Lockheed Martin Space Operations
Science, Engineering, Analysis, and Test
2400 NASA Road 1, P.O. Box 58561 Houston, TX 77258-8561
Telephone (218) 333-5411

LOCKHEED MARTIN

September 17, 1999
Sub-Task Order: 9HECECAYS
Contract: NAS9-19100
HDID-2G42-1164

TO: Dr. C. H. Lin/EC2
M. K. Ewert/EC2

CC: Distribution

VIA: F. F. Jeng
J. F. Keener
A. H. Milliken

FROM: H. Y. Yeh

SUBJECT: VPCAR and BWRS Trade Study

Attached please find a copy of the document in support of the VPCAR and BWRS Trade Study.

If you have any questions or comments, please give me a call at (281) 333-7682 or email me at jannivine.yeh@lmco.com.

Contract: NAS9-19100
Subtask Order: 9HECECAYS

VPCAR and BWRS Trade Study

Prepared by

H. Y. (Jannivine) Yeh

Approved by

F. F. Jeng, Lead

J. F. Keener, Project Manager
Thermal and Fluid Process Analysis Projects

A. H. Milliken, Section Manager
Thermal, Fluid Flow, and Systems Engineering Section

SEPTEMBER 1999

LMSEAT 33212
HDID-2G42-1164

EXECUTIVE SUMMARY

Development of a highly reliable and efficient Water Recovery System for the space habitat to recover potable water from the wastewater generated by crewmembers has become a necessity to reduce costly water resupply needs for long duration space missions.

Many water recovery technologies have been developed since the 60's. Besides the International Space Station Water Recovery System (ISS WRS), two other Integrated Water Recovery Systems (IWRS) that can generate potable quality H_2O are the Bioregenerative Water Recovery System (BWRS) and the Vapor Phase Catalytic Ammonia Removal (VPCAR) process.

BWRS, developed by JSC since 1991, adopts the biological wastewater treatment technology, a widely accepted technology currently used for treating industrial and municipal wastewater. After years of system improvement and redesign, BWRS was able to demonstrate its capability to generate potable water and was used as the water treatment system for the Lunar-Mars Life Support Test Project 90-day Test to continually produce potable water in 1997.

VPCAR developed since 1968 was designed to remove ammonia (NH_3) and volatile organic compounds (VOC) from the wastewater stream for space applications. After years of system improvement and redesign by different organizations, Ames Research Center has finalized the design with the current configuration. Its latest experimental results have proven its capability to generate potable water from wastewater as well.

Although many trade studies have been done based on similar functions of the H_2O treatment technologies, none of them seem to have performed a thorough evaluation of the IWRS for potable quality H_2O recovery from the feed stream containing an equivalent mixture of the wastewater from crewmembers different activities during the mission. Therefore, NASA/JSC/EC management initiated the idea to perform a detailed evaluation of the IWRS that can generate potable water and are currently under development. Two of the IWRS that qualify to fall into this category are VPCAR and BWRS.

A thorough process evaluation of the BWRS and VPCAR for space application using ISS WRS as a trading basis was initiated and completed.

The study concluded that the BWRS is a promising process for TOC removal. More work is required to validate and refine the nitrification process. The longer startup/turnaround time is a disadvantage for this system in case any unpredicted malfunction occurs to the biological reactors or any unpredictable microorganisms behavior takes place during operation.

VPCAR system is a promising NH_3 and VOC converter. Suppression of biological contaminants in the product water is the advantage for this process, because product H_2O is condensed out from a H_2O vapor stream of 250 C. VPCAR is very competitive with the BWRS and ISS WRS from a mass, power and volume standpoint. Its power intensity may make the system less attractive to deal with large volume of gases at the vacuum condition.

More work is required for the nitrification process of the BWRS, and VPCAR is at its early stages of development for space application. Due to the different strengths and weaknesses of the two systems, it is difficult to conclude that one process is better than the other at this point in time.

For a more in-depth understanding of the VPCAR and BWRS feasibility for different space applications, it is strongly recommended to continue the following efforts:

1. Continue development of the VPCAR and BWRS, and prepare for integrated testing
2. Continue analysis and re-visit this trade study after VPCAR testing is complete and all the major equipment of the BWRS is better defined.

TABLE OF CONTENTS

I. INTRODUCTION

In conjunction with human missions to Mars in the near future, reduction of costly potable water (H_2O) resupply needs in the Mars Transit Vehicle or on the Martian surface has been a popular issue in the space industry. Development of a highly reliable and efficient water recovery system for the space habitat to recover potable water from the wastewater generated by the crewmembers has become an essential goal for long duration space missions. For that reason, NASA has funded its research centers, affiliates, universities, and private sector to identify and develop different water recovery processes for space applications since the 60's. (Ref. 14, 15, 19, 22, 23, 24, 26-30)

Besides the International Space Station Water Recovery System (ISS WRS), two other Integrated Water Recovery Systems (IWRS) that can generate potable quality water are the Bioregenerative Water Recovery System (BWRS) and the Vapor Phase Catalytic Ammonia Removal (VPCAR) process.

BWRS, developed by JSC since 1991, adopts the biological wastewater treatment technology, a widely accepted technology currently used for treating industrial and municipal wastewater. After years of system improvement and redesign, BWRS was able to prove its capability to generate potable water and was used as the water treatment system for the Lunar-Mars Life Support Test Project 90-day Test to continually produce potable water in 1997.

VPCAR, developed since 1968, was designed to remove ammonia (NH_3) and volatile organic compounds (VOC) from the wastewater stream for space applications. After years of system improvement and redesign, Ames Research Center has finalized the design with the current system configuration. Its latest experimental results have proven its capability to generate potable water from wastewater as well.

Trade studies for different water treatment technologies for similar functions have also been conducted (Ref. 7, 11, 17, 19.) These studies have based on a combination of several key factors: on-orbit mass and volume, resupply and return to Earth logistics, power consumption, technology readiness level, heat rejection, chemicals requirements for the system, and scheduled maintenance time, etc.

Although many trade studies have been done, none of them seem to have performed a thorough evaluation of the Integrated Water Recovery Systems (IWRS) that can generate potable quality water from the feed stream containing an equivalent mixture of wastewaters from crewmembers' different activities during the mission. Without a detailed sizing of the systems from their up-to-date process/experimental data, it is not likely that a good trade can be made possible. For that reason, NASA/JSC/EC management initiated the idea to perform a more detailed evaluation of the IWRS that can generate potable water and are currently under development. Two of the IWRS that qualify to fall into this category are VPCAR and BWRS.

A thorough process evaluation of the VPCAR and BWRS for space application using ISS WRS as a trading basis was initiated.

Literature search and review of the information related to the ISS WRS, the BWRS, and the VPCAR processes were conducted.

Sizing data for the ISS WRS were collected from published information (Ref. 2, 3, 4, 12, 25) and MSFC personnel. Sizing data for the VPCAR were collected from Ames Research Center (ARC)'s system principal investigator (Ref. 5, 7, 9, 10) and validated with VPCAR recent test results from experiments conducted at ARC. The VPCAR experimental protocol and test results are included in Appendix A and B respectively. Process data of the BWRS next generation unit were collected from NASA/JSC system principal investigators/monitors, and support contractors. Sizing estimate of the major equipment of the BWRS system was performed.

The VPCAR and BWRS systems were sized based on the ISS WRS daily potable water requirement with a shower. Assessment of the integrated water recovery systems was conducted based on their specific mass, estimated system volume, specific energy, and annual resupply.

II. BRIEF DESCRIPTION OF THE WATER RECOVERY SYSTEMS AND THEIR DEVELOPMENT HISTORIES

A. International Space Station Water Recovery System (ISS WRS) (Ref. 12, 25)

With years of research and development, MSFC has completed designing an integrated Water Recovery System. It is currently under the preliminary design review.

The ISS WRS comprises the Urine Processor Assembly (UPA) and the Water Recovery Assembly (WRA).

The UPA currently selects the Vacuum Compression Distillation (VCD) technology to treat the urine and urinal flush stream before its distillate is combined with other wastewater streams in the hygiene water tank for further treatment.

Figure II.1 shows the Process Block Diagram of the ISS WRS. The distillate from the VCD goes to the WRA's Hygiene Water Storage Tank and combines with the wastewater streams from crew activities such as shower, oral hygiene, hand wash, and aspiration/perspiration.

