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A PHYSICOCHEMICAL ENVIRONMENTAL CONTROL/LIFE SUPPORT SYSTEM FOR THE MARS TRANSIT VEHICLE

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ABSTRACT

The environmental control/life support system (ECLSS) of the Mars transit vehicle (infrastructure) must be as small and maintenance free as possible to allow maximum mission flexibility. This paper describes a "new technology" physicochemical ECLSS concept similar in many ways to several of the partially closed ECLSS concepts proposed for the Space Station (SS). However, this new concept eliminates several of the SS ECLSS subsystems and potentially eliminates the use of cryogenics and high-pressure gaseous storage.

The unique technology in the new concept is supercritical water oxidation (SCWO). The properties of supercritical water allow it to act as a medium in which organics and oxygen can mix freely. The extreme conditions that form supercritical water (630 K, 250 atm) also induce complete combustion of the organics. Virtually all organics break down and reform into carbon dioxide, water, and nitrogen. Inorganics form salts which are less soluble in supercritical water than in water in its natural state. Invariably, the inorganics precipitate out. This paper will explain how technology based on these phenomena can be used in an ECLSS for carbon dioxide removal, partial humidity control, trace contaminant control, water reclamation, nitrogen generation, and untimately trash and garbage reduction. Then a qualitative comparison between an ECLSS using SCWO technology and an ECLSS using SS era technology will be given. Mass balances are included to enhance the comparison.

INTRODUCTION

The environmental control/life support system (ECLSS) of the Mars transit vehicle (infrastructure) must be as small and maintenance free as possible to allow maximum mission flexibility. This paper describes a physicochemical ECLSS concept similar in many ways to several of the partially closed ECLSS concepts proposed for the Space Station (SS). However, this new concept eliminates several of the SS ECLSS subsystems by performing more than one ECLSS function in one "new technology subsystem. Furthermore, inherent in the simplified concept is the potential for eliminating the use of problematic cryogenics and high-pressure gaseous storage (the forms of nitrogen supply considered for the SS). Other advantages of the new concept are discussed and additional quantitative studies are recommended to increase confidence in supporting development of the unique technology in the new concept.

To summarize, the SCWOS technology is based on the physics and chemistry of water molecules (H_2O) at conditions above their super-critical pressure and temperature (at 25.3 MN/m^2 (250 atm) and 627.59 K (670^o F) (Anon., 1982; Josephson, 1982; Temberlake, 1982; Modell, 1983; Swallow, 1984-85). Under these conditions, the dielectric constant of H_2O weakens which causes two important phenomena to occur: hydrocarbons and other normally immiscible organics become miscible in the water medium, and normally-dissolved inorganic salts precipitated out of solution. Solid salts can be separated from the process stream in the same solids separator that removes any metal particles found in solution. At the high temperature, complete combustion of the organics result if sufficient oxygen (O_2) is presesnt. Complete combustion yields H_2O, carbon dioxiode (CO_2) and N_2.

To achieve and sustain the high temperature for the supercritical combustion, O_2 and hydrogen (H_2) can be introduced to the feed mixture for their "heat of reaction" value (O_2 + $2H_2$ > $2H_2O$ + heat) (Modell, 1984). An alternative, which is to preheat the feed electrically, would consume about the same amount of energy; however, the effect of the extreme conditions on the heat exchanger would make corrosion and structural problems difficult to control (Modell, 1984). These problems could be avoided by using the O_2/H_2 feed method. Maintaining the temperature is a matter of "superinsulating" the system. The vacuum of space could be utilized for this purpose. The heat of combustion of the reactants ensures that the temperature during reaction would not fall below the lower limit for rendering complete combustion. Reaching and maintaining the desired pressure is also achievable using current technology.

BASIC LIVING REQUIREMENTS FOR A MARS TRANSIT VEHICLE

The basic living requirements (i.e., maximum partial pressure of CO_2, minimum partial pressure of O_2) (Lin, 1983) for a Mars transit vehicle are the same as those for the SS. However, the ground rules and methods for meeting those requirements may be different for the Mars transit vehicle, especially since the mission objectives are so different.

