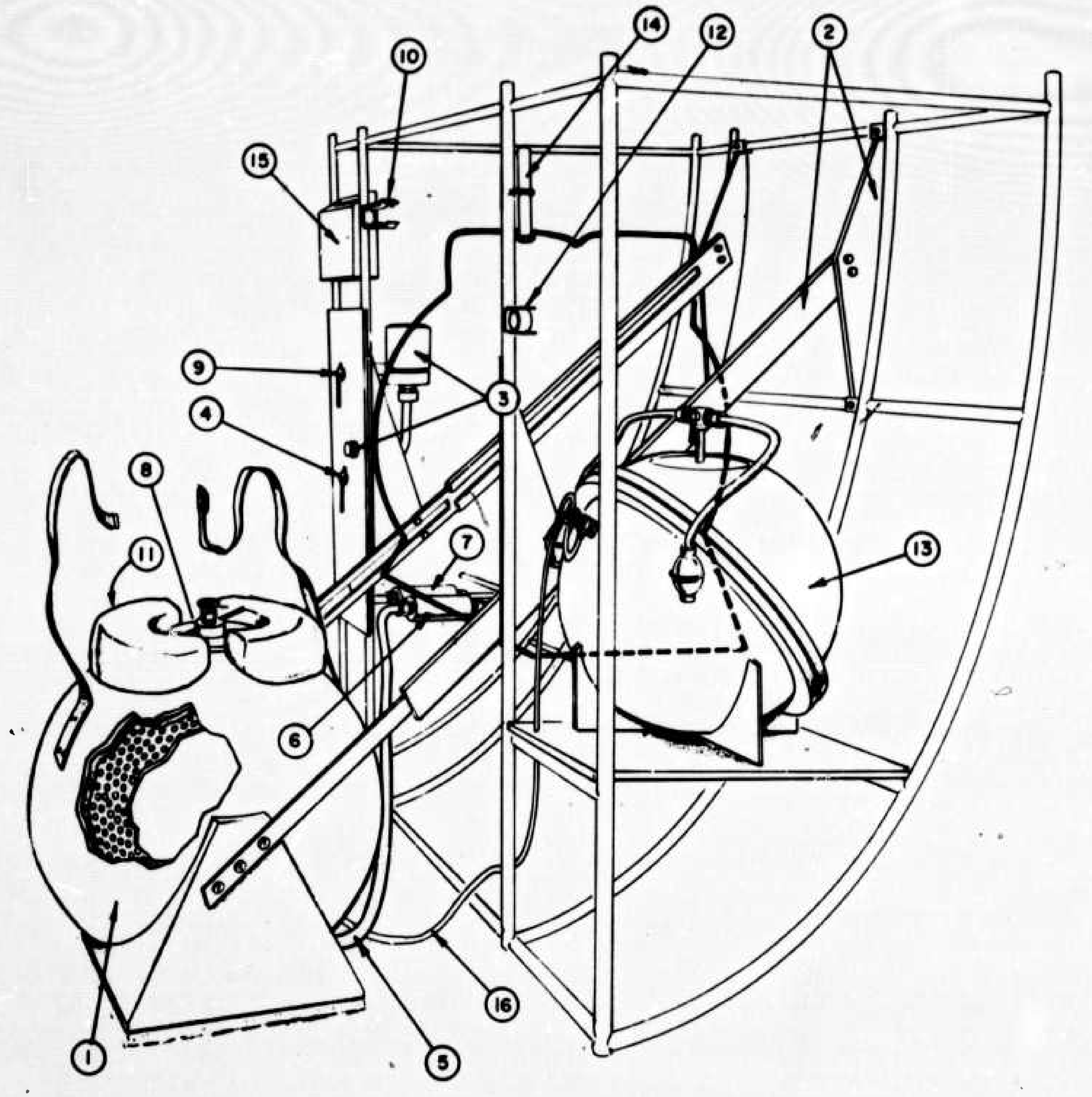
The prototype unit described herein is designed for minimum weight but is not weight optimized. In the selection of certain components, e.g., the fiberglass spheres, off-the-shelf availability and cost were considered. This results in small compromises with regard to minimum weight but allows fabrication of an operating prototype at minimum cost.

FECES-HANDLING EQUIPMENT

The fecal waste collection and storage unit consists of the following components based on a 7-man, 15-day mission.

Feces Collector

This is a 17-inch OD external sphere having a wall thickness of 3/32 inch with a 3/4-inch vent in the bottom. A 4-inch diameter hole in the top is provided with a valved, pressure-sealing cover. Two kidney-shaped, foam-pad surfaces are provided around the top of the hole. These padded surfaces are spaced to provide an opening approximately 1-inch square at both the front and rear when the crewman is seated. The material recommended for the spherical shell is a fiberglass-resin layup with an inside gel coat. A sphere was chosen to optimize the strength-to-weight ratio. There is a 14-inch diameter, perforated internal sphere, having a 4-inch iron pipe size (IPS) hole tapped in the top, and joined to the outer sphere by a 4-inch IPS schedule 40 aluminum pipe. This sphere is concentrically placed to provide an interspherical flow path 1-1/2 inches wide and functions both as the collector of the waste material and as an impingement barrier. This sphere is constructed of 3/32-inch thick, fiberglass-resin lay-up, perforated over the entire surface with 3/16-inch diameter holes on 1/2-inch centers. On the outside of this perforated sphere is one thickness of 4 oz. nylon felt. The collection sphere assembly is mounted on draw slides to accommodate the storage of the vessel within the cylindrical contour of the two-man simulator located at the Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.



