National Aeronautics and Space Administration

# EXTENDED MISSION LIFE SUPPORT SYSTEMS

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## FOREWORD

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## LIST OF ACRONYMS

| | |
|---|---|
| ARS | Air Revitalization System |
| ARX-1 | Air Revitalization System (Experimental) - 1 person |
| ASF | Amps per Square Foot |
| CELSS | Controlled Ecological Life Support System |
| C/M I | Control/Monitor Instrumentation |
| CRT | Cathode Ray Tube |
| EC/LSS | Environmental Control/Life Support Systems |
| EDC | Electrochemical Depolarized Concentrator |
| EDO | Enhanced Duration Orbiter |
| IARS | Independent Air Revitalization System |
| NSS | Nitrogen Supply Subsystem |
| OGS | Oxygen Generation Subsystem |
| PEP | Power Extension Package |
| R&D | Research and Development |
| RLSE | Regenerative Life Support Evaluation |
| RO | Reverse Osmosis |
| SF-WES | Static Feed - Water Electrolysis Subsystem |
| SOC | Space Operations Center |
| SPE-WES | Solid Polymer Electrolyte - Water Electrolysis Subsystem |
| SR&T | Supporting Research and Technology |
| SSP | Space Station Prototype |
| TIMES | Thermoelectric Integrated Membrane Evaporation Subsystem |
| VCD | Vapor Compression Distillation |
| WVE | Water Vapor Electrolysis |

## INTRODUCTION

Extended manned space missions, including interplanetary missions, will require regenerative life support systems. In order to place manned mission life support considerations into perspective, this paper will review previous manned space life support system technology, activities and accomplishments in NASA's current supporting research and technology (SR&T) program, the life support subsystem/system technologies required for an Enhanced Duration Orbiter (EDO) and a Space Operations Center (SOC), regenerative life support functions and technology required for manned interplanetary flight vehicles, and future development requirements.

## BACKGROUND

The life support systems technology utilized on Projects Mercury, Gemini and Apollo used expendables: liquid oxygen ($O_2$) for breathing; lithium hydroxide (LiOH) canisters for carbon dioxide ($CO_2$) removal; activated charcoal canisters for trace contaminant removal; stored water for drinking and washing; stored freeze-dehydrated food, urine collection and storage and/or overboard dump; and collection, stabilization/treatment and storage of solid waste. These spacecraft had an atmosphere of 5 psia $O_2$ with no inert diluent gas.

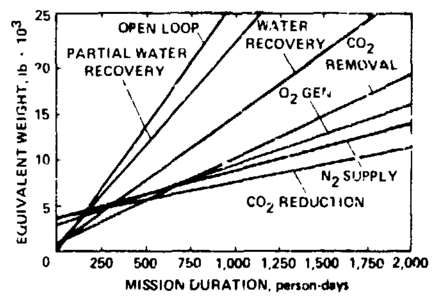
Skylab utilized a two-gas atmosphere ($N_2$ diluent at 1.5 psia) with a total pressure of 5 psia. Skylab also used a regenerable $CO_2$ removal subsystem (molecular sieve/silica gel adsorption beds).

The Space Shuttle Orbiter (Space Transportation System) ushers in a new era in American manned space vehicles. Not only is the Shuttle a reusable spacecraft, but the space cabin atmosphere is maintained at Earth ambient pressure of 14.7 psia (20% $O_2$ and 80% $N_2$). The early Shuttle flights will be seven-day flights, and the life support system flight hardware will still utilize expendables.

## ADVANCED LIFE SUPPORT SYSTEMS TECHNOLOGY

Growth in space transportation capability will provide extended stay times for the Shuttle Orbiter, permanent manned facilities in low earth orbit, and ultimately, manned planetary vehicles. Regenerative life support technology is one of the rate controlling technologies for future manned space habitability including EDO, SOC and future manned planetary flight vehicles.

The use of expendables for life support, rather than regenerative techniques, for future manned missions beyond the seven-day Shuttle Orbiter, will become prohibitively expensive in terms of logistics costs. For example, the Skylab missions required the launching of 12,000 pounds of water. Regenerative systems hardware tends to be bulkier, heavier and more power consuming than short-term expendable systems. However, for some missions of only 40 person-day durations the penalties for utilizing the expendable approach will exceed any drawbacks of regenerative systems. Equivalent weight trade-off of regenerative *vs* total expendable (open loop) life support systems is shown in Figure 1.




**SEQUENTIAL STEPS IN LOOP CLOSURE**

| DEFINITION | DESCRIPTION |
|---|---|
| PARTIAL WATER RECOVERY | HUMIDITY CONDENSATE COLLECTION |
| WATER RECOVERY | POTABLE WATER RECOVERY AND TREATMENT FROM URINE AND WASH WATER |
| $CO_2$ REMOVAL NONEXPENDABLE | REPLACEMENT OF EXPENDABLE LiOH WITH REGENERATIVE $CO_2$ COLLECTION TECHNIQUE |
| $O_2$ GENERATION | GENERATION OF $O_2$ THROUGH WATER ELECTROLYSIS USING RECLAIMED WATER |
| $N_2$ GENERATION | GENERATION OF $N_2$ THROUGH DISSOCIATION OF HYDRAZINE |
| $CO_2$ REDUCTION | DECREASE IN EXPENDABLE WATER BY RECOVERING PRODUCT FROM $CO_2$ REDUCTION (SABATIER) PROCESS |

**Figure 1. Regenerative vs Open Loop EC/LSS**

Advanced life support systems technology also referred to as Environmental Control/Life Support Systems (EC/LSS), consists of a number of areas including air revitalization, water reclamation, solid waste management, food service, and control/monitor instrumentation.

1. Air Revitalization System — This system integrates processes (subsystems) for: $CO_2$ removal, $CO_2$ reduction, $O_2$ generation, $N_2$ generation, humidity control, water handling, trace contaminant control, and control/monitor instrumentation for subsystem and integrated system operation.

2. Water Reclamation System — This system provides integrated processes for recovery of potable water from fuel cell water, cabin humidity condensate, wash water and urine. The system(s) must also include provisions for water quality monitoring, sterilization, and control/monitor instrumentation for subsystem and integrated system operation.

3. Solid Waste Management System - This system includes the collection, transfer, treatment and subsequent storage of treated/stabilized waste mass. Treatment processes are designed to minimize storage requirements, increasing in complexity from vacuum drying to sterilization to oxidation. Fecal water reclamation is feasible, but it is

impractical unless the solid waste treatment process can totally oxidize solid organic wastes. Fecal treatment leading to food generation is considered to be part of the Controlled Ecological Life Support System (CELSS) program and is not included in this paper.

4. Food Service System — This system involves packaging, storage and service of expendable foods for maintenance of proper human nutrition.

5. Control/Monitor Instrumentation — This technology category deals with the control, monitoring and fault diagnostic instrumentation required for reliable computer-controlled subsystem and/or system operation.

All of these technology areas, with the exception of Food Service System, will be discussed in this paper. This paper will emphasize the technology developments in Air Revitalization because of their relative complexity and the corresponding amount of SR&T activities completed and currently underway.

## AIR REVITALIZATION

### $CO_2$ Removal

Regenerable $CO_2$ removal techniques can utilize cyclic sorbers or continuous $CO_2$ removal processes such as an Electrochemical Depolarized Concentrator (EDC).

#### $CO_2$ Sorbers

Some solid materials such as molecular sieves or solid amines have the capability of preferentially adsorbing gases such as $CO_2$ on their surfaces. The adsorbed gases can then usually be desorbed by a combination of thermal and vacuum treatment processes. In all sorber system applications continuous adsorption capability is achieved only by using parallel adsorption beds which alternately cycle between adsorption and desorption operational modes.

