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UNIVERSITY ROLE IN ASTRONAUT LIFE SUPPORT SYSTEMS: WATER RECOVERY SYSTEMS

by John R. Tole

Prepared by
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Mass. 02139
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16. Abstract

One of the vital spacecraft life support systems is that used to supply water. Short duration missions allow storage of sufficient water, but for long duration missions, the weight of such a supply becomes unacceptable.

This paper reviews techniques for recovering potable drinking and wash water from spacecraft waste water. Emphasis is placed on problem areas which exist in such recovery and which may be suitable topics for university type research. Areas covered include nature of waste waters which might be processed, potability requirements and monitoring techniques, existing and possible future recovery techniques, means of selecting a suitable technique from a number of different types, and problems of a fringe nature such as means of monitoring body mass to keep track of human water exchange. An attempt is made to stimulate new ideas based on present knowledge.

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I. INTRODUCTION

One of the most vital spacecraft life support systems is that used to supply water. That water is essential to the maintenance of life is well known. For missions of relatively short duration, it is possible to simply store sufficient water on board the spacecraft prior to launch or to recover water from a fuel cell [42]. If, however, a spacecraft were to carry enough water to maintain life on a voyage of one year or more, the weight of the supply would far exceed that of the spacecraft and all its equipment[14]. One means of alleviating this problem is to use regenerative systems for water similar to the solution proposed for atmospheres. On the surface, this would appear to be a relatively simple matter of determining the correct process or processes. However, the peculiarities of the space environment and the complexities of such processes as urine distillation rapidly raise the magnitude of the problem and challenge the existing state of the art in this area.

A number of the problems associated with water recovery systems for spacecraft are in need of answers which research on the university level may be able to provide. Keeping in mind that weight reduction is the motivating factor for all of this work, let us examine the problem areas.

1.1 Recovery Requirements

A major factor to be considered in the operation of a water recovery system is the daily rate of human water exchange. Some work has been done in this area, but there are still some important questions without answers[2,18,36,24,49]. The major contributions to human water exchange are given in table I. As can be seen from the figures, humidity condensate constitutes a large portion of the waste water. The amount of condensate lost is a function of a number of factors such as barometric pressure, breathing rate, psychogenic condition of the astronauts, temperature, and metabolic level. A prolonged change in any one of these factors may seriously affect the water balance in the spacecraft if the water recovery and supply system cannot cope with the change rapidly enough.

CONSUMED AND PRODUCED		WASTE	
Food	0.23#	Urine	3.30#
Drinking and Food Preparation	7.65#	Fecal	0.25#
Metabolic	0.72#	Discarded in Food	0.16#
		Humidity Condensate	4.89#
	8.60#		8.60#
Wash Water (estimated quantity)	3.30#	Wash Water	3.30#
	11.90#		11.90#

Table I Human Water Exchange on Spacecraft for one Man-Day (From Ref. 2)

A certain minimum water level is required to maintain proper kidney function. In a situation such as this, it has been suggested that a lower protein diet will cause a reduction in obligatory urine volume [20,24]. It has also been hypothesized that the water content of the body will drop some 2-5% in the weightless environment. For these reasons and to maintain a check on the day-to-day normal water balance, it is felt that a rapid and accurate means of measuring body mass on board the spacecraft would be useful. This will be dealt with under the section on fringe considerations.

It is currently felt that the reclamation system should receive inputs of urine, humidity condensate and wash water though not necessarily mixed. The other potential source is fecal water, but this represents only a very small portion of the water balance for the spacecraft, and is difficult to process. There is, therefore, little to be gained in the near future in considering fecal water recovery, unless recovery efficiencies for the other waste water inputs cannot be maintained at high enough levels [1,2].

High efficiency levels are required not only because a limited amount of water is in the cycle, but also since some of the water may be needed for electrolysis [7]. The latter process may be necessary in order to replace oxygen lost through unavoidable seal leakage, if oxygen stores are not carried. While the efficiency question hinges on factors such as this, the general agreement is that limits of more than 99% for urine recovery are the minimum acceptable for long term operations. In some instances, efficiencies approaching 99.5% for all three waste water sources have been recommended[1]. Whether these limits can be acheived on a actual flight is not known.

1.2 Characteristics of Waste Water

Of the three sources of waste water, urine is the most complicated in chemical makeup[22] and, hence, requires the most processing. Table II shows a typical analysis of urine in addition to its basic H_2O content. The amount shown in table II will vary considerably between subjects and even for an individual depending on his diet.

ORGANICS	CONCENTRATION (P.P.M.)
Urea	25,000
Phenols	1,700
Amino Acids	1,600
Lactic Acids	1,000
Creatinine	800
Ammonia	500
Citric Acid	500
Uric Acic	500
Hippuric Acid	400
Hydroxylamine	280
Other Organic Acids	200
Vitamins	60
Miscellaneous	100
	32,660
INORGANICS	
Chloride (NaCl)	9,500
Sodium	3.000
Potassium	1,500
Phosphorus	900
Sulfur	800
Nitrates	400
Calcium	150
Magnesium	100
	16,350
Gases	700
Particulates	1,300
	51,000

TABLE II. Typical Urine Analysis. (From Ref. 1)

When urine leaves the body, it is essentially free from microbiological contaminants but represents an excellent medium in which they might grow [12]. Therefore, it must be assumed that microorganisms will also be present when the raw urine reaches the processing unit.

Waste water may be nearly as complicated as urine depending on the type of detergent used and the soilants to be removed. Detergents generate foam to a greater or lesser extent. In order to combat this problem, it has been suggested that a detergent with low cloud point be used and the temperature of the processing unit be maintained as high above that as practical [1]. The detergent should also be compatible with other constituents to avoid precipitation.

A typical wash water analysis is shown in table III. It should be noted that, with the exception of the detergent, the analysis is similar to that for a dilute urine sample. Microbiological contaminants will almost certainly enter the wash water from the atmosphere and from contact with the astronauts.

DISSOLVED SOLIDS	CONCENTRATION (P.P.M.)
Chloride (NaCl)	340
Urea	100
Sebum	180
Lactic Acid	75
Other	205
Particulates	1000
Detergent*	1000
	2900 //

Typical pH : 4.8 or Higher

* Type and Amount of detergent may vary considerably

// Numerous micro-organisms may also be present requiring germicide to be added

TABLE III. Typical Washwater Analysis (Modified from Ref. 1)

Humidity condensate, the third source of raw water, should require the least processing. It will be especially susceptible to airborne micro-organisms but should not present any other major difficulties because of its simple chemical makeup.

1.3 System Restrictions

A number of physical restrictions must be placed on the processing unit (s) [31]. Perhaps the most obvious is that it be suitable for operation, in a weightless environment either inherently or by creating a pseudo gravity environment integral with itself. Low power and weight go hand in hand as restrictions [11]. The power required is determined partly by the nature of the process involved and also by the type of power supply to be installed on the overall spacecraft. If a special power supply is required for life support, the total weight of the spacecraft will almost certainly increase. Weight is dependent on the type of process, number of units and on mission length, increasing typically in a logarithmic manner [2].

Common methods of relating power and weight for life support systems are the concepts of total equivalent weight or effective weight [1]. This is expressed as the sum of the weights of the processing unit, supporting equipment, power supply, heat source, and spare components. This method can be used as a rough comparison of physical properties between competitive units, if their reliabilities and useful life are nearly equal.

A limit on process temperature also seems advisable for two reasons. The first is to decrease the possibility of fire and/or excess heat in the cabin and the second is that urea $[CO(NH_2)_2]$ the major component of urine, decomposes at 160° F into ammonia and other toxic compounds which may be dispersed in the atmosphere or dissolved in the condensate.

Even if urea can be fixed by chemical pretreatment of urine or other techniques, the possible safety hazard would still make a low temperature process seem attractive [1,31].

On the other hand, some Russian workers have mineralized liquid wastes and dilute urine-fecal mixtures using thermal and thermocatalytic oxidation at high temperatures with little apparent hazard [36]. This method has been applied to large scale municipal water supplies and it has also been suggested that it may be feasible on a small scale for spacecraft if it receives further attention [51]. Still the safety factor should not be overlooked.

Finally, and most important of the specifications, the system or systems used must be able to produce a sufficient amount of potable water for the duration of the mission. This implies extremely high reliability and a clear definition of potability.

1.4 Potability

Medical personnel at the Manned Spacecraft Center feel that a clear definition of water potability and rapid means of monitoring it are among the most vital problems facing the manned space program [17,27]. Answers to these two problems would also be of inestimable value on earth in dealing with water pollution [72].

Laboratory techniques for determining potability are well defined and have been used in water pollution studies [63]. A sample of suspected water is placed in a culture medium and incubated. At the end of this period, a count is made of the micro-organisms, if any, present in the culture according to prescribed methods. This process, however, can require hours, an unacceptably long delay in primary monitoring of a spacecraft water system. Certain limits are set on the nature and number of organisms and other contaminants. These limits are changed from time to time and there appears to be no general concensus on a clear and complete definition of potability[64,63,41]. This question will probably be debated for some time.

The most common monitoring practices to date for water systems have measured the conductivity of the product water or have assumed that the process being used produces sterile water[1]. The first procedure is valid only for electrolytic contaminants neglecting micro-organisms[6,21,25] and other non-electrolytic constituents of the water. The second practice seems dangerous since the continued sterility of any system cannot be guaranteed under all circumstances.