1. Fecal collection sphere
2. Collection sphere frame and draw bars
3. Cabin air blower and switch
4. 3 way selector valve
5. Flexible hose
6. Bacterial filter cartridge
7. Activated carbon cartridge
8. Removable cover
9. Space vacuum shut-off valve
10. Cover clip
11. Latex urinal and adapter (not shown)
12. Urinal insert dispenser
13. Urine storage sphere
14. Sterilizing tablet dispenser
15. Tissue dispenser
16. Urine transfer tubing

FIGURE 15. WASTE MANAGEMENT SYSTEM SHOWING CUTAWAY VIEW OF FECAL COLLECTION SPHERE (Frame Shown is Part of Existing Water Recovery Unit)

Air System

The cabin air flow and filtering system consists of a blower fastened to the stationary framework and two filter cartridges, one bacterial (capable of 100% removal of 0.5 micron particles) and one activated carbon. The airflow is from the bottom of the fecal collection sphere, through a reinforced flexible plastic hose capable of withstanding high vacuum, to the bacterial filter and activated carbon cartridge in series, thence to a 3-way, 2-position, aluminum valve. This valve is supplied with a special vacuum grease for the plug and is given a helium-spectrometer in-leakage test by the manufacturer. From the 3-way valve, one port is connected to the blower and thence to the cabin. (The blower is described below.) The other port of the valve is connected with 3/4-inch tubing to a two-way teflon plug valve that serves as a shutoff for the high vacuum (space vacuum) source.

When the 3-way selector valve is in the blower position and the blower is turned on, the internal air flow system provides positive feces motion (under weightless conditions) and odor control. This airflow is used only when the sealing cover is removed for defecation. The blower switch and valves are located on a panel handy to the user. The high vacuum valve is opened only after the selector valve has been turned to the high vacuum position, and is left open for about 15 minutes. Bacteria are removed in the common filter before going to high vacuum. All interconnecting piping is made of 3/4-inch aluminum tubing with 0.035-inch wall thickness and is connected with flare fittings and ferrules for tight joints, hence, is light-weight and easy to maintain. When the collector is in use, the air flow pattern imparts an acceleration to the stool of about 0.1 ft/sec.^{2} in addition to the initial velocity resulting from sphincter muscle action in separating the stool from the anus. (See Miner et al. Ref. 13.)

The activated carbon cartridge (sized with a safety factor of 25) is housed in a resin-coated enclosure of aluminum. The bacterial filter enclosure is also fabricated of aluminum.

Cabin Air Blower

To impart the necessary air velocity through the anterior and posterior openings made by the human form and the kidney-shaped pads, it has been determined that a minimum flow of 5 cfm at a ΔP of 0.2 psi would be necessary. During the time air is flowing at this rate, the blower will require 0.025 hp. A blower of the following characteristics was chosen: radial vane blower, 19000 rpm, 400-cycle, single phase, 115 V; 5 cfm at 6 inches water static pressure, power consumption 22 watts. This blower would be operated for approximately 1 hr/day. The blower switch has a self-contained light which glows when the blower is on.

URINE-HANDLING EQUIPMENT

The urine collection and storage system consists of a latex urinal with sanitizing accessories, and a spherical storage tank sized to hold urine accumulation for one day.

Urinal and Accessories

The urinal consists of three parts, namely: a latex collecting bag which is a common item; a penile adapter disc, which is a personal item; and a disposable plastic insert which is a one-use, sanitary item.

The collecting urinal is a thin-walled, antistatic, latex bag, molded flat and tapered at one end. The urinal has a conical section at its large end. The design of the urinal minimizes the possibility of entrapped air. The large end is provided with a semirigid penile adapter disc which serves as a retaining device and a secondary seal, and is connected to the urinal by permanent magnets. The conical section at the top of the bag is the primary seal, preventing escape of the contents during use. The mouth of the urinal is provided with a disposable, plastic insert pretreated with a sterilizing agent. This provides prophylaxis for successive users of the urinal and sterilization of the liner for storage after use. A spring pinch-type clamp is provided for positive urinal closure at time of removal. The urinal is provided with two Velcro fastener areas for attachment to the front of the feces collecting sphere for use while defecating and for storage when not in use. The urinal is connected at the tapered end to the storage tank by means of a tubing adapter and plastic tubing.

Urinal inserts will be stored in a dispensing tube fabricated from thin-wall aluminum tubing. Used liners can be deposited in one end as the unused liners are withdrawn from the other. A partition separates used and unused inserts.

Sterilizing tablets (Diaparene chloride) are provided in a handy dispenser. One of these tablets is placed within the urinal just before each use to sterilize the urine before storage and prevent odor and bacteria build-up in the stored urine.

Urine Storage Tank

The urine storage sphere has an internal diameter of 11 inches and a capacity of 10.5 liters. Penetrating the liquid side of the sphere are two valved outlets. The top outlet is for filling and the bottom for emptying. On the air side of the bladder, a connection in the sphere goes to a 2-way, 3-port selector valve. One of the external ports is connected to a hand-operated, vacuum squeeze bulb and the other to a pressure bulb. When urine is being transferred into the tank from the urinal, the selector valve is in the vacuum position. When urine is being removed for processing or disposal, the valve is at the pressure position.

