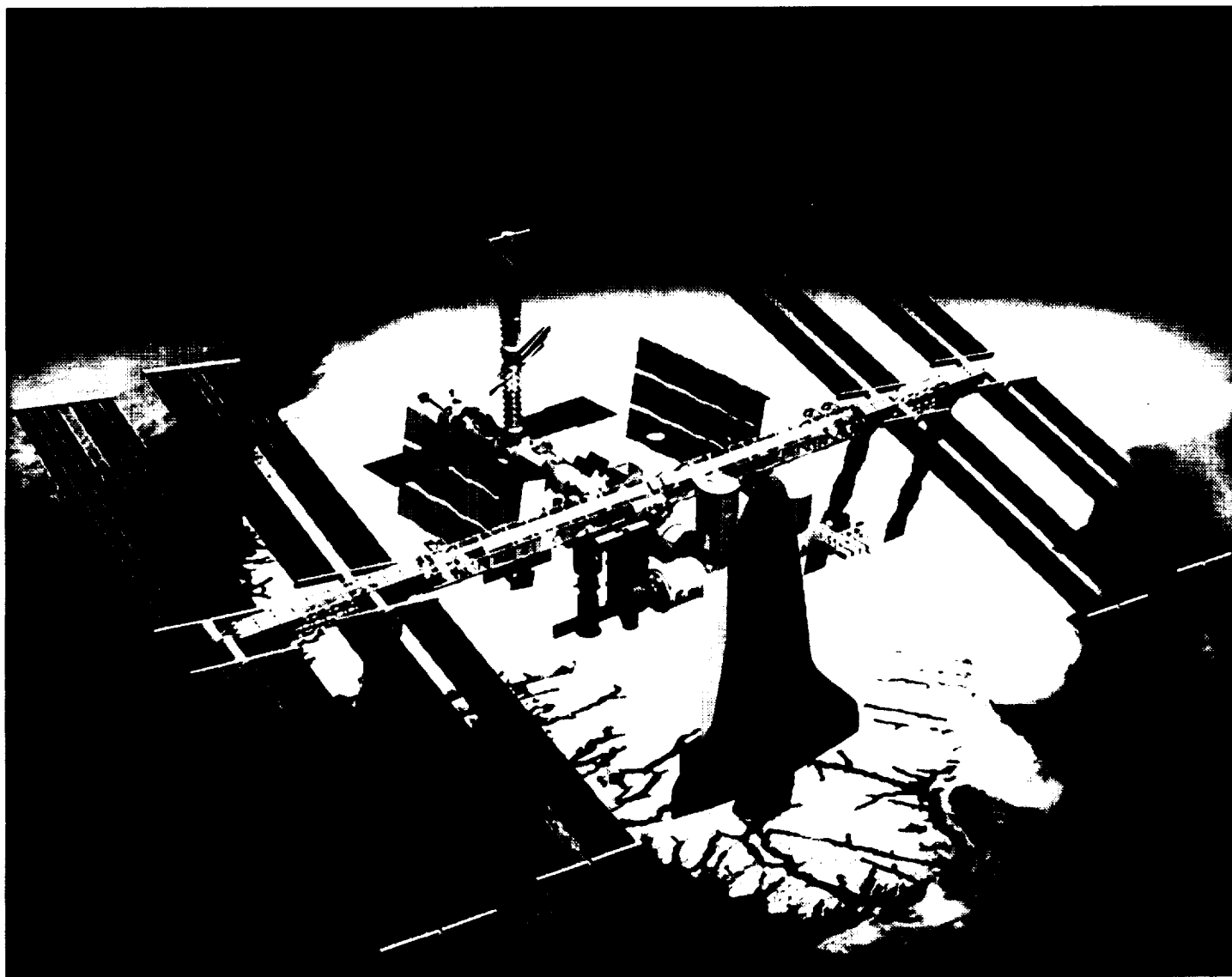
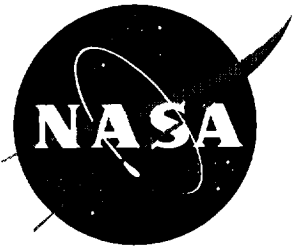