1.5 Storage

Once the potability of the reclaimed water has been ascertained, it (the water) must be held in a potable state until required by the astronauts. The most reliable means of doing this at present appears to be pasteurization at 160°F[1]. Provisions are then necessary to cool the water to various suitable temperatures before use. Silver ion dosing also works though it is somewhat more complicated than pasteurization[26]. Chlorine has also received attention and was used on Apollo flights[70]. In the event of contamination of the storage container, a rapid means of sterilization such as steam should be available.

The entire water storage and potabilitiy matter brings up an interesting question, that is; is 100% sterility of water really desirable? A number of workers, but not all[44], feel that it may not be, since total sterilization may eliminate some beneficial bacteria and/or compounds in the water[1,21,16]. (The Russians reported adding salts and micro-organisms to their processed water in a recent manned experiment[59].) At the very least, it seems that we do not know enough about the balance of such trace elements in the human and the relationshipes of these elements to the overall ecology[12,20,13,36,47]. The Russians, in the experiment cited found no significant alteration in the balance of micro-organisms, but since the report is somewhat sketchy, it is not clear exactly what they mean by this statement. A more detailed quantitative study of this matter would be of extreme interest and value.

1.6 Recommendations for University Research

1. Better understanding of the human water exchange in spacecraft and its effect on water recovery systems.
2. Determine means of limiting water use on spacecraft during emergency situations.
3. Continue studies of fecal water systems as they may become important in the future.

4. Determine acceptable temperature limits for water recovery processes.
5. Clearly establish a definition for potability.
6. Study microecological balance in more detail.
7. Improve washwater detergents to reduce foaming.

II. AUTOMATIC POTABILITY MONITORING TECHNIQUES

Several rapid on-line techniques for monitoring potability have been and are being developed. These fall into two general groups, one for organic and the other for microbiological contaminants. The plating technique (see 1.4) has also been recommended as a secondary periodic check on other techniques because of its proven ability to detect contaminants [1].

2.1 Organic Carbon Monitors

Total organic carbon, a common measure of organic content of a substance, is determined by monitoring chemical oxygen demand (COD) by any of several methods [69]. One is to oxidize a sample of organic material to CO_2 and remove the water vapor. The CO_2 is then analyzed in a non-dispersive infra-red analyzer. The peak on the recorder indicates the total carbon content of the sample (not the same as total organic carbon). This procedure requires about two minutes and is subject to some artifacts associated with purging of the water vapor.

A variation of the above technique employs oxidation at two temperatures, a low temperature yielding the CO_3 content of the sample and a high temperature indicating the total carbon content of the sample. The difference in readings at the two temperatures is then the total organic carbon present in the sample.

2.2 Microbiological Monitoring

Microbiological organisms also present a serious problem in potability and component operation. One source [1] enumerates the reasons: " 1) pathogenic micro-organisms will transmit disease, 2) certain microbes will produce exotoxins or endotoxins that can kill or debilitate (exotoxins are poisons secreted by bacteria to their surroundings while endotoxins are held within the bacteria until it is disturbed in some way), 3) micro-organisms will produce malodorous and foul tasting by-products, and 4) micro-organisms will secrete enzymes and acids which will deteriorate and/or corrode system components. "

Bioluminescent Assay

The microbiological quality of water can be determined with a bioluminescent assay [68,69]. It has been found that living organisms contain a compound known as adenosinetriphosphate (ATP) which is a necessary reactant in the process by which the firefly produces light. The amount of ATP present in a sample has been shown to be proportional to the number of micro-organisms present in the substance examined. In order to measure this number quantitatively, a light sensitive instrument is calibrated by injecting a known amount of ATP into a reaction mixture of substrate (luciferin), enzyme (luciferase) and magnesium sulfate ($MgSO_4$). Then a sample of water is injected into a similar reaction mixture and its light response compared to that of the standard, the difference in readings being the amount of ATP present in water.

A similar assay technique utilizes a substance necessary for the bacterial bioluminescent reactions, flavin-mononucleotide (FMN) which has also been found in all organisms studied. The assay, like the ATP method is rapid (1 second for FMN, 30 seconds for ATP) and sensitive (to 10 picograms of of FMN) , and yields a light output which is proportional to the number of organisms present.

Both the ATP and FMN techniques pose the problem that the reference enzymes cannot at present be stored for more than six months without deteriorating. If either technique is to be applied on a space mission longer than six months in duration, the storage problem must be overcome.

Ultraviolet Radiation

A slightly different approach to microbiological monitoring is to apply ultraviolet radiation to a suspected sample [65]. At some optimal wave length(s) , any organism(s) in the sample will phosphoresce, producing a decay characteristic which is felt to be an imprint of the particular species present. The instrumentation for this method is complex and there are some questions concerning the artifacts it may produce. It does, however, appear promising not only as a potability monitor, but also as a tool in biological research both in space and on earth.

Other Microbiological Monitors

The amount of infrared light emitted from a culture sample gives some indication of the number of organisms present.

Several groups have developed methods for measuring this but they appear to be slow and not particularly accurate [1].

It has been suggested that the standard culture growth test mentioned earlier be performed periodically during a flight as a check on other monitors. This seems quite acceptable if it does not involve too much time on the part of the astronauts and the method is adapted for use in in 0-g.

Natural enemies of micro-organisms such as antibodies might be incorporated in a monitoring scheme. Such devices have been developed as biological warfare monitors, but no one has applied them to water monitoring to this point. This may be a very promising technique.

2.3 Other Potability Monitoring Techniques 69

If radioisotopes are to be used in the water reclamation process, or if the water is subject to other sources of radioactivity, some type of scintillation counter should also be included in the potability check.

Total solids content of a solution is currently determined in a vacuum rotary unit. This method is not presently suitable for on-line monitoring. However, pH and conductivity tests together with organic tests may be sufficient to monitor solids in reclaimed water.

Physical properties of the product water, color turbidity, taste, and odor can be monitored by the astronauts senses, though the first two might be better measured with automatic instrumentation.

Since urea is basically a nitrogenous compound, it has been suggested that nitrogen monitoring should be considered under potability. Little has been done in this area to our knowledge,

A final aspect on monitoring which deserves attention is the compatability of spacecraft water monitors with those for cabin atmospheres [69]. Dual purpose monitors would free additional space and weight for other functions as well as increase the overall reliability of the air and water systems.

2.4 Recommendations for University Research

1. Integrate atmosphere and water monitoring equipment
2. Improve enzyme shelf life for bioluminescent assay
3. Further investigate antibody type monitors
4. Simplify and expand the range of ultraviolet monitor
5. Coordinate monitoring techniques with terrestrial environment problems where possible

III. RECOVERY TECHNIQUES

The processing methods proposed to date may be divided roughly into distillation and filtration techniques. Combined with either of these two general techniques can be pretreatment and/or post-treatment for removing bacteria and/or fixing various chemical contaminants not directly processed by the main unit. Of the two processes, filtration is somewhat simpler in concept and implementation than distillation. Also, NASA is especially interested in systems which will not employ phase changes since the weightless space environment can make such processes somewhat difficult to implement. This is not to say that distillation processes which involve phase changes are not to be considered. Rather, simple and reliable techniques are sought and non phase change processes appear to present fewer difficulties in a weightless environment than do those employing phase change.

3.1 Filtration

Multifiltration:

The most basic filtering method employs activated charcoal beds through which the raw water is passed[1,2,11,33,49]. Ultrafine bacteria filters are also used to limit carryover of microbiological contaminants. The process is unsuitable for urine but a number of studies have deemed it the best system for humidity condensate. With modification, it may also be suitable for wash water if the detergents used can be handled