DESIGN DRAWINGS

The above system is fully defined in detailed design drawings, General Dynamics/Electric Boat Nos. 200514, 200515-1, and 200515-2.

SECTION 9

METHOD OF OPERATION

This section describes the step-by-step operating procedure for the Waste Management System.

DEFECATION

1. Release catch and pull out fecal collection unit until it rests on floor.

2. Open high vacuum valve momentarily to purge collection sphere of decomposition gases; then close valve.

3. Turn selector valve from high vacuum to cabin air flow position.

4. Open bleed valve in cover to equalize pressure.

5. Unlock and remove cover from top of sphere and immediately start blower; place cover in clip provided.

6. Assume sitting position on sphere seat and fasten Velcro straps.

7. Defecate. Wad used toilet tissue to minimum volume and deposit in sphere.

8. Replace cover, lock, close bleed valve, and turn off blower.

9. Turn selector valve to high vacuum position.

10. Return collection sphere to storage position and lock.

11. Open high vacuum stop valve for 15 minutes, then close.

URINATION

The storage position of the urinal on the sphere is so oriented that the urinal can be used during defecation without repositioning. Urination is accomplished by the following steps:

1. Remove penile adapter disc from urinal by breaking magnetic force.

2. Remove clamp.

3. Place sterilizing tablet in urinal.

4. Place clean urinal insert in the conical opening.

5. Place penile adapter disc on penis.

6. Attach disc to urinal and urinate.

7. Replace clamp on folded section of urinal directly below penis extremity.

8. Remove urinal.

9. Remove and store used insert.

10. Place 3-way valve on urinal storage tank to "fill" position.

11. Open storage tank inlet valve and empty urinal by applying vacuum with squeeze bulb.

12. Close tank inlet valve.

13. Replace clamp on tapered end of urinal.

14. Place urinal in storage position on fecal collection vessel with Velcro fastener.

URINE TRANSFER

1. The urine storage tank is emptied once every 24 hours. With inlet valve closed, place 3-way valve on "empty" position.

2. Open tank outlet valve and apply pressure by squeeze bulb until all urine is transferred (to water-recovery unit or to disposal).

3. Close tank outlet valve.

SECTION 10

CONCLUSIONS

The optimum waste management system is based on separate collection of urine and feces. The feces are collected, stored, and partially dried by space vacuum in one piece of equipment; urine is collected in plastic urinals, sterilized, and transferred to a diaphragm-type, spherical, storage tank for intermediate storage prior to water recovery, treatment, or disposal.

Tests performed with a breadboard model of the feces collector demonstrated the feasibility of the recommended approach with regard to: (a) lack of pressure buildup with partially dehydrated feces, (b) satisfactory odor removal from recycled air, and (c) complete bacterial removal from vented gases.

REFERENCES

1. Bogan, R.H., Chapman, D.D. and Ericcson, L.H., "Aerobic Biological Degradation of Human Waste in Closed Systems," Presented at American Astronautical Society 6th National Meeting, New York, New York, 18-21 January 1960.

2. Chapman, D.D., "Biological Conversion of Human Waste by the Activated Sludge Process," Lectures in Aerospace Medicine, USAF School of Aerospace Medicine, Brooks Air Force Base, Texas, 1963.

3. Des Jardins, J., Zeff, J.D. and Bambenek, R.A., Waste Collection Unit for a Space Vehicle, WADD Technical Report 60-290, Wright Air Development Division, Wright-Patterson Air Force Base, Ohio, 1960.

4. Goldblith, S.A. and Wick, E.L., Analysis of Human Fecal Components and the Study of Methods for Their Recovery in Space Vehicles, ASD Technical Report 61-419, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, 1961.

5. Golveke, C.G., Oswald, W.J. and McGauhey, P.H., "The Biological Control of Enclosed Environments," Sewage and Industrial Wastes, 31:1125-1142. 1959.

6. Hawk, P.B., Oser, B.L. and Summerson, W.H., Practical Physiological Chemistry, 13 Ed., McGraw-Hill Book Company, Inc., New York, 1954.

7. Ingram, W.T., Microbiological Waste Treatment Processes in a Closed Ecology, Technical Documentary Report AMRL-TDR-62-126, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1962.

8. Jaffe, L.D., Sterilization of Unmanned Planetary and Lunar Space Vehicles - An Engineering Examination, JPL TR-32-325, Jet Propulsion Lab., Pasadena, California, 1963.

9. Konikoff, J.J. and Okamoto A.H., Study of the Purification of Water from Biological Waste, Space Sciences Laboratory, General Electric Company, Philadelphia, Pennsylvania, 1962.

10. Leone, D.E., Biological Waste Treatment in the Closed Ecosystem for Space, R&D Report #U-413-63-041, General Dynamics/Electric Boat, Groton, Connecticut, 1963.

11. Leone, D.E. and Benoit, R.J., "Biological Treatment of Concentrated Organic Wastes Including Sewage Sludge," J. Water Pollution Control Federation, (In Press), 1963.

12. Mallman, W.L., and Chandler, W.L., "On the Disinfection of Avian Fecal Material," J. Am. Vet. Med. Assoc., 36:190-196, 1933.

13. Miner, H., Speziali, V. and Rabe, A., Waste Collection and Storage Subsystem for Project Apollo, Report No. U413-62-203, General Dynamics/Electric Boat, Groton, Connecticut, 1962.

