SOLID WASTE TREATMENT PROCESSES FOR SPACE STATION

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ABSTRACT

The purpose of this study was to evaluate the state-of-the-art of solid waste(s) treatment processes applicable to a Space Station. Previous studies, since the earlier 1960's, were collected to establish a project library and interviews were conducted of numerous personnel with NASA, from industry, and other researchers. From the review of available information a source term model for solid wastes was determined. An overall system is proposed to treat solid wastes under constraints of zero-gravity and zero-leakage. This study contains discussion of more promising potential treatment processes, including super-critical water oxidation, wet air (oxygen) oxidation, and chemical oxidation. A low pressure, batch-type treatment process is recommended. Processes needed for pretreatment and post-treatment are hardware already developed for space operations. The overall solid waste management system should minimize transfer of wastes from their collection point to treatment vessel.

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INTRODUCTION

In this report potential processes are investigated for the treatment of solid wastes from the crew and tasks performed in a Space Station. A Space Station has been proposed by NASA as its next major program with an operational Station before the turn of the century. The Space Station would continuously orbit the earth for years, be operated (initially) by a six-man crew, and be resupplied by a Shuttle on about a ninety-day frequency. Resupply of the Station precludes the need for a closed environmental life support system, but the Station will have to treat wastes in order to at least reduce their volume prior to their return to Earth in the Shuttle. It is here assumed that wastes cannot be jettisoned to space from the Station; this is an important constraint to this evaluation of possible treatment systems. The Space Station treatment system will also need to function under zero-gravity conditions. In general, the Station environment will compare to a community with a high population density, limited available utilities (water, electricity, fuel, and air),and operate in a spacecraft with constraints on system size, weight, etc. There is no convenient place for waste disposal and no established recycle options for the waste materials.

The Space Station solid wastes are: feces, urine, paper trash, food wastes including food containers (plastics), and other

solid wastes from routine maintenance operations and special biological, physical and engineering tasks. These materials might somehow be converted to substances needed on the Station. For example, wastes containing carbon could be oxidized to carbon dioxide that could be reduced to oxygen needed for life supprt. Water in wastes could be separated, filtered, and recycled. Food wastes and metabolic wastes contain nitrogen compounds that could be a source of nitrogen gas needed to maintain cabin atmosphere. These examples do not exhaust the possible uses for solid wates, but are indicative of more likely practical uses for wastes. Furthermore, solid wastes will need to be treated in order to maintain the habitability of the Space Station.

The primary purpose of this study was to evaluate the feasibility and potential of supercritical water oxidation and other waste incineration processes for use on a Space Station.

THEORY

In order to achieve the project objectives information was retrieved by means of a literature search and by direct discussions with knowledgeable personnel. At the start of the project only a few reports on supercritical water oxidation were in-hand. A computerized literature search was immediately initiated through the Technical Library of the Johnson Space Center. This search used the NASA/RECON data file. The useful reports were retrieved either in hard copy or microfiche form and

organized into an information file. References cited in the reports were checked and copies of applicable documents were added to the file. A limited "hand" search of current Chemical Abstracts and Science Citations was also done. By these means the solid waste treatment information file was developed as listed in table Footnotes and in References. References were classified into four main topics: Process Reviews, Supercritical Water Oxidation, Zimpro Process, and Treatment Processes.

In addition to the library search, many discussions were held with both NASA and non-NASA personnel. A list of people contacted is at the end of this report, after References. These discussions were very helpful towards the rapid establishment of major problems likely to be encountered and the state-of-the-art of solid waste treatment processes.

The scope of this study did not include experimental measurements.

On the basis of the in-hand documents and interview data, the available information was evaluated and organized into two major areas; namely, Source-Term (solid waste(s) mass rates and composition) and Treatment Processes.

RESULTS

The results of this evaluation of Space Station solid wastes and treatment processes are presented below. Results for the Source Term are presented first, then Treatment Proceses.

A. Source Term

Metabolic solid wastes from the crew include feces and urine, primarily. Wastes, hair, skin tissue, and nails are relatively small contributions. Toilet tissue paper and wipes are generated along with metabolic wastes but these items are discussed later.

FECES

The rate, solids contents, and elemental composition of feces are listed in Tables 1 to 3. The reported total fecal rates range from 0.060 to 0.50 kg/man-day. This factor of eight difference can be due to many reasons. Variations in diet, particularly fiber content, is an important parameter. Another important factor is the duration of fecal rates, that is whether over 1-day or 1-month, etc. There are many other factors to be considered. In Table 2 results are listed from reports of fecal measurements, not second-hand sources which were included in Table 1. The data in Table 2 indicates a range of 0.1 to 0.4 or a factor of four. The results for Skylab (1974) and the McDonnell-Douglas (1971) have the largest experimental basis. This author would weigh the data towards the Skylab results which were made in a zero-gravity

TABLE 1 FECAL MASS RATE

YEAR	AUTHOR	MASS RATE, KG/MAN-DAY SOLIDS	WATER	TOTAL	COMMENT
1983	Wydeven	0.044	(0.060)	0.104	NASA/AMES for CELSS model; Bioastronautics Data Book
1983	Rapp	-	-	0.25 to 0.30	NASA/JSC, estimated for astronauts
1982	Guston and Vinopal	0.11	0.09	0.20	Boeing Aerospace Design Study; Bioastronautics Data Book
1981	Brose	0.032	-	-	Hamilton Standard Design Study
1976	Jagow	-	-	0.125	Lockheed Design Study
1975	Jones	-	-	0.168	USSR 1-year Test (ground) begun in 1967
1975	Bioenvironmental Systems	0.0338	-	-	Review Study
1974	Sauer, R.	0.0413	0.116	0.157	Skylab Summary Data
1972	Nelson and Cody	-	0.12	-	Space Station Design Study - 6 man crew
1971	McDonnell-Douglas Astron.	0.133	0.260	0.393	Operational 90 Day Manned Test (ground), average of 319 uses.
1970	Schaedle and Laubach	0.036	0.113	0.150	Rockwell; Space Station Waste Model
1969	Hamilton Standard	0.050	0.113	0.163	Design Study
1965	Rich, Ingram and Berger	(0.025 to 0.037)	(0.075 to 0.113)	0.100 to 0.150	Review for U.S. PHS. Basis 1956 Study (Ingram) of cabin cruiser wastes.
1964	Dodson and Wallman	(0.0375)	(0.1125)	0.150	General Dynamics; Ignition ASH @ 1/16 total Mass.
1964	Webb	0.020 to 0.075	-	0.060 to 0.370	Various diets, compilation of results from 9 sources.
		0.0235 to 0.035	-	0.35 to 0.50	General Range.Feces solids contents 15 to 35 %
		0.061		0.150	Mixed diet - Wright - Patterson AFB study (1961)
		0.020		0.120	Unspecified diet - Wright - Patterson AFB study (1962)

NOTE: Numbers in parenthesis calculated in this work.

TABLE 1

REFERENCES

Dodson L. and Wallman, H., "Research on a Waste System for Aerospace Stations," Technical Documentary Report No. AMRL-TDR-64-33, 1964.

Webb, P., Ed., Bioastronautics Data Book, National Aeronautics and Space Administration, NASA-SP-3006, section 13 pp. 213-239, 1964.

Rich, L.H., Ingram, W.M., and Berger, B.B., "Waste Disposal on Space Craft and Its Bearing on Terrestrial Problems," U.S. Department Health, and Welfare, Public Health Service, PB 168787, 1965.

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Schaedle G.C. and Laubach G.E."An Introduction to the Waste Management Problem for Large Space Stations," American Society of Mechanical Engineers., Proceedings Space Systems and Thermal Technology for the 70's Part 1, Los Angeles, CA June, Paper 70-Av/SpT-24, 1970.

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Bioenvironmental Systems Study Group of the Society of Automotive Engineers, "Evaluation and Comparison of Alternative Designs for Water/Solid-Waste Processing Systems for Spacecraft," Final Report, NASA-CR-162492, 1975.

Jones, W.L., "Life-Support Systems for Interplanetary Spacecraft and Space Stations for Long-Term Use," in Foundations of Space Biology and Medicine, Calvin, M.and Gazenko, O.G., Eds., National Aeronautics and Space Administration, Vol. III p.270,1975.

Brose, H.F., "A Regenerative Life Support System for Space Operations Center (SOC) - A Probable First Flight Application," American Society of Mechanical Engineers, Paper 81-ENAs-12, 1981.