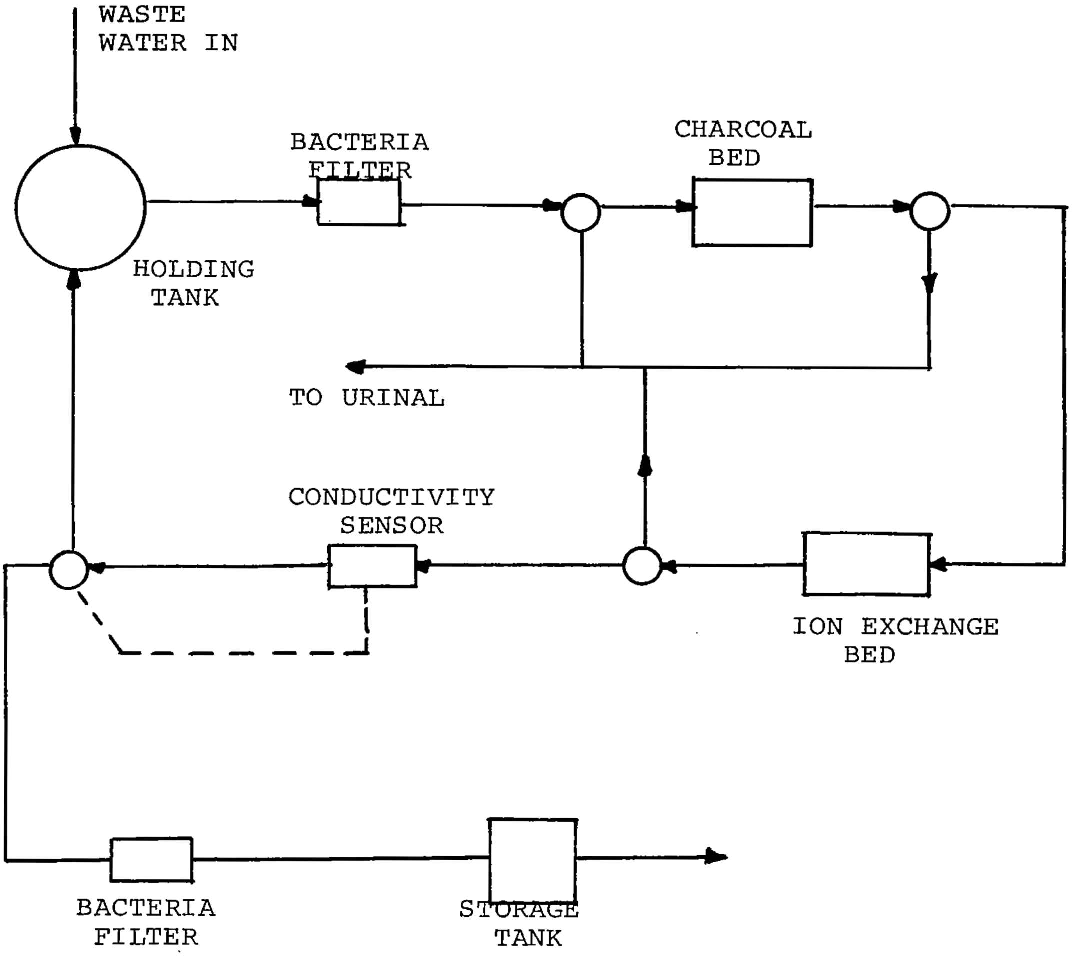


FIGURE 1

MULTIFILTRATION
SYSTEM SCHEMATIC
(FROM REF. 1)

by the system. Such a system for wash water is shown in figure I. In addition to the charcoal beds and filter mentioned above, a bed or beds of ion exchange resin is included to remove ionic salts and to adjust the pH of the product water. An additional bacteria filter is included to prevent bacteria from growing in the filter beds. A conductivity sensor determines whether the product water is "potable", shunting it back to the holding tank if it is not.

Multifiltration is simple and only requires power to operate a pump and the conductivity sensor. It is highly reliable and occupies little space.

Problems with the system are the charcoal and exchange resin may be unable to handle some trace impurities and excess quantities of certain gases. Also, charcoal retains a good deal of water in proportion to its weight (as much as 0.7 lbs. per lb.) and will probably require replacement during a long voyage adding to the system's overall weight. Still, at present it is the top competitor for humidy condensate recovery.

Two somewhat more complicated methods also fall under the general heading of filtration. These are electrodialysis and reverse osmosis.

Electrodialysis

Electrodialysis employs an electric force field across a semipermeable membrane in order to remove ionic contents of the waste water [1,11,72,31]. A schematic is shown in figure 2. The electrodialysis cell is shown in figure 3. In the cell,

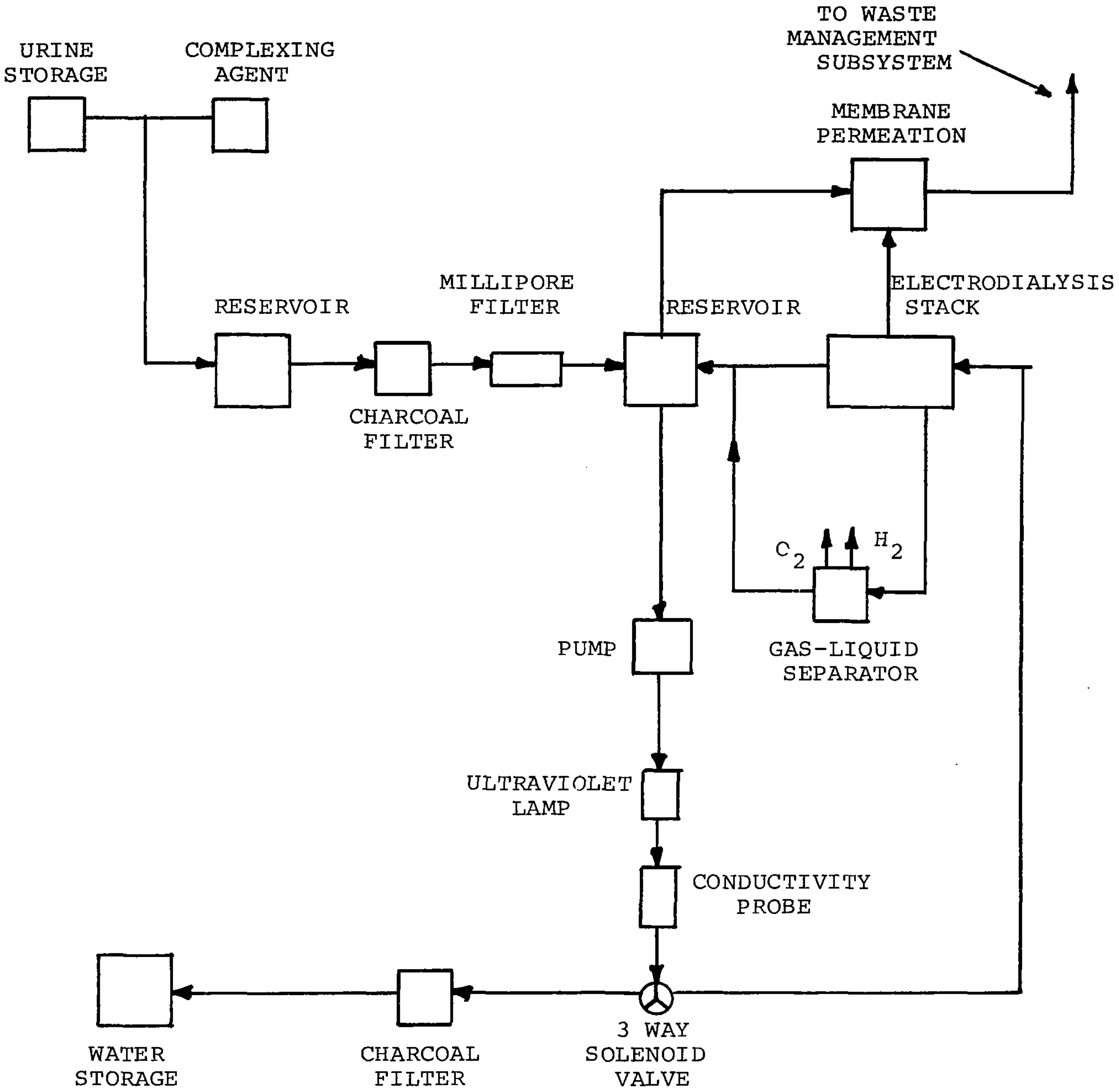
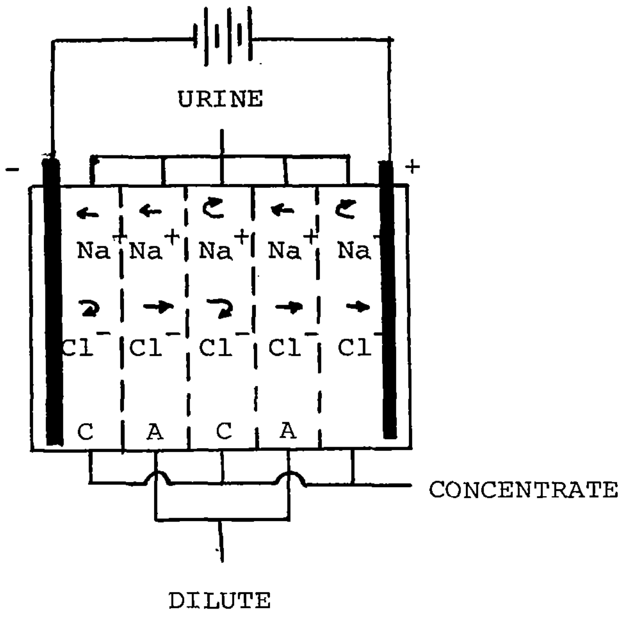


FIGURE 2.

ELECTRODIALYSIS PROCESS
SCHEMATIC

(FROM REF. 9)



A = ANION TRANSFER MEMBRANE
C = CATION TRANSFER MEMBRANE

FIGURE 3

ELECTRODIALYSIS CELL

(FROM REF. 5)

electrolytes are removed as follows: positive charged ions move toward the cathode and negative charged ions toward the anode. The anion and cation transfer membranes effectively separate the solution into concentrated and dilute sections from which the two concentrations are pumped out.

The technique is not complete in that urea is not removed by the primary process. Rather it (urea) is handled by either a charcoal or electrochemical pretreatment unit which increases the weight and complexity of the system. Electrodialysis have been developed to the hardware stage. The electrochemical pretreatment process presents something of a hazard since gaseous O_2, N_2, CO_2, and H_2 are produced. O_2 and H_2 are also produced during electrodialysis. Bacteria filters and ultraviolet light have been used as post-treatment techniques and a conductivity probe controls channeling to the storage tanks. The process has been used in desalting brine.

