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STUDY OF LIFE SUPPORT SYSTEMS FOR SPACE MISSIONS EXCEEDING ONE YEAR IN DURATION PHASE IA

FINAL REPORT
VOLUME I: ANALYSIS OF NEW CONCEPTS

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PHASE IA

FINAL REPORT

VOLUME 1: ANALYSIS OF NEW CONCEPTS

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SUMMARY

The study covered by this report is a continuation of the work conducted under contract NAS 2-3012, "Study of Life Support Systems for Space Missions Exceeding One Year in Duration," Phase I. The previous work compared biological and chemical food-processing systems with a stored food system for a hypothetical mission of from 10 to 100 men for 1 to 3 years. The follow-on work (Phase IA), the subject of this report, reviewed new concepts for waste processing and food manufacture in the closed system such as wastes for radiation shielding, wastes for propulsion, glycerol synthesis using chromatographic reactors, glycerol synthesis using acetylene as an intermediate, and new biological system approaches. The most promising of these new concepts were combined with the food-producing systems evolved in Phase I and compared for three specific model missions: earth orbit, lunar, and Mars. The effects of spacecraft power penalty, leakage rate, radiation shielding requirements, and extravehicular expendables requirements were assessed and a cost-effectiveness analysis was completed for each mission. The cost analysis compared the launch cost savings of the advanced systems with the R&D costs required to produce a flight-ready system. The study results indicate that systems using wastes for radiation shielding, leakage makeup, or EVA expendables are very competitive with the biological and chemical food systems for all missions. The stored food baseline system and wastes for propulsion ranked poorly in the comparison studies.

The final report for Phase IA of the "Study of Life Support Systems for Space Missions Exceeding One Year in Duration" is presented in two volumes. Volume I presents the "Analysis of New Concepts" and Volume II presents the "Mission Studies."

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INTRODUCTION

The degree to which wastes are processed to provide useful materials to man for a long-duration space mission is the subject of the "Study of Life Support Systems for Space Missions Exceeding One Year in Duration." The Phase I study compared biological and chemical methods of synthesizing foods with a baseline stored food system. The results of the Phase I effort indicate that Hydrogenomonas and glycerol food-manufacturing systems look attractive for long-duration missions. The Phase I effort, however, did not consider other uses of wastes such as radiation shielding, propulsion or leakage makeup,and did not consider specific space missions such as earth-orbiting space stations, lunar bases, and interplanetary flights. The Phase IA study considers these latter aspects of life support and also reviews some new concepts evolved after the completion of the Phase I work.

The first 6 months of the Phase IA study was directed toward the review and analysis of ten aspects of life support that warranted further analysis than was possible in the Phase I study. The ten topics are listed below.

- A Survey of Less Studied Candidates for Microbial Life Support Systems
- The Need for More Desirable Strains of Algae and Hydrogenomonas
- The Use of Radioisotope-Phosphors for Illumination of Algae
- Chemical Synthesis of Fats and Proteins
- Formaldehyde Synthesis Using Chromatographic Reactors
- Chemical Synthesis of Glycerol Using Acetylene as an Intermediate
- Animal Links in the Closed System
- The Use of Biological Wastes for Propulsion
- The Use of Biological Wastes for Radiation Shielding
- Waste Regeneration in the Closed System

Volume I of the report covers the ten topics and a review of current R&D efforts under the title "Analysis of New Concepts."

The remainder of the Phase IA study combined the most promising new concepts from the above list with the Phase I food-producing systems of Hydrogenomonas and glycerol and compared them for selected earth-orbiting, lunar base, and Mars space missions. These mission studies are presented in Volume II.

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A SURVEY OF LESS-STUDIED CANDIDATES FOR MICROBIAL LIFE SUPPORT SYSTEMS

In Phase I of the "Study of Life Support Systems for Space Missions Exceeding One Year in Duration," an abbreviated survey was conducted of microorganisms other than algae and Hydrogenomonas that might have potential application in manned space flight missions. The survey was conducted primarily from the viewpoint of using microorganisms to convert certain undesirable and/or useless toxic gases to useful materials and the conversion of chemically synthesized food materials to cell material which could be used as a more complete food for the crew. It was the general conclusion of the survey that possibilities appear favorable for the microbial utilization of synthesized glycerol and/or glyceraldehyde and of the waste gas, ethane. In the current study, the literature was reexamined with special attention given to the sources which were not available during the Phase I study. This report gives consideration to the microbial utilization of methane, methanol, glycerol, and hydrocarbons.

METHANE

Methane

It was previously reported that the literature indicated several species of Pseudomonas, Methanomonas, and Mycobacterium as methane oxidizers. The work of Brown and Strawinski (ref. 1) with Methanomonas methanooxidans indicated that approximately 85% of the methane carbon is converted to cell substance or intermediates by this organism. However, little or no information was found to indicate the growth rates of these organisms. No new information about such specific details was found, but it has been reported in Chemical News (refs. 2 and 3) that the petroleum industry is investigating the microbial utilization of methane for cell synthesis as a means of increasing the protein supplementation of food materials. Rothschild (ref. 3) reports that investigators at Shell Research Ltd. of England have successfully isolated pure cultures of methane-oxidizing bacteria from a number of natural sources, such as oil field soils and fresh water. High yields of these microorganisms have been obtained by incubation in simple salt solutions of nitrate, phosphate, and potassium through which air and methane are bubbled. The work to date has been limited to laboratory-scale investigations of a limited number of strains, and very few specific details are available. It is reported that pure culture work has yielded a powdered product that is roughly 50% protein and has a nutritionally satisfactory amino acid content. Yields in a production-scale operation are being estimated as 1 ton of protein from 200,000 cu ft (about 4 tons) of natural gas. Assuming that the estimated 50% protein yield is correct, the remaining 50% is carbohydrate, lipid, and minerals, and therefore a yield of 1 lb of powdered cells is postulated for 2 lb of methane utilized. The assumption is made that "powdered product" is equivalent to dried cells and, thus, the above estimate is on a dry weight basis. On a wet weight basis, approximately 2.5 lb of cells would be produced from 2 lb of methane.

As noted previously, most of the methane-utilizing microorganisms that have been reported are members of the Psuedomonas and Methanomonas genera of bacteria. Recently, Foster and Davis (ref. 4) have reported the isolation of a methane-dependent coccus for which they have proposed the name Methylococcus capsulatus. This organism is capable of aerobic growth in a mineral salts solution with either methane or methyl

alcohol as the sole source of carbon. It was found that when the organism was grown with methane, 86% of the methane carbon was fixed in the organic form and that the remainder was oxidized to carbon dioxide. This correlates well with the reports of Brown and Strawinski on Methanomonas methanooxidans, where 85% of the methane carbon was converted to the organic form.

Johnson and Quayle (ref. 5) in studies of Pseudomonas methanica found that 70 to 90% of the radioactivity of utilized C^{14}-methane appears in glucose- and fructose-phosphates of the cell. Their analysis showed that the hexose phosphates are the primary stable products of C^{14}-methane metabolism. Other compounds which were found labeled with C^{14} included glycine, serine, glutamate, aspartate, malate, citrate, and alanine.

In the absence of specific details concerning cultural characteristics of the methane-utilizing bacteria that are being considered for food supplementation, it is difficult to propose definitive schemes which might use these organisms in space missions. However, it is strongly recommended that consideration be given to a feasibility study of the following scheme: the conversion of carbon dioxide respired by the crew to methane by physicochemical means and then the microbial conversion of the methane to cell substance which could be used as a food source. In addition to methane from reduced carbon dioxide, fecal waste may also be a source of methane since a considerable amount of this gas is generated from anaerobic biodegradation. If growth rates are reasonable and methane conversion yields approximately 85%, then this scheme would appear to have some merit for use in space systems.

Methanol

The literature reports that certain species of Pseudomonas and Hyphomicrobium are capable of utilizing methanol (refs. 5 through 11). Johnson and Quayle (ref. 5) report that the conversion products of C^{14}-methanol grown cultures of Pseudomonas methanica are approximately the same as those reported above for C^{14}-methane grown cells; i.e., 70 to 90% conversion to glucose- and fructose-phosphates. Peel and Quayle (ref. 6) have reported the isolation of an organism identified as Pseudomonas AM1, which grew aerobically on methanol as a sole source of energy and carbon. The optimum growth conditions for this organism were reported as a temperature of 30°C, a pH of 7.0, and a methanol concentration of 0.5 to 1% (v/v). Anthony and Zatman (refs. 8, 9, and 10) have reported the isolation of several strains of Pseudomonas which grew aerobically with methanol as the sole source of energy and carbon for cell synthesis. However, they concentrated their studies on one strain which has been designated as Pseudomonas Sp. M27. Their studies showed that the cells of this organism contain an enzyme which catalyzes the oxidation of methanol and other normal alcohols. It is reported that similar enzymes are found in the following bacteria: Pseudomonas AM1, Ps. methanica, Protaminobacter ruber, and Bacillus extorquens. In addition to the pseudomonads, other investigators (refs. 7 and 11) have reported on their studies of methanol utilization by Hyphomicrobium vulgare.

The investigations of methanol-utilizing organisms that have been reported in the literature have been concerned primarily with metabolic pathways and, therefore, little information of a practical application nature is available. However, consideration

should be given to these organisms from the viewpoint that if chemical synthesis and microbial utilization of the synthesized product might be a part of the life-support system, methanol would be simpler to synthesize than some of the other chemicals that have been proposed. Therefore, additional consideration should be given to the feasibility of a methanol synthesis/microbial utilization system.

Glycerol

No new significant information on the microbial utilization of glycerol was found in this study. This point is made again because if glycerol should be the chemical of choice for synthesis, there is some doubt that it would be completely acceptable as a food in its natural form. The microbial conversion of glycerol to cell substance which could be used as food is one possible way of enhancing its acceptability. As reported previously, there are several microbial species which are capable of utilizing glycerol, and if the decision should be to synthesize glycerol, then these organisms should be examined more closely in laboratory investigations to determine their potential for converting glycerol to utilizable cell material.

Hydrocarbons

Since research on the microbial utilization for food supplementation has been an active area of investigation, some of the more recent reports were examined to ascertain any potential use of this concept in space life-support systems. Even though several species of fungi, yeasts, and bacteria can apparently utilize hydrocarbons (ref. 13) such utilization would appear not to be adaptable to space missions. The reports (refs. 12 through 15) indicate that most of the conversions occur with the longer chain-length hydrocarbons; i.e., eight carbons or longer. The availability of this type of substrate in space-flight conditions appears improbable.

Conclusions

The search for microorganisms of potential use in space-flight missions has led to the following conclusions:

- Although the literature is lacking in certain specific details of an application nature, the reports of methane-utilizing microorganisms are encouraging, and it is recommended that a study be conducted to determine the feasibility of using a system in which carbon dioxide is converted to methane by physicochemical methods and the methane converted microbially to cell material which could be used as a food source.

- There is a possibility that synthesized methanol could be converted microbially to cell material for food, but a great deal of information must still be developed.

- If glycerol is to be a synthetic food substance for space missions, laboratory investigations of microbial utilization should be conducted to determine the feasibility of using glycerol-grown microbial cells as a food source.

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THE NEED FOR MORE DESIRABLE STRAINS OF ALGAE AND *HYDROGENOMONAS*

Whenever a biological system is used to perform a certain process, the question always arises, "Is there another organism, another species or another strain that could accomplish the process better?" Such a question arises in relation to the use of algae and hydrogen-fixing bacteria as the biological agents in bioregenerative life-support systems. Are there species or strains of these two groups of organisms that are more desirable for use than those presently being considered, or could better strains be developed through the use of mutagenic agents and induced mutations? These questions have been carefully considered and the opinions which are expressed are based upon available experience, information, literature reports and the present state of the art. Each of the two groups of organisms is considered separately.

Algae

The desirable characteristics for an alga to be used in a bioregenerative photosynthetic system have been examined (refs. 16, 17, and 18). These characteristics include the following:

- High growth rate
- Growth in elevated temperature range
- Acceptability as food for human nutrition
- Stability
- Ability to utilize urea (or urine) as nitrogen source
- "Clean" growth with little or no foam and residue
- Ability to grow in mass culture with adequate gas exchange ratio for man

The green alga, *Chlorella pyrenoidosa*, was the organism selected by Meyers (ref. 19) for studies on photosynthetic gas exchangers in 1954. This organism was selected "because of our more extensive and reliable data on this species." Since that time, a number of species of various algal genera including *Anacystis*, *Synechocystis*, *Scenedesmus*, and *Synechococcus* have been evaluated by a number of investigators (refs. 16, 20, 21, and 22). More recently, several members of the marine flagellates (Polyblepharidaceae) were evaluated for growth and productivity under conditions of mass culture (refs. 23 and 24). None of these studies revealed any algal genera or species which fit the requirements any better than *Chlorella*.

A thermotolerant or high-temperature strain of *Chlorella* had been isolated and studied (ref. 25). This organism, which is generally designated *Chlorella* 71105, under conditions of light saturation at 35° to 39°C exhibits growth rates of approximately seven

generations per day as compared to two generations per day of the mesophilic strain. With this type of growth rate, one would expect a more suitable system for space application. However, it was found that a thermotolerant strain produced only 15% more cells than the mesophilic strain under mass culture conditions (ref. 26). The primary reason for the decreased growth rate of the thermotolerant strain is the inability to obtain conditions of light saturation in mass culture.

Screening studies of other Chlorella strains have been made (refs. 27 and 28). Ward tested 56 isolates of Chlorella spp., and 35 of this number were found to be thermotolerant strains. Richards isolated 40 thermotolerant or thermophilic cultures of algae, and growth measurements were made on 33 of these. Most of the isolates appeared to be "Chlorella-like." Of all of the isolates tested, none appeared to be significantly better than the original Chlorella strains.

New strains of organisms are the result of so-called natural or spontaneous mutations. Certain physical and chemical agents to which an organism may be exposed induce or increase the rate of mutation. It is logical to conclude that by inducing mutations, a strain (or strains) could be found that would have more desirable characteristics than the parent. Unfortunately, most mutations are deleterious to the organism because of losses or alterations in certain metabolic activities. Since these types of changes do occur in induced mutants, the process is nicely adaptable to studies of metabolic pathways. In some cases, mutations have been successful in industrial microbiology. For example, the production of penicillin was increased three- to five-fold by x-ray and ultraviolet-induced mutations. However, such a success is accompanied by a great number of failures.

There are several reports in the literature (refs. 29 through 39) dealing with mutations in algae. Most of these have been reported from the standpoint of studies in photosynthesis and metabolism. Only one report (ref. 28) was observed dealing with an attempt to induce mutants for possible use in bioregenerative systems and this attempt was unsuccessful. Most of the reports indicate considerable losses or changes in chlorophyl and carotenoid pigments which decrease growth rates. Kvitko (ref. 29) reported the comparison of growth of mutants with that of the parent, Chlorella vulgaris. Of the 37 mutants examined, none of them exhibited any growth advantages over the parent strain.

The literature reports that there have been attempts to isolate better algal strains; there have been no large projects to accomplish this purpose. Such projects are expensive and time-consuming with no guarantee of success even though the possibility always exists that a better strain will be found. Even if a more desirable strain were found, it is doubtful, considering the present state of the art, whether such a strain would overcome the large culture volume and lighting problems associated with algae systems in general. Two recent contract study reports (refs. 40 and 41) on life-support systems have indicated that the algal photosynthetic bioregenerative system is not recommended for extended space missions because of the physical and engineering limitations of the system. The inefficient conversion of electrical energy to light energy and the poor distribution of light energy to the algal cells will be a problem no matter how efficient the alga strain may be. The experience with the thermotolerant strain of Chlorella is an example. Thus, it appears that the potential gains of a program to develop more desirable strains of algae are too limited to justify the expenditure of additional R&D funds.

Hydrogenomonas

To date, there has been a relatively small effort devoted to the study of Hydrogenomonas as a candidate for a bioregenerative life-support system. Canfield and Lechtman (ref. 42) appear to be the only ones who have reported any type of screening study of Hydrogenomonas. In their study of hydrogen-fixing bacteria for use in bioregenerative systems, they report the screening of the following hydrogenomonads: Hydrogenomonas eutropha, Hydrogenomonas facilis, Hydrogenomonas ruhlandii, Hydrogenomonas H-20. Of these, H. eutropha was selected as having the best characteristics. There are several other species and strains of Hydrogenomonas that have been isolated, but apparently have not been screened to determine their potential as organisms in biogenerative systems. These organisms are: H. pantotropha, H. carboxydovorans, H. vitrea, H. flava, and H. agilis. Investigators at the University of Göttingen, Göttingen, West Germany, have been studying hydrogen-fixing bacteria for several years and may have available a number of strains for screening studies. Miss Dianne Davis (ref. 43), at the University of California, Berkeley, indicated that she had isolated approximately twelve strains of Hydrogenomonas. Thus, it appears that since the time of the Canfield study, a number of Hydrogenomonas strains have been isolated, and it is advisable that available cultures be processed through a screening program to determine their potential for use in a bioregenerative system. Any decision as to whether or not an expanded screening program would be desirable or necessary should await the results of screening presently known isolates and the results of bioregenerative research with H. eutropha.

No evidence was found of any induced mutation investigations and it is quite probable that little or no work is being done in this area. It does not seem advisable to develop a program to induce and screen mutants until sufficient work has been done with Hydrogenomonas eutropha. At the present time, little is known about the problems that will be encountered when this organism is used in a continuous culture bioregenerative system. Problems which might arise may be due to the characteristics of the organism; or to engineering design of apparatus and equipment; or combinations of both. However, until the time that definite unresolvable problems due to the organism are determined, it is not logical to conduct a program to search for more desirable mutants since it is not known for which characteristics to screen, except for the more obvious ones; e.g., growth rate and culture density. The characteristics must first be established in order to develop adequate procedures of screening to select the desirable mutants. As was pointed out previously, this type of program is costly and time-consuming with no guarantee of success. Definite characteristics desired in the mutant must be specified if there is to be any resonable chance of success.

Conclusions

In response to the question of whether or not more desirable strains of algae or Hydrogenomonas can be found for bioregenerative systems, the following conclusions have been developed:

- The relatively low probability of developing a strain of algae that can overcome the lighting and large culture volume problems associated with known algae systems does not justify the expense of such a program.

- It is recommended that other known natural species of Hydrogenomonas be screened and compared with H. eutropha.

- It is not advisable to search for induced mutants of Hydrogenomonas until the characteristics of the presently proposed system are determined and, therefore, the primary research effort should be on investigations of continuous culture of Hydrogenomonas entropha or other naturally occurring species.

THE USE OF RADIOISOTOPE-PHOSPHORS FOR ILLUMINATION OF ALGAE

The comparison of biological and physiochemical food-producing systems conducted during Phase I of "Study of Life Support Systems for Space Missions Exceeding One Year in Duration" pointed out the primary disadvantages of an algal system to be the large weight penalty for lights, light fixtures, lighting controls, and large culture volume, and the power penalty for lighting. The concept of using a radioisotope-scintillator combination as a source of light in an algal system was discussed in the research and development specifications report (LMSC 4-06-66-6, Appendix I, March 15, 1966). In such a system, small radiation sources are placed in a scintillator material and the resulting pellets are placed in the algae growth chamber. By mixing the light source with the algae, the culture chamber can be simplified to a spherical shape, the culture volume can be reduced, and the lights, fixtures, and controls can be eliminated. The light sources are held in the growth chamber by screens. The algae circulation, gas exchange, nutrient makeup, and harvesting systems would not be affected by this new concept.

Calculations based on a set of reasonable assumptions show about 400 lb/man weight savings for a radiophosphor-illuminated algae system as compared to an electrically illuminated system which is based on a 600-gm/day algae production rate and 100-lb/kw power penalty. The required volume is a factor of nine lower, and the algae growth chamber can be arranged as a sphere 2 ft in diameter. Radiation exposure of the algae is small compared to the 10^4 rad dose which, as noted in the literature, shows no effect on Chlorella pyrenoidosa. Table 1 presents the basic radiophosphor design, and Table 2 compares it to the electrically illuminated growth chamber. Inspection of the weights listed in Table 2 will show that much of the weight savings associated with the elimination of the lighting system and the power penalty are lost with the addition of the radiophosphor light sources; substantial weight savings, however, are still realized.

The remaining discussion of the use of radiophosphor for illumination of algae presents an analysis of the system.

Illumination Conditions and Growth Chamber Design

Below a threshold irradiance of 3.5 mw (light)/cm^2, algae yield per unit light flux is constant at 31.5 gm/kw hour (light), for light in the range of 4000 to 7000 A (ref. 44). Higher irradiance is wasteful of power; i.e., at twice saturation irradiance, algae yield is 69% higher than at saturation irradiance; at three times saturation, the yield is 110% higher; and at ten times saturation irradiance, the yield is only increased 230%. Saturation irradiance was therefore used for further calculations.

At the 600 gm/man-day algae requirement, and at saturation irradiance, 0.792 kw (light) is needed. To meet the maximum irradiance requirement, an area of at least 2.26×10^5 cm^2 (244 ft^2) is needed. From other considerations the volume of the radiophosphor dispersion is 5.48×10^4 cm^3 (1.95 ft^3). These two figures give the maximum

TABLE 1

CHARACTERISTICE OF RADIOPHOSPHOR ALGAE LIGHT SOURCE

Radioisotope:	Promethium 147
	• Half-Life 2.67 hr
	• Pure Beta Emitter 67 keV (av.), 230 keV (max.)
	• Specific Power 0.362 w/gm (6.1 lb/kw)
	• Required Total Disintegration Power 9.1 kw
Scintillation Phosphor:	Calcium Iodide
	• Conversion Efficiency 25% (Emitted Proton Energy/Incident Particle Energy)
	• Emission Spectrum Centered at 4700 A, 280 A Full Width at Half Maximum
Radiophosphor Dispersion:	Radioisotope, Phosphor, and Coating Mixture
	• 10% by Weight Radioisotope
	• Assumed Conversion Efficiency 10%
	• Light Source Size 1.45 cm Diameter Spheres
	• Total Light Source area 2.26×10^5 cm (244 ft^2)
Algae Growth Chamber:	Two-Foot-Diameter Sphere
	• Total Volume Algae Solution Plus Radiophosphor 110 liters
	• Apparent Algae Solution Thickness (Solution Volume/Illuminated Surface) 0.24 cm
	• Illumination at Algae Solution Surface 3.5 mw light/cm^2
	• Specific Algae Yield 31.5 gm/kw-hr (light)

TABLE 2

COMPARISON OF RADIOPHOSPHOR AND ELECTRICALLY ILLUMINATED ALGAE GROWTH CHAMBERS

(One-Man System)

Equipment	Weight (lb) Radiophosphor System	Electrically Illuminated System
Lighting System (Lights Fixtures and Controls or Radiophosphors)	556	80
Culture Chamber (1 cm Plastic Panels or Sphere)	40	120
Culture (Nutrient and Algae)	160	260
Other Common Equipment	76	76
Subtotal	832	536
Power Penalty at 100 lb/kw	60	760
Total	892	1,296

size of an individual radiophosphor dispersion pellet as 1.45 cm (0.57 in.) diameter spheres, or cylinders with height = diameter = 1.28 cm (0.5 in.). At this size the pellets can be restrained by coarse screens to remain within the growth chamber, while the algae solution is circulated for gas exchange and harvested in a manner similar to that used in electrically illuminated systems.

For closely packed spheres, the void volume is about 30%. A figure of 50% is used in sizing the growth chamber, which leads to 54.8 liters for algae solution volume, and a total chamber volume of 109.6 liters (3.9 ft^3). As the light is presented to the algae outer surface at the saturation irradiance, there is no penalty involved in thick dense solutions. Even so, the effective thickness of the algae solution (volume divided by illuminated surface) is 0.24 cm, which is well below the 0.5 or 1 cm rule of thumb commonly used.

Radioisotope and Scintillator Selection

Required characteristics of the radioisotope are that it have a convenient half life, high specific power, and easily absorbed radiation, and that it be potentially available at reasonable cost. Among the radioisotopes examined but discarded were: cadmium–109 and cobalt–57 (specific power of about 1 mw/gm too low); curium–244 (required neutron shield thickness of 70 cm water for 10 kw source attenuated to 10 mrem/hr at 1 meter is excessive); and polonium–210 (half life of 0.38 yr is too short–during a 1 yr-mission, the light light output would decrease by a factor of 6.3). Note that remote location of the radioisotope has not been invoked herein as a method of avoiding shielding weight penalty, since as it is not believed to be realistic. delete

Plutonium–238 and promethium–147 are the radioisotopes that are best suited. The plutonium isotope has an 89-yr half life, a 0.56 w/gm specific power, and is mainly an alpha emitter. Neutrons emitted require about 30 cm of water shield (10 kw source shielded to 10 mrem/hr at 1 m), much of which would be provided by the algae solution and the scintillator dispersion.

Promethium–147 has been selected as the reference radioisotope. Its characteristics are (refs. 45 and 46):

Half-Life	2.67 yr	
Specific Power	0.362* w/gm (6.1 lb/kw)	
Disintegration Mode	Beta emitter	67 keV average energy 230 keV maximum energy
Estimated Cost	$90/w	
Annual Availability	11 kw	

The basis for selection of promethium–147 over plutonium–238 is a factor of 10 lower estimated cost, the absence of possible lattice damage problems due to helium production, the comparable range of the emitted radiation, and the comparable specific power.

The range in promethium metal for the average beta energy is 1.6×10^{-3} cm and for the maximum beta energy is 1.6×10^{-2} cm. By restricting the dimensions of the promethium to a fraction of the range, self-absorption can be made negligible. A reasonable and easily attainable size is something like 1.6×10^{-4} cm or 1.6 μ. (Note that uranium dioxide is commercially available in an average size of 0.4 to 4 μ diameter.) A dispersion of promethium particles of the required size in the selected scintillator should exhibit a conversion efficiency comparable to that of the pure scintillator.

The reference scintillator material is calcium iodide (europium activated). At the reported 25% conversion efficiency (ref. 47), CaI_2 is twice as efficient as sodium iodide, the present standard scintillator. The correct conversion efficiency can only be

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* Values from 0.33 to 0.397 are quoted in the literature. The most accurate is probably 0.377 measured at Oak Ridge National Laboratory. This would reduce quoted weights by 4%.

by The use of anthracene, plastic scintillators or glass scintillator microcrystals, 0.5 - 10 μ diameter.

estimated previous to an experimental determination. A factor of 2.5 degradation in conversion efficiency has been allowed. This seems reasonable, in light of two factors. One is that Harshaw Company is now offering commercially scintillation crystals of sodium iodide doped with an alpha emitter, americium-241. The technique being considered is similar. The second factor is the success of a technique for detecting low energy radiation in which use is made of microcrystals which are 0.5- to 10-μ diameter and which are made of anthracene, plastic scintillator, or glass scintillator. Should conversion efficiency drop too much, the alternative of using a solid plastic solution scintillator as the matrix material is possible. Conversion efficiency of plastic scintillators should not be affected by dispersing foreign material in the plastic. As the conversion efficiency is about 3.8%, about three times the inventory of radioisotope would be required should this alternative be needed.

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The final assumption required to calculate the system weight is the loading of radioisotope in the radioistope mixture. A value of 10% by weight was assumed for end-of-life conditions. The fraction of total radioisotope disintegration energy reaching the scintillator is directly proportional to the weight fraction of the scintillator in the mixture, or 90%. A further 5% allowance is made for self-shielding within the radioisotope. These factors, plus the assumed 10% nuclear radiation to light-conversion efficiency, lead to a 9.1-kw disintegration power requirement.

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THE CHEMICAL SYNTHESIS OF FATS AND PROTEINS

During the Phase I study, little attention was given to the physiochemical synthesis of fats or proteins in space. This omission was justified by the fact that carbohydrates were notably easier to manufacture and were known to be acceptable as a source of over 90% of the body's energy requirements. As missions increase in duration, however, even 10% stored food eventually becomes an important logistics consideration. Fats and/or proteins would also, at least potentially, add greatly to taste variety. In order to evaluate the advantages and disadvantages of fat and protein synthesis more fully, certain physiochemical methods for synthesizing edible fats, fatty acids, amino acids, proteinoids, and proteins have been studied. The existing literature has been searched for pertinent data on the desired processes; the following are reviewed: the German process, developed in the 1940's, which includes the manufacture of edible fats from carbon monoxide and hydrogen (Fischer-Tropsch synthesis); the pan-synthesis of amino acids and proteinoids from methane, water, and ammonia; and the synthesis of straight-chain amino acids from fatty acids.

A short review of the biosynthesis of amino acids and proteins by microorganisms from aliphatic hydrocarbon and other simple compounds is included because of its direct relation to the Fischer-Tropsch synthesis.

Synthesis of Fatty Acids and Edible Fats

Fatty or carboxylic acids from which fats are derived are all straight-chain compounds, ranging in size from 3 to 18 carbon atoms; except for the C_3 and C_5 compounds, only acids containing an even number of carbon atoms are present in any substantial amounts in natural fat. Besides saturated acids, there are unsaturated acids containing one or more double bonds per molecule.

During the years from 1935 to 1943, the Germans developed a completely synthetic process for the manufacture of edible fats from carbon monoxide and hydrogen (refs. 48 through 52). The carbon monoxide and hydrogen were obtained either as direct or indirect products from coal, petroleum, or refinery wastes. The $(CO+H_2)$ mixtures were then used in the Fischer-Tropsch synthesis for the production of hydrocarbons. This process was originally designed for the manufacture of synthetic gasoline and other fuels, and resulted in a number of byproducts. One of these byproducts is a soft paraffin wax with a boiling point range of 320° to 450° C. No careful chemical analysis has ever been made of this so-called Gatsch wax or Fischer wax, but it is known to consist of a mixture of normal paraffins with chain lengths of C_{20} to C_{30}, plus small amounts of isomeric branched paraffins, olefines, aromatics, and oxidation products. This wax after purification was cleaved by oxidation to form a mixture of carboxylic acids, mainly the normal aliphatic acids. This mixture was then purified and reacted with glycerol to form triglycerides or synthetic fat. This synthetic fat differed from natural fat in that it contained odd-numbered acids (i.e., number of carbon atoms) in a 50% mixture with the even acids, and contained more saturated acids. The resulting fat, which closely resembled lard, was then purified by treatment with superheated steam and used in extensive human and animal tests before receiving limited approval by the German government for consumption as food. This synthetic product, however, proved uncompetitive with natural fats. Research was therefore not continued.

NON

Since 1943, a number of developments related to the Fischer-Tropsch reaction have made it possible to improve upon the German process in many respects. These developments have included the use of: iron, cobalt, nickel, ruthenium, zinc oxide, and thorium oxide catalysts; various temperature and pressure ranges; and a number of space velocities. In addition, the kinetics and thermodynamics of many of the pertinent reactions have been worked out, with the result that more complete analyses are possible. The most favorable of these, the medium-pressure synthesis using iron catalyst, produces about a 20% yield of soft paraffins, but requires pressures of 20 to 30 atm and temperatures of 220° to 255°C. Generally, all of the steps of purification previously used are still required.

Summary of considerations of edible fat synthesis. – Some variation of the German process using the Fischer-Tropsch reaction of CO and H_2, or perhaps the controlled polymerization of ethylene in a Ziegler reaction as recently recommended by the Esso Research and Engineering Company (NASA Contract NAS 2-3708) seems minimally feasible for space application as a method of producing edible fatty acids from human wastes. The problems, however, seem to be of one to two orders of magnitude greater than those involved in the synthesis of a simple carbohydrate or glycerol. At this time, there seems to be no cogent nutritional reason why more than a trace of fatty acids are necessary in the diet. The complex nature of the synthesis process seems to preclude its development for spacecraft use in the mission-duration category of 1 to 3 yr. If longer missions are considered and the need for significant quantities of fat in the diet is established, perhaps fat synthesis may be a candidate for inclusion in the system.

If further work were to be done in this field, the following three considerations would apply:

- The use of modern chemical techniques such as spectroscopy (IR, UV, NMR, ESR, Visual, etc.), chromatography (gas, column, thin-layer, etc.), mass spectrometry, and molecular distillation should be investigated for both the separation and analyses of the various components during and after synthesis. One especially useful development has been the use of zeolites and molecular sieves in separating the desired straight-chain aliphatics from other reaction products.

- As recommended by the Germans, further physiological testing must be completed before the feasibility of fat synthesis for food can be established. With today's modern clinical techniques and instruments, exhaustive and complete studies could be made, especially upon the effects of synthetic fats on human metabolism and the metabolic route of the odd fatty acids. One important example of the need for further testing has been the discovery in petroleum waxes of carcinogens, i.e., benzopyrene and dibenzanthracene, by the use of gas chromatography. Molecular sieves have been found to be extremely useful in separating aromatics (including carcinogens) from aliphatic hydrocarbons.

- Thermodynamic and kinetic data are now available for the Fischer-Tropsch reaction (ref. 53). The free energies and the equilibrium constants have been recently calculated for the formation of the fatty acids (ref. 54). These data can now be utilized to calculate the optimum reaction conditions for the various steps in the synthesis process.

Synthesis of Amino Acids and Proteins

Unlike the situation for fats, as mentioned previously, a substantial requirement for proteins is well documented; this is about 35 gm/day for an average man. A high acceptance diet for citizens of the United States would probably include about 100 gm of protein/day. The extra protein would have high morale value as steak. Its value when served as amino acid broth is, to say the least, questionable. At the present time, only simple amino acids or polypeptides can be synthesized from simple inorganic compounds, and even these processes are quite complicated. Since the penalty for carrying the minimum supply of protein is only about 36 lb/man/yr, it seems unlikely that extensive development efforts in this area can be justified.

Amino acids. – Twenty-six amino acids occur naturally (Table 3), ten of which are essential to human nutrition. All of these have been chemically synthesized and the chemical literature abounds with thousands of syntheses for specific amino acids. However, most of these syntheses begin with relatively complex organic intermediates and under laboratory conditions which render them impractical or unsuitable for present space applications.

In 1955, S. L. Miller (ref. 55) reported his experiments with electric discharges (spark and silent) through enclosed atmospheres of methane, ammonia, hydrogen, and water to simulate primordial conditions and reported the findings of milligram quantities of the following amino acids: aspartic, glutamic, glycine, alanine, α-amino butyric, β-alanine, sarcosine, and N-methyl alanine; none of these are essential amino acids.

Later, others performed similar experiments utilizing other sources of energy such as ultraviolet light, α-, β-, γ-, and x-rays. Most promising of these, however, is the work of Fox and Harada (refs. 56 through 60) using thermal heat as the energy source. By bubbling methane through 14N aqueous ammonia and passing it through solid silica gel or silica sand and heating the mixture in a glass "vycar" vessel at 900° to 1100°C, 14 to 15 amino acids were synthesized (Table 4). Although the actual yields were very small (the authors do not specify yields by weight), 14 of the 18 amino acids common to protein are synthesized by this process simultaneously.

The 4 amino acids which were missing are: trytophan, histidine, cystine, and methionine. The first two were not detected because of analytical difficulties, and the last two were not expected since sulfur was not utilized in the process.

This thermal synthetic technique seems to be the most promising of all existing techniques because of the larger variety of amino acids produced and the possibility of larger yields and commercial applications. At the present time, however, all of the research being carried out in this area appears to be in its nascent stages and a great deal of work will have to be done before useful applications can be made. Suggestions for areas of further research in the thermal synthesis are:

(1) Use of pure ammonia, liquid or gas, instead of the aqueous ammonia solution, since current work indicates higher yields under anhydrous conditions, due to the omission of hydrolysis of reaction products

TABLE 3

NATURAL AMINO ACIDS

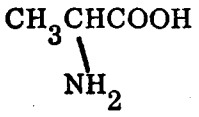
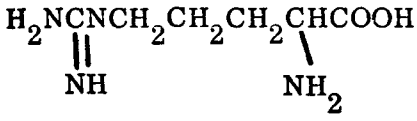
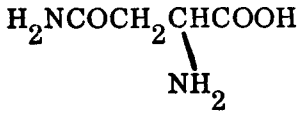
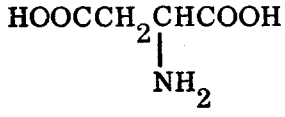
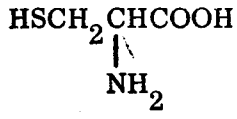
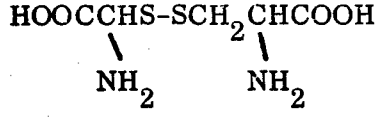
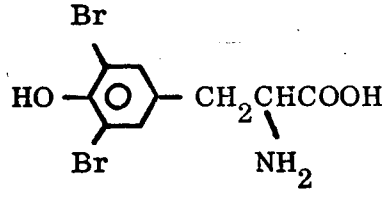
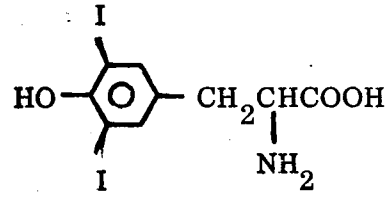
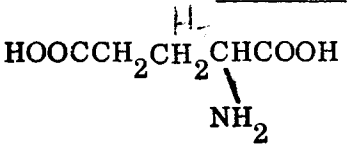
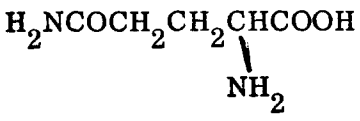
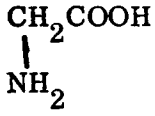
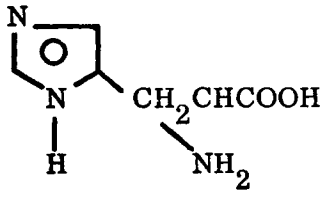
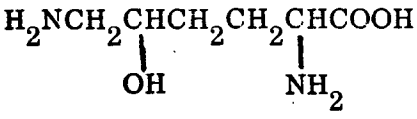
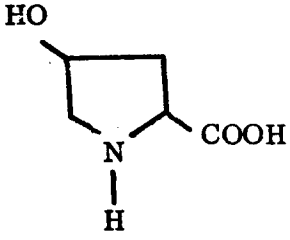
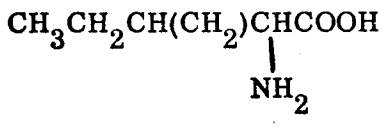
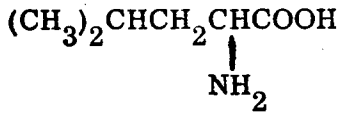
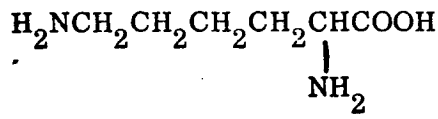
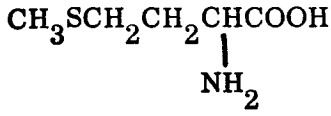
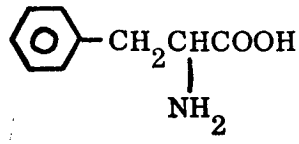
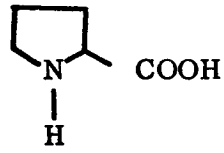
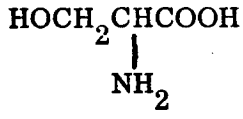
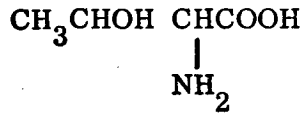
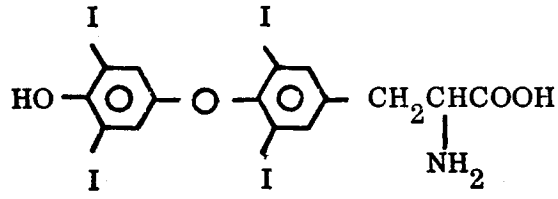
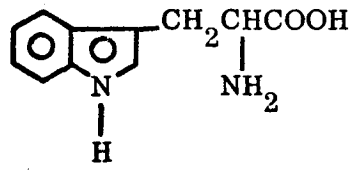
Name	Formula
(+) Alanine	
(+) Arginine	
(-) Asparagine	
(+) Aspartic Acid	
(-) Cysteine	
(-) Cystine	
(+) 3,5-Dibromotyrosine	
(+) 3,5-Diiodotyrosine	

TABLE 3 (Cont.)