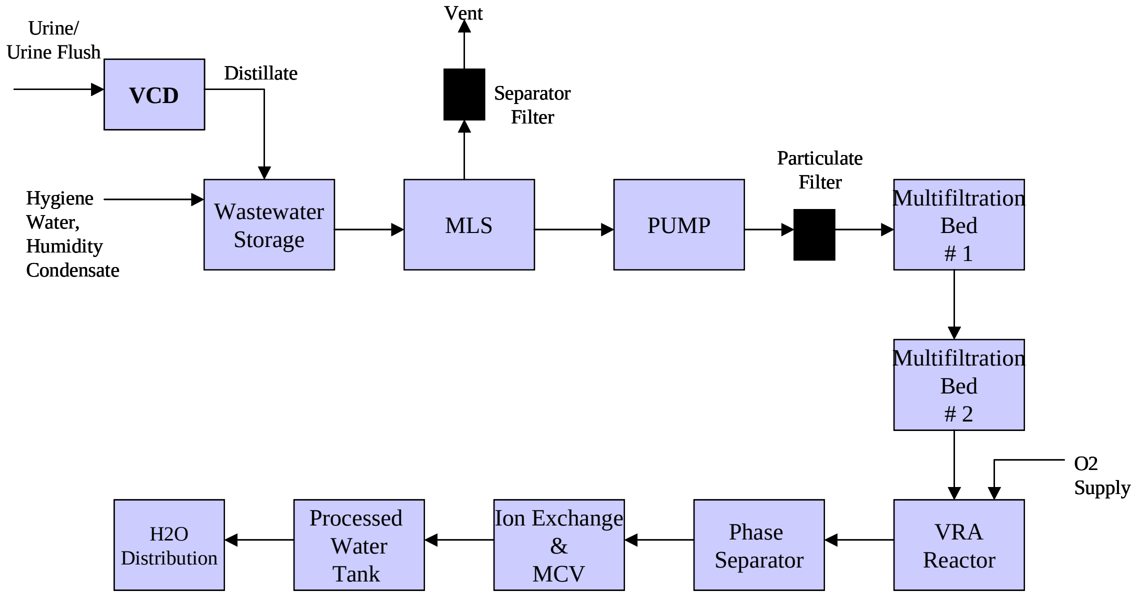

Figure II.1. ISS WRS Process Block Diagram

The WRA contains: the Hygiene Water Storage Tank ORU, Mostly Liquid Separator (MLS) ORU, the Pump ORU, Separator Filter ORU, Particulate Filter ORU, Multifiltration Bed #1 (MF #1) ORU, Multifiltration Bed #2 (MF #2) ORU, Catalytic Reactor Assembly (VRA) ORU, Phase Separator ORU, Ion Exchange Bed & Microbial Check Valve (IX & MCV) ORU, the Product Water Tank ORU.

The MLS separates the gas from the wastewater and provides the process pump with gas-free water to prevent gas binding of the multi-filtration beds.

The Separator Filter ORU removes odors from the gas separated from the wastewater in the MLS.

The Particulate Filter ORU removes particulate from the wastewater to protect the MF beds.

The Multifiltration Beds #1 and #2 then remove the non-volatile organic and inorganic impurities from the wastewater. The two beds are used in series with #2 unit rotating into #1 position at change out.

The VRA catalytic reactor oxidizes the volatile organic compounds remaining in the wastewater and provides microbial control.

The Gas Separator removes free oxygen (O_2), carbon dioxide (CO_2), and any dissociated gas from the system. The gas is vented to the cabin interface while the liquid stream is sent to the Ion Exchange Bed for further polishing.

The Ion Exchange Bed removes the remaining byproducts (bicarbonates, acetic acid, and propionic acid) produced by the catalytic reactor and iodinates the processed water.

The Microbial Check Valve ORU prevents back-flow of the wastewater and microbes from the wastewater loop to the clean water loop. Iodine is added for microbial control with a dosage of 1 to 4 ppm at 69 to 113 degree F, or with a dosage of 1 to 10 ppm at 113 to 137 degree F.

The Product Water Tank holds the processed delivery water for use.

B. Vapor Phase Catalytic Ammonia Removal (VPCAR)

The development of the VPCAR technology dates back to 1968 when both AiResearch and the Aerospace Medical Research Laboratories had active research programs. (Ref. 14, 15) These initial programs resulted in the development of lab-scale glassware configurations. During the late 1960's and early 1970's, General Electric developed and tested a VPCAR like system and in 1989 Texas A&M University refurbished and re-tested this unit (Ref. 13). Work conducted by GARD for Ames Research Center (Ref. 8, 17), from 1977 to 1985, resulted in the development of a bench scale unit whose configuration is conceptually close to the current VPCAR design. (Ref. 9)

In addition to the government funded work, both Wheelabrator Clear Air Systems, Inc. (formerly Chemical Waste Management, Inc.) and ARI Technologies developed a process called PO*WW*ER technology which is functionally similar to VPCAR. The PO*WW*ER technology is used to treat and reduce complex industrial and hazardous wastewater containing mixtures of inorganic salts, metals, volatile and nonvolatile organics, etc. A commercial plant with a capacity of 50 GPM using PO**WW**ER technology is in operation at Ysing Yi Island, Hong Kong. A pilot-scale unit, with a capacity of 1 to 1.5 GPM, is available at RUST Remedial Services' Clemson Technical Center in South Carolina (Ref. 18). VPCAR is in the early stage of development for space application.

Figure II.2 shows the process flow diagram of the VPCAR system with detailed operating conditions.

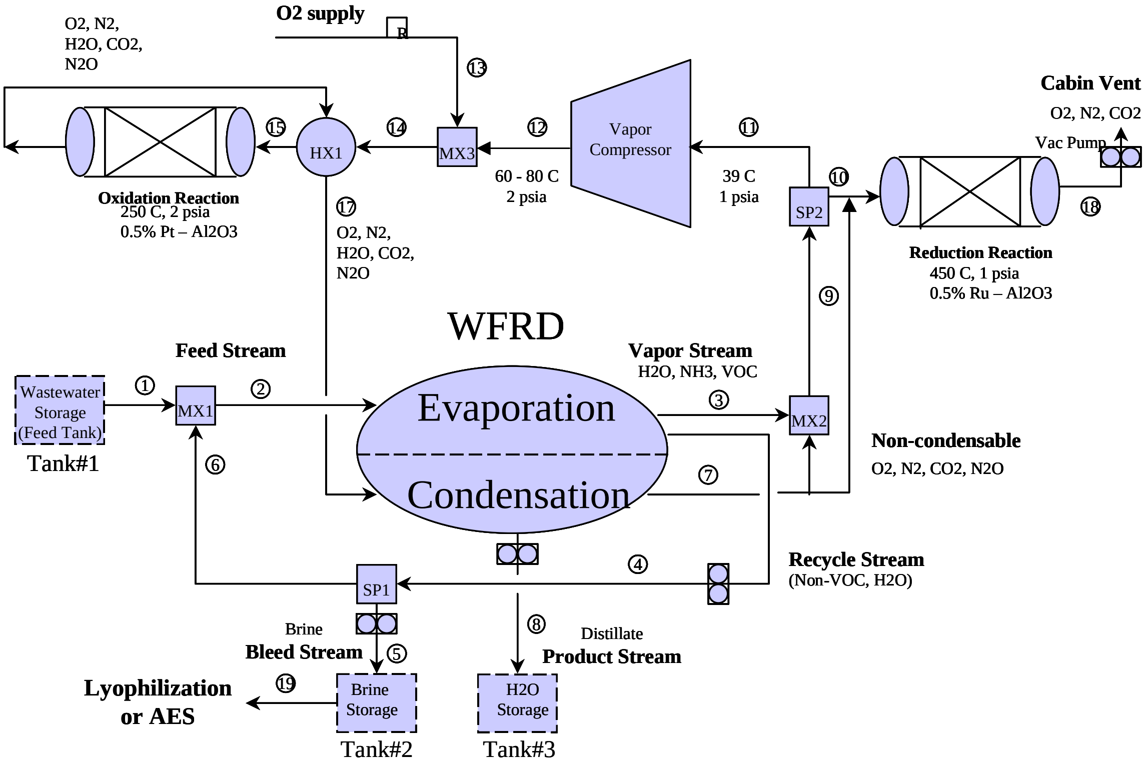

Figure II.2. VPCAR Process Flow Diagram

As mentioned in reference 9, the core of the VPCAR process is the Wiped-Film Rotating-Disk evaporator (WFRD). The WFRD removes inorganic salts and non-volatile organic contaminants with high molecular weight from the feed water stream by concentrating these undesirable components into a bleed/brine stream. The WFRD evaporator uses thin flat stainless steel disks as a heat transfer surface and flexible wiper blades to distribute the feed on the evaporation side of the disk. Condensation occurs on the opposite side of this disk (Ref. 9, 10).

Therefore, the WFRD is used as the evaporator of the feed stream and the condenser of the product stream coming from the oxidation reactor. The WFRD is used in the VPCAR process for its high heat transfer coefficient and its functioning as a gas-liquid separator.

The vapor stream carrying waste H_2O, NH_3, and VOC leaves the evaporating chamber of the WFRD and is compressed by a blower to 2 psia and 60-80 C. The pressurized gas, after combining with the O_2 feed, flows through a cross heat exchanger where it is preheated by the 250 C product stream from the reactor.

The waste stream with oxygen enters the reactor filled with platinum-alumina catalysts. At 250 C, 2 psia, and with 700% excess oxygen, NH_3 and VOC are reacted and converted into H_2O, CO_2, N_2, and nitrous oxide (N_2O). The product stream is precooled inside the cross heat exchanger (not included in the current VPCAR system); H_2O is condensed in the condensing chamber of the WFRD. The gas stream containing the non-condensables such as N_2, O_2, CO_2, and N_2O leaves the WFRD condensing chamber and is constantly sent through a bleed valve to the reduction reactor filled with ruthenium-alumina catalysts (not included in the current VPCAR system). At 450 C and 1 psia, N_2O is decomposed into N_2 and O_2. The product gases are vented to the cabin.

