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Generation Rates and Chemical Compositions of Waste Streams in a Typical Crewed Space Habitat

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SUMMARY

A judicious compilation of generation rates and chemical compositions of potential waste feed streams in a typical crewed space habitat was made in connection with the waste-management aspect of NASA's Physical/Chemical Closed-Loop Life Support Program. Waste composition definitions are needed for the design of waste-processing technologies involved in closing major life support functions in future long-duration human space missions. Tables of data for the constituents and chemical formulas of the following waste streams are presented and discussed: human urine, feces, hygiene (laundry and shower) water, cleansing agents, trash, humidity condensate, dried sweat, and trace contaminants. Tables of data on dust generation and pH values of the different waste streams are also presented and discussed.

INTRODUCTION

In the relatively short-duration human space missions flown to date, essential consumables (e.g., food, water, oxygen) have been provided at launch while the wastes generated have been returned to Earth in what is termed open-loop life support. Closing the major life support functions on future long-duration human space missions by recycling water and air, growing plants for food, and managing waste, may lead to significant reductions in launch weight by reducing the need for large quantities of expendables and even eliminating resupply requirements (Evanich, 1988). To achieve these reductions, NASA's Physical/Chemical Closed-Loop Life Support (P/C CLLS) Program aims at identifying and developing critical chemical engineering technologies to enable closure of the air and water loops and the processing of waste streams within future spacecraft and space habitats. Currently, human space missions contemplated beyond Space Station Freedom are the establishment of a lunar base and a piloted mission to Mars (Ride, 1987). Although partial closure of the atmospheric and water loops for the Space Station life support system is now achievable, there is a need to develop *fully regenerative* physical-chemical life support systems for extended human space missions where resupply is not feasible. Such systems may allow for eventual integration of biological subsystems to augment air, water and waste processing or recycling, and to provide for food production, as visualized in a Controlled Ecological Life Support System (CELSS) (MacElroy et al., 1989).

One element of the P/C CLLS Program involves waste management. This paper specifically addresses the subelement of waste composition definitions—a compilation of available information on sources, generation rates, and chemical compositions of various waste streams emanating from humans and equipment in a closed environment in space. The selection, monitoring, and sizing of suitable processes for recycling air, water, and other essentials in space (either in a spacecraft or on a planetary surface) require such information concerning the waste streams to be processed. The information is also crucial to developing simulation models for waste treatment. The importance of computerized simulations to aid in the development of chemical processing systems applied to advanced P/C CLLS technologies was recently emphasized (Evanich, 1988). A further use for waste composition definitions is to identify those streams that may contain toxic or hazardous constituents.

In this study we consider a hypothetical long-duration human space mission in which food is provided at launch, no recycling processes are involved, and no plant or animal cultivation occurs in the space habitat. Thus, waste streams deriving from plants and animals, such as inedible biomass, are disregarded, as are wastes resulting from on-board scientific experiments, primarily because such experiments have not been identified or selected. Processed waste streams—streams derived from processing primary streams, such as ash from incineration of trash—are also excluded. [For a consideration of waste streams present in a space habitat having higher plants as a source of food, see the paper by Wydeven et al. (1989); and for waste recycling issues in bioregenerative life support and related matters, see the paper by MacElroy and Wang (1989) and other papers in a recent issue of *Advances in Space Research* (MacElroy et al., 1989).]

Although this paper deals with waste management for "extraterrestrial" closed environments, it nevertheless has practical implications for waste management in the terrestrial sphere, which is also a closed environment. The waste streams identified below for a typical crewed space habitat are not exotic but have their counterparts on Earth. Where differences between extraterrestrial and terrestrial closed systems exist, these have to do with such matters as zero or partial gravity versus Earth gravity, and the time scales and magnitudes of the respective waste management operations. However, it is expected that optimization of techniques for handling wastes and recycling nonrenewable resources for long-duration space missions may rely upon suitable adaptations of ground-based waste management technologies; conversely, innovative procedures developed independently for space application may well lead to useful spin-offs for waste management at the terrestrial level.

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WASTE STREAM TABLES

Production Rates and Solids Contents

Developing process technologies for a CLLS system is expected to be complicated because of the different phases (solid, liquid, and gas) the waste streams exhibit in a space habitat, as well as the need to process these streams under conditions ranging from zero gravity to in excess of Earth gravity, depending on the mission. The various liquid streams cover a range in concentrations from a few percent of solids (urine) to very dilute streams containing less than 0.1% solids (dish or shower/hand-wash water), as indicated in Table 1. This table presents a compilation from various literature sources of the data considered best representative of the major human-derived waste feed streams in a closed space environment. The principal contributor to solid waste is trash, with minor contributions from urine, feces, toilet paper, and perspiration and respiration. Although not specifically reported as such, the dry weight formation rates of trash from Space Shuttle Flights STS-29 and -30 (Anon., 1989a, b) are estimated to be 1.0-1.1 kg/person-day from the wet-weight formation rates and weight percent solids shown in Table 1 for entries with superscripts q and r. The volume formation rates of trash in those flights were reported to be 0.49 and 0.47 ft^3 ($\equiv 1.39$ and $1.33 \times 10^{-2}\ m^3$) per person-day, respectively—much higher than the 0.20 ft^3 ($\equiv 0.57 \times 10^{-2}\ m^3$) per person-day found for

Space Shuttle Flight 51D (Wydeven et al., 1989). Liquid streams besides urine are urinal flush water, the various hygiene waters, humidity condensate, and water from perspiration and respiration. Finally, the gaseous waste stream is represented by exhaled CO_2 (respiration) and an assortment of trace contaminants in air.