Guston, E. and Vinopal T., "Controlled Ecological Life Support System Transportation Analysis," NASA Contractor Report - 166420, pp. 48-51, 1982.

Rapp, R., Personal Communication, 1983.

Wydeven, T., "Composition and Analysis of a Model Waste for a CELSS," Preprint, to be published as a NASA Technical Memorandum, 1983.

Reference Addes in Proof

Sauer R.L., "Summary Sky Lab Intake-Output Data Sheet, Personal Communication 1983.

TABLE 2. FECAL MASS RATE - EXPERIMENTAL VALUES

YEAR	AUTHOR	RATE, KG/MAN DAY TOTAL	SOLIDS	SOLIDS %
1983	Rapp	0.25 to 0.30	-	-
1981	Onisko and Wydeven [a]	-	-	20
1971	McDonnell-Douglas (90 day ground study)	0.40	0.13	33.8
1975	Jones (USSR data of 1967)	0.17	-	-
1974	Sauer	0.16	0.041	26
1964	Webb	0.35 to 0.50	-	15 to 35
	Webb (Wright-Patterson AFB, 1961)	0.15	0.061	40.7
	Webb (Wright-Patterson AFB, 1962)	0.12	0.020	16.7
1965	Rich, et al.(Ingram, 1956)	0.10 to 0.15	0.025 to 0.037	25

a. Onisko, B. L. and Wydeven, T., "Wet Oxidation as a Waste Treatment Method in Closed Systems," NASA Conference Publication 2247, pp. 51-53, 1981.

TABLE 3. FECAL SOLIDS ELEMENTAL AND ASH COMPOSITION

ELEMENT	REFERENCE A	B	C	D	E
C	41.92	41.92	26.3	67.73	-
O	-	-	34.6	11.71	11.71
N	8.26	8.26	3.92	4.00	6.0
H	6.59	6.59	6.98	11.71	-
K	2.8	2.8	-	-	0.88
Ca	2.5	2.5	-	-	3.5
CL^-	2.1	2.1	-	-	-
Na	1.8	1.8	-	-	0.34
P	1.4	-	0.99	-	-
Mg	0.66	0.66	-	-	0.77
S	-	-	0.39	0.28	
Fe	0.043	0.043	-	-	0.087
Si	0.040	0.040	0.20	-	-
Zn	0.027	0.027	-	-	-
Mn	0.017	0.017	-	-	0.010
Cu	0.0040	0.0040	-	-	0.0032
B	0.0015	0.0015	-	-	-
V	0.0006	0.0006	-	-	-
ASH	-	-	9.34 (DRY)	4.53 (DRY)	3.1

A. Wydeven, T. 1983, op. cit.

B. Carden, J.L. and Browner, R., "Preparation and Analysis of Standardized Waste Samples for Controlled Ecological Life Support Systems (CELSS), "NASA Contractor Report 166392, 1982.

C. Onisko, B. L. and Wydeven, T., 1981, op. cit.

D. Bioenvironmental Space Systems Study Group, 1975, op. cit.

E. Goldblith, S. A. and Wick, E.L., "Analysis of Human Fecal Components and Study of Methods for Their Recovery in Space Systems, Aerospace Medical Laboratory, Wright-Patterson Air Force Base, 1961.

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environment for about 120 days by nine different astronauts. The McDonnell-Douglas study was in a 1-g-gravity environment for 90 days by four men. The average of these two programs is 0.28 kg/man-day and for a weighted average take 0.25 kg feces per man per day. This average agrees well with Rapp's (1983) estimate of 0.25 to 0.30 kg/man-day.

The total solids content of feces varies from about 15 to 40 percent. This author takes an average value of 25% which is above the Ames data, below the McDonnell-Douglas results, and in agreement with results by Ingram (1956) and Skylab (Sauer). Data for the elemental composition of feces was not readily available, see Table 3. Rough estimates of the carbon, hydrogen, oxygen, and nitrogen levels are 26%, 7%. 35%, and 4%, respectively. These concentrations are basically values reported by NASA/Ames (Onisko and Wydeven, 1981).

On the basis of the above average fecal mass rates and composition, the elemental and water mass rates can be calculated. The results are as follows:

	Rate, kg/man-day
Carbon	0.016
Hydrogen	0.0044
Oxygen	0.022
Nitrogen	0.0025
Water	0.19

The total energy available from the burning of feces, assuming a heat of combustion of 7700 Btu/lb (18,000 kJ/kg) and a fecal rate of 0.25 kg/man-day, was calculated to be 5×10^{-5} kilowatts per man-day. Thus, feces is not a practical energy source by any incineration or oxidation process.

URINE

The urine mass rate and elemental composition data are presented in Tables 4 and 5, respectively. Variations in the urine rates are not as great as the fecal data. This author takes an average value of 1.6 kg per man per day. The Skylab average equals 1.58 kg/man day. During the Mercury-Apollo flights (6, 7 and 9) the urine rates varied considerably from 0.7 to 3.5 kg/man day, but the average value of these 3 flights is 1.8 kg/man day which is reasonable agreement with Skylab data. The solids content of urine is 5% based on the experimental data. Thus, from urine 1.52 kg of water per man day are available for recycle. The elemental composition of solids in urine is taken as follows:

TABLE 4. URINE MASS RATE[a]

YEAR	AUTHOR	MASS RATE, KG/MAN-DAY SOLIDS	WATER	TOTAL
1981	Brose	0.059	1.50	1.56
1976	Jagow	-	-	2.18
1975	Jones	-	-	1.28
1975	Bioenvironmental Systems Study	0.064	-	-
1974	Sauer	-	-	1.58
1972	Nelson and Cody	-	-	1.64
1971	McDonnell-Douglas Astronautics	-	-	1.5
1970	Schaedle and Laubach	0.059	1.57	1.63
1969	Hamilton Standard	0.70	0.70	1.4
1969	Shook and Thomas	not available		
1965	Rich, Ingram and Berger	0.06	-	1.2
1964	Webb Avg.	-	-	1.2
	Mercury-Apollo Flt. 6	-	-	1.3
	Mercury-Apollo Flt. 7	-	-	3.5
	Mercury-Apollo Flt. 9	-	-	0.7
1964	Dodson and Wallman	0.075	-	1.5
1962	Mattoni and Sullivan	0.070	1.33	1.40

a. Footnotes are listed in Table 1 plus the following:

Mattoni, R.H. and Sullivan, G.H., Sanitation and Personal Hygiene During Aerospace Missions," Wright-Patterson Air Force Base, Ohio, Technical Documentary Report No. MRL-TDR-62-68, 1962.

Dodson, J. and Wallman, H., "Research on a Waste System for Aerospace Stations," Wright-Patterson Air Force Base, AMRL-TDR-64-33, 1964.

Shook, R.E. and Thomas, E.C., "Urine Output Parameters for Space Cabin Environments," McDonnell-Douglas Astronautics Company, Paper 10069, April 1969.

TABLE 5. URINE ELEMENTAL COMPOSITION AND DRY WEIGHT [A]

SUBSTANCE	B	C	D	E	F	G
			WEIGHT, %			
N	21.69	21.69	20.1/20.7	20.69	21.91	21.92
C	17.58	17.58	19.9	17.62	18.29	18.55
H	4.93	4.93	4.62	3.83	4.06	4.08
O	-	-	25.9	21.10	17.21	22.28
S	1.80	1.80	0.97	1.76	0.36	0.362
Na	6.8	6.8	-	8.05	-	-
O	1.6	1.6	-	14.38	-	-
P	1.40	-	1.87	0.13	-	-
Si	0.015	0.015	0.046	-	-	-
K	4.2	4.2	-	6.21	-	-
Ca	0.45	0.45	-	5.72	-	-
Mg	0.21	0.21	-	0.51	-	-
Dry weight	-	-	3.12	-	-	-
ASH (dry)	-	-	30.6	-	38.18	-

Footnotes:

A. Tabulation excludes extensive data compiled by Webb, 1964; these data are rates (mg/24 hr) of numerous compounds as well as their range.

B. Wydeven, T., 1983; op. cit.

C. Carden, J. L. and Browner, R., 1982, op. cit.

D. Onisko, B. L. and Wydeven, T., 1981, op. cit.

E. Hoshizaki, T. and Hansen, B.D., "Generic Waste Management Requirements for a Controlled Ecological Life Support System (CELSS), American Society of Mechanical Engineers, Paper 81-ENAs-23, 1981.