Adsorption materials cannot provide a constant adsorption rate for any gas since the adsorption rate and capability of the material are dependent on the quantity of gas already adsorbed on the material. The adsorption rates attainable with a "nearly-spent" adsorption material are very low. As a result, the maintenance of low cabin partial pressures of the gas in question (e.g., $pCO_2$ = 2-3 mm Hg) necessitates frequent bed recycling and large volume beds.

The molecular sieve material used for Skylab is a good $CO_2$ adsorber, but the material also preferentially adsorbs water vapor vs $CO_2$. Therefore, a silica gel sorber bed was required in series with the molecular sieve bed in order to preserve the $CO_2$ adsorption capability. The desorption cycle consisted of thermal treatment and overboard venting of the $CO_2$ and water vapor to space vacuum.

[1]References cited are listed at end of paper.

Solid amine $CO_2$ adsorption material is made from a spherical porous substrate coated with a non-volatile liquid amine. The substrate is a polymeric acrylic ester similar to plexiglas and the coating is a polyethylenimine with a molecular weight of 1800. The solid amine adsorbs $CO_2$ and also adsorbs water vapor.

The thermal/vacuum operational desorption mode for solid amines also involves the overboard venting of $CO_2$ and water vapor adsorbed on the bed[1]. Such venting by any sorber subsystem may be used only on missions in which overboard $CO_2$ and water vapor dumping is permissible and advantageous. The solid amine sorber subsystem does, however, offer advantages over the silica gel/molecular sieve subsystem: lower weight, lower volume, reduced cabin heat load, and lower power requirements. The solid amine material has demonstrated negligible off-gassing (i.e., ammonia) with 1300 hours of endurance test time.

The solid amine $CO_2$ adsorber subsystem has also been proposed to be used in a steam desorbed mode (212 F, 14.7 psia), so that interfacing with spacecraft $CO_2$ reduction subsystem is possible[2]. Before this operational mode can be seriously considered the stability of the resin bed to a significant number of steam desorption cycles must be demonstrated, which has not occurred to date.

#### EDC

The EDC offers significant operational advantages and weight savings over non-regenerative techniques and sorber beds, especially at low cabin $CO_2$ partial pressures (2-3 mm Hg.)[3].

The EDC is an electrochemical method that continuously removes $CO_2$ from a flowing air stream and concentrates the $CO_2$ to a level useful for $O_2$ recovery. The $CO_2$ removal takes place in an electrochemical module consisting of a series of cells. Each cell (see Figure 2) consists of two electrodes separated by a matrix containing an aqueous carbonate electrolyte ($Cs_2CO_3$). Plates adjacent to the electrodes provide passageways for distribution of gases and electrical current. The electrochemical and chemical reactions that take place are:

Cathode:

$$O_2 + 2H_2O + 4e^- = 4OH^-$$

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

Anode: (depolarized with $H_2$)

$$2H_2 + 4OH^- = 4H_2O + 4e$$

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

Overall:

$$2CO_2 + O_2 + 2H_2 = 2CO_2 + 2H_2O + \text{electrical energy \& heat}$$

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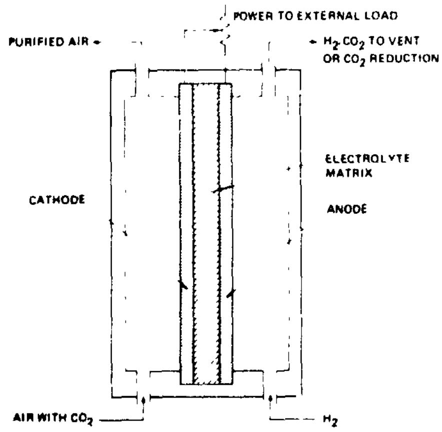


**Figure 2. EDC Cell Functional Schematic**

Two moles of $CO_2$ are theoretically transferred for one mole of $O_2$ consumed. This ratio represents the process efficiency, and 100% efficiency occurs when 2.75 g of $CO_2$ is transferred for each g of $O_2$ consumed. The electrical power produced by the EDC can be directly utilized by the Oxygen Generation Subsystem.

Considerable research and development work has been carried out with this concept and has resulted in increased process efficiency, demonstrated long-term performance and advanced hardware development status[4]. Extended testing with EDC modules (single cells to six-person cell stacks) has exceeded over 2,000,000 cell-hours. Recent developments in the R&D program have resulted in a one-person capacity liquid-cooled module that has demonstrated a constant $CO_2$ removal efficiency of 91% over an inlet relative humidity range of 16-75%. In addition, this advanced module has demonstrated a static pressure differential capability of 60 psid, which is extremely important in interfacing with the Sabatier $CO_2$ reduction subsystem.

A three-person capacity EDC subsystem has been developed for the Regenerative Life Support Evaluation (RLSE) program (see Figure 3)[5]. The EDC module in this subsystem is air-cooled, has demonstrated in excess of 72% $CO_2$ removal efficiency at 85% inlet relative humidity, and the $CO_2$ removal efficiency was increased by approximately 12% by operating the module at a 60% inlet relative humidity.

### $CO_2$ Reduction

There are two principal methods for combining $CO_2$ with $H_2$ to form water for the eventual recovery of $O_2$. These are the Sabatier and Bosch processes. The factors that govern process selection deal with the availability of $H_2$ and the requirement for no overboard dumping of gases.

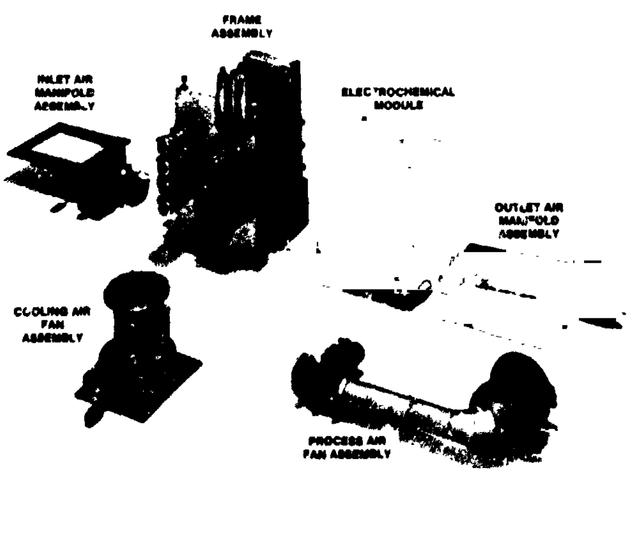


**Figure 3. Three-Person RLSE $CO_2$ Removal Subsystem**

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**Sabatier Process**[6]

This $CO_2$ reduction process is ideally suited for an air revitalization system that uses a hydrazine-based $N_2$ generation subsystem. $CO_2$ and $H_2$ from the EDC enter the Sabatier reactor (see Figure 4) and are converted to methane ($CH_4$) and water per the following reaction:

$$4H_2 + CO_2 = 2H_2O + CH_4 + \text{heat}$$

The reaction occurs around 700 F and is aided by a catalyst. The water is condensed in a liquid cooled porous plaque condenser/separator. The exhaust gases, primarily $CH_4$, are vented overboard. Single pass high conversion efficiency (98-99%) subsystems have been developed.

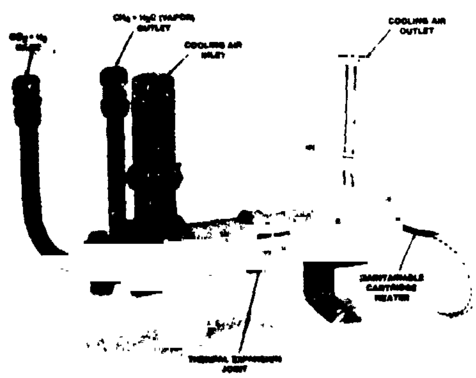

**Figure 4. Sabatier Reactor**

**Bosch Process**[7]

This $CO_2$ reduction process reduces $CO_2$ and $H_2$ to solid carbon (C) and water. The reaction occurs in the range of 980 1340 F in the presence of an iron (Fe) catalyst. The overall reaction is:

$$CO_2 + 2H_2 = C + 2H_2O + \text{heat}$$

In practice, single pass efficiencies through the Bosch reactor are less than 10%. Complete conversion is obtained by recycling the process gases with continuous deposition of carbon and removal of water vapor. The recycled gas mixture contains $CO_2$, carbon monoxide (CO), water vapor and $CH_4$. The carbon remains in the reactor and is collected in expendable cartridges. The Bosch development efforts have been limited, and a laboratory breadboard subsystem is shown in Figure 5.