The problem of inaccessibility to civilization for resupplies is much more profound for Mars missions than the SS missions. The astronauts will have to take everything they need (for themselves and for the vehicle) to survive over two years without resupply. Therefore, the less dependent on terrestrial resupplies the mission is, the more flexible the mission can be, and the less the time wasted on housekeeping.

CANDIDATE ECLSS CONCEPTS

Many elements are common to the proposed Mars transit vehicle ECLSS (Fig. 1) and a SS-type ECLSS (Fig. 2). Both have the same atmospheric pressure/composition control subsystem, O_2 generation subsystem, CO_2 reduction subsystem, and hygiene facilities. In fact, most of the hardware in the two ECLSS's is the same, but the few differences make the two concepts quite dissimilar.

SCWOS-ECLSS

Food, water posttreatment supplies, and a nitrogen-containing solid, which is discussed later, are the required resupplies for the ECLSS designed around an SCWOS. The byproducts would be salts, minerals, dense carbon, and excess water and hydrogen, all of which could be used elsewhere on the Mars transit vehicle or Mars base. A mass balance and a functional schematic for the SCWOS-ECLSS is shown in Figure 1.

Five subsystems would make up the air management group of the SCWOS-ECLSS: the atmospheric pressure/composition control subsystem, the O_2 generation subsystem, the SCWOS (for CO_2 removal, trace contaminant control, N_2 makeup, and partial humidity control), the CO_2 reduction subsystem, and the humidity/temperature control subsystem. The multifunctional SCWOS also would be part of the waste management group and the water management group, which are discussed later in more detail.

The atmospheric pressure/composition subsystem would be similar to that of the Space Shuttle; however, the sources of the gases (O_2 and N_2) would be different. Oxygen would be generated by water electrolysis