F. Bioenvironmental Systems Study Group, 1975, op. cit.

G. Putnam, D.F., "Composition and Concentrative Properties of Human Urine," NASA Contractor Report 1802, 1971.

carbon - 18%, hydrogen 4.9%, oxygen 25%, nitrogen 21%. Other elements are not included here, for additional details see Table 5. The elemental and water release rates from urine are calculated to be as follows:

	kg/man-day
Carbon	0.014
Hydrogen	0.0039
Oxygen	0.020
Nitrogen	0.017
Water	1.52

FOOD

The wastes generated from food include uneaten foods and used food containers. On the basis of Shuttle data 3.6 pounds (1.64 kg) of food (dry food, water in food, and packaging) are provided per person per day. This includes 0.73 kg of dry food per person per day and 0.46 kg of water. Not all the food is eaten. Assume 10% of the food is wasted; then 0.046 kg of water per person per day are available for recovery. If food is assumed to approximate sugar $C_6H_{12}O_6$, which is a crude assumption, but useful for the determination of elemental release rates. The carbon, hydrogen and oxygen available from wasted food are estimated to be as follows:

	kg/man-day
Carbon	0.03
Hydrogen	0.005
Oxygen	0.04

The amount of carbon, etc. from wasted food containers is discussed under plastics.

PAPER

Paper wastes would be generated on a Space Station due to personal hygiene requirements, used paper towels, wipes, gauze, Q-tips and miscellaneous other paper products. These wastes exclude washcloths, fecal-emesis collection bag, and a trash container liner spare. The total amount of cellulosic materials is estimated to be 1 kg per man-day. The empirical formula for cellulose is $C_6H_{10}O_5$, or 44% is carbon, 6% is hydrogen and 50% is oxygen. This estimate neglects th presence of water. The elemental release rates are calculated:

	kg/man-day
Carbon	0.44
Hydrogen	0.06
Oxygen	0.50

PLASTICS

Wastes composed primarily of polyethylene are generated from food containers, packing materials, medical supplies, and from experimental work. Food containers are used at a rate of about 0.45 kg per man-day. Packing materials and other plastics could be triple this amount, or 1.4 kg per man-day. This author assumes that the plastic wastes consist mostly of polyethylene. From plastics the elemental release rates are:

	kg/man-day
Carbon	1.6
Hydrogen	0.26

The total wastes generated are summarized in Table 6, and a summary of the elemental release rates and water are presented in Table 7. The total solid waste feed rate is 5.4 kg per man day, plastics will constitute the largest amount followed by food and urine. The weight of paper wastes is less than these latter three wastes, but its bulk volume will be the largest. Feces amounts to about five percent of the total mass. These results indicate that water is available in wastes (1.8 kg per man-day) to provide the drinking needs for 2 astronauts per day. Carbon oxidation would require 7.5 kg of oxygen per man-day because the amount of

TABLE 6

SOLID WASTE(S) TREATMENT SYSTEM FEED WASTES

WASTE	RATE kg/man-day
FECES	0.25
URINE	1.6
FOOD	1.6
PAPER	1.0
PLASTICS	1.9
TOTAL	5.4

TABLE 7

SUMMARY OF ELEMENTAL AND WATER WASTE RATES

Element/ Waste	Carbon	Hydrogen	Oxygen	Nitrogen	Water
			rate, kg per person per day		
Feces	0.016	0.0044	0.022	0.0025	0.19
Urine	0.014	0.0039	0.020	0.017	1.52
Food	0.03	0.005	0.04	-	0.046
Paper	0.44	0.06	0.50	-	-
Plastics	1.6	0.26	-	-	-
TOTAL	2.1	0.33	0.58	0.020	1.8

oxygen in the wastes is insufficient for complete combustion. Relatively small amounts of nitrogen are available for utilizat' on a Space Station.

Table 8 presents the heat of combustion of waste materials.

B. TREATMENT PROCESSES

There are many possible treatment processes for Space Station solid wastes. Some are conventional technology, for example, incineration and others are high technology processes, like electric discharge plasma and supercritical water oxidation. This report will discuss only a few of the processes. Information about others can be obtained from references cited in this report.

SUPERCRITICAL WATER OXIDATION

In 1975 Modell discovered that supercritical water would oxidize specific organic compounds. Supercritical water is water at temperature and pressure levels above water's critical point, 374 degrees C and 218 atm, see Figure 1. In 1979, supercritical water oxidation (SCWO) was applied to mixtures of organic wastes. Tests were conducted to show its effectiveness in destroying organic halides which are now commonly known as hazardous wastes. The exploitation of the SCWO process was commercialized in 1980 by Modell whc formed Modar, Inc.

TABLE 8.

HEATS OF COMBUSTION

	$\frac{Btu}{Lb}$	$\frac{kJ}{kg}$
Cellulose	7500	17,000
Feces (dry)	7700	18,000
Polystyrene	17,200	40,000
Polyethylene	19,000	44,000

In the SCWO both organic material and oxygen dissolve in supercritical water and then oxidation is carried out in supercritical water medium. Organic substances and gases are completely soluble in supercritical water but inorganic salts exhibit greatly reduced solubilities. This is just the opposite effects of solubilities at normal conditions. Thus oxidation may be carried out in a homogenous system and salts separated. Figure 2 is a schematic of the SCWO process. The supercritical water reactor is described in Figure 3.

The SCWO process can be described in five steps:

(1) The solid waste is slurried with make-up water to provide a mixture of about 5 to 10 weight percent organics. The slurry is pressurized and heated to supercritical conditions. Heating is attained by mixing the feed with superheated SCW, which is generated in a subsequent step. During the period outside the oxidizer, organic materials in the feed are converted to combustible gases, low to intermediate molecular weight compounds (alcohols, aldehydes, furans) and inorganic salts.

(2) Oxygen or air is pressurized and mixed with the feed. In the adiabatic reactor organics are oxidized at residence times of less than one minute. The heat released by combustion is sufficient to raise the fluid phase to temperatures where all organics are rapidly oxidized, temperatures are about 550 degrees C.

(3) Effluent from the reactor/oxidizer is fed to a salt separator where inorganics originally present in the feed precipitate.

(4) A portion of the superheated SCW is recycled to an eductor upstream of the oxidizer. This recycle stream provides sufficient thermal energy to heat the feed to the oxidizer to supercritical conditions.

(5) The remainder of the superheated SCW (with some CO_2 and N_2) is available for power generation or use as high-pressure steam.

The available data from SCWO is presented in Tables 9 to 15.

For urea destruction, Figure 4 shows the pertinent reactions, including heats of reaction and temperatures. At certain temperatures all the nitrogen in urea ($(NH_2)_2CO$) is not produced as N_2, but can be in the form of ammonia NH_3 or nitrous oxide N_2O. Figure 5 depicts the ammonia, nitrogen, and nitrous oxide weight ratios as a function of SCWO reactor temperature.

The advantages and disadvantages of the SCWO process are as follows. The process can treat acqueous waste streams with a wide range of flows and composition. The streams may contain both inorganic and organic compounds. The reaction exotherm is sufficient to make the oxidation self-sustaining and to provide preheat for feed to about critical temperature. No catalysts are required for this oxidation process. Inorganic salts can be readily removed by precipitation. Finally, the necessary residence time in the reactor/oxidizer is from one-half to one minute, only. The disadvantages of the SCWO process are that it requires extremely high temperature and pressures. Large

TABLE 9

SCW - U.S. PATENT 4,113,446 (1978)

RESULTS AT CRITICAL CONDITIONS (647K AND 218 ATM)

GLUCOSE IN WATER*

RUN	CARBON CLOSURE	% C AS VOLATILE GAS	H_2	CH_4	CO_2	CO	C_{2+}
9(c)	97	10	30	1.5	42	27	–
10	86	8	25.8	1.3	34.4	38.5	–
11(c)	86	20	45.1	3.2	38.5	12.5	0.7
12(c)	94.1	23.3	45.13	2.9	40.6	12.6	0.75

C DENOTES CATALYST RUN.

RUNS 9 AND 10 FOR ONE HOUR.

RUNS 11 AND 12 FOR 30 MINUTES.