In terms of equivalent weight, the Sabatier and Bosch $CO_2$ reduction processes trade off as shown in Figure 6 for an 8-person capacity SOC Application. The Bosch $CO_2$ reduction process does not trade off favorably with a Sabatier oriented ARS that uses a hydrazine-based $N_2$ generation subsystem. However, as cabin atmosphere leakage is reduced (less $H_2$ available for $CO_2$ reduction) and/or overboard venting of gases becomes detrimental to a mission, the Bosch process becomes attractive.

**Oxygen Generation**

Oxygen generation in a regenerative air revitalization system involves electrolyzing water recovered from on-

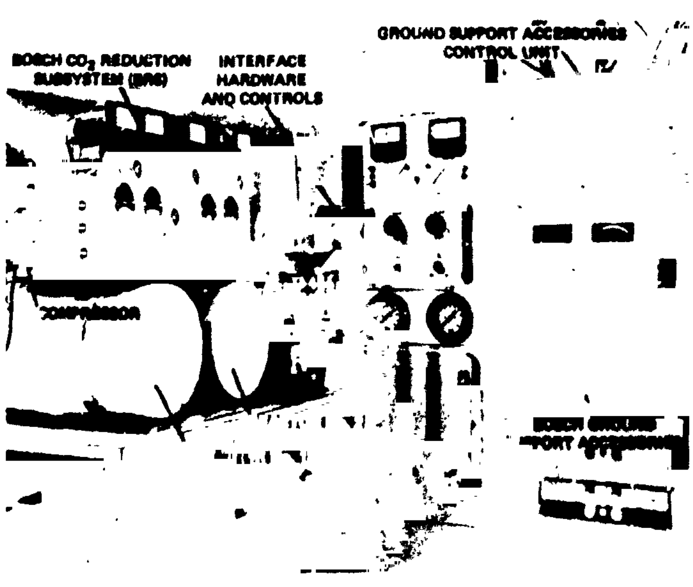


**Figure 5. Bosch Laboratory Breadboard Subsystem**

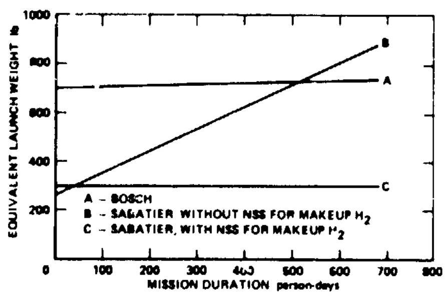


**Figure 6. Comparison of $CO_2$ Reduction Subsystem Concepts**

board waste water sources, cabin humidity condensate and from the $CO_2$ reduction process. In the electrolysis subsystems the electrolyte must be maintained between the electrodes, and the water that is electrolyzed must be replenished. This is not a simple task in zero gravity.

Two liquid-feed water electrolysis concepts offer the potential for minimizing and containing bulk electrolyte and maximizing the subsequent reliability and safety of the $O_2$ Generation Subsystem (OGS). These two concepts are the Solid Polymer Electrolyte (SPE-WES) and Static Feed (SF-WES) Water Electrolysis Subsystems.

### SPE-WES(8)

The SPE-WES uses a perfluorinated sulfonic acid polymer membrane electrolyte in the electrolysis cells (see Figure 7). The electrolyte membrane is in contact

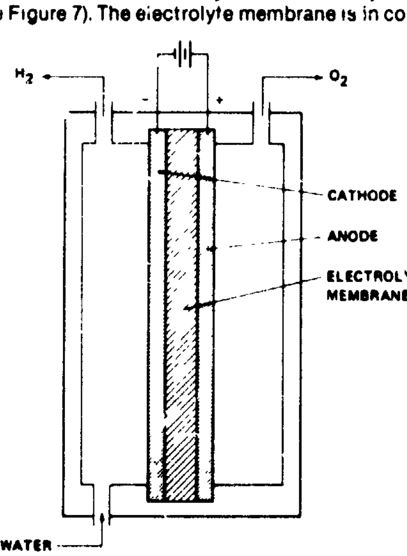


**Figure 7. SPE-WES Cell Functional Schematic**

with two electrodes and must be kept moist. In the case represented in Figure 7, the cathode cavity is flooded with liquid water. The electrochemical reactions that occur are:

Cathode:

$$4H^+ + 4e^- = 2H_2$$

Anode:

$$2H_2O = 4H^+ + 4e^- + O_2$$

A three-person capacity SPE-WES OGS that includes a twelve-cell electrolysis module (see Figure 8), has been developed for the RLSE program. This subsystem has demonstrated voltages of approximately

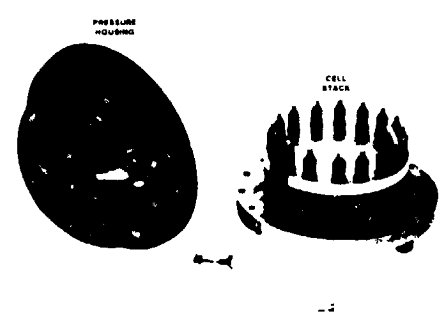


**Figure 8 RLSE SPE-WES Module**

1.6 volts (V) at operating conditions of 180 F and a current density of 150 Amps per square foot (ASF). This subsystem offers advantages over other acid electrolyte water electrolysis technologies (low voltages and no free electrolyte in the subsystem), but it does require subsystem support components (and complexities) to deal with gas/liquid separation and removal of dissolved gases in the condensed water exhaust.

### SF-WES(9)

This concept utilizes static-feed water addition to an alkaline electrolyte (see Figure 9). The water is fed as vapor through the $H_2$ cavity to the electrolysis site (cathode/matrix/anode composite assembly). The reactions occurring in the alkaline electrolysis cells are:

Cathode:

$$4H_2O + 4e^- = 2H_2 + 4OH^-$$

Anode:

$$4OH^- = 2H_2O + O_2 + 4e^-$$

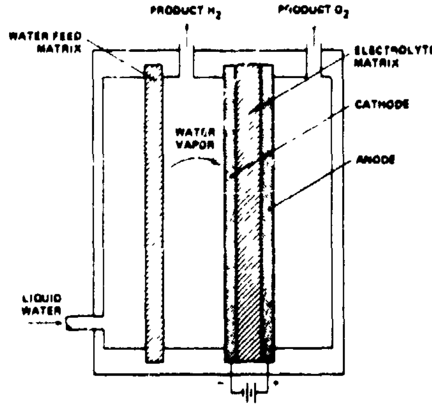


Figure 9. SF-WES Cell Functional Schematic

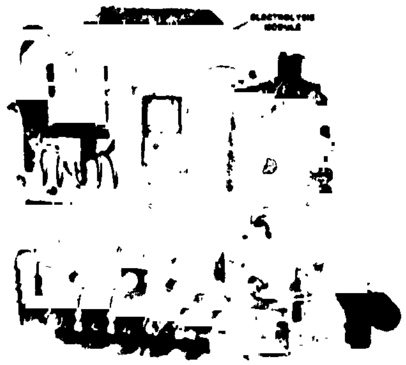

Figure 10. One-Person SF-WES OGS

Initially the water feed cavity, the water feed matrix and the cell matrix (with electrodes) contain an aqueous solution of potassium hydroxide (KOH) electrolyte at equal concentrations. When power is applied to the electrodes, water from the cell electrolyte is decomposed and the cell electrolyte concentration increases, with a resultant decrease in electrolyte vapor pressure. The vapor pressure of the electrolyte in the feed matrix causes water vapor to diffuse through the $H_2$ cavity and to be absorbed in the cell electrolyte matrix. This process establishes a new equilibrium based on the water requirements for electrolysis and humidification of the product gases and continues as long as electrical power is applied to the cell electrodes. When electrical power is discontinued, water vapor will continue to diffuse across the $H_2$ cavity until the electrolyte concentration in the cell matrix is equal to that in the water feed matrix and the water feed compartment.

