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A Survey of Some Regenerative Physico-Chemical Life Support Technology

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INTRODUCTION

Food, oxygen, and water are basic physiological needs which must be satisfied to sustain man. In the terrestrial environment, these needs are met through the evolution of life forms that effectively use human waste products in conjunction with energy received from the Sun, to produce fresh supplies of food, oxygen, and water. Likewise, in the artificial environment of a space habitat, food, oxygen, and water must be provided and the waste products that humans generate must be stored or processed. The space habitat environment, however, does not have the capabilities or resources that are supplied by the Earth's biosphere to carry out these life-sustaining processes. Artificial methods must be utilized to supply man's needs.

To date, manned spaceflight has used the relatively simple technique of bringing all the necessary sustenance for the duration of the mission and collecting and storing waste products for return to Earth. This approach is referred to as an open life support system. It was recognized early, as manned missions became longer and crew size increased, that the weight, volume, and transportation penalties of storing or routinely resupplying consumables would at some point become too expensive. Since the early 1960s, regenerative environmental control and life support system (ECLSS) technology has been under development, and there now exists a foundation in both subsystem technology and systems definition to support long-duration manned missions (Gustan and Vinopal, 1982). (A regenerative ECLSS is referred to as either a partially closed or closed system depending upon the extent of closure.) In many cases this development has reached the engineering prototype stage, particularly for physico-chemical subsystems.

In this article, physico-chemical processes and subsystems designed for carbon dioxide (CO_2) concentration, CO_2 reduction, oxygen (O_2) and nitrogen (N_2) generation, water reclamation, solid waste processing, and trace contaminant control will be described. Food regeneration will not be discussed because physico-chemical processes for regenerating food from space habitat wastes have met with only limited success. Emphasis will be placed on physico-chemical waste conversion and related processes which provide sustenance and not on environmental factors or subsystems such as temperature and humidity control, space habitat architecture, decor and lighting, noise control, hygiene, etc. However, it is well recognized that these factors are closely allied to the space habitat ECLSS because they strongly influence a person's ability to lead a healthy and productive life in space.

ECLSS FOR THE SPACE STATION FREEDOM

With the advent of the Space Station Freedom, the United States has for the first time a long-duration space mission in which a regenerative ECLSS is significantly more cost effective than an open system (Hall et al., 1984). Figure 1 is a flow diagram showing mass balance for a conceptual design of a partially closed ECLSS for the Space Station Freedom. This flow scheme clearly demonstrates the complexity of even a partially closed system. Partial closure of this system arises from the need to resupply food and makeup N_2 because of space-cabin leakage. Figure 1 is a useful reference for locating within an integrated ECLSS some of the different subsystems that will subsequently be described.

CARBON DIOXIDE REMOVAL AND CONCENTRATION

A person's average daily production rate of CO_2, a metabolic waste product, is shown in table I. Carbon dioxide in a space-cabin atmosphere must be removed and concentrated to prevent it from reaching toxic levels and to provide a concentrated carbon dioxide stream to the CO_2 reduction subsystem for further processing. Table I shows the average design load for the Space Station Freedom CO_2 removal subsystem and table II gives the design requirements.

In an open ECLSS, CO_2 is removed from the spacecabin atmosphere by flowing CO_2 laden air through a canister containing a packed bed of lithium hydroxide (LiOH) granules. The spent LiOH is not regenerated and the canisters are returned to Earth for replenishment with fresh absorbent. The amount of LiOH required to remove one person's average daily output of CO_2 is shown in table III. Carbon dioxide removal by LiOH is acceptable for short, but not for long-duration, space missions because of its high weight penalty.

For a regenerative ECLSS there are several candidate subsystems for CO_2 removal and concentration. The three most popular and highly developed subsystems are the molecular sieve, electrochemical CO_2 concentrator, and solid amine resin.

Molecular Sieve Carbon Dioxide Removal Subsystem

The manned space mission called Skylab was the first United States spaceflight to use a regenerable CO_2 removal subsystem (RCRS). This subsystem contained a molecular sieve (zeolite) for adsorbing carbon dioxide, and, unlike LiOH, CO_2 adsorption on molecular sieve is easily reversible. The molecular sieve subsystem was selected for Skylab because an LiOH system would have weighed approximately 545 kg (1200 lb) while the RCRS system weighed only 15.4 kg (34 lb) (Coull, 1972).

The RCRS subsystem, figure 2, employed two canisters of molecular sieve for CO_2 adsorption. Each canister contained a predrier section of 13X molecular sieve and a CO_2 adsorption section of 5A molecular sieve. The predrier was required for the removal of water vapor in the air stream prior to reaching the CO_2 adsorption section. While one canister was adsorbing water (H_2O) and CO_2, the second canister was desorbing the previously adsorbed gases. The complete cycle took 1.8 ksec (30 min); i.e., 0.9 ksec (15 min) to adsorb and 0.9 ksec to desorb. The adsorption process was achieved by flowing cabin air through the canisters at cabin pressure and returning the CO_2 depleted air back to the cabin. The desorption cycle was achieved by merely exposing a canister to space vacuum. At the end of the desorption period, the regenerated canister was ready for readsorbing H_2O and CO_2. Because of an incremental amount of gas remaining on the molecular sieve at the end of each desorption cycle, a periodic bake out was necessary. Bake out was accomplished by merely heating the molecular sieve bed to 478 K while it was exposed to space vacuum.

It was found that a critical factor in the performance of a molecular sieve bed was the level of moisture present (Coull, 1972). Water adsorption on the 5A molecular sieve reduced the rate of CO_2

adsorption. For example, as a result of H_2O migration and loading of the molecular sieve bed after bake out, the partial pressure of carbon dioxide (pCO_2) in a simulated cabin environment increased about 2.7×10^3 Pa (0.2 mm Hg)/20 day interval.

If a pCO_2 level of 4.0×10^2 Pa (3.0 mm Hg), table II, instead of 8.3×10^2 Pa (6.2 mm Hg), was the design constraint, the RCRS would require modification. The modified version would need a regenerable silica gel bed instead of 13X molecular sieve for water removal at the inlet to the molecular sieve canister. This modification would use the dry CO_2-free effluent gas from the outlet of the molecular sieve bed to desorb water from the loaded silica gel bed. The moisture laden air would then be returned to the cabin to minimize H_2O loss to space during the molecular sieve desorption cycle. The heat necessary for desorption of H_2O from the silica gel would be derived from the heat of adsorption occurring on the adjacent adsorbing sieve bed. The proposed optimum design of this version of the RCRS would eliminate the 13X molecular sieve from the canister and also reduce the amount of 5A sieve required. The RCRS ranked below the solid amine resin and electrochemical subsystems for CO_2 removal in a technology assessment study for the Space Station Freedom (Hall et al., 1984).

Electrochemical Depolarized Carbon Dioxide Concentrator

Another highly developed CO_2 removal subsystem is the electrochemical depolarized CO_2 concentrator (EDC) (Heppner and Schubert, 1983). The EDC removes CO_2 continuously from low CO_2 partial pressure in a flowing air stream. The CO_2 exhaust from the EDC is premixed with hydrogen (H_2) and can be sent directly to a CO_2 reduction subsystem. The EDC also generates direct current (DC) power which can be used by other ECLSS subsystems.

In the EDC, CO_2 is continuously removed from the atmosphere by passing cabin air through a module consisting of a series of electrochemical cells, figure 3. The specific electrochemical and chemical reactions which take place within each cell are as follows:

Cathode Reactions:

$$1/2\ O_2 + H_2O + 2e^- = 2OH^- \tag{1}$$

$$CO_2 + 2OH^- = H_20 + CO_3^= \tag{2}$$

Anode Reactions:

$$H_2 + 2OH^- = 2H_2O + 2e^- \tag{3}$$

$$CO_3^= + H_2O = 2OH^- + CO_2 \tag{4}$$

Overall Reaction:

$$CO_2 + 1/2\ O_2 + H_2 = CO_2 + H_2O + \text{Electrical Energy} + \text{Heat} \tag{5}$$

Reactions (1) and (3) are the same electrochemical reactions that occur in a hydrogen-oxygen (H_2-O_2) fuel cell with an alkaline electrolyte. The products of this electrochemical reaction are H_2O and DC power. With CO_2 present in the cabin air stream, the hydroxyl ions (OH^-) being generated at the cathode react with the CO_2 to give carbonate ions ($CO_3^=$) and H_2O, shown as reaction (2). The product

$CO_3^{=}$ now takes the place of the OH^- as the primary charge carrier within the cell, migrating toward the anode where a shift in pH results in the CO_2 being released from solution as shown in reaction (4). The overall reaction occurring in an EDC produces DC power as shown by equation (5).

Figure 3 illustrates the construction of a typical EDC cell showing an electrode/matrix/electrode assembly and the various fluid streams. Each cell consists of two electrodes separated by a porous matrix containing an aqueous electrolyte, cesium carbonate (Cs_2CO_3). Approximately 25% of the heat generated by the reactions occurring in the EDC is removed by the process air and the H_2-CO_2 streams. The remaining heat is removed by a separate liquid cooling stream. The liquid coolant temperature is controlled to maintain the electrolyte moisture balance within desired limits, allowing the EDC to operate over the relative humidity range of about 20 to 80%. Typical operating characteristics of an EDC module are given elsewhere (Heppner and Schubert, 1983).

The EDC can be operated in a continuous or cyclic mode. The capability of operating in either mode is particularly attractive for day-night cycling to conserve power aboard a solar-cell-powered space habitat. Another advantage of the EDC is that with the same size subsystem, different CO_2 removal rates can be achieved by merely changing operating conditions, specifically the current level. For the Space Station Freedom application, the DC power generated by the EDC can be used directly by the electrochemical module of the O_2-generation subsystem (a water electrolyzer to be described later) resulting in an offset of about 10% of the total DC power needed. The major weight penalty for the EDC is the indirect penalty for power required by an O_2-generation subsystem to produce the O_2 consumed by the EDC. Hall et al. (1984) ranked the EDC first among the three candidate CO_2 removal subsystems considered for the Space Station Freedom.

Solid Amine Resin Carbon Dioxide Removal Subsystem

The evolution of amine resin usage to control CO_2 in a confined environment can be traced back to work related to submarine air purification (McConnaughey et al., 1957) and research associated with gas sorbents used in anesthesiology (Smart and Derrick, 1957). Subsequent laboratory studies (Tepper et al.. 1968) showed weak base amine resins were promising for CO_2 removal and a commercial resin IR-45 (now designated Amberlite IRA-45, manufacturer Rohm and Haas Chemical Co.) was selected for scale-up studies.

A two-bed, solid-amine-resin, CO_2 removal subsystem is illustrated by the schematic in figure 4. The two major components of this subsystem are the canisters which contain the resin absorbent and the steam generator (Dresser and Cusick, 1984). The resin scrubs CO_2 from the air and the steam is used to desorb CO_2 from the spent resin. The active chemical or resin in the canisters is 0.52-1.13-mm-diameter beads of a polystyrene-divinylbenzene copolymer aminated with diethylenetriamine and designated IRA-45. This substrate exposes a large surface area of amine to the spacecabin atmosphere for CO_2 removal. This CO_2 removal subsystem is referred to as the solid amine water desorbed (SAWD) subsystem.

The resin absorbs CO_2 by first combining with water to form a hydrated amine which in turn reacts to form a bicarbonate. These reactions are represented by the following two equations:

$$\text{Amine} + H_2O = \text{Amine} - H_2O \qquad (6)$$

$$\text{Amine} - H_2O + CO_2 = \text{Amine} - H_2CO_3 \qquad (7)$$

The amine is regenerated by applying heat to break the bicarbonate bond thus releasing CO_2 by the reaction:

$$\text{Amine} - H_2CO_3 + \text{Steam Heat} = CO_2 + H_2O + \text{Amine} \qquad (8)$$

Water is important to the absorption process because the dry amine cannot react with CO_2 directly. Between 20- and 35-wt % water in the resin bed is required for optimum absorption. This requirement impacts operating ranges by reducing CO_2 absorption capacity at a low relative humidity for the spacecabin.

During desorption, an electrically heated steam generator converts H_2O into steam. The steam heats the bed and pushes residual ullage air out of the canister at a low flow rate. As steam/air reaches the outlet end of the bed, a CO_2 wave evolves off the bed, sharply increasing the flow rate. A flow sensor detects the flow increase and activates a valve, switching the CO_2 flow to a CO_2 accumulator for subsequent use in a CO_2 reduction subsystem. By using steam desorption at 2.1×10^5 Pa (30 psi), CO_2 can be compressed in the accumulator. The desorption temperature is controlled by the saturation temperature of steam. The steam used for desorption is recovered by first evaporating it into the process air flow during CO_2 absorption then condensing it in the humidity control heat exchanger of the ECLSS. Recently, it was reported that toxic decomposition products arise from the resin by steam desorption (Wood and Wydeven, 1987). The major weight penalty associated with the SAWD system is that associated with steam generation and heat rejection.