* TABLE III

TABLE 10

SCW - GLUCOSE AND WOOD

Reproducibility of Results; Glucose Feed and 60-Min. Residence Time

Run No.	Carbon in Feed (g)	Ave. Temp. (C)	Gas Composition H_2	CO	CH_4	CO_2	C_2^+	Carbon Gasified (%)
G-1	2	377	16.3	67.1	1.2	14.8	0.6	16.9
G-2	2	377	10.2	70.8	1.5	17.5	-	16.6
G-3	2	377	14.4	63.0	1.9	17.8	0.9	21.3
G-4	2	377	11.5	70.8	1.5	15.5	0.7	22.9
Ave.	2	377	13.1	68.4	1.5	16.4	0.3	19.5
G-5	2	371	19.9	53.5	2.3	23.3	1.1	25.9
G-6	2	371	8.5	54.6	0.8	34.8	1.2	25.0
Ave.	2	371	14.2	54.1	1.6	29.1	1.1	25.5
G-8	4	371	12.3	43.9	0.9	41.7	1.7	10.7
G-9	4	371	25.8	38.5	1.3	34.4	-	8.2
Ave.	4	371	19.1	41.2	1.1	38.1	0.9	9.5

MODELL, M. (1977)

TABLE 11

SCW - GLUCOSE AND WOOD

Product Distribution in the Critical Region

Feed (Run No.)	Reaction Time (min)	Carbon in Feed (g)	Ave. Temp. (C)	Gas Composition H_2	CO	CH_4	CO_2	C_2^+	% Carbon as: Gas	Extracted Liquid	Recovered Water (cm^3)
Glucose											
G-1-4	60	2	377	13.1	68.4	1.5	16.4	0.3	19.5	1.2	266
G-5,6	60	2	371	14.2	54.1	1.6	29.1	1.1	25.5	2.5	280
G-7	150	2	371	12.3	42.8	1.2	41.4	2.3	28.9	-	271
G-8,9	60	4	371	19.1	41.2	1.1	38.1	0.9	9.5	-	265
Levulinic acid											
L-1	60	4.82	377	4.8	87.9	0.6	6.6	-	10.8	-	251
Maple sawdust											
M-1	5	.59	377	8.3	79.2	2.3	10.1	-	16.8	1.1	241
M-2	15	.96	377	17.9	69.4	3.7	9.1	-	18.1	1.5	258
M-3	30	.10	377	15.9	65.5	5.1	13.0	0.5	88.3	-	249
M-4	30	.67	377	5.0	82.4	2.9	9.6	0.1	33.1	0.6	252
M-5	60	.29	377	16.8	57.2	5.6	19.6	0.9	39.5	6.2	258

MODELL, M. (1977)

TABLE 12

SCW - U.S. PATENT 4.113 446 (1978)

RESULTS AT CRITICAL CONDITIONS (647 K AND 218 ATM)*

RUN #	CARBON CLOSURE %	% CARBON VOLATILE	GAS COMPOSITION (MOLE % DRY) H_2	CH_4	CO_2	CO	C_2+
CELLULOSE 13	95.7	18.31	14.5	1.5	19.7	64.2	0.13
POLYETHYLENE 15	90.3	2.30	26.6	2.54	65.87	≤5.0	—
POLYETHYLENE 16	93.7	4.01	35.75	3.73	54.43	≤5.0	1.2
UREA 17	88.8	11.11	—	—	100	—	—

ALL RUNS WITH CATALYST.

* TABLE IV

TABLE 13

SUPERCRITICAL WATER OXIDATION - UREA DESTRUCTION: (O_2, 23 SEC, 25 cc/MIN)

$$(NH_2)_2CO + 3/2\ O_2 \longrightarrow N_2 + CO_2 + 2H_2$$

REACTOR INFLUENT: 10 % UREA IN WATER

	RUN No.				
	81A	81B	81C	82	225
Temperature (°C)	561	596	621	632	670
Nitrogen In (mg/l) (water + feed)	51422	50501	50825	50935	56679
Effluent Liquid Composition (mg/l)					
Nitrate N	100	85	29	57	.04
Nitrite N	-	-	-	-	0.005
Ammonia N	17537	15798	3447	2719	1.65
Effluent pH	9.21	8.95	7.92	7.52	7.24
Effluent Gas Composition (mole %)					
O_2	95.59	90.18	37.61	20.46	8.09 (3.63)*
CO_2	0.45	1.05	18.38	38.48	41.28 (18.53)
N_2	3.60	7.92	41.72	39.04	50.63 (22.73)
H_2O	0.37	.85	2.33	0.51	0.00 (0.00)
Nitrogen in Liquid Effluent (%)	26.7	26.7	5.9	4.5	0.0
Nitrogen in Gas Effluent (%)	5.2	11.6	59.4	69.2	97.7
Nitrogen Recovery (%)	31.8	38.3	65.3	73.7	97.7

* Values in parentheses represent the actual measured quantities. For Run 225, with 40% helium present, values are normalized for comparison purposes.

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TABLE 14

SCW - ORGANIC HALIDE DESTRUCTION

SUMMARY OF RESULTS: OXIDATION OF ORGANIC CHLORIDES

Run No.	11	12	13	14	15
Residence Time (min)	1.1	1.1	1.1	1.1	1.3
Carbon Analysis					
Organic Carbon In (ppm)	26,700.	25,700.	24,500.	38,500.	33,400.
Organic Carbon Out (ppm)	2.0	1.0	6.4	3.5	9.4
Destruction Efficiency (%)	99.993	99.996	99.975	99.991	99.97
Combustion Efficiency (%)	100.	100.	100.	100.	100.
Gas Composition					
O_2	25.58	32.84	37.10	10.55	19.00
CO_2	59.02	51.03	46.86	70.89	70.20
CH_4	-	-	-	-	-
H_2	-	-	-	-	-
CO	-	-	-	-	-
Chloride Analysis					
Organic Chloride In (ppm)	876.	1266.	748.	775.	481.
Organic Chloride Out (ppm)	.023	.037	<.028	.032	.036
Organic Chloride Conversion (%)	99.997	99.997	99.996	99.996	99.993
GC/MS Effluent Analysis					
Compound B (ppb Cl)	-	-	-	-	-
C	-	-	-	-	-
E	-	9	-	14	-
F	18	12	18.	-	-
H	-	-	<4.	-	-
K	5	16	<5.	6	-
M	-	-	0.2	-	-
N	-	-	0.3	-	36
O	-	-	-	12	-

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TABLE 15

SCW - ORGANIC HALIDE DESTRUCTION

TABLE 2. COMPOSITION OF FEED MIXTURES FOR RUNS 11 - 15

		wt %	wt % Cl
Run 11			
DDT	$C_{14}H_9Cl_5$	4.32	2.133
MEK	C_4H_8O	95.68	-
		100.0	2.133
Run 12			
1,1,1-trichloroethane	$C_2H_3Cl_3$	1.01	0.806
1,2-ethylene dichloride	$C_2H_2Cl_2$	1.01	0.[illegible]29
1,1,2,2-tetrachlorethylene	C_2Cl_4	1.01	0.866
o-chlorotoluene	C_7H_7Cl	1.01	0.282
1,2,4-trichlorobenzene	$C_6H_3Cl_3$	1.01	0.591
biphenyl	$C_{12}H_{10}$	1.01	-
o-xylene	C_8H_{10}	5.44	-
MEK	C_4H_8O	88.48	-
		100.0	3.284
Run 13			
hexachlorocyclohexane	$C_6H_6Cl_6$	0.69	0.497
DDT	$C_{14}H_9Cl_5$	1.00	0.493
4,4'-dichlorobiphenyl	$C_{12}H_8Cl$	1.57	0.495
hexachlorocyclopentadiene	C_5Cl_6	0.65	0.505
MEK	C_4H_8O	96.09	-
		100.0	1.99
Run 14			
PCB 1242	$C_{12}H_xCl_{4-6}$	0.34	0.14
PCB 1254	$C_{12}H_xCl_{5-8}$	2.41	1.30
transformer oil	C_{10}-C_{14}	29.26	-
MEK	C_4H_8O	67.99	-
		100.0	1.44
Run 15			
4,4'-dichlorobiphenyl	$C_{12}H_8Cl$	3.02	.96
MEK	C_4H_8O	96.98	-
		100.0	0.96

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temperature gradients apparently exist in the system which may make it difficult to duplicate measurements and to scale available data. The oxygen or air flow requires precise control along with the waste feed stream. The particle size in the waste stream, solids in water, must be reduced to less than a millimeter in diameter. The data available for the SCWO indicates that the gaseous effluents are not simply carbon dioxide and nitrogen but may contain significant amounts of carbon monoxide, methane, and hydrogen. The presence of these gases would require extensive post-treatment for Space Station application.