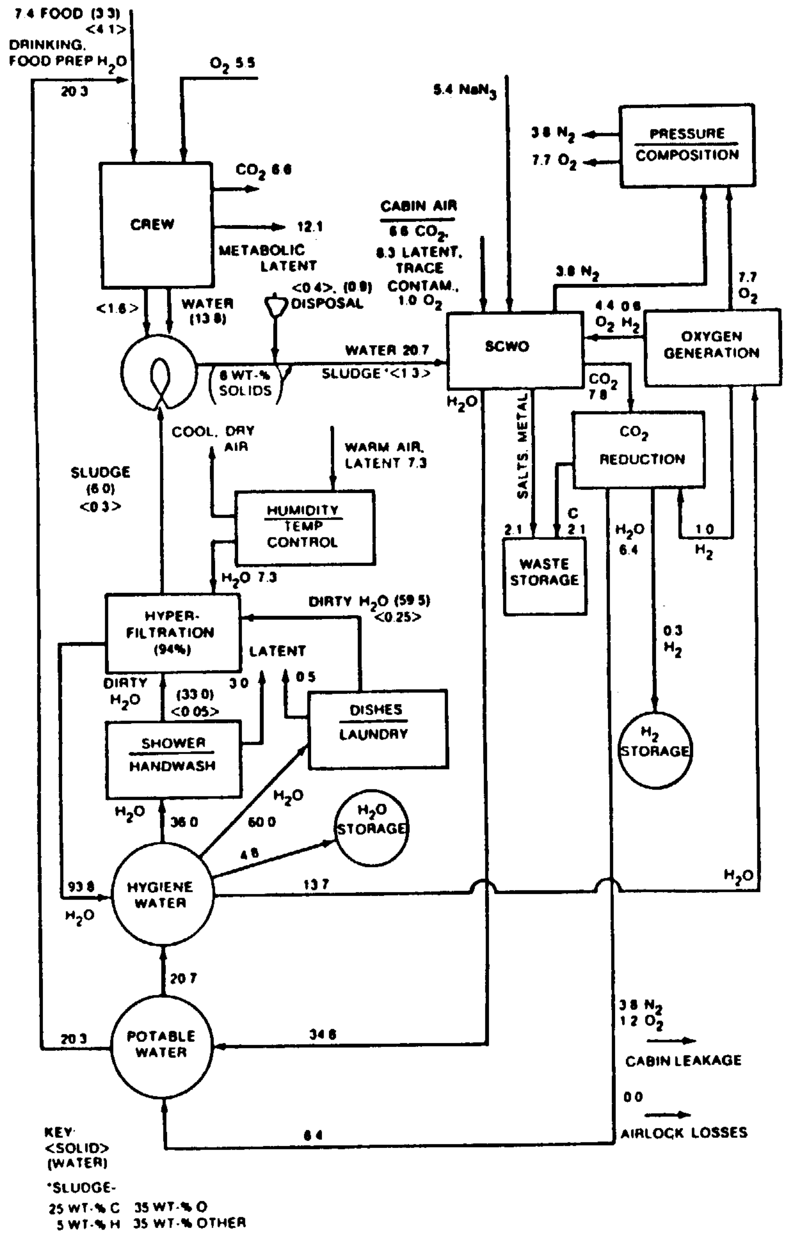

Fig. 1 - SCWOS-ECLSS; daily mass balance for a three-member crew.

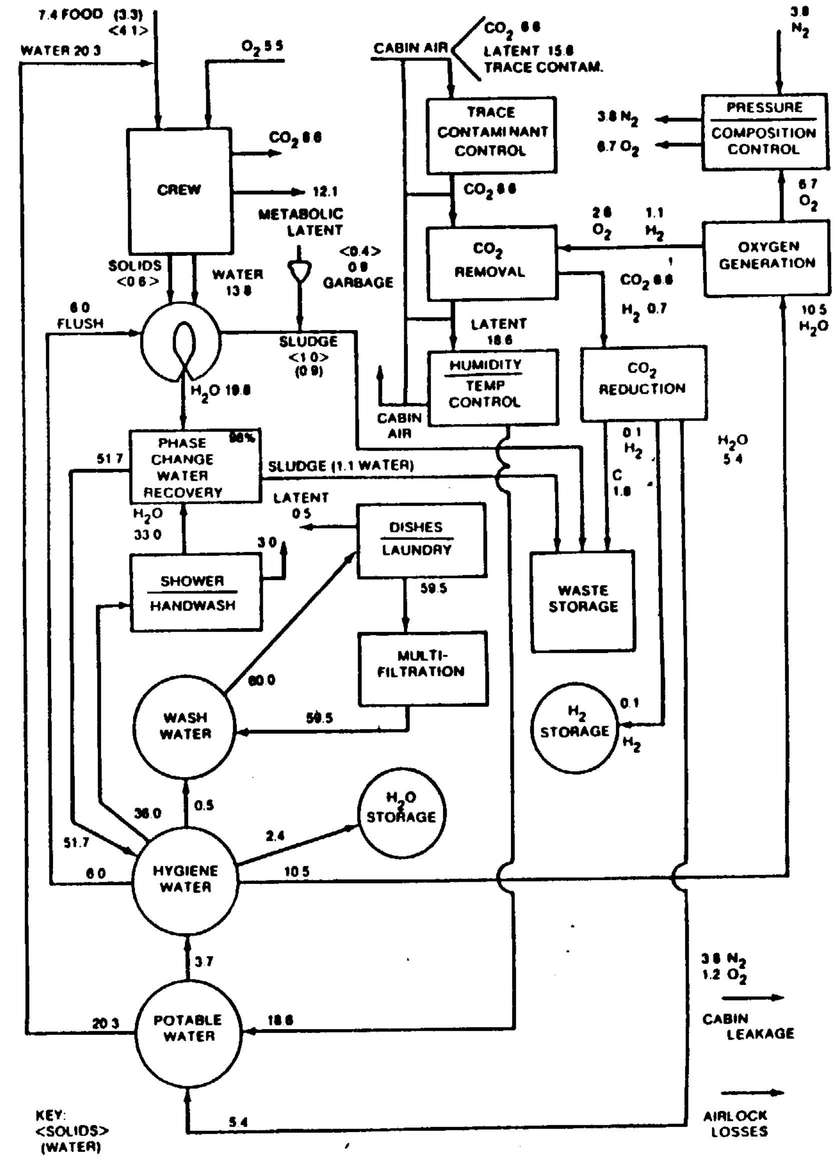

Fig. 2 - Space Station-type ECLSS daily mass balance for a three-member crew.