A two-canister SAWD subsystem, figure 4, operates by alternating the absorb/desorb cycles of each canister. For space missions where power may be limited during specific portions of an orbit (e.g., a solar-cell-powered mission in the dark interval of an orbit) the SAWD subsystem would be desorbed on the light side where power is readily available and absorption would take place on the dark side only.

CARBON DIOXIDE REDUCTION

In a partially closed or closed physico-chemical ECLSS the output from the CO_2 concentration subsystem is used as the input for the CO_2 reduction subsystem. (Carbon dioxide reduction is not required for an open ECLSS.) Carbon dioxide is chemically reduced in the CO_2 reduction subsystem, figure 1. Two methods for CO_2 reduction have received the most attention to date, the Sabatier and Bosch processes. Of these two processes, the Sabatier process and hardware are particularly well developed.

Sabatier Process

In the Sabatier process, CO_2 is reduced by H_2 in the presence of a catalyst according to the following equation:

$$CO_2 + 4\,H_2 = CH_4 + 2H_2O + \text{heat} \qquad (9)$$

The exothermic heat of reaction is 4.2×10^3 joules/gr CO_2 at 700 K. In a space habitat, the exothermic heat would be removed by the thermal control subsystem. Hydrogen for the reaction is obtained from H_2O electrolysis. Water vapor exiting the Sabatier reactor would be condensed and stored for subsequent consumption by the crew or electrolyzed to produce O_2 for respiration or to meet other water needs. Methane (CH_4) would be either vented to space, decomposed to reclaim H_2 or used for propulsion or navigation. Venting of CH_4 to space is undesirable if CH_4 interferes with astronomical instrumentation or observations.

Figure 5 is a simplified schematic of a Sabatier reactor. A more detailed schematic can be found elsewhere (Kleiner and Cusick, 1981). Hydrogen and carbon dioxide, free of contaminant gases, flow into the reactor where CO_2 is catalytically converted to CH_4 and H_2O vapor. A nominal CO_2 flow rate into the reactor is 41.8 gr/person-hr. Typical total supply pressure of reactants ranges from 124 to 138 kPa (18-20 psi). An effective catalyst for the reduction reaction is 20 wt % ruthenium supported on alumina (Kleiner and Cusick, 1981). Because of the high activity of this catalyst, reduction begins at 450 K and from then on the reaction is self-sustaining, (i.e., no external heat is required), a particularly attractive feature for most space habitats where power is limited. Above 866 K the reverse endothermic reaction (eq. (9)) occurs which prevents overheating. Typically, the operating temperature range of a Sabatier reactor is 450-800 K. Single-pass conversion efficiencies of the lean component are reported to be in excess of 98% for molar ratios of H_2/CO_2 ranging from 1.8 to 5.0 (Kleiner and Cusick, 1981). The lean component is H_2 for molar ratios of H_2/CO_2 from 1.8 to 4, and CO_2 for molar ratios from 4 to 5. Any excess H_2 is recycled to the inlet of the reactor. By-products such as carbon (C) or carbon monoxide (CO) are minimized when H_2/CO_2 feed ratios slightly exceed stoichiometric values; i.e., 4:1.

A preprototype Sabatier reactor which operates independent of gravity has been built and extensively tested (Kleiner and Cusick, 1981). This subsystem had the capacity to reduce the average amount of CO_2 respired by five people. The assembly weighed 43.1 kg (95.0 lb) and had the dimensions: 61 x 63.5 x 45.7 cm deep (volume 6.3 ft^3).

Bosch Process

In the Bosch CO_2 reduction process, CO_2 reacts catalytically with H_2 from water electrolysis to form solid C and H_2O, with the C depositing on the catalyst. The overall equation describing the Bosch process reaction is:

$$CO_2 + 2H_2 = C + 2H_2O + \text{heat} \qquad (10)$$

The exothermic heat of reaction is 2.3×10^3 joules/gr CO_2 at 922 K and it would be removed in a space habitat by the thermal control subsystem. Solid C deposits on the catalyst and the catalyst-carbon combination would be periodically replaced with a cartridge of fresh catalyst. In a space habitat, the H_2O vapor exiting the reactor would be condensed and stored for subsequent consumption by the crew, electrolyzed to produce O_2 for respiration or to meet other water needs.

Figure 6 is a simplified schematic of a Bosch reactor. The feed gases, CO_2 and H_2, are compressed and heated before contacting the catalyst bed. A typical Bosch process total feed gas pressure is 1.29×10^5 Pa (19 psi) and temperature is 922 K. Activated steel wool has generally been used as the catalyst; however, other catalysts, including some ruthenium-iron alloys, have also been used successfully in laboratory studies (Sophonpanich et al., 1985). Single-pass CO_2 reduction efficiencies are generally less than 10% with the Bosch process. Therefore, to obtain complete reduction with this process the reactor must be run in a recycle mode. The reactant molar ratio used to achieve 10% efficiency is $2H_2{:}1CO_2$. The recycled gas mixture contains CO_2, CO, CH_4, H_2, and H_2O vapor. Carbon is continuously deposited on the catalyst and H_2O vapor is continuously condensed and separated from other gases at the reactor outlet. The activity or adsorption capacity of the C produced in a Bosch reactor has also been studied. These studies revealed that Bosch C had an adsorption capacity about a factor of 50 lower than commercial-gas-phase-activated C adsorbents (Manning and Reid, 1973). High-C activity is desirable if the carbon is to be used for space habitat atmospheric or waste water contaminant removal.

Bosch process hardware is less developed than the hardware for the Sabatier process. Therefore, firm estimates for the weight, volume and power required by a Bosch subsystem are unavailable. Estimates for a three-person-capacity subsystem (with six-person maximum capacity) are 91 kg (200 lb), 9 ft^3 and 250-350 W.

Selection between a Bosch or Sabatier subsystem for the United States Space Station Freedom will be influenced by the venting or overboard dumping requirement for this vehicle. If the requirement does not allow venting to space, then the Bosch subsystem appears to be the stronger candidate. If venting is allowed or if the methane from a Sabatier reactor can be used effectively for propulsion or space habitat orientation or if the methane can be efficiently decomposed, then the Sabatier subsystem may be selected. A Sabatier reactor coupled with a methane decomposition unit is being investigated (Noyes and Cusick, 1985). A recent comparison study describes further the advantages and disadvantages of the Sabatier and Bosch processes and the operational impact of both on a space habitat (Spina and Lee, 1985).

OXYGEN GENERATION

In an open ECLSS, the O_2 required to meet a person's metabolic requirement, table III, and to make up for spacecabin leakage is obtained from a stored cryogenic O_2 source and scavenged from spent O_2 fuel tanks. In a regenerative ECLSS, particularly for the first generation of very long duration manned space missions such as the Space Station Freedom, it is generally agreed that water electrolysis will be used to regenerate O_2 for respiration (Wydeven and Johnson, 1968). Design loads and requirements for the O_2 subsystem of a Space Station Freedom ECLSS are given in tables I and II. The by-product H_2 from H_2O electrolysis would be used to regenerate H_2O by reduction of expired CO_2 (eqs. 9 and 10). Supply H_2O for the electrolyzer would come from a storage tank which contains H_20 from CO_2 reduction, thus completing the cycle of O_2 recovery from CO_2.

The importance of H_2O electrolysis to the physico-chemical life support system has prompted one author (Schubert et al., 1984) to refer to it as "a Space Station Freedom utility." The importance arises from the multiple uses for the O_2 and H_2 produced by H_2O electrolysis. For example, the H_2 and O_2 may be used as fuels for a regenerative H_2-O_2 fuel cell power supply or for flight experiments which require these gases.

Two different electrolyzers designed to operate independent of gravity have been under development for more than 20 years, the solid polymer electrolyte (SPE) and the static feed H_2O electrolysis subsystems (SFWES) (Titterington and Erickson, 1975; Schubert et al., 1981). A much less developed method for O_2 generation is CO_2 electrolysis. This O_2 recovery method uses CO_2 from the CO_2 concentrator as the process gas instead of water. An ECLSS, which relies on CO_2 electrolysis for O_2 generation, does not require a CO_2 reduction subsystem such as a Sabatier or Bosch subsystem. Solutions to some technological problems (e.g., high temperature ceramic-to-ceramic seals) must be overcome before this approach to O_2 generation becomes competitive with H_2O electrolysis.

Solid Polymer Water Electrolysis Subsystem

The solid polymer water electrolysis concept is an extension of solid polymer fuel cell technology. The solid polymer fuel cell was the primary electrical power source aboard the space habitats for NASA's Gemini and Biosatellite space missions. The first prototype SPE electrolyzer was built in 1970.

The electrolyte in the SPE is a solid plastic sheet or membrane of perfluorinated sulfonic acid polymer about 0.30 mm (0.012 in.) thick. When saturated with H_2O, this polymer is an excellent ionic conductor (15 ohm-cm resistivity) and is the only electrolyte required in the system (Titterington and Erickson, 1975). An SPE cell is shown schematically in figure 7 along with its associated electrode reactions. Catalyzed electrodes for improving power efficiency are placed in intimate contact with both sides of the membrane. The cell membrane prevents intermixing of O_2 and H_2 gases and also eliminates the need for an H_2O-O_2 separator on the O_2 outlet side of the cell.

The deionized process H_2O used in the SPE subsystem acts as both a reactant and coolant and is fed to the H_2 electrode side of the cell. The SPE cell membrane is sufficiently permeable to allow H_2O to diffuse from the H_2 electrode or cathode to the O_2 electrode or anode where it is electrochemically decomposed to provide O_2, hydrogen ions (H^+) and electrons. The hydrogen ions move to the hydrogen evolving electrode by migrating through the membrane. The electrons pass through the external electrical DC circuit to reach the hydrogen electrode. At the hydrogen electrode, the H^+ and electrons recombine electrochemically to produce H_2 gas. Hydrogen gas is separated from the water feed by a dynamic 0-g phase separator pump located external to the electrolyzer. The SPE subsystem can deliver O_2 or H_2 at any pressure required by simply back pressuring the corresponding gas side. However, for high-pressure operation (790 kPa (115 psi)), the cell is enclosed in a pressure vessel and the differential pressure across the SPE is controlled by the subsystem gas regulators.

A six-person capacity preprototype SPE electrolyzer module made up of 13 single cells has been designed, assembled, and tested (Titterington and Erickson, 1975). The stack of cells was enclosed in a pressure vessel which was pressurized with N_2 to approximately 345 kPa (50 psi) above the cell internal operating pressure. The pressurized jacket eliminated gasket blowout from high cell pressures while providing an inert gas blanket in the event of a module gasket failure. The nominal operating temperature of the module was 355 K. Power was delivered to the electrolysis module from a 28-V-DC power supply through a power conditioner which acted as a current regulator for maintaining a selected gas production rate. Representative module operating conditions are given in table IV.

The SPE can be operated either continuously or cyclically. Cyclic operation is beneficial for reducing power consumption aboard a solar-cell-powered space habitat when it is shielded from the Sun. A high pressure 20,700 kPa (3000 psi) SPE O_2 generation single cell has also been designed and tested for its potential applicability to a Navy submarine environmental control system or for recharging high-pressure O_2 gas bottles needed for extravehicular activity in space.

Static-Feed Water-Electrolysis Subsystem

An O_2 generation subsystem based on the static-feed water-electrolysis concept (SFWES) and using an alkaline electrolyte has been under development for use in a space habitat for about 14 yrs. In addition to being developed for O_2 generation, an SFWES has also been designed and tested for regenerative H_2-O_2 fuel cell technology for a space habitat and other energy storage applications (Schubert et al., 1981).

An SFWE cell functional schematic and the accompanying electrochemical reactions are shown in figure 8. Power for electrolysis is provided by a DC power supply and waste heat is removed by a circulating liquid coolant located adjacent to the O_2-generation cavity. Water for electrolysis is provided by the water feed matrix. Water evaporates from the feed matrix and condenses on the cell matrix where it is subsequently electrolyzed. Both the water feed and cell matrices consist of thin asbestos sheets saturated with a hygroscopic aqueous potassium hydroxide (KOH) solution. Poisoning of the catalyst on the metal electrodes of the electrolysis cell is prevented by not allowing liquid feed water which may contain catalyst poisons from contacting the electrodes. At the start of electrolysis, both the water feed and cell matrices have equal KOH concentrations. As DC power is supplied to the electrodes, water in the cell matrix is electrolyzed, thereby increasing the KOH electrolyte concentration. The KOH concentration gradient which then exists between the cell and water feed matrices causes water vapor to diffuse from the feed to the cell matrix. Water removed from the water feed compartment is statically replenished from an external water supply tank.