ZIMPRO PROCESS

The Zimpro process was invented about 50 years ago, in the mid-1930's. This process is also a wet air (oxygen) oxidation process but at temperatures and pressures well below water's critical conditions. Figure 6 is a schematic of a wet air oxidation (WAO) system. In WAO molecular oxygen reacts with suspended solid matter or dissolved organics almost complete (90 to 95%) reduction of the wastes to carbon dioxide and water. With a residence time of 90 minutes and temperatures/pressures below critical conditions the maximum amount of carbon monoxide is estimated to be 1000 ppm, average carbon monoxide concentrations are 200 ppm. The organic materials, if not converted to carbon dioxide, go to the water phase as alcohols, aldehydes, and ketones. The degree of oxidation can be controlled by WAO temperature, pressure, and residence time. For some applications catalysts have been used. The major advantage of WAO is that

contaminants tend to stay in the aqueous phase; effluent gas consists mainly of carbon dioxide and spent air (or excess oxygen).

As evident from Figure 6 the WAO system is similar to SCWO, Figure 2, except for the salt precipitation. In this report details of the WAO operating procedure are not described. However, the WAO operates at temperatures of 200 to 300 degrees C which are much less than SCWO. It is important to note that the WAO is commercially available with decades of operations in more than 200 units, world-wide. These units have been applied mostly to sewerage sludge treatment and manufacturing process wastewaters.

The wet air oxidation system can be used either on a batch or continuous basis.

CHEMICAL OXIDATION

Chemical agents such as potassium permangate, potassium dichromate, and many other alkali metal salts can oxidize solid wastes. The advantage of a chemical oxidation process is that it would operate at about 1 atm pressure, or be a low pressure system in contrast to the SCWO and WAO processes. A chemical oxidation system would need heating to temperatures from a minimum of 100 degrees C to several hundred degrees Celsius. About one kilogram (kg) of oxygen is needed to oxidize an equal mass of solid wastes. If a chemical oxidizer was provided than the mass of oxidizer

would be no more than twice that of pure (liquid) oxygen; however, the volume of chemical oxidizer would be about the same since the salts have a density more than twice that of liquid oxygen. The salts might also provide nitrogen needed for atmospheric control. With chemical oxidation system reactor materials of construction would have to be carefully considered. More expensive materials such as titanium and Hastelloy-C would probably be required. But, Hastelloy-C is often used in the WAO process.

Chemical oxidations could operate in a batch or continuous mode. Due to the nature of the solid wastes on a Space Station a batch type treatment process is suggested. This would allow the collection of materials for say about one week, then their oxidation.

OTHER PROCESSES

A few other processes were considered, namely the IT Enviroscience homogenous catalyst system, Figure 7 and the plasma torch under development at the Royal Military College, Ontario, see Figure 8. With regard to dry combustion, a study of General American Transportation (1968) of fecal matter incineration indicates that it is feasible but that such a system requires precise control of oxygen flow rate, and continuous monitoring of

temperature and oxygen concentration. This experimental study determined that dry feces will ignite at about 200 degrees C, and will burn very rapidly - under certain conditions will detonate. Thus, the collection and storage of dried fecal matter on a Space Station should be considered a potential fire hazard.

The burning of polyethylene (wastes) is difficult and would probably not be practical on a Space Station.

Biodegradation processes would probably require too much astronaut attention and too much space in the Station.

SPACE STATION TREATMENT PROCESS

A proposed solid waste management treatment system for a Space Station is presented in Figure 9. This schematic diagram indicates that the transfer of solid wastes from the collection point to the treatment system should be minimized. Furthermore, the maceration shredding, grinding of plastic and cellulosic wastes, if attempted, will pose severe maintenance problems. The specific type of treatment process needs to be developed. Prior to any chemical reactions the system would dry and compact the solid wastes. The treatment reactor is envisioned to be about 5 gallon capacity, with no penetrations between the reactor cavity and the outside. This could be done by means of a magnetically controlled stirrer, with a chain drive. Equipment other than the

tre ..it reactor has been used in e.. ting spacecraft or developed. The proposed system wou.. exhibit zero-leakage except for spent filters and in-exchange resins. The amount of solid ash from the treatment process should be a few percent of the total feed mass.

Figures 10 to 13 summarize the principle reactions for oxidation of wastes, considered as a mixture of carbon, hydrogen and oxygen, and subsequent reduction of carbon dioxide to oxygen and either carbon or methane.

CONCLUSIONS

As a result of this study the following general conclusion is made; a solid waste(s) treatment process for a Space Station needs further study to achieve a reliable operational system. The solid waste rates determined in this study, especially those due to food wastes, paper and plastics, need to be better acertained from at least Shuttle operational data. Processes for the conversion of solid wastes to carbon dioxide and other inert substances need additional experimental measurements.

There are a few feasible treatment processes, chemical or wet air oxidation; supercritical water oxidation does not appear suitable for a Space Station. In addition to the treatment system design needs, the problem of mechanical transfer of wastes from collection point(s) to the treatment vessel is critical. This

aspect along with total systems integration needs to be considered.

Finally, when design criteria for a Space Station are better established and better data are available on treatment performance, a trade study should be conducted to evaluate alternatives.

NAME LIST OF PERSONS CONTACTED REGARDING TREATMENT OF SOLID WASTES OF A SPACE STATION

NASA Employees	non-NASA Personnel
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Martin, R.	Engmann, R. (Zimpro)
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Samonski, F.	Lamparter, R. (Michigan Tech)
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	O'Connor, T. (Univ. Missouri-Columbia)
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	Weitzmann, A. (Lockheed)

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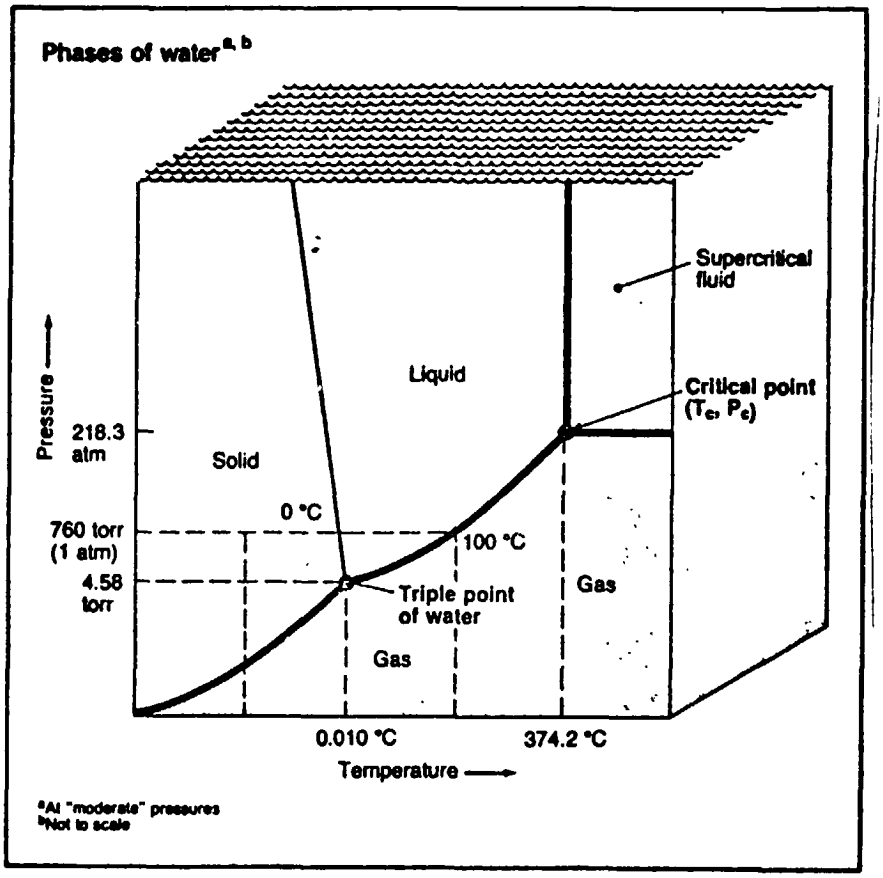


Figure 1.