14. Miner, H.C., Sanford, H.L. Segal, M.R., Wallman, H.W., Collection Unit for Wastes During Space Travel, ASD TR-61-314, Wright Patterson Air Force Base, Ohio, 1961.

15. Moyer, J.E., Aerobic Waste Disposal Systems, Technical Documentary Report AMRL-TDR-62-116, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1962.

16. NASA Report on the Research and Technological Problems of Manned Rotating Spacecraft, Technical Note NASA-TN-D-1504, Langley Research Center, Langley Station, Virginia, 1962.

17. Nuccio, P.P., Tomsik, C.M., and Zeff, J.D., Waste Disposal for Aerospace Missions, AMRL Technical Documentary Report TDR-63-4, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1963.

18. Pipes, W.D. and Quon, J.E., "Growth of Chorella on Products from the Incineration of Human Wastes," Biologistics for Space Systems Symposium, AMRL-TDR-62-116, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1962.

19. Reddish, C.F., "Antiseptics, Disinfectants, Fungicides, and Chemical Physical Sterilization," Lea and Febiger, Philadelphia, Pennsylvania, 1957.

20. Reynolds, L.W. and Konikoff, J.J., Study of the Purification of Water from Biological Waste, General Electric Company, Missile and Space Vehicle Department, Space Sciences Laboratory, Philadelphia 4, Pennsylvania, 1960.

21. Roth, N.G., Wheaton, R.B. and Morris, H.H., "Control of Waste Putrifaction in Space Flight," Developments in Industrial Microbiology, Vol. 3, pp 35-44, Plenum Press, Inc., New York, New York, 1962.

22. Sandage, C.N., Techniques for the Sterilization of Wastes, ASD-TDR-61-575, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, 1961.

23. Slonim, A.R., Hallam, A.P., Jensen, D.H., Kammermeyer, K., Water Recovery from Physiological Sources for Space Applications, MRL-TDR-62-75, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1962.

24. Taylor, E.R., "Physical and Physiological Data for Bioastronautics," Presented at USAF School of Aviation Medicine, Randolph Air Force Base, Texas, 1958.

25. Thompson, H.C. and Gerdeman, J.W., "An Improved Method for Sterilization of Agar Media with Ethylene Oxide," Phytopathology, 52:167-168, 1962.

26. Topley, W.W.C., and Wilson, G.S., The Principles of Bacteriology and Immunity, Vol. 1, Edward Arnold and Company, London, England, 1931.

27. Van der Wal, L., "Sanitation in Space," Journal of the Water Pollution Control Federation, 32:333-343, 1960.

28. Wallman, H. and Barnett, S.M., Water Recovery Systems (Multivariable), WADD TDR-60-243, Wright Air Development Division, Wright-Patterson AFB, Ohio, 1960.

29. Wheaton, R.B., Symons, J.J., Roth, N.G., and Morris, H.H., "Gas Production by Stored Human Wastes in a Simulated Manned Spacecraft System," Biologistics for Space Systems Symposium, AMRL-TDR-62-116, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1962.

30. Zeff, J.D. and Bambanek, R.A., Development of a Unit for Recovery of Water and Disposal or Storage of Solids from Human Wastes, Part I - The Study Phase, WADC Technical Report 58-562(I), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1959.

31. Zeff, J.D. and Bambanek, R.A., Development of a Unit for Recovery of Water and Disposal or Storage of Solids from Human Wastes, Part II - Design, Fabrication and Testing of the Prototype System, WADC Technical Report 58-562(II), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1960.

32. Zeff, J.D., Neveril, R.B., Norell, M.W., Davidson, D.A. and Bambenek, R.A., Storage Unit for Waste Materials, ASD-TDR-61-200, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, 1961.

APPENDIX I

PROCESS DESIGN COMPARISONS

WEIGHT AND VOLUME OF SPHERICAL CONTAINER

Basis: 7 men/14 days

Type of Waste/man/day	Waste (gm)	Water (gm)	Solids (gm)
Feces	150	112.5	37.5
Bags of Tissue	50		50.0
Urine	1500	1425.0	75.0
Total/man/day	1700	1537.5	162.5

For these calculations, we have used 1530 gm H_2O (90%) and 170 gm solids (10%).

Zeff and Bambanek (Ref. 31) determined the specific volume of solid waste to be 11 cm^3/gm. Since only feces, bags, and tissue will be treated in this study, we have assumed a value of 5 cm^3/gm, which is a conservative figure.

Assuming that all the water in the waste is evaporated in one day, the storage volume of the wastes can be computed from this equation:

$$V = (1530 + 170\ V_s D)M$$

When V = storage volume required in cm^3

V_s = bulk density of solid waste in cc/gm

D = Mission length in days

M = crew size

The storage volume is primarily affected by the size of the crew and secondarily by the duration of the mission. The following sample calculations are based on 7 men for 14 days:

$$V = (1530 + 170V_s D)M$$

$$V = \left[1530 + 170(5)(14)\right]7$$

$$V = 94{,}000\ cm^3 = 3.32\ ft^3$$

$$V = \frac{\pi d^3}{6};\ d^3 = \frac{6V}{\pi}$$

$d^3 = 180,000\ cm^3$

$d = 56.5\ cm = 22.25$ inches I.D.

Wt of Aluminum Sphere 0.1-inch gauge, density = 0.098 $lb/inch^3$

O.D. Sphere = 22.45 in. I.D. = 22.25 in.