Different phases and ranges in concentrations of waste streams as well as different gravity conditions combine to pose complex problems in the design of physical-chemical processes for the treatment of waste streams in a space environment. Such processes will constitute the first stage in the development of advanced waste management systems that will be ultimately required for a regenerative CLLS system for habitats on the lunar or Martian surface. Understandably, still other waste streams will have to be considered in the eventual planning of CLLS systems for deep-space exploratory missions, e.g., those generated in on-board health care facilities. For the present, the data in Table 1, with extensive footnotes, constitute an initial survey of the types and amounts of wastes—both wet and dry—that will have to be processed in order to regenerate oxygen, resupply nitrogen, remove carbon dioxide, reclaim water from the various aqueous feed streams, dispose of trash, and provide for detection and control of trace contaminants in the space environment. The constituents of the various waste streams listed in Table 1 and their chemical compositions or formulas are presented in Tables 2-11. Since most of the waste stream data presented in this paper are of a biological nature and are mean values, which reflect neither considerable individual variation nor extreme values, ranges of values must be taken into account when sizing or designing a waste management process for use in space.

Besides the various waste streams indicated in Table 1, several very minor waste products generated by the human body should be mentioned: flatus, saliva, hair, fingernails and toenails, dried skin and skin secretions, tears, ear wax, and semen. Since these waste products are deemed inconsequential from the standpoint of their masses relative to the other waste streams discussed in this paper, their generation rates and compositions are not included here, but they may be found in a comprehensive report by Webb (1964). However, these minor body wastes may present some unknown contributions to the trace contaminant load.

Toilet Waste

As indicated in Table 1, toilet wastes comprise urine, feces, toilet paper (or wipes), urinal flush water, and pads/tampons and menstrual solids. Although the last item constitutes a very minor potential waste stream, it and pads/tampons are included here because of their inclusion in the comprehensive study by Parker and Gallagher (1988) of human wastes for long-duration space missions in which some 25,000 person-days of data were analyzed. However, in contrast to urine and feces, no separate tables are presented in this paper for the constituents or compositions of pads/tampons and menstrual solids; the former, as well as toilet paper, may be regarded as largely cellulosic $[(C_6H_{10}O_5)_x]$, and the latter is substantially the same as blood solids (Diem and Lentner, 1970). Nor is there a table for urinal flush water since it is essentially "clean" water. As for urine itself, Table 2 presents the principal constituents and their chemical formulas and concentrations, as obtained from various references. For convenience, only the 25 major constituents are given in this table. [The reader may consult the extensive list of 158 constituents found in *Bioastronautics Data Book*, edited by Webb (1964).] Because urine is an aqueous solution of an assortment of solid substances, it can serve as a feedstock for water reclamation, while the solutes can be separated and stored for eventual disposal.

Unlike the situation with urine, there are no comparable data available on the specific chemical constituents found in feces, the second most important toilet waste after urine. Instead, Table 3 presents the general composition of dried human feces, and Table 4 presents the elemental composition of freeze-dried feces together with corresponding data on freeze-dried urine. There is controversy as to whether diet affects fecal composition, some stating that the composition is relatively unaffected by variations in diet because a large fraction of the fecal mass is of nondietary origin (Ganong, 1987), and some stating that the composition varies greatly (see, e.g., Orten and Neuhaus, 1982). The odor of feces is caused principally by the products of bacterial action which vary from person to person; the actual odoriferous products include indole, skatole, mercaptans, and hydrogen sulfide (Guyton, 1981).

Hygiene Water

As shown in Table 1, waste streams emanating from the use of hygiene water consist of laundry water and shower/hand-wash water; also listed under hygiene water is dish-wash water, although this presumably would be drawn from a source of potable water. Table 5 presents the solids content of a model proposed by Putnam (1989) for hygiene water which includes contributions from clothes and towels and/or crew to laundry water and shower water; also included are contributions from the cleansing agents sodium methyl cocoyl taurate (SMCT) and sodium dodecylbenzenesulfonate (SDBS) to shower use and laundry/dish-wash water use, respectively. In developing the data for laundry water, new cotton-polyester long underwear and cotton towels were washed a number of times to establish a baseline (approached asymptotically) for the solids released from clothes and towels in each washing. Following use of underwear and towels by the test crew, the baseline solids (column 2 in Table 5) were subtracted from the total laundry water solids to yield the results shown for the crew (column 3). The solids data given for shower water (column 4) represent material sloughed off from the body during showering. As for the solids content of dish-wash water, it amounts to the cleansing agent (1165 mg/person-day of SDBS) plus an unspecified amount of debris from food preparation and consumption.

An alternative view of the solids content of raw shower water may be seen in the data of Table 6 obtained by Verostko et al. (1989) for a prototype microgravity whole body shower and waste water recovery system. In that study, test persons showered following a protocol similar to that anticipated for Space Station Freedom (once every 48 hours; partial body cleaning between showers using towelettes and wipes in unlimited amounts), and the raw shower water was collected and subjected to various purification treatments prior to recycling. Those workers called attention to the development of microbial biofilms in the whole body shower system, and they provided information on the variety of bacteria and fungi that form and require disinfection in order to produce hygiene water for reuse (Verostko et al., 1987, 1989). The biofilms are composed of bacteria and extracellular polymer which the bacteria employ to attach themselves to metal surfaces and each other. Although the recycled shower waters were favorably rated by shower volunteers, microbial control was recognized as potentially a major obstacle for large regenerative waste water recovery systems. It should be noted that there are some discrepancies in the data of Tables 5 and 6: from Table 6 we calculate the average amount of urea in shower water generated per person-day as (26 mg/l × 3.56 l)/2 days = 46.3 mg, while the corresponding figure in Table 5 is 257 mg; also, the average amount of ammonia in shower water generated per person-day in Table 6 is (16 mg/l × 3.56 l)/2 = 28.5 mg, versus 1.8 mg in Table 5. On the other hand, the shower soaps, although formulated differently, were comparable in amounts (1.55 and 1.8 g/person-day in Tables 5 and 6, respectively). There is a need for additional experimental work to resolve the differences noted between those two tables concerning urea and ammonia in shower water. To conclude this section, Table 7 presents the chemical compositions of candidate laundry and shower/hand-wash cleansing agents for Space Station Freedom. Still to be defined is a cleansing agent for dish-wash use, tentatively considered to be SDBS.