The 2-3% of water remaining in the brine stream can be recovered either by the Lyophilization process or by the Air Evaporation process. It is also possible that the 2-3% water may be extracted from the Martian base resource as a makeup for the water loss in the brine stream.

Reactions involved in this process are listed below:

Ammonia (NH_3) Removal:

$$4\ NH_3 + 3\ O_2 \xrightarrow[250\ C,\ 2\ psia]{Pt\text{-}Al_2O_3} 2\ N_2 + 6\ H_2O \qquad \text{Primary Reaction} \tag{1a}$$

$$2\ NH_3 + 2\ O_2 \xrightarrow[250\ C,\ 2\ psia]{Pt\text{-}Al_2O_3} N_2O + 3\ H_2O \qquad \text{Secondary Reaction} \tag{1b}$$

$$2\ N_2O \xrightarrow[450\ C,\ 1\ psia]{Ru\text{-}Al_2O_3} 2\ N_2 + O_2 \tag{2}$$

Volatile Organic Compounds (VOC) Removal:

$$CxHy + (x+0.25y)\ O_2 \xrightarrow[250\ C,\ 2\ psia]{Pt\text{-}Al_2O_3} x\ CO_2 + 0.5y\ H_2O \tag{3}$$

C. Bioregenerative Water Recovery System (BWRS)

The BWRS adopts the biological wastewater treatment technology as its key element of the treatment process. It is a well-established technology for municipal and industrial wastewater treatment**.** Work started at JSC in 1991 for development of a system for space applications. Numerous variations of the system were tested between 1991 and 1997. The system was used as the water treatment system for the Lunar-Mars Life Support Test Project 90-day Test to continually produce potable water. BWRS is in the middle stage of development for space application.

The BWRS comprises the following major equipment: the Packed-bed Biological Water Processor (PBWP), the Nitrification Biological Water Processor (NBWP), Gas Liquid Separator #1 (GLS#1), the Nitric Acid (HNO_3) tank (for start-up), Gas Liquid Separator #2 (GLS#2), the Reverse Osmosis Subsystem (RO), the Air Evaporation Subsystem (AES), and the Ion Exchange Mixed Bed Subsystem for trace inorganic salts/organic compounds removal.

Figure II.3 shows the Process Flow Diagram of the Bioregenerative Water Recovery System. It reflects the current configuration before system optimization will be done.

The wastewater stream, a mixture of urine/urinal flush, shower water, oral hygiene water, and hand wash water is fed to the PBWP. The operating condition of the PBWP is controlled at 25 psig, 27 C, and at a pH value between 6.5 & 7.5. The pH value is controlled by adding HNO_3 to the PBWP's feed. Effluent from the PBWP is sent to the GLS#1 through an automatic valve controlling the back pressure of the PBWP.

GLS#1 separates the gas constituents, mainly CO_2 and N_2, from the liquid and the gases are vented to the cabin through a filter for deodorizing. From the GLS#1, 55% of the liquid is sent to the NBWP for nitrification, while the balance is recycled to the PBWP by combining it with the fresh feed from the feed tank and with the recycled stream from the NBWP after GLS#2.

The gas liquid separation technology to be used by the GLS#1 and #2 for microgravity application has not yet been determined. It is expected that either membrane technology or centrifugal separation will be used.

HNO_3 from the nitric acid supply tank serves two purposes: 1. To control the pH of the PBWP, 2. To provide the nitrogen and oxygen source to the microbes in the PBWP at startup. Two to three weeks after the startup, the NBWP will generate NO_3^- needed for the TOC digestion.

In the NBWP reactor, oxygen is injected and ammonium salts from the PBWP are nitrified by the selected micro-organisms to mainly NO_3^-, and NO_2^- as byproduct.

The effluent of the NBWP goes to GLS #2 to separate the excess oxygen from the liquid. Part of the effluent from the NBWP reactor is fed to the Reverse Osmosis (RO) subsystem feed tank (Storage Tank #5), the remainder being recycled back to the inlet of the PBWP. The RO subsystem is a single-stage pressure-driven membrane process that operates in a batch mode. Batch mode operation was chosen because it yields significantly higher average permeate quality than continuous mode operation at high levels of permeate recovery. The RO subsystem utilizes a positive-displacement energy-recovery pump with 0.65 sq m of membrane area. It produces permeate at a nearly constant flow rate of 12.9 L/hr, while the feed pressure increases as each batch becomes more concentrated. At the end of each batch, the highly concentrated retentate brine is purged from the subsystem and sent to the Air Evaporation Subsystem (AES) feed tank. The RO subsystem achieves 85-90% recovery of the feed waste water as permeate.

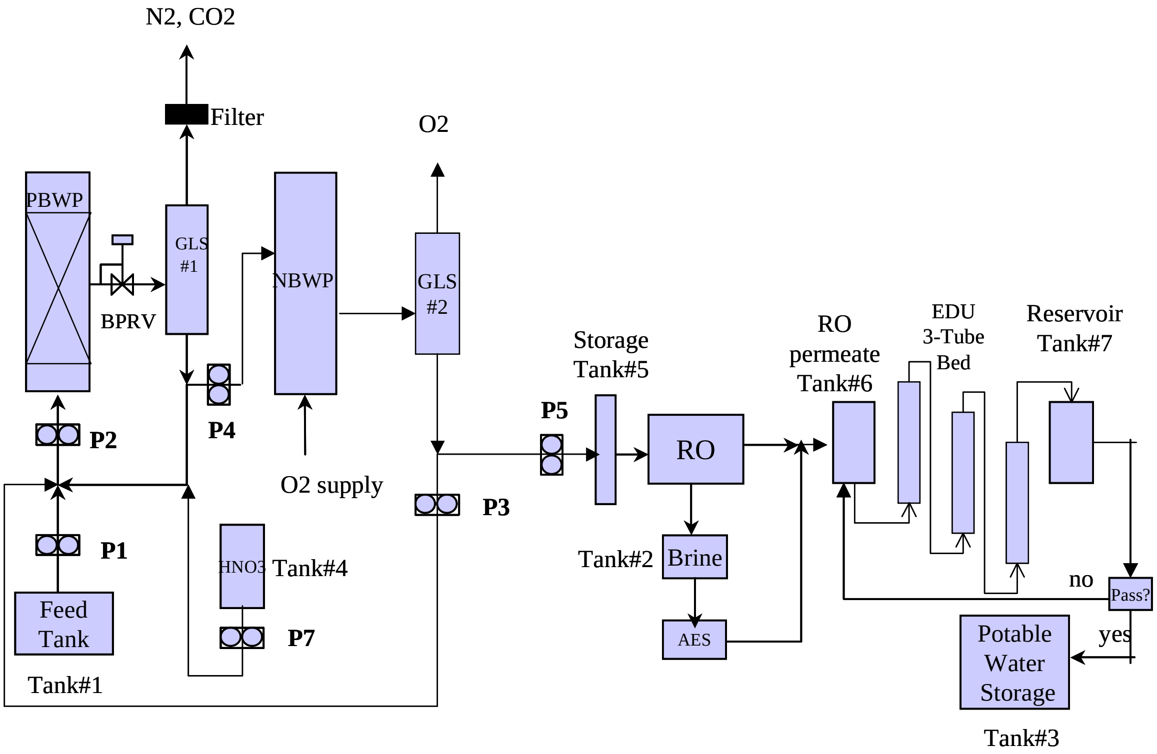

Figure II.3. BWRS Process Flow Diagram

The brine stream containing the remaining 15% of the processed water rejected by the RO is further processed by the AES. The AES evaporates water from the brine stream by retaining dissolved salts on a fiber wick housed in the evaporator section of the subsystem. Water vapor is condensed and collected in the AES condensate tank. The condensate combines with the RO permeate for further polishing.

The EDU 3-Tube Beds subsystem uses a combination of the ion exchange technology and the absorption technology to remove any residual inorganic salts, and organic compounds that remain in the RO permeate and AES condensate. The first column is packed with cation and anion resins for removing the residual inorganic salts by ion exchange. The second column, packed with carbonaceous material and cation resins further removes the residual anions and organic compounds in the processed water. The third column packed with carbonaceous material and cation resin is for further polishing of the processed water.

Three sets of 3 columns are operated in series, a single set of 3 columns is removed from service and repacked as the capacity of each bed is expended.

The processed water is polished by the EDU 3-Tube Bed, it then flows through a 0.2 micron filter to provide disinfection. The water then passes through a microbial check valve (MCV) that adds 2-5 mg/l of iodine to the water as a residual disinfection. The TOC of the product water is controlled under 0.5 ppm (500 ppb).