Name	Formula
(+) Glutamic Acid	
(+) Glutamine	
Glycine	
(-) Histidine[(a)]	
(-) Hydroxylysine	
(-) Hydroxyproline	
(+) Isoleucine[(a)]	
(-) Leucine[(a)]	

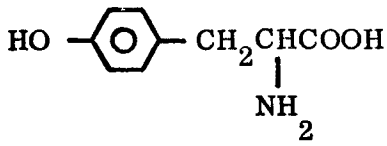
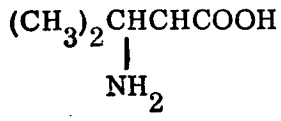
(a) Essential amino acid.

TABLE 3 (Cont.)

Name	Formula
(+) Lysine[a]	
(-) Methionine[a]	
(-) Phenylalanine[a]	
(-) Proline	
(-) Serine	
(-) Threonine[a]	
(+) Thyroxine	
(-) Tryptophane[a]	

(a) Essential amino acid.

TABLE 3 (Cont.)

Name	Formula
(-) Tyrosine	
(+) Valine[(a)]	

(a) Essential amino acid.

TABLE 4

AMINO ACID COMPOSITIONS PRODUCED THERMALLY IN THE PRESENCE OF SILICA

Amino Acids	Silica Sand 950°C (%)	Silica Gel 950°C (%)	Silica Gel 1050°C (%)
Aspartic acid	3.4	2.5	15.2
Threonine	0.9	0.6	3.0
Serine	2.0	1.9	10.0
Glutamic acid	4.8	3.1	10.2
Proline	2.3	1.5	2.3
Glycine	60.3	68.8	24.4
Alanine	18.0	16.9	20.2
Valine	2.3	1.2	2.1
Allo isoleucine	0.3	0.3	1.4
Isoleucine	1.1	0.7	2.5
Leucine	2.4	1.5	4.6
Tyrosine	0.8	0.4	2.0
Phenylalanine	0.8	0.6	2.2
α-NH_2-butyric acid	0.6	–	–
β-Alanine	(b)	(b)	(b)

(b) β-Alanine peak obscured by other unknown peak.

(2) Use of sulfur and/or sulfur compounds in the reaction to attempt the synthesis of sulfur-containing amino acids; e.g., cystine and methionine

(3) Study of the effect of varying the reaction pressures above ambient

One important fact which must not be overlooked is that the amino acids resulting from the above synthesis are racemic; i.e., equimolar mixtures of the optical D- and L-isomers, whereas natural amino acids have the L-conformation. Although there seems to be a genuine lack of information in this respect, it has been reported that D-isomers and DL-mixtures of amino acids produce gastronomical disturbances in humans. Hence, amino acids synthesized in this manner would first probably have to be resolved into their separate isomers before they could be utilized as food.

Another interesting synthetic pathway is the synthesis of linear α-amino aliphatic acids from the corresponding α-bromo carboxylic acids. Using the fatty acids produced in the fat synthesis, many of the C_{10}-C_{18} acids can first be converted into α-bromo acids by the Hell-Volhard-Zelinsky reaction (ref. 61)

$$RCH_2COOH + Br_2 \xrightarrow{P} \underset{\displaystyle Br}{\overset{\displaystyle |}{RCHCOOH}} + HBr$$

In this reaction, halogenation of the acid occurs exclusively at the α-position by an ionic mechanism in the presence of a small amount of phosphorous. Next, by reacting the α-halogenated acid with an excess of ammonia, the halogen is nucleophilically displaced and eliminated to yield the α-amino acid:

$$\underset{\displaystyle Br}{\overset{\displaystyle |}{R\text{-}CHCOOH}} + \text{large excess of } \underset{\displaystyle NH_3}{} \longrightarrow \underset{\displaystyle NH_2}{\overset{\displaystyle |}{RCHCOOH}}$$

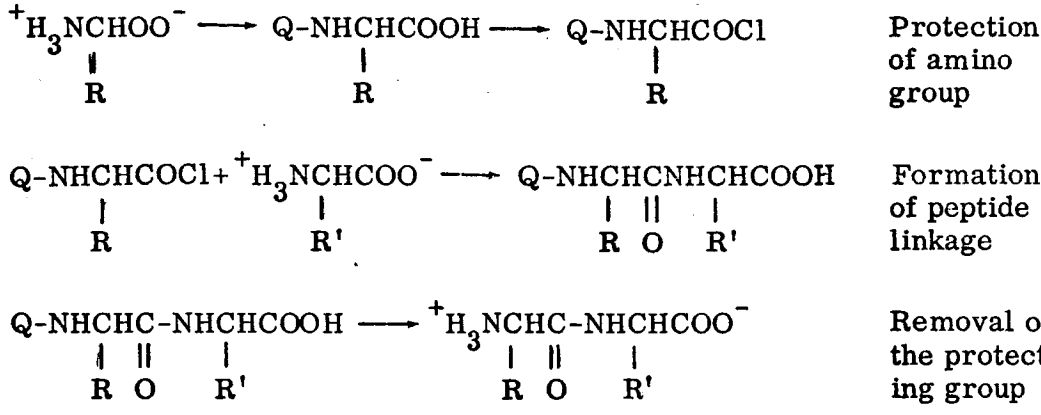
By this synthesis, the following α-amino acids were obtained, with very good yields: propionic 67%, butyric 64%, valeric 55%, hexanoic 74%, 2-methyl-hexanoic 100%, octanoic 100%, nonanoic 95%, decanoic 94%, hendecanoic 82%, lauric 100%, tridecanoic 80%, pentadecanoic 80%, palmitic 75%, heptadecanoic 100%, stearic 72%, and nonadecanoic 75%. The synthesis of mixed amino acids has been accomplished from the C_5-C_{10} and C_{10}-C_{20} acids (ref. 62).

Although α-amino propionic acid (alanine) is the only naturally occurring one, a nutritive study of both the individual and mixtures of the amino acids may prove interesting. Also, these amino acids could serve as intermediates for the synthesis of the more complex and essential ones.

Proteinoids (Polypeptides). – Peptides are amides formed by the interaction between amino groups and carboxyl groups of amino acids. The amide group, -NHCO- in such compounds, is often referred to as the peptide linkage.

Depending upon the number of amino acid residues per molecule, they are known as dipeptides, tripeptides, and polypeptides. By convention, peptides of molecular weight up to 10,000 are known as polypeptides and above that, as proteins.

Methods have been developed by which a single amino acid or di- or tripeptide can be polymerized to yield polypeptides of high molecular weight. The basic problem of peptide synthesis has been the protection of the amino group. In bringing about interaction between the carboxyl group of one amino acid and the amino group of a different amino acid, one must prevent interaction between the carboxyl group and the amino group of the same amino acid. Hence, the typical synthesis is:*



Recently, Fox and Harada (refs. 56 through 60) have demonstrated that polypeptides can be synthesized in a simpler way, the thermal panpolymerization of amino acids. This technique was formerly disregarded because of the total decomposition of amino acids when heated above the boiling point of water. This thermal technique is as follows: A mixture of 18 dry amino acids and sufficient aspartic and glutamic acids (dicarboxylic acids) are heated at 170°C for 6 hr; the resulting light-colored product is soluble in dilute alkali and can be reprecipitated by salting out, a standard purification technique. Yields are 10 to 40% and can be increased by the addition of various phosphates.

Analysis of the resultant polymer, which is called a "proteinoid," shows that it contains proportions of each of the 18 amino acids which have undergone little or no decomposition in this process. The polymerization yields products in the molecular weight range of 3500 to 8500. Structural analysis by x-rays shows that there is very little branching in the polymer molecule.

Two important properties exhibited by these proteinoids are: (1) the proteinoids are split by proteolytic enzymes and (2) nutritive quality.

The proteinoids can be used instead of peptone by Lacto bacillus arabinosus and by Proteus vulgaris. The former has amino acid requirements resembling those of man. Another principal inference from this work is that very complex compounds can arise in very simple ways.

Table 5 indicates another mode for synthesis of proteinoids through the Leuchs anhydrides of the amino acids. This kind of synthesis is far from simple. It requires the blocking of the reactive side chains of nine of the amino acids and the removal of the blocking groups, following polymerization. The amino acids, however, are not substantially racemized in this synthesis, and the proportions are less subject to internal control than are the proportions in thermal proteinoids. This synthesis can simulate exactly a natural protein in proportions of individual amino acids.

*Q = protecting group, R = alkyl group.

TABLE 5

FLOWSHEET FOR A SYNTHESIS OF LEUCHS PROTEINOIDS

A

O-Ac-DL-Threonine	(0.550 gm)
O-$PhCH_2$-L-Serine	(0.850 gm)
S-$PhCH_2$-L-Cysteine	(0.165 gm)
O-$PhCH_2$-L-Tyrosine	(0.520 gm)
L-Proline	(0.420 gm)
Glycine	(0.495 gm)
L-Alanine	(0.483 gm)
L-Valine	(0.428 gm)
L-Methionine	(0.149 gm)
L-Isoleucine	(0.480 gm)
L-Phenylalanine	(0.402 gm)
L-Tryptophan	(0.148 gm)

$\xrightarrow[\text{Dioxane}]{COCl_2}$ Crude mixture of 13 amino acid NCA's $\xrightarrow[\text{Acetone}]{Ag_2O}$ Halogen-free mixture of 13 amino acid NCA's (HFNCA's)

B

Freshly Prepared	
E-N-Cbzo-L-Lysine NCA	(0.945 gm)
N^W,N^{W1}-diCbzo-L-Arginine NCA	(1.572 gm)
HFNCA's + im-N-$PhCH_2$-L-Histidine NCA	(0.375 gm)
β-$PhCH_2$ L-Aspartate NCA	(1.320 gm)
γ-$PhCH_2$ L-Glutamate NCA	(1.670 gm)

$\xrightarrow[Et_3N]{\text{Dioxane}}$ Protected Leuchs Proteinoid (PLP) 8 gm

C

4g PLP $\xrightarrow[\text{Dialysis}]{NH_3(l)\text{-}Na,\ H_2O,pH3}$ Leuchs Proteinoid $\rightarrow$ Water Soluble 1.0 gm; Water Insoluble 0.4 gm

NCA = N-carbonic anhydride.
HFNCA's = Halogen-free N-carbonic anhydride.

Complementary use of these proteinoids may be most valuable.

replace with above

For the objective of nutritional investigation, the thermal proteinoid and the Leuchs proteinoid each has its own features. They may be most valuable when used complementarily. Composition, as indicated, can be controlled chemically and evaluated nutritionally. For the objective of space nutrition, the Leuchs proteinoid may be of particular investigative interest for missions requiring an optimally balanced nutritional polymer of amino acids. The thermal proteinoid should be more interesting for studies underlying chemical regeneration and studies aimed at prolonged missions.

Proteins. – Except for the work done by Fox and Harada on the synthesis of proteinoids and others on lower weight polypeptides (ref. 63), no work has been done in the area of protein synthesis from basic components by chemical means. However, work on the proteinoids seems very promising and these polypeptides of high molecular weight (3500 to 8500) may prove adequate substitutes in the human diet.

Biosynthesis of amino acids and proteins. – Parallel to the physiochemical synthesis of amino acids and proteins, which are both necessary and suitable for human nutrition, is the biosynthesis of nutritional materials from the metabolism of microorganisms utilizing hydrocarbons and other basic compounds. The extensive research and consequent success of the petroleum industry in this area suggest that consideration be given to such a concept. For example, Esso Research and Engineering Company has produced a food product containing 70 to 75% protein by growing Micrococcus cerificans in a solution of straight-chain aliphatic hydrocarbons. The Societe Francaise des Petroles reports similar success with yeasts; e.g., Candida lipolytica, or bacteria; Bacterium megaterium, B. subtilis or Pseudomonas aeruginosa in solutions containing kerosine, light or heavy gas oil, and lubrication oil. Japanese chemists have reported similar results. The Russians have reported producing carotenoids with petroleum fractions from the yeast Rhodotorula. More recent work by Shell Research, Ltd., has been with bacteria that metabolize methane, whereas Institut Francais du Petroles has been developing a process using algae that metabolizes carbon dioxide to yield a high protein food; the latter contains 62 to 68% protein, provitamin A, several B vitamins, and all essential amino acids except those containing sulfur.

Since the larger aliphatic hydrocarbons are the primary products of the Fischer-Tropsch synthesis, the possibility of coupling the the synthesis of the raw hydrocarbons from carbon monoxide and hydrogen and the biosynthesis of proteins and amino acids by microorganisms is potentially attractive.

Conclusions

In terms of practical chemical applicability, the German technique for the total synthesis of edible fats could be successfully adapted, with refinements, to space use. Further study in the purification processes and physiological testing would be necessary. The problem of the chemical synthesis of amino acids and proteins is more complex; intensive research in this area would be required before successful applications could be made. At the present time, the thermal pansynthesis of amino acids and proteinoids hold the most promise, although the investigation of using the fatty acids as intermediates in the synthesis of simple amino acids may prove rewarding.

The biosynthesis of amino acids and proteins holds immediate promise because of the variety, high yield, and relative lack of complex synthesis. The idealized system

might be a combination of physiochemical and biosynthesis processes, utilizing completely the products of the Fischer-Tropsch reaction for the manufacture of edible fats, amino acids, fatty acids, proteinoids, and proteins.

The fact remains, however, that manufacturing of even simple compounds like glycerol and ethyl alcohol are of somewhat marginal utility for 1- to 3-yr missions even when as much as 50 to 90% of the diet is considered. The complexity of synthesis and the relatively low requirement for fats and protein in the diet argue against the advisability of developing fat and protein synthesis methods for space application.

FORMALDEHYDE SYNTHESIS USING CHROMATOGRAPHIC REACTORS

Major emphasis in the Phase I study was placed on oxidation of methanol as the technique for producing formaldehyde, condensation of which yields edible carbohydrates. As was pointed out in the Phase I final report, direct oxidation of methane is a possible route to formaldehyde. The history of this process indicates that overoxidation is a serious problem. Several companies, including Celanese Corporation and B. A. S. F. of Germany, have tried unsuccessfully for a number of years to develop the methane oxidation process using more conventional reactors (ref. 64). Indications are that formaldehyde yields obtained were too low to make the process attractive even under spacecraft constraints. NASA-Ames Research Center is presently sponsoring work to determine the utility of conventional catalyzed methane oxidization methods for producing formaldehyde. As of this writing, yields of 1 to 1-1/2% per pass have been reported (ref. 65), but recycling had not yet been attempted.

A variation of the methane oxidization method which appears to have many advantages has been analyzed, and plant parameter estimates have been prepared. The process consists of oxidation of methane to formaldehyde using a chromatographic reactor:

$$CH_4 + O_2 \longrightarrow HCHO + H_2O$$

The synthesis works at ambient pressures and moderate (600°F) temperatures. Because of the difference in retention time of the reactants and the products (the chromatographic principle), overoxidation should not be an appreciable problem.

Process Chromatography

Although first introduced commercially only within the past ten years, gas chromatography is today widely used throughout the world for the analysis of gases and liquids, particularly in low concentrations.

The basic principle underlying gas chromatography is that a pulse injection of a mixture of vapors into a carrier gas passing through a column of suitable sorbent material will result in fractionation of the vapors; i.e., ideally the vapors will emerge from the column separately. This fractionation occurs because each component has a differing retentivity or heat of adsorption on the sorbent material. This difference results in varying retention times, since a component passes through the column via a number of adsorption-desorption steps, and the longer the desorption time the greater the heat of adsorption.

Process chromatography involves simply using the principles of gas chromatography with a technique (usually automated) for collecting the respective elution fractions separately. By introducing pulses of a mixture successively into the column, the mixture can thus be separated, purified, and collected in a device that does not depend on gravity for its operation. Process chromatography has a number of advantages over distillation

as a separation method, and the advantage becomes more pronounced for difficult separations (relative volatility less than 1.3). Some of the advantages are:

- Column heights about 1/10th those for distillation
- Operation in zero gravity
- Ability to overcome normal azeotropes
- Operation at lower temperatures – particularly advantageous for heat-sensitive compounds
- No requirement for vacuum operation
- Low residence times
- No mechanical entrainment limitations
- Amenability to automation and control

A new technological development proposed for use here is that of using a chromatographic reactor, in which chemical reactions can be carried out beyond the normal thermodynamic equilibrium (refs. 66 through 68). At the same time the advantages discussed in relation to process chromatography apply.

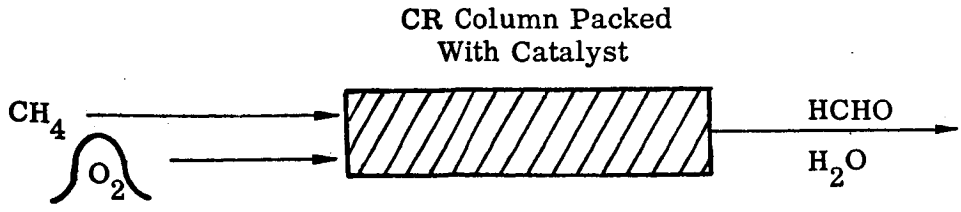
Formaldehyde and D-Fructose Synthesis

Synthesis of HCHO is discussed here using process chromatography and chromatographic reactors, where applicable, to steps in the basic processes outlined in LMSC 4-06-66-6 (final report, Contract NAS 2-3012).

The reaction scheme is envisioned as follows, with process chromatography indicated by the letters PC and chromatographic reactors by CR:

$$CH_4 + O_2 \xrightarrow{CR} HCHO + H_2O$$

This reaction would be performed by using CH_4 as the carrier gas and injecting repetitive pulses of O_2.



Injection volumes, column length, and temperature profile along the column would be selected to maximize the HCHO yield by inhibiting further oxidation. The CR unit also acts as a product purifier and separator.

Fructose synthesis from HCHO is less amenable to CR techniques because many of the reactions take place in solution and are homogeneous rather than heterogeneous.

More attention should be devoted to the following possibilities:

- HCHO $\xrightarrow[\text{MgOH Catalyst 4 to 5 hr at 130°C Under Pressure}]{\text{CR (He or } N_2 \text{ Carrier Gas)}}$ DL-Glyceraldehyde + Dihydroxyacetone

- DL-Glyceraldehyde + Dihydroxyacetone $\xrightarrow{\text{Conventional Synthesis as in LMSC 4-06-66-6}}$ DL-Fructose + DL-Sorbose

- DL-Fructose $\xrightarrow{\text{PC With Optically Active Column}}$ D-Fructose + L-Fructose

Very recent work has been done on the chromatographic separation of optical isomers using optically active columns. For example, in a chromatographic experiment using L-tyrosine resin as a column packing and methanol as the elutant, DL-mandelic acid was resolved partially; one fraction contained a 2% excess of D-isomer. Recycling should result in further enrichment. This is far from being a practical process step, and considerable research needs to be done to make it feasible.

A recent extensive review of knowledge concerning the oxidation of methane (ref. 69) contains summaries of the work done by various investigators such as Norrish and Semenov on the mechanism, kinetics, and equilibria involved. Unfortunately for our purposes, this work is concerned primarily with the homogeneous gas-phase reaction, i.e., not involving catalysts.

However, combining the above work with other reports of the catalytic reaction (ref. 70), we can conclude that the byproducts of methane oxidation to formaldehyde are: CO, CO_2, H_2O, and H_2. At pressures considerably above atmospheric, CH_3OH is also produced.

Overall chemical reactions (not mechanistic steps) in methane oxidation have been stated by Walker (ref. 71) as follows:

- $CH_4 + 1/2\ O_2 \longrightarrow CH_3OH$ $\quad \Delta H = -67.6$ kcal
- $CH_3OH + 1/2\ O_2 \longrightarrow HCHO + H_2O$ $\quad \Delta H = -37$ kcal
- $HCHO \longrightarrow CO + H_2$ $\quad \Delta H = 2$ kcal
- $HCHO + 1/2\ O_2 \longrightarrow CO + H_2O$ $\quad \Delta H = -56$ kcal
- $HCHO + O_2 \longrightarrow CO_2 + H_2O$ $\quad \Delta H = -124$ kcal

(Heats of reaction are at 298°K.)

The main difficulty in achieving high HCHO yields appears to lie not so much in preventing the thermal decomposition as in controlling the oxidation reaction. It is precisely this control which may be achieved using the technique of catalytic process chromatography.

Process Design

The proposed process for HCHO synthesis, incorporating recent LMSC technological developments, is shown in fig. 1.

The methane feed plus recycle stream is heated to close to reaction temperature. Oxygen injections into this stream are made at an appropriate frequency. This mixture is passed into the chromatographic reactor. The exiting product stream, which at this point contains water produced by the reaction, is cooled below the dew point in a condenser. Formaldehyde is very soluble in the water mist formed; this liquid phase is then continuously separated from the gas phase in a zero-gravity de-mister (water separator) unit. A 7-in. de-mister, developed by LMSC, has been tested and found to remove 100% of the water droplets in a gas stream of 100 CFM with a pressure drop of less than 1-in. H_2O (ref. 72). The HCHO product stream is thus removed at this point, and the remaining gas is passed through a regenerable CO_2 absorber before being recycled. This process has the great advantage of avoiding intermittent product collection, yet utilizing chromatographic reactor principles to "freeze" the reaction at an intermediate oxidation product (formaldehyde).

Overall material balance. – Basis:

HCHO Production Rate = 18.2 lb/day = 0.607 moles/day

The equilibrium constant for Reaction 1:

$$CH_4 + O_2 \rightarrow HCHO + H_2O \quad \Delta F^\circ = -68.9 \text{ kcal}$$

is so large that at equilibrium virtually 100% conversion of CH_4 is achieved.

Based on information in ref. 73 (also reported by Russian investigators in ref. 74), 90% of the methane reacted can be assumed to form HCHO with the balance yielding CO_2. Thus, the two reactions below are assumed:

90% yield: $CH_4 + O_2 \rightarrow HCHO + H_2O$

10% yield: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

HCHO output: 0.607 mole/day
CH_4 input: 0.607/0.9 = 0.674 mole/day
O_2 input: (0.674 - 0.607) + 0.674 = 0.741 mole/day
H_2O output: 0.741 mole/day

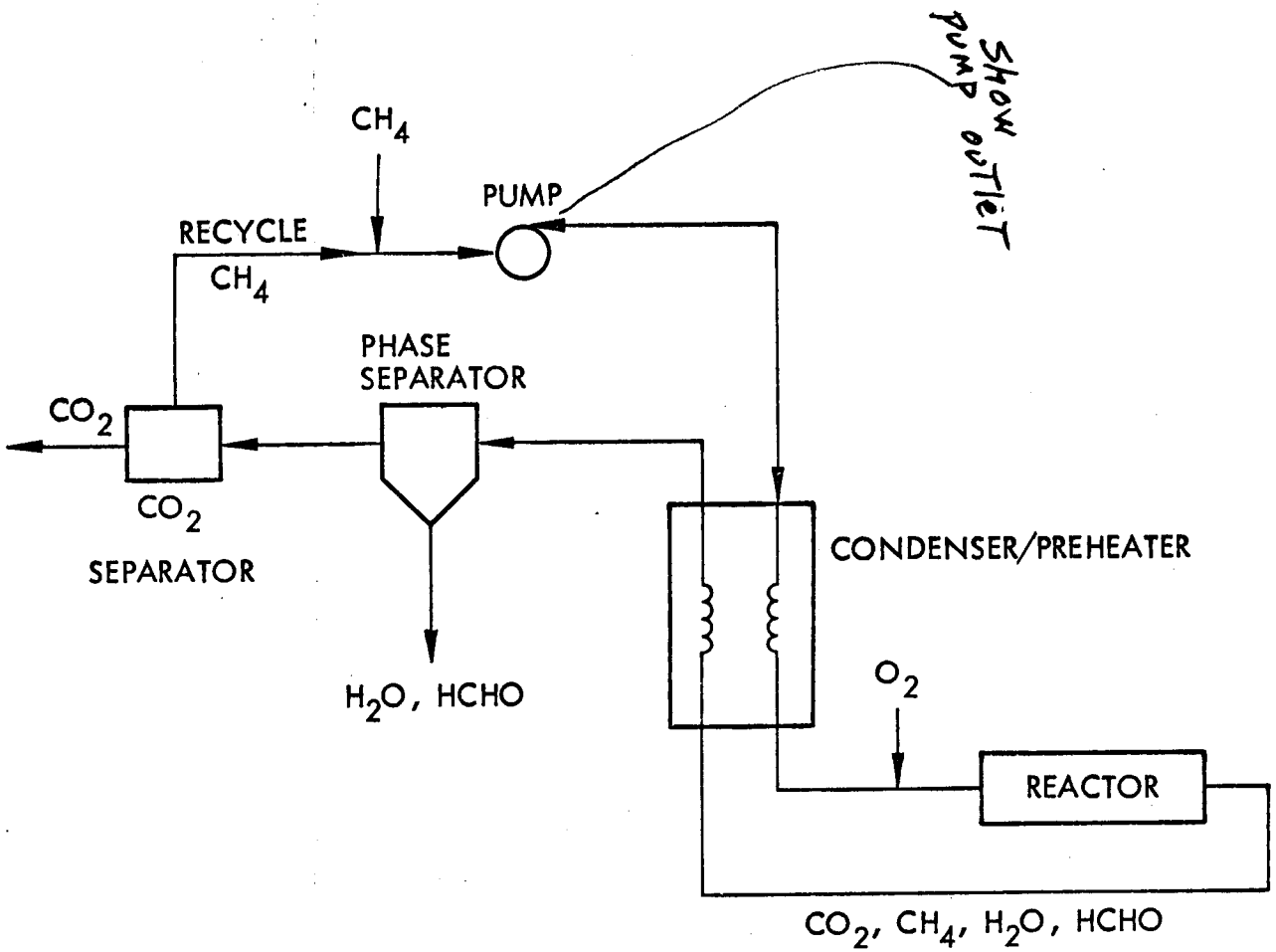


Fig. 1 Formaldehyde Synthesis Flow Chart

Chromatographic reactor design. – Two general criteria must be met in designing the reactor:

- Sufficient contact time for kinetic conversion to occur
- Good separation of HCHO and O_2 to avoid further oxidation

To perform design calculations, certain minimum information is required, such as adsorption isotherms of the gases in question on the catalyst, pore diffusivities, and kinetic information including rate orders on the catalytic reactions occurring.

Because this information is lacking, a number of assumptions have been made to estimate design magnitudes. It is strongly urged that the required information be experimentally obtained in order to confirm these assumptions.

Kinetic considerations. – If the form of the rate equation is found to be $r = kc^n$, and the order n is determined, the rate equation can be integrated to give the relationship between rate constant, conversion, and space velocity.

Since rate-equation information is not available, the following assumption is made: Since CH_4 is present in great excess, and O_2 is not appreciably adsorbed,

$$r = k' C_{O_2} C_{CH_4} = k C_{O_2} .$$

Thus, the rate is assumed to be first order, and, upon integration:

$$\ln \frac{1}{1 - x} = \frac{k}{s}$$

where

x = conversion
k = rate constant
s = space velocity
C = partial pressure of reactant

A generalized correlation of k/s vs. conversion has been prepared (ref. 75) for convenience in extrapolating from one set of operating conditions to another.

Otsuka et al. (ref. 76) using a copper oxide catalyst in a conventional reactor, found 4% conversion of CH_4 to HCHO at $s = 100{,}000\ hr^{-1}$ and $T = 850°C$.

From these data and the generalized correlation mentioned above, 4% conversion corresponds to $k/s = 0.05$. At a desired conversion of 99%, $k/s = 5.0$. Thus, the design space velocity $s = 100\ hr^{-1}$.

Separation requirements. – If sufficient experimental information were available, the desired separation and peak shape description could be calculated from present theory (ref. 77). The following procedure would be followed: Assuming O_2 is not

adsorbed, its stoichiometric time t_s is the retention time of the carrier gas. A Peclet number, $Pe = du/D_f$ is calculated, where d = particle diameter, u = fluid velocity, D_f = thermal diffusivity, and a particle diffusivity estimated. The number of theoretical plates N is then evaluated from a generalized plot of Peclet number vs. N such as appears in refs. 77 or 78.

From N and t_s the peak width w can be calculated from the relation

$$N = 16(t_s)^2/w .$$

A similar procedure applies to HCHO except that to obtain t_s the adsorption coefficient Ka is required: $t_s = Ka\ m/F$, where F = flow rate, and m = mass of catalyst.

A suitable separation criterion would be that

$$(t_s)_{HCHO} - (t_s)_{O_2} \sim (W_{O_2} + W_{HCHO})/2$$

in less than about 10% of the total bed length. This would fix the cycle time, although an optimization of cycle time vs. loss of HCHO, via oxidation to CO and CO_2, should be performed. Kinetic data would be needed for such an optimization.

An estimate of the flow requirement for adequate separation can be made from the chromatographic data of Sandler and Strom on HCHO (ref. 79). Calculation of a Peclet number Pe from their data follows:

$$Pe = \frac{du}{D_f} = \frac{10^{-1} \times 164}{0.01} = 1640 .$$

Space velocity s in their column is as follows:

4-ft column = 120 cm
Column volume = 14.6 cm^3
F = 20 cm^3/sec
S = 4930 hr^{-1}

From the relation between Pe and N, the Pe can be reduced by more than an order of magnitude with no decrease (in fact, an increase) in column-separation efficiency.

Thus, our design space velocity of 100 hr^{-1} appears to be acceptable from the point of view of separation requirements.

At this point, a calculation of column throughput and size is needed. Lacking such information as stoichiometric times, the best possible case in the chromatographic mode will be considered. The wave shapes in the column are assumed triangular and abutting, and the peak HCHO concentration is assumed to be 10%. These assumptions give a column methane throughput rate of 60 × HCHO output. Assuming a 50% void volume in the column and the 100 hr^{-1} space velocity, reactor size can be calculated and weight estimated.

A heat balance on the system shows that sensible heat to supply reactant gases is close to latent heat that needs to be removed to condense product water; a preheater-condenser unit is assumed to handle this heat exchange. Heat of reaction must be removed from the chromatographic reactor. Pumping power required is estimated based on the circuit pressure drop and a mechanical efficiency of 75%. Table 6 shows the resulting process estimates for the entire synthesis starting with CH_4 and O_2. As in the previous work, estimates have been doubled to account for uncertainties. Process steps following HCHO synthesis are assumed to be the same as estimated previously.

TABLE 6

GLYCEROL SYNTHESIS PLANT ESTIMATES – FORMALDEHYDE VIA CHROMATOGRAPHIC REACTOR OXIDATION OF METHANE

Step	Weight (lb)	(10 Men) Electrical Power (kw)	Thermal Requirements (kw)	
			Heating	Cooling
Formaldehyde (18.2 lb/day)	360	1.0	–	0.8
Trioses (13.4 lb/day)	20	nil	0.08 (200°F)	0.008
Glycerol (13.0 lb/day)	160	nil	6.7 (200°F)	6.7
Waste Incinerator (5.5 lb/day)	15	–	neg.	0.4
	555	1.0	6.78 (200°F)	7.98

CHEMICAL SYNTHESIS OF GLYCEROL USING ACETYLENE AS AN INTERMEDIATE

The use of acetylene as an intermediate in glycerol production has been proposed as an alternate to the formaldehyde-triose-hydrogenation route advocated in the Phase I study. In this section, acetylene production methods potentially suitable for spacecraft operation are discussed, subsequent routes to glycerol are outlined, and the conclusion that the formaldehyde route is preferable is explained.

Acetylene Production

At least three schemes could be used to synthesize acetylene from metabolic wastes. One scheme is to heat carbon (obtained from a Bosch reaction) with calcium oxide to form calcium carbide. Hydrolysis then yields acetylene and regenerates the calcium oxide. The high temperature and power required make it unnecessary to consider this carbide scheme further.

Thermal cracking of methane (obtained from a Sabatier reactor) is feasible:

$$CH_4 \rightarrow 1/2\ C_2H_2 + 3/2\ H_2 \qquad \Delta H^\circ = 96.7 \text{ kcal}$$

$$\Delta F^\circ = -1.2 \text{ kcal}$$

As shown by the enthalpy change at 820° C, the reaction requires high-energy input. The free energy change of -1.2 kcal at 820° C is modestly favorable but the competing reaction:

$$C_2H_2 \rightarrow 2C + H_2 \qquad \Delta F^\circ = -34.4 \text{ kcal}$$

has a much more favorable free-energy change. Thus, successful acetylene production is dependent on reaction kinetics rather than equilibria; i.e., in the reaction chain, methane $\xrightarrow{k_1}$ acetylene $\xrightarrow{k_2}$ carbon + hydrogen, the rate constant k_1 must be fast compared to k_2, or the reaction quenched at acetylene with critical process control. Hoppel, Othmer, and Kramer have studied the reaction kinetics and have reported that at temperatures of 1700° to 1800° C yields of 95% or greater acetylene and little carbon formation are obtainable. Similar pyrolysis reactions using flame heating are known, but characterized by yields of 10 to 30% (ref. 80).

Microwave plasma processes for reducing methane to acetylene are presently under study by Battelle Memorial Institute, sponsored by the Research Systems Branch of AMRL (ref. 81). Table 7 gives the results of recent tests using 2450 Mc/sec frequency. The specific power requirement calculated for Test 1 is about 200 kw-hr of microwave power per pound of acetylene. It is amusing to compare this to the 7.5 kw-hr/lb quoted for commercial electric arc processes by ref. 80.

INTERESTING

TABLE 7

REACTION OF METHANE IN MICROWAVE PLASMA

Test Number	Temp. (° C)	Pressure (mmHg)	Microwave Power Input (w)	Tube ID (mm)	Methane Flow Rate (gm/min)	Products
1	~ 35	10 to 20	250	25	0.11	9.2% C_2H_2 10% C_2H_6 No Carbon, Polymers, or Liquids
2	> 50	10 to 20	430	25	not specified	78% C_2H_2 12% C_2H_6 Liquids Formed and Polymers Deposited
3	950 to 1000	10 to 20	570	7	0.073	Polymers and Carbon

It appears that spacecraft synthesis of acetylene would be characterized by very high power and weight penalties. However, even if acetylene were easily available, its utility in glycerol synthesis, as the following section indicates, is by no means clear.

Acetylene to Glycerol

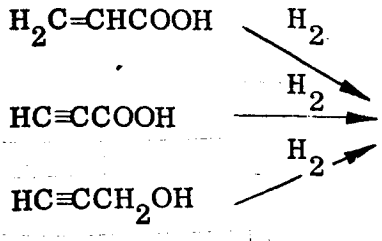
A number of reactions may be used to produce glycerol, starting with acetylene, as shown below:

$$C_2H_2 \xrightarrow[\text{catalysis}]{CO,\ H_2O} H_2C{=}CHCOOH \qquad \text{(step 1a)}$$

$$C_2H_2 \xrightarrow[\text{base}]{CO_2} HC{\equiv}CCOOH \qquad \text{(step 1b)}$$

$$C_2H_2 \xrightarrow[\text{base, cat.}]{HCHO} HC{\equiv}CCH_2OH \qquad \text{(step 1c)}$$

Any of these intermediates could then be reduced to allyl alcohol:



(step 2)

The final step in glycerol synthesis would then be conversion by hydroxylation:

$$H_2C{\equiv}CHCH_2OH \xrightarrow[\text{catalysis}]{H_2O_2} CH_2OHCHOHCH_2OH \qquad \text{(step 3)}$$

This appears to occur by the intermediate formation of an epoxide:

$$H_2C{\equiv}CHCH_2OH \xrightarrow[\text{catalysis}]{H_2O_2} H_2C\overset{O}{\diagup\diagdown}C - CH_2OH \xrightarrow{H_2O} CH_2OHCHOHCH_2OH$$

Rather than H_2O_2, HOCl could be used to form the epoxide.