Reverse Osmosis

The Reverse Osmosis process employs pressure across in semipermeable membrane to remove the ionic and organic constituents of waste water. Some feel that reverse osmosis is highly adequate for processing wash water and humidity condensate. As fig. 4 indicates, pressures under 100 psi give recovery efficiencies of about 90% for these two water sources. The same is true for humidity condensate.

The process alone will probably never be suitable for

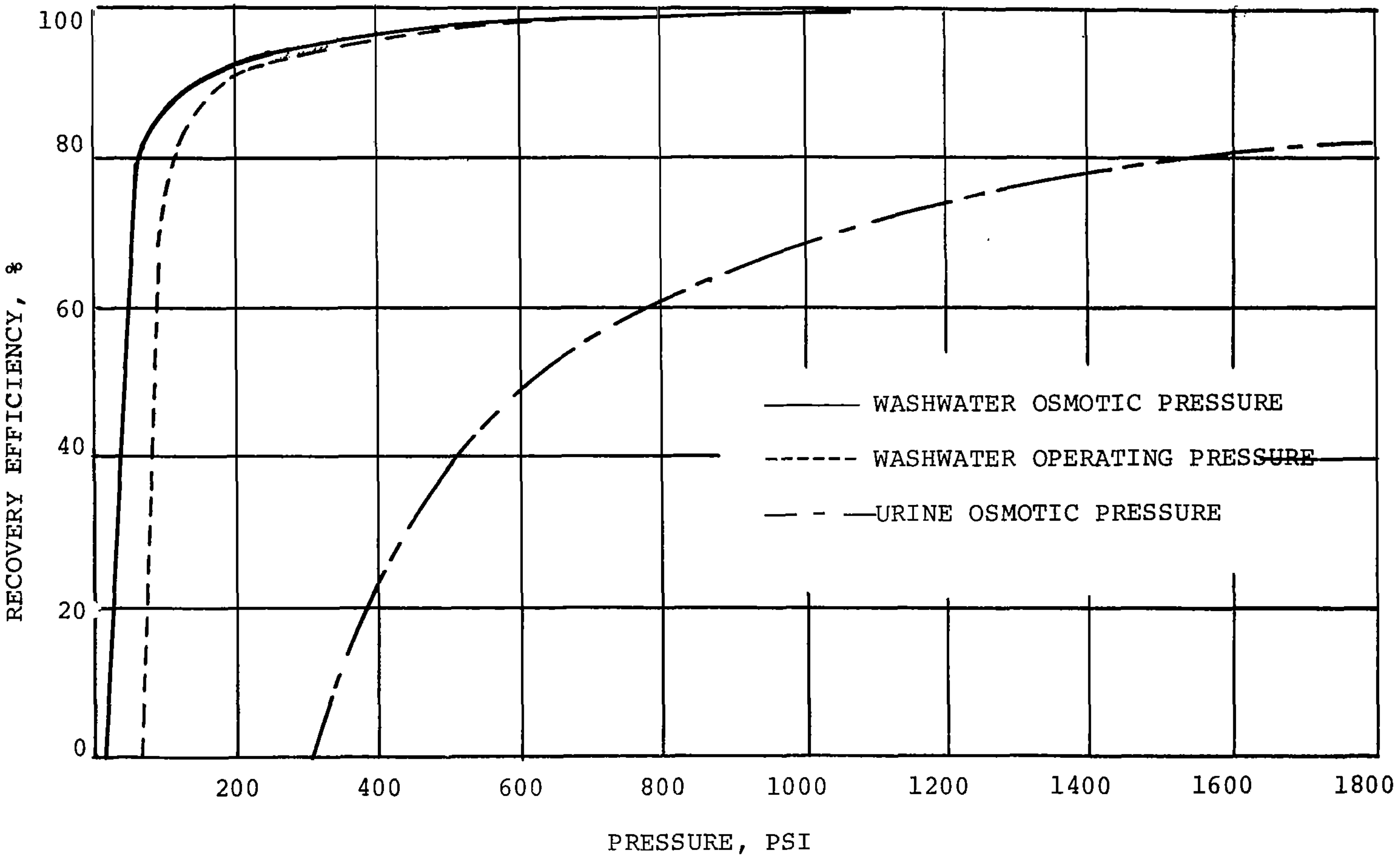


FIGURE 4

RECOVERY EFFICIENCY VS. OSMOTIC PRESSURE FOR TYPICAL REVERSE OSMOSIS PROCESS

(FROM REF. 1)

processing urine. As fig. 4 indicates, in order to remove urea by reverse osmosis, high pressures are required and even then the recovery efficiency is less than 90%.

The current approach appears to be to use reverse osmosis to remove the salts from urine while allowing the membrane to be permeable to urea pre-or post-treatment is then used to fix the urea. With this approach it is possible to operate the unit at pressures less than 1000 psi.

At one time the membrane used in this process posed a number of failure problems, mainly creep. However, recently developed cellulose acetate membranes, which are permeable to urea, appear to be quite durable and reliable when used in a turbular module arrangement.

Reverse osmosis does not employ a phase change and is receiving intensive study for use in desalination of salt water.

3.2 Distillation

A number of distillation techniques have been proposed and several are considered suitable for urine processing. The latter will be dealt with after a discussion of several other distillation techniques.

Air Evaporation

Perhaps the simplest technique, conceptually, of the distillation group is air evaporation of which there are two varieties, open and closed cycle [1,7,6,11,51a]. Both pass a heated gas stream past urine saturated wicks, thereby evaporating

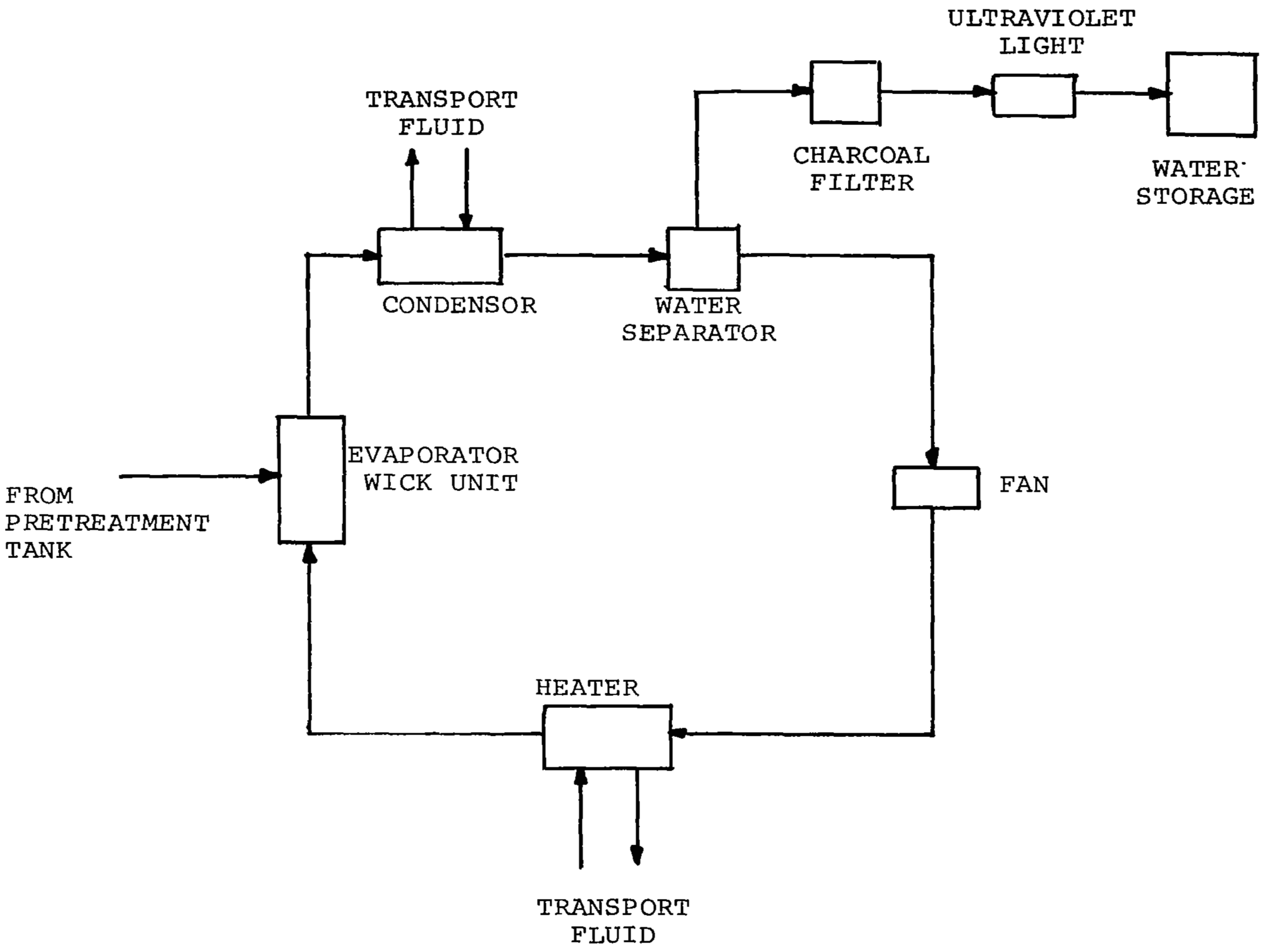


FIGURE 5

CLOSED CYCLE AIR EVAPORATION PROCESS SCHEMATIC

(FROM REF. 51a)

water from the wicks and carrying it to a condensor and porous plate separator for recovery. In the open cycle, cabin air is passed over the wicks while in the closed cycle gas is recirculated in a loop. The vaporized water from either method is condensed and filtered to remove bacteria. The closed cycle schematic is shown in figure 5.