The static-feed water addition concept is simple, reliable and minimizes subsystem components and controls. In addition, the use of alkaline electrolyte allows low cell voltages, which result in low power penalties. Long duration testing with the SF-WES and electrochemical modules has demonstrated voltages of 1.45-1.49V at operating conditions of 180 F and a current density of 150 ASF.

A self-contained one-person capacity SF-WES has been developed and is currently undergoing tests (see Figure 10).

**Nitrogen Generation**

With the advent of a two-gas space cabin atmosphere using nitrogen ($N_2$) as the diluent, storage and supply of $N_2$ for cabin leakage make-up is essential. The preferred method of providing $N_2$ make-up is to store the $N_2$ as hydrazine ($N_2H_4$), to catalytically dissociate the $N_2H_4$ into $N_2$ and $H_2$, and to separate the $N_2$ and $H_2$ gases[10]. This concept is especially attractive if the Sabatier $CO_2$ reduction process is utilized (see Figure 6).

This Nitrogen Supply Subsystem (NSS) has a module containing catalytic dissociation and Pd/Ag passive gas separation stages. Dissociation of $N_2H_4$ (at 1350 F, 250 psia) involves the equilibria in the following reactions:

$$(1)\quad N_2H_4 = \tfrac{1}{3}N_2 + \tfrac{4}{3}NH_3$$

$$(2)\quad \tfrac{4}{3}NH_3 = \tfrac{2}{3}N_2 + 2H_2$$

A staging concept has been developed in order to separate the $H_2$ from the product $N_2$ and to reduce the $NH_3$ concentration in the product $N_2$ gas. A schematic demonstrating the staging concept is shown in Figure 11. All of the $N_2H_4$ and some $NH_3$ are catalytically dissociated in the first stage. The $N_2$, $H_2$ and non-dissociated $NH_3$ enter the first $H_2$ separation stage where most (90%) of the $H_2$ is removed and collected for use in the $CO_2$ reduction subsystem. The $N_2$ product gas stream then passes successively through

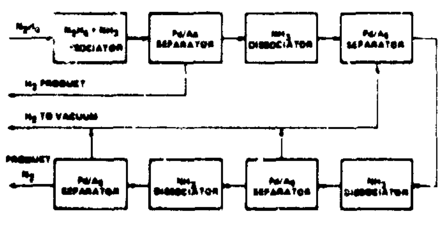


Figure 11. Nitrogen Generation Subsystem Schematic

three additional dissociation/separation stages. This alternate dissociation/separation staging and subsequent venting of $H_2$ to vacuum (10%) is necessary to favor further $NH_3$ dissociation and thus to lower the $H_2$ and $NH_3$ concentrations in the product $N_2$. A nitrogen generation module that includes these stages is shown in Figure 12. Testing with this NSS hardware has demonstrated that the product $N_2$ stream contains less than 10 ppm $NH_3$ and 0.5% $H_2$.

Nitrogen generation using hydrazine should be considered as both a spacecraft resource or function and an air revitalization function. The hydrazine based $N_2$ generation approach utilizes expendable $N_2H_4$ (11 lb/day) to generate $N_2$ (9.6 lb/day) and provides $H_2$ (1.23 lb/day) for air revitalization. It is assumed that the NSS will be located external to the manned space cabin with bulkhead feedthroughs for product $N_2$ and $H_2$. This subsystem isolation not only contributes to safety considerations, but passive thermal control of the $N_2$ generation module and the use of space vacuum for byproduct $H_2$ would also be possible

**Trace Contaminant Control**

Contaminants in manned spacecraft emanate from both the crew and the equipment. As mission durations, vehicle sizes, crew sizes, and vehicle payload and experiment complexities increase and as spacecraft leak rates decrease, there will be a concomitant increase in concentration and variety of potential contaminants. In addition, the increased crew exposure time (with longer mission durations) will dictate a reduction in the allowable contaminant concentrations.

A spacecraft contaminant control subsystem that deals with an expected wide variety of contaminants will involve several elements including catalytic oxidation, charcoal adsorbers and chemical absorbers. No single contaminant control process is suitable for all contaminants. Some, such as CO, $CH_4$ and $H_2$, can be catalytically oxidized to $CO_2$ and water relatively easy. Some gases will poison oxidation catalysts and must be removed by pre-sorbent beds to protect the

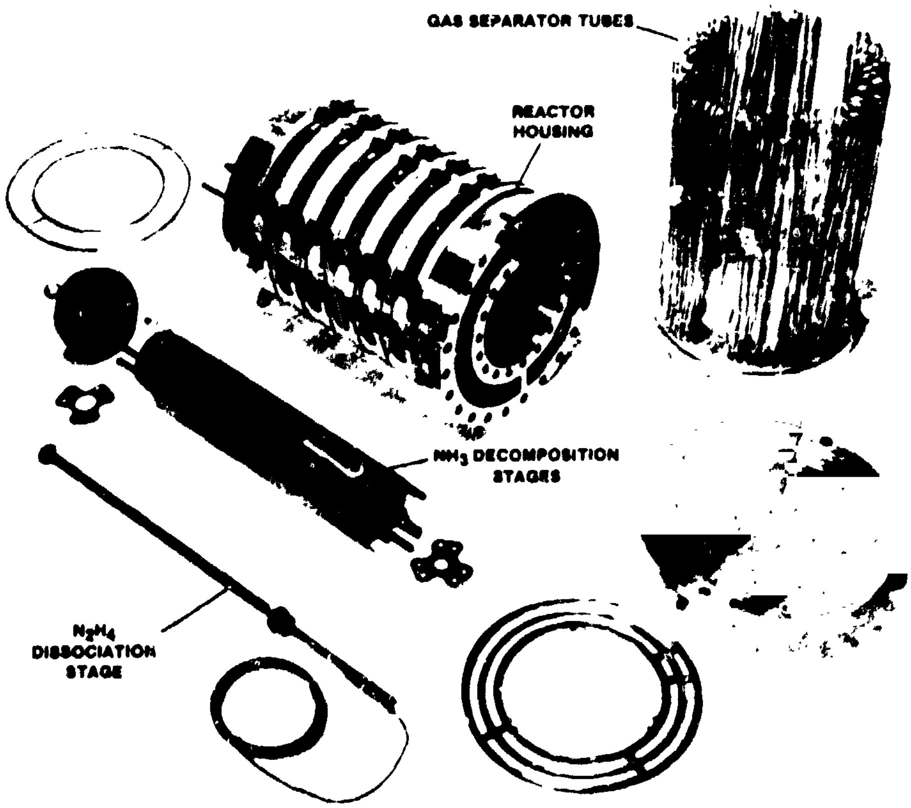


**Figure 12. Advanced $N_2$ Generation Module**

catalyst. Some gases, when oxidized, form extremely toxic substances (i.e., fluorocarbons form carbonyl fluoride) that must be removed by post-sorbent beds, and some organic materials cannot be oxidized efficiently and must be adsorbed.

A limited amount of work has been performed on adsorber/absorber characterization and on catalytic oxidation schemes. Some development efforts have also been directed toward regeneration of activated charcoal. These contaminant control R&D efforts have been very sporadic, and the technology has not progressed sufficiently to be commensurate with other regenerative air revitalization processes.