Trash

The chemical composition of the trash brought back to Earth aboard Space Shuttle Flight 51D and analyzed at NASA Ames Research Center is shown in Table 8 (Wydeven et al., 1989). The objective of that analysis was to gain insight into the composition, amount, and volume of trash produced during a typical short-term human space mission (see also Table 1). Such information is important for the design of waste management facilities for future long-duration human space missions, such as a lunar base or a piloted flight to Mars. As seen in Table 8, plastic food containers (along with plastic bags and miscellaneous plastics) constitute the major component of the solid trash in Flight 51D.

The trash brought back to Earth aboard Space Shuttle Flights STS-29 and -30 was analyzed at NASA Johnson Space Center (Anon., 1989*a*, *b*). In addition to the total volumes of trash noted earlier from that study and the corresponding weight data shown in Table 1, the following breakdown of trash by volume % was reported for *both* STS-29 and -30: food containers, 85%; food, 7%; personal hygiene softgoods, 3%; and miscellaneous (e.g., printer paper and washcloths), 5%. For purposes of comparison with the data from Flight 51D, it would have been helpful to have had the weights of the various types of trash from STS-29 and -30. However, the compositions of the trash recovered from these three space shuttle flights were qualitatively similar.

Humidity Condensate

Some thirty different organic substances were identified in the humidity condensate from Spacelab 3 (Verostko, private communication, 1989). These subtances with their chemical formulas and concentrations are listed in Table 9. Also indicated in the table are unknown carboxylic acids, several inorganic impurities, and a number of phthalate esters which were presumed to be sample contaminants. For total organic impurities in the humidity condensate of 172 mg/l (≡ 172,000 PPB), 74.3% or 93.6 mg/l represented the organic carbon content.

Perspiration and Respiration Water

The solid substances associated with perspiration and respiration water are those found in dried sweat, the principal components of which are shown in Table 10 together with their formulas and relative amounts. Insensible perspiration (macroscopically invisible sweat and transepidermal water loss under normal conditions) occurs at the rate of 0.3-0.5 l/24 h (≡ 0.3–0.5 kg/person-day), whereas the rate of sweat production for a 65-kg man doing light work in an environmental temperature of 29°C is 2-3 l/24 h (≡ 2-3 kg/person-day); over short periods, the maximum rate of sweating is 2-4 l/h

(Diem and Lentner, 1970). [Similar rates of generation of sweat for various physical conditions may be found in the *Bioastronautics Data Book* of Webb (1964).] The data presented in Table 10 are approximations, inasmuch as they are derived from compilations of analyses of individual constituents of sweat performed by many investigators. Moreover, the relative amounts of most constituents vary widely, so that the values indicated in the table should be regarded only as average values.

Trace Contaminants

Contaminants in air constitute another waste stream that must be treated in the closed environment of a space habitat. In addition to CO_2 and water vapor from perspiration and respiration, and latent water, contaminants in cabin air include volatile compounds emanating from human bodies, on-board experiments, and equipment, as well as airborne particles. Table 11 presents the principal constituents of two trace contaminant load models for Space Station Freedom, together with formulas, estimated metabolic and/or generation rates, and spacecraft maximum allowable concentrations. Of the 217 potential trace contaminants listed by Leban and Wagner (1989), only 70 are included in the table. All 32 contaminants listed by Yoshimura et al. (1988) are included. Because of overlapping data, the table contains a total listing of 71 contaminants, these being the principal ones in each of the various chemical categories indicated. The load models considered here should be regarded as preliminary and subject to expansion and updating as new data on Space Station Freedom become available, but they will serve as starting points for load models of gaseous trace contaminants for long-duration space missions.

The estimated generation rates and sizes of airborne dust particles expected to be encountered in Space Station Freedom are given in Table 12. These estimates were arrived at on the assumption that about 90% of the particles would be derived from humans and their activities, and the rest would arise from other sources. Thus, to obtain the estimated total generation rate of dust particles expected aboard the Space Station, the data in column 2 of the table must be multiplied by the number of crew members and by the factor 1.1 to allow for nonhuman sources.

pH Values of Waste Streams

The pH of a waste stream has a bearing on the selection of materials used in the transport, storage, and treatment of the stream. Materials used in the waste management system must be resistant to corrosion, thereby minimizing or preventing the formation of extraneous corrosion products that could also be toxic. Water reclamation involving reverse osmosis is an example of a process that is influenced by pH; e.g., the efficiency for filtering certain solutes from contaminated water via reverse osmosis, such as organic acids, is strongly dependent upon pH. Consequently, we conclude this report with Table 13 showing the pH values of various waste streams.

CONCLUSIONS

This report addresses the question of "waste composition definitions," a subelement of "waste management," one element of NASA's P/C CLLS Program, which is aimed at identifying and

developing critical chemical engineering technologies to enable closure of the air and water loops within future spacecraft and space habitats. A judicious compilation of generation rates and chemical compositions of potential feed streams in a typical crewed space habitat has been made, drawing upon available literature as well as private communications, where appropriate. Tables of data are presented and discussed for the constituents and chemical formulas of the following waste streams: human urine, feces, hygiene (laundry and shower) water, cleansing agents, trash, humidity condensate, dried sweat, and trace contaminants. Tables of data on dust generation and pH values of the different waste streams are also presented.

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Table 1. Waste Feed Stream Production Rates and Solids Contents in a Crewed Space Habitat

Stream ID	Wet weight formation rate, kg/person-day	Dry weight formation rate, kg/person-day	Weight percent solids, %
Toilet waste			
Urine	2.11[a], 1.50[b], 1.39[c], 1.27[d]	0.059[b]	3.9[b], 4.1[e]
Feces	0.0955[a], 0.132[f]	0.0205[a], 0.03[b], 0.021[f]	21.4[a], 15.9[f]
Toilet paper		0.0051[g], 0.0411[h]	
Urinal flush water	0.494[b]		
Pads/tampons		0.0035[a]	
Menstrual solids		0.0004[a]	
Hygiene water			
Laundry water	12.5[b,i]		0.023[i]
Clothes & towels		0.0007[i]	
Crew		0.0014[i]	
Cleansing agent		0.0007[j], 0.025[k]	
Shower/hand-wash water	5.4[b], 5.5[i]		0.060[i], 0.097[l], 0.13[m]
Crew		0.0017[i]	
Cleansing agent		0.0016[n], 0.0085[o]	
Dish-wash water	5.4[i]		0.022[i]
Cleansing agent		0.0012[j]	
Trash	0.816[b], 1.00[p], 1.49[q], 1.62[r]		72.7[q], 64.7[r]
Humidity condensate	0.52[s]		
Perspiration and respiration water	1.82[b], 2.50[t]	0.016[t], 0.02[u]	0.65[t], 1.05[v]
Metabolic CO_2		1.00[b]	
Trace contaminants in cabin air		See Tables 11 and 12	

[a] Data from Parker and Gallagher (1988).