International Space Station ECLSS Technical Task Agreement Summary Report

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Acronyms

%	Percent
°C	Degrees Centigrade
°F	Degrees Fahrenheit
µg/L	Micrograms per Liter
4BMS	Four-Bed Molecular Sieve
Al ₂ O ₃	Alumina
AIT	Analysis and Integration Team
APA	Aqueous Phase Adsorption
AR	Air Revitalization
ARC	Ames Research Center
BA	Boeing
BMI	Battelle Memorial Institute
BOST	Baseline Operations System Test
C/MI	Control/Monitor Instrumentation
CASE/A	Computer Aided System Engineering and Analysis
cc	Cubic centimeters
CDR	Critical Design Review
CDRA	Carbon Dioxide Removal Assembly
CFM	Cubic feet per minute
CFU/m ³	Colony Forming Units per cubic meter
CH ₂ Cl ₂	Dichloromethane
CH ₄	Methane
CHeCS	Crew Health Care System
CHX	Condensing Heat Exchanger
CMS	Core Module Simulator
CO ₂	Carbon dioxide
DC	Direct Current
DMSO	Dimethylsulfoxide
DNA	Deoxyribonucleic Acid
DTO	Design Test Objective
DVB	Divinylbenzene
dynes/cm	Dynes per centimeter
EBCT	Empty Bed Contact Time
ECLSS	Environmental Control and Life Support Systems
ED62	Environmenta Control and Life Support Branch
EIS	Electrochemical Impedance Spectroscopy
EL65	Development Test Branch
EMA	Electrochemical Module Assembly
EMU	Extravehicular Mobility Unit
EPA	Environmental Protection Agency
EPT	Extended Performance Test
FAME	Fatty Acid Methyl Ester
FC	Fictive Component
FCA	Fictive Component Analysis
FEDS	Functional ECLSS Data System
FID	Flame Ionization Detector
FORTTRAN	Formula Translator

Acronyms (continued)

FY	Fiscal Year
g	Grams
GAC	Granular Activated Carbon
GC/MS	Gas Chromatography/Mass Spectrometry
gm/l	Grams per liter
GUI	Graphical User Interface
H ⁺	Hydrogen ions
H ₂	Hydrogen
H ₂ O	Water
H ₂ SO ₄	Sulfuric Acid
HS	Hamilton Standard Space Systems International
HTCO	High Temperature Catalytic Oxidizer
IART	Integrated Air Revitalization Test
IAST	Ideal Adsorbed Solution Theory
IML	International Microgravity Laboratory
ISS	International Space Station
Kg	Kilograms
KOH	Potassium Hydroxide
KSC	Kennedy Space Center
lb/day	Pounds per day
lb/hr	Pounds per hour
lbs oxygen/day	Pounds of oxygen per day
LFSPE	Liquid Feed Solid Polymer Electrolyzer
LIMS	Laboratory Information Management System
LiOH	Lithium Hydroxide
LSI	Life Systems, Incorporated
M/N	Model number
m ³ /hr	Cubic meters per hour
MCA	Major Constituent Analyzer
MCL	Maximum Contaminant Level
MCV	Microbial Check Valve
MFB	Multifiltration beds
mg/L	Milligrams per Liter
mL	Milliliters
MLS	Mostly Liquid Separator
mm Hg	Millimeters of Mercury
MSFC	Marshall Space Flight Center
MTU	Michigan Technological University
N ₂	Nitrogen
NASA	National Aeronautics and Space Administration
ND	Not Detected
NDIR	Non-Dispersive Infrared (methane analyzer)
NTU	Nephelometric Turbidity Units
O ₂	Oxygen
OC	Organic contaminants
OGA	Oxygen Generation Assembly
ORU	Orbital Replacement Unit

Acronyms (continued)