Extensive testing of the SFWE concept has been carried out at both the single cell and multiman module level. The characteristics of an SFWE module capable of meeting one person's metabolic requirement are given in table V. In the module, process gas flowed in parallel through the cells which were connected electrically in series. Lower module voltage was achieved by operating at an elevated temperature of 339 K. To prevent condensation of water in the cooler hydrogen and oxygen outlet lines when operating at elevated temperatures, the module was operated at a water feed pressure of 1.34 MPa (195 psi). Expansion from the operating to ambient pressure lowered the product gas dew point sufficiently to eliminate the need for any condenser/separator. Design operating pressures for the O_2 and H_2 cavities in the module were 1282 and 1261 kPa, respectively.

If coupled to a water vapor electrolysis dehumidifier module, water vapor can be removed from the effluent O_2 line of a SFWES, thereby providing additional oxygen and eliminating the need for a water-vapor/O_2 separator (Schubert and Wynveen, 1977). Like the SPE, the SFWES can be operated continuously or cyclically and if desired at high pressures (~1000 psig) (Quattrone and Wynveen, 1983). Additional information regarding the SFWES can be found elsewhere (Larkins and Kovach, 1985). In a technology assessment study for the Space Station Freedom, Hall et al. (1984) recommended the SFWES for metabolic O_2 recovery.

Carbon Dioxide Electrolysis

Carbon dioxide electrolysis using a solid oxide electrolyte is another method for regenerating O_2 aboard a space habitat (Weissbart et al., 1969; Reid, 1970). This method takes CO_2 directly from the CO_2 concentrator and electrolyzes it to generate O_2. The solid electrolyte subsystem can electrolyze both CO_2 and H_2O vapor to continuously generate enough O_2 to meet a person's metabolic requirement and make up for spacecabin leakage, thereby eliminating the need for an additional water electrolyzer. Only oxide ions ($O^=$) can migrate through the solid electrolyte; consequently, separation of O_2 from CO_2 and other product gases is excellent. Since CO_2 electrolysis is an electrolytic process, it is capable of operating at several times its design capacity. Increased O_2 output is achieved by merely increasing the DC voltage applied to the electrolyzer. Technological problems, such as ineffective high-temperature ceramic-to-ceramic seals, have prevented the solid electrolyte subsystem from reaching the same level of development as the SPE and the SFWES.

In the solid electrolyte process, advantage is taken of the fact that $O^=$ will transfer through certain ceramic oxides at high temperatures when driven by a DC voltage, figure 9. The process gases, CO_2 or CO_2 and H_2O vapor, are heated to about 1200 K and fed to the cathode side of the solid electrolyte. Both sides of the electrolyte are coated with a porous metal catalyst-electrode, such as platinum. The electrodes are connected to a DC power supply and the following reduction reaction occurs at the cathode when using CO_2 as the process gas:

$$CO_2 + 2e = CO + O^= \tag{11}$$

where e refers to electrons. Oxide ions diffuse across the electrolyte by ion conduction; at the anode, the following oxidation reaction occurs:

$$O^= = 0.5\ O_2 + 2e \tag{12}$$

In a space habitat, the O_2 would be returned to the spacecabin for respiration. Any unreacted CO_2 and CO leave the cell and are cooled to about 800 K. The CO flows to another reactor where most of it reacts by disproportionation as follows:

$$2CO = C + CO_2 \tag{13}$$

Solid C deposits on the disproportionation reactor catalyst and the CO_2 formed is recycled to the electrolysis cell. In the CO reactor, nickel, iron, or cobalt catalysts are ordinarily used to accelerate the disproportionation reaction. No problems are anticipated in operating a solid electrolyte subsystem in zero gravity since no liquid phases are present in any process steps.

The solid electrolyte O_2 recovery process is still in the early developmental phase. Consequently, it is difficult to make meaningful weight, volume, and power estimates for a solid electrolyte subsystem. Certainly this process shows great potential if long-term, leak-free operation can be demonstrated, if the power requirements can be held low, and if the CO or H_2 (when using the solid electrolyte for H_2O electrolysis) can be removed without subsystem degradation (e.g., reduction of the electrolyte itself by CO_2 or H_2).

Superoxides

Alkali and alkaline earth metal superoxides are solid chemicals which serve the dual purpose of providing O_2 and scrubbing CO_2 in a life support system. The usefulness of these active chemicals arises from the reactions that occur when these compounds are exposed to water vapor such as that present in human breath.

The available Soviet popular and technical literature related to the Soviet man in space program has consistently referred to the use of "active chemicals" as the prime method of maintaining habitable atmospheres in Soviet spacecabins (Petrocelli, 1965). These "active chemicals" are believed to be superoxides. Active chemicals have not been used aboard United States space vehicles.

In the case of superoxides, stored O_2 is released according to the reaction:

$$2MO_2(s) + H_2O(v) = 2MOH(s) + 1.5\ O_2(g) \tag{14}$$

where s, v, and g refer to a solid, vapor, and gas, respectively. Carbon dioxide is removed from the atmosphere by reacting with the product hydroxide (MOH) causing formation of carbonate (M_2CO_3) and bicarbonate ($MHCO_3$):

$$2MOH(s) + CO_2(g) = M_2CO_3(s) + H_2O(l) \tag{15}$$

$$2MOH(s) + 2CO_2(g) = 2MHCO_3(s) \tag{16}$$

where l refers to a liquid.

The only superoxide produced on an industrial scale is potassium superoxide (KO_2); therefore, it is the only active chemical that has been used extensively in breathing applications. Potassium superoxide canisters used in self-contained breathing apparatus for fire fighting and mine rescue work have exhibited poor utilization efficiency (50-80%) and some overheating problems because of the high exothermic heats of reaction (Buban and Gray, 1974). The low efficiency was attributed to the formation of a hydrous coating of reaction products on the surface of unreacted KO_2 (Wood and Wydeven, 1985). This problem led to recent research on other superoxides, particularly calcium superoxide ($Ca(O_2)_2$) and mixtures of $Ca(O_2)_2$ and KO_2 (Wood and Wydeven, 1983). Calcium superoxide also has a higher available O_2 content and a greater CO_2 scrubbing capacity per unit weight of chemical than KO_2, table VI. Mixtures of $Ca(O_2)_2$ and KO_2 show improved utilization efficiencies when compared to KO_2.

Consideration is being given to using a superoxide for O_2 storage in a safe haven for the United States Space Station Freedom in the case of an emergency. A solid chemical is particularly suited for this application because it has an indefinite shelf life, unlike cryogenic O_2.

NITROGEN GENERATION

It will be necessary to replenish the diluent gas (generally nitrogen) lost through leakage in a human space habitat with an air atmosphere. Nitrogen will also be needed on the Space Station Freedom for periodically purging other life support subsystems and the space habitat airlock. The projected leak rate of nitrogen for the Space Station Freedom ECLSS configuration shown in figure 1 is 2.8 kg/day.

Nitrogen is resupplied from high pressure gas bottles for short-duration missions, e.g., the Space Shuttle. For longer duration missions, such as the Space Station Freedom, consideration will be given to using other N_2 supply methods to reduce the weight of this resupply subsystem. Only one method of nitrogen generation has been extensively developed. It is based on the thermal catalytic dissociation of hydrazine (N_2H_4) (Powell and Schwartz, 1985). Hydrazine is a commodity aboard most space habitats for rocket engine propulsion and refueling of satellites which use N_2H_4 thrusters.

Thermal catalytic dissociation of N_2H_4 at 1005 K and 1.7 MPa (250 psi) followed by catalytic ammonia (NH_3) decomposition involves the following equilibria:

$$3N_2H_4 = N_2 + 4NH_3 + \text{heat} \tag{17}$$

$$4NH_3 + \text{heat} = 2N_2 + 6H_2 \tag{18}$$

Catalytic ammonia decomposition and hydrogen separation are carried out in several stages following N_2H_4 dissociation. Hydrogen is separated from N_2 using palladium-silver alloy tubes and is then available for carbon dioxide reduction, attitude control or other laboratory uses. An N_2H_4 dissociator having an average generating capacity of 4.4 kg N_2/day was recently tested (Powell and Schwartz, 1985). Test results have shown that the N_2H_4 dissociation/separation concept is feasible and the technology is undergoing further development.

TRACE CONTAMINANT CONTROL

Airborne biological and chemical contaminants, including particulates, in the closed environment of a space habitat must be controlled to prevent them from adversely affecting the astronauts and instrumentation. Space maximum allowable concentration (SMAC) levels in a spacecabin atmosphere have been established for many individual and classes of contaminants (e.g., table VII) (Wydeven et al., 1988). The function of the contaminant control subsystem is to eliminate odors and prevent allowable contaminant levels from being exceeded. To reduce the burden on the removal subsystem, precautions are taken in the design and assembly of space habitats to use materials which minimize the release of contaminants to the atmosphere.

In past United States spaceflights, contaminants and odors were controlled primarily by nonregenerable activated charcoal located in the LiOH canisters and filters for particulates and microbes. After the third Space Shuttle flight, a low-temperature catalytic oxidizer was added primarily to control CO. Coincidentally, some contaminants are also removed by the condensing heat exchanger of the cabin humidity control subsystem. As crew size and mission duration increase, contaminant control aboard manned space habitats will become increasingly more important and the removal subsystem will become more complex.

The contaminant load model determines the configuration and size of a contaminant removal subsystem, particularly the amount of activated charcoal needed (Olcott, 1975). Figure 10 delineates a contaminant control subsystem designed for the load model given in table VII. The major elements of the subsystem are the nonregenerable and regenerable activated charcoal beds, a high-temperature catalytic oxidizer and pre- and postsorbent LiOH beds. The nonregenerable activated charcoal bed, impregnated with phosphoric acid, is designed for control of well-adsorbed contaminants, ammonia and water-soluble contaminants. A filter located downstream of the fixed bed prevents particulates from entering other parts of the system.

About 10% of the effluent from the fixed bed enters the smaller regenerable activated charcoal bed while the remaining air is ducted to the cabin. The low air-flow rate (long residence time) through the regenerable bed relative to the nonregenerable bed, aids in the removal of contaminants that are poorly adsorbed by charcoal. The use of the combined nonregenerable and regenerable charcoal beds reduced the weight of charcoal needed to handle the load model. The regenerable bed was reactivated by using heat and vacuum desorption. At the end of a desorption cycle the charcoal bed temperature was 366 K and the pressure inside the charcoal canister was 6.7 x 10^{-3} Pa (5 x 10^{-5} mm Hg). The time required for regeneration was 11.7 ksec (195 min) (Olcott, 1972, 1975).

A nonregenerable LiOH presorbent bed is located upstream of the catalytic oxidizer to prevent acid gases (e.g., HCl and SO_2) from entering the oxidizer and poisoning the catalyst. The high-temperature catalytic oxidizer contains an oxidation catalyst, such as palladium on alumina, and operates at 711 K. The primary function of the catalytic oxidizer is to oxidize hydrocarbons not adsorbed in the charcoal beds. The effluent from the oxidizer flows to the nonregenerable postsorbent LiOH bed which removes any undesirable acidic products of oxidation. Halogenated compounds if allowed to reach the oxidizer could produce acidic compounds.

A prototype contaminant control subsystem containing the components described above has been assembled and tested (Olcott, 1975). The integrated subsystem was operated for 215 days with a simulated contaminant load. It maintained the levels of gas in the atmosphere below the maximum allowable concentration with the exception of CO and methyl alcohol which only slightly exceeded the allowable levels. Only two equipment malfunctions were encountered during the test period. A most significant finding of the test program was verification of the techniques used in constructing the removal subsystem to handle a given load model. These techniques will allow new contaminant control subsystem designs to be generated for differing requirements, as well as predicting the performance of existing designs. Further details of the test program can be found elsewhere (Olcott , 1972, 1975).

TRACE CONTAMINANT MONITORING

A prerequisite to controlling atmospheric contaminants is being able to monitor both the types and concentrations of contaminants. Monitoring is a particularly difficult task because of the variety of chemical species to be monitored and the high sensitivity required. Often sensitivity is required in the parts per billion range, especially for the more toxic species of contaminants. Work on the development of monitoring instrumentation to meet space habitat standards (i.e., lightweight, low-power consumption, and automatic operation) has been on-going since about 1968.

One of the most developed monitoring instruments for space habitat usage is the mass spectrometer (MS). This MS is coupled to an inlet system for concentrating contaminants on selected sorbents (Rotheram and Ruecker, 1972). When coupled with an inlet system for concentrating contaminants the MS has the required sensitivity for detecting low concentrations and provides directly relatable data for compound identification. Finally, mass spectrometers have flown on experimental rockets and satellites for over 30 yrs and can withstand the rigors of spaceflight.