[b] Data from Schubert et al. (1984).

[c] Data from Leach (1983).

[d] Based on normal human excretion of 1250 ml/24 h and a density of 1.020 g/ml (Considine and Considine, 1989).

[e] Average value from Putnam (1970). The wet weight values indicated for footnotes a and c were calculated from urine volumes, assuming the density given in footnote d.

[f] Data from Diem and Lentner (1970), p. 657.

[g] Male contribution (Parker and Gallagher, 1988).

[h] Female contribution (Parker and Gallagher, 1988).

[i] Data from Putnam (private communication, 1989).

[j] Sodium dodecylbenzenesulfonate ($C_{12}H_{25}C_6H_4SO_3Na$), an anionic detergent—active component only (Putnam, private communication, 1989).

[k] See Table 7 for chemical composition. The amount of cleansing agent represents 0.2% by weight of the indicated laundry water usage.

Table 1. Footnotes (Concluded).

[l] Data from Verostko et al. (1989).

[m] Given in Schubert et al. (1984) as "expended water solids"; additionally, "waste wash water solids" is given as 0.44% (versus 0.023 + 0.022 = 0.045% for laundry water and dish wash water solids in Putnam (private communication, 1989)).

[n] Sodium methyl cocoyl taurate, an anionic detergent—active component only; the chemical formula is $RN(CH_3)CH_2CH_2SO_3Na$, where R is represented appoximately by $C_{11}H_{23}CO_2$ (as a mixture of different fatty acids). This amount of cleansing agent represents only the shower use, per Putnam (private communication, 1989).

[o] See Table 7 for chemical composition and proposed usage; this amount of cleansing agent is based on one shower every other day plus 6 hand washes per day.

[p] From Space Shuttle Flight 51D (49 person-day flight); see Wydeven et al. (1989).

[q] From Space Shuttle Flight STS-29 (25 person-day flight); see Anon. (1989*a*).

[r] From Space Shuttle Flight STS-30 (20 person-day flight); see Anon. (1989*b*).

[s] Comprises hygiene latent water (0.43), food preparation latent water (0.03) and laundry latent water (0.06 kg/person-day), as given in Schubert et al. (1984).

[t] Average values for sweat from Diem and Lentner (1970), p. 679.

[u] Sweat solids from Schubert et al. (1984).

[v] Data from Webb (1964), p. 225.

Table 2. Principal Constituents of Human Urine

Substance	Formula	Amount, mg/l		
		Footnote a	Footnote b	Footnote c
Urea	H_2NCONH_2	9,300-23,300	10,100-22,900	4,800-14,400 (N)
Chloride	Cl^-	1,870-8,400	3,400-6,800	3,200-6,400
Sodium	Na^+	1,170-4,390	2,200-4,000	1,600-3,200
Potassium	K^+	750-2,610	1,100-2,500	1,200-1,600
Creatinine	$HNC(=NH)N(CH_3)CH_2C=O$	670-2,150	800-2,000[d]	240-640 (N)
Sulfur, inorganic	S	163-1,800	856-1,040[e]	480-1,440
Hippuric acid	$C_6H_5CONHCH_2CO_2H$	50-1,670	800-2,000	32-64 (N)
Phosphorus, total	P	470-1,070	640-1,600	560-1,280
Citric acid	$HOC(CH_2CO_2H)_2CO_2H$	90-930	72-667	
Glucuronic acid	$C_6H_{10}O_7$	70-880	154-473[d]	
Ammonia	NH_3	200-730	270-960	320-800 (N)
Uric acid	$C_5H_4O_3N_4$	40-670	64-781	64-160 (N)
Uropepsin (as Tyrosine)	$HOC_6H_4C_2H_3(NH_2)CO_2H$	70-560	5.6-22[f]	
Bicarbonate	HCO_3^-	20-560		
Creatine	$NH_2C(=NH)N(CH_3)CH_2CO_2H$	0-530	8.8-220[d]	
Sulfur, organic	S	77-470	100-140[g]	48-160
Glycine	$NH_2CH_2CO_2H$	90-450	42-250[d]	
Phenols	C_6H_5OH; $H_3CC_6H_4OH$	130-420	58-100[h]	
Lactic acid	$CH_3CHOHCO_2H$	30-400	80-480	
Calcium	Ca^{++}	30-390	100-260	80-240
Histidine	$C_3H_3N_2CH_2CH(NH_2)CO_2H$	40-330	16-170[d]	
Glutamic acid	$HO_2CCHNH_2(CH_2)_2CO_2H$	<7-320		
Androsterone	$C_{19}H_{30}O_2$	2-280		
1-Methylhistidine	$C_3H_3N_2CH_2CH(NHCH_3)CO_2H$	30-260	18-124[d]	
Magnesium	Mg^{++}	47-158	47-158	80-160

[a] Webb (1964), pp. 215-218, lists 158 different chemical constituents in human urine; a condensed list of 68 of them having concentrations exceeding 10 mg/l is given in Putnam (1970).

[b] Adapted from Diem and Lentner (1970), pp. 661-676, and assuming normal human urine excretion of 1250 ml/24 h, as indicated in references of footnote c.

[c] Based upon data in Smith et al. (1983) and cited in various encyclopedias (e.g., Considine and Considine, 1989).