($2H_2O$ + electrical power > $O_2 + 2H_2$). Nitrogen would be derived from the SCWOS.

Since not enough N_2 for ECLSS needs could be generated by the normal ECLSS wastes fed to the SCWOS (urine, feces, garbage, dirty water, and trace contaminants) (Marrero, 1983), the SCWOS feed could be supplemented with a nitrogen-containing solid or liquid compound supplied from Earth. There are several compounds to choose from that would benefit the Mars transit vehicle in ways beyond N_2 generation. Information on several nitrogen-containing compounds is contained in Table 1 (Sax, 1965; Weast, 1977). As discussed later in the comparison between ECLSSs, the most important consequence of the use of this N_2 generation concept is that the compound could be resupplied as a solid or liquid. If this N_2 generation scheme is rendered undesirable, the SCWOS-ECLSS could revert to the same N_2 supply subsystem to be used for the SS (probably cryogenic storage). The atmospheric pressure/composition control subsystem would regulate the release of O_2 and N_2 into the cabin to maintain the cabin O_2 content and total pressure.

The CO_2 reduction subsystem in the air management group would receive all the H_2 from the O_2 generation subsystem except that used in the SCWOS. All the CO_2 entering the SCWOS with the process air and that formed by combustion inside the reactor would leave the SCWOS in a concentrated stream. The CO_2 reduction subsystem would receive this CO_2 stream and convert the CO_2 and H_2 into water and dense carbon. The excess H_2 would be stored for other Mars transit vehicle or Mars base needs.

The SCWOS-ECLSS water management group would consist of two water loops: the potable water loop and the hygiene water loop. Normally, to save energy and expendables, the hygiene water would not be made potable (in the palatable sense) but nonetheless free from contamination.

"Prepotable" water would come from urine, water vapor in the air (e.g., metabolic latent), SCWOS combustion product water, and CO_2 reduction product water. Potable water would be derived from two intense sterilizing processes which operate at temperatures above 533 K (500^{o} F): the CO_2 reduction subsystem and the SCWOS. The sterile water would be chemically enhanced for flavor and for bacterial growth prevention to yield potable water. Once the potable water tanks were full, the

TABLE 1

NITROGEN-CONTAINING COMPOUNDS WHICH ARE CANDIDATES REACTANTS FOR NITROGEN GENERATION

[From Sax, 1965, and Weast, 1977]

Compound and description	Molecular formula	Molecular weight g/g-mole	Density or specific gravity (a)	Melting point	Boiling point	Heat of formation, kcal/g-mole	Comments (b)
Ammonium hydroxide Colorless liquid	NH_4OH	35.5	---	-77° C	---	-87.64 (acqueous)	---
Hydrazine Colorless fuming liquid, white crystals	N_2H_2 $(NH_2\text{-}NH_2)$	32.05	1.011^{15} (liquid)	1.4° C	113.5° C	+12.05	Flash point is 126° F (open container) Autoignition occurs at 518° F
Hydrazine axide White powder	$N_2H4\text{-}HN_3$	75.07	---	75.4° C	---	---	---
Hydrazoic acid (Azoimide) Colorless liquid	HN_3	43.03	1.094^{25}	80° C	37° C	70.3	May be used to sustain SCWOS reaction temperature
Sodium Amide White crystalline powder	$NaNH_2$	39.02	---	210° C	400° C	-28.04	Yields heat with moisture
Sodium axide Colorless hexogonal crystals	NaN_3	65.01	1.846^{20}	---	---	---	Decomposes in a vacuum
Sodium nitride Dark grey crystals	Na_3N	82.98	---	$300^{\circ}C$[c]	---	---	To be considered only if sodium ions are highly desirable
Sodium nitrite Slightly yellowish or white crystals	$NaNO_2$	69.00	2.168^{0}	271° C	320° C[c]	-85.9	The oxygen elements may fuel the SCWOS combustion reaction
Sodium Nitrate Colorless crystals	$NaNO_3$	84.99	2.261	308.8° C	380° C[c]	-101.54 (crystalline) 106.65 (aqueous)	The oxygen elements may fuel the SCWOS combustion reaction (aqueoous)

[a] Superscripts and subscripts are temperatures in deg C.