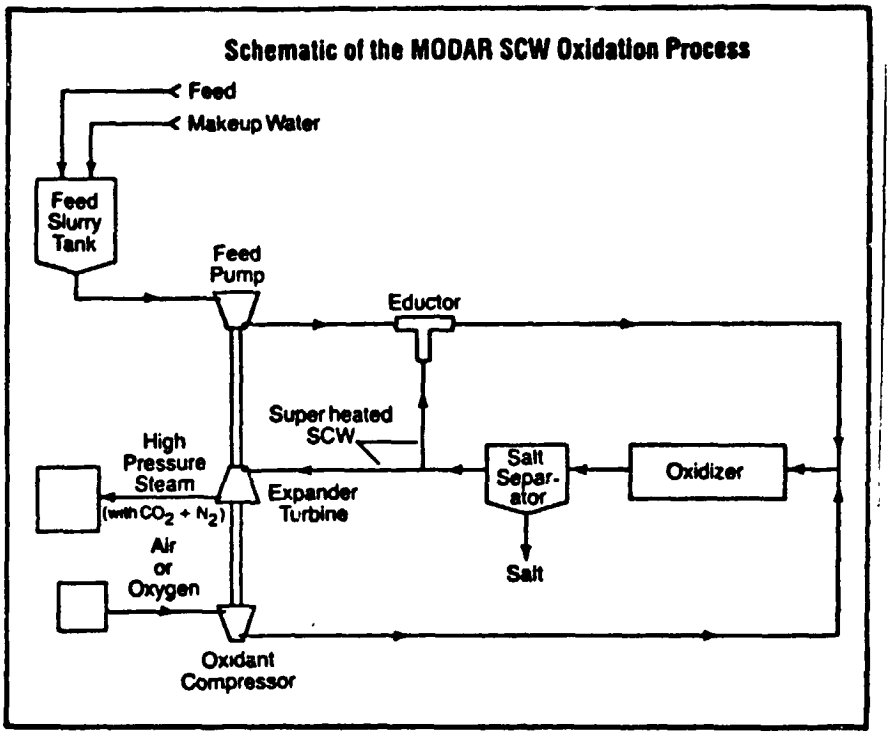
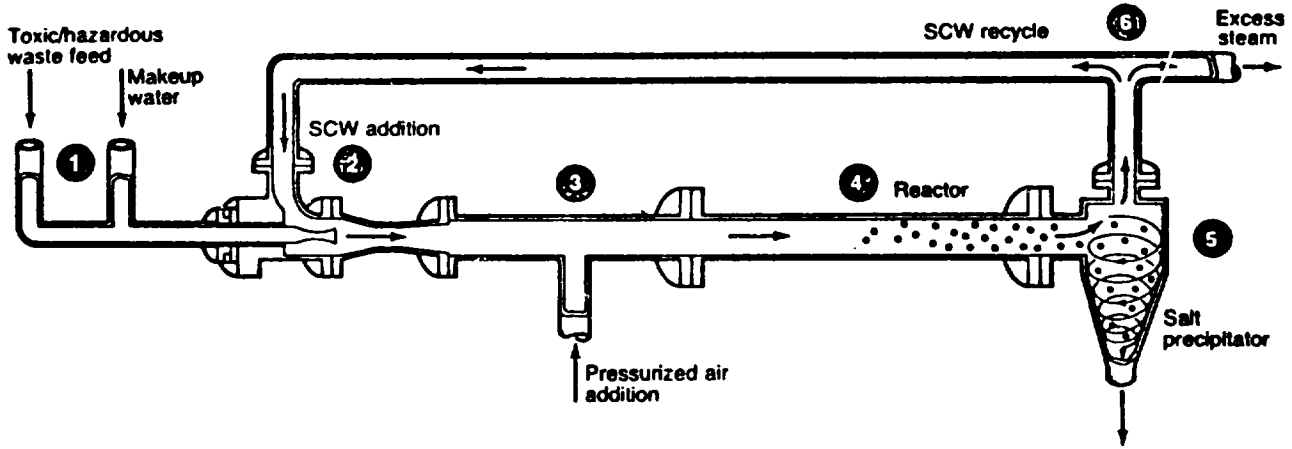

Schematic of the MODAR SCW Oxidation Process
Feed
Makeup Water
Feed Slurry Tank
Feed Pump
Eductor
Super heated SCW
High Pressure Steam
(with CO_2 + N_2)
Expander Turbine
Salt Separ-ator
Oxidizer
Salt
Air or Oxygen
Oxidant Compressor

Figure 2.

Supercritical water reactor



1. Toxic/hazardous wastes, in solution, are fed into system automatically and under pressure; then they are mixed with makeup water.
2. SCW heats the solution to initial reaction temperature and adjusts organic content to a concentration of 2–5%, after which pressurized air is added.

3.–4. In the reactor, organics oxidize rapidly in a controlled reaction; heat evolved raises temperature to point at which salts precipitate out.

5. Reactor effluent is fed to salt separator (note cyclone arrangement) that collects the salts.

6. A portion of the SCW is recycled to the reactor; any excess can be converted to steam for other plant operations or energy needs.

Source: Michael Modell, Modar Inc.

Figure 3.

UREA REACTIONS IN SUPERCRITICAL REGION

Overall Reaction at High Temperature

$(NH_2)_2CO + 3/2O_2 \longrightarrow N_2 + CO_2 + 2H_2O$ $\quad \Delta H_{R,298} = -632.2$ kJ
Urea

Step 1: Hydrolysis of urea to ammonia and carbon dioxide — INITIAL

$(NH_2)_2CO + H_2O \longrightarrow 2NH_3 + CO_2$ $\quad \Delta H_{R,298} = 45.6$ kJ
Urea

Step 2A: Oxidation of ammonia to nitrogen

$2NH_3 + 3/2O_2 \longrightarrow N_2 + 3H_2O$ $\quad \Delta H_{R,298} = -765.8$ kJ; $\Delta H_{R,873} = -631.5$ kJ — $\approx 561\,^{\circ}C$

Step 2B: Oxidation of ammonia to nitrous oxide

$2NH_3 + 2O_2 \longrightarrow N_2O + 3H_2O$ $\quad \Delta H_{R,298} = -684.2$ kJ; $\Delta H_{R,873} = -549.7$ kJ — $\approx 621\,^{\circ}C$

Step 3: Decomposition of nitrous oxide to nitrogen and oxygen — $\approx 670\,^{\circ}C$

$2N_2O \longrightarrow 2N_2 + O_2$ $\quad \Delta H_{R,298} = -163.3$ kJ; $\Delta H_{R,873} = -162.5$ kJ

Figure 4.

SCW - UREA DESTRUCTION

DISTRIBUTION OF NITROGEN SPECIES IN THE LIQUID AND GASEOUS EFFLUENTS (TIMBERLAKE, S.H., ET AL., 1982)

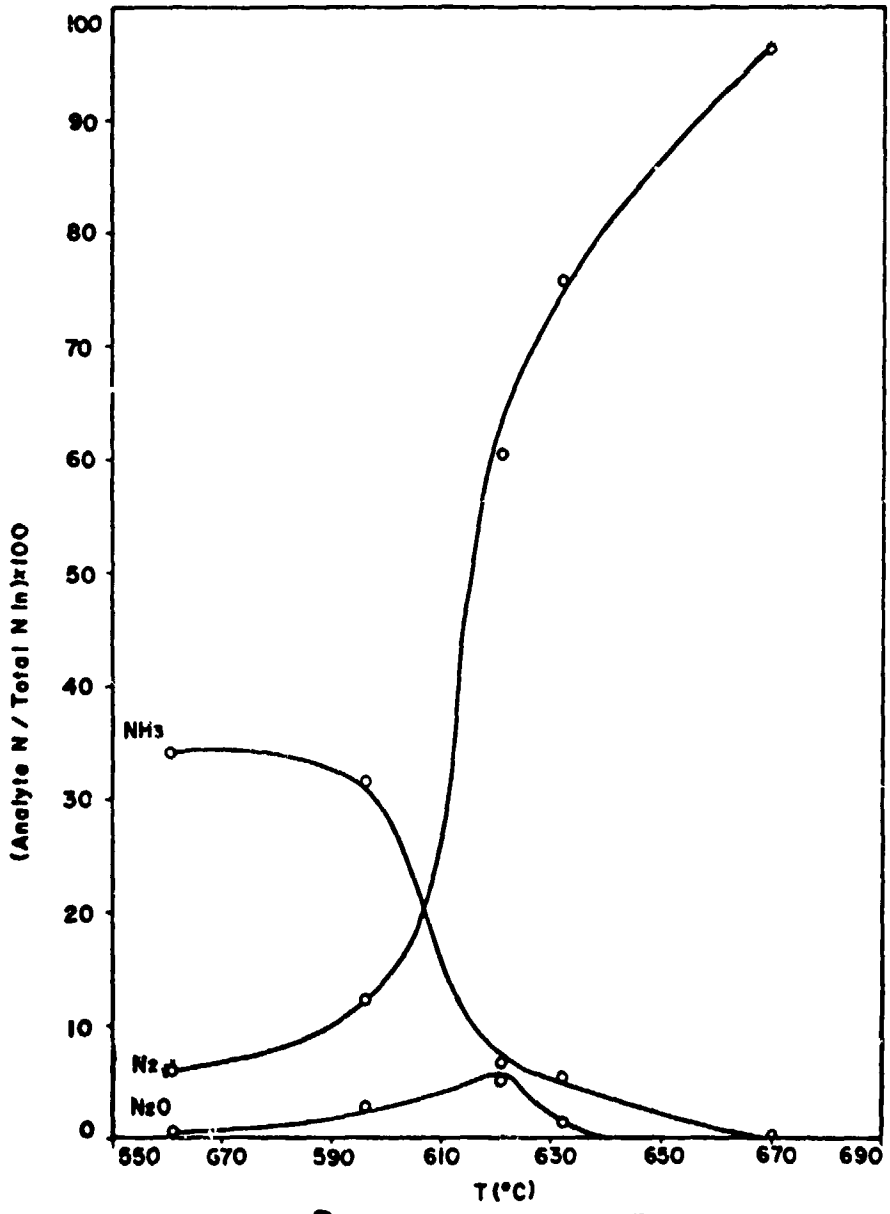


Figure 5.