P	Pressure
PCA	Pressure Control Assembly
PCR	Polymerase Chain Reaction
PCWQM	Process Control Water Quality Monitor
Pd	Palladium
PDR	Preliminary Design Review
PFU/100 mL	Plaque Forming Unit per 100 milliliters
POST	Predevelopment Operational System Test
ppCO ₂	Carbon Dioxide partial pressure
pph	Pounds per hour
ppm	Parts per million
ppO ₂	Oxygen partial pressure
PSDM	Pore and Surface Diffusion Model
psi	Pounds per square inch
psia	Pounds per square inch absolute
psid	Pounds per square inch delta
psig	Pounds per square inch gauge
Pt/Co	Platinum/Cobalt
PWP	Potable Water Processor
QFD	Quality Function Deployment
Rc	Rockwell Hardness Scale C
RH	Relative Humidity
RNA	Ribonucleic Acid
RO	Reverse osmosis
rpm	Revolutions per minute
rRNA	Ribosomal Ribonucleic Acid
RTD	Residence Time Distribution
S&E	Science and Engineering
SAC	Strong acid cation
SBA	Strong base anion
SCMT	Sodium-N-methyl-N-"coconut oil acid" taurate
SEM	Scanning Electron Microscopy
SFE	Static Feed Electrolyzer
SLD2	Spacelab D Mission
SLJ	Spacelab J Mission
SLS2	Spacelab S Mission
SPA	Solid Phase Acidification
SPDFR	Surface to pore diffusion flux ratio
SPE	Solid Polymer Electrolyzer
SPE OGA	Solid Polymer Electrolyzer-Oxygen Generation Assembly
SS	Stainless steel
SSF	Space Station Freedom
STP	Standard Temperature and Pressure
TCA	Thermal Control Assembly
TCB	1,2,4-Trichlorobenzene
TCCS	Trace Contaminant Control Subsystem

Acronyms (continued)

TCE	Trichloroethylene
TCRS	Trace Contaminant Removal System
THC	Temperature and Humidity Control
TM	Technical Memorandum
TOC	Total Organic Carbon
TON	Threshold Odor Number
TTA	Technical Task Agreements
TTN	Threshold Taste Number
UP	Urine Processor
UPA	Urine Processor Assembly
UPN	Unique Program Number
US	United States
USML	United States Microgravity Laboratory
USOS	United States On-Orbit Segment
VCD	Vapor Compression Distillation
VRA	Volatile Removal Assembly
WAC	Weak acid cation
WBA	Weak base anion
WDS	Water Degradation Study
WP	Water Processor
WRM	Water Reclamation and Management
WRT	Water Recovery Tests
WWORU	Waste Water Orbital Replacement Unit
WWP	Wastewater Water Processor

1.0 INTRODUCTION

This document provides a summary of work accomplished under Technical Task Agreements (TTA) by the Marshall Space Flight Center (MSFC) regarding the Environmental Control and Life Support Systems (ECLSS) of the International Space Station (ISS) program. All the activities were approved in task agreements between the MSFC and the National Aeronautics and Space Administration (NASA) Headquarters Space Station Program Management Office located at Johnson Space Center and their prime contractor for the ISS, Boeing. These MSFC activities were in-line to the designing, the development, the testing, and the flight of ECLSS equipment planned by the Boeing Company in Huntsville supporting the prime contractor Boeing in Houston. MSFC's unique capabilities for performing integrated system testing and analyses, and its ability to perform some tasks cheaper and faster to support ISS program needs are the basis for the TTA activities.

Tasks were completed in the Water Recovery Systems, Air Revitalization Systems, and microbiology areas. The tasks in the Water Recovery and Air Revitalization areas were divided into component design, development and testing; subsystem and integrated systems testing; analytical model development; life testing; and preliminary definition of flight experiments for the Phase I Shuttle/Mir missions. In the microbiology area, assessments of microbial degradation of Space Station materials and the Polymerase Chain Reaction microbial monitor were conducted. The results of each of these tasks are described in this report. More detailed reports are referenced and are available upon request from the MSFC Document Repository.