Both processes (open and closed cycles) employ chemical pretreatment to kill bacteria and to fix ammonia in the urea. Both are relatively simple and are the most highly developed processes to date. The open cycle method presents a definite safety hazard in that bacteria and other contaminants may be directly passed to and from the cabin atmosphere.

Waste heat from other spacecraft systems can be used in air evaporation, it is capable of zero-g operation, has low sensitivity to temperature variations and operates at ambient pressure. The major problems to date have been wick clogging as solid residues collect on them when water is removed and the high volume of the units. Wick changes present a possible contamination problem.

The closed cycle wick evaporation unit has received extensive and apparently successful testing in the NASA Langley Research Center integrated life support system.

Vapor Compression

Conservation of the heat of condensation is a primary factor in the operation of the vapor compression still, which is shown schematically in figure 6 [1,51a].

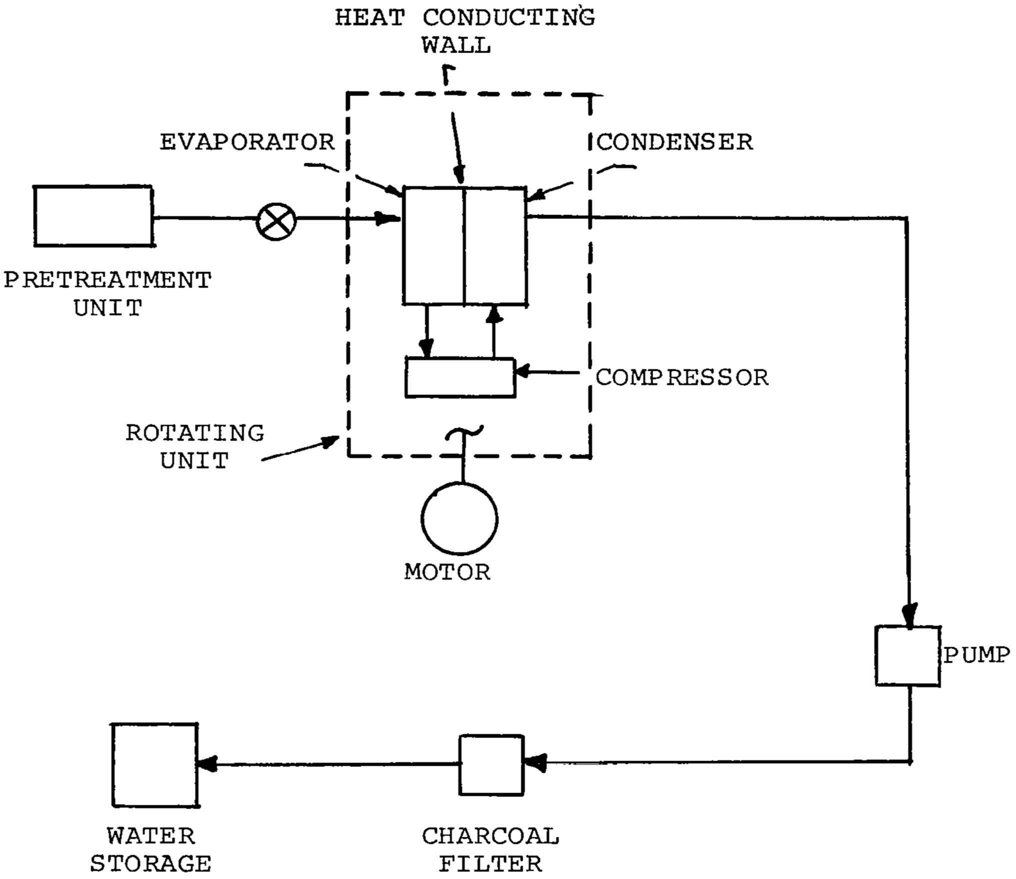


FIGURE 6

VAPOR COMPRESSION PROCESS SCHEMATIC

(FROM REF. 51a)

Pressure in the evaporator is lowered until the incoming waste water begins to evaporate. The pressure and temperature of the vapor are raised in the compressor. The wall of the condensor is in contact with that of the evaporator. The condensor surrounds the evaporator in the actual unit. When the vapor at high temperature and pressure is condensed, the heat of condensation is passed directly back to the evaporator through this wall and hence is conserved. The motor rotates the compressor and evaporator, driving the concentrated waste water in the evaporator to the outer wall by centrifugal force, thus making the process theoretically capable of zero-g operation. In recent versions, solid residues have then been recycled to vacuum dryers. Bacterial contamination has been found to be a problem, though some of the more advanced micro filtering techniques may help this. Precise control of temperature and pressure are required, but overboard purge of contaminants appears to accomplish this fairly well.

The advantages of the vapor compression technique are fairly low weight, volume and power requirements.

Thermoelectric Vacuum Distillation[1]

Thermoelectric distillation is basically the same process as vapor compression, except that thermoelectric elements act as heat transfer pumps between the condensor and evaporator. These elements are apparently the downfall of the process for while individually they have fairly long life, collectively, in series in the actual unit, they do not last for sufficiently long periods. There appears to be little motivation to produce high quality elements, since to do so would mean extracting them from a high volume production run similar to that used for high quality semiconductors. The process is mentioned merely because it closely resembles the previous technique.

Vapor Pyrolysis

Vapor pyrolysis employs catalytic oxidation in order to oxidize organic vapors and destroy bacteria [1,51a,32]. The process employs an "oven" in which the contaminants are fixed or destroyed. The vapor condenses in a porous condensor of a positive expulsion type. The latter, together with the overall process scheme is shown in figure 7. The process appears to be very good at removing urine constituents, simple in operation and reliable.

It has been suggested that vapor pyrolysis might be an attrative partner with another process, such as vapor compression, in order to improve the overall operation of both systems, if the pressure is not high. Also, some work has been done recently on [42, 37] low temperature catalysts making this process more safe than it has been in the past. The flash evaporation technique to be discussed shortly uses a version of this process

Some attention has been given to the use of radioisotopes and low temperature catalytic oxidation [42, 26a].

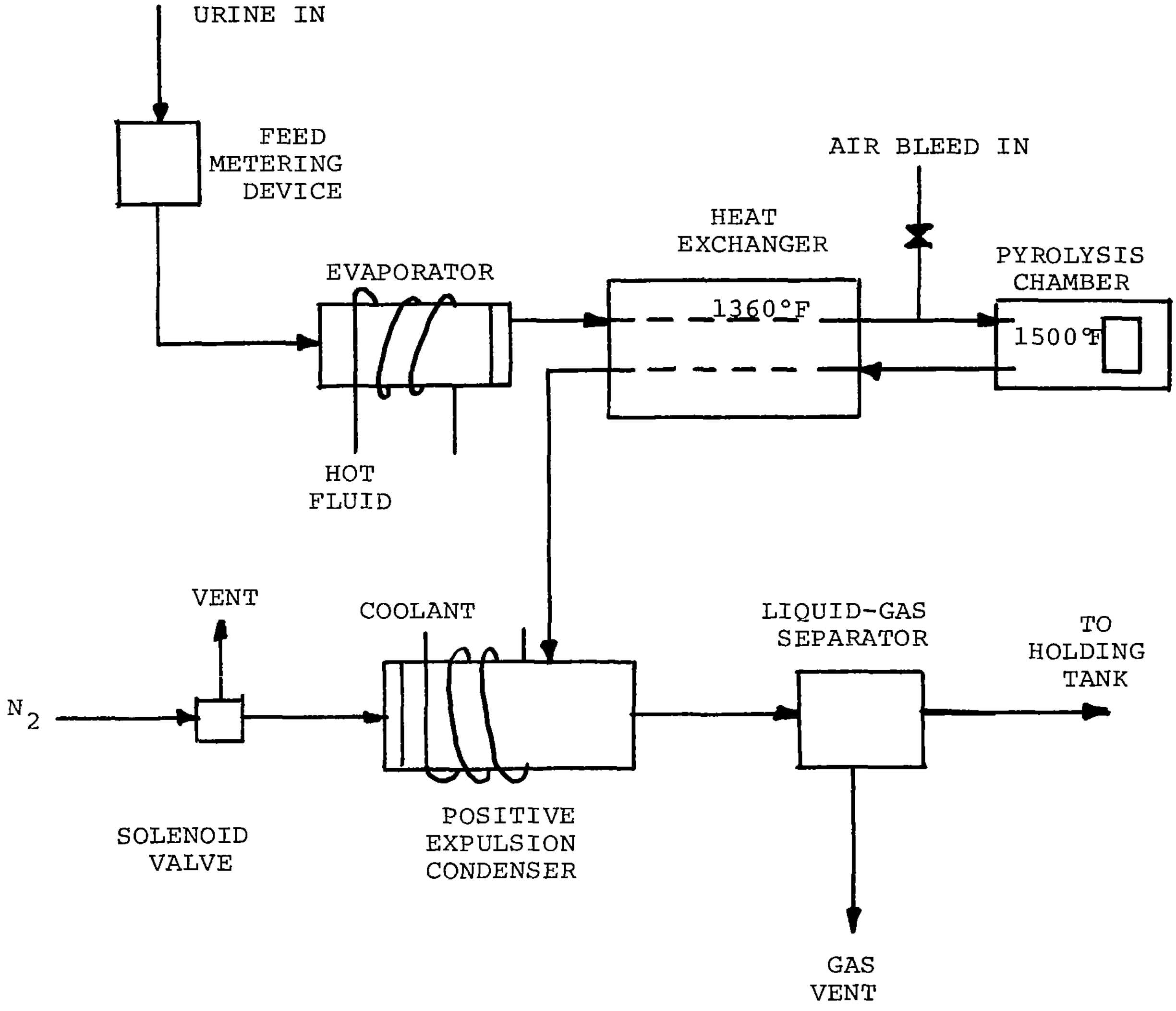


FIGURE 7

VAPOR PYROLYSIS PROCESS
SCHEMATIC

(FROM REF. 51a)