Volume of metal = $\frac{\pi}{6}(O.D.^3 - I.D.^3)$

$\frac{\pi}{6}(22.45^3 - 22.25^3) = 156.5\ inches^3$

Wt of Al = (Volume)(density)

= 156.6 x 0.098 = 15.4 lb

WEIGHT OF INSULATION

Insulation 3/8-inch thick; density 0.0015 $lb/inch^3$

Basis: 7 men for 14 days

I.D. = 22.45 inches O.D. = 23.20 inches.

Volume of insulating shell = $\frac{\pi}{6}(23.20^3 - 22.45^3) = 610\ inches^3$

Add 15% for joints and door

$V = 700\ inches^3$

Wt of ins. = (volume)(density)

= 700 x 0.0015 = 1.05 lb

WEIGHT OF CABIN AIR LOSS

Free volume in sphere at day 1 = $87,300\ cm^3$

at day 14 = $10,700\ cm^3$

Average free volume of air for 14 days

$$\frac{87,300 + 10,700}{2} = 49,000\ cm^3 = 49.0 \text{ liters}$$

Total volume of gas lost = (14)(49.0) = 686 liters = 24.2 ft^3

Assume all air to be removed in process each day. Then the weight of gas can be computed by the gas law

$$PV = nRT$$

$$n = \frac{PV}{RT}$$

P = 7.35 psia

$V = 24.2\ ft^3$

$T = 530^oR$

$R = 1543$

n = Number of lb-moles

M.W. = 29.6

$$n = \frac{(7.35)(144)(24.2)}{(1543)(530)} = 0.031 \text{ lb-moles}$$

Wt of air lost = (n)(M.W.)

(0.031)(29.6) = 0.91 lb

WEIGHT OF INCINERATOR SHELL

The bulk density of the bagged fecal matter is taken as 5 cm^3/gm. The mass is 200 gm/man/day.

Volume per man per day is then:

$5 \times 200 = 1000$ cm^3/man/day

or 7000 cm^3/day for 7 men

Add 20% for free space:

$7000 + 1400 = 8400$ cm^3

A series of computations was made to determine optimum cylinder dimensions. This cylinder is 9 inches in diameter and 8 inches in length.

The basic cylinder wall will be made of CRES 316, 3/16-inch gauge and ends of 3/8-inch plate. Density of CRES 316 is 0.29 lb/$inch^3$.

To obtain weight of basic shell, the metal volume is determined and converted to weight.

Volume of metal shell = 2 ends + cylinder shell

$$= 2\left(\frac{\pi d^2}{4}\right)(3/8 \text{ inch}) + (A_2 - A_1)(8.04)$$

$$A_1 = 9^2 \times \frac{\pi}{4} = 63.6 \text{ inch}^2$$

$$= 2(63.6)(3/8 \text{ inch}) + (69.2 - 63.6)(8.04)$$

$$A_2 = \overline{9.375}^2 \times \frac{\pi}{4} = 69.2 \text{ inch}^2$$

$$= 47.8 + 45 = 93 \text{ inches}^3$$

Weight of metal shell = (93)(0.29) = 27 lb

The weight of the furnace door and lock is estimated at 6 lb.

WEIGHT OF INSULATION

The insulation will be 4 inches of 85% MgO with a density of 0.0145 lb/$inch^3$.

The net volume of insulation is the difference between the volumes of two concentric cylinders. The inside cylinder is 9.5 inches in diameter and 8.5 inches in length. The outside cylinder is 17 inches in diameter and 16 inches in length.

$$V = V_o - V_i$$

$$= (17)^2(\tfrac{\pi}{4})(16) - (9.5)^2(\tfrac{\pi}{4})(8.5)$$

$$= 3640 - 605 = 3035 \text{ inches}^3$$

Weight of Insulation = 3035 x 0.0145 = 44 lb

WEIGHT PENALTY FOR OXYGEN CONSUMPTION

For each man's fecal waste (200 gm/day) there is 112 gm free water and 88 gm of solids.

Each 88 gm of solids has the following weight relationships:

Element	Percent	Wt/man/day (gm)	Wt/7 men/day (gm)
C	39.7	34.9	244
H_2 Total	5.8	5.1	36
O_2 Combined	30.4	26.7	187
N_2	8.9	7.9	55
Ash	15.2	13.4	94
H_2 Free		1.8	12.6

Oxygen Required for Incineration

	Wt/7 men/day (gm)
$C + O_2 \longrightarrow CO_2$	651
$2H_2 + O_2 \longrightarrow 2H_2O$	286
Sub Total	937
Less combined O_2	187
Theoretical O_2	750
20% Excess O_2	150
Total Oxygen	900
Total Oxygen in lb	2.0

Wt penalty for oxygen = 2.0 lb.

Wt penalty for containers based on cryogenic storage = 1 lb of container for 1 lb of oxygen.

Oxygen storage container = 2.0 lb.