**Air Revitalization System Integration**

As mentioned previously, an Air Revitalization System (ARS) requires the individual subsystem technologies listed in Figure 13. An engineering breadboard integrated air revitalization system (ARX-1), including all ARS subsystem functions with the exception of contaminant control has been fabricated (see Figure 14).

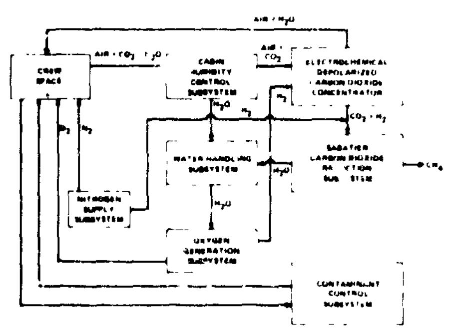

**Figure 13. Air Revitalization System Block Diagram**

Preliminary testing of the ARX-1 was conducted for a period of 120 days and included checkout, shakedown and endurance testing. Almost 500 hours of integrated operation at nominal steady-state conditions corresponding to a one person level were achieved. Additional testing, currently underway, will examine subsystem interactions by varying parameters such as $CO_2$ generation rate, humidity load, coolant temperature and power availability. One goal of this testing is to demonstrate the readiness of this integrated air revitalization system for prototype development and flight demonstration.

**Control/Monitor Instrumentation**

A major development goal of the advanced life support program is long duration operation with minimal servicing and maintenance by the crew and the avoidance

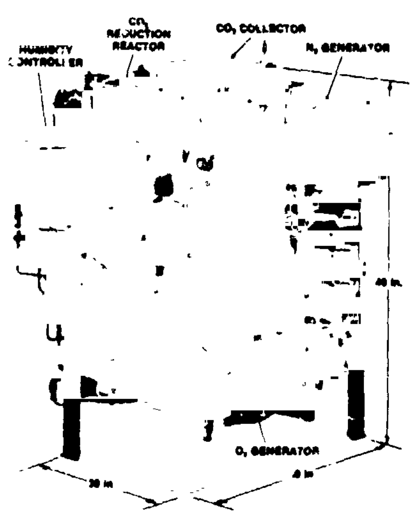


**Figure 14. ARX-1**

of excessive crew training requirements. An integrated air revitalization system, for example, contains a range of electrochemical, chemical, mechanical and electrical components/subsystems; and automatic process control and monitoring are an absolute necessity.

This computer-based Control/Monitor Instrumentation (C/M I) must provide monitoring capability, control functions including subsystem system mode transitions; and fault diagnostics including fault prediction, fault detection, fault isolation, fault correction, and fault correction instructions. In addition, the C/M I hardware and software must be "operator error-proof."

Advanced life support C/M I developments have progressed along with current life support technology advancements. The early stages of C/M I development provided for manual or automatic operation. C/M I development has progressed through the hard wired primary and emergency controller stage to a programmable mini-computer with a customized keyboard for operator commands, a Cathode Ray Tube (CRT) for operator/system messages, a system status panel, a system control panel, and an actuator override panel (see Figure 15).

The current stage of developmental C/M I is dedicated to the control and monitoring of engineering breadboard systems, such as the ARX-1 (see Figure 14). Test programs with advanced life support developmental hardware involve off-design, parametric and life testing. Therefore, C/M I components such as an actuator override panel are included. Advanced life support flight hardware will, of course, be dedicated to steady state operation; and the same is true for the

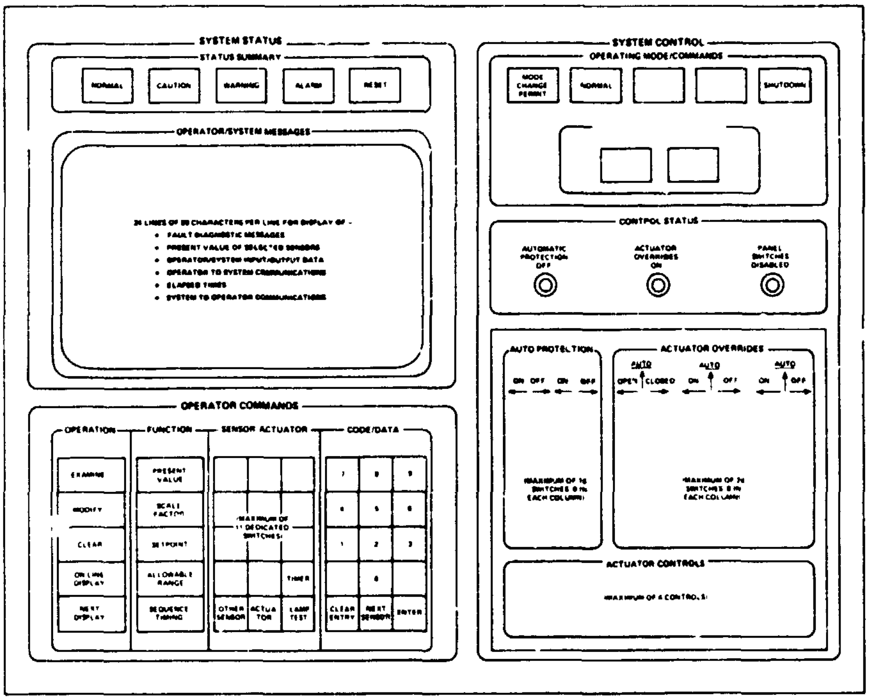

Figure 15. C/M I Control Panel

C/M I. Therefore, flight C/M I hardware will become considerably smaller and will utilize dedicated microprocessors. A flight oriented C/M I design concept for an EDC subsystem is shown in Figure 17.

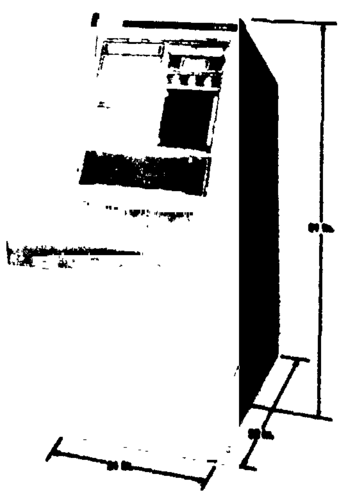

Figure 16. ARX-1 C/M I

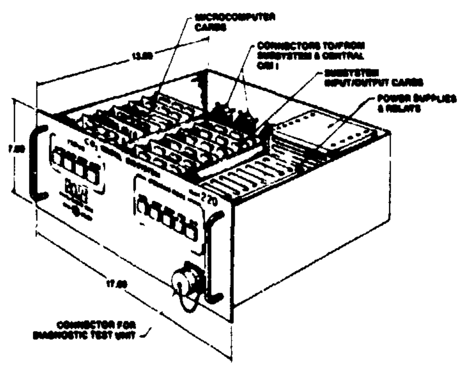

Figure 17. Flight-Oriented C/M I For $CO_2$ Removal Subsystem



C-3

**Independent Air Revitalization System**

NASA has investigated partial air revitalization systems for intermediate manned space applications. One of these is an Independent Air Revitalization System (IARS), which is perceived as a "semi-portable" ARS. The IARS includes a water vapor electrolysis (WVE) subsystem and an EDC subsystem. The IARS provides simultaneous $CO_2$ removal, $O_2$ generation and partial humidity control[11]. The IARS can operate as a separate system, or it can operate as a back-up to a central ARS, described previously. A schematic of the IARS is shown in Figure 18.