Vapor diffusion

The vapor diffusion method is essentially a zero-g distillation unit [1,30,40,39]. A batch of chemically pretreated urine is pumped past a semi-permeable membrane through which water vapor from the solution passes (see figures 8 and 9). The water vapor diffuses through a pressurized gas "diffusion gap" and condenses on a cool porous plate. The pressure of the gas is slightly above ambient and thereby forces the condensed water through the plate into a collection passage. When no water vapor is moving across the gap, the water on the plate and the membrane tend to resist leakage of the pressurized gas by setting up capillary action at the two boundaries.

The urine solution is circulated past the membrane until the removal of water causes the solute concentration to reach a fixed limit. At this limit, the "brine" (concentrated urine) is drained off to the solid waste processing subsystem and a new batch of urine is then introduced into the system. The water collected on the product side of the still is run through charcoal and bacterial filters and delivered to storage tanks.

The system is attractive for several reasons. It operates at nearly ambient pressure, employs no excessive temperatures, has inherent zero-g capabilities, low volume and power requirements, recovers well in excess of 95% of the urine water, and has few expendables.

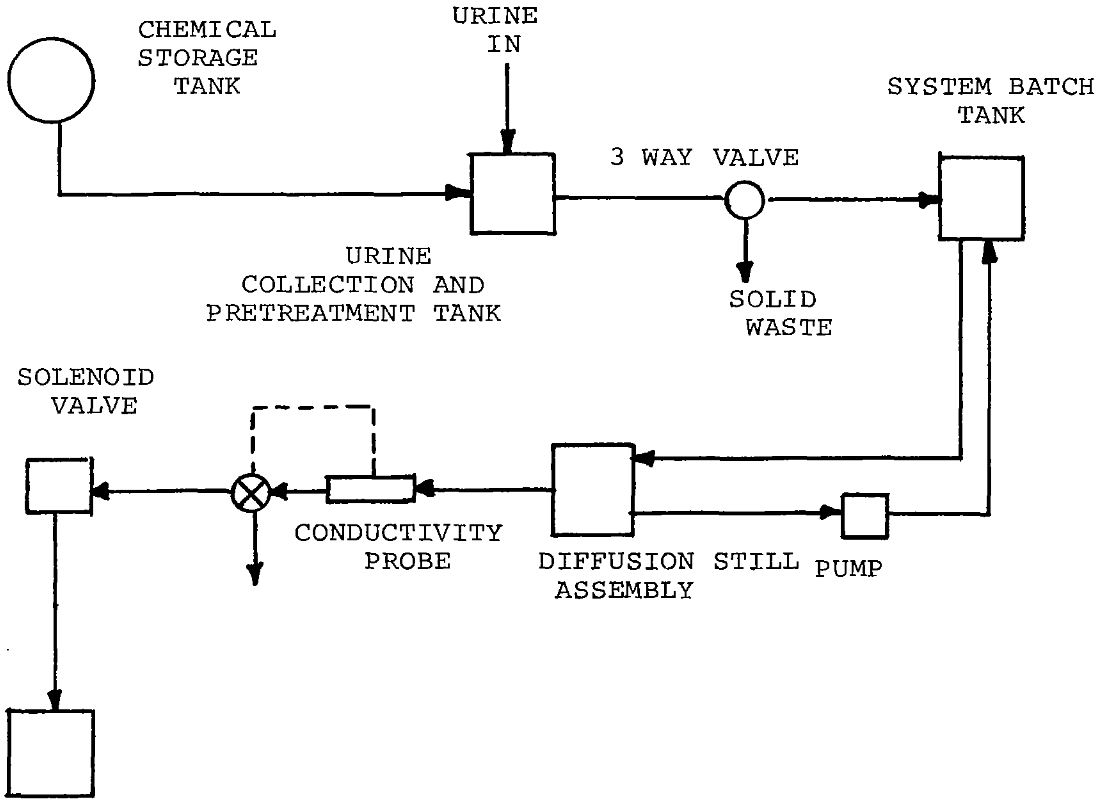


FIGURE 8

SIMPLIFIED VAPOR DIFFUSION PROCESS SCHEMATIC

(REV. FROM A HAMILTON STANDARD DWG.)

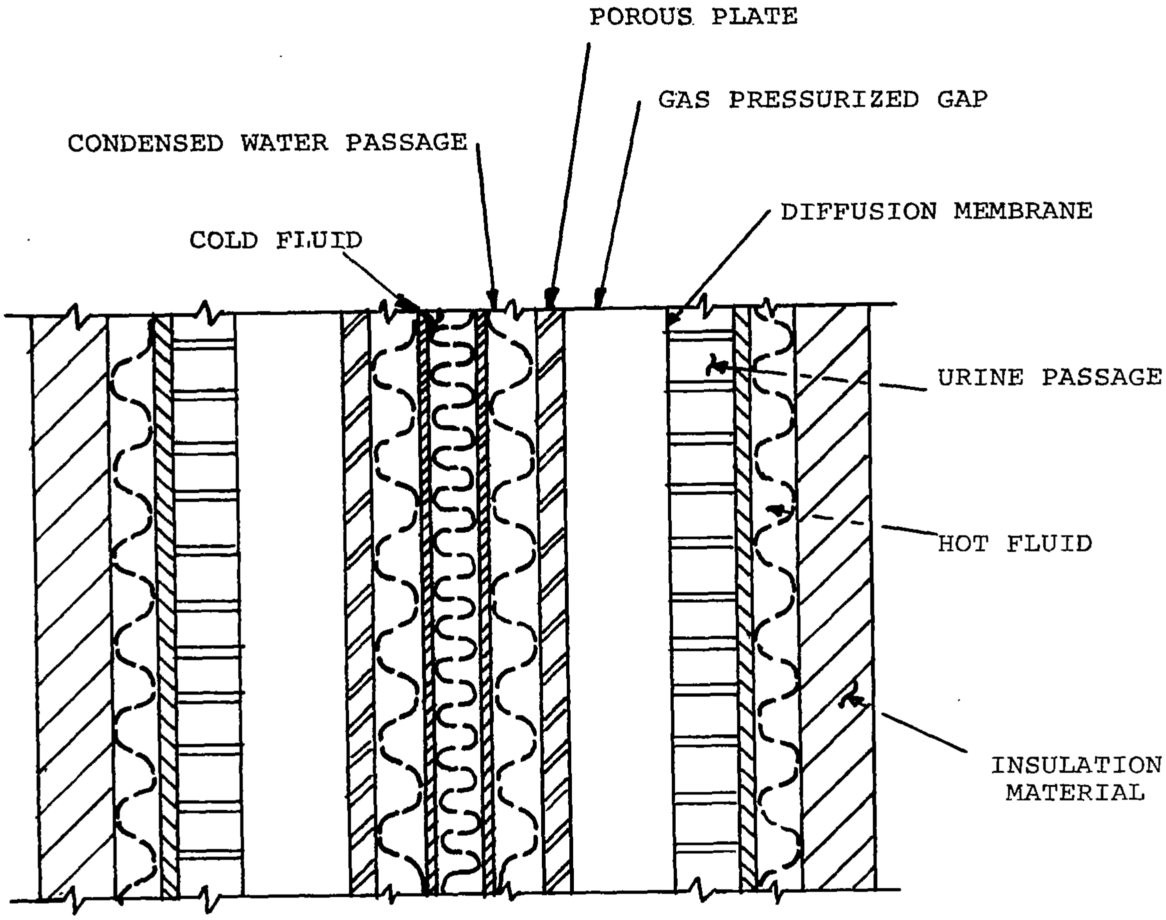


FIGURE 9

CROSS SECTION OF A DIFFUSION
STILL MODULE-SCHEMATIC

(FROM A HAMILTON STANDARD DWG.)

Two problems with the process are notable, and both appear to be within the scope of university research. The first is the need for improved membranes having superior chemical and mechanical properties and high permeability constants. At present, only certain varieties of cellophane have been successful in the still, and the life of such membranes is not sufficient for long duration operations. The hoped-for goal is a membrane which will be essentially maintenance free for the duration of an expected mission.