[b] Many of the compounds are dangerous, some explosive; however, if there are ways to minimize the danger, they have been retained for comparison.

[c] Decomposition point.

processed water would be redirected to the hygiene water supply. In fact, the mass balance (Fig. 1) shows that there would be enough of this redirected water to be used for taking showers or for rinsing in the dishwasher and laundry machine.

Ordinarily, hygiene water would be used for laundering, dishwashing, showering, and handwashing. Surplus hygiene water could be stored for other Mars transit vehicle or Mars base operations. Dirty hygiene water and whatever humidity condensate was not processed by the SCWOS would be cleaned by reverse osmosis, a selective regenerable filtering process. After posttreatment, the clean water would be returned to hygiene water storage.

SPACE-STATION-TYPE ECLSS

One SS ECLSS (SS-ECLSS) concept (Anon., 1983; Lin, 1984) is depicted in Figure 2. This ECLSS concept is closed and resupply-free except for water filters, posttreatment chemicals, N_2 makeup, and food. Feces, garbage, hygiene sludge, and carbon (C) would be the byproducts requiring extensive waste management facilities. Excess clean water, however, would have many other uses outside the ECLSS. The system would need little scheduled maintenance except for frequent water filter changes, but even this chore represents a waste of time and precious storage space.

Seven subsystems would make up the air management group: the atmospheric pressure/composition control subsystem, the N_2 supply subsystem, the O_2 generation subsystem, the CO_2 removal subsystem, the CO_2 reduction subsystem, the trace contaminant control subsystem, and the humidity/temperature control subsystem. The water management group would have three reclamation subsystems: one for producing drinking water, one for hygiene water, and one for wash water (laundry and dishwashing). Having these three water groups would minimize energy and expendables.

COMPARISON OF THE ECLSS CONCEPTS

The differences between the two ECLSS concepts go beyond what appears on the schematics. Several ways in which the concept differences impact the Mars mission are disclosed in the following discussion.

As mentioned earlier, resupply weight and volume requirements are extremely crucial design considerations. The handling of wastes (trace contaminants, feces, trash, and garbage) by the SCWOS-ECLSS saves significant resupply weight and volume in terms of filters, bactericides, and waste containers. The wastes (solid, liquid, and gaseous) would actually be broken down into harmless combustion products. Bacteria would be destroyed, so concern about masking or filtering odors, resupplying bactericides, or venting and dumping wastes would be greatly reduced. In fact, the materials derived from the SCWOS-ECLSS waste reduction could be incorporated back into the ECLSS to help further close the system: CO_2 would go the CO_2 reduction, H_2O would go to potable water storage, and N_2 would go to the atmospheric pressure/composition control subsystem.

The N_2 supply concept of the SCWOS-ECLSS may be preferable to cryogenic storage. Cryogenic N_2 requires insulation and isolation to reduce boiloff. If boiloff rates exceed use rates, a high-pressure tank and pump may be required to eliminate loss of N_2. High-pressure storage is costly in terms of volume and weight. These problems may be eliminated in the SCWOS-ECLSS. The alternative offered by the SCWOS is to carry a powder, a grindable solid, or a liquid that is rich in elemental nitrogen (N) which can be reduced to N_2. The compound, being solid or liquid, would assume any desired shape for storage. In addition, several of the candidate compounds would break down into wastes that would reduce resupply weight elsewhere. Carrying nitrogen in solid or liquid form would greatly simplify logistics. The potential for this simplification exists with the SCWOS-ECLSS.