[d] Overlapping values for men and women.

[e] Inorganic sulfate-S.

[f] Tyrosine.

[g] Sulfuric ester-S + neutral-S.

[h] Phenol + *p*-cresol.

Table 3. General Composition of Dried Human Feces

Substance	Approximate Percent Composition	
	Footnote a	Footnote b
Dead bacteria	30, ≈33[c]	14-30
Fats[d]	10-20	≈17
Inorganic matter[e]	10-20	≈33
Protein	2-3	f
Food residues[g]; dried constituents of digestive juices[h]	30	25-40

[a] Data from Guyton (1981).

[b] Data from Diem and Lentner (1970), p. 657.

[c] Data from Anon. (1988).

[d] Large amount of fat derives from unabsorbed fatty acids from the diet, fat formed by bacteria, and fat in sloughed epithelial cells; about one-third of fats are sterols, chiefly cholesterol (Anon., 1988). For a breakdown of the C_6-C_{20} saturated and unsaturated fatty acids in fecal lipid, see Webb (1964), p. 221.

[e] E.g., calcium and iron phosphates (Anon., 1988); Ca, P, K, Mg and Na are the principal inorganic substances (Diem and Lentner, 1970).

[f] Amount not indicated; proteins consist mainly of undigested nutrient proteins and bacterial proteins (Diem and Lentner, 1970). For an indication of some 18 different amino acids in fecal proteins, see Webb (1964), p. 221.

[g] Cellulose, muscle fibers, etc. (Diem and Lentner, 1970).

[h] E.g., bile pigment and sloughed epithelial cells (Guyton, 1981).

Table 4. Elemental Compositions of Freeze-dried Feces and Urine[a,b]

Element	Percent by Weight	
	Feces	Urine
C	41.92	17.58
H	6.59	4.93
N	8.26	21.69
O	31.84[c]	39.32[c]
P	1.4 ± 0.2	1.4 ± 0.3
S	---[d]	1.80
Cl	2.1	1.6
Na	1.8 ± 0.1	6.8 ± 0.6
K	2.8 ± 0.4	4.2 ± 0.5
Ca	2.5 ± 0.3	0.45 ± 0.02
Mg	0.66 ± 0.06	0.21 ± 0.02
Si	0.040 ± 0.004	0.015[e]
Cu	0.0040[e]	0.0019 ± 0.0004
B	0.0015 ± 0.0001	0.0014 ± 0.0003
Zn	0.027 ± 0.004	0.0013 ± 0.0004
Fe	0.043[e]	0.0007 ± 0.0003
V	0.0006[e]	0.0004 ± 0.0002
Mn	0.017 ± 0.0014	---[d]
Total:	100.0	100.0

[a] Based on data from Carden and Browner (1982) which were cited by Wydeven (1983).

[b] For an indication of the various organic compounds present in feces, see Diem and Lentner (1970), pp. 658-660, and Webb (1964), pp. 220-221.

[c] Not actually reported; the value shown is the assumed % O to allow for 100% total elemental composition.

[d] Not determined.

[e] Estimate.

Table 5. Solids Content of Proposed Hygiene Water Model[a,b]

Components	Laundry water		Shower water, Crew	Total
	Clothes and Towels[c]	Crew[d]		
Suspended solids				-
particle size (μm)				
>30	135	22.3	470	627
8-30	224	165	168	557
3-8	4.7	0	4.4	9.1
1.2-3	0	2.4	0.3	2.7
0.45-1.2	4.7	12.9	5.9	23.5
Sub-total	368	203	649	1219
Dissolved solids				
Chloride	23.5	98.9	96.6	219
Lactic acid	6.9	152.0	61.9	220
Sodium	96.8	96.4	109	302
Urea	90.2	253	257	600
Potassium	13.8	63.5	70.4	148
Calcium	12.5	4.9	3.4	20.8
Ammonia	3.1	6.7	1.8	11.6
Magnesium	13.9	5.5	1	20.4
Iron	1.9	0.13	0.14	2.2
Copper	0.30	0.20	0.22	0.72
Unidentified organics	68.8	560	473	1102
SMCT[e,g]	--	--	--	1550
SDBS[f,g]	--	--	--	1865[h]
Sub-total	332	1241	1074	6062
Total Solids	700	1444	1723	7281

[a] All units in mg/person-day; model is based on a crew of four members.

[b] Data from Putnam (private communication, 1989) and rounded off as supplied by this reference.

[c] Baseline or equilibrium solids content in a single washing after a series of washings on new clothes and towels.

[d] This corresponds to the contribution to the waste load from human origin. The total load of dirty material is the sum of the quantitites indicated for clothes & towels *plus* crew.

[e] Sodium methyl cocoyl taurate—cleansing agent for shower use.

[f] Sodium dodecylbenzenesulfonate—cleansing agent for laundry/dish wash use.

[g] Active component only; other compounds include NaCl, methyl taurate, Na_2SO_4, unreacted alkyl benzene, lecithin, and Luviquat.

[h] The proposed use of SDBS is 700 and 1165 mg/person-day for laundry and dish wash, respectively.

Table 6. Contents of Raw Shower Water[a,b]

Component	Amount, PPM[c]		
	Highest	Lowest	Average[d]
Organic carbon	891	230	470
Inorganic carbon	27	<1	9.4
Ammonia	43	2	16
Urea	87	<1	26
Total Solids	1412	611	970
Microorganisms[e]	TNTC[f]	2×10^2	4×10^7

[a] Data from Verostko et al. (1989).

[b] The showers were taken using either filtered deionized water or reclaimed water from a waste water recovery system; for the composition of the candidate Space Station shower soap formulation, see Verostko et al. (1987) and Table 7; the average amount of this soap ("6503.45.4") used per shower is ca. 3.6 g, while the average volume of water is 3.56 l.

[c] 1 PPM (part per million) ≡ 1 mg/l.

[d] To obtain averages of components in mg/person-day, multiply the PPM values in this column by 1.78, the average daily volume of shower water in liters.

[e] Measured as colony forming units per ml.