Contaminant monitoring has not been a major concern on United States spaceflights to date, primarily because of short mission duration. However, for longer manned missions such as the Space Station Freedom it will be necessary to monitor the atmosphere to detect the buildup of undesirable products in the crew compartment or experiments laboratory.

WATER RECYCLING

Projected water needs and sources of waste water for the United States Space Station Freedom are given in table I. The estimated total amount of water required for an open ECLSS is given in table III. The lower value in table III is the minimum estimated water requirement and the higher value is the typical amount of water required for terrestrial applications. The higher value is also considered more desirable for a space habitat. The amount of water required ranges from 57 to 73% of the total expendables. In light of the large amount of water required relative to other expendables, a high priority must be placed on water recycling if the weight of the ECLSS for a long-duration space mission is to be reduced or minimized.

Water has been stored aboard the space habitat or reclaimed from H_2-O_2 fuel cell by-product water for short-duration missions. However, others have shown that for missions even as short as 60 person-days (number of astronauts x mission duration, days) water recovery has a lower weight penalty than stored water (Schubert, 1983).

Methods under consideration for recycling water aboard a space habitat can be placed into two categories, distillation and filtration processes. Among the distillation or phase change processes, three different approaches have been pursued, vapor compression distillation (VCD), thermoelectric integrated membrane evaporation (TIMES), and vapor phase catalytic ammonia removal (VAPCAR). The filtration processes receiving the most attention are reverse osmosis (RO) and multifiltration. The process selected for water recycling will depend on the source of waste water and the quality of water needed for a given application. It is anticipated that for the first generation of long-duration space missions there will be two water recycling and storage subsystems. One subsystem will process concentrated feeds, such as urine and flush water, and the second, a more dilute feed such as laundry or shower water. Potable water will probably be recycled using a phase change process while lower quality water will be recovered by filtration. The ultimate goal, however, is to have one space habitat water recovery subsystem.

In addition to the subsystems designed specifically for reclaiming space habitat waste water, by-product water is derived from other space habitat subsystems, such as H_2-O_2 fuel cells, CO_2 reduction (eqs. 9 and 10) and the space habitat condensing heat exchanger used for cabin humidity control. Water from CO_2 reduction is of high quality since it was derived from a high-temperature process which destroys harmful bacteria. Also, the feed gases used for CO_2 reduction are clean. Water derived from fuel cells and the condensing heat exchanger may require posttreatment to remove chemical and biological impurities prior to being reused. Each of the water recovery processes being considered for use in space will be described next.

Vapor Compression Distillation

Vapor compression distillation is a phase change water recovery process which has been under development for more than 20 years and it is the most highly developed of the space habitat water purification subsystems (Schubert, 1983).

A conceptual schematic of the VCD process is shown in figure 11. The recovery of latent heat in the VCD process is accomplished by compressing the vapor or steam to raise its saturation temperature and then condensing the vapor on the surface in direct thermal contact with the evaporator. The resultant heat flux from the condenser to the evaporator, driven by this saturation temperature differential, is sufficient to evaporate a mass of water equal to that being condensed. Thus, the latent heat of condensation is recovered for the evaporation process. The only energy required by the VCD process is that necessary to compress the vapor and overcome thermal and mechanical losses.

The VCD process is a thermally passive process and requires no active temperature control. Waste heat generated by the process results in an operating temperature slightly above ambient; i.e., between 294 and 308 K. The resulting nominal condenser pressure is 4.8 kPa (0.7 psia). The evaporator, condenser, and condensate collector are rotated to provide for zero-gravity phase separation. The VCD process has evolved to enable recovery of more than 96% of the water contained in urine, concentrating the urine to over 50% solids. Higher recovery percentages result when processing more dilute water streams. The quality of the water recovered from the VCD process will depend on the volatile organics and ammonia that co-condense with the water. Pretreatment of VCD waste water feed (e.g., with an acid) will probably be necessary to stabilize urea and prevent its decomposition to ammonia. Posttreatment of VCD product water may also be necessary before it is reused. Any noncondensible gases (CO_2, N_2, volatile organics, etc.) evolved during distillation by the VCD process cause a pressure build-up and reduced evaporation efficiency. Restoration of efficiency requires periodic evacuation of the evaporator and treatment of the undesirable volatiles.

Thermoelectric Integrated Membrane Evaporation Subsystem

The thermoelectric integrated membrane evaporation subsystem (TIMES) employs a phase change process which uses a thermoelectric heat pump to transfer heat from a water condenser to an evaporator. This process has not been under development as long as the VCD process, but remains a candidate for recycling water on long-duration missions (Schubert, 1983).

A schematic of the TIMES concept is shown in figure 12. This process recovers only a portion of the latent heat of condensation and transfers this heat to the evaporator via multiple thermoelectric elements. Waste H_2O is heated to 339 K in a heat exchanger both by heat actually pumped by the thermoelectric elements and by heat generated because of inefficiency of these elements. The waste H_2O is then pumped through hollow fiber membrane evaporator modules. The exterior of the fibers is exposed to reduced pressure (17.2 kPa (2.5 psia)) causing H_2O to evaporate from the outer tube surfaces. The vapor is condensed on a porous plate surface in contact with the cold junctions of the thermoelectric elements.

Thermal control is required by the TIMES process since a major portion of the heat generated by the inefficiencies of the thermoelectric elements is used to partially offset the heat required for vaporization. An equivalent amount of latent heat liberated during vapor condensation is, therefore, not used and must be rejected from the process. Thermal control is maintained by circulating a portion of the condensate through an external heat exchanger and rejecting heat to the ambient.

The solids concentration in the TIMES recycle loop can be increased until 93% of the water in the H_2O feed is recovered; i.e., until the solids concentration reaches 38% (Schubert, 1983). The quality of TIMES H_2O, like VCD H_2O, will depend on the amount of volatile organics and ammonia that cocondense with H_2O. Therefore, TIMES feed H_2O may also require acid pretreatment to stabilize urea in urine and posttreatment before being reused.

A comprehensive comparison between VCD and TIMES was recently conducted (Schubert, 1983). Based on this comparison study it was projected that a TIMES subsystem would be 26% heavier, have a

56% higher total equivalent weight and need over twice the energy per unit mass of H_2O recovered than a VCD subsystem (203 versus 101 W-h/kg of H_2O purified).

Vapor Phase Catalytic Ammonia Removal

Vapor compression distillation and TIMES generally require expendable chemicals for pre- and post-treatment of H_2O before and after distillation. Expendable chemicals increase the weight penalty of these two subsystems. Another phase change process, referred to as vapor phase catalytic ammonia removal (VAPCAR), is designed to eliminate the need for expendable chemicals (Budininkas and Rasouli, 1985). Unlike VCD and TIMES, VAPCAR is a physico-chemical process that combines vaporization with high-temperature catalytic oxidation of the volatile impurities, such as ammonia and any organic compounds, that vaporize along with the H_2O.

Figure 13 is a simplified flow diagram of the VAPCAR process using urine as a representative feed. The evaporator contains a bundle of hollow fiber membranes made from a perfluorinated ion-exchange polymer. Waste H_2O is fed to the interior of the fibers and vaporizes from the exterior.

The VAPCAR process employs two catalyst beds: in the first bed ammonia is oxidized to a mixture of nitrous oxide (N_2O) and N_2 and volatile hydrocarbons are oxidized to CO_2 and H_2O; in the second bed, N_2O is catalytically decomposed to N_2 and O_2. The N_2 and O_2 by-products from N_2O dissociation can be used to replenish spacecabin N_2 and O_2. The ammonia oxidation reactor contains 0.5% platinum on alumina oxidation catalyst pellets and operates at about 523 K. The N_2O decomposition reactor contains 0.5% ruthenium on alumina catalyst pellets and operates at about 723 K.

The urine recycle and vapor loops in the VAPCAR subsystem are maintained above pasteurization temperature (347 K or 165°F) to maintain H_2O quality by minimizing or eliminating the growth of microorganisms. Unlike dry heat, wet heat as employed in the VAPCAR process is particularly effective in killing microorganisms.

Recently, a comparison was made between the quality of H_2O from the three phase change processes discussed here, table VIII (Budininkas and Rasouli, 1985). It is evident that VAPCAR yields the highest-quality H_2O based on ammonia content, conductivity, and total organic carbon in the recovered H_2O.

A design value for the specific energy required to produce H_2O by VAPCAR is 217 W-h/kg of H_2O purified. The specific energy required using VAPCAR for H_2O recovery is greater than VCD, but comparable to TIMES. The VAPCAR process has not been developed to the extent of either VCD or TIMES and consequently further improvements, such as a lower specific energy for water production can be expected in the future. Based on certain assumptions, a recent trade-off study ranked VAPCAR first among several candidate processes for either space habitat urine/flush water or all space habitat H_2O recovery (Hall et al., 1984).

Reverse Osmosis

Figure 14 is a simplified schematic of the reverse osmosis (RO) process. Reverse osmosis is a pressure-driven membrane separation process and involves no phase change. The membrane itself is the key element of the process. In RO, a feed solution is pressurized, typically between 690 and 5500 kPa

(100 and 800 psi), against a semipermeable membrane. Water selectively permeates the membrane, while ions and organic compounds (including bacteria not previously separated from the feed H_2O) are rejected. Consequently, the RO process separates the feed solution into a relatively pure, high-volume permeate and a concentrated, low-volume reject solution. Total H_2O recovery by RO is impractical because of the high osmotic pressure of the feed solution at high solids concentrations. The most attractive features of RO for space habitat H_2O recovery are low energy consumption and no requirement for a gas-liquid phase separator in zero gravity.

Two membranes have received the most attention for RO in space, the inside skinned hollow fiber membrane (Ray et al., 1984; Ray, 1985) and the dual layer membrane (Hester and Brandon, 1973; Reysa et al., 1983). The hollow fiber membrane consists of a porous polysulfone base with a proprietary solute rejecting thin skin deposited on the fiber interior. The hollow fiber configuration has a high membrane surface area-to-volume ratio which increases module compactness. Waste H_2O is fed to the interior of the hollow fibers to minimize fouling or the collection of contaminants on the membrane surface. The dual-layer membrane is made from a mixture of zirconium oxide and polyacrylic acid deposited on the interior of a porous metal or ceramic tube. The attractive features of this membrane are its high H_2O flux or throughput (1.9×10^{-5} m/sec (40 gal/ft^2/day) versus 1.1×10^{-5} m/sec (2.5 gal/ft^2/day) for the hollow fiber membrane at 2.8×10^6 Pa (400 psi)) and its stability at pasteurization temperature, 347 K (165 F).

The projected specific energy required for wash water recovery using the hollow fiber and dual layer membranes is about 10 W-h/kg water recovered (Reysa et al., 1983; Ray, 1985). The specific energy for water recovery by RO is about one order of magnitude lower than the energy required using VCD which in turn has the lowest energy requirement among the phase change processes described here. Although the water quality using RO is high (Ray, 1985), a direct comparison of water quality between phase change processes and RO is difficult because different feed solutions have been used in gathering experimental data.

Multifiltration

Multifiltration is another filtration process under consideration for space habitat H_2O purification (Wong and Putnam, 1973). In this process, waste H_2O is purified by flowing it through filters and packed columns connected in series. The only pressure required to sustain H_2O flow through the multifilter is that needed to overcome the small pressure drops across the filters and packed beds. One of the attractive features of multifiltration is that it is a relatively uncomplicated technology which requires very little development for use in space. Disadvantages of multifiltration are the need for expendables to regenerate the ion-exchange beds and a suitable regeneration scheme for activated charcoal.

In multifiltration there are three basic steps, the removal of particles by filtration, the removal of organics by adsorption, and the removal of inorganic salts by ion-exchange. The removal of suspended particles by mechanical filtration is accomplished by a series of filters with decreasing pore size. The organic contaminants in waste water are removed by passing water through a bed of activated charcoal. Inorganic salts are removed by cation and anion exchange resin beds. Microbial control is achieved by heating the entire subsystem to pasteurization temperature; i.e., 347 K (165°F).

Multifiltration has been used for H_2O recovery in ground-based manned chamber studies (Wong and Putnam, 1973) and it remains a strong candidate for space habitat H_2O recovery. A recent trade-off study ranked multifiltration first among several candidate processes for recycling wash water and humidity condensate aboard the Space Station Freedom (Hall et al., 1984).