Reactions in the PBWP are:

$$342\ NO_3^- + 55\ C_9H_{16}N_2O_4\ \text{(organics)} + 25\ H_2O \Longrightarrow 171\ N_2 + 400\ HCO_3^- + 91\ NH_4^+ + 33\ OH^- + 19\ C_5H_7NO_2\ \text{(biomass)}$$

$$50\ NO_2^- + 5\ C_9H_{16}N_2O_4\ \text{(organics)} + 12\ H_2O \Longrightarrow 25\ N_2 + 35\ HCO_3^- + 8\ NH_4^+ + 23\ OH^- + 2\ C_5H_7NO_2\ \text{(biomass)}$$

Reactions in the NBWP are:

$$55\ NH_4^+ + 76\ O_2 + 5\ HCO_3^- + 47\ H_2O \xrightarrow{\text{Nitrosomonas}} 54\ NO_2^- + 104\ H_3O^+ + C_5H_7NO_2\ \text{(biomass)}$$

$$400\ NO_2^- + 195\ O_2 + 5\ HCO_3^- + NH_4^+ + H_2O \xrightarrow{\text{Nitrobacter}} 400\ NO_3^- + 4\ OH^- + C_5H_7NO_2\ \text{(biomass)}$$

III. SIZING REQUIREMENTS AND RESULTS OF THE WATER RECOVERY SYSTEMS

All water recovery systems were sized based on the ISS WRS requirement with a shower (no laundry), to recover potable water for a crew size of 4, and to process 50.9 kg daily. The feed stream consists of 6.82 liters of urine, 2.27 liters of urinal flush, 9.54 liters of humidity condensate, and 32.26 liters of hygiene water including shower, oral hygiene, and hand wash water.

A. International Space Station Water Recovery System (ISS WRS)

The ISS WRS is designed to process 50.9 kg/day (112 lb/day) of wastewater generated by a 4-member crew (Ref. 12) in 8 hours. The resupply mass was calculated based on a 10- year life for all major equipment. The annual resupply mass was computed by averaging the value over the period of ten years. (Ref. 12, 25)

Table III.1 shows a detailed breakdown of the mass, volume, and power of the major equipment of the ISS WRS system.

Table III.1. Sizing Data of the ISS WRS (1)

Subsystem	**Mass, kg**	**Power, watt (Peak/Avg)**	**Resupply, kg/yr**
Pressure Control & Pump	51.36		12.84
Fluid Control & Pump	51.36		25.68
Recycle Filter Tank	19.20		230.40
Water Storage (UA)	12.84		
Distillation Assembly	71.91		17.98
Separator Plumbing	15.41		15.41
Power Module	13.75		
Data Module	9.82		
Electrical Cabling	TBD		
Interconnecting Plumbing	TBD		
UPA (VCD)	**245.65**	**429**	**302.31**
Waste Water	82.23		8.22
Pump/MLS	26.45	30	13.05
MLS Filter	4.95		4.95
Multifiltration Bed #1 & #2	106.80	?	282.70
Sensor	7.10		
Rack Resident - Rack 2	30.95		
Subtotal Rack #2	**258.48**	**539**	**308.92**
Particulate Filter	17.23		156.77
Catalytic Reactor	55.77	255	5.58
Gas/Liquid Separator	31.10	40	30.50
Ion Exchange Bed	11.73		71.55
Product Water Storage	46.73		4.67
Water Delivery system	43.82	10	8.76
Microbial Check Valve	3.73		4.50
Process Controller	42.82	180	4.28
Rack Resident - Rack 1	113.64		
Reactor Health Sensor	14.45		2.90
Subtotal Rack #1	**366.57**	**1249**	**289.51**
Valves (13)		10	
Start-up Filter	8.64		
Total ISS WRS, kg	**879.34**	**2227/1450**	**900.74**
Notes:			

1. Sizing data extracted from OGA/WRA DR#1 by Hamilton Standard & OGA/WRA/UPA PDR by MSFC

B. Vapor Phase Catalytic Ammonia Removal (VPCAR)

The VPCAR system is designed to process 10 kg/hour of wastewater. The N_2O reduction reactor and the heat exchanger are not included in the current system. Mass of the reduction reactor and heat exchanger are estimated and included in the system total mass.

Table III.2 shows a detailed breakdown of the mass, volume, and power of the major equipment of the VPCAR system.

Table III.2. Sizing Data of the VPCAR Process

Subsystem	Mass, kg (2, 3)	Power, watt (4)	Resupply, kg/yr (5)
Oxidation Reactor		200	2
Reduction Reactor	15		
Compressor		1300	
Vacuum pump		550	
Pumps		150	
WFRD		180	
Heat Exchanger (HX)	4		
Feed Tank #1 (6)			
Brine Tank #2 (6)			
Product Water Storage #3 (6)			
Piping, 5% of equip total	12.3		
Instrumentation, 10% equip total	24.6		
Total VPCAR	**283**	**2380**	**2**

Notes:

1. Current processing rate = 5.6 kg/hour
2. Total mass of components included in current system = 227 kg
3. Current system does not include HX and Reduction Reactor. Estimated mass of HX (4 kg) and Reduction Reactor (15 kg) are added to the total mass.
4. Actual power consumption measured by running the experiment
5. Assuming that the catalysts will be replaced annually (TBD)
6. Not included in total mass estimate by assuming that both VPCAR and BWRS will need all 3 tanks for the feed, brine, and product water storage

C. Bioregenerative Water Recovery System (BWRS)

The BWRS is sized to process 50.9 kg/day and to operate 24 hours daily. Major equipment of the BWRS system is sized based on the process information provided for the system's next generation, although BWRS system process flow diagram reflects the current system configuration. Sizing results will be updated whenever system optimization is completed in the near future.

Table III.3 gives a detailed breakdown of the mass, volume, and power of major equipment of the BWRS system.

Table III.3. BWRS Sizing Results

Subsystem	Mass, kg (1)	Mass, kg (2)	Power, watts	Resupply,kg/yr
PBWP (TOC converter) (3)	153.93	82.27		
GLS #1 (12)	10.00	10.00	TBD	TBD
NBWP (Nitrifier) (4, 5, 6, 7)	117.38	117.38		
GLS #2 (12)	10.00	10.00	TBD	TBD
Feed Pump (P1) (10)	2.00	2.00	10.00	
Total Feed Pump (P2) (10)	2.10	2.10	50.00	
Nitrifier Recycle Pump (P3) (10)	2.00	2.00	15.00	
GLS#1 harvest pump (P4) (10)	2.00	2.00	15.00	
Nitrifier Harvest Pump (P5) (10)	2.00	2.00	10.00	
Air Pump (P6) (11)				
Feed Tank # 1 (8)				
Brine Tank # 2 (8)				
Product H_2O Storage Tank # 3 (8)				
HNO_3 Tank # 4 (9)				
NBWP Product water Tank #5 (9)				
RO Permeate Tank # 6 (9)				
EDU 3-Tube Bed Product H_2O Tk #7 (9)				
Reverse Osmosis (RO)	30.20	30.20	125.60	5.00
Air Evaporator (AES)	45.30	45.30	577.90	26.07
EDU 3-Tube Bed	11.70	11.70		147.26
Piping, 5% of equip total	19.43	15.85		
Instrumentation, 10% of equip total	38.86	31.70		
Total BWRS	**408.04**	**332.80**	**803.50**	**178.33**

Assumptions for BWRS sizing:

1. TOC converter: SS 316L vessel
2. TOC converter: SS 316L flat heads, polymer shell
3. The current size of the TOC will hold the liquid and substrate only. The operating condition (P & T) specified for the TOC converter will be sufficient to keep the gases, such as CO_2, N_2, and O_2 in the liquid phase.
4. Spiral type reactor for nitrification; made of polymer
5. Nitrifier will function at the conversion efficiency claimed by Allied-Signal.
6. No hydrocyclone is needed to recycle the microbes from the nitrifier. Nitrifier will be designed to ensure that no microbes will be present in the effluent.
7. The nitrifier will be optimized to generate sufficient nitrate for the TOC converter as predicted by Kevin Lange's Model.
8. Not included in total mass estimate by assuming that both VPCAR and BWRS will need all 3 tanks for the feed, brine, and product water storage
9. All 4 tanks including the HNO_3 tank, the nitrifier product tank, the RO permeate tank, & the EDU 3-TUBE Bed product H_2O tank, will be eliminated after optimization.
10. Mass and power consumption of all pumps are estimated.
11. Air pump will be removed if O_2 is used for the nitrifier instead of air
12. Membrane type separators will be used for gas-liquid separation. No microbes exist in the effluent streams from the bioreactors. Mass estimate includes membrane and pump. TBD for power requirement and resupply.

IV. ADVANTAGES AND DISADVANTAGES OF THE WATER RECOVERY SYSTEMS

A. International Space Station Water Recovery System

Advantages

1. High technology readiness level for most of the treatment processes used in the system except for the VCD. The multifiltration beds, the ion exchange beds, and the VOC reactor are all well-established technologies. They have been used in the industry for many decades. Operation of the system is expected to be relatively trouble-free.

2. Low risk: subsystems such as the multifiltration beds, ion-exchange beds, and VOC reactor are well-established technologies. The multi-filtration beds can be accounted for the removal of most of the organic compounds and the inorganic salts in the wastewater stream until the capacities of the absorbents/ion-exchange resins in the beds become exhausted. And, at that point, the spent unit can be easily replaced with the new ones. The VOC reactor is a reliable technology for oxidizing the VOC in the wastewater stream. The ion-exchange bed can remove the trace amount of byproducts (bicarbonates, acetic acid, and propionic acid).