[f] TNTC = too numerous to count.

Table 7. Chemical Compositions of Candidate Cleansing Agents for Space Station Freedom[a]

Constituent	Chemical Formula	Percent by Weight
	Laundry Cleansing Agent[b]	
Igepal CO-630	$(C_2H_4O)_nC_{15}H_{24}O$	53.0
Briquest 543-33S	$C_9H_{28}N_3O_{15}P_5Na_7$	28.7
Tinopal CBS	$C_{28}H_{22}(SO_3Na)_2$	0.2
Aerosil 200	SiO_2	2.0
Termamyl 300L	See footnote c	6.0
Esperase 8.0L	See footnote d	6.0
Celluzyme	See footnote e	4.0
	Shower/Hand wash Cleansing Agent[f]	
Igepon TC-42	See footnote g	98.65
Lecipur 95-F	See footnote h	0.50
Luviquat FC-500	$(C_6H_9N_2 \cdot C_6H_9NO \cdot Cl)_x$	0.75
Formalin	37% CH_2O; 11% CH_3OH	0.10

[a] Information obtained through the courtesy of S. E. Lentsch, Ecolab Center, St. Paul, MN.

[b] Proposed use: 0.2% by weight of wash water.

[c] A liquid enzyme (an endoamylase) which will hydrolyze 1,4-alpha-glucosidic linkages in amylose and amylopectin.

[d] A liquid preparation containing an endopeptidase of the serine type which hydrolyzes all proteinaceous substances normally encountered in laundry.

[e] A detergent cellulase with beneficial properties for use in laundry of cotton-containing fabrics.

[f] Proposed use: 5 g per shower; 1 g per handwash.

[g] Sodium N-coconut acid-N-methyl taurate, or sodium methyl cocoyl taurate.

[h] Soybean lecithin.

Table 8. Chemical Composition of Trash from Space Shuttle Flight 51D (49 Person-Day Flight)[a]

Constituents	Weight, kg	Typical moisture content, %	Percent by mass (dry basis)					
			Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Food containers[b]	23.0	0.2	85.2	14.2	--	<0.1	<0.1	0.4
Paper[c]	6.4	10.2	43.4	5.8	44.3	0.3	0.2	6.0
Biomedical[d]	6.4		Indeterminate (See footnote)					
Leftover food[e]	4.8	70.0	48.0	6.4	37.6	2.6	0.4	5.0
Plastic bags[f]	3.2	0.2	85.2	14.2	--	<0.1	<0.1	0.4
Grey duct tape[g]	1.6	negligible	72.7	10.8	16.5	--	--	--
Aluminum cans[h]	1.2	2	4.5	0.6	4.3	<0.1	--	90.5
Miscellaneous[i]	2.6	0.2	60.0	7.2	22.8	--	--	10.0
Total:	49.2							

[a] Data from Wydeven et al. (1989); moisture and composition data in Table are based on relevant data found in Tables 26-27 to 26-29 in Perry and Green (1984).

[b] Containers were made of high density polyethylene, and the moisture and composition on this line reflect that. However, the containers included 12.2 kg of uneaten food and beverages, the composition of which may be regarded as comparable to that of leftover food indicated three lines below.

[c] Data given for "paper (mixed)."

[d] And personal hygiene items, of sufficient diversity to preclude useful data entries.

[e] And food remains; data given for "food wastes (mixed)."

[f] Trash bags, presumed to be polyethylene bags; data given for polyethylene.

[g] Calculated for polyethylene (1/3 by weight) laminated to cotton cloth (1/3 cellulose) using a natural rubber adhesive (1/3 polyisoprene); 2% of the total weight is a resin (proprietary) of unknown composition, and is disregarded in the calculation (Benfield, 1989).

[h] Data given for "Metal, nonferrous" and "Metals (mixed)."

[i] Principally plastic materials; data given for "plastics (mixed)."

Table 9. Organic Impurities in Humidity Condensate from Spacelab 3[a,b]

Substance	Formula	Concentration, PPB[c]
Ethanol	C_2H_5OH	86,000
Propionic acid	$C_2H_5CO_2H$	35,400
Caprolactam	$C_6H_{11}NO$	15,000
Benzyl alcohol	$C_6H_5CH_2OH$	4,700
Methanol	CH_3OH	4,000
N-methyl-N-ethylformamide	$HCON(CH_3)(C_2H_5)$	2,000
N,N-dimethylformamide	$HCON(CH_3)_2$	1,100
2-Ethyl hexanoic acid	$C_4H_9CH(C_2H_5)CO_2H$	750
Benzoic acid	$C_6H_5CO_2H$	500
N-butyl-N'-ethyl thioglycinamide	$C_2H_5NHCSCH_2NHC_4H_9$	500
Caprylic acid	$C_7H_{15}CO_2H$	410
N-Ethyl morpholine	$C_6H_{13}NO$	400
3-Methoxy-butyl acrylate	$CH_3OCH{=}CHCO_2C_4H_9$	200
Butyl cellosolve	$C_4H_9O(CH_2)_2OH$	100
Dimethylbenzyl amine	$C_6H_5CH_2N(CH_3)_2$	100
Di-*n*-butyl amine	$NH(C_4H_9)_2$	100
N-methyl pyrrolidone	C_5H_9NO	100
3-Hydroxy-2,4,4-trimethyl-pentylisobutyrate	$C_{12}H_{24}O_3$	100
N,N-di-*n*-butylformamide	$HCON(C_4H_9)_2$	80
Cyclohexanone	$C_5H_{10}CO$	50
Ethyl propyl ether	$C_3H_7OC_2H_5$	50
Diacetone alcohol	$(CH_3)_2C(OH)CH_2COCH_3$	30
Triethyl phosphate	$(C_2H_5O)_3PO$	30
2,6-Di-*t*-butyl-*p*-cresol	$C_{15}H_{24}O$	20
Cyclic tetramethylene adipate	$C_{10}H_{16}O_4$	20
Acetophenone	$C_6H_5COCH_3$	20
Triallyl isocyanurate	$C_{12}H_{18}N_3O_3$	20
Nonanedioic acid	$HO_2C(CH_2)_7CO_2H$	10
N-*n*-butyl benzenesulfonamide	$C_6H_5SO_2NHC_4H_9$	10
Tetramethyl pyrophosphate	$(CH_3)_4P_2O_3$	10
Unknown carboxylic acids	---	5,480

[a] Data obtained through the courtesy of C. E. Verostko (private communication, 1989) who presented these results at NASA-JSC Water Quality Conference, July 1-2, 1986.