2.0 TASK AGREEMENTS

The MSFC initiated supporting development task agreements with the NASA Headquarters Space Station Program Office in Fiscal Year 94 (FY-94) and they cover projected activities through Fiscal Year 2000 (FY-00). In addition, some Fiscal Year 93 (FY-93) ECLSS funded tasks were also approved by the program office in 1993. Results of the FY-93 and FY-94 activities are summarized in this ECLSS report. Although MSFC has many tasks with the program office, only the ECLSS activities are summarized in this report.

The current ECLSS activities are managed under two program office task agreement Unique Program Numbers (UPN) 478-31-34 and 478-31-41. Those agreements provide a task summary description, cost by fiscal year, and civil service manpower to accomplish the work.

3.0 ORGANIZATION

Organizations which support TTA activities and their interfaces are shown in Figure 3.0-1. The Environmental Control and Life Support Branch (ED62) of the Structures and Dynamic Laboratory within the Science and Engineering (S&E) Directorate of MSFC managed the overall ECLSS TTA work. Within ED62, engineers were assigned responsibilities to develop test requirements, perform analyses of test results, support actual testing, and manage special tasks performed under NAS8-38250 (test services contract). The Development Test Branch (EL65) of the Systems

Analysis and Integration Laboratory in S&E provided the test facilities and performed the testing of the ECLSS at MSFC. The test services contractor, ION Electronics, provided test support, analytical modeling of integrated test configurations, test support and studies from ECLSS subcontractors, and analytical model development. Key Boeing-Huntsville support to MSFC integrated systems testing is the chemical/microbial laboratory analyses of air and water samples and the providing of test subjects used to generate metabolic waste water products for the water reclamation systems testing. Overall results of the Boeing-Huntsville chemical/microbial laboratory analyses and the sensor data is maintained in a database developed by MSFC and utilized by all space station participants. Products provided to the ISS program included computer models, reports, and test reports/findings.