WEIGHT PENALTY FOR POWER

Power Input

The power input can be estimated according to Nuccio et al. (Ref. 17), from a system energy balance stated as:

$$Q_i + Q_{nc} = Q_{sw} + Q_{ss} + Q_e + Q_{sg} + Q_l + Q_f$$

where:

Q_i = Heat input

Q_{nc} = Net heat of combustion

Q_{sw} = Heat of sensible wastes

Q_{ss} = Heat of sensible system

Q_e = Latent heat free water

Q_{sg} = Sensible heat of gases

Q_l = Net heat losses

Q_f = Heat of fusion, polyethylene

From data at hand, all these quantities cannot be accurately determined. If the assumption is made that the net heats of combustion are offset by the sensible heat of the system plus the heat losses, then the heat balance can be stated as:

$$Q_i = Q_{sw} + Q_f + Q_e + Q_{sg}.$$

All the terms on the right side of the equation can be calculated.

Q_{sw} Calculation	Wt, gm	c_p	Δt, °C	Kg cal/day
Feces	88	0.40	745	26.2
Water	112	1.00	105	11.8
Paper	10	0.30	745	2.3
Bags	40	0.30	110	13.2
Base temperature for Δt = 15.6°C				73.5

Q_{sw} = 73.5 Kg cal/day/man

Q_{sw} for 7 men = 515 Kg cal/day

Q_e **Calculation**

Latent heat of water at 250°F = 525 cal/gm

112 (525) = 58.75 Kg cal/day/man

or 412 Kg cal/day for 7 men

Q_f Calculation

Heat of fusion of polyethylene is 23 cal/gm

40 gm polyethylene/man, or 280 gm/7 men

(280)(23) = 6.44 Kg cal/day

Q_{sg} Calculation

Basis: 1 man/day

The composition of exit gases with 20% excess oxygen at 250°F.

CO_2 from carbon = $(34.9)(\frac{44}{12})$ = 128 gm

N_2 from feces = ignore

O_2 excess = 21.5 gm

H_2O from dry waste = $5.1 \times \frac{18}{2}$ = 46 gm

Total wt of gas = 195.5 gm

Assuming no heat exchange between the exiting gases and the incoming oxygen, the enthalpy of the waste gases can be estimated by decrements from 250° to 1400°F. The decremental increases are shown on the following page.

$Q_1 = Q_{sw} + Q_f + Q_e + Q_{sg}$

$Q_1 = 515 + 6.44 + 412 + 191$

$= 1124$ Kg cal/day

Assuming 12-hour cycle, then

Q_1 in Kg cal/hr = $\frac{1124}{12}$ = 95 Kg cal/hr

95 Kg cal/hr = 110 watts

Power input is 110 watts

Wt penalty for power is 0.300 lb/watt

Wt penalty = (110)(0.300) = 33 lb

Decrement #	Gas	Wt (gm)	gm cal/gm/°C (cp)	t°F	Δt,°F (t-60)	Q-(gm/cal)	Subtotal (gm/cal)
1	CO_2	12.8	0.230	307	247	404	
	O_2	2.15	0.230		(137°C)	58	
	H_2O	4.60	0.460			190	752
2	CO_2	12.8	0.265	422	362	682	
	O_2	2.15	0.235		(201°C)	103	
	H_2O	4.60	0.470			426	1211
3	CO_2	12.8	0.270	537	477	915	
	O_2	2.15	0.237		(265°C)	135	
	H_2O	4.6	0.475			576	1626
4	CO_2	12.8	0.272	652	592	1145	
	O_2	2.15	0.240		(329°C)	170	
	H_2O	4.6	0.480			726	2041
5	CO_2	12.8	0.275	767	707	1385	
	O_2	2.15	0.245		(393°C)	206	
	H_2O	4.6	0.480			870	2461
6	CO_2	12.8	0.280	882	822	1640	
	O_2	2.15	0.247		(457°C)	242	
	H_2O	4.6	0.500			1050	2932
7	CO_2	12.8	0.281	997	937	1870	
	O_2	2.15	0.255		(520°C)	286	
	H_2O	4.6	0.510			1220	3376
8	CO_2	12.8	0.285	1112	1052	2135	
	O_2	2.15	0.260		(585°C)	326	
	H_2O	4.6	0.520			1380	3841
9	CO_2	12.8	0.290	1227	1167	2405	
	O_2	2.15	0.262		(648°C)	362	
	H_2O	4.6	0.525			1560	4327
10	CO_2	12.8	0.292	1342	1282	2660	
	O_2	2.15	0.265		(712°C)	405	
	H_2O	4.6	0.530			1735	4800

Total gas 195.5 gm Total Enthalpy 27.367 K_g cal/day

Q_{sg} for 7 men 191 Kg cal/day

STORAGE OF FECES IN CANS

WEIGHT PENALTY

Basis: 7 men/14 days

Outside dimensions of friction lid can = 11 cm dia. x 11 cm long

Volume = 1000 cm^3 Wt = 0.32 lb

Capacity of can = 950 cm^3

Capacity of can at 25% head space = 710 cm^3

Bagged feces-rolled and packed tightly has a density of approx. 0.9 gm cm^3; at 200 gm per man/day = 222 cm^3

$\frac{710}{222}$ = 3.2 men

One can will hold the packed fecal waste of 3 men. Then the number of cans required will be:

(7)(14)(1/3) = 33 cans

Wt of cans = (33)(0.32) = 10.6 lb

VOLUME PENALTY

It is intended that the cans before use for feces will be used to contain stored food. The volume penalty is, therefore, the difference between an 11-cm cube and a cylinder 11 cm in diameter and 11 cm long.