WATER QUALITY MONITORING

Water quality monitoring is a prerequisite for maintaining a safe space habitat H_2O supply. Space habitat potable and wash-water or hygiene water standards have been established (National Academy of Sciences, 1971, 1972; revised stricter standards are being established at the Johnson Spacecraft Center) and it is the function of the H_2O quality monitoring subsystem to ensure that these standards are continuously met. A monitoring subsystem should be automatic and the important parameters which determine H_2O quality should be continuously or frequently measured. The parameters to be frequently monitored include pH, ammonia content, total organic carbon, electrical conductivity, and microbial concentration. Commercial sensors are available for making these measurements. Less frequently monitored parameters are color, odor, turbidity, foaming, and heavy metal concentrations. The taste of potable H_2O must also be unobjectionable. Microbial content may be monitored indirectly by measuring biocide levels to ensure that biocide is always present.

SOLID WASTE PROCESSING

United States spaceflights through the Space Shuttle era have relied on stabilization and storage of solid wastes such as wet and dry trash, feces, and food-preparation wastes, until the space habitat returned to Earth. Waste storage for longer missions is unacceptable because of the large weight and volume penalty and the potential for space habitat contamination from chemical and biological waste degradation. Furthermore, plants will eventually be grown in space to provide food and at that time large amounts of inedible plant material will need to be processed along with other solid wastes to provide CO_2 and mineral nutrients for the plant growth chamber. Inedible plant material will comprise about 98% of the total dry solid wastes (Wydeven, 1983).

Space habitat solid waste processing has not received the same amount of attention or development effort devoted to other ECLSS subsystems. Accelerated development of solid waste processing can be anticipated during the Space Station Freedom era to accommodate the long lead time needed for proper subsystem development, testing, and integration for manned space missions beyond the Space Station Freedom.

Candidate physico-chemical processes for treating solid wastes are dry incineration, wet oxidation, and supercritical H_2O oxidation. Each of these three processes is described next.

Dry Incineration

Dry incineration involves the combustion of a concentrated solid waste feed. The waste feed is concentrated by evaporation to a solids content of about 50% by weight before being heated in air or O_2 near ambient pressure to a temperature of about 813 K (Labak et al., 1972). Pure O_2 is the preferred oxidizing agent. The end products of dry incineration are sterile, and consist of water condensate, inorganic ash, and gases (primarily CO_2). A catalytic afterburner may be required when using dry incineration to further the extent of combustion. Disadvantages of dry incineration are: a) incomplete combustion, even with an afterburner; b) product water may require further processing before being reused; and c) an energy intensive evaporation or predrying step is required before combustion can take place.

Wet Oxidation

Wet oxidation or the Zimpro Process involves the oxidation of either a dilute or concentrated waste slurry at an elevated pressure and temperature. Combustion takes place in air or O_2 at a pressure of about 14 MPa (2000 psi) and temperatures ranging from 473 to 573 K. Wet oxidation, unlike incineration, does not require a predried feedstock. Dilute wastes (5% solids) can be oxidized using this technique.

The primary advantages of wet oxidation for space habitat applications are the recovery of useful water and the reduction of solid wastes to a very small weight and volume of sterile, nondegradable ash (Johnson and Wydeven, 1985). Wet oxidation is particularly attractive for space habitats where plants are grown to provide food. Carbon dioxide from combustion of organics and the mineral nutrients in the aqueous phase and precipitates appearing after wet oxidation can be used as plant nutrients. Incomplete combustion by wet oxidation may require posttreatment of the product gas and liquid (Johnson and Wydeven, 1985). A four-man prototype wet oxidation subsystem for space habitats has been built and tested (Jagow, 1972).

Supercritical Water Oxidation

Waste destruction by the supercritical H_2O waste treatment process makes use of H_2O in its supercritical state (above 647 K and 2.15×20^7 Pa) as the process medium for carrying out the destruction of organic compounds by oxidation. Water exhibits unique properties in the supercritical state which make this process particularly attractive for waste destruction. Organic substances and O_2 are completely soluble in supercritical H_2O which permits oxidation to occur in a single phase, unlike wet oxidation. Inorganic salts are only sparingly soluble in supercritical H_2O which aids in separating salts from the aqueous product phase. The temperatures and molecular densities allow the oxidation reactions to proceed rapidly and essentially to completion. For example, organic materials can be oxidized with efficiencies greater than 99.99% for residence times of less than 1 min (Timberlake et al., 1982). With proper reactor design, as in the case of wet oxidation, the heat generated by waste oxidation in supercritical H_2O can be retained in the reactor thereby minimizing the amount of external heat or energy required for the process. It is anticipated that supercritical H_2O oxidation of space habitat wastes will be more complete and for a shorter residence time than by wet oxidation. However, supercritical H_2O oxidation as a solid waste treatment process is in its infancy and development work is ongoing so that this method can be quantitatively traded off against other solid waste treatment processes.

INTEGRATED ECLSS

So far in this article the discussion has focused on the function and description of subsystems within a regenerative or integrated ECLSS. Integration of these subsystems to form a partially closed or closed ECLSS introduces a new series of problems not encountered in subsystem development. In an integrated ECLSS the output from one subsystem serves as the input for another subsystem. This requires that production and consumption rates of paired subsystems be closely matched and well understood. Likewise automatic operation of an integrated ECLSS is essential to minimize the use of costly astronaut time. Automation requires that adequate subsystem and system monitoring and control instrumentation be located within the ECLSS. Also, monitoring and control instrumentation must be in place to detect and isolate faulty operation so that corrective action or repairs can be quickly undertaken. When repairs of an integrated system become necessary, system design must allow for easy access for module replacement or repair with simple hand tools. Commonality is also preferred in the design of an integrated ECLSS to minimize the inventory of spare parts needed in the space habitat. Monitoring and control instrumentation will improve system reliability which is of primary importance to ensure astronaut safety. Reliability and astronaut safety also requires that ground-based, manned-chamber testing of an integrated ECLSS be done under normal and emergency operating conditions before using a regenerative ECLSS in a space habitat. Astronaut safety also requires adequate subsystem redundancy. Finally, if doubts remain concerning the zero- or reduced-gravity behavior of either a given subsystem or the integrated system then flight experiments must be conducted prior to using the integrated system to support a person in space. Solutions to the problems of ECLSS automation, monitoring and control, maintainability, and integration will be actively pursued in the coming years.

THE FUTURE

On future long-duration human space exploration missions, a partially closed regenerative ECLSS in which subsystem processes are based on physico-chemical principles will be required to minimize resupply requirements. The cost effectiveness of a regenerative ECLSS as opposed to an open system dictates this approach. Physico-chemical instead of biological subsystems will be used for the first generation of space habitats, including the Space Station Freedom, because of our better understanding and the higher level of development of these subsystems.

Beyond the first generation ECLSS, some of the physico-chemical subsystems will be replaced by higher plants. Through photosynthesis, higher plants scrub CO_2, regenerate O_2, aid in water purification by plant transpiration and above all, produce fresh food. However, physico-chemical subsystems are still expected to play an important role in this hybrid ECLSS. Physico-chemical subsystems have, and will continue to have in the foreseeable future, an advantage over biological processes for solid waste processing. Physico-chemical subsystems have no apparent competition from biological processes for contaminant control. The type of ECLSS to be used on the surface of the moon or a planet as compared to inside a space habitat will greatly depend on the resources the planet itself can provide. If the planet cannot provide any of the resources needed to sustain man, then an ECLSS similar to that used aboard a space habitat may also be used on the surface of a planet.

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TABLE I.– SPACE STATION FREEDOM ECLSS DESIGN AVERAGE LOADS[a,b] (QUATTRONE AND WYNVEEN, 1983)

Metabolic O_2	0.835
Metabolic CO_2	0.999
Food solids	0.617
Drinking water	1.30
Food preparation water	1.77
Food water	0.499
Metabolic water production	0.354
Clothing wash water	12.48
Hand wash water	3.18
Shower water	2.27
Perspiration and respiration water	1.82
Urinal flush water	0.495
Urine water	1.50
Hygiene latent water	0.427
Food preparation latent water	0.027
Experiments latent water	0.454
Laundry latent water	0.059
Urine solids	0.059
Fecal solids	0.032
Sweat solids	0.018
Charcoal required	0.059
Food packaging	0.454
Trash	0.817
Trash volume	2.8×10^{-3} m^3/person-day
Waste wash water solids	0.44%
Expended water solids[c]	0.13%
Metabolic sensible heat	7.4×10^6 joules/person-day

[a] Excluding extravehicular activity loads.
[b] Units: Kilograms/person-day unless otherwise noted.
[c] Assumed shower and hand wash.

TABLE II.– SPACE STATION FREEDOM ECLSS DESIGN REQUIREMENTS (QUATTRONE AND WYNVEEN, 1983)

Parameter	Operational	90-day degraded[a]	21-day emergency
O_2 partial pressure, kPa[b]	19-22	16-26	16-27
CO_2 partial pressure, kPa	0.40[c]	1.0[c]	1.6[c]
Total pressure, kPa	101	69-101	69-101
Trace contaminants	24 hr Ind. Standard	8 hr Ind. Standard	8 hr Ind. Standard
Microbial count, per m^3	3530	---	---
Temperature, K	291-297	289-302	289-305
Dew point, K[d]	278-289	275-294	275-294
Ventilation, m/sec	0.076-0.20	0.051-0.51	0.025-1.02
Potable water, kilogram/person-day	3.09-3.68	3.09[e]	3.09[e]
Hygiene water, kilogram/person-day	5.4[e]	2.7[e]	1.4[e]
Wash water, kilogram/person-day	13[e]	6.4[e]	0
Maximum crew member, per space station	8	8	12
Maximum crew member, per habitat module	4	8	8

[a] Degraded levels meet "fail operational" reliability criteria.
[b] In no case shall the O_2 partial pressure be below 16 kPa or the O_2 concentration exceed 26.9%.
[c] Maximum.
[d] In no case shall relative humidities exceed the range 25-75%.
[e] Minimum.

TABLE III.– OPEN LOOP EXPENDABLE REQUIREMENTS PER PERSON (QUATTRONE AND WYNVEEN, 1983)

Life support needs	Expendables, kilograms/day	Tankage/packaging, kilograms/day	Total, kilograms/day
O_2[a]	0.981	0.981	1.96
N_2	0.558	0.558	1.12
LiOH (CO_2 removal)	1.35	0.676	2.03
Food	0.617	0.309	0.926
Water	4.73-9.65	0.944-1.9	5.63-11.6
Total	8.24-13.2	3.47-4.42	11.7-17.6

[a] Includes leakage requirement.

TABLE IV.– SPE OPERATING DATA AT 790 kPa/m^2 (115 psia) NOMINAL PRESSURE (TITTERINGTON AND ERICKSON, 1975)

Module terminal voltage (13 cells)	22.8 VDC
Average single cell voltage	1.723 VDC
Module current	75 amp
Cell current density	350.3 mamp/cm^2
Module H_2O inlet temperature	338.2 K
Module H_2/H_2O outlet temperature	364.3 K
System process H_2O flow rate	9.34 kg/hr
Regulated O_2 pressure	931 kPa
Regulated H_2 pressure	724 kPa
System input voltage	29 VDC
System input power	2.18 kW
Module heat rejection	0.296 kW
O_2 production rate	6.82 kg/day

TABLE V.– THE SFWE MODULE CHARACTERISTICS (SCHUBERT ET AL., 1981)

Module weight	25 kg
Module dimensions	13 x 25 x 30 cm
Number of cells	6
Active area per cell	92.9 cm^2
Nominal current density	206 mA/cm^2
Current	19.1 amp
Cell voltage	1.52 VDC
Power consumed	174 W
Waste heat produced	4.6 W
O_2 generated	0.82 kg/day
H_2O consumed	1.0 kg/day
Specific power	212 W/kg O_2-day

TABLE VI.– AVAILABLE O_2 AND CO_2 SCRUBBING CAPACITIES OF KO_2 AND $Ca(O_2)_2$

Compound	O_2 kilograms per kilograms of compound	CO_2 kilograms per kilograms of compound
KO_2	0.34	0.31
$Ca(O_2)_2$	0.46	0.42

TABLE VII.– CONTAMINANT LOAD MODEL (OLCOTT, 1975)

Contaminant class	Number of contaminants in the class	Production rate range, grams per day	Maximum allowable concentration, milligrams per m^3
Alcohols	13	0.025-2.5	0.5-300
Aldehydes	8	0.0005-2.5	0.12-11,800
Aromatic hydrocarbons	13	0.025-2.5	3.0-190
Esters	8	0.025-2.5	30-120
Ethers	9	0.025-2.5	3-200
Chlorocarbons	16	0.025-2.5	0.16-260
Chlorofluorocarbons	11	0.025-2.5	24-2,380
Fluorocarbons	3	0.025-2.5	12-205
Hydrocarbons	36	0.025-33.1	3.4-3,500
Inorganic acids	3	0.025-0.25	0.08-1.5
Ketones	5	0.025-10.2	29-710
Mercaptans	3	0.0005	2.0-82
Nitrogen oxides	4	0.025-0.25	0.9-9
Organic acids	6	0.0005-1.26	0.90-155
Organic nitrogens	6	0.025-0.25	0.10-45.0
Organic sulfides	4	0.025-0.25	0.37-6.0
Miscellaneous	6	0.0005-4.0	1.5-240