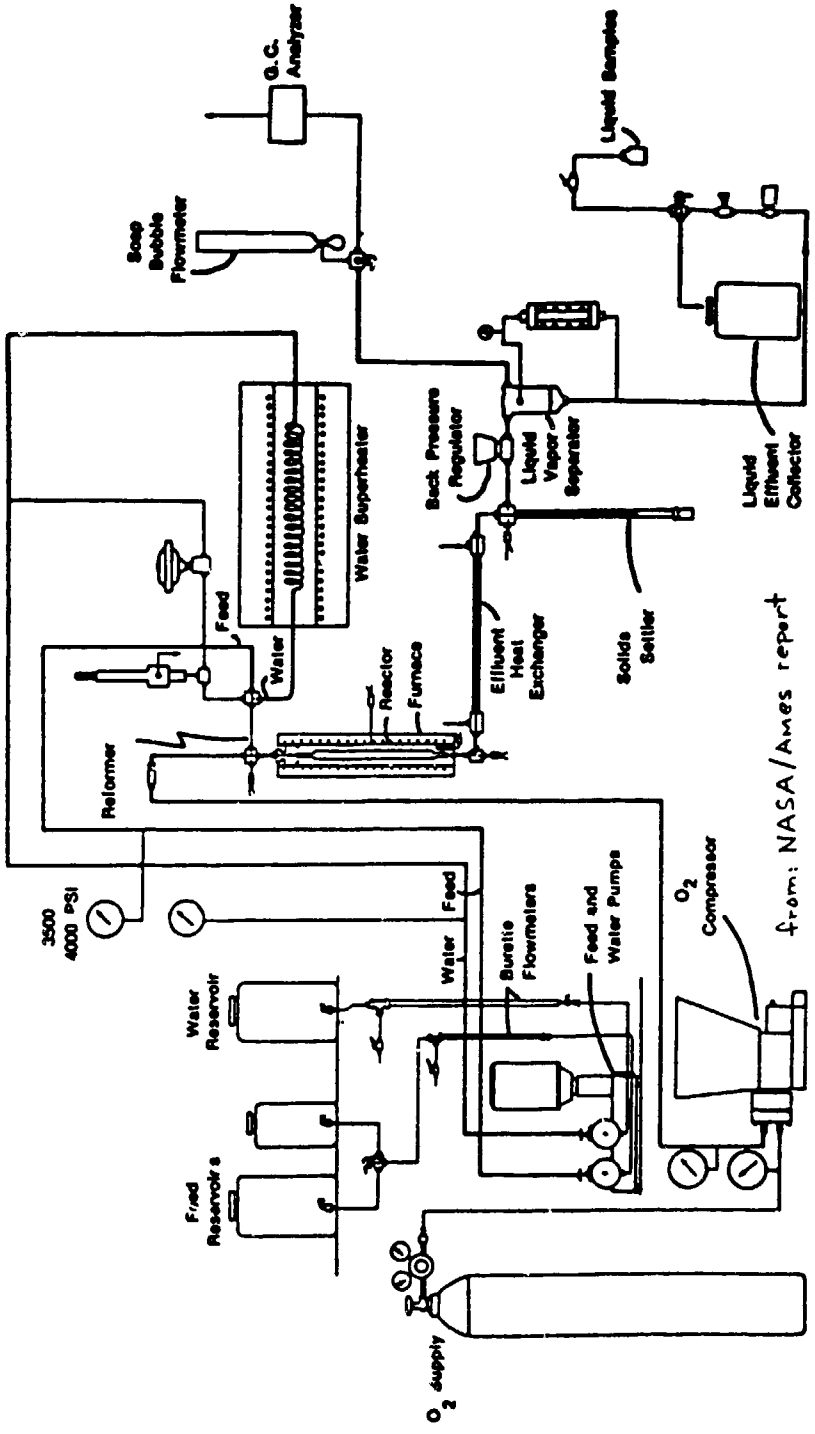


Figure 6.

I T ENVIROSCIENCE PROCESS CONCEPT

FOR

HOMOGENEOUS CATALYST

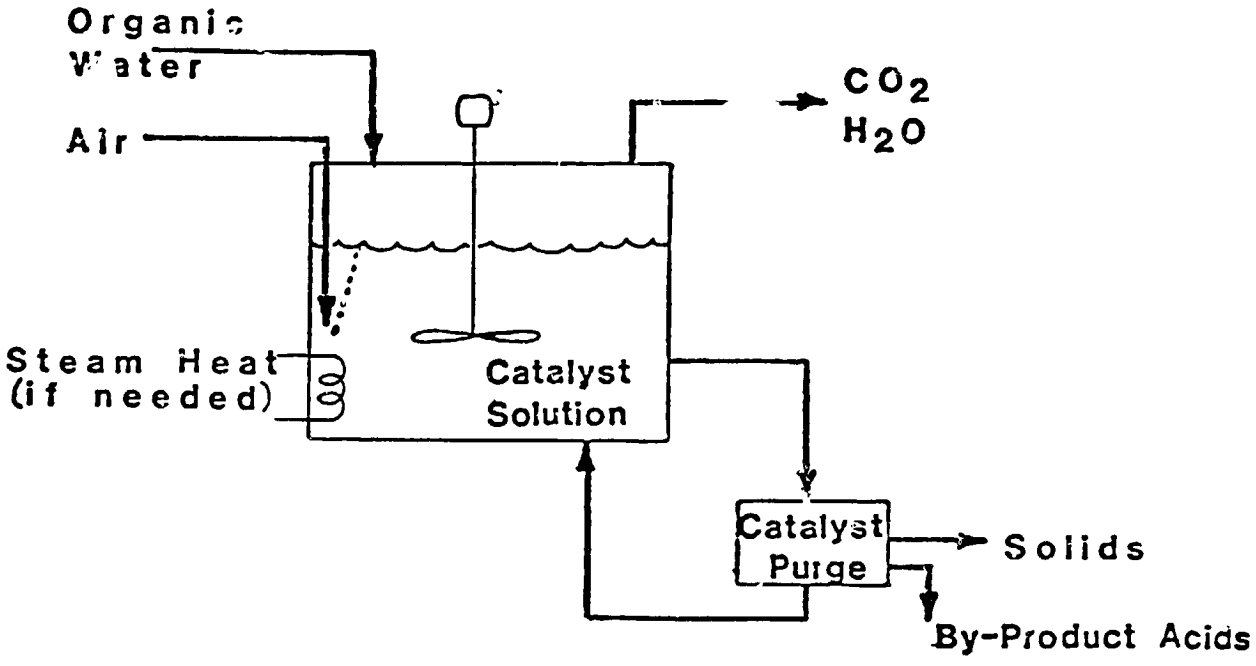


Figure 7.