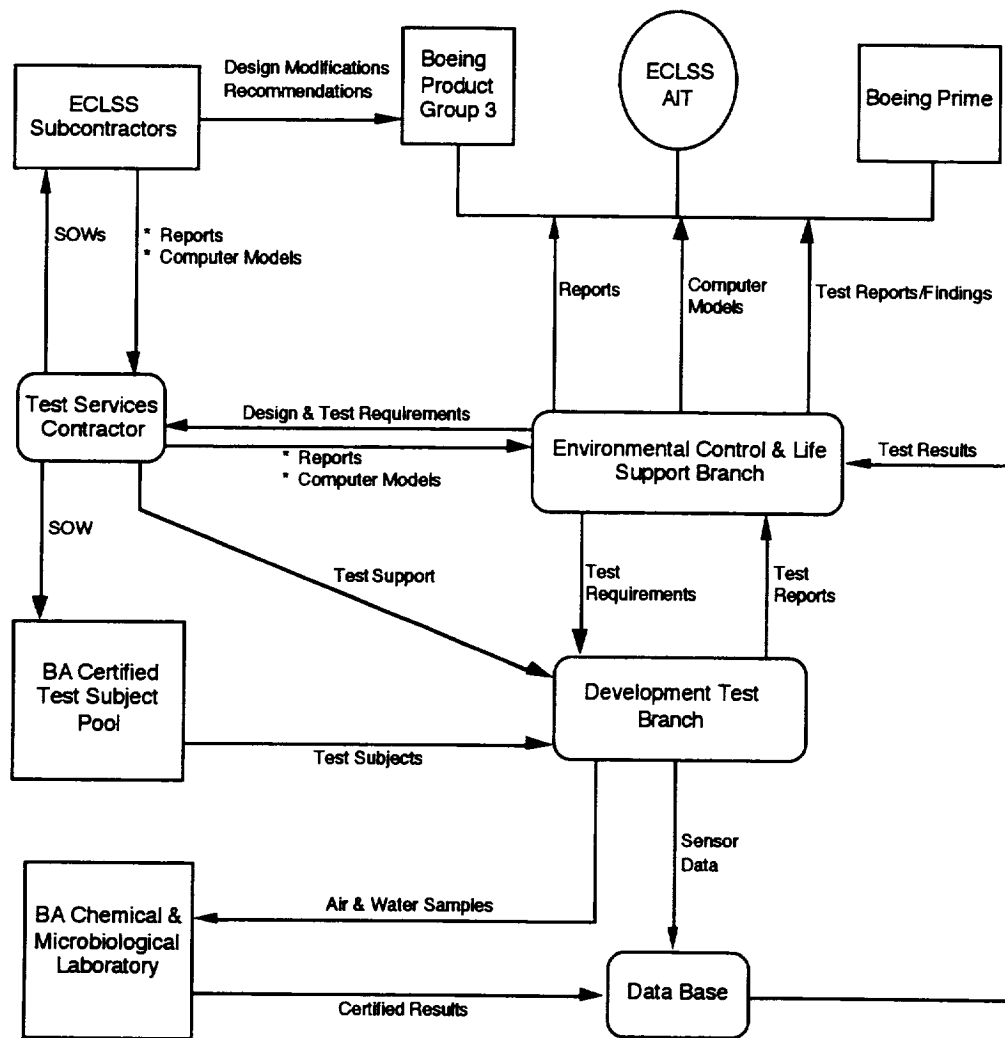


Figure 3.0-1 ECLSS Technical Task Agreement Organizational Interface

4.0 WATER RECOVERY SYSTEMS

4.1 Component Design and Development

There are several outstanding design issues associated with components in the United States (US) segment water recovery systems which require early development attention. The following sections describe the specific component, the design issue, and the on-going supporting development activity that is addressing the issues.

4.1.1 Process Pump ¹

The process pump is an integral part of the Waste Water Orbital Replacement Unit (WWORU) within the ISS Water Processor (WP). The function of the WWORU is to degas waste water, store waste water prior to processing, and pump waste water through the WP. The process pump's function is to supply the system's flow rate and operating pressure of 15 pounds per hour (pph) and approximately 70 pounds per square inch gauge (psig), respectively.

During the first and second quarter of 1992, HS evaluated prototype Process Pump model number (M/N) 2992 for performance capabilities in meeting the Space Station Freedom (SSF) requirements. Two identical gear pump assemblies were procured from Howden Fluid Systems, formerly Pneu Devices Inc. The pump and motor controller are shown in Figure 4.1-1. The gears were manufactured of nitrided 17-4PH stainless steel (SS). Testing efforts were terminated due to high motor temperature and no flow conditions indicating pump failure. After extensive review, the failure resulted from corrosion of a low carbon steel plug in the test rig. Particles from the corroded plug flowed into the pump which caused gear lock-up. Internal evaluations of the pump head showed several areas of corrosion and concluded that the corrosion resistance of the gear and cartridge materials needed to be improved to meet the life requirements.