TABLE VIII.– COMPARISON OF H2O QUALITY FROM DIFFERENT DISTILLATION PROCESSES (BUDININKAS AND RASOULI, 1985)

Parameter	Process		
	VPCAR	VCD	TIMES
Ammonia concentration, grams/liter	0.09	0.3	0.8
Total organic carbon, grams/liter	2	16-18	48-150
pH	4.5-5.5	3-4	3.3-3.6
Conductivity, microreciprocal ohms/centimeter	18	35	198

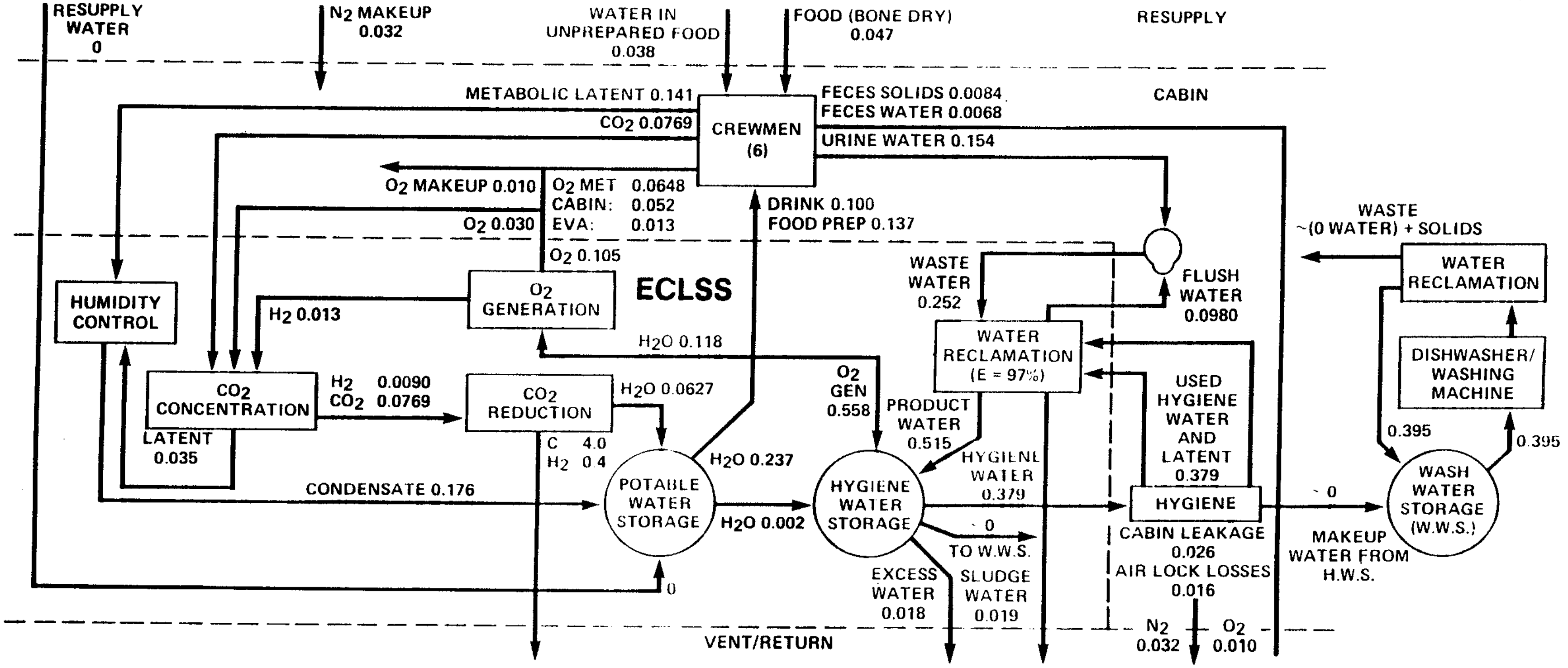

Figure 1.– Representative partially closed Space Station Freedom ECLSS mass balance for a crew size of six persons. Note the laundry water recovery subsystem is separate from the potable water subsystem (reprinted with permission cc 1983 Society of Automotive Engineers, Inc.).

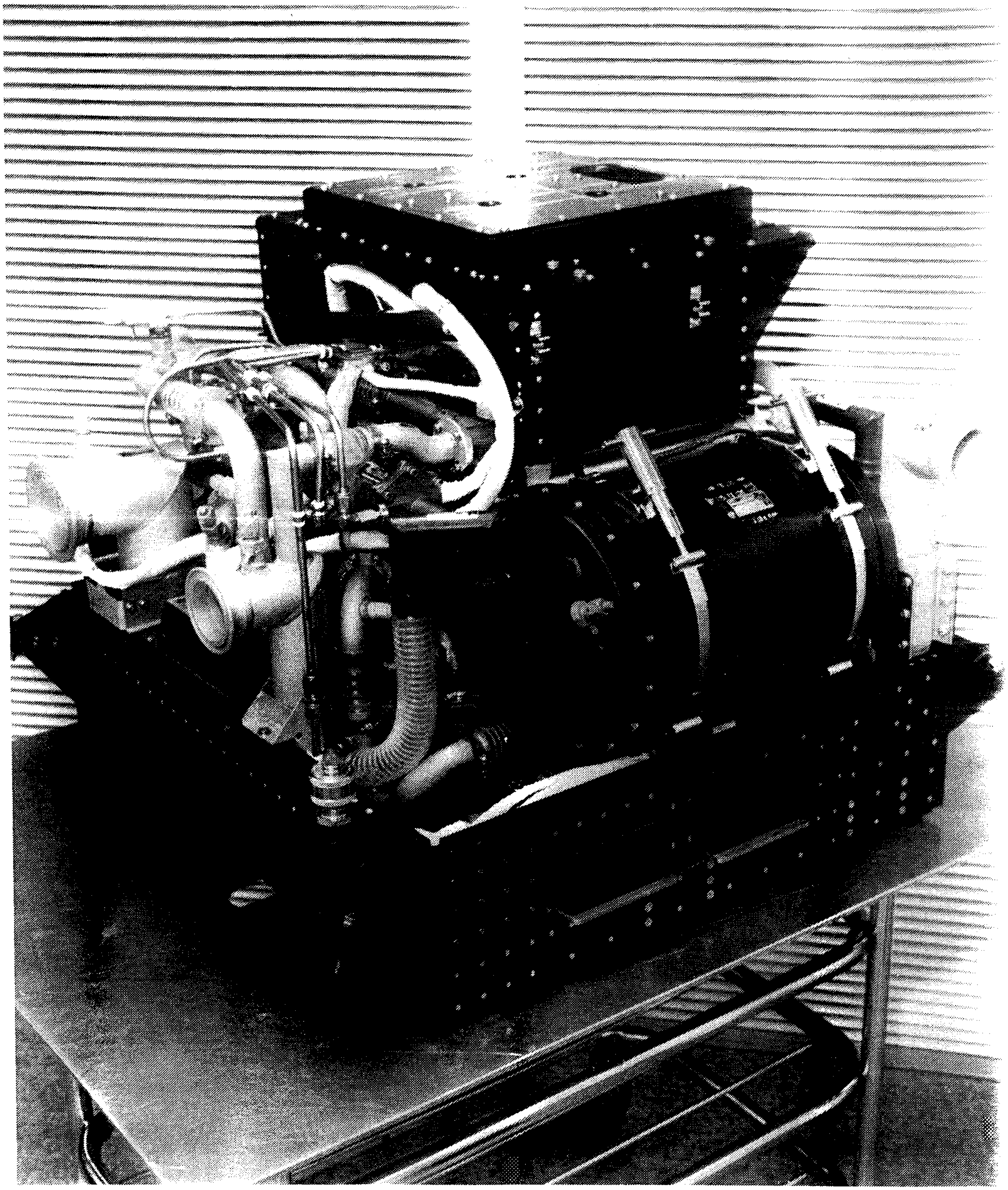

Figure 2.– Regenerative molecular sieve CO_2 concentration subsystem (Coull, 1974) (reprinted with permission © 1972 The American Society of Mechanical Engineers).

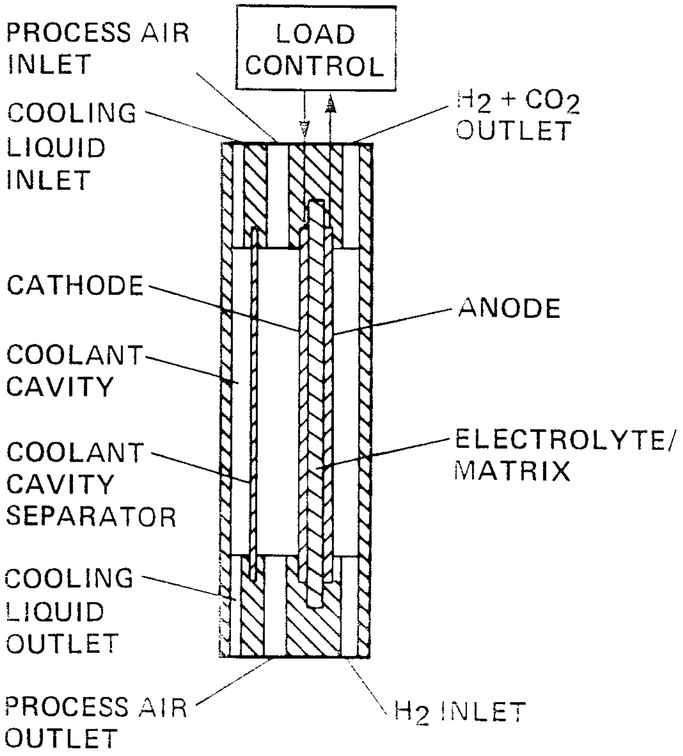

Figure 3.– The EDC single cell functional schematic (Heppner and Schubert, 1983) (reprinted with permission cc 1983 Society of Automotive Engineers, Inc.).

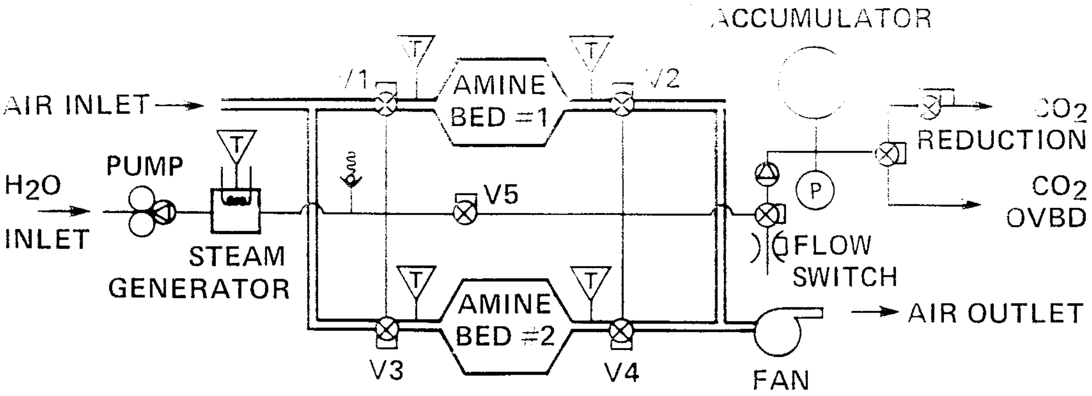

Figure 4.– Schematic of a two-bed, solid-amine-resin, CO_2 removal subsystem (Dresser and Cusick, 1984) (reprinted with permission cc 1984 Society of Automotive Engineers, Inc.).