[b] Non-organic impurities include NH_3 (4,400), Ni (<50), K (30,000) and Zn (1325 PPB). Also found were phthalate esters (15,049 PPB) that are deemed to be sample contamination (Verostko, private communication, 1989).

[c] 1 PPB (part per billion) $\equiv 10^{-3}$ mg/l.

Table 10. Approximate Composition of Dry Substance in Sweat[a]

Substance	Formula	Percent by weight	
		Footnote a	Footnote b
Lactic acid	$CH_3CHOHCO_2H$	24	31
Sodium	Na^+	16	18[c], 13[d]
Chloride	Cl^-	24	16
Urea	H_2NCONH_2	3.3	11
Amino acids	e	4.2	7.3
Potassium	K^+	7.0	4.5[c], 6.0[d]
Mucoproteins	f	--	4.6
Sulfate	g	1.2	1.5
Ammonia	NH_3	2.2	1.3
Calcium	Ca^{++}	0.2	1.0
Urocanic acid	$C_3H_3N_2CH{=}CHCO_2H$	--	0.88
Pyruvic acid	CH_3COCO_2H	--	0.61
Reducing substances	h	1.9[i]	0.46
Magnesium	Mg^{++}	0.02	0.37
Phosphate	PO_4^{3-}	0.15	0.22
Uric acid	$C_5H_4O_3N_4$	0.02	0.12
Creatinine	$C_4H_7N_3O$	0.07	0.07
Zinc	Zn^{++}	--	0.02
Phenol	C_6H_5OH	0.05	--
Iron	$Fe^{++(+)}$	0.003	0.02[c], 0.03[d]
Fluoride	F^-	--	0.02
Total:		84.5	99.0[c], 95.5[d]

[a] Based on data from Webb (1964), p. 225, wherein dry substance in sweat is averaged at 1.05% by weight.

[b] Based on data from Diem and Lentner (1970), pp. 679-681, wherein dry substance in sweat is averaged at 0.65% by weight.

[c] Data for men.

[d] Data for women.

[e] Some 18 different amino acids have been identified in sweat.

[f] Conjugated proteins; no single substance.

[g] Less than 50% is inorganic sulfate.

[h] As glucose; not more than 25% of the reducing substances of sweat consist of glucose.

[i] Sugar (as glucose).

Table 11. Principal Constituents of Trace Contaminant Load Models

Category	Constituents[a]	Formula	Metabolic rate, mg/person-day	Generation rate, mg/day		SMAC,[d] mg/m^3
				SP ST[b]	JEM[c]	
Alcohols	1-Butanol	C_4H_9OH	1.33	6922	1954.3	121.0
	Ethanol	C_2H_5OH	4.00	5216	1307.1	94.0
	2-Propanol	$CH_3CHOHCH_3$	0	2022	507.9	98.3
	Cyclohexanol	$C_6H_{11}OH$	0	1288	327.6	123.0
	2-Methyl-1-propanol	$CH_3CH(CH_3)CH_2OH$	1.20	728.4	--	121.0
	Methanol	CH_3OH	1.50	707	175.3	52.4
Aldehydes	Butanal	C_3H_7CHO	0	1470	388.1	18.0
	Propanal	C_2H_5CHO	0	87	--	95.0
	Ethanal	CH_3CHO	0.09	48.2	33.8	54.0
	Pentanal	C_4H_9CHO	0.83	22.7	--	106.0
Ketones	Acetone	CH_3COCH_3	0.20	4212.4	1053.0	712.5
	Methyl ethyl ketone	$C_2H_5COCH_3$	0	3760	1238.8	59.0
	Methyl isobutyl ketone	$(CH_3)_2CHCH_2COCH_3$	0	1335	516.6	82.0
	Cyclopentanone	C_4H_8CO	0	845	--	29.2
	Diisobutyl ketone	$[(CH_3)_2CHCH_2]_2CO$	0	711	--	58.1
Aliph. hydrocarbons	Methane	CH_4	160	1620	2700.0	1771.0
	Cyclohexane	C_6H_{12}	0	624	387.6	206.0
	4-Methyl cyclohexene	C_7H_{12}	0	253	--	393.2
	Propadiene	$CH_2{=}C{=}CH_2$	0	180	--	81.9
	Ethane	C_2H_6	0	166	--	1230.0
	Isoprene	$CH_2{=}CH(CH_3){=}CH_2$	0	148	--	557.0
	Pentane	C_5H_{12}	0	134	--	590
	Cyclopentene	C_5H_8	0	130	--	167.0
	1-Heptene	$C_5H_{11}CH{=}CH_2$	0	113	--	201.0
	Methyl acetylene	$CH_3C{\equiv}CH$	0	8.7	250.0	409.5
Arom. hydrocarbons	*m*-Xylene	C_8H_{10}	0	3539	1258.3	86.8
	Toluene	$C_6H_5CH_3$	0	1351	340.0	75.3
	p-Xylene	C_8H_{10}	0	780	--	86.8
	Propyl benzene	C_9H_{12}	0	269	--	49.1
	Ethyl benzene	C_8H_{10}	0	182	--	86.8
	Benzene	C_6H_6	0	27	6.8	0.3
Halocarbons	Freon TF	$Cl_2CFCClF_2$	0	13801	--	383.0
	Freon 113	$Cl_2CFCClF_2$	0	9180	--	383.0
	Dichloromethane	CH_2Cl_2	0	1746	2252.3	86.8
	Chlorobenzene	C_6H_5Cl	0	1240	--	46.0
	Freon 124	CF_2ClCHF_2	0	750	--	555.0
	Tetrachloroethylene	$Cl_2C{=}CCl_2$	0	553	--	34.0
	Ethyl chloride	C_2H_5Cl	0	545	--	263.7
	Halon 1301	$CBrF_3$	0	474	560.4	608.8

Table 11. Concluded.