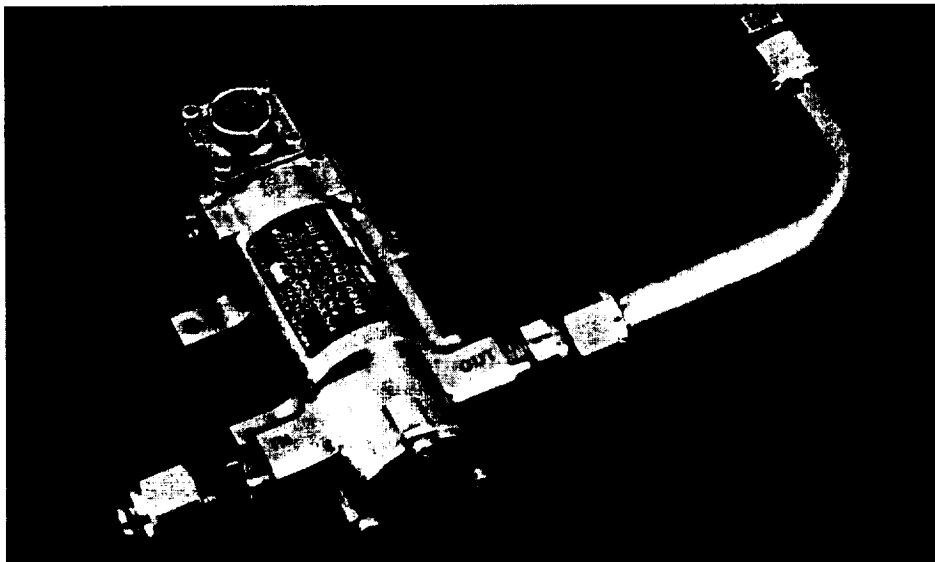


Figure 4.1-1 Water Processor Pump Prototype

The primary goal of the program that began March 1994 and concluded July 1995, was to continue the development of the 2992 process pump by significantly improving corrosion resistance while still meeting the mechanical requirements for the pump. The first gear materials evaluated included Inconel 718 and 15-5 PH stainless steel. These gear materials were tested during August and September 1994.

4.1.1.1 Inconel 718 2992 Pump

The Inconel 718 gear pump operated for approximately 30 seconds before it locked-up. The tear down investigation revealed that significant galling deformation had occurred. The galling was found between the side plate and the gear end faces along with between the drive faces of the gears. The galling at the gear end face appeared to cause the pump lock-up.

The conclusion from this test indicated that the surface hardness of the gears in a non-lubricating fluid was insufficient to provide proper wear resistance. The hardness of the Inconel 718 gears tested was approximately 40 - 41 RC (Rockwell Hardness Scale C), which compared to a standard nitrided 17-4 PH SS gear material hardness of 58 - 65 RC, is relatively low. It was originally anticipated that the pump operating conditions would allow lower gear surface hardness but the results indicated this was not true.

4.1.1.2 Stainless Steel 15-5 2992 Pump

The 15-5 PH SS gear pump was tested for 188 hours using waste water. The testing was initiated with a two hour operational check out, the pump and cartridge assembly were then disassembled to inspect the gears. The inspection found no galling and only a slight wear pattern on the gear teeth. The slight wear was judged normal; therefore, testing continued.

After the test was stopped at 188 hours, the pump was disassembled and the cartridge assembly was inspected. The inspection revealed that the drive faces of both gears had significant wear which led to the pump's performance decrease. Similar to the conclusion reached on the Inconel 718 gears, the 15-5 PH gear surface hardness was too low to provide adequate life in the non-lubricating fluid.

Following the conclusion of these tests, a program review meeting resulted in the development of a new action plan to continue the gear pump development. Three major tests were developed to further evaluate improvements in gear life performance. These included: (1) operating a 15-5 PH SS gear set at lower speeds to determine if life performance is improved; (2) fabricate and test a borided Inconel 718 set of gears; and (3) fabricate and test a borided cobalt alloy Stellite 6B set of gears. The stellite gears were manufactured for a larger pump (M/N 2941) for pump operation at approximately 1500 revolutions per minute (rpm). This pump would be used to further evaluate lower operating speeds. The three options listed were fabricated and tested from January through June 1995.

4.1.1.3 Low Speed 15-5 2992 Pump

Since an additional set of 15-5 PH SS gears was already available, it was decided that a low cost and quick method of obtaining some quantitative results on this parameter would be to operate the 2992 pump at a reduced speed and evaluate any improvement in performance life. The test accumulated 257 hours of operation before stopping the test due to a significant performance reduction.

Following the test the pump and cartridge were disassembled and inspected. The inspection revealed that damage similar to the initial 15-5 PH SS had occurred. Although the lower speed pump test operated approximately 37 percent (%) longer, the initial 170 hours were operated at a lower pressure (i.e., 55 psig); therefore, lower gear loading resulted. Also taking into account that this test was conducted with a limited number of samples, the results indicate no significant improvements in pump life was achieved.

4.1.1.4 Borided Inconel 718 2992 Pump

An initial check-out test was conducted on the borided Inconel 718 pump using clean deionized water as the test fluid. At test beginning the pump operated smoothly and quietly. No noise readings were taken but the pump could not be heard over the laboratory background noise. The test was stopped as a result of a pump lock-up after 87 test hours. A tear down and inspection revealed significant damage to the gear drive faces. The metallurgical examination found that the boride layer on the gear drive faces had been removed. Once the borided surface was removed, galling occurred resulting in pump lock-up. No corrosion or damage to the cartridge was found.