Disadvantages

1. High resupply rate: most of the treatment processes use expendable materials such as absorbents and cation/anion resins. Subsystems such as multi-filtration and ion exchange beds, etc. used by the ISS WRS are expendable materials. The ion resins can not be regenerated in the space environment as it is commonly done on earth. Therefore, it increases the resupply of the system and consequently the transporting cost for bringing the expendable materials to the Martian base.

B. Vapor Phase Catalytic Ammonia Removal (VPCAR)

Advantages

1. Low degree of complexity: Total of 5 pieces of major equipment including heat exchanger and reduction reactor.

2. Suppression of biological contaminants in the product water: The Product Water is condensed from a H_2O vapor stream at 250 C; microbes are not likely to survive or grow under this temperature.

Disadvantages

1. Can be power intensive: Due to the compression of large volume of water vapor.

C. Bioregenerative Water Recovery System

Advantages

1. High TOC conversion rate
2. Less power intensive
3. Higher water recovery rate

Disadvantages

1. Difficulty of 3 phase management when replacing reactor core
2. Longer startup/turnaround time if any unpredictable problem happens to the system or the micro-organisms

V. SUMMARY

Process assessment of the BWRS and VPCAR for space application using ISS WRS as a trading basis was completed.

Process and sizing data collected for the water recovery systems were used to calculate the system mass and power requirement based on a daily capacity of 50.9 kg of wastewater for a crew size of four. Due to the different processing rates for the three water recovery systems, evaluation based on their system launch mass and power is not as meaningful as evaluation based on their specific mass, specific energy, and system volumes. Annual resupply was also estimated based on a daily processing capacity of 4-crewmembers load.

Cases compared in this study are: 1. ISS WRS1 - includes ISS resident racks, storage tanks, and process controller mass; 2. ISS WRS2 - more comparable to others without rack mass, etc.; 3. VPCAR - based on Ames experimental unit with a mass estimate for heat exchanger and reduction reactor added; 4. BWRS1 - based on JSC design for next generation unit using stainless steel TOC reactor; 5. BWRS2 - based on JSC design for next generation unit using polymer TOC reactor with stainless steel ends.

Table V.1 summarized the evaluation results of the water recovery systems. Comparison curves of the specific mass, system volume, specific energy, and annual resupply of the water recovery systems were shown in figures V.1, V.2, V.3, V.4 respectively.

Table V.1 Summary of Evaluation

Evaluation Criteria	**ISS WRS1 (1)**	**ISS WRS2 (1)**	**VPCAR**	**BWRS1 (5)**	**BWRS2 (6)**
Number of Major Equip (excl. tanks,pumps, and filters)	7	7	5	7	7
Mass, kg	879.34	550.13	283	408.04	332.80
Volume, ISS Racks	2	2	1	2	2
Power, watts	1450	1270	2380	803.5	803.5
Specific mass1, kg/kg (8)	17.28	10.81	5.56	8.02	6.54
Specific mass, kg/(kg/hr) (9)	138.21	86.46	50.54	192.40	156.92
Specific Energy, watt-hour/kg	227.90	199.61	425.00	217.44	217.44
Oxidant to be used (O2/air)	O2	O2	O2	O2	O2
Oxidant feed, gm/kg					
CO2 generation rate, gm/day					
Resupply rate, kg/year (7)	900.74	900.74	2	178.33	178.33
% NH3 removal in key process	99	99	99.9	70	70
% TOC removal in key process	91	91	(Note 4)	98	98
Chemicals (excluding catalyst, ion exchange resins, etc.)	H2SO4/Oxone	H2SO4/Oxone		HNO3 (Startup)	HNO3 (Startup)
Water Recovery, %	98 - 99 (Note 2)	98 - 99 (Note 2)	98	100	100
Technology Readiness Level	6	6	3.5	4	4
Crew Time, MMH/year	29.12/52 (Note 3)	29.12/52 (Note 3)	?	?	?
System life, years	10	10	3	?	?

Notes:

1. ISS WRS1 system mass includes mass of ISS racks, plumbing systems, process controller, etc., and contingencies
   ISS WRS2 system mass equals ISS WRS1 system mass minus total mass of ISS rack residents, process controller, wastewater storage, and product water storage, and UA wastewater storage
2. Depends on the water recovery % of the VCD subsystem
3. From PDR dated 4/17/99. Preliminary mean maintenance crew hours/year predicted: UPA=13.04; WPA=12.01; Rack component=4.07; Total combined=29.12.
   WRS allotted = 52 hours/year
4. Depends on concentration of VOC in the feed stream
5. TOC reactor: SS 316L vessel
6. TOC reactor: SS 316L flat heads; polymer shell
7. Catalysts included
8. Total system mass/Daily processing capacity
9. Total system mass / processing rate