Conclusion

Consideration of this set of possible reactions shows that in all cases consumable reactants such as formaldehyde (HCHO), hydrogen peroxide (H_2O_2), or hypochlorous acid (HOCl) must be synthesized. A study of these alternatives resulted (ref. 80) in the selection of Steps 1c, 2 and 3 as the glycerol synthesis route. The catalyst for Step 1c is copper acetylide which is extremely hazardous when dry. Both Steps 1c and 3 require additional reactants (HCHO and H_2O_2) on a mole-for-mole basis with the glycerol production. As HCHO production is the basis of the alternate glycerol synthesis scheme, the comparative evaluation goes as follows:

- Synthesis via acetylene – Produce n moles of acetylene, n moles of formaldehyde, n moles of hydrogen peroxide; then run series of three reactions to get glycerol.
- Synthesis via formaldehyde condensation – Produce 3n moles of formaldehyde; then run two reactions to get glycerol. This process is recommended. It should be noted that in a similar evaluation, the same conclusion was reached by another group (ref. 80).

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ANIMAL LINKS IN THE CLOSED SYSTEM

During Phase I of this study, the closed systems considered were those involving the synthesis of a single food. The single food was either a chemically synthesized compound or a simple plant. It was shown that such diets, with modest supplimentation, could supply all of man's known nutritional needs. Human experiments of duration as long as six months were reviewed which indicated a lack of significant evidence of physiological or performance decrement as a direct result of continuous intake of comparable artificial monotonous diets.

The fact remains that all psychologists and nutritionists consulted, not to mention the potential consumers, expressed grave doubt that such a diet would prove psychologically satisfying in space. This doubt is based on many factors, ranging from the need for stimulus of enzyme flow through sight and smell stimuli and the need for satiety, to the little understood, but sharply felt, need for variety of texture and taste just to make life worth living. An analysis of the validity of these doubts is not within the scope of this study. Based, however, mainly on the desire to increase the psychological acceptability of a space diet, some investigation was made of the possibility of including animal links in the closed system. A system is selected and the logistics associated with its use are indicated.

The Man-Plant-Animal System

Figure 2 is a simplified schematic diagram of a closed system with one type of plant and one type of animal ("animal" in this section means food source, not man). Only the major processing steps are shown, i.e., those requiring major chemical modification. In a weightless space cabin, every step requires elaborate techniques for collection, storage, and distribution.

Before the detailed analysis is made, an overview is helpful. The first assumption will be that one half of the man's calories will be supplied by eating the plant and the other half by eating the meat from the animal. This assumption is not made entirely for the mathematical convenience of the authors but in fact reflects the approximate preferred diet of the U.S. middle class. The problem is to provide a nutritious and appetizing diet to the human while balancing all inputs and outputs and while minimizing both processing and required stored metabolic supplements. The last two requirements are complementary in that the more the processing, the fewer the stores required, and vice versa.

Difficult as it is to develop a feasible system of the type shown in fig. 2 for spaceflight, it is not quite as difficult as it might appear in one respect, viz., balance. In the past, undue emphasis has been placed on the precise balancing of RQ's of man with PQ's of plants, water requirements with water production, etc. These problems of imbalance are generally resolved by adding modest amounts of physiochemical processing to the system, e.g., oxidation of cellulose fibers to carbon dioxide and water, electrolysis of water, incineration of feces, etc.

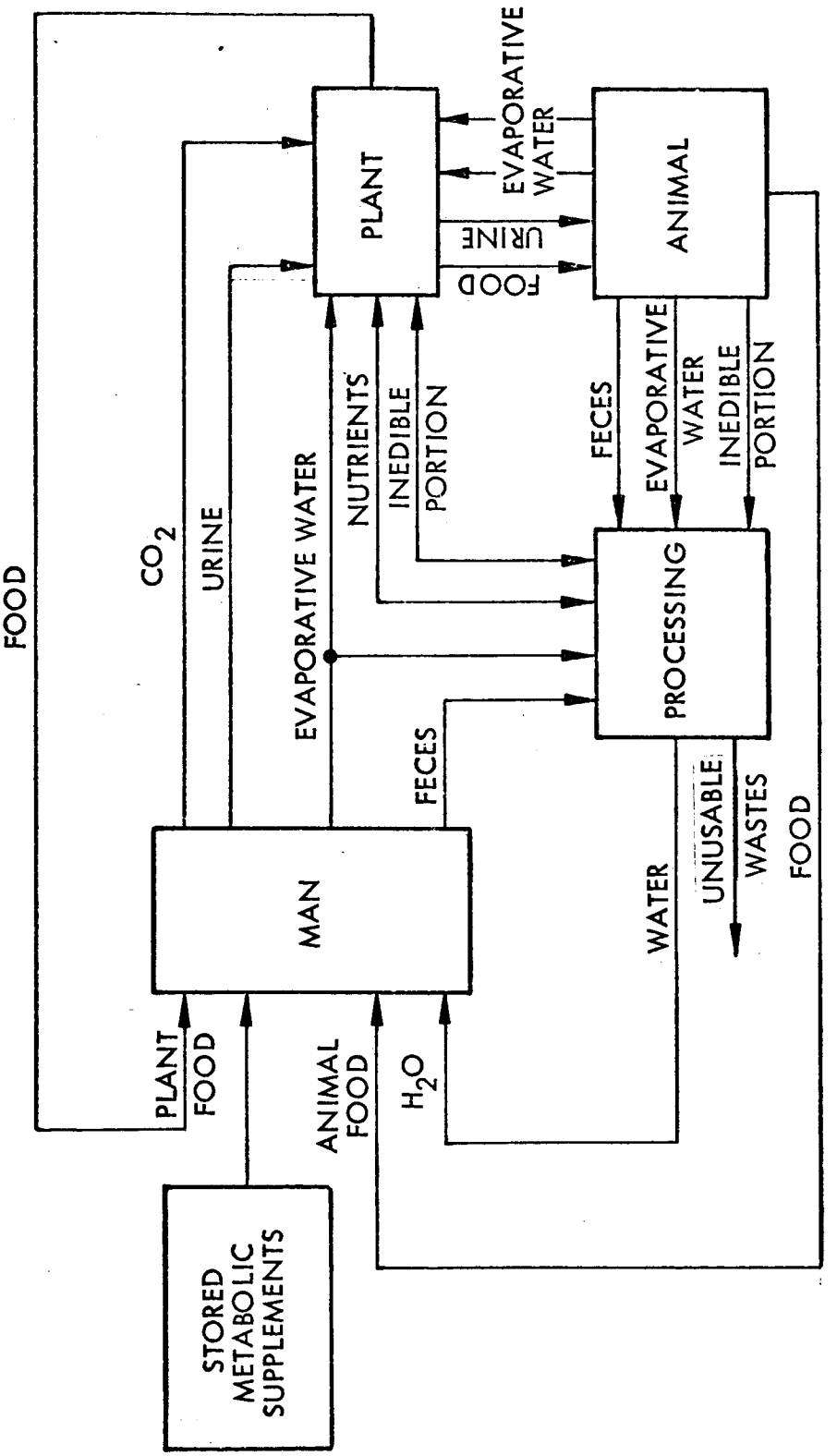

Fig. 2 Plant/Animal Food System

The problem is not imbalance, but the weight, power, and volume penalties associated with the recycle of byproducts. For a simple man-plant system, as shown during Phase I, the penalties due to recycle of byproducts are quite small relative to the penalties associated with the basic system. For a system including an animal, however, the case is quite different. Over 80% of the weight of an animal system is due to the necessity of processing unusable byproducts. This is not only because the animal contains inedible bones, horns, and skin but also because only a portion of an animal's food is used to build up tissue, while a large portion is used to maintain metabolism. For every animal there is a limit to the percentage of food eaten which will be incorporated as tissue, especially lean tissue. It is not uncommon for vertebrates to eat 30 lb of food for every pound of lean tissue growth even during their rapid growth phase.

replace with criteria

Selecting the plant. – Desiderata of a plant in a man-plant-animal system are largely the same as those of a plant in a man-plant system such as discussed in detail in the Phase I Final Report. In addition, of course, it must provide an acceptable diet for the animal, and it is desirable that the animal's waste products be usable with minimum processing as plant nutrients. Throughout the remainder of this discussion, Hydrogenomonas will be assumed to be the plant. This assumption is in no way justified by the meager rat feeding studies of Dr. Doris Calloway of the University of California. As it will appear, however, even with this optimistic assumption, an animal link does not appear competitive with stored food for one- to three-year missions. There is also no certain reason why Hydrogenomonas will not be acceptable.

Selecting the animal. – The obvious attributes of the animal are: (1) high-percent of edible meat, (2) ability to incorporate high percentage of feed as tissue, preferably lean, and (3) minimum processing requirement of its wastes before their return to the cycle. There are many other desired or necessary qualities, however, in the ideal closed-space ecology animal. It should be capable of living in a largely automated zero-g system. It should not be bound to a fixed yearly cycle but, throughout the mission, should admit of a heterogeneous population, relative to age. Preparation and cooking should be reasonably simple. An individual animal should not constitute more than a few meals in order to minimize preservation problems. Al Capp's Schmoo* leaps to mind, but few real animals offer such advantages.

Add XX

In a real system, the main problems will probably be digestion and eliminating toxic properties of the plant for man and animal. All of the plants presently being considered for space ecologies could theoretically constitute an almost complete diet, i.e., their protein, fat, and carbohydrate composition is within the tolerance limits of man and most prospective food animals (refs. 82 and 83). The supplementation required in the form of vitamins, minerals, or perhaps a few grams of an essential amino acid will be small. The work required to determine the supplementation requirements precisely would be extensive, but preciseness will not be required since it will be possible to take a complete store of trace nutrients without undue weight penalties. For very long missions, some serious thought will have to be given to preservation of bottled nutrients. Shelf life is mainly a function of environmental temperature.

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* The Schmoo thrived on love alone, produced milk and eggs. It tasted like steak when broiled, chicken when fried, and ham when baked. There is no record on whether it produced trace contaminants.

Though animals are similar in their basic biochemical requirements, they differ greatly in their digestive apparatus and differ substantially in their sensitivity to trace contaminants in the diet. Little attention is given to these problems here, but they would require major research efforts before a feasible man-plant-animal space system could be realized.

The choice of animal here will be based only on gross efficiency factors. The first intuitive response is to look for a large animal since the larger the animal, the lower his heat loss relative to his weight. It turns out, however, as shown in Table 8 (ref. 84), that relative food capacity, i.e., maximum daily intake of food energy divided by daily energy loss during fasting, is quite similar for animals of very different sizes.

TABLE 8

RELATIVE FOOD CAPACITY VERSUS BODY SIZE

Animal	Body Weight (kg)	Max. Daily Intake Per Unit of Metabolic Size U ($kcal/kg^{3/4}$)	Daily Loss During Fasting Size B ($kcal/kg^{3/4}$)	Relative Food Capacity U/B
Chick	0.078	360	81	4.4
Rabbit	2.36	253	50	5.1
Sheep	50	305	69	4.4
Swine	130	363	64	5.7
Steer	427	452	81	5.6
Steer	444	373	88	4.2

The equality of animals as food utilizers is shown even better by Table 9 (ref. 85). The same animal weight gain, 240 lb, resulted from the intake of 1 ton of hay by 1300 lb of of steer, or 1300 lb of rabbit. The space engineer will note that the heat load on the cabin is also the same for both cases. The rabbits achieve their growth, however, four times as fast as the steer. This concept is very important. Although such figures are not available for the entire animal kingdom, there is little theoretical reason to believe it possible to find great variation in utilization efficiency.

In practice, the efficiencies implied by Table 8 are not attained because the animal does not achieve 100% utilization of its food for either maintenance or growth due to energy losses in feces, urea, methane, and other excretia. Kleiber has accumulated actual efficiencies in terms of energy used for weight gain divided by metabolizable energy above maintenance requirements in feed. Table 10 shows the results (ref. 86).

The efficiencies of Table 10 must be reduced by about another 20% (see Table 8) to account for maintenance requirements resulting in 40 to 72% as the overall efficiency, i.e., growth energy divided by input energy. Considering the steer of Table 10 to have an overall efficiency e of about 50%, it is possible to compare him with the steer of

TABLE 9

FOOD UTILIZATION VERSUS BODY SIZE

Food Intake	1 Ton of Hay	1 Ton of Hay
Animal	1 steer	300 rabbits
Total body weight	1,300 lb	1,300 lb
Food consumption per day	16-2/3 lb	66-2/3 lb
Duration of 1 ton of food	120 days	30 days
Heat loss per day	20,000 kcal	80,000 kcal
Gain in weight per day	2 lb	8 lb
Gain from 1 ton of food	240 lb	240 lb

TABLE 10

EFFICIENCY OF ENERGY FOR FATTENING

Animal	Feed	Efficiency (%)
Steer	Starch	63
	Protein (gluten)	48
	Fat (peanut oil)	64
	Cellulose	63
	Sugar (molasses)	63
Swine	Starch	83
	Protein (gluten)	74
	Fat (peanut oil)	93
	Crude fiber	59
	Sucrose	72
Sheep	Starch	79
	Fodder	62
Rabbits	Dry matter as corn fodder:	
	Green	78
	Chopped, dry	39
	Chopped, moistened	46
	Ground, moistened	48

Table 9. The latter gained about 240 lb after ingesting 2000 lb of hay, of which about 1100 lb was metabolizable. Since the weight gain was mainly fat, its caloric value was about twice that of the metabolizable portion of the hay. The e of the latter steer was then about 480/1100 or 45%. The two steers had relatively similar e's.

There is a great deal of variation in such efficiency measurements, however, as a function of the animal's age. Table 11 from ref. 87 shows this effect clearly although based on wet weights of both animal and feed.

TABLE 11

EFFICIENCY OF FOOD UTILIZATION FOR GROWTH

AS A FUNCTION OF AGE

Species	Gram of Gain/Gram of Feed			
	At 10% Mature Weight	25%	50%	90%
Dairy cattle	0.50	0.29	0.17	0.05
Beef cattle	0.62	0.28	0.15	–
Rat	0.42	0.34	0.14	–
Swine	0.37	0.27	0.21	–
Chicken	0.50	0.42	0.33	0.19
Turkey	0.46	0.42	0.34	0.23

It is clear from Table 11 that only young animals are capable of the maximum efficiencies indicated in Table 8.

A question not yet discussed is the one of edibility. Edibility is almost entirely a function of processing and taste. Whithin reasonable processing and taste limits, edibility is a function of animal age, diet, fatness, and, of course, the skill of the cook. Table 12 is representative of average U. S. slaughterhouse values (ref. 88).

There are few people, however, who actually consume by choice all of the material labeled, e.g., beef, edible offal, or edible fat. Since the whole purpose of this particular investigation is the provision of a tasty diet, it is probably reasonable to assume only 40% of the energy in an animal is available to man. It was indicated above that a 50% efficiency was about the most to be expected in the conversion of plant energy to animal energy. The overall plant-to-animal-to-man efficiency would be about 20%. It is interesting to compare this 20% with Table 13, adapted from Kleiber (ref. 89).

Kleiber's 22% for pork agrees with our 20% estimate only because of compensating differences in calculational methods. Kleiber's pig is eating a less metabolizable diet than we assumed, but his wording seems to imply less critical human consumers.

TABLE 12

SLAUGHTERHOUSE PRODUCTS

Cattle	% of Live Animal	Sheep	% of Live Animal	Pigs	% of Live Animal
Beef	55.0	Mutton	50.0	Pork	70.0
Edible offal	3.5	Edible offal	2.0	Edible items	5.25
Edible fats	2.5	Edible fats	2.0	Inedible products	4.0
Hide	6.0	Pelt	12.0	Loss, intestinal content, etc.	20.75
Blood	1.5		0.7		
Horns, hoffs, etc.	1.5	Blood	1.0		
Inedible tallow	1.0	Inedible tallow	0.5		
Casings	0.5	Casings	4.0		
Misc.	1.0	Misc.			
		Loss, intestinal content, etc.	27.8		
Loss, intestinal content, evaporation, valueless material	27.5				
Total	100.0	Total	100.0	Total	100.0

TABLE 13

UTILIZATION OF PLANT ENERGY FOR ANIMAL PRODUCTS

Product	N/U[(a)] (%)
Milk: 1200-lb cow fed hay and beets	16
Pork: Quick fattening on potatoes, concentrates, and silage	22
Eggs: 50 eggs/100 hens/day; 10 Scandinavian feed units	4

(a) N = energy in animal product available to man
U = energy in animal feed.

How real is the assumption that the space animal will be able to absorb and utilize a high percentage of its Hydrogenomonas diet? Some hint of what might be expected can be obtained from Table 14, adapted from Albritton (ref. 90).* Based on Table 14 and on Dr. Calloway's preliminary results with rats,** one could reasonably expect over 90% digestion of the high-protein, low-fiber Hydrogenomonas by our space animal.

TABLE 14

APPARENT DIGESTIBILITY OF NUTRIENTS: CATTLE

Food or Feedstuff	Carbohydrate			
	Protein (gm/100 gm)	Fiber (gm/100 gm)	Other (gm/100 gm)	Fat (gm/100 gm)
Animal Products				
Fish meal	76	—	—	97
Milk, milk products	96	—	99	100
Milk, skim, dried	96	—	100	38
Plant Products				
Concentrates				
Cereal, grains, seeds				
Barley	70	6	88	63
Corn, gluten meal	86	70	88	74
Corn meal, whole, ground	63	13	88	83
Cottonseed meal	81	57	80	92
Oats, whole grain	74	13	76	84
Wheat bran	76	30	76	74
Fat	—	—	—	77
Roughages				
Green				
Kentucky bluegrass	68	70	65	51
Pasture grass, mixed	75	74	77	42
Silage, corn	45	64	69	70
Timothy	59	68	72	57
Dried				
Alfalfa hay	71	55	70	58
Clover hay	49	46	62	47
Timothy hay	36	51	62	63

* The numerous examples based on cattle or swine do not imply that these animals are leading choices for a space ecology, but only that detailed nutritional data for these animals are available.

** Indicating over 90% protein absorption.

Table 15 (ref. 91) shows the relative utilization of different components of average diets and the routes by which energy is lost. Such values vary greatly with diet. Particularly, the efficiency of animals fed more concentrated foods is much higher than the efficiencies shown by Table 15.

Sample System

For calculation purposes, the space animal will be considered cattle. Many other animals would have a higher percentage of acceptably edible food (small fish), would lend themselves to a space ecology better, and would be of a more convenient size. Since taste is the chief criterion, however, beef have probably the greatest acceptance and variety. The main reason for using cattle in the calculation, however, is the availability of the data and the indication (see Table 8) that the efficiency of the cow is fairly representative of vertibrates. Figure 3 indicates a representative mass balance for a plant-animal ecology in which the plant is the bacterium Hydrogenomonas and the animal is a young steer. It is assumed that the man receives one-half of his calorie requirements from Hydrogenomonas and the remainder from animal products.

A 50% meat diet would require approximately doubling the Hydrogenomonas output, doubling the processing of feces, metabolic carbon dioxide, and urine (or uric acid), and, most importantly, the burning in the incinerator, or bacterial reduction, of about an additional 3.0 lb/day/man of inedible portions of the animal. The latter would then have to have the carbon dioxide from this source reduced, and the water purified and partly electrolyzed. The weight effect would be to add about 2500 lb of fixed weight to the 10-man Hydrogenomonas system and add about 9 kw to the power requirement. All of this assumes that the problems of space animal husbandry could be solved. As soon as enough Hydrogenomonas becomes available, it would be interesting to conduct nutritional studies involving arthropods, fish, and several small mammals.

Organisms such as yeast are known which produce 100 times its weight per 24 hr (ref. 92) in largely nutritionally adequate food with high efficiency. These organisms are generally less satisfactory, however, as a morale-building dietary element.

TABLE 15

CALORIE VALUES OF NUTRIENTS

Each Calorie value applies to 1 gram of the ingested nutrient -- protein, carbohydrate, fat -- of origin specified at head of its column. The quantities and percentages, except for the values in line 1, are subject to marked change with variation in the diet. High dietary cellulose content increases fecal losses of other nutrients.

	One Gram of Ingested Nutrient	Man						Monkey				Cattle				Chicken		
		Caloric Value for						Caloric Value for				Caloric Value for				Caloric Value for		
		Protein		Carbohydrate[1]		Fat		Protein		Carbohydrate[1]	Fat	Protein	Carbohydrate		Fat	Protein	Carbohydrate[1]	Fat
		From Plant	From Animal	From Plant	From Animal	From Plant	From Animal	From Plant	From Animal	Mostly Plant	Mostly Plant	From Plant	Plant Fiber[1]	Plant NFE[2]	From Plant			
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)	(M)	(N)	(O)	(P)	(Q)	(R)
1	Total energy content by bomb calorimeter[3]	5.65	5.65	4.15	3.90	9.30	9.40	5.65	5.65	4.1	9.3	5.65	4.25	4.23	8.72[4]	5.70	4.20	9.47[5]
2	Lost in rumen gases[6]												0.33	0.47				
3	Lost in feces[7]	0.85[8]	0.15[8]	0.15[9]	0.10[9]	0.95[10]	0.45[10]	0.56[11]	0.56[11]	0	0	1.64[12]	1.89	0.95	2.90[13]	1.37[14]	0.84[14]	1.89[14]
4	Virtually absorbed[15]	4.80	5.50	4.00	3.80	8.35	8.95	5.09	5.09	?	?	4.01	2.03	2.81	5.82	4.33	3.36	7.58
5	Virtually absorbed as % of 1A	85	97+	97-	98-	90-	95+	90	90			71	48	66	67	76	80	80
6	Virtually absorbed as % of 1A on average diet		92[16]		97[17]		95[18]		90			71		62[19,20]	67	76	80	80
7	Lost in urine[21]	1.06[22]	1.21[22]	0	0	0	0	1.68[23]	2.04[23]	0	0	1.30[24]	0	0	0	0.87?	0	0
8	Lost in urine as % of 4A	22	22					33	40			32				20?		
9	Lost in urine as % of 4A on average diet		22[16]						39.3[25]			32				20?		
10	Metabolized for heat, activity, growth[26]	3.74	4.29	4.00	3.80	8.35	8.95	3.41	3.05	?	?	2.71	2.03	2.81	5.82	3.46	3.36	7.58
11	Metabolized for heat, activity, growth[26] on average diet		4.08[16]		3.99[17]		8.90[18]		3.09[25]			2.71[20]		2.6[19,20]	5.82[20]	3.46	3.36	7.58
12	Metabolized (line 11) rounded off to:		4.0		4.0		9.0					2.7		2.6	5.8			

/1/ Carbohydrate of plant origin (except from potatoes, white flour, starch, etc.) is likely to include more or less of "fiber", chiefly cellulose. This carbohydrate has the same bomb calorimeter value as has starch, but is poorly digested, except by ruminants. In these, fermentation in the rumen breaks down complex carbohydrates to simpler forms (including organic acids) that are digestible or directly absorbable (see also Fn 6). /2/ NFE = nitrogen free extract = hemicellulose, starch, sugar, organic acids, etc. /3/ 1 gram of (chemically pure) nutrient specified at top of column, burned, yields Calories as given. /4/ Mean of 7.96 for fat from roughage and 9.47 for fat from grain. /5/ Fat from grain. /6/ From fermentation of fiber and NFE (Fn 2) in rumen of cattle. A 550 kg cow may lose 4,000 Calories/day (= 400 liters of methane). /7/ Fecal nitrogen x 6.25 = "protein". Fecal fat (= ether extract) contains excreted lipids and fecal bacterial lipids. /8/ Fecal protein = 15% of ingested protein if of plant origin; 3% if of animal origin; 8% on average diet. /9/ Fecal carbohydrate = 3% of ingested carbohydrate if of plant origin; 2% if of animal origin; 3% on average diet. The fecal loss is larger if plant carbohydrate includes much cellulose. /10/ Fecal fat = 10% of ingested fat if of plant origin; 5% of ingested animal fat; 5% on average diet. /11/ Fecal protein = 10% of ingested protein. /12/ Lost in feces: 30% of protein from roughage and 25% of protein from concentrates. Approximately 44% of dietary protein is from roughage, 56% from concentrates. /13/ Lost in feces: 49% of fat from roughage and 18% of fat from concentrates. Approximately 50% of dietary fat is from roughages, 50% from concentrates. /14/ Consistent with digestibility coefficients of Fraps (ref. 11), applied to a growing ration. /15/ Line 1 minus lines 2 and 3. /16/ Dietary protein, U. S. A., = 39% of plant, 61% of animal origin. /17/ Dietary carbohydrate, U. S. A., = 95% of plant, 5% of animal origin. /18/ Dietary fat, U. S. A., = 8% of plant, 92% of animal origin. /19/ Assumed diet contains 27% of carbohydrate as fiber, 73% as NFE. /20/ Maintenance ration for mature cow is usually 100% roughage. Production ration usually 70-75% roughage, 25% concentrates. /21/ Chiefly urea for man, uric acid for chicken. /22/ Calculated from 1.25 urinary Calories per gram of virtually absorbed protein, by 1.25 x 5B and 1.25 x 5C. /23/ Based on urea only. Loss calculated as 2.29 and 3.31 if based on total urinary N. /24/ All Calories in urine attributed to protein metabolites. /25/ Assumed dietary protein = 10% of plant, 90% of animal origin. /26/ Net physiological energy per gram of ingested nutrient.

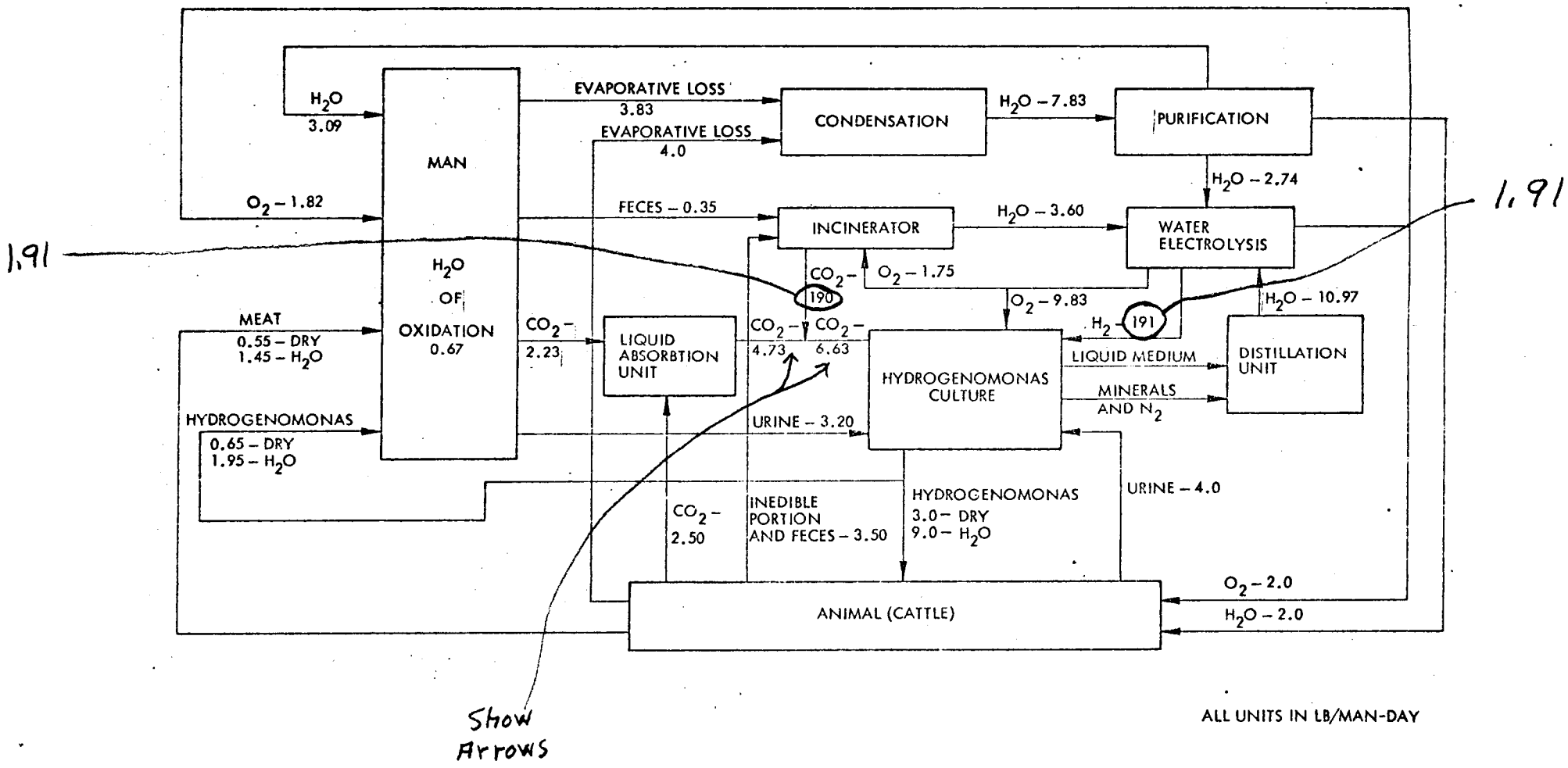

Fig. 3 Representative Mass Balance for Space-Plant-Animal-Man Ecology

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THE USE OF BIOLOGICAL WASTES FOR PROPULSION

The use of biological wastes for propulsion was studied to examine the feasibility of such a system for long-duration missions. A comparison was made between (1) a totally closed food and water cycle based on Hydrogenomonas with a storable propellant for propulsion, and (2) a system using stored food and water with human wastes as materials for propulsion. Two basic concepts for using wastes for propulsion were examined: the use of electrical heat in conjunction with conventional nozzles and the use of a monopropellant produced by mixing wastes with chemicals. Both of these concepts are under experimental evaluation, and work to date has been encouraging with respect to development progress. The range of application of these concepts, however, is yet to be established. Three stored propellant concepts were analyzed to serve as a basis for comparison with waste propulsion system: ion electrical, bipropellant, and monopropellant.

In general, the study was conducted by: (1) establishing the total impulse available from waste materials; (2) establishing the quantity of stored propellant required to provide the same total impulse; (3) estimating the total weight of each life support/propulsion concept by combining stored food, water, oxygen, and propellant requirements with the life-support equipment weights and adding a weight penalty for power; and (4) comparing the resulting total equivalent weights of the concepts. The weight of the propulsion engine was not included because it is extremely small compared to the weight of waste materials or propellants.

For the more advanced concepts such as plasma accelerators, the major weight penalty lies in supporting equipment and not in the mass of propellant. Waste materials for such an engine would trade off on an even basis with other propellant materials.

Concepts Studied

The waste materials which are available for propulsion include:

(1)	CO_2	2.23 lb/man-day
(2)	Urine	3.20 lb/man-day
(3)	Evaporative water	3.83 lb/man-day
(4)	Feces	0.35 lb/man-day

(5) Other material such as food wastes, hair, nails, and clothes are considered negligible by comparison.

For electric heat-energy systems using conventional nozzles, the wastes must be purified and all solids removed to prevent clogging of the small nozzle throat. As a result, the physicochemical systems currently used to purify these waste materials will be required to provide the CO_2 and pure water for use in these systems. The only

savings will lie in the final processing required to remove bacteria and trace gases. The quantities of waste available after separation and purification are:

(1) CO_2 2.23 lb/man-day

(2) Urine water 2.95 lb/man-day

(3) Evaporative water 3.83 lb/man-day

(4) Incinerator water 0.35 lb/man-day

(5) Miscellaneous solids Negligible

The specific impulse of a propellant serves as a measure of the energy available for propulsion. In conventional nozzle systems depending on the discharge of gases for propulsion, the temperature level and the molecular weight of the propellant gases are the main parameters. Figure 4 presents the specific impulse for the water and the CO_2 waste materials as a function of total nozzle inlet temperature. As can be seen, the performance of these materials as a propellant increases as the temperature level is raised. This curve can be divided into three principal regions depending upon the temperature level of the waste materials. These regions are:

(1) Cold gas – ambient temperature region where temperature is less than 550°R

(2) Hot gas – resistojet region where temperature is less than 2500°R

(3) Hot gas – arc jet regions where temperature is less than 6000°R

When the penalty of a hot-gas system is evaluated as a function of temperature, the minimum penalty results at the highest operating temperature for each of these regions. This results from the relatively low penalty for electrical energy, with a nuclear power source, when compared with the large amount of waste materials used. Another observation for each of these regions is that the equipment weight penalty is several orders of magnitude less than the propellant mass and, as a result, can be neglected in these calculations. This equipment will weigh only a few pounds as compared with a typical waste propellant quantity in excess of 30,000 lb. The important relationships which were used in the evaluation of these systems are as follows:

$$P = \dot{W} C_p (T - T_o)$$

$$\frac{I_s}{I_{so}} \propto \left(\frac{T}{T_o}\right)^{1/2}$$

$$I_t = I_s W$$

$$F = I_s \dot{W}$$

where

I_{so}	=	specific impulse at T_o	lb-sec/lb
I_t	=	total impulse	lb-sec
F	=	thrust	lb
W	=	total propellant	lb
$\dot{W}$	=	propellant flow	lb-sec
T	=	thrustor inlet temperature	°R
T_o	=	ambient temperature	550°R
P	=	power	w
C_p	=	specific heat	w-sec/lb °R

Cold gas. – This system takes the waste materials which are delivered from the collection and purification system and discharges them through a conventional nozzle. The maximum thrust and total impulse are realized when the wastes are heated to the highest temperature readily available from on-board waste heat sources. This may be as low as 550°R if ECS and cold plate heat sources represent the only available heat sources. These heat sources must be used to evaporate any water wastes before they can be used in such a system. Since cold gas systems do not consume large quantities of electrical energy, the total penalty will be related only to the total impulse and not the thrust level since fixed weights are small and specific impulse is set by the level of waste heat. As a result, the only penalty associated with using wastes in a high-thrust engine on some scheduled basis instead of a continuously operated low-thrust engine would be some small storage capability.

Hot gas – resistojet. – This system (refs. 93 and 94) is identical to the cold gas system in concept except that electrical energy is used to elevate the chamber inlet temperature. The energy is supplied in the form of an electrically excited resistance heater. These units may be used over a wide range of thrust levels assuming that the required power is available. The efficiency for systems of this type can be considered as 100% with the exception of about a 10-w radiated power loss to ambient. Thrust levels for resistojet systems may vary over a wide range. However, if the duty cycle of the thruster is less than 100%, the power penalty rapidly rises making the system increasingly less desirable. In some cases, the vehicle heat rejector may permit the use of waste heat at temperatures well into the resistojet region. Use of waste heat would result in weight savings by reducing power penalty. This would be most important for thrusting with a duty cycle less than full time. In general, resistojet engine weights are the same as those of a cold-gas system except for a small addition for the thruster heater.

Hot gas – arc jet. – The next level of operating temperature beyond the cold gas and resistojet levels is achieved with the use of arc jets. In this system, heat is supplied to the propellant through an electric arc which is located in a nozzle inlet chamber. Use of an electric arc considerably raises the temperature level of the system with the elimination of the materials limitation problem of the resistojet. These higher temperatures do

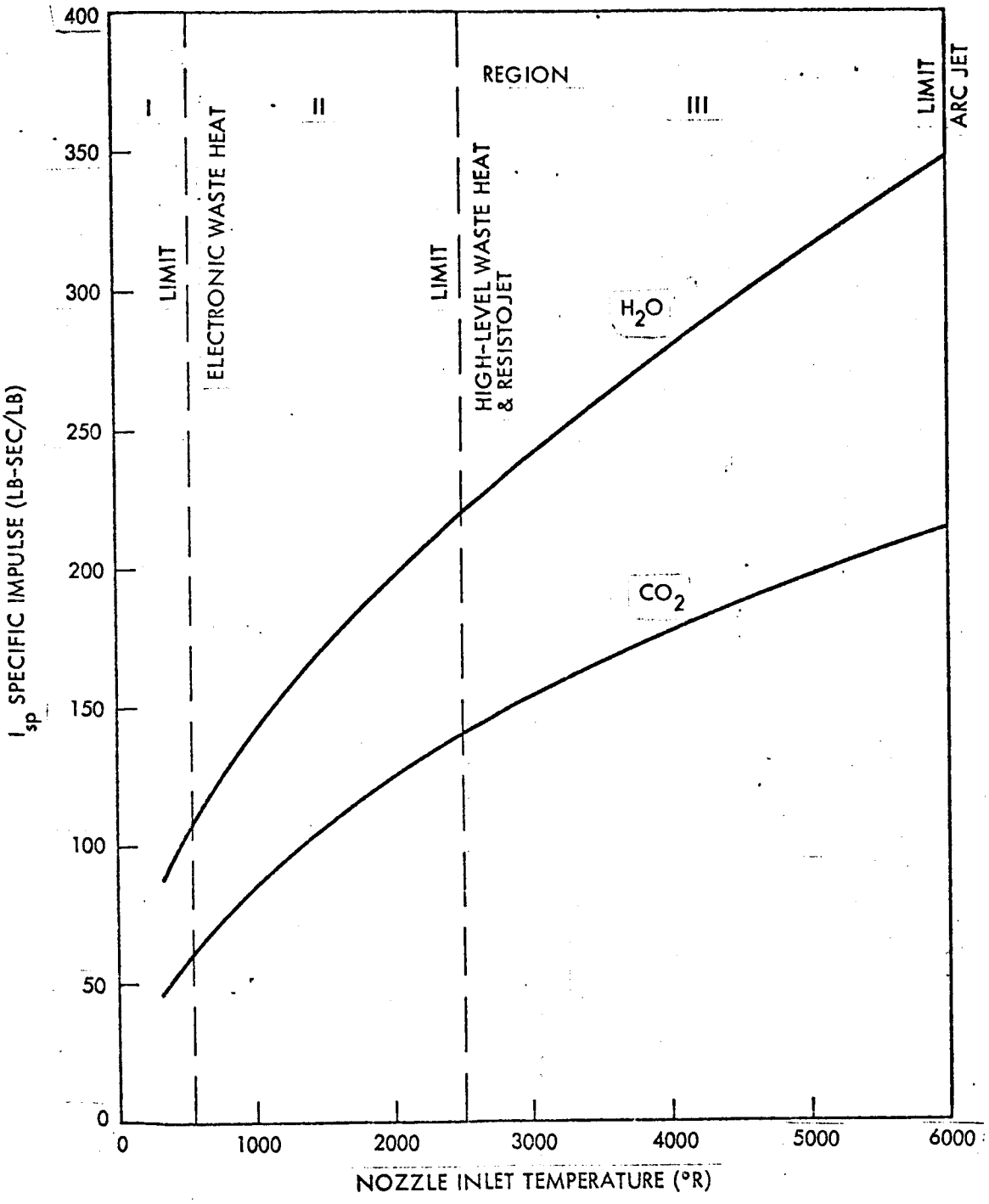


Fig. 4 Wastes for Propulsion – Specific Impulse Available from Waste Materials

result in higher loss, and efficiencies of about 50% are typical for these systems. The duty cycle considerations of resistojet systems are even more important to arc jet systems with these higher operating power levels. Weight of these units will still be negligible but slightly higher than the cold gas and resistojet due to a more complex heating chamber and a small expendable rate due to erosion of the electrode material.