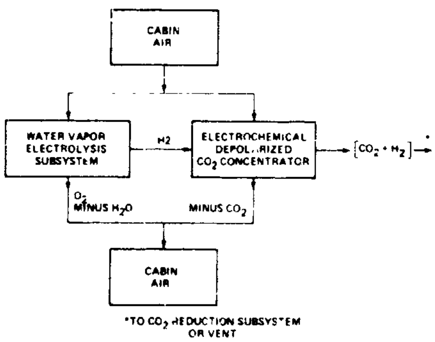


**Figure 18. IARS Schematic**

**Water Vapor Electrolysis Subsystem**

The WVE subsystem, which uses a hygroscopic electrolyte ($H_2SO_4$), absorbs water vapor from the cabin air stream and generates $O_2$ and $H_2$ per the following reactions:

Anode:

$$H_2O = \frac{1}{2}O_2 + 2H^+ + 2e^-$$

Cathode:

$$2H^+ + 2e^- = H_2$$

A functional WVE cell schematic is shown in Figure 19. Cabin air moisture is absorbed at the anode/electrolyte interface and the $O_2$ generated by electrolysis is released into the cabin air flowing through the anode compartment. Hydrogen ($H_2$) is generated at the cathode and is utilized at the anode of the EDC subsystem.

**EDC Subsystem**

The EDC subsystem technology used in the IARS has already been described in an earlier section of this paper and the subsystem electrochemical module hardware is similar to the EDC RLSE hardware shown in Figure 3.

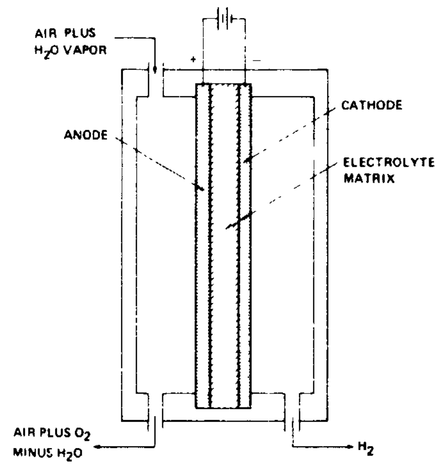


**Figure 19. WVE Cell Functional Schematic**

**IARS Development Unit**

A functional IARS development unit has been developed for the NASA RLSE program (see Figure 20), and a ninety (90) day characterization/endurance test program has been successfully completed with this three-person capacity IARS. Characterization testing included measuring the effect of cabin air $pCO_2$ and moisture levels on electrochemical cell performance (EDC and WVE cell voltages) and on $CO_2$ removal efficiency. For nominal operating conditions the EDC voltage averaged 0.4 V/cell at 20 ASF while the WVE voltage was 1.70 V/cell at 42 ASF. The $CO_2$ removal efficiency averaged 80% (2.2 lb. of $CO_2$ removed per pound of $O_2$ consumed). Additional testing of the above unit is scheduled.

**WATER RECLAMATION**

Water reclamation in a manned spacecraft is of equal importance with air revitalization. Water reclamation involves processes to reclaim water from waste water sources such as fuel cell water, cabin humidity condensate, wash water and urine. These waste water sources represent increasing degrees of contamination and will generally require reclamation processes of increasing complexity. Various processes, including multi-filtration, phase change and membrane processes, have been investigated for these applications; and limited subsystem and component development efforts have been undertaken to date.

Recovery of fecal water is considered to be difficult but feasible. Fecal water reclamation will be discussed briefly in the solid waste treatment section of this paper.

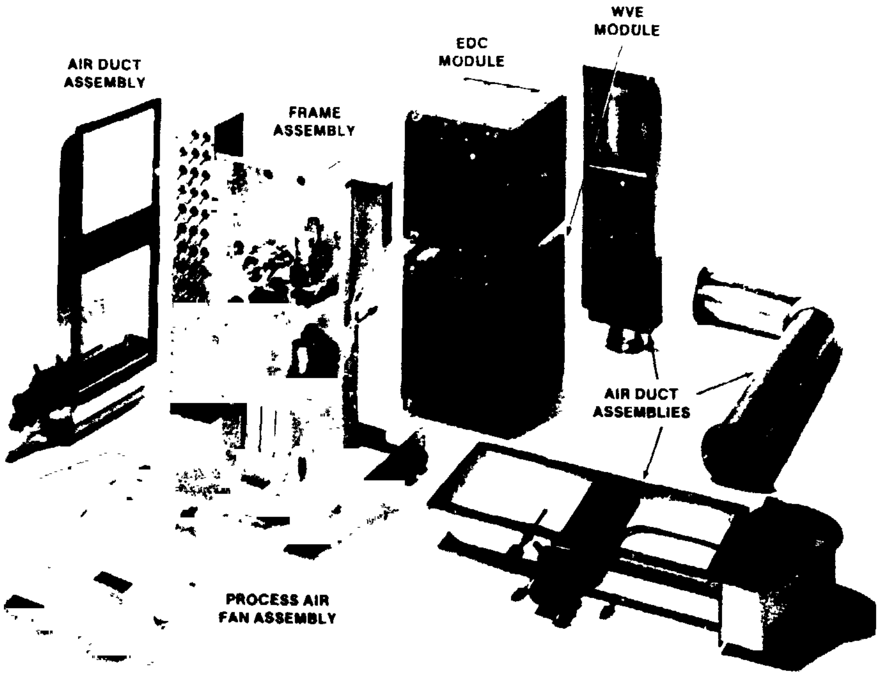


Figure 20. IARS RLSE Development Hardware

**Multi-Filtration**

Multi-filtration processes can be used for treating waste water containing contaminants in low concentrations (e.g., fuel cell water, cabin humidity condensate, and possibly wash water) Typically, a multi-filtration process will include a particulate/bacterial filter, an activated charcoal canister, an anion exchange resin bed, and a cation exchange resin bed[12] Very little development work has been performed in this area, and this process technology will not be discussed in further detail in this paper.

**Phase Change Processes**

Phase change processes that have been considered for spacecraft water reclamation from waste water sources such as urine include air evaporation, vapor compression distillation, vapor diffusion/evaporation, and a relatively new concept that uses vapor phase ammonia removal. In a distillation/condensation process, the goal is to retain the solutes (in a stabilized form) in the evaporator and to reclaim the energy involved with the vaporization process. Three of these concepts will be discussed in the following sections of this paper.

**Vapor Compression Distillation**

A Vapor Compression Distillation (VCD) process schematic is shown in Figure 21[13]. The recovery of latent heat in the VCD process is accomplished by compressing the vapor to raise its saturation temperature and then condensing the vapor on a surface which is in thermal contact with the evaporator. The resultant

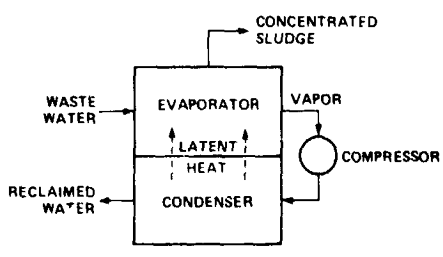


**Figure 21. Vapor Compression Distillation Schematic**

heat flux from the condenser to the evaporator is sufficient to evaporate an equal mass of water. Thus the latent heat of condensation is recovered for the evaporation process; and the only energy required by the process is that necessary to compress the vapor and to overcome the thermal and mechanical inefficiencies.

The VCD process occurs in a 70 to 95 F temperature range by maintaining a nominal condenser pressure of 0.70 psia. The evaporator, condenser and condensate collector are rotated at approximately 220 rpm to provide zero-gravity phase separation. The VCD components are sized to recover 96% of the water from the waste water feed by concentrating this feed stock to 50% solids. The VCD process requires pretreatment chemicals to complex with urea and to provide antifoaming in the evaporator. The product water from this subsystem requires post-treatment in charcoal and ion exchange beds in order to remove trace amounts of organic materials and dissolved $NH_3$, and the product water also requires the addition of small amounts of biocide to control bacterial growth.

Testing of two six-person capacity preprototype VCD units (one shown in Figure 22) has been completed with over 1000 hours of test time accumulated on each unit. Pretreated urine has been concentrated to 50% solids with water quality at projected levels (pH 5.0, conductivity of 16 μmho/cm nominal). Specific energies, expressed in watt-hours per pound of water recovered (the key VCD performance parameter), averaged from 45 to 55 W-h/lb. Additional testing of existing VCD units plus the development of an advanced development unit are underway.