For each can this is:

1331 - 1000 = 331 cm^3

For 7 men/14 days the penalty volume is:

$\frac{(331)(33)}{28,320} = 0.386 \ ft^3$

COMBINED COLLECTION AND STORAGE OF FECES

VOLUME OF COLLECTION SPHERE

Basis: 7 men/14 days

The volume required will be the volume of the feces, the volume of the wipes and a reserve volume of 2 liters (122 inches^3). Taking net density of feces as 1.0 g/cm^3.

$$\text{Wt of feces} = \frac{150(7)(14)}{454} = 32.3 \text{ lb}$$

$$\text{Volume of feces} = \frac{(32.3)(1728)}{62.4} = 897 \text{ inches}^3$$

Volume of wipes:

At 3 wipes/man/day, an expanded volume of 6 cm^3/wipe, and a stored density of 6.05 lb/ft^3,

where: 1 inch^3 = 16.39 cm^3

$$V = \frac{3(7)(14)(6)}{16.39} = 109 \text{ inches}^3$$

Reserve volume = 122 inches^3

Required total volume = 1128 inches^3

To determine I.D. of sphere:

$$V = \frac{\pi d^3}{6}$$

$$d^3 = \frac{(1128)(6)}{3.14} = 2170 \text{ inches}^3$$

$$d = 13.0 \text{ inches}$$

WEIGHT OF INNER SPHERE

Material 30 mesh aluminum screening at 0.095 lb/ft^2

$$A = \pi D^2 = 3.14\ (169) = 530 \text{ inches}^2$$

$$Wt = \frac{(530)(0.095)}{144} = 0.35 \text{ lb}$$

Inner Sphere Baffle Disc

Estimated Weight = 0.1 lb

WEIGHT OF OUTER SPHERE

Material: Built up fiberglass, 3/32 inch wall thickness, 0.05 lb/inch^3 on outside surface, 1/4 inch spacers

D_1 = Inside Diameter = 13.0 + 2(0.25) = 13.5 inches

D_2 = Outside Diameter = 13.5 + 2(3/32) = 13.69 inches

$$V = \frac{\pi}{6}(D_2^3 - D_1^3)$$

$$= 0.523(2656 - 2460) = 55 \text{ inches}^3$$

Wt = (55)(0.05) = 2.75 lb

WEIGHT OF NYLON FELT LINER

Material: Nylon felt single ply - 1 sq. yd., weight - 4 oz. Surface of inner sphere is to be covered with 1 ply. 1 sq. yd. = 1296 inches^2

$A = \pi(D)^2 = 169 \text{ inches}^2$

$$\text{Weight of Nylon Felt/inch}^2 = \frac{0.25 \text{ lb}}{1296 \text{ inch}^2}$$

$$Wt = \frac{169(0.25)}{1296} = 0.03 \text{ lb}$$

The total weight of the collection assembly is:

Wt of tissue wipes (storage)	0.38
Wt of inner sphere screening	0.35
Wt of outer sphere	2.75
Wt of felt liner	0.03
Wt of spacers	0.02
Wt of disc	0.10
Wt of cover	0.77
Wt of legs	0.10
Wt of carbon filter shell	0.20
Wt of bacteria filter shell	0.10
Wt of activated charcoal	0.27
Wt of filter assembly and anchors	0.25
Wt of 2-way valve	0.24
Wt of screens	0.07
Wt of misc. fittings	0.50
Wt of seat cushion	0.34
Wt of assembly	6.47 lb

WEIGHT OF CABIN AIR LOSS

Basis: 7 men/14 days

Assuming 7 defecations per day:

Free volume at start = 1128 $inch^2$

Free volume at 14 days = 122 $inch^3$

Average vol. per day = 625 $inch^3$

Average volume per day is assumed for each defecation.

Total volume of air lost in space is:

$$\frac{(7)(625)(14)}{1728} = 35.2 \ ft^3$$

Cabin pressure = 7.35 psia

Sphere pressure at full blower suction = 6.85 psia

The weight of 1 lb-mole of cabin gas = 29.6 lb

From the gas law:

$$PV = nRT$$

$$n = \frac{PV}{RT}$$

P = Pressure in psia

V = volume in ft^3

$T = 530^{o}R$

R = 1543

n = number of lb-moles

$$n = \frac{(6.85)(144)(35.2)}{(1543)(530)} = 0.0352 \text{ lb-moles}$$

Wt of lost cabin gas is:

Wt = n (M.W.) = (0.0352)(29.6) = 1.15 lb

WEIGHT OF BLOWER

Estimated at 3 lb

WEIGHT OF POWER PENALTY

Capacity of blower 5cfm at Δp 1/2 psia or 14 inches water

1 inch water = 5.19 psi

$$hp = \frac{PV/min.}{33000} = \frac{(5)(5.19)(14)}{33000} = 0.0111 \text{ hp}$$

Assuming mech eff. = 50%

$$\text{Line hp} = \frac{0.0111}{0.50} = 0.0222 \text{ hp} = 16.5 \text{ watts}$$

Wt Penalty for power = 16.5 (0.30) = 4.95 lb

APPENDIX II

SYSTEM DESIGN CALCULATIONS

SIZE OF COLLECTION VESSEL

Basis: 7 men - 15 days

The volume required (V_s) will be the volume of the feces (V_f) plus the volume of the tissue wipes (V_w) and a reserve volume (V_r) of 25%.