Chemical heat source. – An alternate method of using the waste materials makes use of the water and solids which are mixed with a chemical heat source before ejection through a nozzle. Such a system is currently being developed by Rocket Research Corporation. The CO_2 is not usable in this system but the carbon formed in a CO_2 reducing unit can be used. In this system, the wastes are combined with an oxidizer (ammonium nitrate) and combustible (aluminum) forming a heterogeneous thixotropic mixture which can be used as a monopropellant. One advantage of this system is the elimination of the waste pretreatment requirement of other systems. Once again the fixed weight of this system is negligible when compared to the propellant flow. This mixture is storable in a high density form for use at high-thrust levels for short periods. This is a capability which the other systems do not have without a large penalty associated with either storage or electrical power.

Baseline Propulsion Systems

In order to make a final evaluation of the desirability of using metabolic wastes for propulsion, data on a fully independent stored propellant system must be generated. For the purposes of this comparison, three stored propellant systems were examined. The assumption that large quantities of electrical power are available at a low penalty suggests the evaluation of an optimum electrical system such as ion propulsion. For systems of greater simplicity but larger flexibility in terms of duty cycle and thrust level, two noncryogenic liquid storable propellant systems have been included. These are a two-fluid combustion system using nitrogen tetroxide and hydrazine and a monopropellent system using only hydrazine.

Ion propulsion. – The oldest and best developed of the electric propulsion systems having a high specific impulse is the ion drive using a cesium propellant (ref. 95). This system is composed of three basic elements.

(1) The emitter, consisting of a device which ionizes neutral matter into separate positive ions and electrons for subsequent acceleration

(2) The accelerator, which receives the ions and electrostatically accelerates them to a high velocity

(3) A beam neutralizer, which recombines the electrons and positive ions before ejection from the drive

Cesium is a prime choice for this system because of the ease with which it can be ionized. This type of propulsion system operates at a low temperature and does not depend on thermal energy for its thrust but rather on an electric field for particle acceleration. The use of waste material in such a device would be desirable but is not possible because of the difficulty of ionizing this matter at an acceptable operating temperature.

Since this system used electrical energy for acceleration of particles to high-energy levels, large power sources must be available. Further, duty cycles of less than full utilization severely penalize the system as was the case in resistojets and arc jets using waste material.

Nitrogen tetroxide-hydrazine. – For long-duration missions, storage of cryogenic propellants presents a major problem. This is especially true when flow rates which are compared with the metabolically generated wastes are considered. A number of storable bipropellant systems are available which have a specific impulse approaching cryogenic systems. The nitrogen tetroxide-hydrazine system (ref. 96) is typical of this class of storable propellants and was chosen as one of the bases of comparison for waste systems. Performance of this type of propulsion is very sensitive to thrust level in the range of waste capabilities. At thrust levels of a few tenths of a pound which are generated by wastes, this system would have a high penalty due to inefficiencies in combustion and natural losses. However, if thrust level is raised to a level of a few pounds, the efficiency may approach ideal. This is done by using a duty cycle of about 10%. The ability of such a bipropellant system to produce high thrust levels with a low-duty cycle at little or no penalty constitutes an advantage over electrically powered systems.

Hydrazine. – The least complex and easiest to handle of all propellants is represented by the storable hydrazine monopropellant system (ref. 96). In this system, hydrazine decomposes when passed over a catalyst and is discharged through a nozzle. The specific impulse for this system is the lowest of those studied, but has been included to show how the simplest storable propulsion system compares to the use of wastes for propulsion. As was the case with the bipropellant system, the hydrazine engine operates most efficiently at thrust levels above those of waste systems and is best considered with a duty cycle of about 10%.

One other type of propulsion system deserves discussion. This is the plasma accelerator which is an advanced system, still in a low state of development, which consumes vast amounts of electrical power and generates high levels of specific impulse. This system uses an electromagnetic field to accelerate a macroscopically neutral mass of gas rather than the purely electrostatic acceleration of separated charge as in the ion engine. The plasma may be generated by passing the propellant material through an arc discharge or by an electrodeless induction heating system. This plasma is then accelerated by one of a variety of systems currently being investigated. The important point in this type of system is that electrical power and supporting equipment constitute the greater portion of the system penalty. The specific impulse achieved by such a system is so high that the mass of propellant ejected becomes a secondary consideration. Metabolic wastes as well as special stored propellants could be used in such a system if developed. As was the case with the ion engine, a plasma accelerator is most efficiently operated on a continuous duty cycle to minimize the large electrical energy penalties.

Propulsion System Comparison Studies

The results of a study of use of metabolic waste material for propulsion will depend on the mission length and crew size because of the variable quantity of total wastes produced. As a result, the data were generated to present the effectiveness of

each of the waste sources in producing total impulse with a one-man basis. These data are then easily expanded to larger crew sizes.

Figure 4 presents the specific impulse of the most plentiful and useful waste materials, water and CO_2, as a function of temperature. This curve may be divided into three regions of potential operation. Region I is the cold gas region in which the wastes are expelled at the ambient temperature. In this, little or no power is required and the only requirement is for a simple nozzle. The upper limit of this region (550°R) has been set at a typical electronics heat-rejection level. Region II is the beginning of the hot gas region. Operation in this region will require either the use of high grade waste heat or electrical heat. This region has been limited at the upper level obtainable by resistance heaters for reliable performance over extended missions. This is about 2500°R. Region III is an extension of the hot gas region in which the temperatures may be produced by an electric arc. Material limitations will set the upper portions of this area of operation at about 6000°R. Under some circumstances, these arbitrary temperature limits may be extended to much higher levels. For example, resistojets have been operated as high as 5000°R. However, the levels in this study have been set lower because of the longer operating life required of these components.

Figures 5 through 8 present the effectiveness of each of the major waste materials in producing impulse as a function of mission duration. The wastes which constitute the major position of material generated include evaporative water, urine, CO_2, and feces. The data for each of these waste materials were generated at the upper limit of each of the aforementioned regions of operation. These are cold gas at 550°R, resistojet at 2500°R, and arc jet at 6000°R. To facilitate the use of these curves, a table has been included with the power level, in watts, required for continuous operation and the thrust levels, in pounds, which results from a one-man system. These values will scale directly with crew size. The electrical efficiency of the resistojets should approach the 100% level which was assumed, and arc jets with higher losses should approach the 50% level assumed in generating these curves.

Figure 9 presents the performance of a typical chemical heat-source system using metabolic wastes. The basis for this curve is data furnished by the Rocket Research Corporation on a system that it is developing. This process mixes the raw solids and water base wastes with aluminum powder and an ammonium nitrate oxidizer. Evaluation of data furnished by Rocket Research shows maximum performance of this system at the highest possible waste-to-chemical ratio. This is set at 45% wastes by weight by the limit of combustion. The flow of waste materials includes all wastes containing water and the carbon generated in a CO_2 reduction process. The flow rate of urine is higher than for the previous curve as the solids are included. Use of wastes in this manner would result in a negligible weight of equipment and a very low power requirement for the mixing of wastes.

Figure 10 shows the weight of three stored propellant systems as a function of total impulse. The weights include propellant, a 15% propellant storage penalty, engines, and power penalties at 100 lb/kw. The specific impulse for the nitrogen tetroxide-hydrazine is 340 lb-sec/lb for vacuum conditions and thrust levels of a few pounds. The weights of a hydrazine system are based on a specific impulse of 220 lb-sec/lb. Since power penalty and system weight are negligible compared to total propellant flow and tankage, both of these curves will pass near a zero system weight at a total impulse

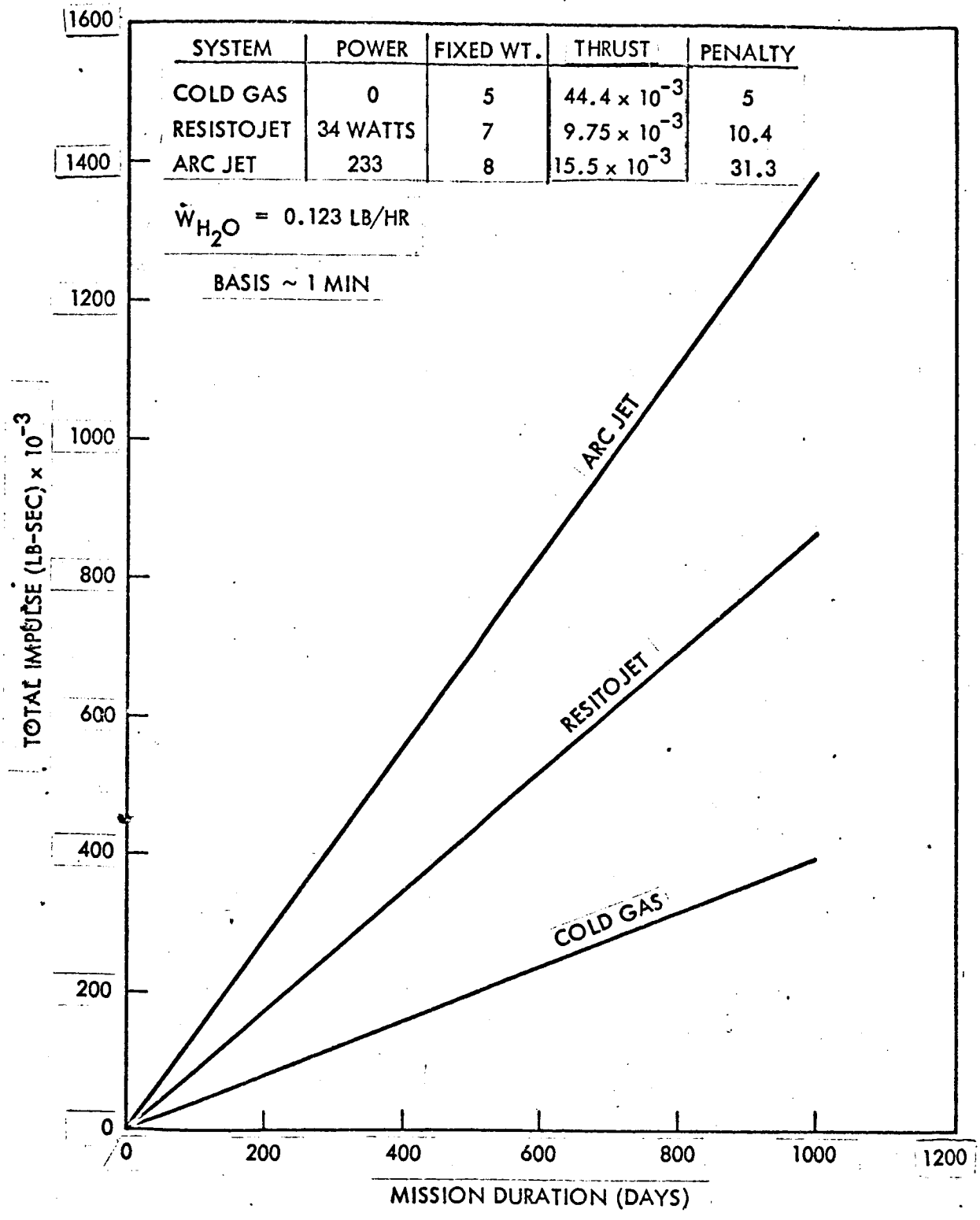
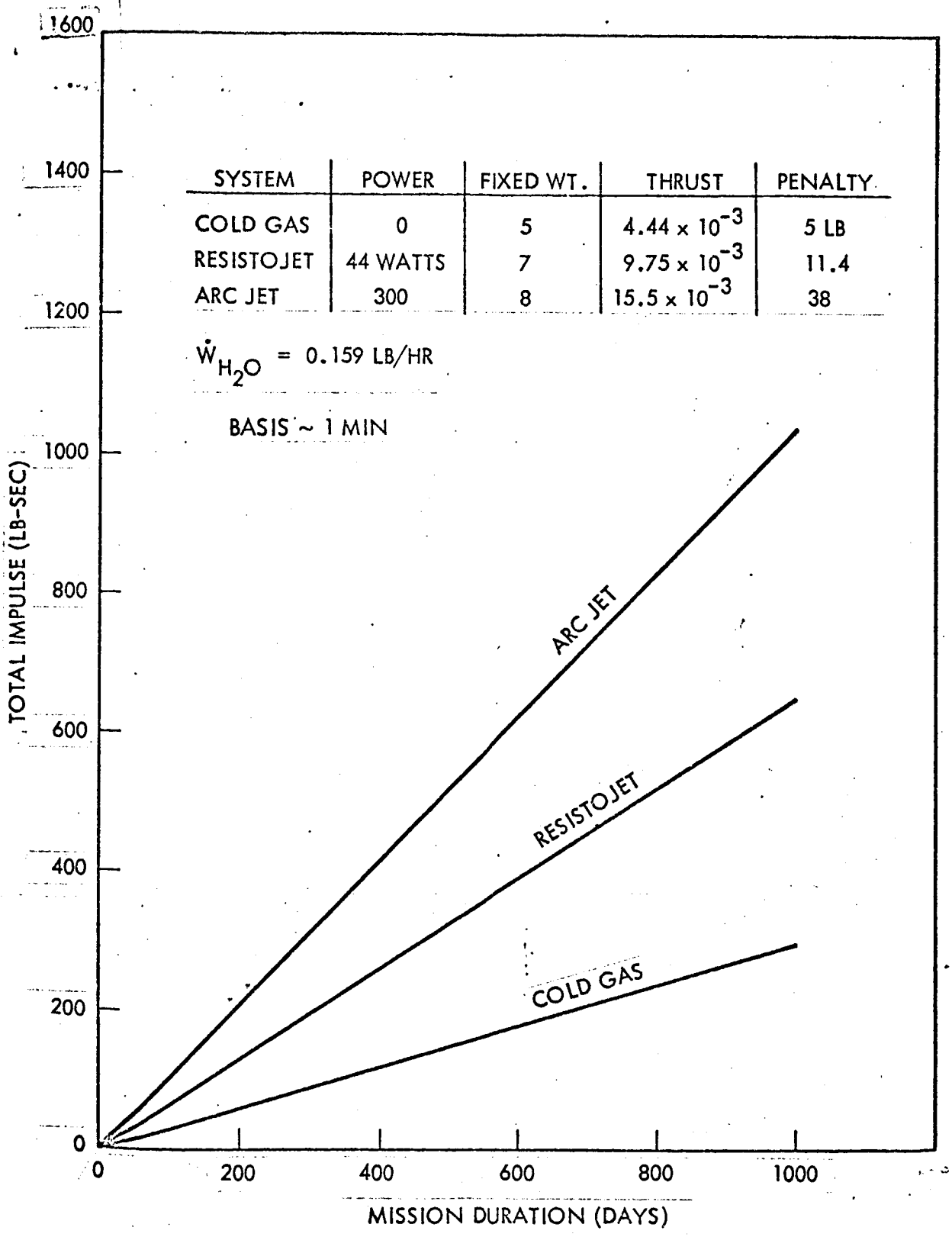


Fig. 5 Wastes for Propulsion – Evaporative Water



SYSTEM	POWER	FIXED WT.	THRUST	PENALTY
COLD GAS	0	5	4.44×10^{-3}	5 LB
RESISTOJET	44 WATTS	7	9.75×10^{-3}	11.4
ARC JET	300	8	15.5×10^{-3}	38

Fig. 6 Wastes for Propulsion – Urine

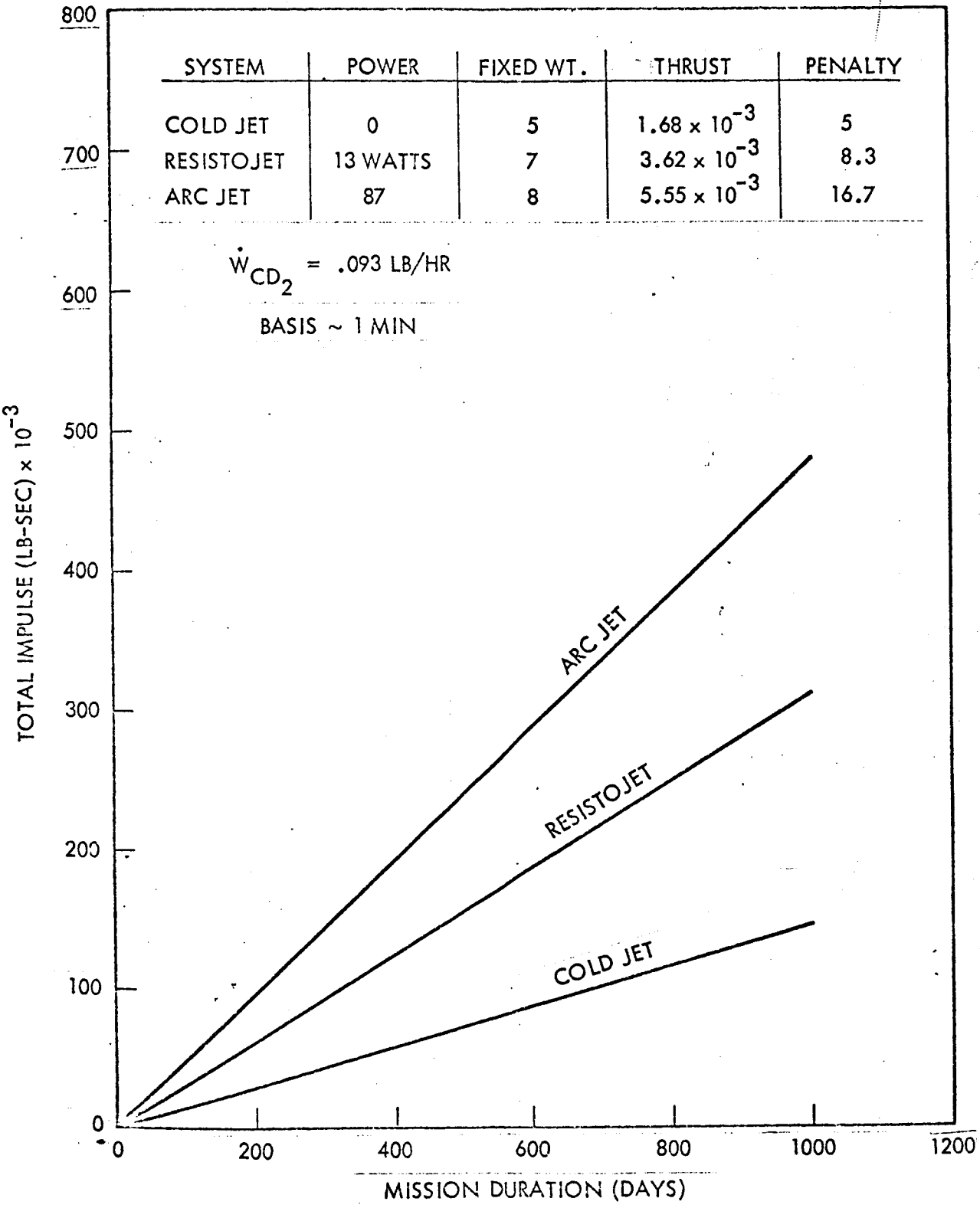


Fig. 7 Wastes for Propulsion Carbon Dioxide

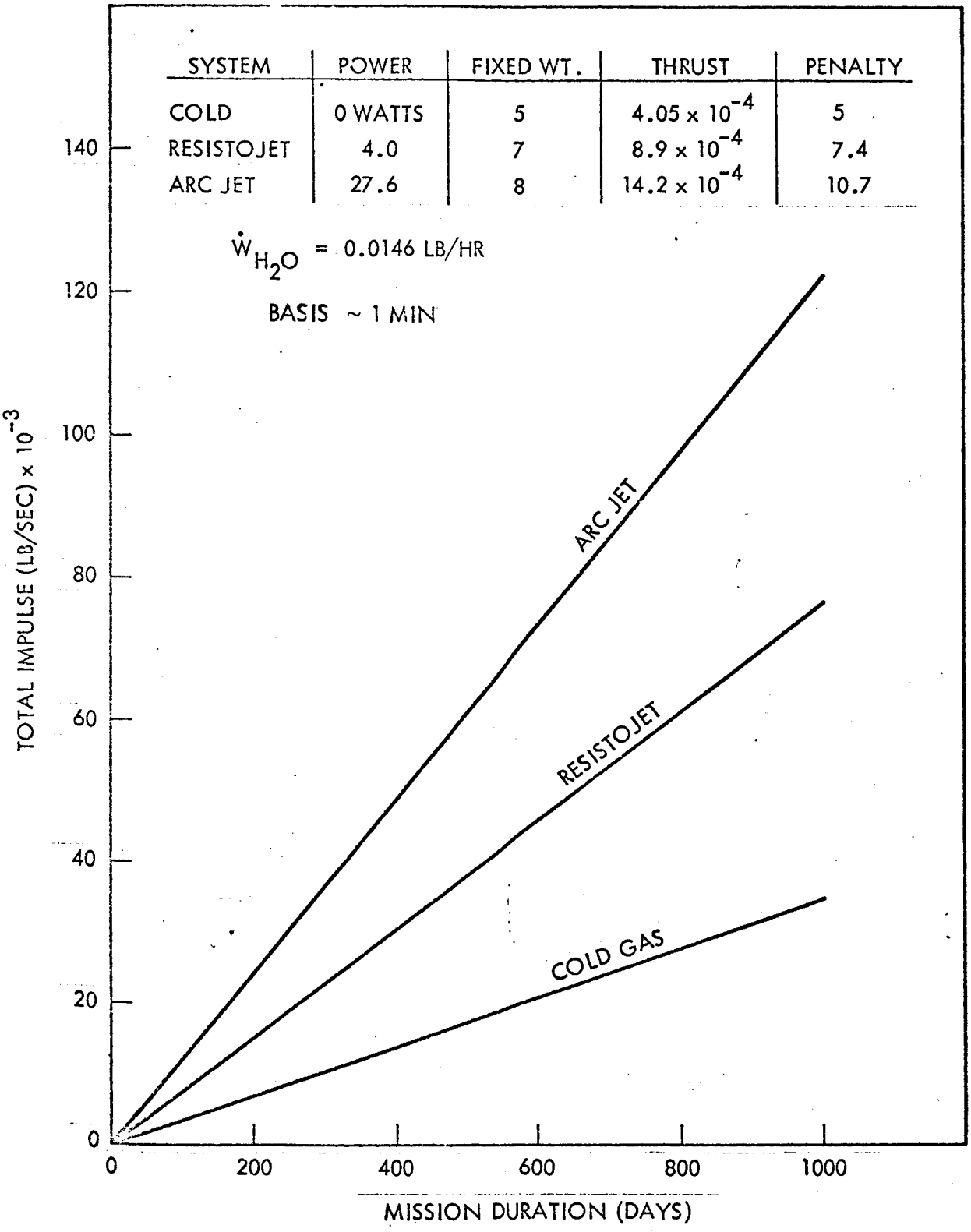


Fig. 8 Waste for Propulsion Feces

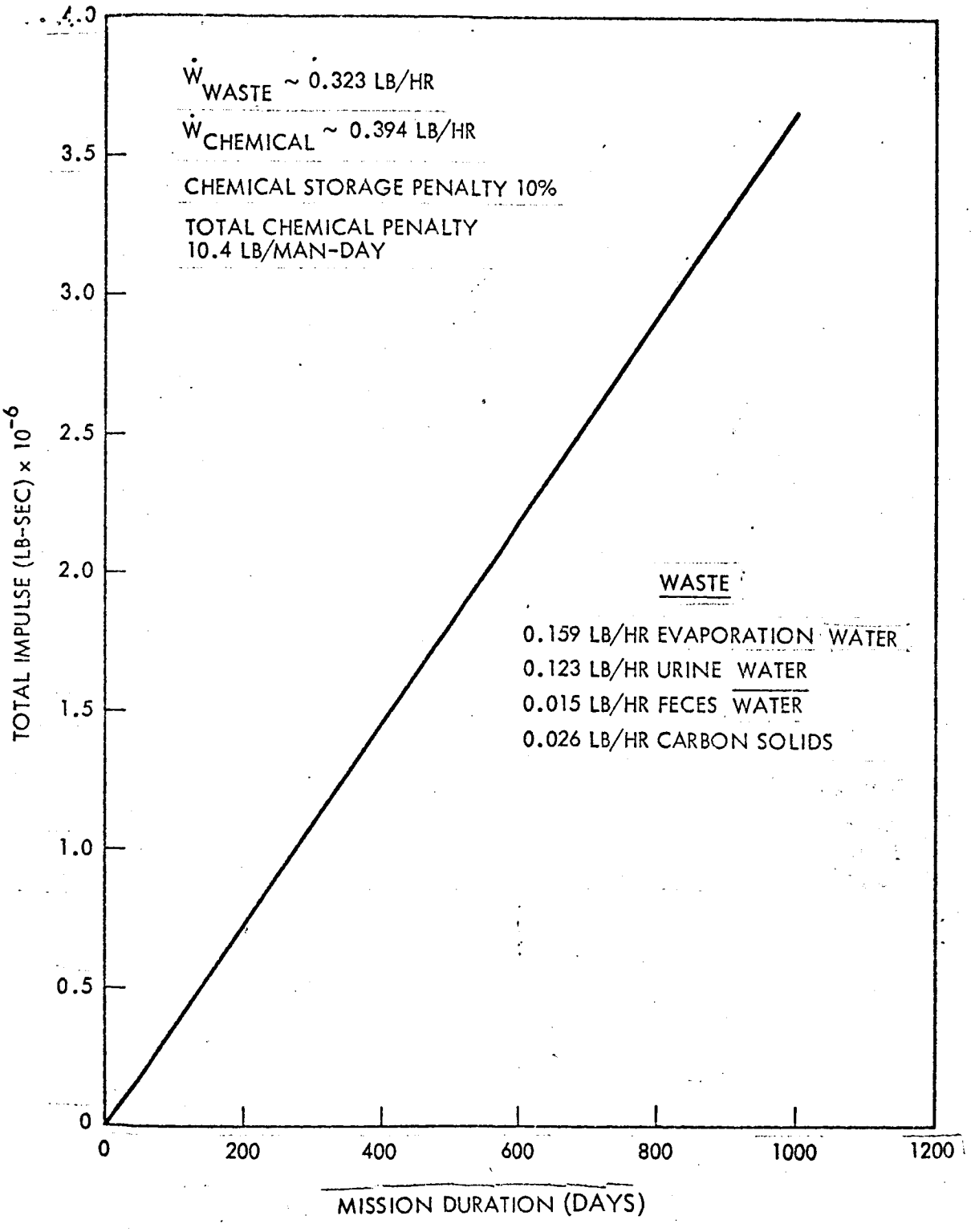


Fig. 9 Wastes for Propulsion – Chemical Heat Source

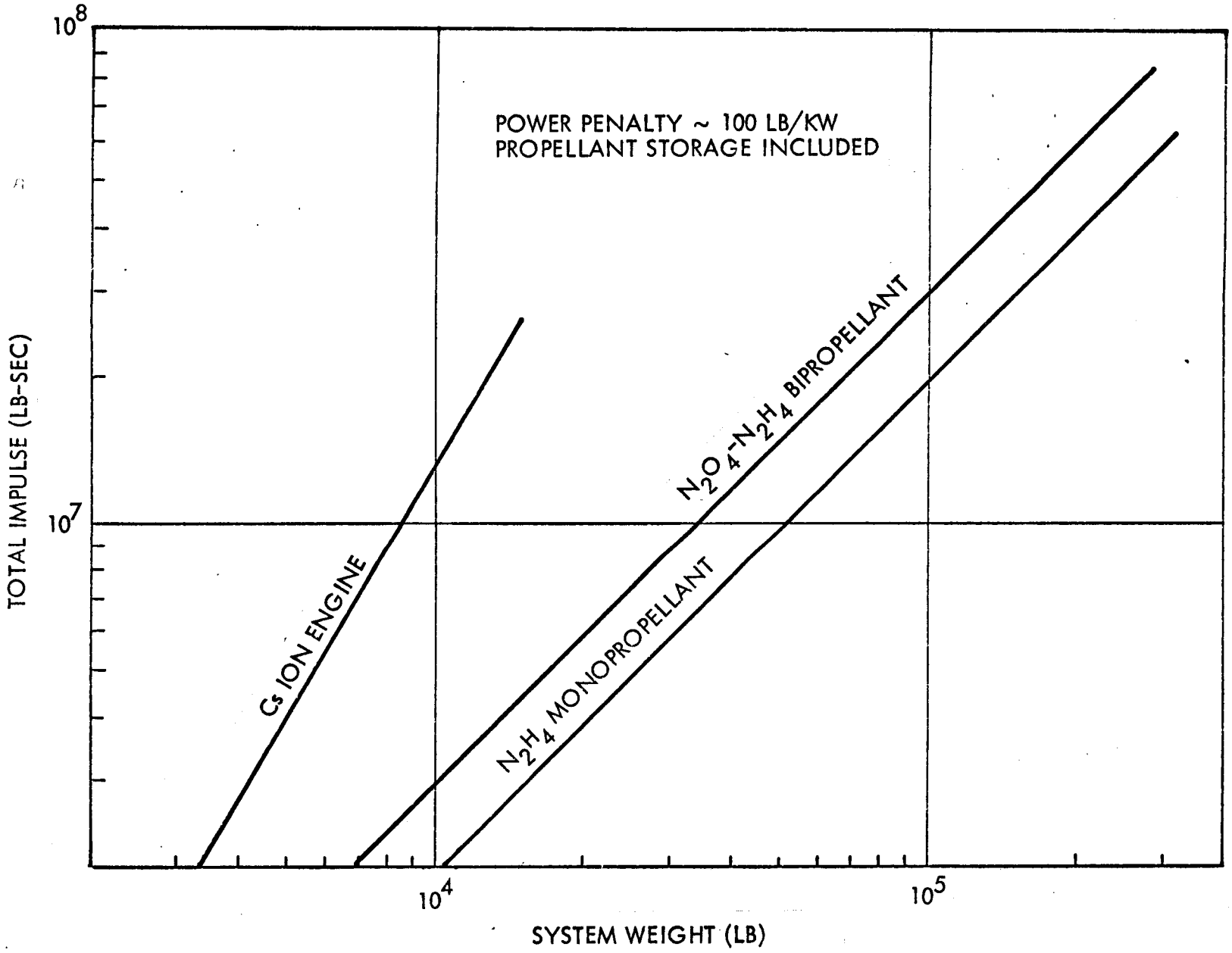


Fig. 10 Wastes for Propulsion – Performance of Baseline Systems

of zero. The data on the cesium ion engine are based on a specific impulse of 5000 lb-sec/lb. This system has a low propellant flow resulting in the steep curve, but a very high fixed weight of both hardware and power.

Since the level of this curve is very sensitive to thrust level because of the high equipment and power penalties, a level of 0.344 lb of thrust has been chosen which corresponds to the steady utilization of all wastes in an arc jet for a 10-man crew. This curve will scale directly with thrust level. Power consumption at this thrust level will be 47 kw which was assessed at 100 lb/kw power penalty as were all other systems considered. In actual experience, the penalty will be somewhat lower because of a lowering of penalty at higher power levels. The fixed weight of this system is 650 lb. As can be seen, a crossover will exist between the electrical ion engine and conventional chemical liquid propellant systems at low total impulse levels.

To make some preliminary evaluation of the desirability of using wastes for propulsion, a mission was established which would reflect the use of wastes under the most favorable conditions. A 10-man 1-yr mission which can make steady use of the waste materials was selected. For comparison, a totally regenerative system using stored propellant and Hydrogenomonas as food was selected. As crew size and mission duration increase, differences between the selected system will also increase. Table 16 shows the results of this comparison. Data on systems using all waste materials for propulsion have been generated for both arc jet and chemical heat-source propulsion schemes. The arc jet was included instead of resistojet because it represents the minimum penalty system using electrical energy. This results from dominance of the waste flow as compared to the power consumption. Steady use of wastes has been assumed to minimize the power penalty.

The second method of using wastes for propulsion presented in Table 16 is the chemical heat source system. As power is not an important factor in this system, thrust level may be at any value. For each of these systems, total system weight, power requirements, total equivalent weight, and total impulse were generated. These data were also generated on the three stored propellant systems presented by fig. 10 using the same total impulse as that generated by the waste propulsion systems. Data on a Hydrogenomonas system and the basic life support system were obtained from the Phase I report. In the case of the stored food and water, a penalty of 15% was included to account for storage. For the oxygen supply, a penalty of 25% was assumed.

Conclusions

Total penalty figures shown in Table 16 show that the use of wastes in an arc jet system is not competitive with an ion engine or a storable bipropellant system. However, it does show an advantage over the hydrazine system. The chemical heat source concept was not competitive with any of the stored propellant systems. A third scheme of using the waste materials will result in a favorable tradeoff. This is the use of a plasma accelerator. As previously mentioned, in this system the major penalty lies in the fixed weight and power penalty and not on a waste or propellant flow. Thus, penalty numbers will be comparable and a waste propulsion will be made more favorable because of the desirability of using fresh food and water supplies.

TABLE 16

COMPARISON OF PROPULSION CONCEPTS

(10-men 1-yr Mission)

WASTES FOR PROPULSION

Item	Arc Jet (F = 0.35 lb) (Continuous Operation)		Rocket Research (Intermittent Operation)	
	Weight (lb)	Power (w)	Weight (lb)	Power (w)
Water for Propulsion	(26,000)	5,630	(26,000)	
CO_2 for Propulsion	8,150	870		
Carbon for Propulsion			(2,200)	
Chemicals and Storage			38,000	
Life Support System	1,380	1,720	1,720	4,500
Stored Water and Tankage	26,800		26,800	
Stored Oxygen and Tankage	8,300		900	
Stored Food and Packaging	6,200		6,200	
TOTALS	42,680	8,220	73,620	4,500
Total Equivalent Weight[a]	43,500		74,070	
Total Available Impulse[a]	10.85×10^6		13.5×10^6	

STORED PROPELLANT SYSTEMS

Item	Cs Ion Engine (F = 0.35 lb) (Continuous Use)		N_2H_4-N_2O_4 (Intermittent Operation)		N_2H_4 (Intermittent Operation)	
	Weight (lb)	Power (w)	Weight (lb)	Power (w)	Weight (lb)	Power (w)
Total Impulse 10.85×10^6						
Life Support System	2,590	9,380	2,590	9,380	2,590	9,380
Propellant and Tankage	3,150	47,000	36,700	0	55,500	0
TOTALS	5,740	56,380	39,290	9,380	58,090	9,380
Total Equivalent Weight[a]	11,380		40,230		59,030	
Total Impulse 13.5×10^6						
Life Support System	–	–	2,590	9,380	2,590	9,380
Propellant and Tankage	–	–	45,600	–	69,200	–
TOTALS	–	–	48,190	9,380	71,799	9,380
Total Equivalent Weight[a]	–		49,130		72,730	

(a) Basis for comparison.

Unfortunately, the results as presented here are not completely conclusive, and a number of other important considerations must be made before a final decision on any particular mission can be made. Some of these considerations are:

(1) Crew size

(2) Mission duration

(3) Required impulse

(4) Thrust level

(5) Duty cycle

(6) Power penalty

Of the parameters, the most important in terms of the tradeoff are the thrust level and duty cycle. If the propulsion requirements are such that higher thrust levels are necessary on an intermittent duty cycle, the power required by the electrical systems will increase in direct proportion to the thrust level. As Table 16 shows, increasing the thrust level from 0.354 lb to the 20-lb level, which is typical for attitude control, quickly rules out the arc jet and ion engines because of excessive power level. The stored propellant systems, on the other hand, function at their highest efficiencies at these higher thrust levels and their performance will be off at the fractional thrust level.