REACTION VESSEL SCHEMATIC

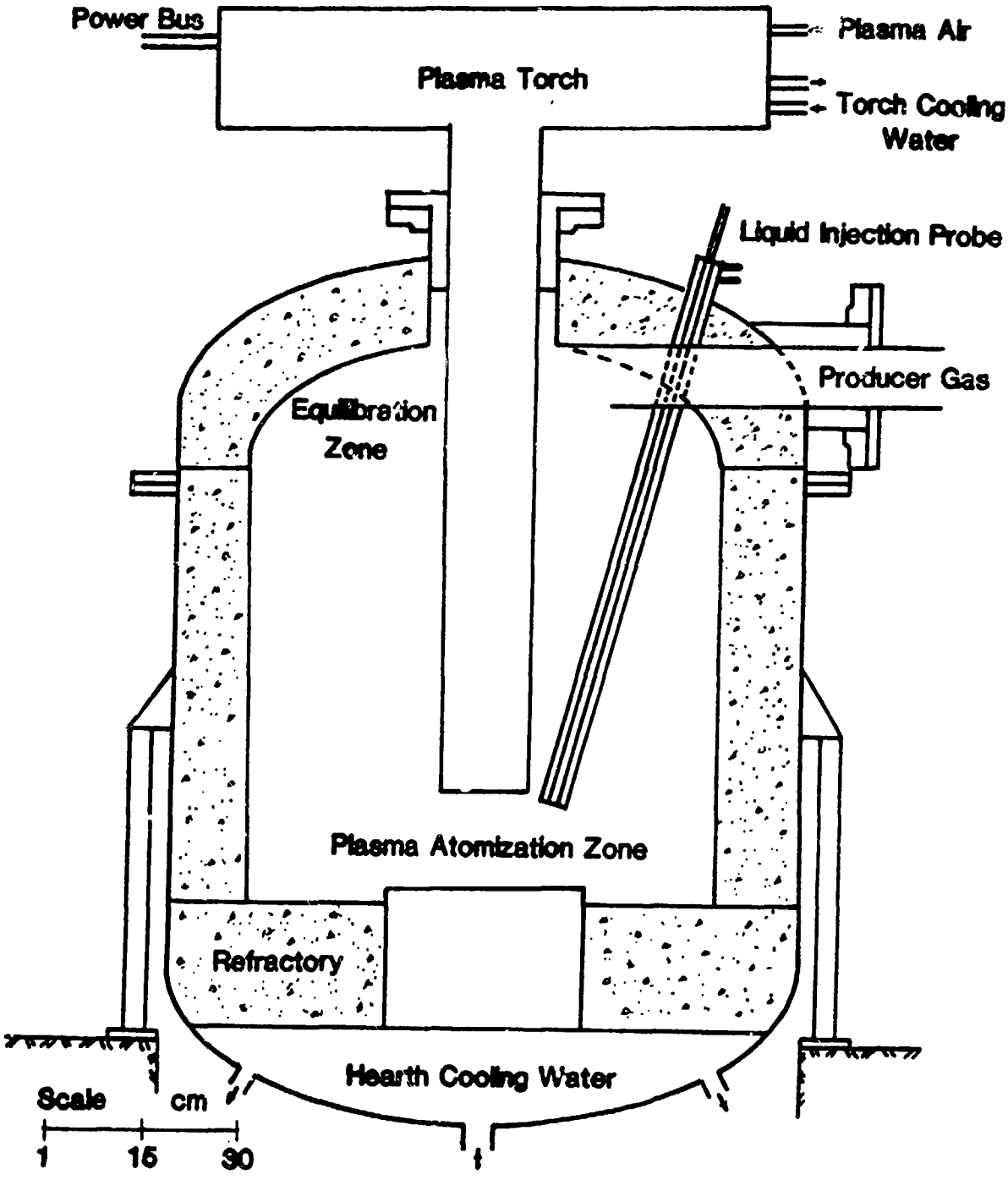


Figure 8.

SOLID WASTES TREATMENT SYSTEM FOR SPACE STATION ZERO-GRAVITY & ZERO-LEAKAGE

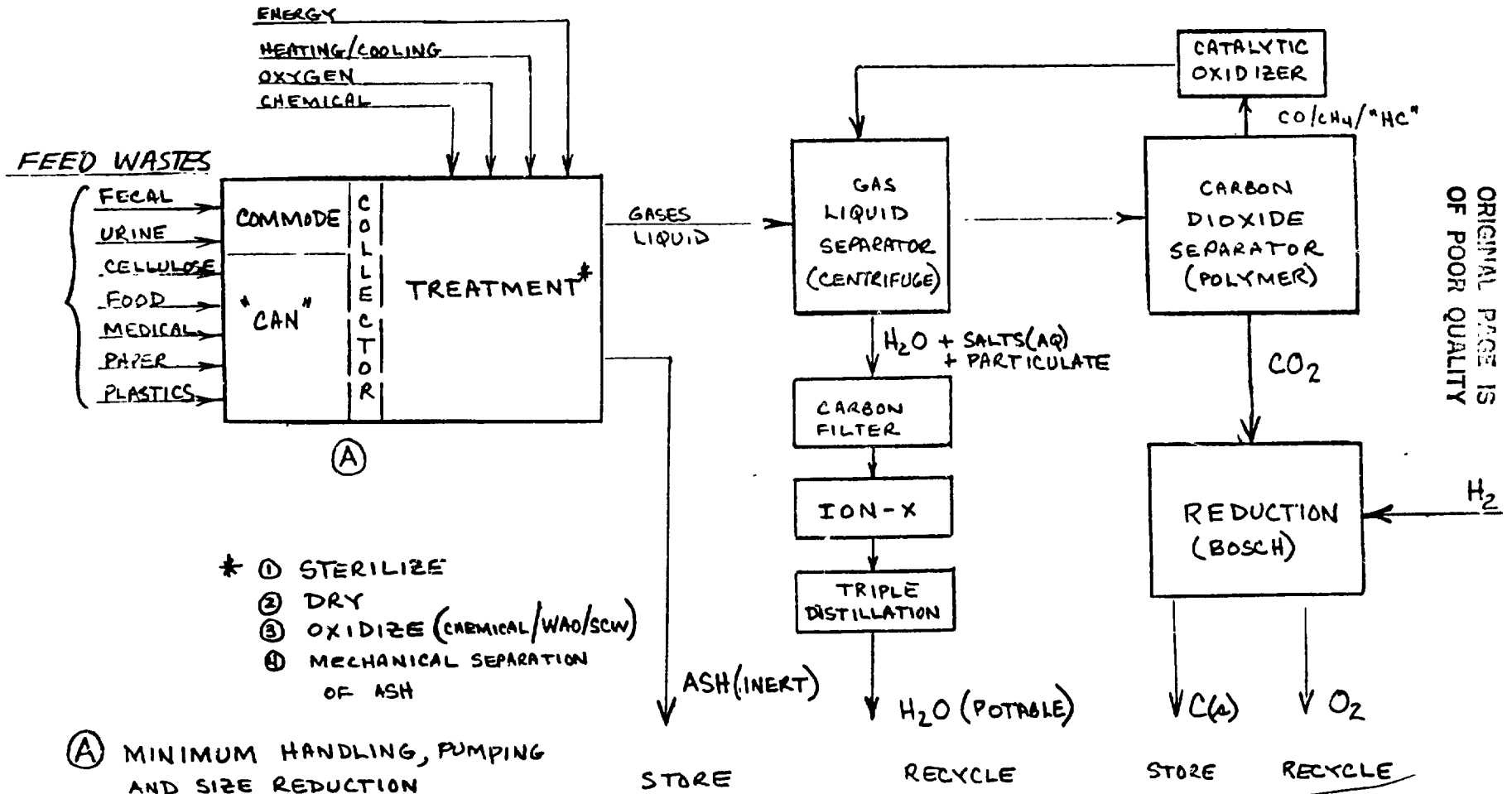


Figure 9.

OXIDATION REACTION(S)

$$4C_aH_bO_c + (4a + b - 2c)O_2 \rightarrow 4aCO_2 + 2bH_2O$$

$$C_aH_bO_c + d\,Cr_2O_7^{=} + 8d\,H^+ \xrightarrow{\Delta} a\,CO_2 + \frac{b+8d}{2}H_2O + 2d\,Cr^{3+}$$

where $d = \frac{2}{3}a + \frac{b}{6} - \frac{c}{3}$

Figure 10.

Carbon dioxide reduction by hydrogen

general

$$x\,CO_2 + y\,H_2 \rightleftharpoons a\,H_2O + b\,C + c\,CO + d\,CH_4$$

$$y = 2x$$

$$a, b, c, d = f(\text{time, temperature, pressure, iniatial concentration of reactants})$$

conversion efficiency = 5 to 8 % (carbon & water)

recycle ratio = 20 to 12

Figure 11.

CARBON DIOXIDE REDUCTION

$$CO_2 + 2H_2 \rightleftharpoons C + 2H_2O$$

iron catalyst

530°C to 730°C

Bosch process

Figure 12

CARBON DIOXIDE REDUCTION

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$$

$$+ 20 \text{ kJoules/gram } H_2$$

Sabatier reactor

Figure 13.