$$V_s = V_f + V_w + V_r$$

Assume density = 62.4 lb/ft^3

Daily production per man = 150 gm

$$\text{Total feces produced} = \frac{(150)(7)(15)}{454} = 35 \text{ lb}$$

$$V_f = \frac{35 \times 1728}{62.4} = 965 \text{ inches}^3$$

Expanded volume of wipes = 6 cm^3/wipe; (1 inch^3 = 16.4 cm^3)

3 wipes per man/day

$$V_w = \frac{(6)(3)(7)(15)}{16.4} = 116 \text{ inches}^3$$

$$V_s = V_f + V_w + V_r = 1081 \text{ inches}^3 + 0.25\ V_s = 1440 \text{ inches}^3$$

If volume is a sphere, then the diameter (d) can be found from

$$V = \frac{\pi d^3}{6}$$

$$d^3 = \frac{(1440)(6)}{3.14} = 2750$$

d = 14 inches

SIZE OF ACTIVATED CHARCOAL FILTER

Assumptions:

(a) Noxious gases adsorbable from fecal decomposition:

H_2S = 100 ppm; odoriferous organics = 200 ppm

(b) Density of feces = 1 gm/cc

(c) Average MW of noxious gases = 80

(d) Density of activated carbon = 0.5 gm/cc

(e) Loading = 0.8 lb adsorbate to 100 lb adsorbent

Feces produced/day:

$$(7)(150) = 1050 \text{ gm/day}$$

Volume of Gases Formed:

According to Wheaton et al. (Ref. 29) the volume of gases produced follows the relationship:

$$V = 2.23 + 2.155 \log t$$

where: V is volume in standard ml/gm of feces and t is decay time for a given quantity in days.

By summing the total production of gas for each day's incremental addition over the appropriate storage period, a total volume of 62.5 standard liters is obtained in the 15-day period.

Wt of Noxious Gases Produced:

$$\frac{(62.5 \text{ liters})(300)(10^{-6}) \times 80 \text{ gm/mol}}{22.4 \text{ liters/mol}} = 6.7 \times 10^{-2} \text{ gm}$$

$$\text{Loading} = \frac{0.8}{100} \text{ adsorbate by weight}$$

Activated Carbon Required:

$$\frac{6.7(10^{-2})}{0.8} \times 100 = 8 \text{ gm carbon}$$

Volume of Activated Carbon:

$$\frac{8 \text{ gm}}{0.5 \text{ gm/cc}} = 16 \text{ cc}$$

Volume of Cartridge Cylinder, 2 1/2-inch diameter and 5 1/2-inch length

$$V = 27 \text{ inches}^3 = 440 \text{ cc}$$

Safety Factor in Design:

$$\frac{440}{16} = 27$$

PRESSURE DROP IN PIPING

Flow: 5 cfm cabin air

$MW = 29.6$

$PV = nRT$

$P = 7.35$ psia

$$n = \frac{(300)(7.35)(144)}{(1543)(530)}$$

$n = 0.389$ lb-mol/hr

$W = 29.6\ (0.389) = 11.5$ lb/hr

$V = 300$ cfh

$R = 1543$

$T = 530^{\circ}R$

Air Density at 70°F and 7.35 psia = 0.0382 lb/ft^3

Pressure drop per hundred feet of pipe for gases may be calculated from:

$$\Delta P_{100} = \frac{(3.36)(10^{-4})\ fW^2V}{d^5}$$

Where: f is friction factor as a function of Reynolds Modulus, Re

W = Mass flow in lb/hr

V = Specific volume in ft^3/lb or 1/density

d = ID of pipe or tube

$$Re = \frac{6.32\ W}{d\mu}$$

$\mu = 0.0193$ at 70°F

$$Re = \frac{(6.32)(11.5)}{(0.68)(0.0193)} = 5550$$

$f = 0.0425$

For 3/4-inch OD and 0.035-inch tubing, ID = 0.68 inches; $d^5 = 0.145$

$$\Delta P_{100} = \frac{(3.36)(10^{-4})(4.25)(10^{-2})(11.5)^2}{(1.45)(10^{-1})(3.82)(10^{-2})} = 0.342 \text{ psi/100 ft}$$

Equivalent lengths of tubing per fitting:

	Length	No. in System	Total Length
Angle Valve Open	8.5 ft	2	17.
Close U Bend	4.5 ft	1	4.5
Std. Tee	3.5 ft	1	3.5
Std. Elbow	1.5 ft	2	3.0
			28.0 ft
4-foot flexible hose			4.0
Total length of tubing			3.0
			35.0 ft

ΔP in piping = (35) x (0.342) = 0.120 psi

ΔP through filters = 0.055 psi

ΔP Total = 0.175 psi

0.175 psi = 4.85 inches of water.

Design for 5 cfm against 6 inches water static head

POWER REQUIREMENTS FOR BLOWER

$$\text{Fan hp} = \frac{V \times 5.202 \times \text{inches } H_2O \text{ static}}{33000}$$

$$= \frac{(5)(5.202)(6)}{33000}$$

$$= 0.00475 \text{ hp}$$

$$\text{hp} = \frac{\text{Fan hp}}{\text{eff.}}$$

$$= \frac{0.00475}{0.20} = 0.0238 \text{ hp at overall efficiency } 20\%$$

Power = 746 x 0.0238 = 18 watts

Based on the above, the blower selected for this service was a Rotron Type RS-201, radial vane blower, 19000 rpm, 5 cfm at 6 inches water static head, 400 cycles, single phase, 115 V. a.c., 22 watts input.