The chemical heat source concept being developed by Rocket Research Corporation is capable of the higher thrust levels at no additional penalty. This system becomes more favorable in partially closed systems where urine processing residue and feces are not considered usable wastes. In such a mission (less than 1 yr), this system would show an advantage over a hydrazine system but would still be considerably heavier than the nitrogen tetroxide-hydrazine system. Another important consideration is the total impulse required. If wastes could provide the total requirement, this may be a desirable method of disposing wastes and providing propulsion. If total-impulse requirements are greater than can be provided by the wastes, it would not be desirable to absorb the penalties of two separate propulsion systems.

THE USE OF BIOLOGICAL WASTES FOR RADIATION SHIELDING

During space missions, it is necessary to shield man from the ionizing radiation known to be periodically emitted by the sun. Predictions of the radiation intensity have been made and, based on these and the "allowable" radiation doses to man, the required shielding mass has been calculated. Since it has been found that this mass is comparable to the mass of stored food required for one- to three-year space missions, the possibility of using stored food, and the metabolic wastes to which it is converted as part of the required radiation shield, appears worthy of consideration.

A preliminary study of this concept has been conducted. Table 17 demonstrates that such a combined food-radiation shield system is attractive. Predicted total system mass for the waste radiation shield concept is only differentially higher than a system comprising conventional shielding and a Hydrogenomonas food and atmosphere-regeneration system. In this circumstance, the preferred approach may well be the stored food/waste shielding concept, especially when human nutrition, personnel satisfaction, and development costs are considered.

In this study it has not been possible to account for the possible use of other on-board space vehicle materials such as propellants, electronic, or experimental equipment or to conduct a detailed shielding analysis. When these materials are included in the radiation shield, the combined food/shield system may not maintain its close mass equivalence with the Hydrogenomonas system. However, the conclusion seems inescapable that for long-duration space missions, radiation shielding mass is a significant portion of the life-support requirement and, as such, would repay increased analysis effort.

Shield Requirements

Calculation of required radiation-shielding thickness involves assumptions about the ionizing radiation sources and the allowable radiation doses which are coupled by the radiation-attenuation analysis. Using the best available estimates for these items, the shield thicknesses shown in Table 18 were calculated based upon a point receiver at the center of a spherical shield. In evaluating shielding weight, a "storm cellar" with a 10-man capacity was used and the weight of shielding calculated. Table 18 gives the results for a 0.999 probability of not exceeding the dose limits chosen. A "storm cellar" is a solar-proton-event shelter.

For these preliminary calculations, no credit has been taken for structures or station mass present for reasons other than radiation shielding. Also, the effects of body self-shielding and of crewmen mutual shielding have been neglected. Weight penalty for radiation shielding will be reduced when these factors are included. It is not possible to account for the effect of space-vehicle location in the solar system without specifying a mission profile (nor is the dependence of solar-proton flux on distance from the sun clearly known). Near-earth fluxes were used in this study.

Solar-proton events.– The most important source of ionizing radiation is that of protons emitted in large solar-flare events. These solar-proton events appear to occur during the upper half of the 11-year solar cycle (1956–1961, 1967–1972, 1978–1983, etc.). A recent NASA report (ref. 97) gives the results of a statistical analysis conducted to obtain the solar-proton flux for missions of 1 to 104 weeks and for encounter probabilities of 0.50, 0.10, 0.01, and 0.001. These data were chosen for use in this study and extrapolated when required. Although there is some discussion of early directional pattern, most authorities agree that free-space proton flux may be assumed to be isotropic (ref. 98). At the probabilities and mission lengths of interest, the mission flux is essentially the same as the one-week flux.

TABLE 17

SYSTEM WEIGHT COMPARISONS[a]
(10-Man Crew)

System Weight (lb)

Item	1-Year Mission				3-Year Mission			
	Separate Shield, Stored Food	Food and Wastes as Partial Shield	Food and Wastes as Entire Shield	Separate Shield, Hydrogenomonas As Food	Separate Shield Stored Food	Food and Wastes as Partial Shield	Food and Wastes as Entire Shield	Separate Shield, Hydrogenomonas As Food
Radiation Shield	19,900	14,800	1,560	19,900	24,500	7,800	-	24,500
Food (Including Packaging)	6,200	6,200	6,200		18,600	18,600	18,600	
Waste Packaging	-	1,320	4,550		-	3,970	5,300	
Water Processing	180	180	-		310	310	270	
Incineration	330	-	-		550	-	-	
Waste Stabilization	-	330	660		-	550	1,100	
Water Electrolysis Credit	-	(40)	(40)	3,500	-	(40)	(40)	4,850
Water Makeup	-	-	11,200		-	-	7,500	
Oxygen Generation and Other ECS	1,770	1,770	1,770		1,770	1,770	1,770	
TOTAL		24,560	25,900		45,730	32,960	34,500	
Water Credit	-	(603)	-		-	(1,809)	-	
Hydrogen Credit	(180)	(132)	(132)		(530)	(396)	(396)	
ADJUSTED TOTAL	28,200	23,825	25,768	23,400	45,200	30,755	34,104	29,350

(a) Including power penalty at 100 lb/kw.

TABLE 18

RADIATION-SHIELDING CALCULATION SUMMARY[a]

Item	Mission Length		
	1	2	3
Source flux (protons/cm^2) E > 30 Mev	1.5×10^{11}	1.6×10^{11}	1.7×10^{11}
Required shield thickness (gm/cm^2 of H_2O)	33.4	36.8	40.5
Required shield weight (lb of polyethylene)	19,900	21,900	24,500
Required shield weight (lb of water)	21,000	23,400	26,300
Required shield weight (lb of aluminum)	25,700	28,100	31,000

(a) Shield weights based on a 10-man module.

The proton-energy distribution has to be specified to define the proton source. The selected ectrum is that given by both refs. 97 and 98:

$$N\ (>R) = N_o \exp\ (-R/R_o)$$

$$N\ (>E) = 18.9\ N\ (>30) \exp\ (-R/R_o)$$

here $N\ (>R)$ = protons/cm^2 of rigidity greater than R

N_o = protons/cm^2 of rigidity greater than 80 MV

R = proton rigidity defined by

$$R = \frac{\left[\left(E + m_o c^2\right)^2 - m_o c^2\right]^{1/2}}{ZE}$$

$$R\ (MV) = E\sqrt{1 + \frac{1876}{E}}$$

E = proton energy (Mev) (For E = 30 Mev, R = 239 MV

N (>30) = protons/cm^2 of energy greater than 30 Mev

N (>E) = protons/cm2 of energy greater than E

The value of 80 MV (ref. 98) was used for this analysis. Although the complete model for lar-proton events includes equal numbers of protons and alpha particles at equal rigidity intervals, he large shield thicknesses of interest, alpha particle dose is negligible.

Galactic cosmic rays.– Although the cosmic-ray primary flux is well established at 2/cm^2 - sec sunspot maximum and 4/cm^2 - sec for sunspot minimum, there is still much discussion of the pper rad and rem dose rates. This discussion arises because cosmic rays are of such high energy at relating cosmic ray doses to a rad or rem dose is difficult. A small number of densely ionizg tracks are found in materials exposed to cosmic rays. These are unique, and thus are separately ported. An unusual feature of cosmic rays is that, because of high penetrating ability, the dose ay be assumed constant, independent of shielding thickness. The data given below are recent calilations - (Table 19).

Table 19

FREE-SPACE COSMIC-RAY DOSE RATE

Reference	Dose Rate (rem /yr)
Folsche 1962 (ref. 99)	25 to 50
Volynkin 1964 (ref. 100)	46 to 100
Folsche 1964 (ref. 101) (inferred at solar maximum)	7

The latest estimate by Folsche was selected for use in this study. This leads to a dose of 7, , and 21 rem for 1-, 2- and 3-year missions. Evoking the concept of dose recovery (allowing % nonrecoverable fraction and a 40-day mean recovery time) would lower these doses to 2.7, 5, and 7 rem, respectively. Since it is not clear that recovery mechanisms are operative for smic-ray doses, no use was made of this possible dose relief.

Other radiation sources.– No other radiation sources were included in this analysis. Although uclear reactor power plants will be present, no data on the expected dose rate are available. rther, it is likely that such sources will be shielded to a few rads per year dose rate, in which se they will not affect these calculations appreciably.

Electrons and protons trapped by the earth's magnetic field constitute a radiation source for ich the probability of encounter is 1.0. The dose received depends on the particular earth es- ape mission profile as well as the shielding afforded by the manned spacecraft. No allowance is ade for this dose since the space radiation shield would result in small doses from trapped belt aversal..

Allowable radiation doses.– Much controversy exists regarding allowable radiation doses in nned space operations. This is aptly demonstrated by the Feburary 1965 comprehensive review 56 references) of the topic published by Aerospace Medicine (ref. 102), which ends without tting general radiation protection guides specifying fixed acceptable values. Even if open to estion, such values must be established to provide a design reference point. For the Apollo ssion, the data shown in Table 20 have been set by NASA and accepted (evidently with some eservation) by the Working Group on Radiation Problems of the National Academy of Science. apply these limits to long-duration flights, some intepretation is necessary. This is generally ne by assuming that the mean average yearly dose figures are those that apply to doses from redictable known sources such as on-board nuclear power plants or the trapped radiation belts. he interpretation of the "maximum permissible single acute emergency exposure" is that the obability of this dose not being exceeded is some large number like 0.99 or 0.999. Published pollo reports indicate that the achieved probability is at least 0.995.

The time over which dose is received is important in establishing dose limits because of the ssible existance of recovery effects. For many types of radiation damage, it has been observed at the injury is largely self-repaired in the course of time. This has led to the concept of an quivalent Residual Dose (ERD) by which the effect, for example, of 2 rads per day for 100 days not 200 rad but only 85 rad because of recovery (ref. 102). It is not clear that ERD applies for e more heavily ionizing radiation sources anticipated, or that it applies to blood-forming organ amage. The recommendation of ref. 102 is that straight dose accumulation be used for evaluating ute or subacute hematopoietic response to fractionated exposures of about 50 or more rem per action, and for dose rates greater that 2 rem/day.

The set of allowable doses given in Table 21 has been used in this study. These dose levels re established by LMSC radiobiologists and consultants. The dose-time matrix was derived iving appropriate consideration to the ERD concept. For interpreting these limits the QF uality Factor or Relative Biological Effectiveness) was taken equal to the Apollo dose limits lues, as these were at the mid-range of the suggested QF.

It will be observed that the acute exposure limits are somewhat lower than the Apollo limits, ile the yearly limits are somewhat higher. The acute dose limits are a factor of 2 to 4 lower an those derived as the threshold for clinical signs from experimental proton irradiations (ref. 04) of monkeys (and suggested as appropriate for humans). Since there is some doubt as to the curacy of the dosimetry system used in the experiments, the factor of 2 to 4 is not excessive. e exposure limits compare favorably with the response criteria just published by the Space adiation Study Panel (Radiobiological Factors in Manned Space Flight, W.E. Langham, 1967).

TABLE 20

RADIATION EXPOSURE DOSE LIMITS[a]

Critical Organ	Maximum Permissible Integrated Dose (rem)	RBE (rem/rad)	Average Yearly Dose (rad)	Maximum Permissible Single Acute Emergency Exposure		Location of Dose Point
				(rad)	(rem)	
Skin of Whole Body	1600	1.4 (approx.)	250	500[b]	700	0.07-mm depth from surface of cylinder 2 at highest dose-rate point
Blood-Forming	270	1.0	55	200	200	5-cm depth from surface of cylinder 2
Feet, Ankles, and Hands	4000	1.4	550	700[c]	980	0.07-mm depth from surface of cylinder 3 at highest dose point
Eyes	270	2[d]	27	100	200	3-mm depth from surface on cylinder 1 along eyeline

(a) J. Billingham, Apollo Dose Limits, NASA SP-71, p. 139 (1964) (ref. 103)
(b) Based upon skin erythema level
(c) Based upon skin erythema level but these appendages are believed to be less radiosensitive.
(d) Slightly higher RBE assumed since eyes are believed more radiosensitive.

TABLE 21

SUMMARY OF RECOMMENDED MAXIMUM RADIATION DOSES TO CRITICAL TISSUES IN REM

Critical Tissue	Tissue Dose-Depth, (cm)	QF Flare	QF Belt	Career Dose (5-yr Sequential Accumulative)	Annual Dose, Maximum in any 1 yr	180-day Dose, Maximum in any 1 flt	60-day Dose, Maximum in any 1 flt	30-day Dose, Maximum in any 1 flt	Maximum Acute Dose, 24-hr (emrg)
Lens of Eye	0.30	1.0-2.0	1.0-1.4	220	220	185	170	160	150
Hematopoietic Tissue	5.00	0.7-1.5	1.0	210	210	130	90	70	50
Abdominal Viscera	5.00	0.7-1.5	1.0	300	300	270	220	160	100
Skin	0.02	1.0-2.0	1.0-1.4	800	800	600	400	300	200
Hands and Feet	0.02	1.0-2.0	1.0-1.4	800	800	700	600	500	400

In applying the above exposure limits, it was assumed that the desired probability of not exeding the cited limits is 0.999. Although arbitrary, this figure seems reasonable.

Attenuation calculation.– A simple physical model was adopted to facilitate calculation of the d dose received for a given flux of protons. This model consists of a spherical shield with a nt receiver of tissue located at the center of the shield. A fixed proton spectrum was used, ich is identical to the source model previously discussed. Free-space proton flux is isotropic. he above assumptions are conservative in that they lead to a greater shield thickness than would obtained if a more detailed analysis were conducted.

Because of the fixed spectral shape, it is possible to calculate a response function just once one material. This gives the rad dose per proton/cm^2 at energy greater than 30 Mev versus terial thickness. Such a response function has been previously calculated. Several such functons for the spectral shape herein considered can be calculated from the literature. These were mpared and the calculation of Burrell of MSFC (ref. 105) adopted. This calculation fits proton nge-energy data in a more refined manner than previous calculations, and includes the effects secondaries. It compares well with detailed calculations conducted by Oak Ridge National aboratory. Figure 11 shows the response function. With the use of this figure, required shield ckness can be obtained directly from the allowable dose divided by the proton/cm^2 source.

Allowable dose is based on Table 21, with the rem dose divided by QF to yield rad dose. posure due to galactic cosmic rays must be subtracted from this value. These calculations ld an aluminum shield thickness. Aluminum is a convenient reference shielding material since can be used in a space environment, is easily fabricated, and shows reasonable weight economy s a shield material.

Since the shielding is accomplished by electrons, materials with a higher atomic number/atomic ass ratio will constitute a lighter shield on a gm/cm^2 basis. Hydrogen, carbon, lithium-6, and ygen are examples of such potentially lighter shield components. Polyethylene, butyl rubber, ter, food, and food residues are usable shield materials. The composition of polyethylene and utyl rubber is almost the same $(CH_2)_n$, so that tabulated polyethylene data can be used for either. ta are also available for water and carbon.

The most recent range-energy data (ref. 106) are used to make a fit to the common approxiation that range = a (energy)^n. Two analytical formulas to approximate dose Al/dose H_2O or H_2 at equal gm/cm2 thicknesses were used. The first is that of Burrell (ref. 105); the other expression is due to Madey (ref. 107) and accounts for both the decrease in transmitted protons due the higher cutoff energy of the water shield, and the decreased ionization of the transmitted otons. The formulas agree fairly well. Madey's formula was used to obtain the polyethylene d water dose response curves shown in fig. 11.

The shielding value of dry food (CH_2O) is close to that of water. Correlations suggested in f. 106 lead to the calculated values of Table 22, which show the differential shielding thicknesses sed in the study, i.e., 1 gm/cm^2 polyethylene = 1.05 gm/cm^2 H_2O = 1.07 gm/cm^2 dry food = .38 gm/cm^2 Al. Stored metabolic wastes (feces, urine and urine distillate residue, carbon) are sumed to be as effective as dry food in proton shielding. On a required gm/cm^2 basis, CO_2 d oxygen fall between the nongaseous metabolic wastes and aluminum. Because of their low denity, however, total shield mass using CO_2 or oxygen would exceed that of all-aluminum shielding, e., at a density of one-tenth that of aluminum, total shield weight is 53,000 lb versus 31,000 unds for an all-aluminum shield, even though the required gm/cm^2 thickness is lower. In addiion, use of CO_2 or oxygen implies a large tankage penalty and the presence of high-pressure or w-temperature storage vessels not readily amenable to periodic interchange. No further considration was given to CO_2 and oxygen as shield materials.

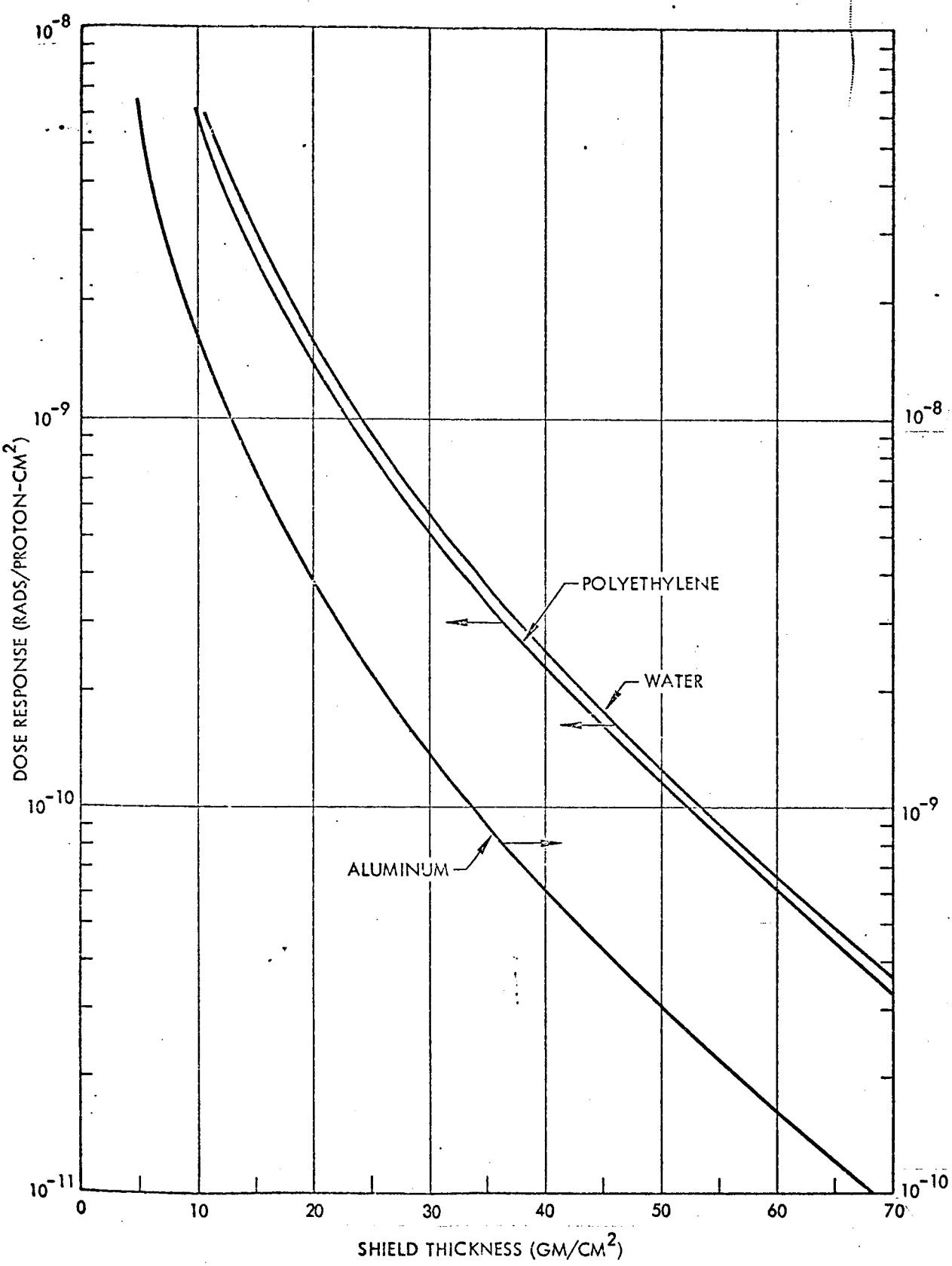


Fig. 11 Shield Effectiveness

TABLE 22

PROTON SHIELDING EFFECTIVENESS
FOR VARIOUS MATERIALS

Material	Mean Excitation Energy (ev)	Relative Shield Thickness (gm/cm^2)[a]
Polyethylene (CH_2)	54.6	1.00
Water	65.1	1.05
Muscle	66.2	-
Food (CH_2O)	69.6[b]	1.07
Carbon	78.0	-
CO_2	85.9	-
Oxygen	89.1	-
Aluminum	163.0	1.38

(a) Approximate values at shield requirement of 40 gm/cm^2 of polyethylene.
(b) Estimated value.

Total shield weight is determined by the volume enclosed and by the shield thickness. Solar proton events last for about 1 to 3 days and frequently come in a group with each event separated by a few days. A communal "storm cellar" – a shielded volume in which the crew spends most of its time during solar-proton events – is a straightforward means of providing the shield. Required volume estimates are in the range of 100 ft^3 per man. Various configurations for 1-, 3-, 5-, and 10-man occupancy were examined. On a mass basis, the best is a one-man cubbyhole, a cylinder about 6 ft long by 1.5 ft diameter. This arrangement is not considered practical because of the need to provide individual life sustenance to each such cubbyhole and because of its asocial aspects. The next best shield, about 50% heavier per man, is a 10-man module in the shape of a cylinder with truncated conical ends as shown in fig. 12. The "storm cellar" provides 2.24 m^3 (79 ft^3) of volume per man, and life-sustenance provisions can be arranged inside. This storm cellar, which in fact may be the spacecraft command and living quarters center, was adopted both because it seems to be a convenient way of arranging spacecraft crew accommodations and is a convenient analysis concept.

Figure 13 shows shield weight versus shield thickness for the 10-man module. Table 18 gives the weight of the radiation shield if fabricated of polyethylene, water-equivalent material, or aluminum. The dose criterion requiring the thickest shield is hematopoietic tissue. Special eye protection is not required.

It is interesting to examine the changes caused by rather drastic changes in calculational inputs. Doubling the allowable dose to 100 rad to the blood-forming organs decreases shield weight about 30%, while doubling the source flux increases shield weight by about 33%. Reducing the probability of not exceeding the specified dose from 0.999 to 0.99 decreases shield weight by about 47%.

Combined System Configurations

As discussed in the last section, dry food or nongaseous metabolic wastes are practical materials for a solar-proton radiation shield. Calculations to indicate the feasibility of such a system were performed in this study. Since the emphasis was on conceptual comparisons, little effort was placed on the mechanics of such a shield. In outline, the shield might be built of a series of food and metabolic waste containers sized to hold one day's supply of dry food or the equivalent replacement one day's output of stabilized wastes. The containers would be placed in a lightweight framework, with access at the food preparation and waste stabilization stations. Each day a food container would be removed from the shield, and a replacement container added to the shield at the opposite side of the shield. In designing such a shield, due attention must be given to minimization of connected voids, to avoid streaming. Both shield arrangement and analysis would present challenging, but not fundamental, design problems.

Another possible problem that has been given only brief consideration is that of possible activation of the stored food. The dose that would be received by unshielded food is about 0.1 megarad, with proton energies in the hundreds of Mev range. Experiments in food sterilization have indicated measurable residual radioactivity caused by meat irradiation at 5.6 megarad dosage with a 16-Mev electron source (ref. 108). Analysis (and ultimately experimentation) on the topic of possible residual radioactivity should be performed. As far as food nutritive value is concerned, the results of the extensive food-irradiation program to date indicate no difficulties at the megarad dose level. It is felt that the higher irradiation energy involved in the food for radiation shielding concept will not alter this finding.

Partial shield system. – Available waste products for radiation shielding include both solid and liquid metabolic wastes and solid residues from spacecraft life-support systems. In the first category considered (see fig. 14), use is made of feces, urine sludge, and carbon residue not otherwise used in the stored food life-support system. These residues constitute 86% of the weight of dry food supplied. Also they provide mass that is not reused in the reference stored food system and, conveniently, can supply much of the bulk needed in the radiation shield. In fact, by obviating the need for oxygen supply to a feces and urine sludge incinerator, solids reuse has the

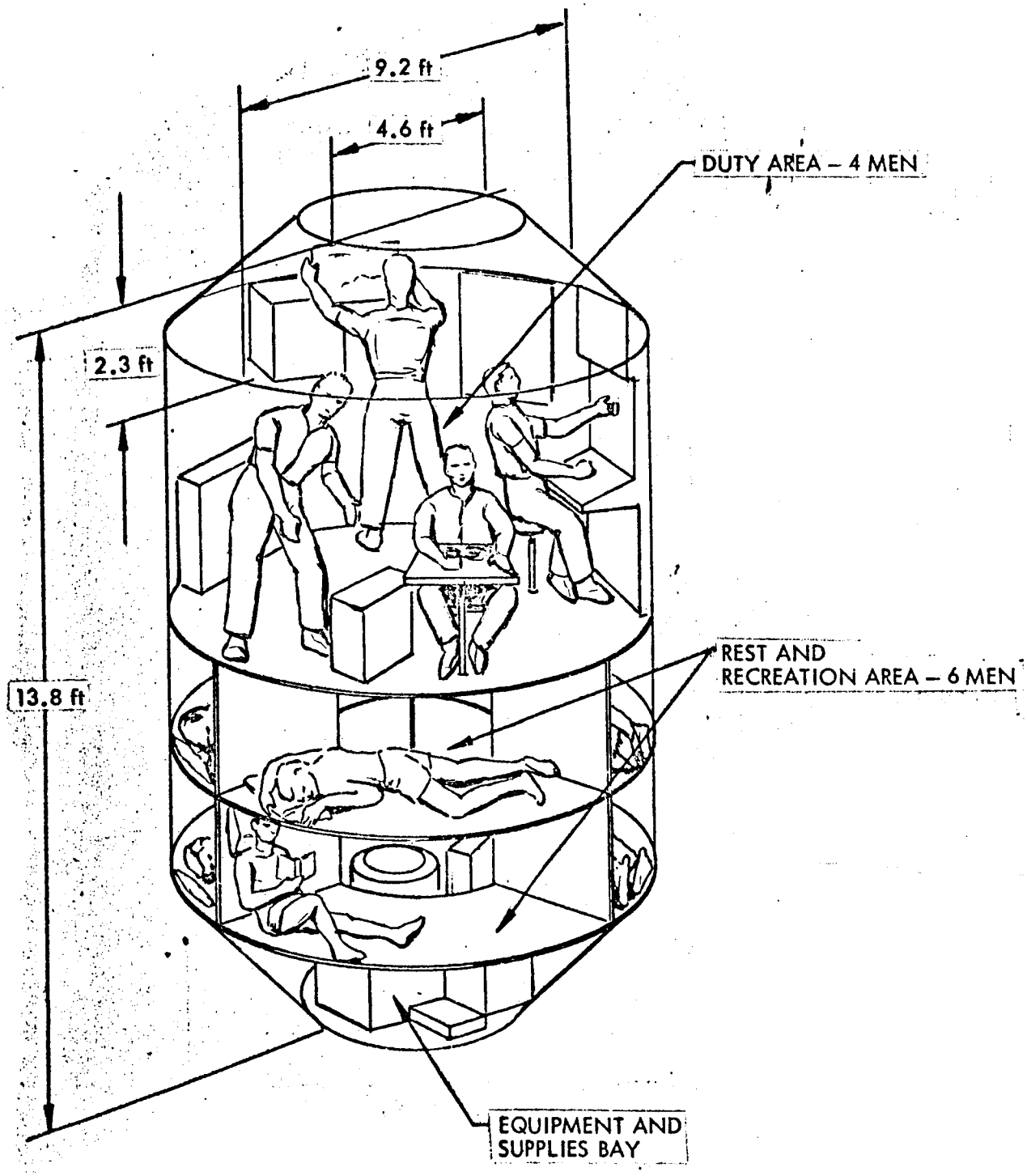


Fig. 12 Storm Cellar for 10 Men

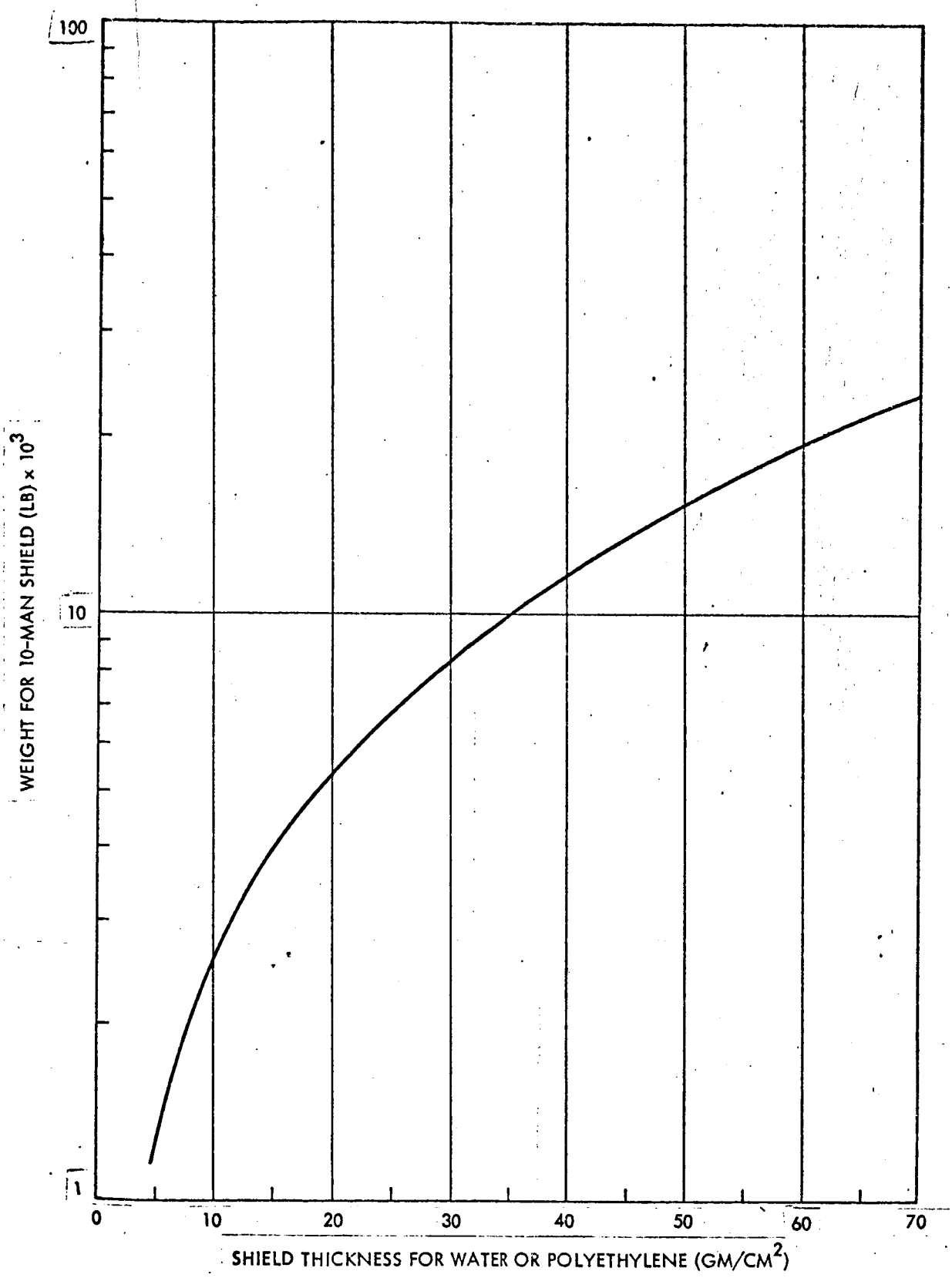


Fig. 13 Radiation Shielding Weights

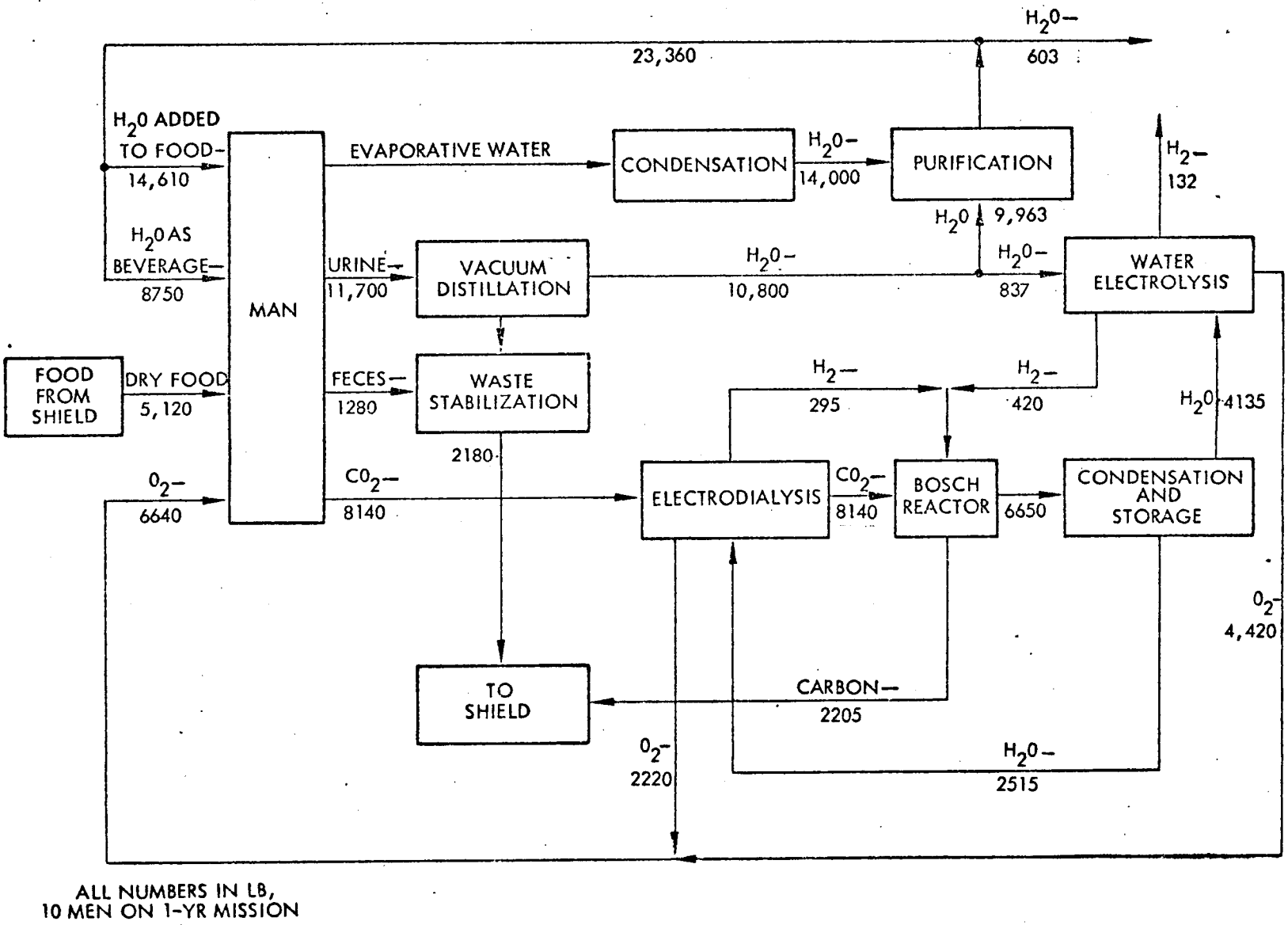


Fig. 14 System Mass Balance – Stored Food & Solid Wastes For Radiation Shielding

effect of releasing water from the metabolic cycle. A weight credit can be taken for this useful space-vehicle commodity, as well as for a slight reduction in the water-electrolysis weight penalty. Figure 14 gives the mass balance for this system for the 10-man crew-year. The 10-man output of 4385 lb per year is some 55% of the required 24,400 lb shield needed for a three-year mission.

Packaging penalties must be included in weight totals. Dry food is packaged at a 21% penalty. Solid metabolic wastes incur a 30% weight penalty for packaging, above the 21% dry-food penalty.

To obtain required shield weight, the weight of solid wastes and packaging are subtracted from the original shield weight. The relative effectiveness of the solid wastes, the packaging material (assumed to be aluminum), and the polyethylene reference shield material are taken into account. It is assumed that waste stabilization requires the same equipment weight and power penalty as did incineration. Probably this is an overestimate of stabilization requirements; temperatures of 250°F should suffice for sterilization. Weight credit is taken for the water produced and the reduced water electrolysis load. As the reference stored-food system produces more hydrogen gas, credit is also allowed for hydrogen production so as to disadvantage the combined stored food-radiation shield system. To provide a basis for comparison of the various systems, the weight needed in ECS provisions unaltered by these changes is added. Table 23 gives the weight penalties (fixed equipment and power) for water reprocessing, incineration, water electrolysis, and oxygen generation. Final comparison results have been given in Table 17 under "Food as Partial Shield." System total weight is about 70% of the separate shield-stored food system and some 5% heavier than a separate shield-Hydrogenomonas system.

TABLE 23

WEIGHT PENALTY FOR PROCESSING STEPS [a]

Process	Mission Duration 1 Year (lb)	2 Year (lb)	3 Year (lb)
Urine vacuum distillation (11,700 lb/year capacity)	180	240	300
Waste incineration (2730 lb/year capacity)	330	440	550
Water electrolysis (5,570 lb/yr capacity)	374	440	480
Oxygen generation and other ECS Requirements	1,770	1,770	1,770

(a) Based on 10-man crew; values from final report NAS 2-3012.