A second problem concerns brine management parameters, especially the mechanism of brine solids accumulation at the membrane urine interface. In this connection, better techniques are also needed for determining the fraction of brine solids and percent of recovery of available water.

Forced Circulation/Flash Evaporation

Another promising technique is the forced circulation/ flash evaporation concept (see figure 10)[1,29,73,9]. In this process, a pump raises raw urine at 89 degrees F. and 1.5 PSIA to a pressure of ∿35 PSIA where it is then heated to 100 degrees F. Some pressure is lost due to friction in the heat exchanger, but not enough to cause boiling. The fluid is then expanded through a valve into the flash evaporation unit and consequently becomes two-phase. The vapor is drawn off and the concentrated fluid is recirculated until it reaches some predetermined concentration on the order of 50-60% and is then dumped.

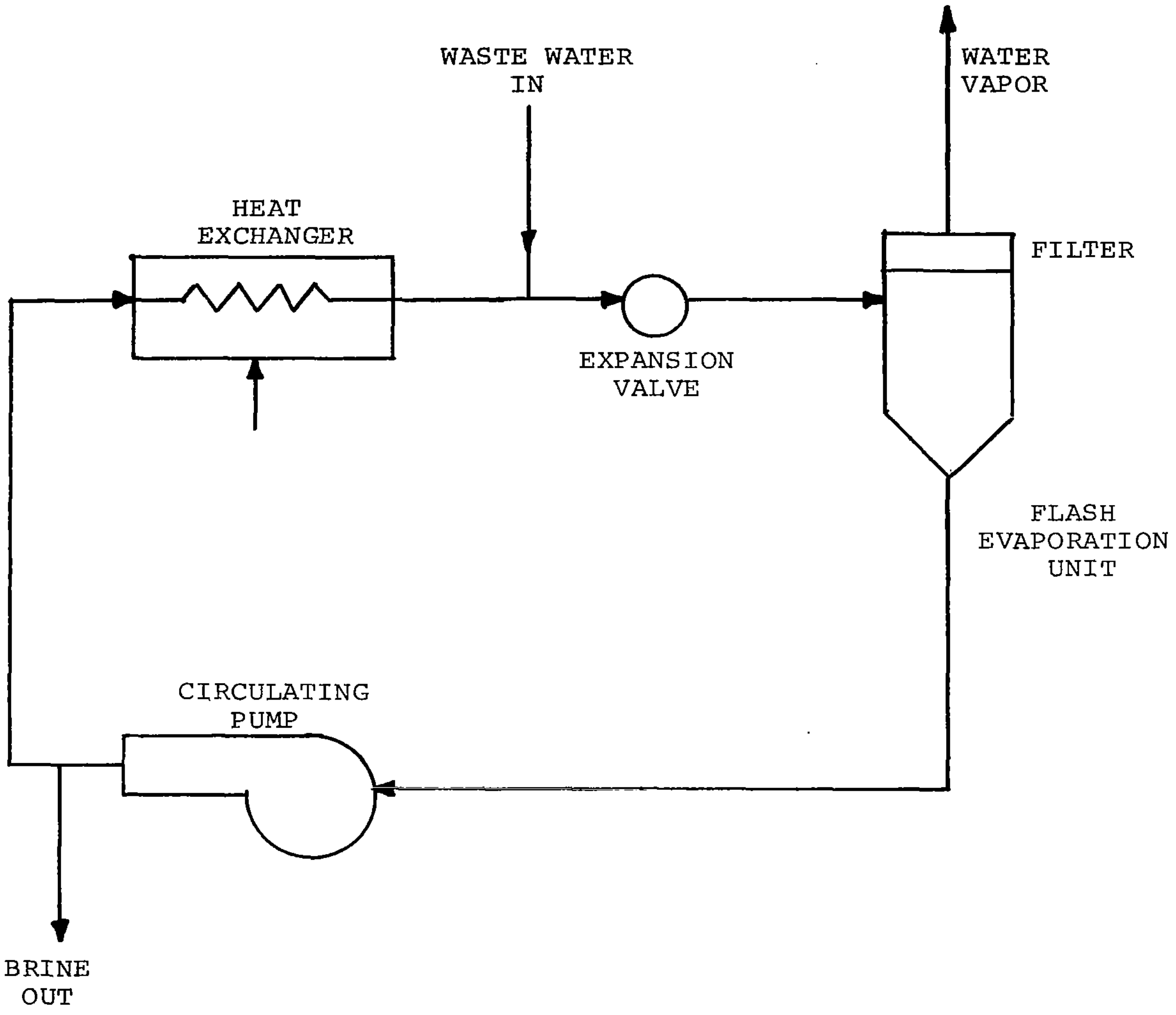


FIGURE 10

FORCED CIRCULATION/
FLASH EVAPORATION PROCESS
(FROM AN AIRESEARCH DWG.)

The method was first proposed for the desalination of sea water, a problem not unlike the recovery of potable water from urine [73]. Work in both areas has shown similar problems in heat transfer, surface fouling, and removal of solid wastes. However, control of the process must be carefully monitored in order to maintain a high recovery efficiency.

The separation of the vapor from the two-phase mixture is a problem in the zero-g environment common to all the processes mentioned. In the present case, membranes and centrifugal units have been applied. Membranes, as mentioned previously, suffer from both plugging and breakage.

A feature of the flash evaporation concept has been the use of catalysis in the treatment of the product vapor. Motivation for this comes from several areas. Ordinary pre- or post-treatment of urine or product water increases the weight of the overall system, affects performance of the process cycle, and potability of the product. It has been found that catalysis eliminates the need for additional treatment and provides a high temperature bacteria barrier between waste and product water. (This brings to mind the arguments for the vapor pyrolysis unit above, which in fact is a kind of catalysis method.) Still required are refinements in the type of catalyst (Pt-Rh mesh is one current type) and design of the reactor. Also, the temperature at which the reactor operates is highly dependent on the type of catalyst used, though low temp catalyst work may aid this situation.

The work on this system has also dealt rather extensively with physical properties of urine brine solutions [29], mentioned as a problem area under vapor diffusion above. Included in these studies have been boiling point elevation, heat capacity, refractive index (may be a good means of measuring solids concentration), specific conductivity, specific gravity, surface tension, and viscosity. This work has not been exhaustive and presents a number of interesting problems suitable for university research.

As it presently exists, the forced circulation/flash evaporation technique is in need of development into a flight operational system. This seems possible in the not too distant future.

3.3 Pretreatment

A brief mention of at least one pretreatment method [28,70,1,43] seems in order. Others are discussed in the references. One such method decomposes urea into CO_2, N_2, H_2, and H_2O electrochemically according to the following equations:

Anode

$$6Cl^- \rightarrow 3Cl_2 + 6e$$

Cathode

$$6H_2O + 6Na + 6e \rightarrow 3H_2 + 6OH + 6Na$$

The sodium hypoxide from the cathode and chlorine from the anode react to produce a hypochlorite ion and:

$$3Cl_2 + 6Na + 6OH^- \rightarrow 3NaPCl + 3Na + 3Cl + 3H_2O$$

$$CO(NH_2)_2 + 3NaOCl \rightarrow N_2 + 3NaCl + 2H_2O + CO_2$$

The four above equations yield:

$CO(NH_2)_2 + H_2O \rightarrow CO_2 + N_2 + 3H_2$

The hypochlorite also acts as an effective bacteriacide. Other popular pretreatment agents are $H_2SO_4 + CrO_3$, $H_2SO_4 + CrO_3 + CuSO_4$, and $CuSO_4(ClO)_2$.

3.4 Biogenic Treatment

Several other solutions to the spacecraft water supply problem have been suggested. One is the biogenic treatment of urine, a method advocated by some Russians [73,47,36,34,12,45 & others]. In theory, the biogenic methods would employ some biomass, such as chlorella, grown on a nutrient of human excrements. This biomass would serve as the primary purifier of water and oxygen and might also be used as food. Processing times for such a scheme would be extremely long compared to mechanical methods and control of a biosystem on a small scale would be very complex. Implicit in this matter is the fact that we really know very little about closed ecological systems on either a macro or a micro scale. It has been feared that the extraterrestial environment may upset the balance of microbiological life but no one appears to have any concrete answers to the question.

In the foreseeable future, it seems obvious that biogenic systems will not be available for spacecraft use. However, their study might be of inestimable value in dealing with problems such as environmental pollution on the earth. Such study in turn could possibly advance both the scientific and technological states of this concept to the point where it would be suitable for spacecraft use. As mentioned above however, the Russians are presently much more interested in this approach than Western researchers though this is changing.

3.5 Ion Thrustor

Another interesting proposal for solving the spacecraft water problem is to store water and food in the form of fuel for an ion thrustor [35,46]. One postulated arrangement for such a system is shown in figure 11. The proposed thrustor would operate on ionic CO_2 and H_2O derived from the crews' metabolic wastes. If these wastes were insufficient during a given period, a portion of the stored food-fuel would be drawn off and used directly as a propellant. This method obviously depends on the development of such a thrustor. A thrustor operating on fecal matter was recently found to be feasible and to warrant futher development. Such a thrustor, this study points out, could also alleviate the problem of disposing of fecal matter. A continuation of this work might be of definite interest to university researchers.