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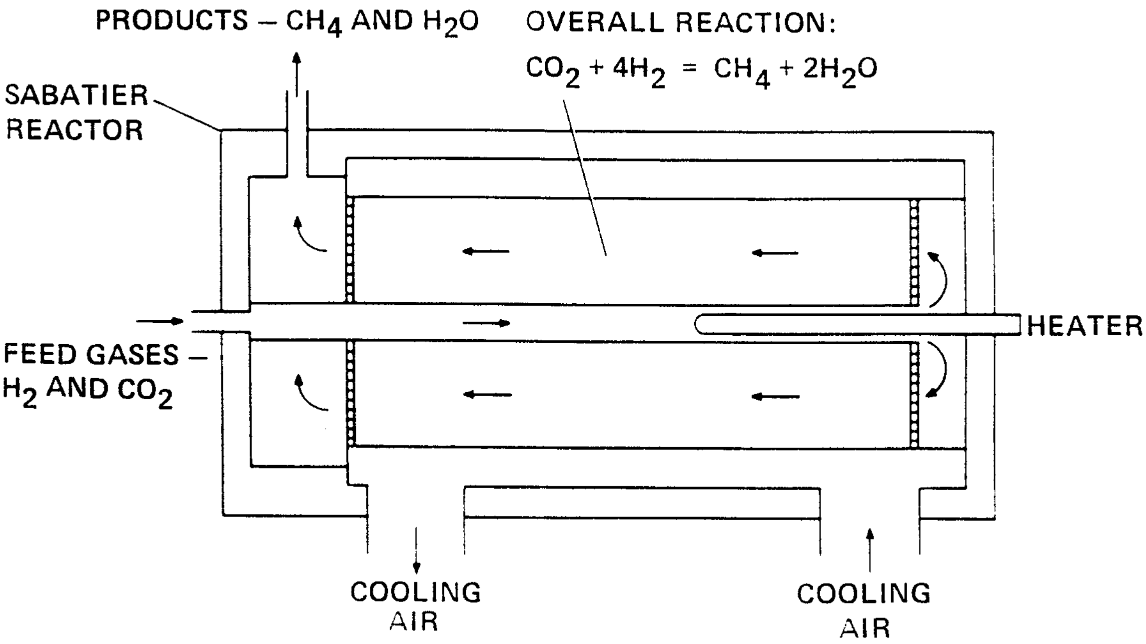

Figure 5.– Simplified schematic of the Sabatier CO_2 reduction process (reprinted with permission of Life Systems, Inc.).

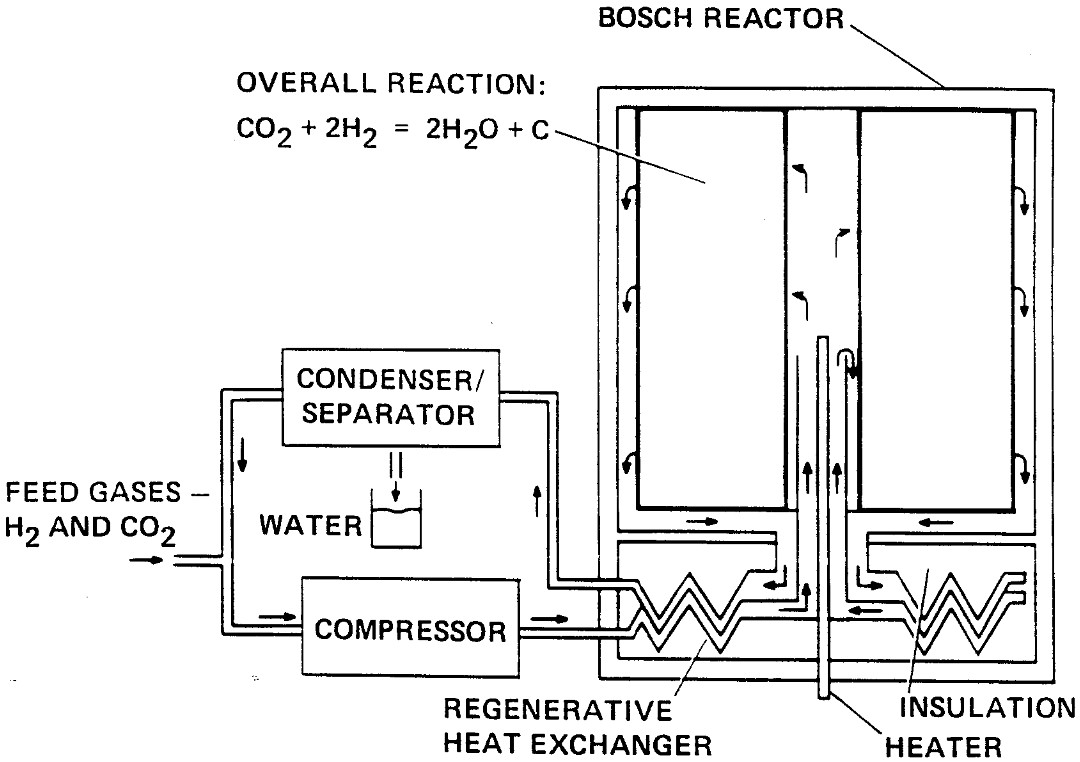

Figure 6.– Simplified schematic of the Bosch CO_2 reduction process (reprinted with permission of Life Systems, Inc.).

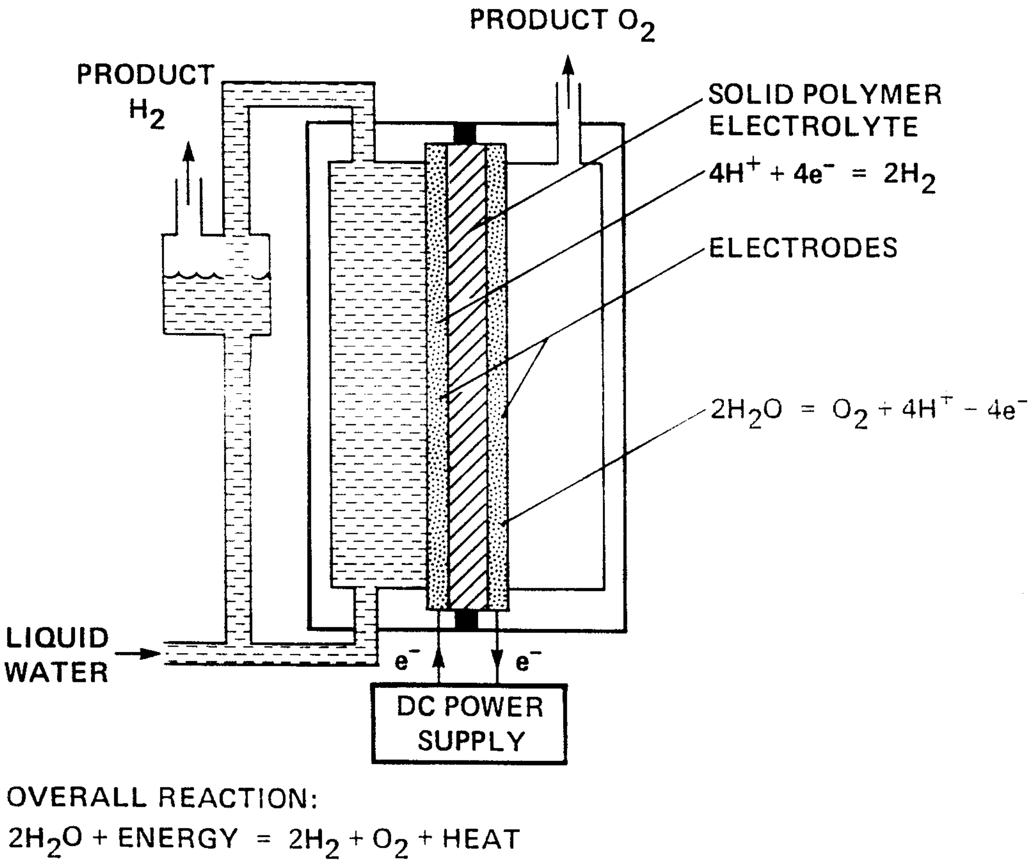

Figure 7.– Schematic of a solid polymer H_2O electrolysis cell (reprinted with permission of Life Systems, Inc.).

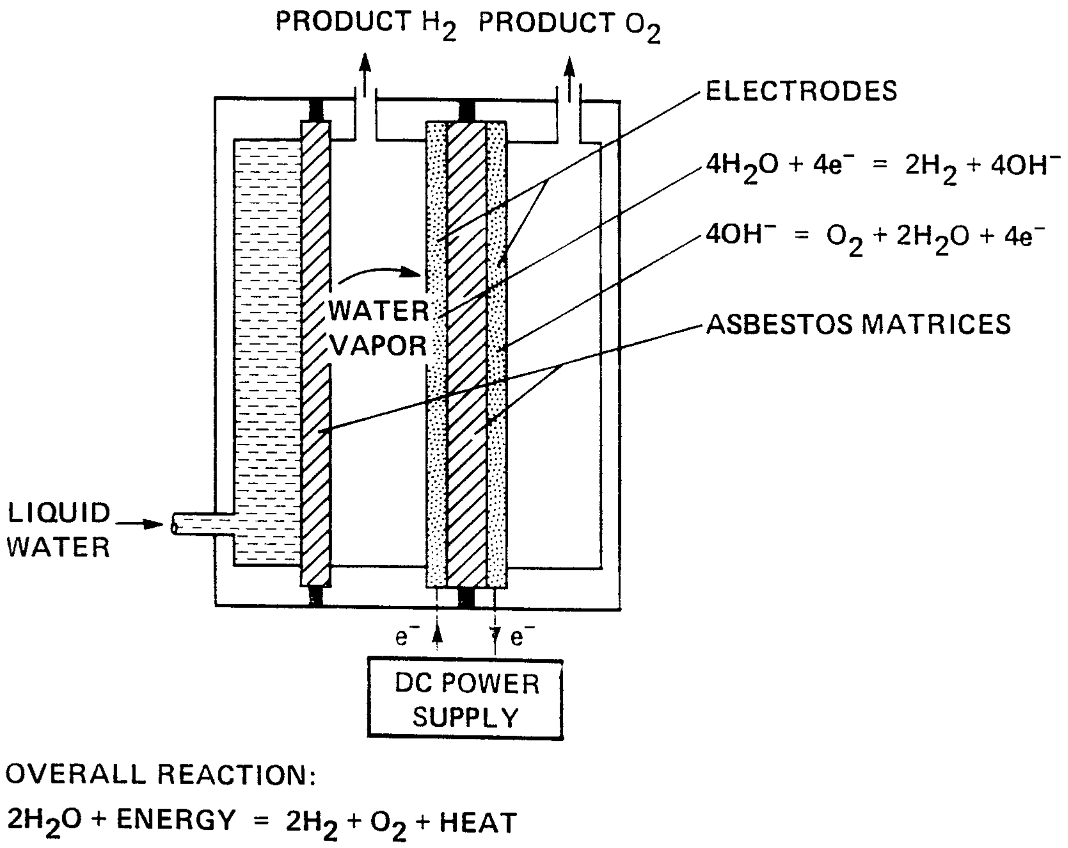

Figure 8.– Schematic of a static feed H_2O electrolysis cell (reprinted with permission of Life Systems, Inc.).

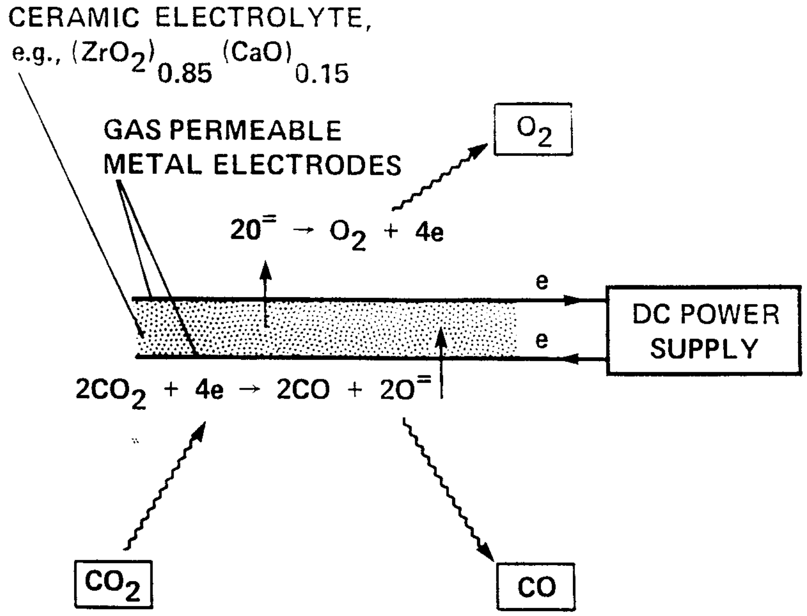

Figure 9.– Schematic of a solid electrolyte CO_2 electrolysis cell (Reid, 1970).