Urine and solid wastes as shield.– The second category of metabolic wastes used for shielding as illustrated by fig. 15. In this case, both feces and urine are used as the shield material. Make-up water is required to replace the water otherwise reclaimed from urine. A water packaging penalty of 10% is charged. Fixed weight for urine vacuum distillation is eliminated in this system. Waste stabilization provisions are charged at 200% of the incineration mass requirements – an increase to account for the need to stabilize urine. Urine storage packaging penalty is assumed to be 30%. Mass accounting is conducted in a similar manner to that explained previously.

For the one-year mission, the weight of reclaimed urine and solids is insufficient for the required radiation shield. Thus, a small intrinsic shield is still required, as indicated in Table 17. Longer missions produce total wastes linearly proportional to duration. Shield requirements increase slowly in this range of duration, so that for longer missions only a portion of urine need be stored as shield. Appropriate adjustments are made in the water-reprocessing-system mass penalty. The mass balance for 2- and 3-year missions is a combination of figs. 14 and 15.

Urine and solids shield systems are about 10% higher in total weight than the "Food as Partial Shield" system. Essentially this reflects the physical fact that, for long missions, water reprocessing saves weight compared to water storage; this holds true even if the water/urine is of use. In the latter case, the fact that the packaging material is less effective than the reference polyethylene shield material results in the weight penalty.

Microbiological Aspects of Waste Stabilization

It is well known that feces and urine must be treated if they are to be stored and handled inside a closed atmosphere system. The preferred stabilization method is sterilization, using either heat or ionizing radiation. The concept is to seal the wastes in a thin gauge can (not necessarily round), sterilize the contents (a pressure-cooker type of heat sterilizer could be used so that the can need not be a pressure vessel), and transfer the can to the shield. Since a nuclear reactor power source is postulated in this study, an ionizing radiation source for sterilization is available, at the penalty of providing access to the reactor or reactor coolant loop. As urine starts at a lower bacterial contamination level, less stringent sterilization processing is required.

As a result of reviewing the waste problem, these general guidelines have been formulated:

- Man's wastes (feces and urine) should be sterilized before being stored for long periods.
- Radiation or heat processing appear to be the best means to accomplish sterilization.
- Sterilized waste must be protected from recontamination in handling and storage.
- Laboratory investigations will be required to establish specific sterilization processing cycles and to determine the physical-chemical effects of sterilization.
- Pressure buildup in sterilized wastes is not expected to be a problem, but this as well as purely chemical instability must be investigated.

The conclusions presented in the above discussion resulted from an analysis of several candidate waste stabilization concepts:

(1) Chemical germicides
(2) Aerobic digestion
(3) Radiation
(4) Heat

Two other processes are arresting microbial growth are incineration and dehydration, but these convert the wastes to an undesirable form or involve unnecessary penalties.

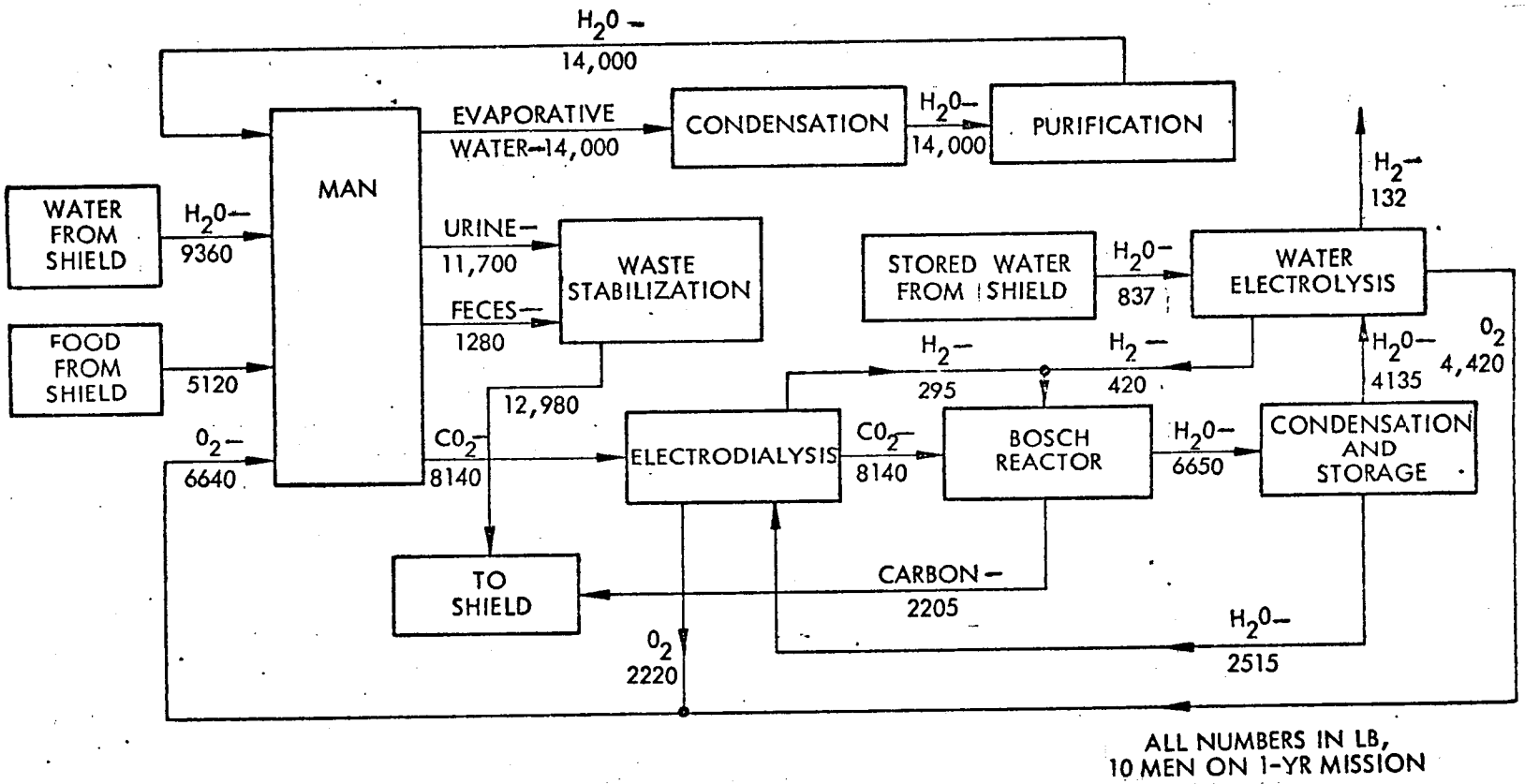


Fig. 15 System Mass Balance – Stored Food, Urine, & Solid Wastes For Radiation Shielding

Chemical germicides. – There are a number of chemical germicides that are active against non-spore forms of microorganisms. However, there are relatively few agents available that are sporocidal, i.e., lethal to bacterial spores which are the most difficult biological forms to kill. Two major problems are apparent in the use of chemicals to inactivate microorganisms in wastes: (1) the difficulty in producing a homogeneous mixture of waste and chemical so that all microbial cells are in contact with the germicidal agent, and (2) the potential corrosiveness or toxicity of the chemicals. Thus, the potential results are that microbial activity may not be completely arrested, and the concept does not appear promising.

Aerobic digestion. – The stabilization of wastes by aerobic digestion usually refers to oxidation stability and does not necessarily mean that microbial activity is inactivated. Viable microorganisms do persist in the waste and can become active if placed under proper environmental conditions. Aerobically digested waste may result in the control or inhibition of oxygen-demanding microorganisms, but those organisms which can grow and reproduce under anaerobic conditions may still be active. Thus, storage of the aerobically digested waste for long periods could give rise to activity of anaerobic bacteria which through their metabolic activity produce obnoxious, toxic, and/or flammable gases in addition to various chemical byproducts such as organic acids that may be corrosive and toxic.

Radiation. – The exposure of wastes to sterilizing doses of radiation appears to be a satisfactory means of controlling the microbial activity since a sterile product is the result of the process (ref. 109). Sterile waste protected from recontamination should remain microbiologically stable for an indefinite time. A considerable amount of data and experience in radiation processing has been accumulated in the food industry. In the processing of wastes by radiation, there would appear to be no restrictions that would prevent obtaining a sterile product. If a nuclear power source is available in the spacecraft, there should be more than ample energy available to supply proper dosage levels to sterilize the waste.

Heat. – Wastes may also be sterilized by exposure to proper time-temperature cycles that will kill microorganisms. The standard sterilization cycle using moist heat is 250°F for 15 minutes (ref. 110 and 111). This time period refers only to that part of the overall cycle when all parts of the material have attained the 250°F temperature. The total time of the cycle may be much longer depending upon the size of the load being processed, heat transfer characteristics, etc. The time-temperature relationship of the cycle may vary somewhat, but it is an inverse relationship - the lower the temperature the longer the time. Temperatures may vary for different cycles from 225° to 300°F, but cycle times cannot be specified without some knowledge of the microbiological loading or population and the physical characteristics of the material being processed. At 250°F the sterilization time for one liter of fluid in a flask is approximately 30 minutes; the heat penetration time from room temperature of 250°F is approximately 17 minutes. The same fluid in a bottle requires 5 minutes longer for sterilization time. Specific sterilization cycles must be established by experimentation.

Incineration. – The process of incineration would be ideal for the control of microbial activity since it would destroy all the microbial cells in the waste. Incineration of wastes introduces toxicological and handling problems since potential oxidation products of oxides of nitrogen and sulfur are produced. Because incineration converts solid to gases, it is a regressive step as far as shielding is concerned.

Dehydration. – The dehydration of wastes appears to be an acceptable means to inactivate microbial activity. In the dehydration process, many cells are killed by desiccation, and those that may survive the process are inactive because there is insufficient water available to carry out the metabolic processes of growth and reproduction. Preliminary experiments with vacuum-dried feces indicate that moisture levels less than 30% resulted in little or no microbial activity as judged by gas production. It should be noted that the dried samples did not undergo long-term storage periods. Any fault in the process which would allow rehydration of the waste would create potential conditions for reactivation of microbial metabolism. Dehydration increases complexity since two waste streams now appear; one is dehydrated solids and presumably stable. Since the resultant water must still be sterilized, the process does not look as promising as conventional heat or radiation sterilization.

WASTE REGENERATION IN THE CLOSED SYSTEM

A review and analysis of waste-processing requirements and the candidate waste processing systems were conducted to a greater depth than was possible during the Phase I study. The objectives of this current study were:

- To define process requirements by reviewing a number of possible long-duration life-support systems including stored food, Hydrogenomonas, and glycerol as food sources with and without wastes for EVA, leakage makeup, radiation shielding, and propulsion
- To define the characteristics and performance of candidate waste-processing systems to match system requirements with system capability
- To select a preferred approach to waste processing for each processing requirement

Waste-Processing Requirements

To assist in defining waste-processing requirements, mass balances were prepared for seven life-support system concepts. Figures 16 through 20 present mass balances for systems using stored food with and without wastes processed to provide materials for EVA, leakage makeup, radiation shielding, and propulsion.

The wastes available for processing were identified to be urine sludge and feces for all systems except the Hydrogenomonas system where feces was the only waste requiring processing, because urine was assumed to be utilized directly by the Hydrogenomonas culture. Wastes such as paper, plastics, and other nonbiological wastes were not considered here because they present a separate problem, primarily one of disposal rather than recovery of useful materials. In addition, most of the life-support systems studied already resulted in excess hydrogen and carbon and the quantity of oxygen that could be recovered from such wastes is small.

Table 24 presents a summary of the unusable materials for each system, which of course is a measure of the completeness of system closure, which in turn is a measure of the system weight. The most significant information to be obtained from Table 24 is that the use of wastes for EVA, leakage, or propulsion reduces almost in half the materials lost from a stored food system, thereby reducing substantially the potential gain of a food producing concept. In fact, glycerol margins over stored food are reduced to a point where use of a glycerol system is much in question for the one- to three-year mission. Switching to stored food seems advisable when development costs and the probability of successful system development are considered. Hydrogenomonas still offers sufficient potential for use in the one-to three-year mission when EVA, leakage makeup, and propulsion are taken into account. When compared with wastes for radiation shielding, however, the Hydrogenomonas system shows little gain. For the waste-regeneration study, it was therefore assumed that a switch to stored food would be made if wastes for radiation shielding is considered.

Table 25 presents the waste-processing system requirements for 10 combinations of the food and waste uses considered. The type of food source is indicated in the first column, and the uses of wastes are indicated by a mark in the next four columns. If no mark appears, wastes are either processed for disposal only or are used to manufacture food. The required recovery products are indicated by a "yes" or "no" in the columns labeled CO_2, H_2O, Nitrogen, and Minerals. The materials to be processed and the system implications are presented in the last column.

By inspection of Table 25, waste processing requirements can be summarized as follows:

Waste Materials To Be Processed

- Urine sludge and feces (all stored food and glycerol systems)
- Feces (Hydrogenomonas system)

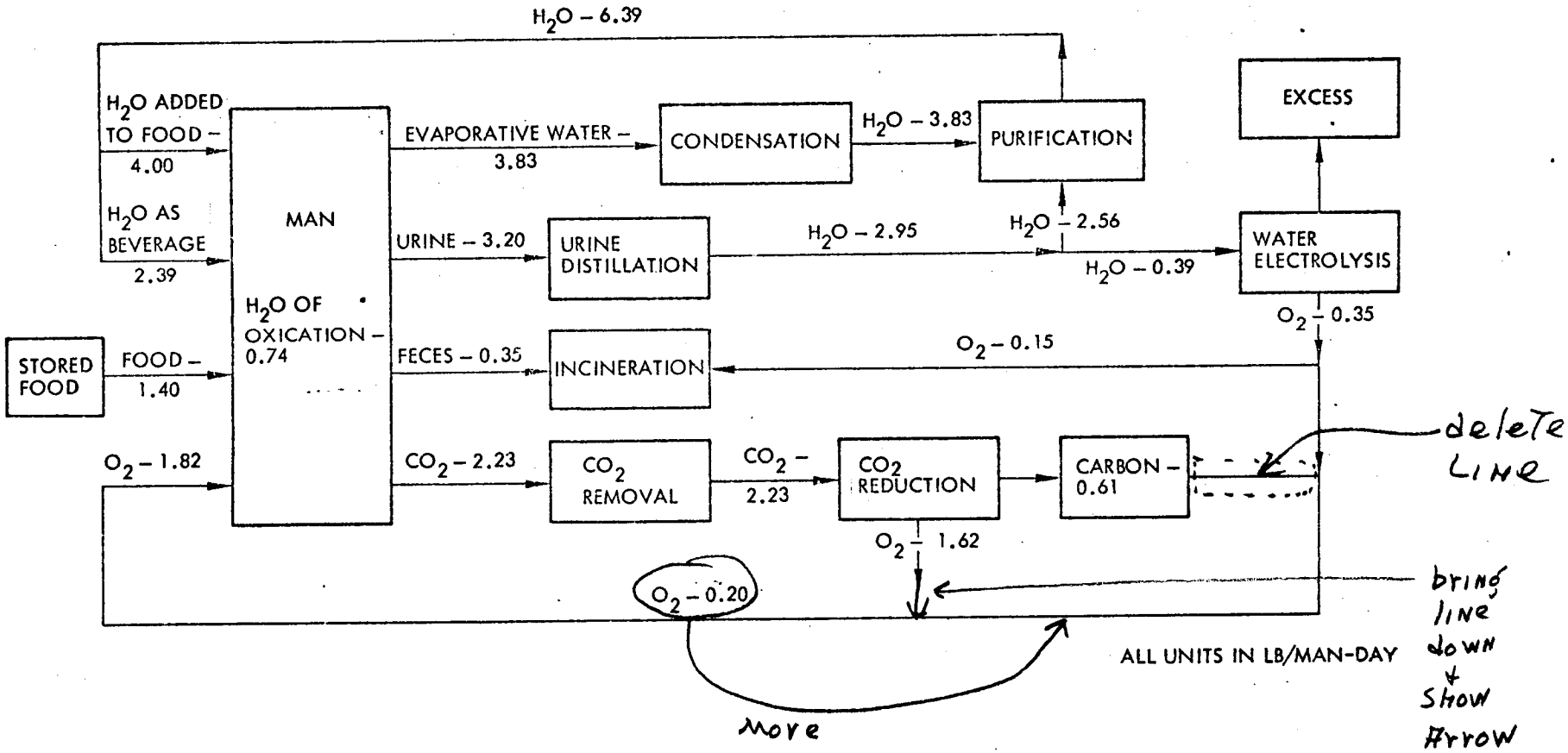


Fig. 16 System Mass Balance – Stored Food, No Uses for Wastes

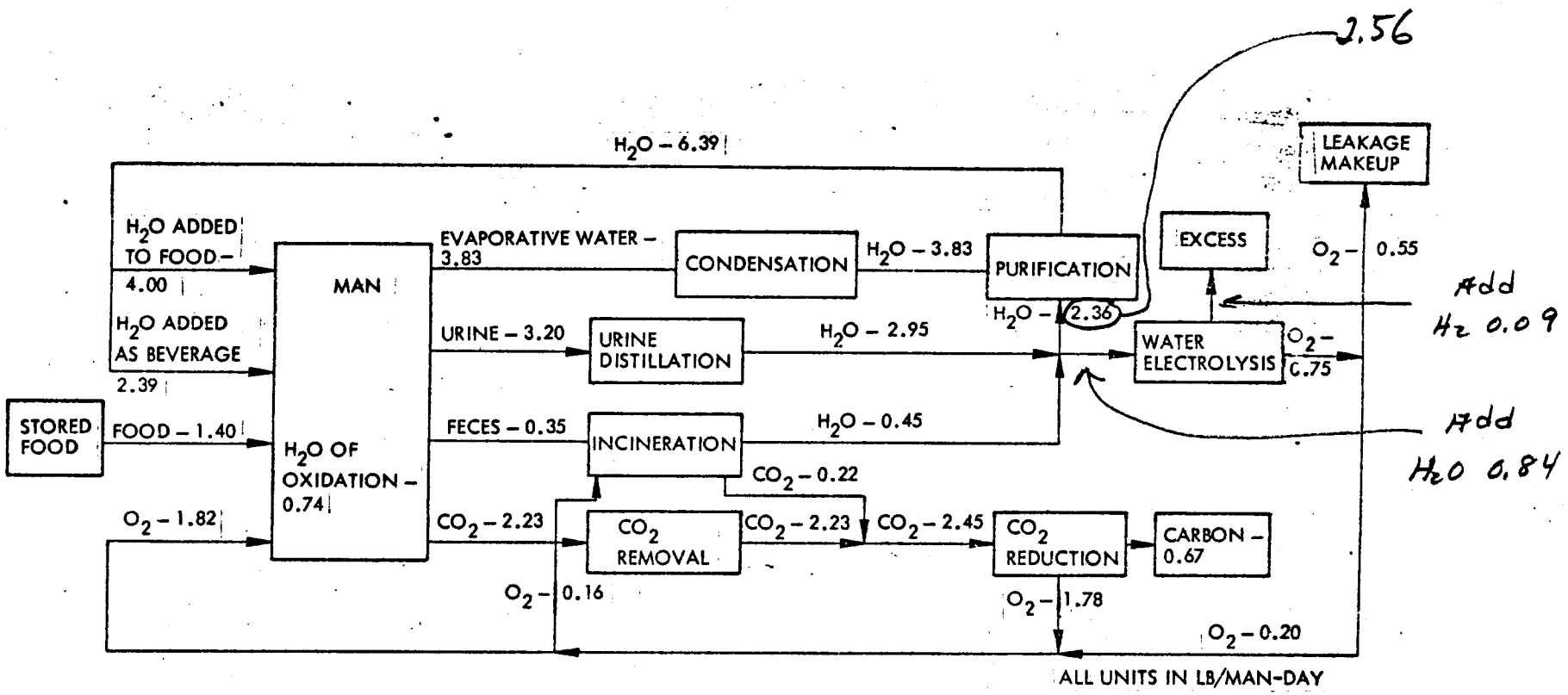


Fig. 18 System Mass Balance – Stored Food, Wastes Processed For Leakage Makeup

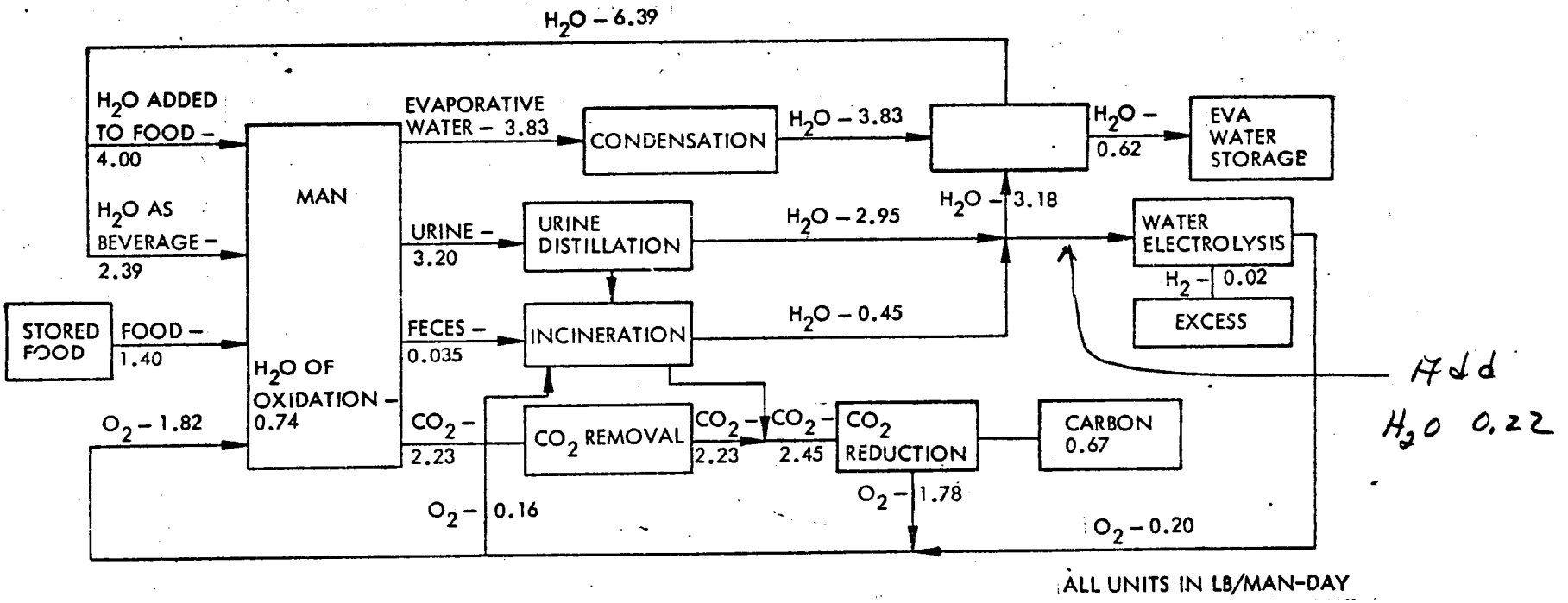


Fig. 17 System Mass Balance – Stored Food, Wastes Processed For EVA Water

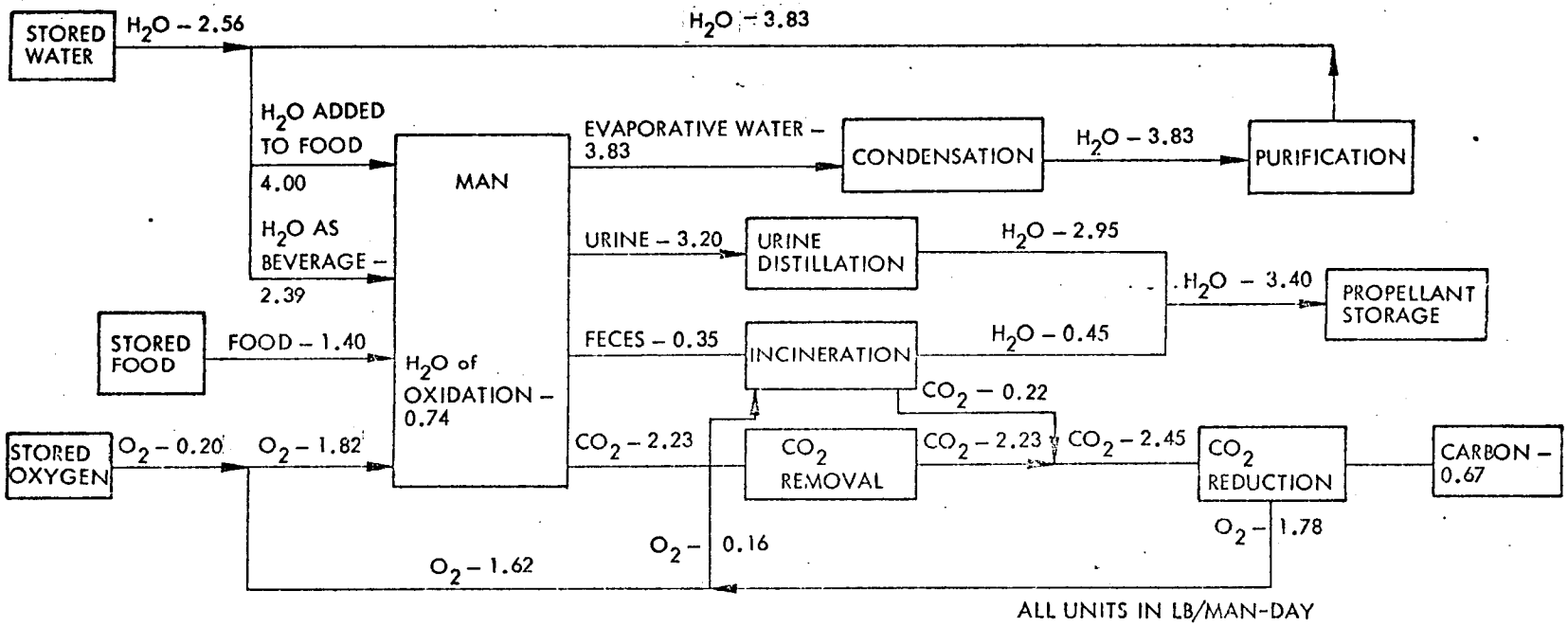


Fig. 20 System Mass Balance: Stored Food – Wastes for Propulsion – Arc Jet

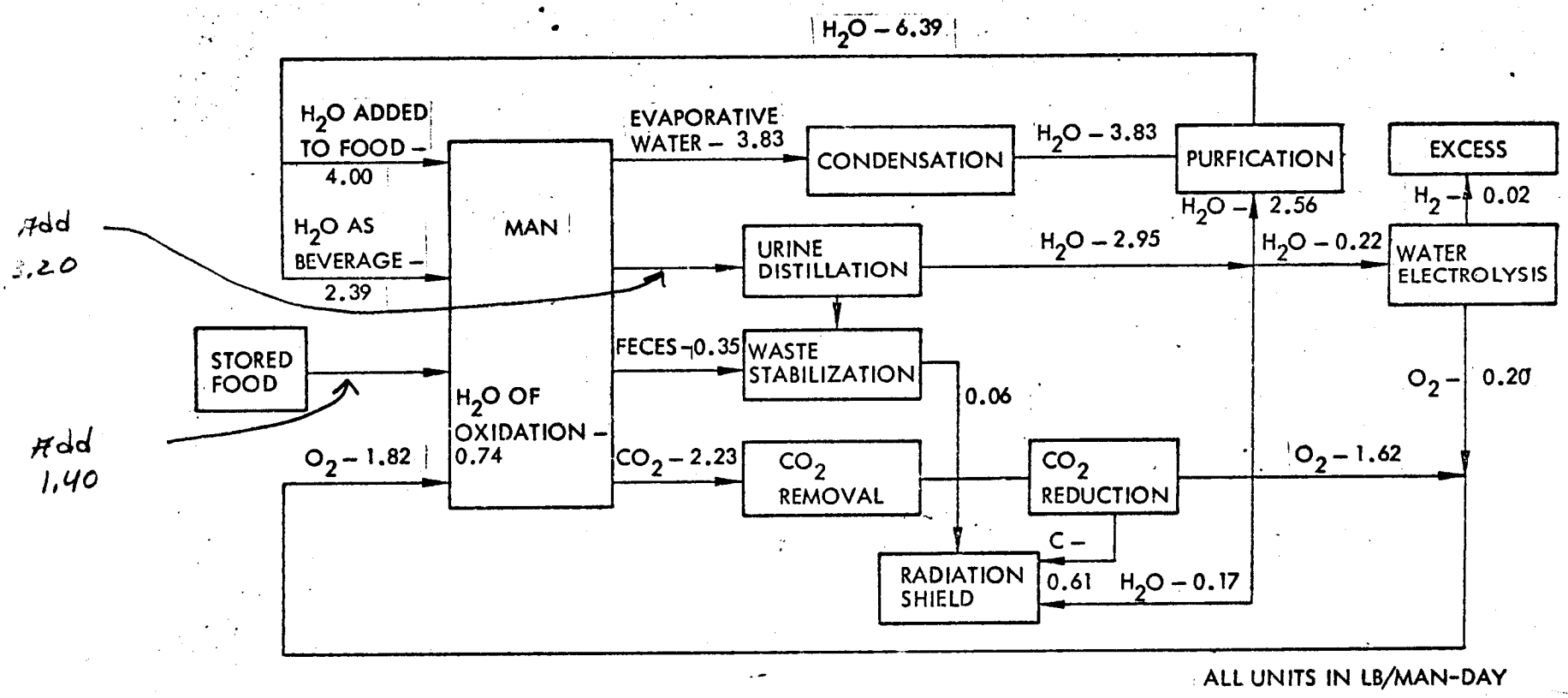


Fig. 19 System Mass Balance – Stored Food, Wastes Processed For Radiation Shielding

TABLE 24

MATERIALS LOST TO SYSTEM

(Weight, lb/man-day)

System	EVA	Leak-age	Radiation Shield	Propul-sion	Solid Carbon	Gaseous Hydrogen	Gaseous Oxides Mineral Ash	CO_2	H_2O	Total Weight Lost to System
Stored food					0.61	0.04	0.09	0.22	0.45	1.40
Stored food	X				0.67	0.02	0.09			0.78
Stored food		X			0.67	0.09	0.09			0.85
Stored Food			X			0.02				0.02
Stored food				X	0.67		0.09			0.75
Glycerol					0.12		0.09			0.21
Hydrogenomonas							0.01(a)			0.01

(a) Assumes that almost all organics can be converted to useful products for Hydrogenomonas growth.

TABLE 25

WASTE-PROCESSING SYSTEM REQUIREMENTS

System	EVA	Leakage	Rad. Shield	Propulsion	Recovered From Wastes: CO_2	H_2O	Nitrogen	Minerals	System Considerations
Stored food					No	No	No	No	Process urine sludge and feces for disposal only
Stored food	X				Yes	Yes	No	No	Process urine sludge and feces for EVA water
Stored food		X			Yes	Yes	No	No	Process urine sludge and feces for oxygen
Stored food			X		No	No	No	No	Sterilize urine sludge and feces for use as shielding; eliminate waste incinerator
Stored food				X	Yes	Yes	No	No	Process urine sludge and feces for propulsion water; process CO_2 for oxygen supply
Glycerol					Yes	Yes	No	No	Process urine sludge and feces for H_2O and CO_2 to support food synthesis
Glycerol	X	X	X	X	Yes	Yes	No	No	Switch to stored food system; glycerol synthesis not warranted to save carbon and hydrogen
Hydrogenomonas					Yes	Yes	Yes	Yes	Direct utilization of urine; process fecal waste for CO_2, H_2O, nitrogen, minerals
Hydrogenomonas	X	X		X	Yes	Yes	Yes	Yes	Store EVA, leakage and propulsion materials; direct utilization of urine, process fecal wastes, for maximum recovery
Hydrogenomonas			X		No	No	No	No	Switch to stored food system. No material savings for growing Hydrogemomonas Sterilize wastes for shielding

Desired Recovery Products

- CO_2 and H_2O (all stored food and glycerol systems except wastes for radiation shielding)
- CO_2, H_2O, nitrogen, minerals (Hydrogenomonas system)
- All wastes sterilized (stored food wastes for radiation shielding)

Candidate Waste Processing Systems

With the establishment of the waste-processing requirements, the next step in the study was to establish a number of candidate waste-processing systems and to predict their performance. The following complete waste processing systems were selected for study:

- Zimmerman wet-oxidation process
- Incineration (rapid-high temperature)
- Incineration (temperature programmed)
- Aerobic digestion and programmed incineration
- Aerobic digestion, secondary biological processing, and programmed incineration
- Aerobic digestion, secondary biological processing, and food processing
- Aerobic digestion, anaerobic digestion, and incineration

The aerobic, anaerobic, and secondary biological processing steps were included in the hope that the organic wastes might be transformed into organic compounds useful for growth of Hydrogenomonas prior to incineration.

Waste composition.—To predict the performance of the waste-processing systems, it was necessary to establish the composition of the urine sludge and feces to be used in the analysis. The composition of organic constituents and ash in urine sludge was calculated from the data of Hawk et al. (ref. 112). An alternate calculation of total ash was made from the data in the Bioastronautics Data Book (ref. 113). The composition of major organic constituents was taken from the Merck Index (ref. 114), and it was assumed that minor organics have the average composition of major organics. Ash was calculated from the apparent electrolytes given in Hawk (ref. 112), and the maximum apparent electrolyte concentration was in the range given in ref. 113. Table 26 presents the resulting urine-sludge compostion.

In establishing fecal waste composition, an analysis of the data given in the Bioastronautics Data Book (ref. 113) was made. Table 27 presents the results of this analysis based on the maximum component values given by ref. 113. The substance, chemical formula, and elemental analysis are listed. Ash was calculated from the maximum electrolyte concentrations in ref. 113. Table 28 presents the ash calculation. Data from Tables 27 and 28 were used to calculate complete fecal waste composition presented by Table 29. Fecal composition and urine-sludge composition were then combined in Table 30, which was used in all subsequent process calculations.

Zimmerman wet-oxidation process.— The wet-oxidation process as described by Zimmerman (ref. 115) is an elevated-temperature, elevated-pressure batch process for the air oxidation of organic wastes. The input liquor may be preheated to 300°F or lower if the concentration of oxidizable materials is high enough. There is a considerable range of temperatures, pressures, waste concentrations, and air (or oxygen) concentrations feasible, subject to the constraints of maintaining a liquid phase in the reactor and carrying out the desired degree of oxidation in the desired time.

TABLE 26

URINE COMPOSITION

Substance	Composition (gm /man-day)					
	Total	C	H	N	O	S
Urea	30	6.0	2.0	14.0	8.0	
Uric Acid	0.7	0.2	0.01	0.2	0.2	
Hippuric Acid	0.7	0.4	0.03	0.05	0.2	
Creatinine	1.2	0.5	0.07	0.4	0.2	
Ammonia	0.7		0.1	0.6		
Minor Organics	0.5					
Amino N	0.2			0.2		
Neutral S	0.1					0.1
Cl^-	7.3					
Na^+	4.0					
K^+	2.0					
Ca^{++}	0.2					
Mg^{++}	0.2					
$PO_4^{=}$	3.4					
$SO_4^{=}$	2.6					
Total	53.8	7.1	2.2	15.5	8.6	0.1

CALCULATED OVERALL COMPOSITION OF SOLIDS

	Percent of Total Organics	Percent of Total Solids
C	21.3	13.5
H	6.6	4.1
N	46.1	29.2
O	25.7	16.3
S	0.3	0.2
Ash	-	36.7

TABLE 27

FECES ANALYSIS (BASED ON REF. 113 DATA)

Substance	Formula	Composition by Weight					Milligram /Man-Day (max.)					
		% C	% H	% O	% N	% S	C	H	O	N	S	Total
Arginine	$C_6H_{14}N_4O_2$	41.4	8.1	18.4	32.2		870	170	387	676		2100
Histidine	$C_6H_9N_3O_2$	46.4	5.8	20.6	27.1		372	46	165	216		800
Indole	C_8H_7N	82.0	6.0		12.0		82	6		12		100
Isoleucine	$C_6H_{13}NO_2$	54.9	10.0	24.4	10.7		1260	230	570	246		2300
Leucine	$C_6H_{13}NO_2$	54.9	10.0	24.4	10.7		1592	290	707	310		2900
Lysine	$C_6H_{14}N_2O_4$	49.3	9.6	21.9	19.2		1430	278	634	557		2900
Methionine	$C_5H_{11}NO_2S$	40.2	7.4	21.4	9.4	21.5	322	59	172	75	172	800
(N Total)										(2100)		(2100)
Threonine	$C_4H_9NO_3$	40.3	7.6	40.3	11.8		886	167	886	260		2200
Urobilinogen	$C_{33}H_{48}O_6N_4$	66.5	8.0	16.1	9.4		186	22	45	26		280
Valine	$C_5H_{11}NO_2$	51.3	9.5	27.3	12.0		1332	247	710	311		2600
(Fiber)	$(C_6H_{10}O_5)$ [a]	44.4	6.2	49.4			4660	650	5190			10500 [c]
Fat Total	$C_{57}H_{110}O_3$ [b]	81.3	13.1	5.6			5680	917	392			7000

TABLE 27 (CONT.)