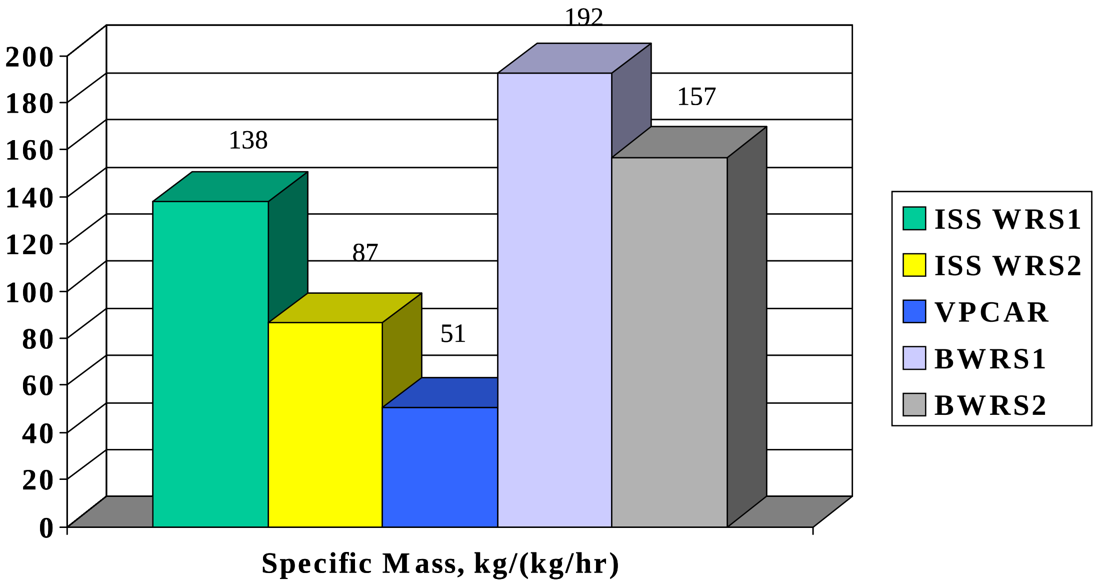

Figure V.1. Comparison of Specific Mass for the Water Recovery Systems

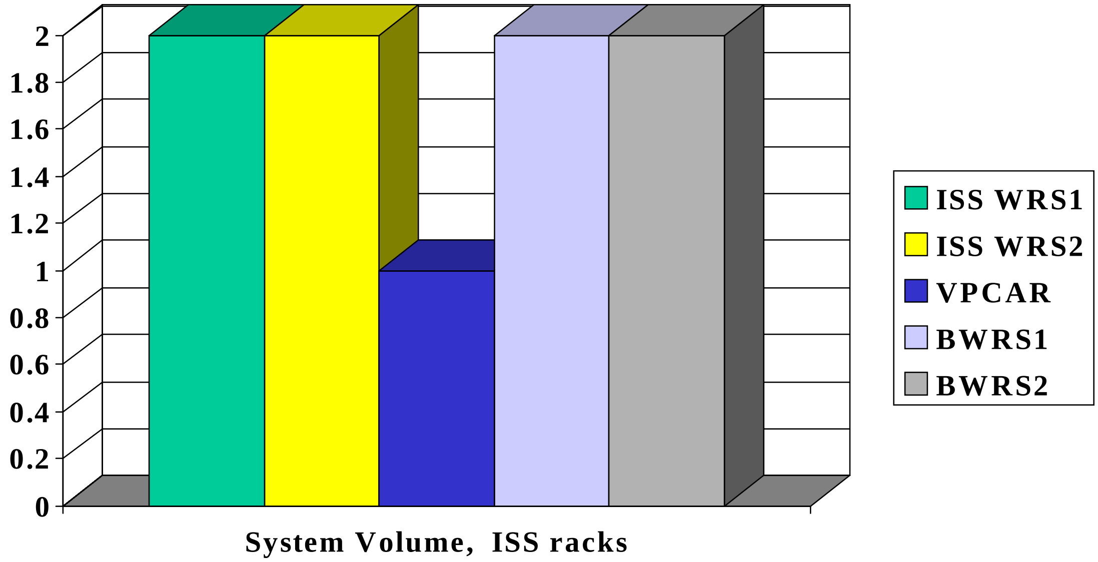

Figure V.2. Comparison of System Volume for the Water Recovery Systems

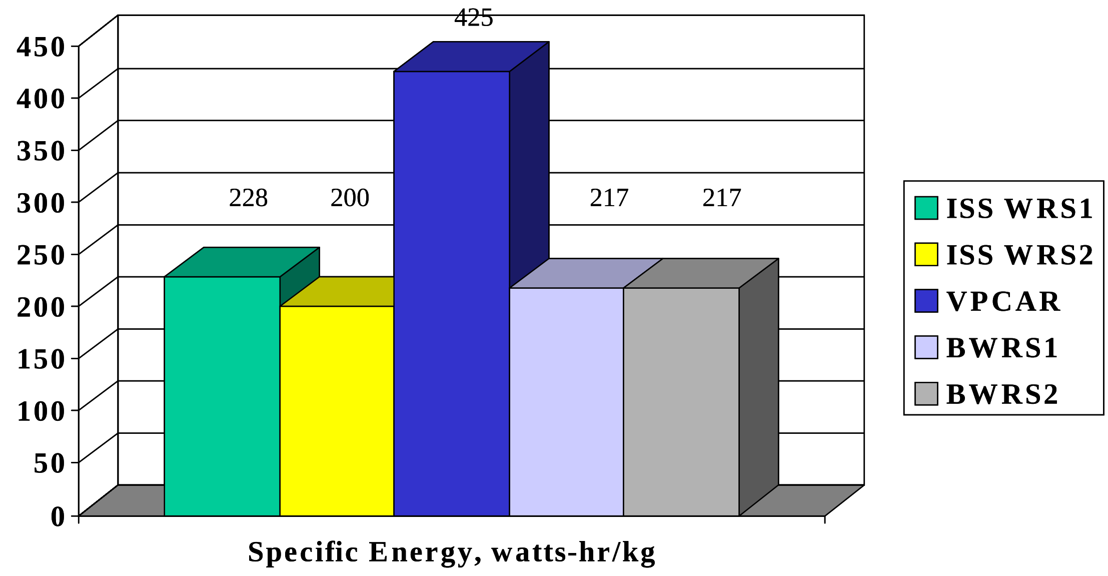

Figure V.3. Comparison of Specific Energy for the Water Recovery Systems

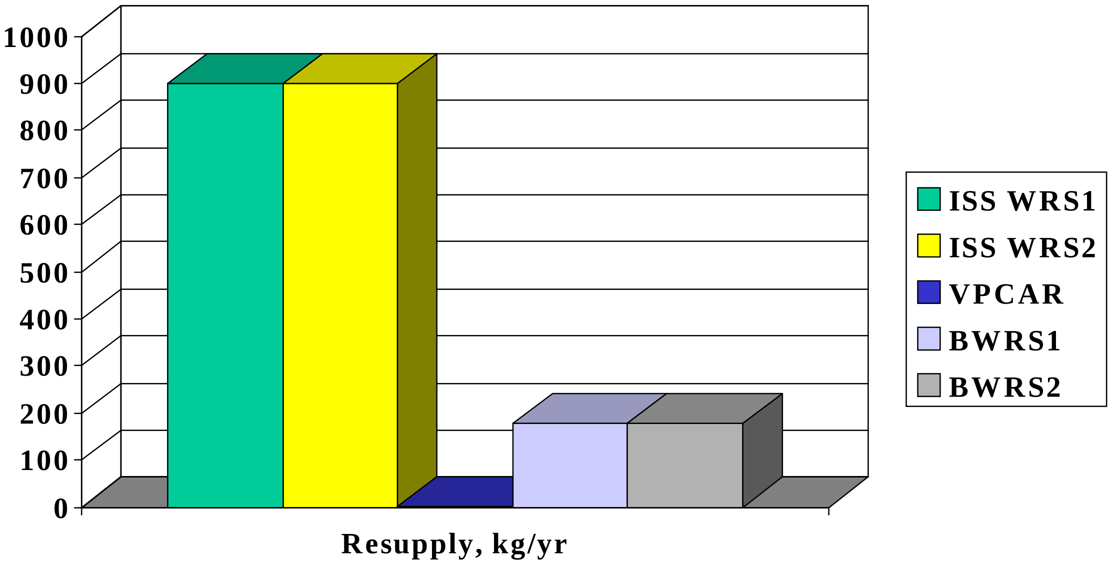

Figure V.4. Comparison of Annual Resupply for the Water Recovery Systems

VI. CONCLUSIONS AND RECOMMENDATIONS

Evaluation of the BWRS and VPCAR water recovery processes was completed. Results have shown that the BWRS is a promising process for TOC removal, more work is required to validate and refine the nitrification process. The longer startup/turnaround time is a disadvantage for this system in case any unpredicted malfunction occurs to the biological reactors or any unpredictable micro-organisms behavior takes place during operation.

VPCAR system is a promising NH_3 and VOC converter. Suppression of biological contaminants in the product water is the advantage for this process. The product H_2O is condensed out from a H_2O vapor stream of 250 C, therefore microbes are not likely to survive or grow under this temperature. VPCAR is very competitive with the BWRS and ISS WRS from a mass, power and volume standpoint. Its power intensity makes the system less attractive to deal with large volume of gases at the vacuum condition.

More work is required for the nitrification process of the BWRS, and VPCAR is at its early stages of development for space application. Due to the different strengths and weaknesses of the two systems, it is difficult to conclude that one process is better than the other at this point in time.

For a more in-depth understanding of the VPCAR and BWRS feasibility for different space applications, it is strongly recommended to continue the following efforts:

1. Continue development of the VPCAR and BWRS, and prepare for integrated testing

2. Continue analysis and re-visit this trade study after VPCAR testing is complete and all the major equipment of the BWRS is better defined:

    A. Conduct a detailed mass and energy balance of the VPCAR system by including the heat exchanger, and the reduction reactor to the system (Without recovering the 2-3% of water from the brine stream.)
    B. Same as recommendation 2A except for the inclusion of air evaporation or lyophilization to recover the 2-3% of the water from the brine stream.
    C. Same as recommendation 2A except for the inclusion of water extraction from the Martian base resource for the makeup of the 2-3% H_2O loss in the brine stream.
    D. Consider effect of laundry water.
    E. Conduct a trade study using VPCAR as a NH_3 converter, and BWRS as a TOC converter.

VII. ACKNOWLEDGMENTS

The author wishes to thank NASA/JSC/EC management for funding the study.
Special thanks also go to the following for providing the sizing/process information and valuable comments: C. H. Lin (JSC-EC2), M. Ewert (JSC-EC2), M. Flynn (ARC), B. Finger (Allied-Signal), K. Pickering (JSC-EC3), C. Verostko (JSC-EC3), M. Edeen (JSC-EC3), N. Packham (JSC-EC3), C. D. Thompson (JSC-EC3), B. Bagdigian (MSFC), J. Knox (MSFC), F. Jeng (LMSO), J. Keener (LMSO), K. Lange (LMSO), and B. Duffield (LMSO), T. Hanford (LMSO).

VIII. REFERENCES

1. Putnam, David F., D. J. Clifford, C. V. Colombo, and D. Price, “Recovery of Hygiene Water by Multifiltration,” SAE Technical Paper No. 891445, 19th International Conference on Environmental Systems, 1989.

2. Carrasquillo, R. L., etc., “International Space Station Environmental Eontrol and Life Support System Technology Evolution,” SAE Technical Paper No. 961475, 26th International Conference on Environmental Systems, 1996.

3. Carrasquillo, R. L., etc., “Summary of Resources for the International Space Station Environmental Control and Life support System,” SAE Technical Paper No. 972332, 27th International Conference on Environmental Systems, 1997.

4. “Living Together in Space: The Design and Operation of the Life Support Systems on the International Space Station,” NASA/TM – 1998-206956, Volume I, Marshal Space Flight Center, Alabama, 1998.

5. Personal communication with Michael Flynn, AMES Research NASA Center, California.

6. Personal communication with Barry Finger, Allied Signal, Houston, Texas.

7. Flynn, Michael, J. Fisher, and B. Borchers, “An Evaluation of Potential Mars Transit Vehicle Water Treatment Systems,” SAE Technical Paper No. 981538, 28th International Conference on Environmental Systems, 1998.

8. Budininkas, P., F. Rasouli, and T. Wydeven, “Development of a Water Recovery Subsystem Based on Vapor Phase Catalytic Ammonia Removal (VPCAR),” SAE Technical Paper No. 860985, 16th International Conference on Environmental Systems, 1986.

9. Flynn, M., and B. Borchers, “An Evaluation of the Vapor Phase Catalytic Ammonia Removal Process for use in a Mars Transit Vehicle,” International Journal of Life Support & Biosphere Science, volume 5, page 415-421, 1998.

10. Tleimat, B., “Wiped-film Rotating Disk Evaporator for Water Reuse,” U.S. Department of the Interior, Bureau of Reclamation, Grant No. 14-34-0001-0537, September 1980.

11. Handford, A. J., “Advanced Life Support System (ALSS) Study – Water Recovery System,” March 27, 1998.

12. “Oxygen Generation Assembly & Water Processor Assembly – Design Review #1, Book 2&3,” by Hamilton Standard, dated November 30 through December 4, 1998.

13. W. Moses, T. Rogers, et. al., “Performance Characterization of Water Recovery and Water Quality From Chemical/Organic Waste Products,” SAE Technical Paper 891509, 19th International Conference on Environmental Systems, July 1989.

14. C. A. Metzger, A.B. Hearld, et. al., “Low Temperature Catalytic Oxidation of Waste Water Vapors,” Aviation and Space Progress and Prospects, American Society of Mechanical Engineers, New York, June 16-19, 1968.