The air management group of the SCWOS-ECLSS is simpler than that of the SS-ECLSS. In one package, the SCWOS would remove the CO_2, the trace contaminants, and more than half of the water vapor from the air. Essentially two and one-half SS-ECLSS air management subsystems would be replaced by the SCWOS. Having fewer unique subsystems would reduce the crew's training load and cut down on the spare parts inventory, not to mention increasing the reliability and decreasing the maintenance of the ECLSS.

The water management group of the SCWOS-ECLSS is also simpler than that of the SS-ECLSS. The former has two water loops; the latter, three. The mass balances mentioned earlier indicate that the potable water supply level of the SCWOS-ECLSS, as compared to that of the SS-ECLSS, is less critically dependent on subsystem production and consumption rates.

In the SCWOS-ECLSS, twice as much potable water is produced daily as is used for drinking and food preparation. In the SS-ECLSS, the ratio of "produced" to "humanly ingested" potable water of nearly one to one signifies greater dependence on timing between the ECLSS entities. The relative abundance of potable water in the SCWOS-ECLSS opens up new integration possibilities, such as potable water showers and potable water rinse cycles for the laundry machine and dishwasher. These luxuries cannot be afforded as easily in the SS-ECLSS.

STATUS OF SCWOS DEVELOPMENT

Substantial work has been done to understand the chemistry of supercritical water oxidation and ways to develop the technology. Many sludges and solutions have been successfully converted to the products of complete combustion (CO_2, H_2O, and N_2) in a breadboard reactor.

However, there are still chemical and mechanical difficulties associated with processing some ECLSS wastes. For instance, although a recent discovery led to the complete combustion of urea (a major component of urine) at a lower than expected temperature (Swallow, 1984-85), the processing of urine has not been successful to date. (The as yet uncontrolled precipitation of urinary salts has clogged the reactor.) Furthermore, the preparation of trash and garbage for processing has not been successful. (Very little work has been done in this area.) Much development work lies ahead in reaction optimization, design optimization, and automation to use this technology for the Mars transit vehicle ECLSS.

For comparison with other candidate ECLSS waste management subsystems, the estimated SCWOS power level for processing the wash water, urine, and feces of an eight-person crew is 300-400 watts, continuous (Thomason, 1985). This power level excludes the energy for producing supplementary oxygen, but does not take credit for the carbon dioxide removal, the trace contaminant control, and the partial humidity control that results from the waste processing. (The process uses cabin air for the combustion oxygen supply.) Since the SCWOS process can be compared favorably with other candidate waste management subsystems, an ECLSS designed around an SCWOS should certainly do well in comparison with the more conventional partially closed ECLSS designs being considered for SS use.

CONCLUSIONS AND RECOMMENDATIONS

The following are some of the many reasons given in this paper for supporting the candidacy (and development) of the SCWOS-ECLSS for operation in the Mars transit vehicle; (1) Trace contaminants would be controlled without the consumption of expendables; (2) Waste management would be simplified and would require less storage room and maintenance; (3) The SCWOS would make useful byproducts out of trace contaminants and wastes; (4) Air management would be simplified; (5) Nitrogen logistics would be more manageable; (6) Logistics would be reduced and facilitated in many ways; (7) Water management would be simplified; (8) Luxuries such as bathing in potable water or having potable water rinse cycles for the laundry machine and dishwasher could be afforded; and (9) The SCWOS-ECLSS would allow more mission flexibility.

Hopefully, these qualitative advantages have stimulated interest in learning more about the quantitative differences (power consumption, heat rejection, weight, and volume differences) between the SCWOS-ECLSS and other candidate ECLSSs. These quantitative analyses are needed to fully appreciate the advantages or disadvantages of the ECLSSs.

The discovery of supercritical water oxidation could be fortunate for space exploration. This paper reveals the manner in which this technology would enhance long-duration Mars missions. Next, quantitative analyses are needed to gain a better appreciation for the advantages and disadvantages of the ECLSS concepts. Preliminary calculations encourage optimism toward the use of the SCWOS-ECLSS. This paper also presents the challenge of determining the nitrogen generation compound that would be most beneficial to the Mars mission.