Category	Constituents[a]	Formula	Metabolic rate, mg/person-day	Generation rate, mg/day		SMAC,[d] mg/m^3
				SP ST[b]	JEM[c]	
	Freon 22	$CHClF_2$	0	467	--	353.6
	1,1,2-Trichloroethane	$CHCl_2CH_2Cl$	0	2.4	184.9	5.5
Esters	2-Ethoxyethanol	$C_2H_5OCH_2CH_2OH$	0	1035	--	73.7
	Butyl acetate	$CH_3CO_2C_4H_9$	0	948	--	190.0
	Propyl acetate	$CH_3CO_2C_3H_7$	0	585	671.0	167.0
	2-Ethoxyethyl acetate	$C_2H_5OCH_2CO_2C_2H_5$	0	545	--	162.0
	Ethyl acetate	$CH_3CO_2C_2H_5$	0	371	--	180.0
Ethers	Tetrahydrofuran	C_4H_8O	0	95	56.6	118.0
	1,4-Dioxane	$C_4H_8O_2$	0	63	--	1.8
	1-Propoxy butane	$C_4H_9OC_3H_7$	0	55	--	186.8
	Diethyl ether	$C_2H_5OC_2H_5$	0	52	--	242.0
	Furan	C_4H_4O	0	1.6	0.4	0.11
Silanes and Siloxanes	Tetradecamethylcycloheptasiloxane	$[(CH_3)_2SiO]_7$	0	555	--	150.7
	Dodecamethylcyclohexasiloxane	$[(CH_3)_2SiO]_6$	0	403	271.0	150.7
	Octamethyltrisiloxane	$[(CH_3)_3SiO]_2Si(CH_3)_2$	0	379	--	114.0
	Decamethylcyclopentasiloxane	$[(CH_3)_2SiO]_5$	0	316	--	150.7
	Tetrasiloxane	$[(CH_3)_2SiO]_4$	0	237	--	114.0
	Siloxane dimer	$[(CH_3)_2SiO]_2$	0	32	8.0	52.4
	Trimethylsilanol	$(CH_3)_3SiOH$	0	12	273.2	1.8
Organic nitrogens	4-Ethyl morpholine	$C_6H_{13}NO$	0	213	--	16.0
	Indole	C_8H_7N	25	100[c]	81.2	0.48
	Acetonitrile	CH_3CN	0	83	--	6.7
	Trimethylamine	$(CH_3)_3N$	--	--	100	(24.1)[f]
Sulfides	Carbon disulfide	CS_2	0	44	--	16.0
	Carbonyl sulfide	OCS	0	5.4	--	12.0
	Dimethyl sulfide	$(CH_3)_2S$	0	0.3	12.5	2.5
Miscellaneous	Epichlorohydrin	C_3H_5ClO	0	5	--	1.2
	Acetic acid	CH_3CO_2H	0	0.02	1.4	7.4
Inorganics	Ammonia	NH_3	475	3806	476.5	17.4
	Carbon monoxide	CO	23	1843	437.8	28.6
	Hydrogen	H_2	26	208	26.0	247.3
	Hydrogen sulfide	H_2S	0.09	0.7	--	2.8

Table 11. Footnotes.

[a] Leban and Wagner (1989) list 219 potential contaminants, the principal ones in 13 chemical categories being presented in the above table; the entire list may also be seen in Wydeven et al. (1989).

[b] SP ST = Space Station Model, with 8 crewmembers; data include corresponding metabolic rate data (column 4) (Leban and Wagner, 1989).

[c] JEM = Japanese Experiment Module, with 2 crewmembers (Otsuji et al., 1988); data include corresponding metabolic rate data (Yoshimura et al., 1988).

[d] SMAC = Space Maximum Allowable Concentration (Leban and Wagner, 1989).

[e] Only 50% of metabolic rate was used to obtain the total Space Station rate (Leban and Wagner, 1989).

[f] Maximum allowable concentration in JEM (Yoshimura et al., 1988).

Table 12. Estimation of Space Station Dust Generation Rate by Humans[a]

Particle Size, microns	Particle Generation, particles/hr/person
0.3 - 0.5	81,341,426
0.5 - 1	34,570,164
1 - 2	4,270,366
2 - 5	1,565,870
5 - 10	211,548
above 10	40,626

[a] Data from Leban (private communication, 1989).

Table 13. pH Values of Waste Streams

Waste Stream	pH
Urine	4.8-7.5[a]; 4.6-8.0[b]
Feces	5.85-8.45[c]; 6.9-7.7[d]
Urinal flush water	≈7.0?
Laundry water	to be determined
Shower water	5.1-7.9[e]
Dish-wash water	to be determined
Humidity condensate	7.0[f]
Sweat	4-6.8[g]

[a] Data from Diem and Lentner (1970), p. 662.
[b] Data from Webb (1964), p. 216.
[c] Data from Diem and Lentner (1970), p. 657.
[d] Data from Webb (1964), p. 220.
[e] Data from Verostko et al. (1989).
[f] Data from Verostko (private communication, 1989).
[g] Data from Diem and Lentner (1970), p. 679.

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16. Abstract

A judicious compilation of generation rates and chemical compositions of potential waste feed streams in a typical crewed space habitat was made in connection with the waste-management aspect of NASA's Physical/Chemical Closed-Loop Life Support Program. Waste composition definitions are needed for the design of waste-processing technologies involved in closing major life support functions in future long-duration human space missions. Tables of data for the constituents and chemical formulas of the following waste streams are presented and discussed: human urine, feces, hygiene (laundry and shower) water, cleansing agents, trash, humidity condensate, dried sweat, and trace contaminants. Tables of data on dust generation and pH values of the different waste streams are also presented and discussed.

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