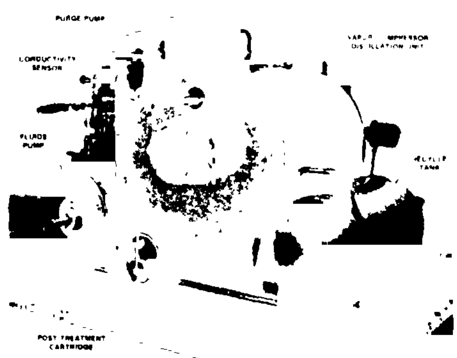

**Figure 22. VCD Water Recovery Subsystem**

**Thermoelectric Integrated Membrane Evaporation Subsystem**

A schematic of the Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES) is shown in Figure 23. This concept[14] recovers the latent heat of condensation and transfers this heat to the evaporator

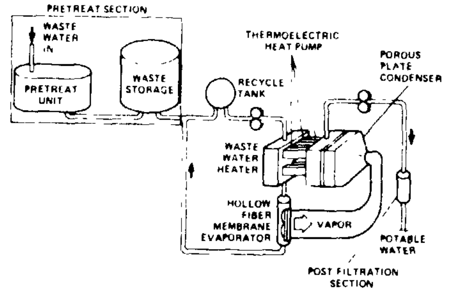


**Figure 23. Thermoelectric Integrated Membrane Evaporation Subsystem Functional Schematic**

via a thermoelectric heat pump. Waste water (urine), pretreated with a sulfuric acid/chromium trioxide solution, is heated to approximately 150 F in the thermoelectric heat exchanger, and the heated waste water is pumped through a hollow fiber polysulfone membrane evaporator module. The exterior of the module tubes is exposed to reduced pressure, and water evaporates from the tube surface and is condensed on a chilled porous plate surface in thermal contact with the cold junction surfaces of the thermoelectric heat exchanger. The heat of vaporization is provided by recycling the waste water to the heat exchanger where it is reheated and recycled. The product water from this subsystem concept requires the same post-treatment steps as those used by the VCD process. Typically the solids concentration in the recycle loop gradually increases until 95% of the original water is removed and the solids concentration is approximately 40%. At this point, the recycle tank containing the concentrated waste water sludge is removed for storage and a replacement tank is installed. The energy requirements for this process are primarily for the thermoelectric heat pump and for the subsystem pumps (recycle, cooling, and condensate).

A photograph of TIMES development hardware is shown in Figure 24. This subsystem has undergone limited testing and an analysis of subsystem performance cannot be made at this time.

**Vapor Phase Catalytic Ammonia Removal**

Ultimately, a water reclamation process that requires neither pretreatment nor post-treatment expendable chemicals would be desirable for manned spacecraft use. The vapor phase catalytic ammonia removal process offers this potential advantage[15]. A schematic of the process is shown in Figure 25.

Waste water (urine) is vaporized, and the vapor stream is mixed with air or $O_2$ and passes through an oxidation reactor. Ammonia, urea and light organics are oxidized in this reactor. Water is condensed and separated, and the vapor phase then passes through a nitrous oxide ($N_2O$) decomposition reactor which converts the $N_2O$ to $N_2$ and $O_2$. Studies with "laboratory-

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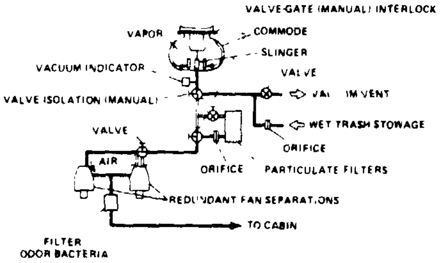


**Figure 26. Solid Waste Management System/Space Shuttle**

**MANNED TESTING AND LIFE SUPPORT INTEGRATION**

The majority of NASA's advanced life support R&D efforts have been directed at subsystem technologies or components, but there have also been efforts to integrate subsystem technologies and to perform manned chamber tests with the most advanced life support hardware available. These efforts were not directed particularly toward subsystem integration optimization, but they were directed toward manned chamber/life support subsystem hardware tests. The early manned chamber tests were performed successively at 30-, 60-, and 90-day durations[18, 19, 20] under the sponsorship of Langley Research Center.

Prototype integrated life support subsystem hardware has also been developed for "integrated systems" programs such as the Space Station Prototype (SSP) program (1971-1975)[21] and the Regenerative Life Support Evaluation (RLSE) program (1975-present) under the sponsorship of Johnson Space Center[22]. This hardware has included: EDC $CO_2$ concentration, Sabatier $CO_2$ reduction, SPE water electrolysis $O_2$ generation, Independent Air Revitalization System (EDC $CO_2$ concentration and WVE $O_2$ generation), VCD urine water recovery subsystem, dynamic membrane wash water recovery subsystem, subsystem computerized C/M I and various components and sensors. The manned chamber tests and the testing of the SSP and RLSE hardware have been limited, but the subsystem SR&T program has benefited from both the hardware development phases and the test results.

**ENHANCED DURATION ORBITER**

As mentioned previously, the early Shuttle Orbiter flights will be limited to seven-day missions. In order to maximize the effective use of this Space Transportation System, Extended Duration Orbiter (EDO) missions of 30, 60 and 90 days are under active consideration. Such extended Orbiter missions will make it mandatory to reduce life support and auxiliary power (fuel cell) expendables. Significant weight savings for these missions can be realized by replacing the expendable lithium hydroxide canisters with a regenerable/continuous $CO_2$ removal subsystem. For longer missions, an IARS may also become applicable

It should also be emphasized that if auxiliary power supplies such as the Power Extension Package (PEP) or a full power module (25 kW) are substituted for the Orbiter fuel cells, large $O_2$ and $H_2$ expendable requirements are eliminated; but large quantities of relatively clean fuel cell water will not be available for reclamation and subsequent use Water reclamation from humidity condensate and wash water would then become attractive and provide weight savings.

**SPACE OPERATIONS CENTER**

The Space Operations Center (SOC) has been conceived as a modular space station serviced by the Space Shuttle. The SOC is a low earth orbit permanent manned facility with a 14.7 psia mixed gas atmosphere A Shuttle resupply interval of 90 days is planned. The nominal volume for SOC is 22,000 $ft^3$, and the vehicle has been planned for a crew size of eight persons[23].

The SOC life support system is regenerative in order to minimize crew expendables. The life support system functional schematic and mass balances are shown in Figure 27. The baseline SOC life support system includes the following subsystems:

(1) liquid water electrolysis $O_2$ generation (solid polymer or static-feed)
(2) VCD urine water recovery
(3) hyperfiltration wash water recovery
(4) condensing heat exchanger humidity control
(5) EDC $CO_2$ control
(6) Sabatier $CO_2$ reduction
(7) hydrazine dissociation $N_2$ generation

The SOC life support system will regenerate all metabolic water and $O_2$ requirements. The only crew expendable requirement is wet food. Resupply of $N_2H_4$ will be required for the $N_2$ generation subsystem and subsequent cabin leakage make-up. Some expendables will also be required for filters, chemical beds, urine pretreatment chemicals, etc.

The SOC life support system configuration is planned so that reclaimed water from urine will be utilized primarily for $O_2$ production. The system will provide drinking water reclaimed from cabin humidity condensate, water vapor from the $CO_2$ concentrating process and water from the $CO_2$ reduction process. The mass balance demonstrates that surplus reclaimed water will be available beyond that required by the crew and the life support processes.