Substance	Formula	Composition by Weight % C	% H	% O	% N	% S	Milligram /Man-Day (max.) C	H	O	N	S	Total
Vitamin A	$C_{20}H_{30}O$	83.9	10.6	5.6			0.3	TR	0.1			0.33
p Amino Benzoic Acid	$C_7H_7NO_2$	61.3	5.2	23.3	10.2		0.2	TR	TR	TR		0.25
(B Vitamins)												(15)
B_2 (Uroflavin)	$C_{17}H_{20}N_4O_6$ (d)	54.2	5.4	25.5	14.9		0.7	0.1	0.3	0.2		1.3
Vitamin B_6												0.8
Biotin	$C_{10}H_{16}N_2O_3S$	49.2	6.6	19.6	11.5	13.1	0.1	TR	TR	TR	TR	0.2
B-Carotine	$C_{40}H_{56}$	89.5	10.5				3.0	0.3				3.3
Vitamin E	$C_{29}H_{50}O_2$	80.9	11.7	7.4			17	2.5	1.5			21
Folic Acid	$C_{19}H_{19}N_7O_6$	51.7	4.3	21.7	22.2		0.2	TR	0.1	0.1		0.3
Pantothenic Acid	$C_9H_{17}NO_5$	49.3	7.8	36.5	6.4		1.9	0.3	1.4	0.2		3.8
Pyridoxin	$C_8H_{11}NO_3$	56.8	6.6	28.4	8.3		0.3	TR	0.2	TR		0.5
4-Pyridoxic Acid	$C_8H_9NO_4$	52.5	5.0	34.9	7.6		0.3	TR	0.2	TR		0.6
Nicotinic Acid	$C_6H_5NO_2$	58.5	4.1	26.0	11.4		3.2	0.2	1.4	0.6		5.5
Thiamine	$(C_{12}H_{17}N_4OS)^+$	54.3	6.4	6.0	21.1	12.1	0.4	TR	TR	0.2	0.1	0.8
Riboflavin	$C_{17}H_{20}N_4O_6$	54.2	5.4	25.5	14.9		0.6	0.1	0.3	0.2		1.2
							18,700	3,085	9,863	2,690	172	34,510

(a) As cellulose.
(b) As glycerol tristearate.
(c) Taken as 30% dry matter.
(d) Uroflavin calculated as riboflavin.
TR = Trace

TABLE 28

CALCULATED FECES ASH COMPOSITION

	Electrolyte Cations			Electrolyte Anions[a]	
Metal	max. mg/man-day	meq.	Anion	max. mg/man-day	meq.
Al	2.9	0.33	$A_5O_4^{\equiv}$	15.3	0.33
Ca	1180	59	MnO_4^-	18.5	0.16
Co	1.4	0.072	$PO_4^{\equiv}$	5220	165
Cu	2.6	0.08	Cl^-	35.6	1.0
Fe	100	4.4	Total	5289 mg	166 meq.
Pb	400	7.6			
Mg	252	20.8			
Mo	4	0.24			
Ni	10	26.5			
K	1037	0.51			
Na	122	5.3			
Sn	32	1.08			
Zn	10.3	0.30			
Total	3154 mg	126 meq.			

Total Ash = 8441 mg/man day

Total Solids = 8441 + 34510 = 42,951 mg.

(a) Assuming highest oxidation states of As, Mn, and P

TABLE 29

FECAL WASTE COMPOSITION
(Based on ref. 113)

% Solid		% Bulk Total	
C	= 43.5	C	= 11.8
H	= 7.2	H	= 1.9
O	= 22.9	O	= 6.2
N	= 6.3	N	= 1.7
S	= 0.4	S	= 0.1
Ash	= 19.7	Ash	= 5.3
		H_2O	= 73.0

TABLE 30

TOTAL WASTE COMPOSITION

Fecal Matter – 0.35 lb/man-day		Urine Sludge – 0.25 lb/man-day	
C	= 0.0413	C	= 0.017
H	= 0.0067	H	= 0.005
O	= 0.0217	O	= 0.020
N	= 0.0059	N	= 0.036
S	= 0.0004	S	= 0.0002
Ash	= 0.0186	Ash	= 0.046
H_2O	= 0.2550	H_2O	= 0.125

Total Waste lb/man-day

C	= 0.058
H	= 0.012
O	= 0.042
N	= 0.042
S	= 0.0006
Ash	= 0.065
H_2O	= 0.380

ypical industrial conditions are 500° to 600°F and 1000 to 2200 psig. Complete oxidation may be chieved at lower temperatures, but at a rate too slow for industrial practice, while the high temperature limit is the critical temperature of water, 705°F.

The degree of oxidation of a given batch of waste may be defined by the chemical oxygen demand (C.O.D.) of the initial and residual waste. Studies have shown that the final C.O.D. is independent of the initial solids or CO_2 concentration and the amount of excess oxygen used when one-hour batch treatment is at a temperature in excess of 450°F. Apparently 75 to 95% oxidation is achieved in a one-hour batch oxidation of sewage sludge at 450° to 600°F. According to Zimmerman, the data on sewage sludge are typical of all waste sludges. At any temperature, an equilibrium percent oxidized is reached, and this equilibrium is reached rapidly (under 1 hour) at temperatures as high as 572°F.

At a fixed temperature, the reactor pressure is the sum of the vapor pressure of water and the pressure of the added air. A fixed total pressure therefore determines the maximum amount of added air that still results in a two-phase system. Isobaric plots are given in ref. 115 for the ratio lb steam/lb dry air as a function of temperature. An example is given for the conditions of 553°F and 1500 psig total. Under these conditions, the weight ratio of steam to dry air is 2.0/1.0 so that 5% solids waste (~8lb/gal H_2O) could tolerate a maximum of 8/2 = 4 lb air/gal to complete oxidation. If more than 4 lb air/gal is added to bring about oxidation, the water vaporizes and oxidation ceases.

The conditions for oxidation of fecal waste in a space-cabin system allow a number of tradeoffs of pressure, temperature, time, reactor volume, and feed concentration, but within the constraints of the maintenance of a two-phase system in the reactor. In addition, the substitution of oxygen for air and the possibility of incremental oxygen additions to the reactor should be considered.

Based on the requirement that a space-cabin disposal problem would involve 0.35 lb feces/man-day and 0.25 lb urine sludge/man-day (50% solids), a sample calculation was carried out to see if typical wet-oxidation process conditions would be feasible without additional water. The calculation indicates that approximately 0.3 lb O_2/man-day would be needed for oxidation and that 0.24 lb H_2O/man-day would have to be added to the reactor to keep a two-phase system at 553°F and 1500 psig.

A mass balance for the wet oxidation process was prepared based on process conditions of 553°F and 1500 psig. As with the case of other incineration processes, no statement was found in the literature on the chemical nature of the nitrogen oxidation products and, therefore, different possibilities have to be considered until their exact nature is experimentally established. One important fact is known: the liquid product is acidic. For the mass balance, carbon and hydrogen were assumed to be completely oxidized to CO_2 and H_2O.

Table 31 presents mass balances for raw materials, oxygen demand, and products for three different cases of nitrogen end products. Case 1 assumes complete nitrogen oxidation and requires the highest oxygen demand (0.421 lb/man-day). Under these conditions, it is expected that the vapor phase will include practically all the CO_2 and that the nitrogen and sulfur will end as soluble nitrate and sulfite ions in the liquor. (0.35 ?)

The apparent stoichiometric oxygen demand is larger than previously calculated on the basis of figures for sewage sludge (ref. 115). However, as pointed out in previously contracted work (ref. 116), the effluent concentration of ammonia and acetic acid is fairly high when the time and temperature of the process do not allow complete oxidation. These would considerably alter the mass balance and lower the oxygen demand. if conditions leading to such products were acceptable. Furthermore, the sewage considered in ref. 115 was not fresh and had probably undergone a significant amount of oxidation under ambient conditions before being introduced into the process.

Case 2 of Table 31 shows a mass balance for an intermediate use where the organic bound nitrogen is oxidized to molecular nitrogen. In a personal communication, February 14, 1967, Dr. D. Drinks of the Sanitary Engineering Department of the University of California, Berkeley, reports that his running of a Zimmerman process at the Richmond Field Station yielded N_2 as the nitrogen end product. However, Dr. Drinks has no data to substantiate his opinion. In this case, the vapor phase will include the CO_2 and nitrogen gases.

TABLE 31

MASS BALANCES-WET OXIDATION WASTE PROCESS

(All numbers in lb/man-day)

	Case 1: $N \rightarrow NO_3^-$ or NO_2		Case 2: $N \rightarrow N_2$		Case 3: $N \rightarrow NH_3$	
Total Input	O_2 Demand	Products	O_2 Demand	Products	O_2 Demand	Products
C = 0.058	0.155	0.213 CO_2	0.155	0.213 CO_2	0.155	0.213 CO_2
H = 0.012	0.096	0.108 H_2O	0.096	0.108 H_2O	0.024	0.027 H_2O
O = 0.042	(-0.042)	———	(-0.042)	———	(-0.042)	———
N = 0.042	0.144 or 0.096	0.186(NO_3^-) or 0.138(NO_2)	———	0.042 N_2	———	0.051 NH_3
S = 0.0006	0.0012 or 0.0006	0.0018($SO_4^=$) or 0.0012(SO_2)	0.0006	0.0012 SO_2	0.0006	0.0012 SO_2
Ash = 0.065	———	0.065 Ash	———	0.065 Ash	———	0.065 Ash
H_2O = 0.380	———	0.380 H_2O	———	0.380 H_2O	———	0.380 H_2O
Totals = 0.599	0.354 or 0.306	0.954 or 0.905	0.210	0.809	0.138	0.737

Case 3 of Table 31 shows the case in which part of the nitrogen is converted to ammonia, which ends up in the liquor as ammonium ion. In these mass-balance calculations, it was assumed that only the organic-bound hydrogen could combine with nitrogen to form ammonia, and since its amount is insufficient to convert all the nitrogen to ammonia, the rest of the nitrogen is oxidized to N_2. In this case, the oxygen demand is the lowest and only a small fraction of the nitrogen ends as N_2 in the vapor phase.

The advantage of the wet oxidation process over other incinerator processes is that, as far as current measurements indicate, the vapor phase is free of contaminant gases that would interfere with water and CO_2 recovery. The liquid phase, however, is contaminated with all the minerals and salts originally in the urine and feces plus those formed by the oxidation process. This liquor should be easier to process than the urine sludge because the organic compounds have been converted to more stable forms. If neutralization is required to recover water from the liquor, a significant weight penalty for expendable chemicals results.

Rapid-high-temperature incineration. – Investigation has been made of rapid-high-temperature incineration as a process (ref. 117) for waste disposal during aerospace missions. During this investigation, the waste used consisted of feces, polyethylene, paper, polyurethane, and water. No urine was used. Pure oxygen was determined to be the best oxidant. This batch process was carried by loading the waste into the incinerator chamber, closing inlet and outlet valves, and electrically heating the contents until the internal pressure reached 30 psia. The outlet valve was opened slightly to maintain the pressure at this value for 10 minutes. The outlet valve was then opened and the vacuum pump started. The pressure was reduced to 160 mmHg (partial pressure of O_2 in air at 1 atm). The oxygen was turned on and the flow rate set at 1940 cc/min at 160 mmHg pressure. The oxygen flow rate was 0.072 lb/hr for 7.5 hr and 0.122 lb/hr for the remaining 3 hours of test. The temperature of successful incineration was determined to be 1000°F. The ash remaining after incineration was dry and powdery, and comprised about 2% by weight of the total load. The only gases and vapors analyzed in the exit stream were: CO_2, CO, H_2O, and the excess O_2. However, a black, waxy substance and oil (comprising about 15.6% by weight of the total charge) were collected with water in the dry ice trap.

The main differences between the above case and the case on hand (0.6 lb/man-day of combined feces and urine sludge) are the composition of raw materials and the complete omission in the referenced study to account for nitrogen. However, in spite of the lack of needed experimental data in the case of the combined feces and urine raw material, some speculation can be made as to the nature of the products.

In the extreme case, when combustion is highly efficient, the material balance is expected to be the same as Case 1 in Table 31. The nitrogen will come out as NO_2 gas, and all the carbon will be converted to CO_2. In this case, there will be a problem of separating the CO_2 and water from the NO_2 and SO_2. This could be accomplished by a water absorption tower which retains the product water, the NO_2 as HNO_3, the SO_2 as H_2SO_3, and a small part of the CO_2. CO_2 has a lower water solubility than the other gases, and most of the CO_2 will leave in the vapor phase. Water will be recovered from this solution by distillation after the concentrated acids are neutralized with NaOH.

The next case to be considered is the more probable incomplete oxidation. Incineration products in ref. 117 were 15.6% condensible black waxy material, and CO appeared as about 10% of the CO_2. The waxy material was most probably a mixture of carbon and an agglomeration of relatively low molecular weight compounds from the incomplete combustion of the polymers present. In the case of feces and urine sludge, it is expected that the carbonaceous condensible matter will be much smaller. However, CO is expected to be present in the effluent gas. In order to simplify product recovery, it is suggested to add to the product stream some extra oxygen and pass it through a catalytic oxidation unit in order to convert the CO to CO_2.

Figure 21 shows a flowsheet of the process, and Table 32 presents a possible material balance. Quantitative experiments using this process are strongly recommended.

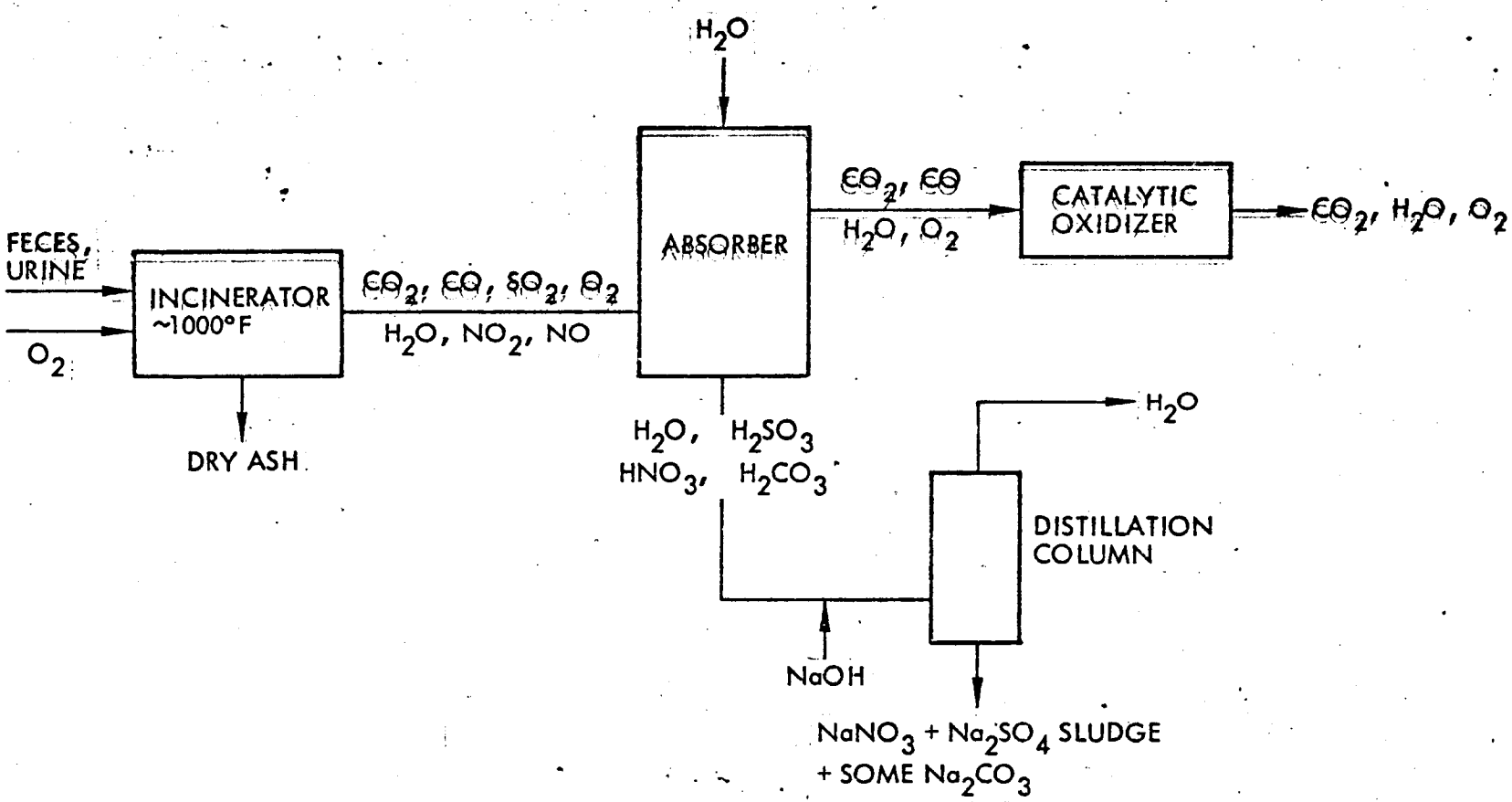


Fig. 21 Rapid-High Temperature Incineration Process Flow Sheet

TABLE 32

MASS BALANCE FOR RAPID-HIGH TEMPERATURE WASTE INCINERATION

Step 1: Incinerator Input

- 0.600 lb feces and urine sludge
- 0.316 lb oxygen – enough excess O_2 to yield 1 atm PO_2 at 1000° F in 4-liter burner

Step 2: Output of Incinerator

- 0.213 lb CO_2 (assuming enough residence time for complete combustion)
- Trace CO
- 0.053 lb NO
- 0.085 lb NO_2

  (Assuming equilibrium at 1000° F and 1 atm O_2)
- 0.488 lb H_2O input Water + combustion of H
- 0.0012 lb SO_2
- 0.038 lb O_2

Step 3: Output of absorber and nitric acid reactor

Probably at 100 psig with water excess

Gaseous vent	0.213 lb CO_2 0.010 lb O_2 Trace CO H_2O Vapor	Cleanup by catalytic oxidation
Liquid discharge	0.0013 lb H_2SO_3 0.192 lb HNO_3 Trace H_2CO_3 H_2O	

Step 4: Neutralization and distillation

Add	0.123 lb NaOH
Sludge	0.002 lb Na_2SO_3 0.411 lb $NaNO_3$
Gaseous Vent	Trace CO_2 H_2O Vapor

Programmed incineration. — Programmed incineration differs from the rapid high temperature incineration by an additional step of pyrolysis which precedes oxidation. The anticipated advantage of this process is that during the pyrolytic stage, one will be able to collect and isolate some compounds, other than CO_2 and water, that can be directly recycled in the life-support system.

No data on pyrolysis products of feces and urine sludge could be found in the literature. After studying the nature of the different compounds present in the raw material, one can only speculate that the pyrolytic products will probably include, among others, acetic acid, acetone, water, ammonia, CO_2, and hydroxyl amines. The most interesting compound on this partial list is ammonia since it may serve as a nutrient for Hydrogenomonas bacteria. However, the separation of the ammonia from the other products is expected to be difficult. These questions will have to be answered before an intelligent assessment of the process can be made; in addition to the possible disadvantage of difficult separation, there is the disadvantage of lengthening the time of the entire batch incineration process. Figure 22 shows a schematic flowsheet of the process.

Aerobic digestion and incineration. — The microbiological processing of domestic waste is a primary method for the stabilization and disposal of sewage. Two types of processes are involved: (1) the aerobic process in which oxygen utilizing microorganisms degrade and biologically oxidize waste materials, and (2) the anaerobic process in which microorganisms that do not require oxygen degrade the waste to simpler chemical components. The primary objective of sewage treatment is to reduce and stabilize the oxygen demand at a level that is safe for the disposal of waste effluent. Since the objective of waste treatment for prolonged space missions is the recovery of useful materials from the waste, most of the information relating to domestic sewage treatment is nontranslatable to the objectives of this study. In fact, there is an extreme paucity of quantitative information applicable to waste treatment for long-term space missions. Therefore, the following evaluation is based upon very preliminary and fragmentary information relating to space application.

Based upon available information, aerobic digestion alone does not appear to be a satisfactory means for the conversion of fecal and urine waste to readily recoverable and utilizable materials. It has been suggested that additional treatments beyond "normal" microbial digestion processes may result in more utilizable products.

A material balance diagram for an activated sludge aerobic digestion process is presented in fig. 23. The material entering the process is based upon the production of 0.24 lb of dry waste (feces and urine solids) per man per day. This is derived from 0.35 lb of feces of which approximately 33% are solids, and 0.25 lb of urine sludge which is approximately 50% solids. Of the 0.24 lb of dry solids 0.13 lb is considered as biodegradable organic material, 0.03 lb is not biodegradable organics and 0.08 lb is nonorganic or mineral. The water required in the digestion process remains essentially constant and is considered to be approximately 22 lb based upon reports that 10 liters per man will supply an adequate system. A 50% conversion of the degradable organics to cell material or biomass has been assumed for this study since conversions ranging from 40% to 60% have been reported. The requirement for 0.095 lb of oxygen is based upon a reported calculation that approximately 1.42 gm of oxygen are required for each gram of cell material produced from degradable organic waste.

The aerobic digestion process takes place in a tank or chamber containing adequate suspending fluid (water) and the microbial suspension. The waste must be finely divided and dispersed in the suspension which must be oxygenated and agitated to ensure gas-liquid mixing so that the microbial cells are supplied with sufficient oxygen to carry out their oxidative processes. Periodically the products of the digestion must be removed for further processing. The solids are separated from the water and a small portion of the biomass is returned to the digestion chamber as inoculum for incoming waste while the bulk of the solids requires additional treatment. The temperature of the digestor should be maintained near 30°C, and the pH between 7 and 8.

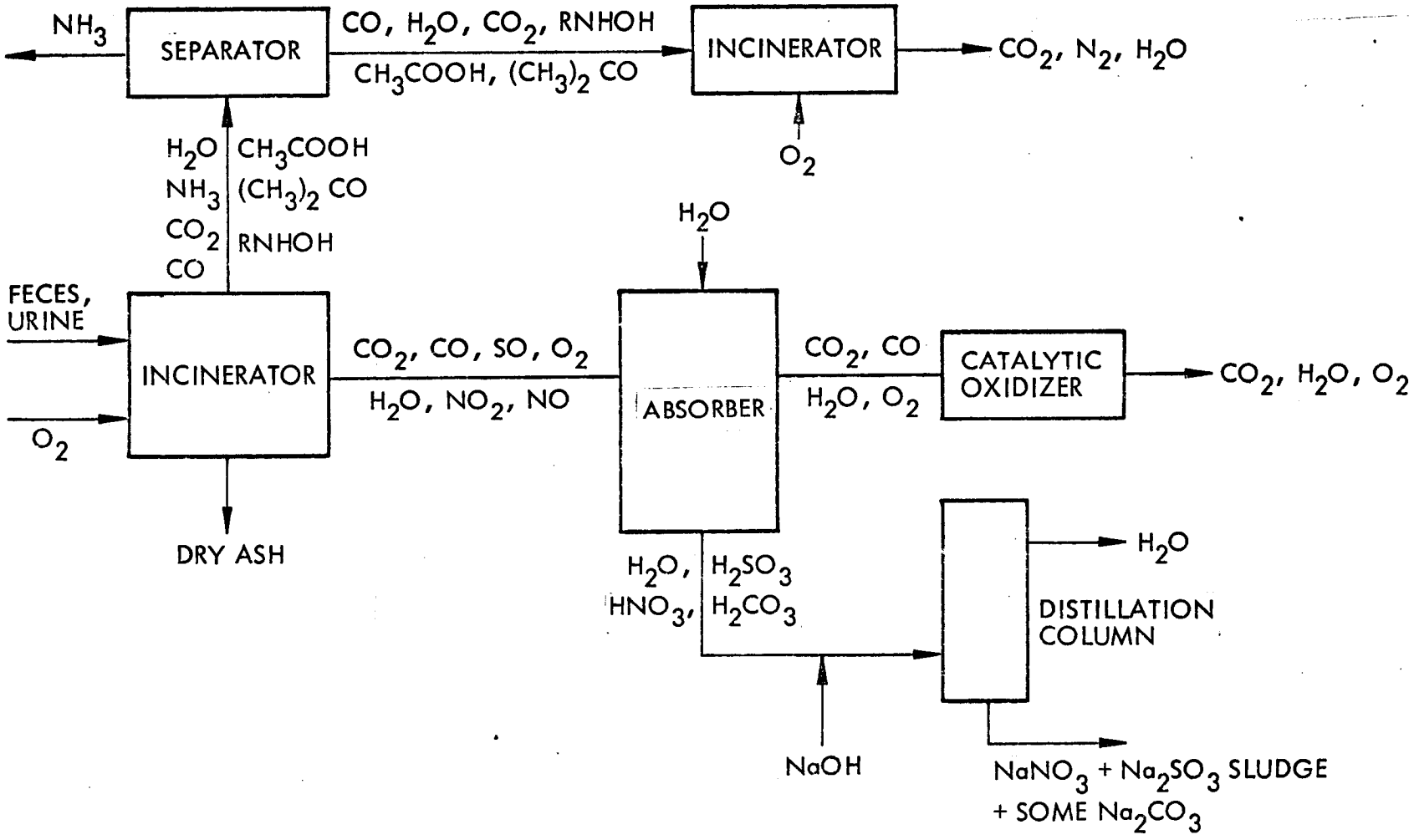


Fig. 22 Programmed Incineration Process Flowsheet

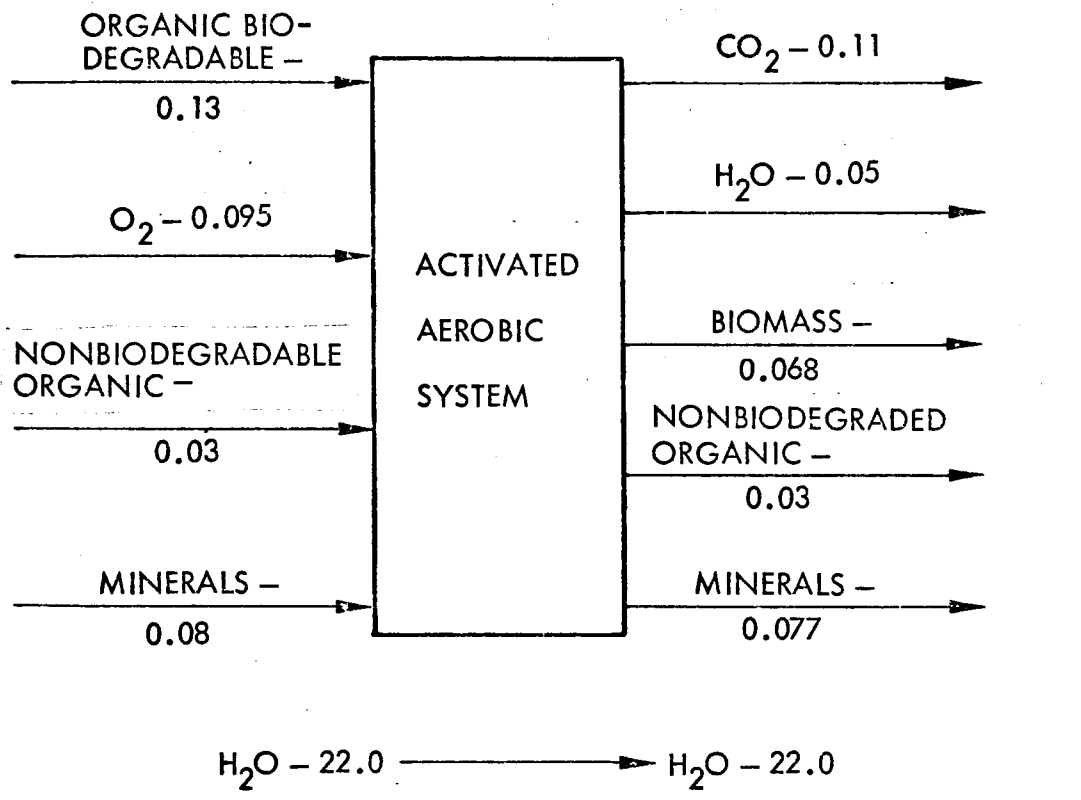


Fig. 23 Aerobic Digestor Mass Balance

In this scheme the mixed aerobic microbial population oxidatively converts 0.13 lb of degradable waste to 0.068 lb of cell mass, 0.11 lb of CO_2 and 0.05 lb of water. Because cell material is created to the extent of 50% of the degraded waste, the reduction in total solids is approximately 27%. It is generally recognized that the rate of oxididation is greatest during the first 24 hours, and it might therefore be expected that the greatest reduction in solids occurs during this time period. However, it may take up to 72 hours to accomplish reductions in the area of 27%. Thus, in aerobic digestion alone the recovery of utilizable materials from waste is quite limited. The CO_2 and water generated during the aerobic digestion can be recovered by physiochemical means. However, recovery of the cell mass from the sludge is a difficult problem and in space would certainly be complicated by the zero-g condition. No evidence was found that this problem has been investigated.

One method of recovery of the chemical elements might be through a process of programmed incineration or stepwise increases of temperature during which certain volatiles might be released and recovered. The material to be treated in this manner would consist of the biomass and the nondegraded organics and inorganics. Based upon bacterial cell composition, the following composition is assumed for the 0.068-lb biomass:

Carbon	0.034 lb
Nitrogen	0.0102 lb
Hydrogen	0.0068 lb
Oxygen	0.0136 lb
Phosphorous	0.0022 lb
Sulfur	0.0007 lb
Other elements	0.0005 lb (Sodium, potassium, calcium, magnesium, iron, etc.)

The nondegradable organic materials are assumed to be cellulosic, and the composition has therefore been considered to be:

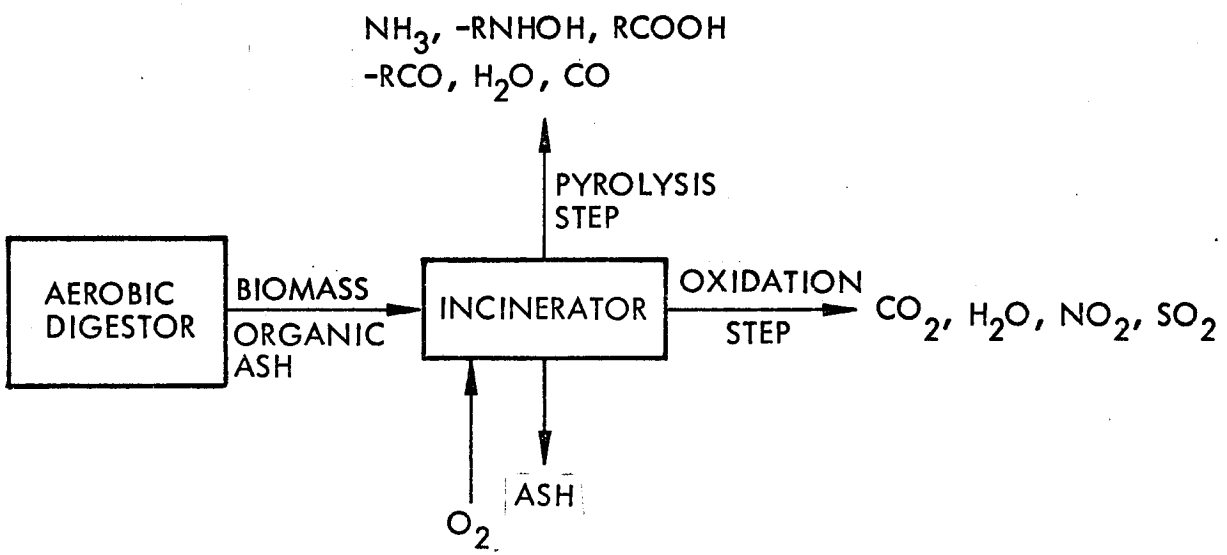
Carbon	0.0123 lb
Hydrogen	0.0027 lb
Oxygen	0.0150 lb

The programmed incineration process is shown diagrammatically in figure 24. This process is depicted to consist of two general phases: (1) a pyrolysis phase in which the material from the aerobic waste digestor is heated without the addition of oxygen, and (2) an oxidative phase in which the heating is continued in the presence of oxygen. In operation the pyrolysis phase is performed first. It has been predicted that during the pyrolytic heating; the following types of volatiles will be evolved: organic hydrox glamines, organic acids, ketones, ammonia, carbon monoxide and water. The products of the oxidative phase are expected to be water and the dioxides of nitrogen, carbon, and sulfur.

hydroxylamines

In considering the use of these compounds in a biological growth system, one can readily predict the use of CO_2 and ammonia in algal or Hydrogenomonas systems, but the microbial utilization of the other types of compounds is not as readily obvious. It is probable that the nitrogen and sulfur dioxides would have to be converted to other compounds for utilization. The organic derivatives are problematical as to their metabolic utilization. A number of species of bacteria are capable of using certain organic acids such as acetic, propionic, and butyric, and to some extent, certain algae may use acetic acid. The extent, if at all, to which Hydrogenomanas may use organic acids is not known at this time. The other two types of organic products are not known to be commonly utilized by microorganisms. It is possible that some microbial species may be capable of metobolizing specific compounds of these types of chemicals but prediciton of utilization is virtually impossible without knowing the specific compounds in question.

A material balance for the complete incineration of the solids from the aerobic digestor is shown in fig. 25. As already indicated, the CO_2 and water may be recovered for biological use, but the dioxides of nitrogen and sulfur would require conversion to other compounds.

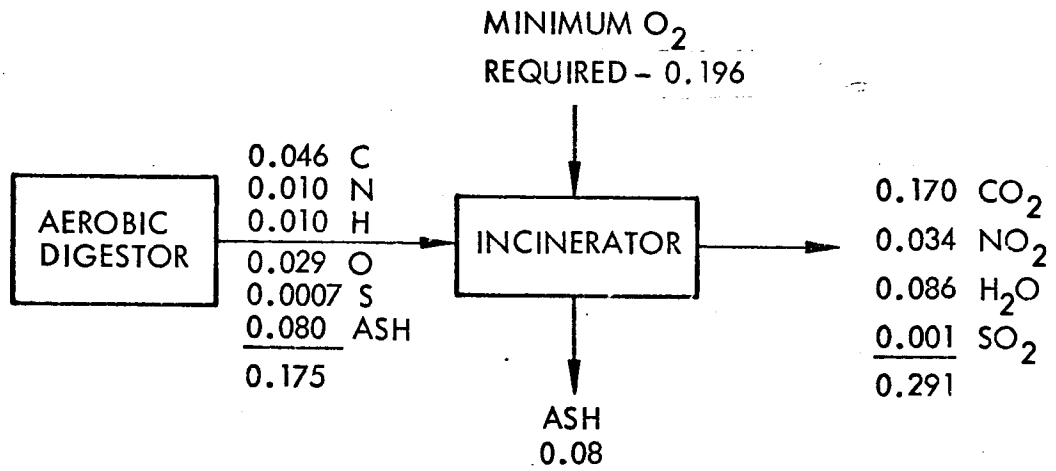


ORDER OF INCINERATION:

(1) PYROLYSIS STEP IS PERFORMED BY HEATING WITH NO ADDED O_2

(2) OXIDATION STEP IS PERFORMED BY CONTINUED HEATING IN AN O_2 FLOW

Fig. 24 Aerobic Digestor Plus Programmed Incineration Process Flowsheet



ALL UNITS IN LB/MAN-DAY

Fig. 25 Aerobic Digestor Plus Complete Incineration Process

Based upon the limited quantitative and qualitative data relating to the chemical changes involved in the above described process, it must be concluded that this method of waste regeneration offers little or no advantage over incineration alone.

Aerobic digestion, secondary biological processing and incineration. – Since, and again based upon the limited knowledge, the aerobic digestion method alone or in conjunction with an incineration process does not appear to offer a solution to the waste-regeneration problem, it has been suggested that a secondary biological treatment might offer some advantage in the conversion of waste to utilizable products. The secondary treatment is considered as the growth of an organism such as a fungus on the remaining organics that were not degraded by the bacteria and on the products of lysed bacterial cells. A number of fungi (including the actinomycetes) are capable of degrading cellulosic materials to compounds which are utilized as carbon sources for metabolism. Thus, the use of these organisms in a secondary biological treatment could result in the further degradation of the original waste material. The products of this degradation are the same as that of the bacterial digestion, cell material, CO^2, and water.

Thus, the net result of the secondary treatment would be an additional reduction in the organic waste material with an increase of cell protoplasm, CO2, and water. The incineration portion of this overall process would be the same as that described in the previous procedure, and the result of the incineration treatment would not be expected to produce any significant change from that in the previous process. Qualitatively the products would be essentially the same but quantitatively there may be an increase in the organic products since there would be an increase in cell mass.

It would appear that this type of processing offers little if any significant improvement over the previously described processes.

Aerobic digestion, secondary biological processing, food processing. – In this process, the secondary biological treatment is somewhat similar to that explained above except that in this instance the organism chosen for the secondary treatment would be one (or more). Not only would it use the organic waste and products of the aerobic digestion, but it would also produce cell material that could be suitably processed as food for the crew of the space vehicle. The organism or organisms in this process might be fungi, yeasts, bacteria, or perhaps combinations of these. A photosynthetic organism such as algae might be considered as a part of this process. The products of aerobic digestion of waste have been shown to support growth of algae cultures. It is highly probable that many species of fungi, yeasts, and mushrooms can be grown on the products of the aerobic digestion especially if the bacteria cells are lysed so that the cell contents are released as a source of nutrients for the organisms of the secondary treatment. Fungi and yeasts have been grown on fecal and urine wastes which is not as rich in nutrients as would be the released contents of microbial cells.

The amount of cell material produced in this process would be dependent upon the metabolic efficiencies of the selected organisms. However, based upon the estimates of cell mass produced in the aerobic digestion process, one might expect to obtain at least a 50% conversion of the original organic waste to cell material. Thus, for an organic waste of 0.16 lb/man-day, 0.08 lb of cell mass for food could be predicted. The time to obtain this amount of mass will vary considerably depending upon the type or organism selected and their environmental growth requirements. Variations may range from a few days–6 to perhaps 30 days. The nutritional value of the cell mass again will vary with the selected organisms. As an approximation, the value might be considered to be similar to algae or Hydrogenomonas. However, different types of organisms vary in their carbohydrate, fat, and protein ratios, and these ratios may be varied further by the type of nutrients supplied during growth. It would appear that this type of processing might afford the chance to alter or vary the diet of the crew.