15. J.P. Byrne, J.U. Littman, “A Forced-Circulation/Flash-Evaporation Concept For Spacecraft Waste Water Recovery,” Aviation and Space Progress and Prospects, American Society of Mechanical Engineers, New York, June16-19, 1968.

16. Mitchell, K. L., R. M. Bagdigian, et. al., “Technical Assessment of MIR-1 Life Support Hardware for the International Space Station,” Structures and Dynamics Laboratory Science and Engineering Directorate, George C. Marshall Space Flight Center, March 1994.

17. Theodore Wydeven, “A Survey of Some Regenerative Physico-Chemical Life Support Technologies,” NASA Technical Memorandum 101004, National Aeronautics and Space Administration, Ames Research Center, Moffett Field, CA, November 1988.

18. “PO**WW**ER process by Wheelabrator Clean Air Systems, Inc.,” http://www.nttc.edu/env/site95/demo/complete/wheel.html

19. Slavin, T. J., F. A. Liening, and M. W. Oleson, R.L. Olson “CELSS Physicochemical Waste Management Systems Evaluation,” NASA Contractor Report 177422, Contract NAS2-11806, June 1986.

20. Carter, D.L., D.W. Holder, and C.F. Hutchens, “International Space Station Environmental Control and Life Support System Phase III Water Recovery Test Stage 9 Final Report,” NASA Technical Memorandum 108498, September 1995.

21. Budininkas, P., F. Rasouli, “Catalytic Distillation Water Recovery Subsystem,” NASA Contractor Report 177382, Gard Division, Chamberlain Manufacturing Corporation, Nile, Illinois (Prepared for Ames Research Center under contract NAS2-11687) September 1985.

22. Okamoto, A. H., and J. J. Konikoff, "Study of the Purification of Water from Biological Waste", General Electric Co., Philadelphia, Pa., June, 1962.

23. Esten, H., et al, "Vacuum Distillation, Vapor Pyrolysis Water Recovery System Utilizing Radio-isotopes for Thermal energy," Report No. 67SD8124, General Electric Co., Philadelphia, Pa., June, 1967.

24. Kolnsberg, H. J., M. D. Dudarevitch, "Water Reclamation by Membrane Vapor Diffusion," Aviation and Space Progress and Prospects, American Society of Mechanical Engineers, New York, June16-19, 1968.

25. "Regenerative Environmental Control and Life Support System (ECLSS) Integrated Rack and Urine Processor Assembly Preliminary Design Review," by MSFC, April 14-15, 1999.

26. Hester, J.C., and C. A. Brandon, "Hyper-filtration technique applied to wash water reclamation at elevated temperatures," ASME Paper 73-ENAs-27, SAE-ASME-AIAA-ASMA-AICHE Intersociety Conference on Environmental Systems, San Diego, CA, Jul. 16-19, 1973.

27. Reysa, R. P., D. F. Price, T. Olcott, and J. L. Gaddis, "Hyper-filtration Wash Water Recovery Subsystem-design and Test Results, SAE Paper 831112, 13th Intersociety Conference on Environmental Systems, San Francisco, CA, Jul. 11-13, 1983.

28. Schubert, F. H., "Phase Change Water Recovery Techniques; Vapor Compression Distillation and Thermoelectric/Membrane Concepts," SAE Paper 831122, 13th Intersociety Conference on Environmental Systems, San Francisco, CA, Jul. 11-13, 1983.

29. Schubert, F. H., R. A. Wynveen, and P. D. Quatrone, "Advanced Regenerative Environmental Control and Life Support Systems: Air and Water Regeneration," Advances in Space Research, Vol. 4, No.12, 1984, pp279-288.

30. Timberlake, S. H., G.T. Hong, M. Simons, and M. Modell, "Supercritical Water Oxidation for Wastewater Treatment: Preliminary Study of Urea Destruction," SAE Paper 820872, 12th Intersociety Conference on Environmental Systems, San Francisco, CA, Jul. 19-21, 1982.

31. Hoffman, Stephen J., and D. I. Kaplan, "Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team," Lyndon B. Johnson Space Center, Houston, Texas, July 1997.

VIII. ACRONYMS

AES:	Air Evaporation Subsystem
Al_2O_3:	Alumina
ARC :	Ames Research Center
BWRS:	Bioregenerative Water Recovery Process
EDU:	Engineering Development Unit
GLS#1:	Gas Liquid Separator #1
GLS#2:	Gas Liquid Separator #2
GPM:	Gallon Per Minute
HX:	Heat Exchanger
ISS:	International Space Station
IWRS:	Integrated Water Recovery Systems
IX:	Ion Exchange Bed
JSC:	Johnson Space Center.
MCV:	Microbial Check Valve
MLS:	Mostly Liquid Separator
MF#1:	Multifiltration Bed #1
MF#2:	Multifiltration Bed #2
MSFC:	Marshall Space Flight Center
MXn:	Mixer #n
SPn:	Splitter #n
NBWP:	Nitrification Biological Water Processor
OGA:	Oxygen Generation Assembly
ORU:	Orbiter Replaceable Unit
PBWP:	Packed-bed Biological Water Processor
PDR:	Preliminary Design Review
ppm:	Parts per million
ppb:	Parts per billion
Pt:	Platinum
RO:	Reverse Osmosis Subsystem
Ru:	Ruthenium
TBD:	To Be Determined
TOC:	Total Organic Carbons
UPA:	Urine Processor Assembly
VCD:	Vacuum Compression Distillation
VOC:	Volatile Organic Compounds
VPCAR:	Vapor Phase Catalytic Ammonia Removal
VRA:	VOC Catalytic Reactor Assembly
WFRD:	Wiped-Film Rotating Disk
WRA:	Water Recovery Assembly
WRS:	Water Recovery System

APPENDIX A

VPCAR Experimental Protocol

The goal of this program is to generate data which will support JSC system analysis requirements. As a result the objectives will conform to those provided by JSC. The following outline was provided by JSC for system requirement.

1. Use a feed stream chemical species concentration based on the International Space Station Water Recovery System's feed concentration.

Urine	1.5 kg (liters)
Urinal flush	0.5 kg (liter)
Humidity condensate	2.1 kg (liters)
Hygiene water	7.1 kg (liters)(shower+oral+handwash)

2. Analyze and quantify the feed stream including the chemical species as suggested.

3. Analyze and quantify the product water stream including the chemical species as suggested.

4. Analyze and quantify the brine stream including the chemical species as suggested.

   Note: *The VPCAR regularly achieves 97 to 98% water recovery. Byproduct streams are commonly fouled with precipitated salts, solidified soaps, and organic compounds. Such high solids samples can not be introduced into our TOC or IC systems. As a result, our ability to quantify this stream will be limited by our ability to solubilize these precipitates through dilutions. It has been our experience that such an approach can be quite difficult if not impossible, especially when calcium containing organic compounds exist.*

5. Record processing rate (total flow of feed) in kg/hour, production rate (total flow of product water) in kg/hour, and waste generation rate (total flow of brine) in kg/hour.

6. Record total mass of feed processed, total mass of product water and brine generated (for overall mass balance and water recovery calculation).

7. Take measurements of pH, conductivity, and TOC of feed, product, and brine streams as applicable.

8. Provide information on mass, volume, and power requirements for the major equipment of the process.

Note: *The determination of component masses will be limited initially. Developing an all inclusive mass breakdown will require extensive disassembly of the VPCAR system. As a result, a final list will not be available until after the unit is upgraded and the second set of experimental evaluations completed later this year. Total system weight will be provided.*

9. Provide O2 consumption rate.

10. A list of the chemical species is included for ARC's use in qualifying and quantifying the feed, product water, and brine streams.

Chemical Species List

Components	Formula	
Ammonium	NH4+	
Bicarbonate	HCO3-	*
Calcium	Ca++	
Carbonate	CO3=	*
Chloride	Cl-	
Fluoride	F-	**
Magnesium	Mg++	
Phosphate	PO4---	
Potassium	K+	
Sodium	Na+	
Sulfate	SO4--	
Nitrate	NO3-	
Total Organic Carbon (TOC)		

* The bicarbonate and carbonate amounts will be determined in accordance with section 4500-CO2D of “Standard Methods for the examination of Water and Wastewater 18th edition”. The forms of CO2 present in the samples will be calculated from the pH and alkalinity results.

** May be a problem if organic acids are present (formic and acetic)

A minimum of three experimental runs will be completed. Each of which will last approximately one day. A series of pre-runs will also be completed to insure the unit is operating properly and to calibrate subsystems. All analytical procedures will be carried out by the ARC Central Analytical Chemistry Laboratory.

Michael Flynn
NASA Ames Research Center
MS 239-15
Moffett Field, CA 94035
650-604-1163

Attachment 1

Preparation of Ersatz Solution

The following procedure shall be used to perform ersatz tests on the VPCAR technology. This ersatz solution is composed of hygiene water, urine, and humidity condensate. During a normal VPCAR run we prepare two carboys of ersatz solutions. Each Carboy contains 18 kg (L) of solution.