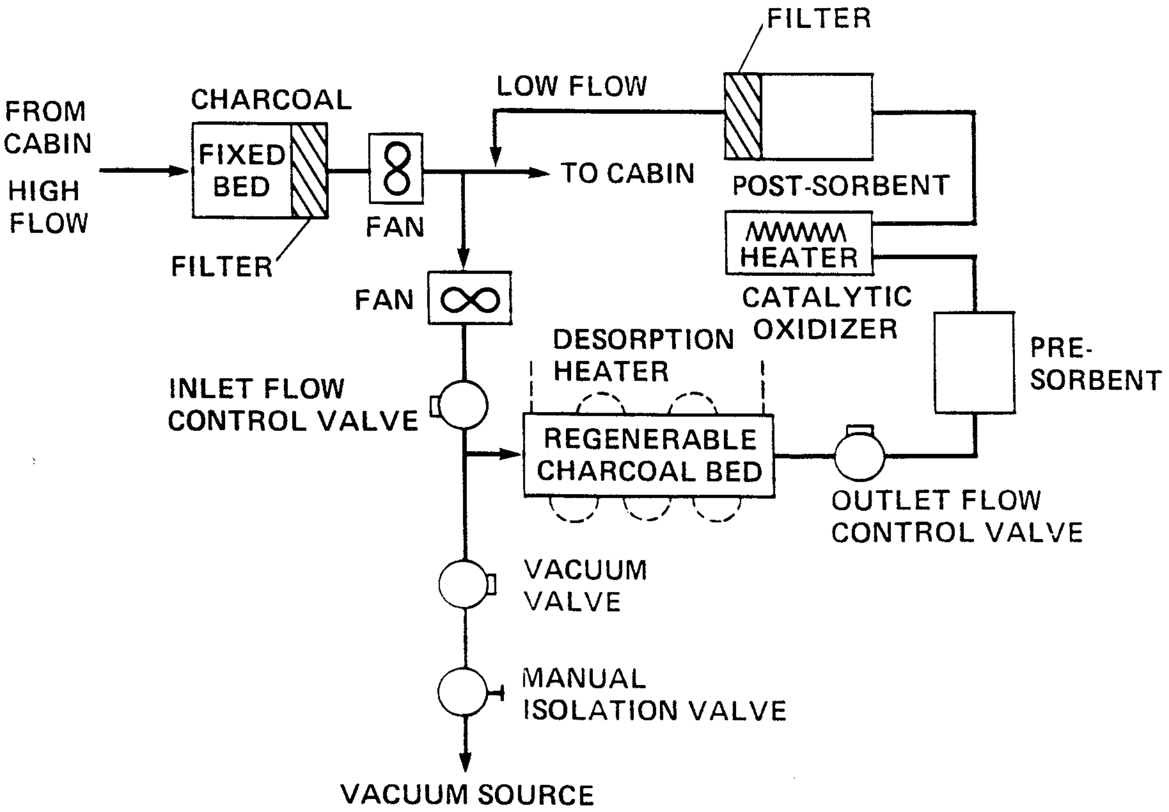

Figure 10.– Flow diagram of a trace contaminant control subsystem (Olcott, 1975) (reprinted with permission cc 1975 The American Society of Mechanical Engineers).

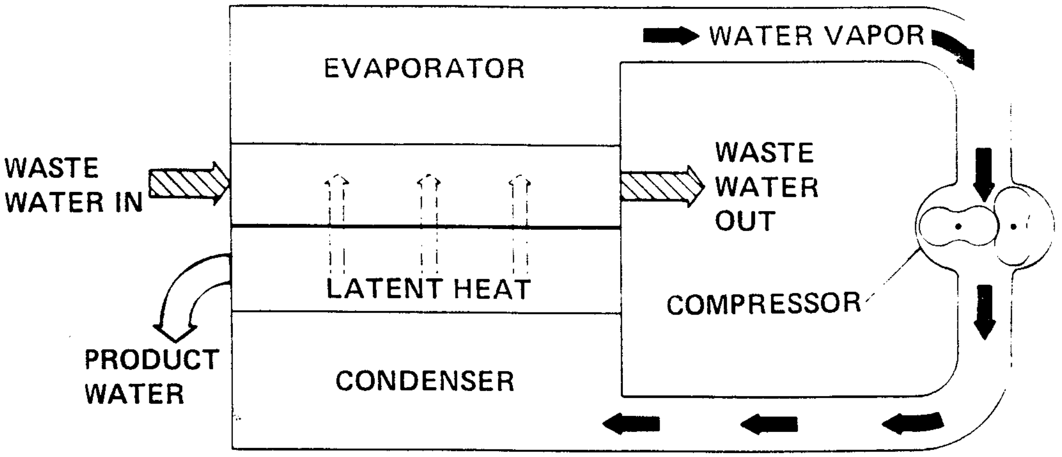

Figure 11.– Simplified schematic of the vapor compression distillation water reclamation process (Schubert, 1983) (reprinted with permission cc 1983 Society of Automotive Engineers, Inc.).

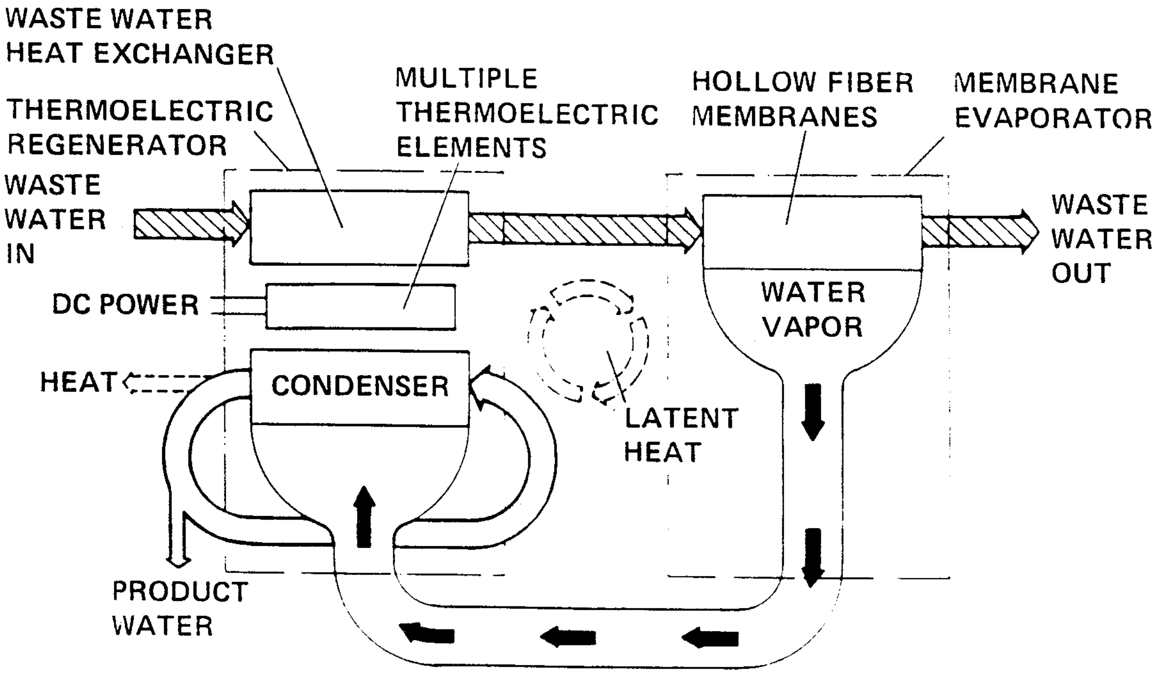

Figure 12.– Simplified schematic of the thermoelectric integrated membrane evaporation process for water recovery (Schubert, 1983) (reprinted with permission cc 1983 Society of Automotive Engineers, Inc.).

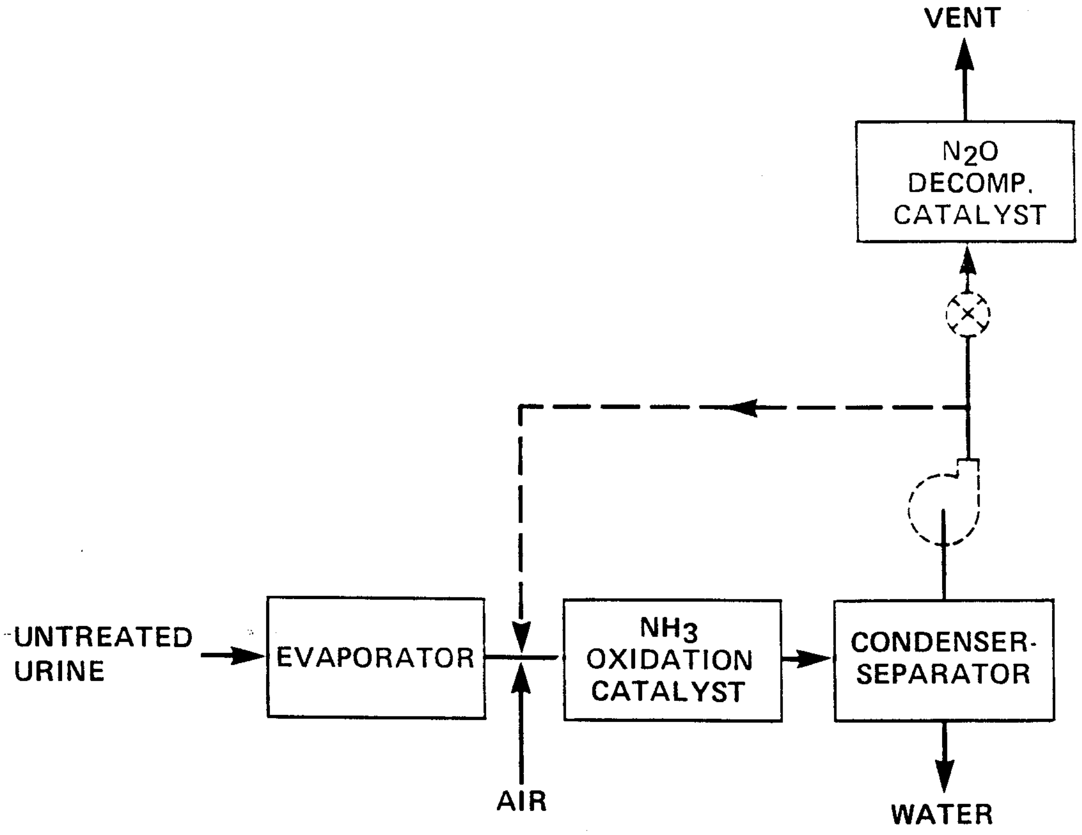

Figure 13.– Simplified flow diagram of the vapor phase catalytic ammonia removal process for water purification.

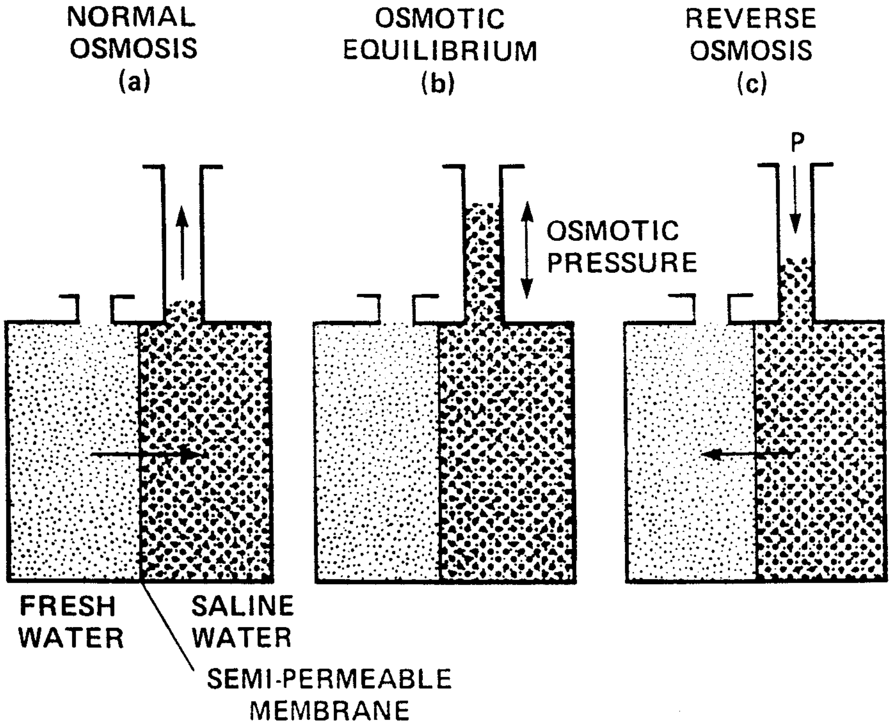

Figure 14.– Diagrams demonstrating the principle of reverse osmosis.

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16. Abstract

To date, crewed spaceflight has used the relatively simple support methodology of bringing all the necessary water, oxygen, and food for the duration of the mission, and collecting and storing waste products for return to Earth. This is referred to as an open system. It was recognized early, as crewed missions became longer and crew size increased, that the weight, volume, and transportation penalties of storing or routinely resupplying consumables would at some point become too expensive. Since the early 1960s, regenerative ECLSS technology has been under development, and there now exists a foundation in both systems definition and subsystem technology to support long-duration crewed missions. In many cases this development has reached the engineering prototype stage for physico-chemical subsystems and in this article some of these subsystems are described. Emphasis is placed on physico-chemical waste conversion and related processes which provide sustenance and not on environmental factors or subsystems, e.g., temperature and humidity control, spacecraft architecture, lighting, etc.

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