It should be emphasized that the SOC program is currently in the early definition phases, and it is possible that other life support subsystem technologies will replace the baseline subsystems in the future. The



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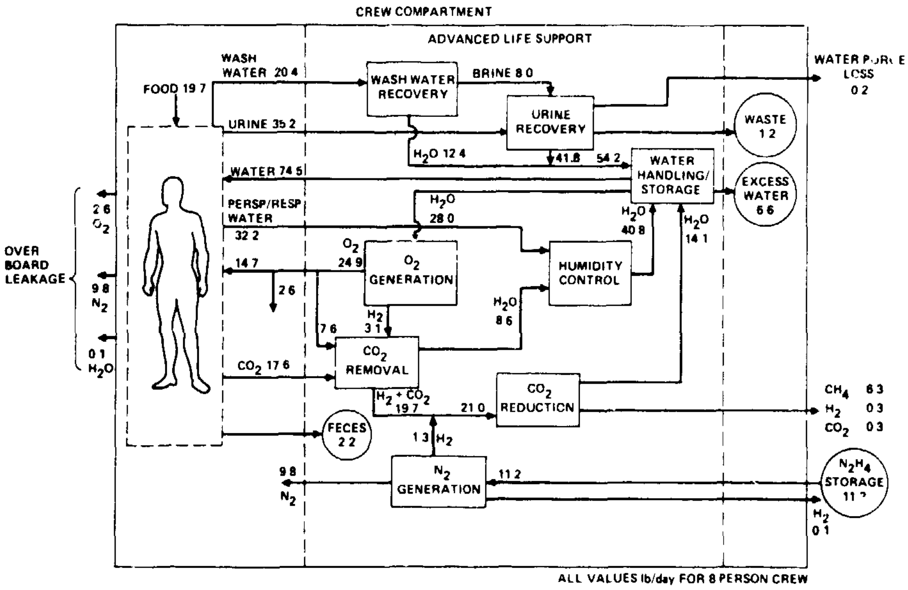


**Figure 27. Space Operations Center Life Support System Functional Schematic and Mass Balance**

controlling factors governing subsystem selection are, of course, the actual SOC project schedule and the concurrent subsystem development status.

## MANNED INTERPLANETARY LIFE SUPPORT SYSTEMS

The life support functions required for manned interplanetary flight vehicles are essentially the same as those provided for Earth orbital space stations, regenerative air revitalization; water reclamation from humidity condensate, wash water and urine, and advanced solid waste management techniques.

It is anticipated that upgrading and possible substitution of subsystem technology will occur in order to increase performance capability and reliability. Subsystem selection and system integration will be dependent on the significant vehicle trade-offs that are relevant at the time of selection.

A Controlled Ecological Life Support System (CELSS) that includes food production is considered to be noncompetitive for a manned planetary flight vehicle, but a CELSS is applicable for space settlements (i.e., lunar, Mars, $L_5$, etc.).

## FUTURE DEVELOPMENT REQUIREMENTS

The ultimate goal of NASA's advanced life support Research and Development (R&D) program is to develop the technology base for future manned space requirements. This program has been responsible for the successful developments that have been discussed in the advanced technology section of this paper.

It should be emphasized, however, that the current technology data base is not adequate for space mission planners. A significant amount of additional development activity in systems, subsystems and components must be accomplished. It should also be emphasized that the advanced life support systems technology developed to date deals with chemical processes that require proper gas/liquid separation in reduced gravity. However, none of the regenerative systems/subsystems/components described in the advanced technology section of this paper have been tested in reduced or zero gravity. Long term tests on spacecraft, such as Spacelab, are absolutely essential to the data base generation and to mission planners. Short term (approximately 30 sec) aircraft parabolic flight tests will not suffice.

NASA's advanced life support R&D program must address these issues in order to guarantee an adequate technology base for future manned space missions. An adequate technology base will not guarantee that future manned missions such as SOC or interplanetary flights will be carried out. The failure to develop the technology base *will guarantee* either that "we aren't going", or that future manned missions will require concurrent program and project hardware developments, which have historically resulted in large cost overruns (e.g., Shuttle).

In order to develop an adequate technology base, it is essential that additional R&D efforts at the following technology levels be carried out:

(1) Flight technology demonstrations

(2) System developments

(3) Subsystem developments

(4) Components/parts developments

(5) Engineering analysis/applications, system and trade studies

(6) Basic and applied research (scientific and engineering data)

These efforts are essential for air revitalization, water reclamation and solid waste management

It is obvious from the advanced technology development section of this paper that the development status for air revitalization, water reclamation and solid waste management systems differs significantly, with air revitalization system/subsystem technology having the highest. A ten-year development plan that delineates the currently obvious additional technology level requirements for air revitalization is shown in Figure 28. This listing is not all-inclusive, but

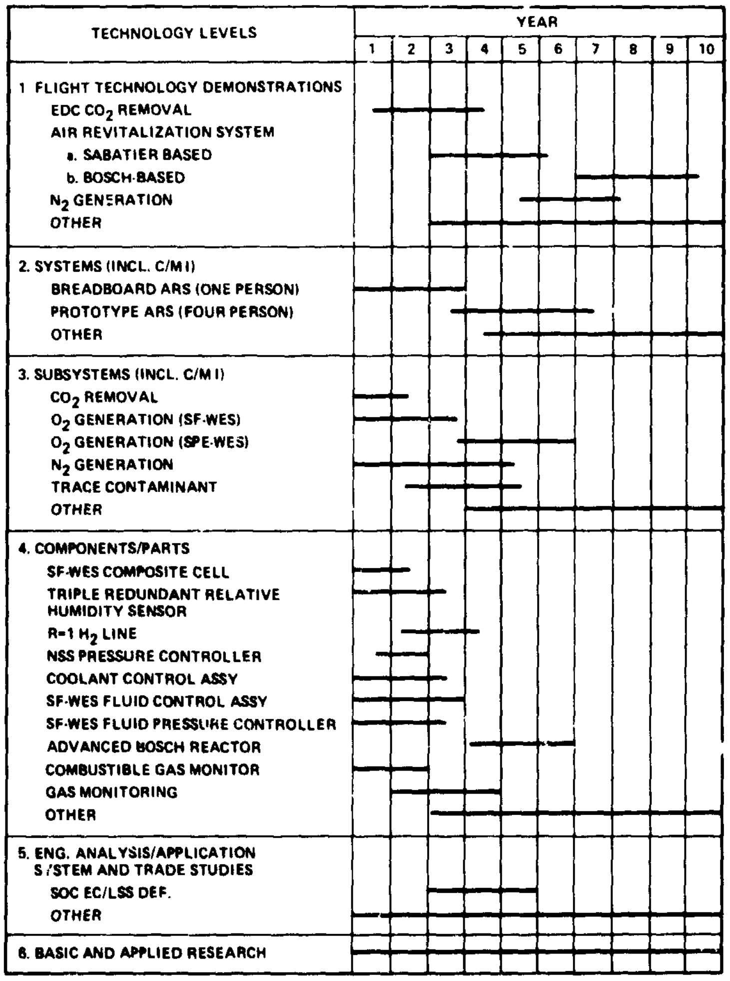


**Figure 28. ARS Development Schedule According To Technology Levels**

it clearly demonstrates the magnitude of R&D activity that must be performed in order to establish the required air revitalization technology base. One of the Space flight technology demonstrations identified in Figure 28 is a Sabatier based Air Revitalization System (ARS). A mock-up of this ARS flight demonstrator is shown in Figure 29.

Program planning activities are required in order to establish similar ten-year program requirements for water reclamation and solid waste management. The identified technology data gaps must, of course be filled if advanced water reclamation and solid waste management systems technology is to be selected and baselined for future manned space flight hardware.

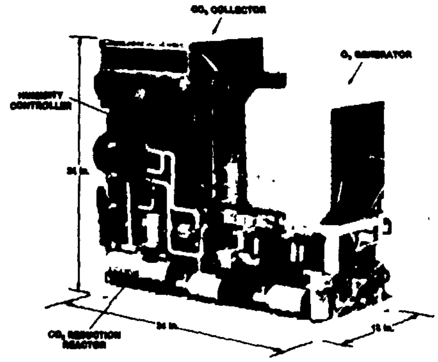

**Figure 29. ARS-Space Flight Demonstrator Mock-Up**

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