Materials

A. (3) 1000mL volumetric flasks
B. (1) 100 ml volumetric flask
C. Reagent grade water: distilled, deionized water
D. Measuring pipettes: 2mL x 0.01 mL, 5mL x 0.1 mL, 10mLx 0.1 mL
E. Microsyringes: 10 µL, 50 µL, 100 µL, 250 µL
F. Analytical balance capable of +- 1 mg accuracy.
G. (2) Carboys
H. Urine collection system

Methods.

Urine

Raw human urine is used for these tests. Urine is collected using the urine collection system. All samples requiring storage will be refrigerated at 4 ^{o}C.

Urinal Flush

Urinal flush will be simulated with distilled water.

Hygiene

Hygiene water is simulated through the use of soap and water. Igepon is used in a concentration of 218.6 mg/L.

Condensate

Condensate is generated according to a recipe provided by JSC

A. Add the following compounds (in the order given) to 800mL reagent grade water in a 1000 mL volumetric flask (label this flask #1)

1.	Formic acid	1.88 mL
2.	Propionic acid	350 µL
3.	Hexanoic acid	97 µL
4.	Zinc acetate dihydrate	4.39 g
5.	Methanol	9.1 mL
6.	2-propanol	4.45 mL
7.	1,2-propanediol	6.9 mL
8.	2-butoxyethanol	400 µL
9.	Phenol	0.010 g
10.	Formaldehyde (37% solution)	1.4 mL
11.	Caprolactam	2.6 g
12.	Acetone	38 µL
13.	4-hydroxy-4-methyl-2-pentanone	41 µL
14.	1,3,5-tri-2-propenyl-1,3,5-triazine-2,4,6(1H,3H,5H)-trione	120 µL
15.	2-(2-butoxyethoxy)ethanol	350 µL

16.	4-ethylmorpholine	465 µL
17.	Urea	0.47 g

Fill the volumetric flask to the mark with reagent water. Shake well for 5 minutes. Allow the flask to stand for 10 minutes before use.

B. Add the following compounds to 75 mL 95% ethanol in a 100 mL volumetric flask (label this flask #2)

1.	Octanoic acid	1.08 mL
2.	Benzaldehyde	6 µL
3.	Diethylphthalate	250 µL

Fill the volumetric flask to the mark with ethanol. Shake well for 2 minutes

C. Add the following compounds to 800 mL reagent grade water in a 1000 mL volumetric flask (label this flask #3):

1.	Ammonium bicarbonate	3.02 g
2.	Ammonium carbonate	2.97 g

Fill the volumetric flask to the mark with reagent grade water. Shake well for 2 minutes. Allow the flask to stand for 10 minutes before use.

D. Fill the third 1000 mL volumetric flask with 3/4 with reagent grade water (label this flask Ersatz Humidity Condensate). Transfer the following amounts per liter of the final solution:

1. Pipette 10 mL of the solution from volumetric flask #1.
2. Inject 173 µL of the solution from volumetric flask #2.
3. Pipette 10 ml of the solution from volumetric flask #3.

Dilute to the final volume with reagent grade water. Shake well for 2 minutes. Allow the flask to stand for 10 minutes before use.

E. Stock solution storage

The stock solutions should be refrigerated at 4 C between uses. Before each use, allow the stock solutions to warm up to ambient temperature.

APPENDIX B

Analytical results of the VPCAR experiment

Test Results #1

Components	**Formula**	**Feed**	**Product**	**Brine**
TOC		704	1.7	7610
Urea (3)	H2NCONH2			
Inorganics:				
Ammonia	NH3			
Ammonium	NH4+	48	<1	370
Bicarbonate	HCO3-			
Calcium	Ca++	16	<1	220
Carbonate	CO3=			
Chloride	Cl-	527	1.9	6050
Fluoride	F-			
Magnesium	Mg++	7.5	<1	93
Phosphate	PO4---	140	<1	1400
Potassium	K+	222	<1	2470
Sodium	Na+	361	2.6	3680
Sulfate	SO4--	105	<1	1150
Nitrate	NO3-	<5	<1	<50
Total inorganic solutes				
pH		6.9	6 to 5.2	6.8
Conductivity, mS		1.5	0.00026	21
Reaction Presure, psia			2	
Reaction Temp., C			180	
O2 flow, g/hr				
Processing Rate, kg/hr			4.2	
Total mass, kg		16.8	16.5	0.3
Notes:				
1. Without raising ammonium concentration of the feed stream				
2. Test run completed on 4/29/99				
3. Included in TOC				

Test Results #2

Components	**Formula**	**Feed**	**Product (hi O2)**	**Product (lo O2)**	**Product (no O2)**	**Brine**
TOC, ppm		813	2.6	3.7	8	8500
Urea (3)	H_2NCONH_2					
Inorganics:						
Ammonia	NH_3					
Ammonium	NH_4^+	602	<0.5	0.7	403	1100
Bicarbonate	HCO_3^-					
Calcium	Ca^{++}	14	1.7	<0.5	<0.5	203
Carbonate	$CO_3^=$					
Chloride	Cl^-	602	1.3	2	6.2	7068
Fluoride	F^-	8	<1	<1	<1	<1
Magnesium	Mg^{++}	3	<0.5	<0.5	<0.5	52
Phosphate	PO_4^{---}	133	<0.5	0.5	<0.5	1464
Potassium	K^+	280	2.2	1.5	5.8	3020
Sodium	Na^+	345	7.9	4.1	4.3	4250
Sulfate	SO_4^{--}	117	0.6	<0.5	1	1375
Nitrate	NO_3^-	4.6	<05	<0.5	<0.5	<50
Total inorganic solutes						
pH		6.9	6 - 5.2	6 - 5.2	10.7	6.8
Conductivity, mS		1.5	19	21	210	21
Reaction Press., psia			2	2	2	
Reaction Temp., C			150	150	120	120-150
O2 flow, gm/hr						
Processing rate, kg/hr			5.2	5.2	5.2	
Total mass, kg		16.8	16.5	16.5	16.5	0.3
Notes:						
1. Raised ammonium concentration of feed stream by injecting NH_4OH						
2. Test run on 5/17/99						
3. Included in TOC						

Test Results #3

Components	**Formula**	**Feed**	**Product (hi O_2)**	**Product (lo O_2)**	**Brine**
TOC, ppm		800	<0.5	<0.5	11000
Urea (3)	H_2NCONH_2				
Inorganics:					
Ammonia	NH_3				
Ammonium	NH_4^+	162	<0.5	<0.5	332
Bicarbonate	HCO_3^-	NA	NA	NA	NA
Calcium	Ca^{++}	23	<0.5	<0.5	260
Carbonate	$CO_3^=$	NA	NA	NA	NA
Chloride	Cl^-	820	<0.5	0.7	9300
Fluoride	F^-	NA	NA	NA	NA
Magnesium	Mg^{++}	10	<0.5	0.7	107
Phosphate	PO_4^{---}	170	<0.5	<0.5	2200
Potassium	K^+	420	<0.5	<0.5	5270
Sodium	Na^+	378	2	1.5	7400
Sulfate	SO_4^{--}	143	<0.5	<0.5	2000
Nitrate	NO_3^-	<0.5	<0.5	<0.5	<50
Total inorganic solutes					
pH		8.8 - 10	5.2 - 6.0	5.2 - 6.0	
Conductivity, mS		2.5	0.009	0.011	17
Reaction Press., psia			2	2	
Reaction Temp., C			200	200	
O_2 flow, g/hr			18	9	
Processing Rate, kg/hr			5.6	5.6	
Total mass, kg		16.83	16.49	16.49	0.295
Notes:					
1. Raised ammonium concentration of feed stream by injecting NH_4OH					
2. Test run on 6/4/99					
3. Included in TOC					

DISTRIBUTION

NASA/JSC
A. F. Behrend/EC
D. L. Henninger/EC
M. K. Ewert/EC2
C. H. Lin/EC2
Kathy Daues/EC3
Nigel Packham/EC3
K. D. Pickering/EC3
F. D. Smith/EC3
C. D. Thompson/EC3
T. O. Tri/EC3
C. E. Verostko/EC3
B. W. Finger/Allied-Signal/EC3

NASA/ARC (NASA Ames Research Center, Moffett Field, CA 94035)
C. K. Finn/MS 239-8
Michael Flynn/MS 239-15
Harry Jones/MS 239-8
Rocco Mancinelli/MS 239-12
R. P. Boulanger/Sverdrup Technology/MS 239-8

NASA/KSC
Alan Drysdale
The Boeing Company
PO Box 21233, MS KA91 F530
Kennedy Space Center, FL 32815

NASA Specialized Center of Research & Training at New Jersey
K. C. Ting (5)
Attn: Sukwon Kang, Luis Rodriguez, Dave Vaccari, Julie Levri
NJ NSCORT
Dept. of Bioresource Engineering
Cook College
20 Ag Extension Way
Rutgers University
New Brunswick, NJ 08901-8500

LMSO
Bruce Duffield/C70
Bruce Gertner/C70
A. J. Hanford/C70
F. F. Jeng/C70
J. F. Keener/C70
Gina Kirby/EC3
K. E. Lange/C70
E. P. McGlothlin/C70
A. H. Milliken/C70
H. Y. Yeh/C70 (2)

Lockheed Martin Library/B15 (2)
Task Order File (2)