Processing the cell mass for food will also vary depending upon the type(s) of organism(s) selected. Two general types of processes will be required: (1) a means of separating the cell material from the growth medium, and (2) a means to cook and/or preserve the cells. In addition, procedures may be required to alter or modify flavor, odor, and digestibility characteristics.

This scheme for the utilization of wastes appears to offer advantages over the two previous procedures, even though there is an extreme lack of knowledge and information in this area.

Aerobic digestion, anaerobic digestion, and incineration. – The process of aerobic digestion, anaerobic digestion, and incineration is similar to the general procedure used in the treatment of domestic sewage except for the incineration phase. The sludge or solids from the aerobic digestion process are passed into an anaerobic digestor where anaerobic microorganisms degrade the sludge compounds. The anaerobic digestion is a two-step process because of the action of two groups of microorganisms. The group which initiates the process degrades the more complex compounds to simpler materials composed of alcohols and organic acids. With the change of pH due to the accumulation of organic acids, the second group becomes predominant and metabolizes the alcohols and acids primarily to methane, CO_2 and water. Cell substance is also produced, but the rate of cell generation is much slower than that found for the aerobic process.

A material balance for the anaerobic digestion process is shown in fig. 26. The 0.175 lb of solids plus some amount of water from the aerobic digestor are passed into the anaerobic digestor. From these ingredients 0.027 lb of methane, 0.033 lb of CO_2, 0.027 lb of water, and 0.011 lb of cell material, and undegraded organics are produced. The mineral or inorganic content remains essentially the same. The temperature of the digestion process may vary from about 40° to 55° C depending upon the types of microorganisms involved. The higher temperature would be more desirable if the organisms were capable of this environment since the increased temperature generally results in an increase digestion rate similar to the effect of increased temperature on the rate of chemical activity. In domestic sewage, treatment time for digestion may extend to 30 days. However, with adequate controls and selected organisms, this time can probably be reduced to 10 to 15 days for space applications.

INSERT d

Although a relatively high percent of reduction of organic waste (estimated as 80% to 90%) can be attained by the use of anaerobic digestion, investigation of its use in space application has been very limited because of the possible disdavantages based upon experience with domestic wastes. The primary disadvantages would appear to be: (1) the time period required for digestion, and (2) the possible production of small amounts of toxic gases such as carbon monoxide and hydrogen sulfide. Whether or not these disadvantages would exist in a system designed for space application has not been established. Other disadvantages from an engineering view point might be: (1) the problem of liquid-gas separations, (2) the conversion of gases to usable compounds (methane for chemical synthesis of food or as a nutrient for methane bacteria which might be utilizable as a food material), and (3) the volume and weight requirement for the digestor may be relatively high because of retention time required for digestion.

The incineration phase of this process scheme is expected to produce the same types of products as those previously shown where cell materials and small quantities of organic matter were the primary incineration materials. The quantitative aspects will vary depending upon the relative amounts of these two primary constituents.

Conclusions

The conclusions reached as a result of the study of waste regeneration can best be summarized in tabular form.

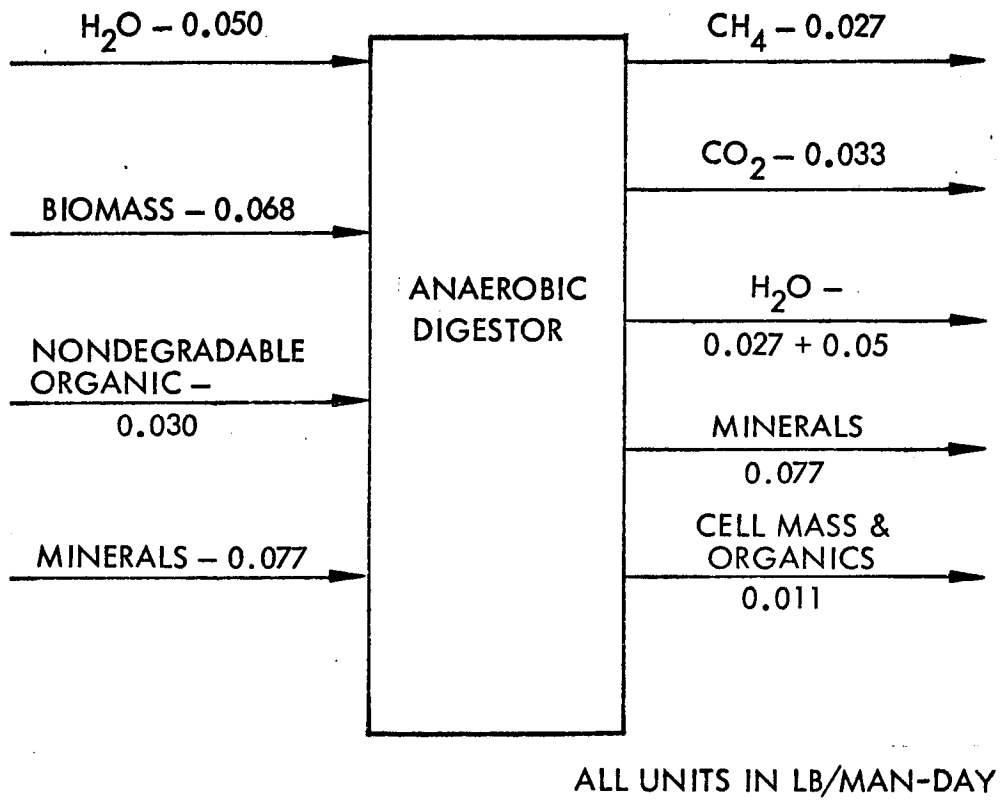


Fig. 26 Anaerobic Digestor Mass Balance

TABLE 33

COMPARISON OF WASTE PROCESSING SYSTEMS

Process	Comments
• Wet oxidation	• Seems to offer potential advantage over dry incineration by producing relatively clean gaseous product, but leaves liquid contaminated.
• Rapid-high temperature incineration	• Produces contaminants that must be removed from gaseous effluent prior to use in CO_2 reduction and H_2O electrolysis units.
• Programmed incineration	• May produce more usable compounds than rapid incineration, but may also produce some undesirable hard to separate organics.
• Aerobic digestion and incineration	• Offers little or no advantage over incineration alone
• Aerobic digestion, secondary biological processing, and incineration	• Offers little or no advantage over incineration alone
• Aerobic digestion, secondary biological processing, and food processing	• Probably still requires some incineration and adds complexity of undefined food producing system
• Aerobic digestion, anaerobic digestion, and incineration	• Still requires some incineration and a long processing period.

In comparing the seven waste-processing systems studied, it was concluded that the incineration processes offer the greatest potential and that the type of process to be used cannot be selected without experimental evaluation. Both the wet oxidation and rapid-high-temperature incineration processes seem attractive candidates.

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EVALUATION OF NEW R&D EFFORTS

As part of the study of advanced life-support systems, a review and evaluation of research and development efforts currently in progress has been made. The evaluation included analysis and review of existing literature, contract reports, and personal communication in the areas of chemical synthesis of food, waste processing, and biological systems.

Chemical Synthesis of Food

Research and development programs in formaldehyde synthesis and glycerol synthesis, including formaldehyde-condensation methods, have been studied. An evaluation of this work is presented below. Efforts were made to discuss the sugar-synthesis program under way at IIT Research Institute but were unsuccessful (ref. 118).

Formaldehyde synthesis. – The process under study by the General American Research Division for NASA Ames is oxidation of methane directly to formaldehyde. The following is a summary of unscreened information presented in a discussion with study personnel (ref. 119). Process conditions under study are nominal pressure and 600° to 1000° F with 0.1 to 0.2% NO and potassium tetraborate as a catalyst. The space velocity is high (1000 hr^{-1}), and pure oxygen in a 1:1 ratio is used. The experimentally achieved yield per pass is about 1-1/2%. Recycle of the product gas will be used in future experiments to obtain the patent claims of up to 60% overall yield. A 3000 ton/yr plant based on this process is now in operation in Romania. Although the original work was done with natural gas or coke furnace gas, the GARD experiments use methane for obvious reasons, i.e., availability in a spacecraft system.

A second process scheduled for investigation uses 1% ozone as a catalyst and air or oxygen at reaction temperatures of approximately 200° F and a space velocity of approximately 200 hr^{-1}. Similar overall yields are cited by the patents.

For either synthesis method, purification is not seen to be a major problem because the formaldehyde-water product readily forms paraformaldehyde, which can be separated by filtration and later reconverted to formaldehyde solution by heating with steam.

The results mentioned by the investigators and given credence by German and Russian patents reported in Chemical Abstracts are in contradiction to data developed during the Phase I study and subsequently documented by personal communications from Celanese Corporation, citing B. A. S. F. of Germany experience, which indicate that direct methane oxidation is inferior to the two-step process involving a high-pressure methanol synthesis followed by oxidation to formaldehyde. The crucial experimental step of recycling product gases to increase overall yield to 35 – 60% has not yet been performed by the study investigation. If successful, it is likely that methane oxidation using this process will be characterized by somewhat lower weight, volume, and power penalties than associated with the synthesis method described in this report under "Formaldehyde Synthesis Using Chromatographic Reactors." Catalyst supply or regeneration may present a significant problem, however. If recycling is not technically

feasible without excessive overoxidation of product formaldehyde, the chromatographic technique or the two-step methanol route remain as worthy of experimental evaluation.

Glycerol synthesis. – The results of an analytical study of glycerol synthesis have been reviewed. This study (ref. 120) by ESSO Research and Engineering Company was sponsored by NASA Ames and resulted in confirmation of a conclusion reached by LMSC during the Phase I study, i.e., chemical synthesis of fats on-board spacecraft is not recommended and that work be concentrated on glycerol synthesis. ESSO discusses several routes to glycerol in ref. 120.

- Direct synthesis from CO and H_2: Using a catalytic reaction at pressures of 500 to 1000 atm, glycerol may be produced by direct reaction of CO and H_2. No yields are given and large amounts of ethylene glycol are usually present in the product.

- Synthesis from acetylene: By use of copper acetylide catalyst, acetylene, and formaldehyde react to give acrolein, which can be hydrogenated to allyl alcohol and in turn hydroxylated to glycerol using hydrogen peroxide and a metal oxide catalyst. The sequence is well known and gives a fair yield; but is not recommended since it involves synthesis of acetylene and hydrogen peroxide, handling of hazardous materials and a three-step sequence.

- Synthesis via ethylene: Allyl alcohol for the above synthesis can alternately be produced by a condensation of formaldehyde and ethylene in a Prins reaction followed by dehydration of the product. It does not appear to be a promising route, however.

- Formaldehyde condensation to trioses: It is not clearly established that condensation conditions leading to a three-carbon compound can be conveniently arranged. A recent Czech patent (ref. 121) claims a triose-specific condensation using magnesium oxide or lead hydroxide catalyst, 10 to 30% formaldehyde solutions and 120° to 140°C. ESSO is skeptical of the claim; somewhat less skepticism is expressed for Kuzin's work (ref. 122) in which 75% yield of glyceraldehyde is obtained starting with glycolaldehyde and formaldehyde. Glycerol synthesis is completed by hydrogenation of the triose, which presents no difficulty.

- Hydrogenolysis of carbohydrates: This synthesis based on a U.S. patent (ref. 123) is preferred by ESSO. Formaldehyde is condensed to 6 carbon sugars and the resultant crude sugars subjected to reductive cleavage. There exists a natural tendency for a 3 to 3 split, and by proper choice of catalyst, glycerol production may be enhanced. Overall glycerol yield, based on formaldehyde consumed, is reported to be 47%. Conditions suggested for the condensation are 2 atm pressure and 210°F. For hydrogenolysis, a pressure of 100 atm at 400°F for 3 hr with nickel or copper catalysts are the reference reaction conditions. The literature cites a range of 100 to 200 atm pressure.

Because the hydrogenolysis reaction requires long residence time and high pressures, large penalties in weight, pumping power, and volume are likely. ESSO states that "The hydrogenolysis of carbohydrates was considered slightly preferrable [as compared to formaldehyde condensation to trioses] and was selected for the engineering case study" (ref. 124). ESSO further states that "There is little to choose between (3) [trimerization] and (4) [hydrogenolysis]" (ref. 125). More detailed work

is required to determine which synthesis should be selected for spacecraft application. Should it prove feasible to obtain a triose from condensation of formaldehyde or from the two-step procedure of glycolaldehyde synthesis followed by formaldehyde addition, the avoidance of the high-pressure reaction conditions that characterize the hydrogenolysis method would be expected to make the triose method superior.

Waste Incineration

Relatively little has been accomplished in the area of waste incineration processes. NASA Ames has initiated a study for evaluation of incineration and microwave treatment of human fecal matter for spacecraft operation. Data from this effort are not yet available, but will include characterization of water purity and effluent gas analyses. The originators of wet oxidation (Zimpro) were contacted to obtain data on the applicability of the process to spacecraft waste-treatment problems. A study of wet oxidation as a combined waste treatment and water-reclamation system is currently in progress at the Whirlpool Corporation under NASA-Langley sponsorship.

At the request of LMSC, Zimpro has analyzed processing of urine sludge and feces with conditions selected to minimize trace-contaminant production. The recommended process is total wet oxidation at 600° to 650° F in a vessel charged at room temperature with oxygen at 1000 psi, using a slight excess oxygen. The reaction would be allowed to proceed for about 1 hr. "There should be no sulphur, nitrogen or phosphorous volatile oxides given off" (ref. 126). It is expected that nitrogen would be present as ammonia, which could be converted to elemental nitrogen using catalysts now in use by Zimpro plants. The net output of the total wet oxidation process is water vapor, CO_2, N_2, and a slurry of soluble and insoluble salts. This slurry would constitute perhaps 5 to 10% of the water charged and represents the most difficult recovery problem associated with the process.

A two-phase wet oxidation process at 550° F and 500 psi is under investigation by Whirlpool (ref. 127). Pure oxygen at slight excess and a catalyst are involved. Ammonia or N_2 can be obtained depending on the catalyst used. When the catalyst producing N_2 is used, gas chromatography analysis does not detect NO, NO_2, SO_2, or CO. The liquid effluent contains short-chain carboxylic acids such as formic, propionic, and acetic. Aldehydes are also reported but can be removed by carbon filtration. Suspended solids can be removed by centrifugation or filtration.

The above is a summary of unscreened information obtained from Zimpro and Whirlpool Corporations. It appears that the wet-oxidation process is a promising method for waste processing. A very positive recommendation is impossible at this time because of the unknown problems of effluent purification of the liquor from the wet oxidation process and the effluent from a high-temperature dry-incineration process.

At the present time the only available source of data on incineration effluents is an LMSC report (ref. 128). Heating a sample of fecal matter resulted in the formation of major amounts of CO_2, CO, and methane. For rapid heating, some 38 additional compounds were detected. An alternate moderate heating program resulted in the formation of 18 trace compounds including hydrogen sulphide, sulphur dioxide, ammonia, nitrogen

Sulfide

dioxide, acetylene, ethylene, and an alkyl cyanide. It is not obvious that practical dry incineration and effluent purification techniques to permit recovery of CO_2 and water can be developed.

Biological Systems

The following information reflects the current status of R&D efforts related to the application of biological systems to closed life-support systems for long-term space missions. The areas of biological application encompassed by the review are: bioregeneration, waste utilization, nutrition, and organism stability.

Bioregeneration. – Biological systems that have been or are being considered for bioregenerative applications are either photosynthetic or chemosynthetic. Photosynthetic systems have been primarily centered on algae although certain higher plants have also been given consideration. For chemosynthetic systems, the hydrogen fixing bacteria belonging to the genus Hydrogenomonas are being investigated.

• Algae: It was concluded in the Phase I study that the weight, power, and volume requirements for an algae bioregenerative system were excessive for the one- to three-year mission. The weight, power, and volume penalties are primarily a direct result of large culture volume requirements and the inefficient conversion and utilization of the electrical-light-chemical energy. In the ensuing time, there have been very few reports of algae investigations relating to space applications. Although there is an abundant literature concerned with the metabolic and photosynthetic mechanisms in algae, no information was found that related to an increased efficiency in the energy conversion chain.

In 1966, Ward and Miller (ref. 129) described a large capacity algal photosynthetic gas exchanger which had been developed contractually for the USAF School of Aviation Medicine. This gas-exchanger system has human life-support capability with sufficient nominal capacity to provide the necessary CO_2-O_2 exchange for two men in a closed environment. A four-phase experimental program was outlined for the evaluation of the system with the final phase being manned tests. The principal investigators were contacted to determine the progress of the program. It was learned that temperature control problems were experienced during early testing of the system, and since that time the unit has been undergoing alterations to correct the problems. Modifications have been completed, and it expected that the unit will be operable in the near future for resumption of the experimental program.

It was noted in previous reports that cultures of algae being considered for use in bioregenerative systems frequently became contaminated with certain types of bacteria whose populations often attained levels of 10^6 to 10^9 viable bacteria per ml of culture. In the past, little significance has been attributed to bacterial contamination of algal cultures and, frequently, it is ignored. Ward and Moyer (ref. 130) have reported the results of research studies on the algal-bacterial culture relationships. In studies with the thermotolerant alga Chlorella pyrenoidosa TX 71105, which is also now known as Chlorella sorokiniana, they found several bacterial species as contaminants that grew abundantly in the algal culture. It appears signficant that Pseudomonas aeruginosa and Mima polymorpha were isolated most frequently in algal cultures obtained from other

laboratories. Although soil, air, and putrefactive bacteria generally did not survive in the algal cultures, it was observed that two enteric pathogens, Salmonella typhii and Salmonella paratyphii grew well for prolonged periods. It was also found that several of the bacteria that did grow in the algal cultures produced an adverse effect on algal growth. Mima polymorpha, Bacterium anitratum, Pseudomonas aeruginosa, and a gram negative Bacillus sp. reduced the algal cell count about 20% and decreased the culture dry weight by 5 to 13%. In other studies (refs. 131 and 132), it was found that the excretory products of Chlorella pyrenoidosa TX 71105 included several organic acids, amino compounds, ammonia, nucleic acids, polysaccharides, and peptides, and that the bacterial contaminants were quite capable of utilizing many of these organic compounds for growth.

Any organism selected for use in a bioregenerative system must be stable or at least not adversely affected in the space environment. Ward and Phillips (ref. 133) have reported information in this regard on the stability of Chlorella exposed to high-altitude and orbital space flights. In their studies, cultures of Chlorella pyrenoidosa, strain SAM 127, were flown and recovered from four high-altitude balloon flights and four Discoverer satellites. Periods of weightlessness ranged from 50 to 75 hr. Radiation levels were generally low, although one satellite was exposed to a 3+ magnitude solar flare. Post-flight comparisons of the test cultures with controls indicated no adverse effects on viability, growth rate, or morphology, and attempts to isolate biochemical mutants were unsuccessful. These results are similar to those reported by Russian workers and, thus, allow some limited level of confidence in the stability of algal cultures, although the level of confidence required for continued development of algal bioregenerative systems can come only from flights of longer duration.

In relation to the use of algal cells for space diets, only one report (ref. 134) was found in the literature and this was of Russian origin. In the reported studies, two groups of human volunteers were fed diets containing dry unicellular algae in amounts up to 150 gm. During the experimental period, chemical analyses were made on various constitutents of the subjects' blood, urine, and feces. No significant changes were observed for the 100-gm level and all analyzed components were within physiological standards. It was concluded that diets containing up to 100 gm of dry algae are satisfactory for feeding up to 22 days.

• Higher plants: No information was found relating specifically to the use of higher plants in bioregenerative life-support systems. However, two reports are worthy of mention since the work was motivated to some extent by potential space application. In the one (ref. 135), Hildebrandt reports the results of a five-year study on the tissue culture of 32 species of higher edible plants. Cells or roots, stems, leaves, seeds, and embryos were used. The primary objective was to determine the nutritional and environmental requirements for the tissue culture growth of the chlorophyllous, photosynthesizing strains of tissues that grow rapidly and contain the desirable qualities of food for human consumption. Although the possible use of these tissues for space food was mentioned, there was no specific evaluation of their application to a space-vehicle environment. The other report (ref. 136) concerns the development of an apparatus for the continuous culture of plant cells. The apparatus, called a phytostat, was used to successfully grow rose stem tissue cells continuously. The unit uses an 8-liter culture volume. The report states "approximately 40 pounds fresh weight of tissue was harvested from seven continuous cultures over a combined total of 222 days; the average yield was 111 gm/l/day during harvesting period; the longest cultures were 55 days; 4.6 gm/l dry weight of tissue...." Again, this report does not specifically consider

space application for this system. However, a potential is indicated and therefore appears worthy of consideration.

• Hydrogen-fixing bacteria: On the basis of engineering evaluations, it was the conclusion of the Phase I study that the chemosynthetic system using the bacterium, Hydrogenomonas, held the greatest potential for a bioregenerative life-support system for use on long-term missions. Several groups of investigators have been conducting research relative to the development of this system. The organism that is predominantly used is H. eutropha, and the investigations have encompassed the following areas: (1) development of continuous culture systems, (2) studies of metabolic activities, (3) studies of the organisms' ability to utilize urinary waste, (4) H. eutropha as a food source for man, and (5) stability of the organism.

At the present time only three groups are known to be working with Hydrogenomonas in continuous culture systems. These investigators are at the Battelle Memorial Institute (BMI), the Research Institute for Advanced Studies (RIAS), and Lockheed Missiles & Space Company (LMSC). The basic system developed at the Battelle Memorial Institute has been described elsewhere (ref. 137). The basic unit consists of a closed cultivation chamber of approximately 5 liter total volume for a 3- to 4-liter working suspension. Each gas (hydrogen, oxygen, and CO_2) is admitted to the system separately on demand through solenoid valves controlled by electrode sensors. The culture vessel is equipped with baffles and an impeller which provides vigorous agitation to assist in rapid gas transfer. A reservoir vessel for the culture medium and an overflow vessel for collected cells removed from the culture chamber are also provided.

In addition to the gases, means are also provided for the measurement and/or control of other environmental parameters such as pH and incubation temperature. More recently the capability to monitor urea and ammonia in the culture medium has been included. The cell density of the culture is controlled at a predetermined range by optical density or turbidometric monitoring with a photoelectric cell which dictates the quantity of fresh nutrient medium to be added to the culture and the volume of cultured cells to be removed. This system is known as a turbidostat since the dilution rate in continuous culture is established by the growth rate.

As described above, the basic or original design of this system was for a 5-liter culture vessel. However, the system has been scaled up so that it is currently being operated with a 20- to 30-liter culture volume in a 56-liter-volume chamber (refs. 138 and 139). The large unit is being used primarily for the autotrophic mass culture of Hydrogenomonas cells which can be used for nutrition feeding studies. The two systems at BMI have not been operated for extended periods. The period of operation is generally from 3 to 5 days.

The continuous culture system in operation at RIAS is an adaptation or modification of the basic 5-liter system developed and fabricated by BMI (ref. 140). Modifications have included changes in the pH, cell density, and CO_2 measurement/control systems with the CO_2 sensor being relocated from the liquid phase of the culture chamber to the gas phase. The study report indicates that improved system performance has been attained. The RIAS unit has been operated in a continuous culture mode for varying periods of time with the longest run reported as 34 days during which a malfunction in

the hydrogen pressure regulator necessitated a temporary shut down on the 26th day. Growth recovery of the culture was incomplete, and the run was discontinued on the 34th day.

The continuous culture system developed at LMSC, which is described in the literature (ref. 141), is also a turbidostat. The culture chamber consists of a modified 7.5-liter fermentor vessel in which a 4-liter culture volume is maintained. The vessel is provided with baffles and an impeller attached to a drive motor capable of speeds up to 2500 rpm. A flow-through gas system is used in which a mixture of hydrogen, oxygen, and CO_2 is supplied to the culture by flowing these gases at different rates through a mixing vessel prior to entering the culture vessel through an immersed sparger. Gas ratios and flows are maintained constant by gas regulators and flowmeters. A constant cell density in the culture is maintained by continually pumping a small fraction of the growth suspension past photoelectric cells which monitor changes in optical density and control an automatic medium dilution and culture harvest mechanism. Temperature is controlled to $\pm 1°C$, and pH is monitored by an internal electrode. This culture unit has currently been in continuous operation for a period of more than seven months. Operative problems that have been encountered have been corrected without discontinuing the run.

There have been a number of reports dealing with various metabolic activities of several species and strains of Hydrogenomonas. However, of primary importance related to the use of the organism in bioregenerative life-support systems are those investigations concerned with the capabilities and capacities of Hydrogenomonas to utilize CO_2 and mans urinary waste products, especially urea. Any discussion of these areas must also consider growth rates of the organism since they are interdependent. It should be noted that the results reported by any investigators are dependent upon many interacting factors and variables peculiar to a given culture environment. Thus, differences in reported results may be due to differences in specific culture environments. Specific details of culture conditions will be reported here only if the reporting here only if the reporting investigator has presented them as conclusive evidence for a given result.

In growth studies of H. eutropha in the BMI culture unit, previous data presented by Foster (refs. 142 and 143) had indicated that for short periods (up to 4 days) a CO_2 consumption value of 10 ml/min/l of culture was obtained in the 2-liter culture volume. Maintaining this level of consumption in a steady-state condition would require a 35-liter culture life-support system to support one man. More recently, Foster (ref. 139) has reported that at certain maximum rates of growth cell, densities of 5 to 6 gm/liter (dry weight) are obtained. The rate of cell production under these conditions is 1.15 gm/hr/1, and the CO_2 gas consumption value is 30 ml/min/1 of culture. If carbon dioxide consumption rates similar to this could be maintained in steady-state, a culture volume of 15 liters or less per man is indicated. However, Foster points out that such a steady-state is difficult to achieve and has not been maintained consistently for long periods.

A recent report by Bongers of the investigations being conducted at RIAS indicate very good rates of growth and gas consumption (ref. 144). In their investigations of cell production under steady-state conditions, Bongers reports the following: "The optimal population density for our experimental conditions if of the order of 4.5 to 5.0 gm (DW)

of cells per liter. Using 3 liters of suspension, a fixation rate of 3 to 4 liters of CO_2/hr was attained. This relatively high rate was found to be easily reproducible and constant during time of observation (approximately 1 week,...)." Although data points during the 1 week run are not given, the figures cited indicate a CO_2 utilization of 17 to 22 ml/min/l of culture. If this condition could be maintained in steady-state for extended time periods, a 20-liter culture system would be sufficient to support one man.

The longest steady-state period during a 210-day continuous run with the 4-liter LMSC system has been 22 days (ref. 145). In the operation of this unit the cell concentration of the culture was maintained at a preselected 1.5 gm/l (dry weight). During the 22-day period, the average gas consumption for CO_2 was 5.7 ml/min/l of culture. The consumption of oxygen and hydrogen averaged 8.7 and 32.9 ml/min/l, respectively. The ratio of gas consumption of hydrogen, oxygen, and CO_2 averaged 1:1.5:5.8. Based upon these values, approximately 60 liters of culture would be necessary to balance the gas exchange for one man. This culture volume is three times that indicated by the work at RIAS. However, it should be noted that the cell density maintained during the LMSC study was one-third of that used in the RIAS investigations.

In culture studies at BMI and RIAS, both Foster and Bongers have worked with relatively high cell densities in the order of 4.5 to 6.0 gm/l (dry weight). These investigators have reported that growth rates and cell production rates decreased at these higher cell density levels. The decrease in growth rate indicates that there were certain limiting factors in the culture environment. Bongers (ref. 140) indicated that his experience in decline of cell production was probably due to lack of sufficient CO_2 but other nutritional deficiencies may also have contributed. Foster (refs. 138 and 139), using urea as the sole nitrogen source for the culture, has observed cyclic variations in growth rate, urea assimilation, and pH, and implies the existence of two paths for urea conversion. Foster postulates that by one path, which apparently is the first in the sequence when urea is added to the culture, there is a conversion of one-half of the urea nitrogen without the intermediate release of ammonia into the medium. The second path involves the urea-urease reaction with subsequent release of ammonia into the medium accompanied also by pH changes. It appeared that the growth of the organism was considerably more rapid by the first path, and when the cells changed to ammonia assimilation by the second path the growth rate became noticeably reduced.

König and coworkers (refs. 146 and 147) in Germany, have investigated the urea-urease reaction in the H 16 strain of Hydrogenomonas. Their work indicates that the presence of urea stimulates the cellular production of urease which catalizes the production of ammonia from urea. A buildup of ammonia represses urease production until ammonia again drops to a minimum level at which time urease production is again stimulated. Thus, in static cultures at least, a cyclic variation was observed with urea and ammonia. Bongers reports that he has confirmed this observation. He also reports that this problem was alleviated in their culture studies by using a mixture of ammonium sulfate and urea. It is postulated that the presence of a certain concentration of ammonia in the culture medium prevents the build-up of relatively high urease activity and, thus, controls the cyclic effect mentioned above. In this manner, relatively high cell densities, 4.0 to 4.5 gm/l (dry weight), have been maintained.

The effect of an unbalanced oxygen supply to autotrophically grown Hydrogenomonas was noted in early experiments with the organism. In studies of gas-absorption rates

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by the culture suspension, Bongers (ref. 144) reports that oxygen transfer constitutes the most critical factor in balancing the gas supply and demand. It has been observed in the continuous culture run at LMSC that relatively small changes (the order of 2 to 3%) in oxygen concentration can elicit marked changes (20 to 50%) in the gas consumption and growth rate of the organism. This may be a critical area to be examined when considering the practical life-support application of the system.

Waste utilization. – In relation to the ability of Hydrogenomonas to use man's metabolic waste, Goldner of TRW, Inc., has recently completed a contract study on the growth of Hydrogenomonas eutropha in urine (ref. 148). In this rather extensive study, growth and gas utilization of the organism cultured in urine collected from three different sources was examined in an autotropic batch culture apparatus that was designed to provide high gas transfer rates under controlled conditions. The urine used in the studies was collected from subjects who consumed an uncontrolled diet (TRW urine) and nutritionally adequate formula diets (Berkeley 1 and Berkeley 2 urine). Experiments were designed to study growth and gas utilization in both undiluted and diluted urine. In practical application, dilution of urine will be required to maintain the desired culture volume. However, dilution of the urine may reduce certain nutrients and metabolites below optimum levels for growth. Thus, experiments were conducted to investigate the effects of urine dilution on the metabolic activities of the organism. In general, the results of the study indicate that there may be several limiting ingredients in diluted urine since gas uptake by the culture in various dilutions of urine was always less than with the undiluted urine. It was found that the addition of mixtures of trace metals and certain organics such as the amino acid glycine increased the gas uptake in certain diluted urine cultures. It was observed that dissolved oxygen concentrations above 8.3% inhibited gas uptake rates in diluted urine. This observation was made on short time period cultures, and long-term effects could not be determined because of the exhaustion of essential nutrients.

Goldner found that the gas uptake rate in the Berkeley 2 urine was markedly lower than in the Berkeley 1 urine even though there were higher levels of all known essential nutrients in the Berkeley 2 urine. Based upon this and the results of other growth medium analyses, he postulates that gas uptake and growth rates are dependent more upon the ratio of nutrients than on the absolute concentration level of the nutrients.

The general conclusion reached by Goldner is that "...urine can provide a major portion of the nutrients required to balance the volume of CO_2 produced by human respiration with the volume of urine excreted. Precise material balance data can only be obtained from large-scale continuous culture studies. Based on the C:N found in cells cultured under optimum conditions for gas utilization, a serious nitrogen imbalance will exist in a closed system unless cultural conditions are modified to increase the ratio of cellular C to N."

Investigations are in progress at LMSC to determine which nitrogen compounds of man's waste products can be utilized by Hydrogenomonas. In these studies (ref. 149), it was found that the organism can utilize uric acid, allantoin, and hippuric acid, as sole sources of nitrogen for growth in addition to the already well-studied compound, urea. Several amino acids, glycine, alanine, serine, glutamine, glutamate, and histidine, also support growth of Hydrogenomonas. It was found that the organism did not utilize creatinine.

Nutrition. – In the area of nutrition for astronauts, the ability of man to use Hydrogenomonas cells as a food source is still to be investigated. However, some animal feeding studies have been accomplished by Dr. Calloway at the University of California, Berkeley. The current status of these nutrition investigations was presented at the 1967 COSPAR meeting in London (ref. 150). In considering the use of this organism as a food source, reasonable caloric intakes for man, based on the composition of the organism as conventionally cultured, would require consumption of 700 to 800 gm of bacterial cells per day, and this would supply 90 to 100 gm of nitrogen and 50 to 60 gm of nucleic acids. A nitrogen intake of this type would require approximately 4 to 5 liters of urinary water to accomplish urea clearance. The nucleic acids, if absorbed, could present a critical problem by being converted to uric acid which may be deposited as urate stones in the kidneys or lead to a gout-like condition. These conditions limit the amount of protein-rich bacteria which can be ingested by man. If it were possible to increase the lipid content of the organism at the expense of protein, less total bacteria would be required in the diet. This would reduce the urea and uric acid load for kidney function and also increase the energy efficiency of the food. Hydrogenomonas cells grown on nutritionally limited medium produce more lipid, primarily as a polymer of beta-hydroxybutyric acid, and less protein. Bacterial cells of this type were fed to mice. The nitrogen digestibility was 93% as compared to the 99% digestibility of the control casein diet. However, the major portion of the lipid was not absorbed and 80 to 90% of it appeared in the feces. No evidence of toxicity of the bacterial cells was observed although food intake and growth were reduced if the cells were not thoroughly washed. Although much more study is required, it was generally concluded that the lipid from the high-lipid containing cells must be processed to produce an available, non-toxic form before it can serve as a food source for man. It is postulated that the most logical approach would be the conversion of the polymer to beta-hydroxybutyrate. Acceptability and safe levels of this compound have not yet been established.

Organism stability. – The question of the reliability and stability of Hydrogenomonas especially under continuous culture conditions has not been answered. DeCicco (ref. 151) has reported that four phage strains active against Hydrogenomonas have been isolated and that two of these strains will lyse the cells under autotrophic culture conditions. In work relating to artificially induced mutations, both DeCicco (ref. 151) and Tischer (ref. 152) have indicated the frequency of mutation is rather low and that the organism appears to be fairly stable at least under earth conditions. Tischer reports the isolation of six polysaccharide producing mutants but they have not been studied sufficiently. DeCicco (ref. 153) has isolated several strains which are suspected of being nutritionally dependent or auxotrophic mutants of H. eutropha. They are being thoroughly investigated and their potential effect if any upon life-support systems using Hydrogenomonas is not known at this time.

There are several other investigations which may find future application or provide support to the use of Hydrogenomonas in a bioregenerative life-support system. McGee (ref. 154) has reported the isolation and study of a thermophilic strain of Hydrogenomonas which has been identified as a new species. This is being examined for its potential use as a bioregenerative organism. However, communication with Tischer (ref. 152) indicates that working with the organism is difficult and little progress can be reported. A study has been reported on the effects of the amino acids L-tyrosine,

L-alanine, and L-glutamic acid on the growth of H. eutropha (ref. 155). Cook (ref. 156) has reported on a study of the carbohydrate metabolism of H. eutropha in which it was found that only fructose of 12 carbohydrates tested supported the organisms' growth and that the organism adapted to fructose under an air atmosphere as well as an H_2-O_2-CO_2 atmosphere. Studies on the fixation of CO_2 by another species of Hydrogenomonas, H. facilis, has been reported by several authors (refs. 157, 158, and 159). Although these later reports may not be directly applicable to life-support system considerations, they may supply some information relative to metabolic studies on H. eutropha.

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CONCLUSIONS

The specific conclusions for each of the ten topics presented in Volume I have been presented at the end of each section. A review of the work presented herein resulted in the decision to carry the work on formaldehyde synthesis using chromatographic reactors, the use of biological wastes for propulsion and radiation shielding, and waste regeneration in the closed system into the mission-analysis studies. The purpose of the mission-analysis studies, presented in Volume II, was to investigate various approaches to closed life-support system design for three specific model missions, i.e., an earth-orbiting space station, lunar base, and interplanetary vehicle.

The other concepts presented in Volume I of the report were not considered for further study. The survey of less studied candidates for microbial life support systems and the analysis of algae and Hydrogenomonas strains did not result in sufficient positive data to allow further work to be accomplished profitably. The use of radiophosphors for illumination of algae provided significant weight savings for the algae system, but still resulted in considerably more weight than the other candidate approaches to life support. The chemical synthesis of fats and proteins is much too complex for spacecraft application in the one- to three-year mission category. The synthesis of glycerol using acetylene as a intermediate is not recommended as the most promising approach, and the use of animal links in the closed system results in severe weight penalties and system-design complications.

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LIBRARY CARD ABSTRACT

LOCKHEED MISSILES & SPACE COMPANY, STUDY OF LIFE SUPPORT SYSTEMS FOR SPACE MISSIONS EXCEEDING ONE YEAR IN DURATION, PHASE IA, FINAL REPORT PREPARED UNDER NASA CONTRACT NAS 2-3818, ed. by R. B. Jagow, December 1967.

The study covered by this report is a continuation of work under NASA Contract NAS 2-3012. New concepts for use of metabolic wastes in closed life-support systems were examined for application to a model earth-orbiting space station, lunar base, and interplanetary vehicle. The processing of metabolic wastes for use as radiation shielding, propulsion propellants, extravehicular life-support system expendables, leakage makeup gases, and starting materials for biological or chemically synthesized food were studied. Systems using these concepts were configured and compared for each model mission. The use of wastes for radiation shielding, EVA expendables, and leakage makeup were found to be very competitive with Hydrogenomonas and glycerol food-synthesis systems for all missions. The use of wastes for propulsion and the baseline system using stored food and dumping wastes to space ranked low in the comparison studies.