Other less attrative current and proposed techniques are mentioned in the references, especially #1 and #11, for those interested. The ones discussed above appear to hold the most promise at present.

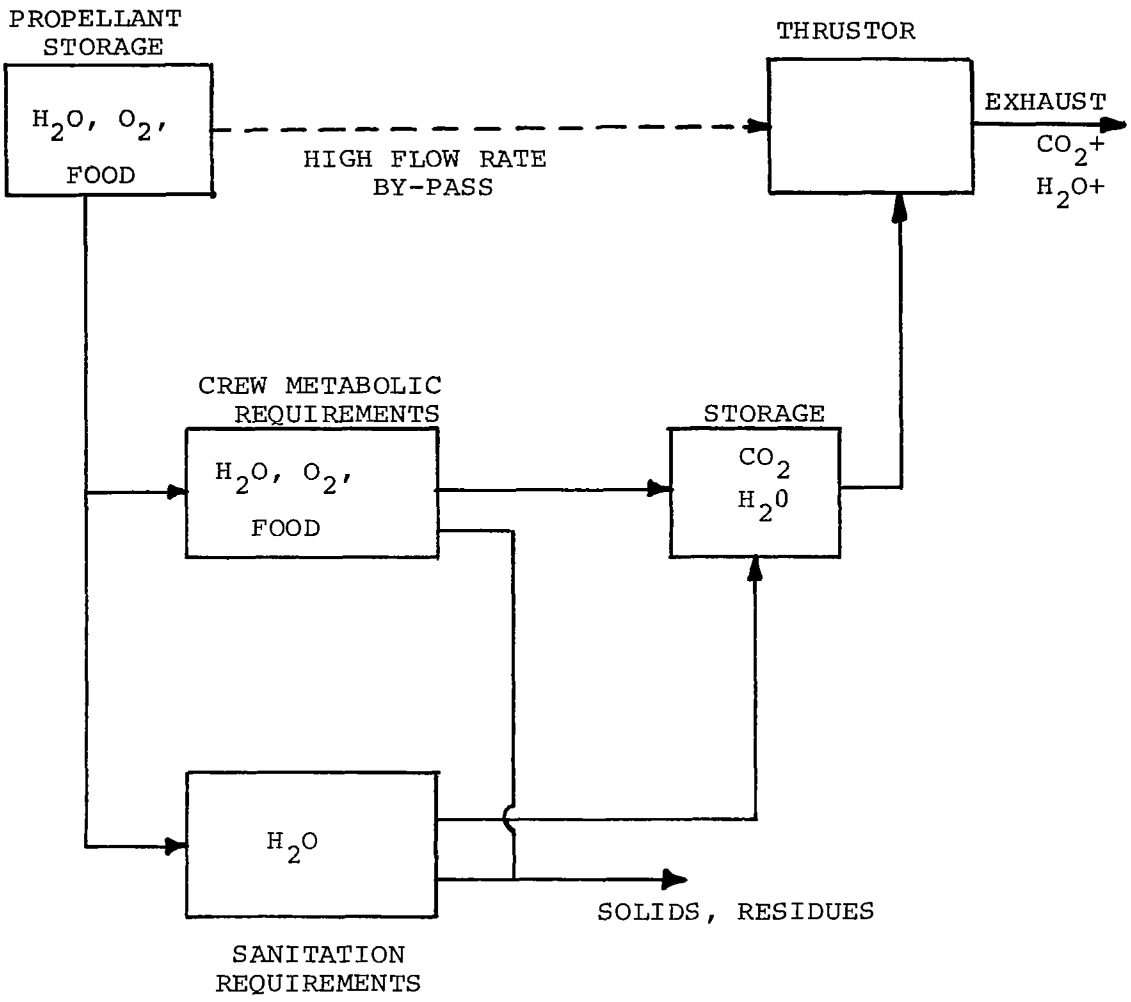


FIGURE 11

PROPOSED ION THRUSTOR
WITH INTEGRAL LIFE
SUPPORT SUPPLY

(FROM REF. 46)

3.6 Systems Selection

Since one cannot employ all of the above systems and since no one system is completely optimum as yet for every mission, some means of selecting a suitable compromise candidate for a particular mission is necessary [16]. In addition, less developed and novel schemes such as the ion thrustor above may become flight operational later, futher complicating the choice. One source [55] states the problem as the "selection of the most promising system from a group of underdeveloped approaches, to perform a multiplicity of functions not yet clearly defined, for use in one of more missions as yet only partially examined and to do so by taking into account all of the criteria significant to the programs to be undertaken."

Several forms of decision theory have been applied to this problem but without a good deal of success, probably due to the large and varied number of uncertainties. A more common procedure has been to assume a number of configurations with a specific mission in mind, then run a computer simulation and vary the configuration(s) until an apparent optimum scheme is reached [53,47,56,58].

Earth based manned tests have been conducted to examine various component configurations [10,61,62]. NASA Langley and several of its contractors have performed rather estensive testing of life support equipment [3]. To the best of our knowledge, however, the longest manned experiment to date was conducted by the Russians [59]. Three men were sealed in a chamber for one year. Catalytic oxidation (which though not detailed in their report is probably similar to the vapor pyrolysis scheme above) was the basic process for urine and wash water. Humidity condensate was sterilized with ultra-violet light. Salts and some micro-organisms were added though the source does not go into detail.

Certainly one means of aiding the selection procedure is to improve the reliability of the systems[57,60,52,75]. Some studies done in this area have shown that a repair/replace philosophy is superior to a parallel redundancy of systems components though there is some disagreement on this point.

The matter of selection is pointed out because it may well influence the nature, number and success of the water recovery system as much and perhaps more than any other factor. For this reason, it should be kept in mind throughout and work should be done on these systems.

3.7 Recommendation for University Research

1. Develop efficient regeneration techniques for resin and charcoal filters for long missions.
2. Continue to improve capacity of charcoal and exchange resin for trace impurities and detergents, or develop better absorbent substances.
3. Investigate regeneration of pre or post-treatment modules also basic studies of these treatments.

4. Cycling rate of air evaporation system could be improved.
5. New ideas on wick clogging in air evaporation system are needed.
6. Lighter weight compressor for vapor compression techniques.
7. Further investigation of low temp. catalysts.
8. Further improvement of membranes for the various processes.
9. Better understanding of brine management parameters--also more work on physical properties of urine.
10. Techniques such as biogenic treatment fit naturally into ecological studies and may be of interest to some.

IV. FRINGE CONSIDERATIONS

A number of interesting problems of a fringe nature are suggested by the basic problem of providing a closed loop water recovery system for spacecraft. One of these mentioned under the matter of water exchange above is the day to day measure of body mass. This can be done by injecting Tritium and observing decay rates in the body, a common but somewhat inconvenient method [18,19]. Another might be to bounce a man in a controlled manner in a seat of some sort. Knowing the force applied and accurately measuring the acceleration, one should be able to determine body mass.

Another proposed method of determining body mass is by use of a short arm centrifuge. One report outlines the procedure for doing so [76]. Small on-board centrifuges have also been suggested as suitable conditioning [18] devices for the cardiovascular system in weightlessness. The question of whether such a device is actually needed (i.e. the seriousness of cardiovascular deconditioning) has not been satisfactorily answered. An answer to that question would undoubtedly be the key to the future of an on-board centrifuge rather than the ability of the device to measure body mass. It does seem to be a technique to keep in mind however.

On any space mission, the influence of gravity and/or the lack of that influence is obviously an important factor. The action of gravity plays an important role in many basic physical processes. This role is often taken for granted in earth based engineering and hence has not received a great deal of attention. The space program has created some interest in basic research into gravity-dependent and related gravity independent processes [71,74]. A number of water recovery techniques might benefit from more knowledge of these processes. Among these are composition mixing, liquid transport in wicks, liquid condensation rate in heat exchangers, liquid transport in gases, centrifuge separation, liquid retention in plumbing and gas free water maintenance [3,20].

A related problem which should receive some attention is that of planetary based modules. Partial gravity environments of planetary stations may alter the requiredments on life support equipment. It may be found desirable to construct gravity dependent units on planets rather than alter spacecraft systems for use in gravity environments should such alteration be necessary [5]. A rotating space station with artificial gravity might also influence the type of water recovery scheme to be used [10,52].

V. SUMMARY

A review of this nature cannot hope to cover every possible topic in the water reclamation area and still generate interest in the problem areas. With this in mind, the topics which appear to hold the most interest for university research are reiterated below:

1. Better understanding of human water exchange.
2. Reduce safety hazards by modification in the various processes mentioned
3. Better utilization and understanding of the space environment's effect on operation of a water reduction system, including vacuum and zero-g characteristics.
4. Improved membranes.
5. Improve or eliminate chemical pre or post treatment.
6. Better understanding of microecology including desirability of 100% sterile environment.
7. Better definition of potability.
8. Rapid potability monitors of all types (especially biological).
9. Applications of potability monitoring and process techniques to problems in terrestrial environments.
10. Liquid phase oxidation of trace contaminants in condensate.
11. Better understanding of properties of the various waste waters & their effects on materials used in processing units.

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