4.1.1.5 Borided Stellite 6B 2941 Pump

An initial check out test was conducted on the borided Stellite 6B pump (M/N 2941) utilizing clean deionized water as the test fluid. This pump was tested in parallel with the M/N 2992 borided Inconel 718 pump. At test beginning the pump operated smoothly, but unlike the M/N 2992 pump, this pump was clearly audible. No noise readings were taken but the pump could be easily heard over the laboratory background noise. An interim clean water performance check indicated a slight decrease in performance. Following this check, the waste water was replaced and the life test was continued.

The test was stopped after 424.75 hours to investigate if any damage had or was in the process of occurring to the Stellite 6B gears. This decision was based on evidence found on the Inconel 718 gears along with the decreased pump performance. The intent of the early shutdown was to find some evidence of possible boride coating failure, possibly in process, on the Stellite 6B gears. The pump performance had decreased from the test start. Specifically, the power had increased approximately 10% and the outlet pressure gauge was fluctuating approximately 20 psig. Also, the noise and vibration from the pump appeared to have increased. This gauge and noise information indicated that possible internal gear damage may have occurred.

A teardown and inspection revealed significant damage to the gear drive faces which was similar to that found on the Inconel 718 gears. The metallurgical examination found that the boride layer on the gear drive faces was removed. Once the borided surface was removed, wear of the gears occurred. The wear/damage to the gears caused an increase to the pump backlash which was believed to have caused the gauge instability and increased pump vibration and noise. Also, the increased backlash was believed to have caused the decrease in pump performance.

The examination of both the Inconel 718 and Stellite 6B gears showed cracking in the areas near the edge of the removed boride. These cracks likely indicated the coating was not sufficient to withstand the gear loading. No corrosion or damage to the cartridge was found.

The following observations were obtained during the Process Pump development program:

- No foreign contaminants were responsible for any pump/gear failures.
- All improvements to the cartridge components appeared to be successful.
- No signs of corrosion were evident on any materials tested.

The following conclusions were drawn:

- The combination of the thin boride diffusion depth of 0.001 inch and the hard/brittle nature of the boride zone led to cracking and removal of the boride layer.
- Borided gears are insufficient for this gear pump application.
- There was no apparent improvement in life performance anticipated with a pump speed reduction of approximately 500 to 600 rpm. Therefore, the 2992 pump configuration was better for further development of this pump. This permits the use of the higher efficiency device.
- A gear pump may not be the proper technology for the ISS WP application.

HS presented the trade study results from Phase 1 of the process pump development effort January 1996. The trade study was based on the Quality Function Deployment (QFD) technique. The pump requirements were selected and prioritized independently from the technology assessment. Eleven major selection criteria were developed and prioritized to assess 50 different pump technology configurations. Go/No Go criteria were developed to screen the fifty technologies before the comparative evaluation was undertaken. As a result of the Go/No Go screening and the combining of similar pump technologies, the 50 pump technology configurations were reduced to 12. The eleven criteria were weighted according to priority, with reliability being the highest priority at 29.9% of the total grade, and reliability, design applicability, and development cycle together accounting for 54% of the total grade. The 12 pump technologies remaining after the screening were then evaluated against each of the 11 criteria. External gear and piston pump technologies were the clear

winners of the trade study. The external gear pump scored the highest in 8 of the eleven criteria, but tied with 3 of the 12 pumps for the lowest score in readability. The piston pump scored the highest in 6 of the eleven criteria, and tied with 5 of the 12 pumps for the second highest score in readability. After review and discussion, NASA and Boeing agreed with HS's trade study results and agreed that gear and piston pump prototype designs should be developed as two of the three technologies called out in the contract. The next highest rated pumps were the vane and diaphragm technologies. Because they were so closely scored (diaphragm scored 429 points and the vane pump scored 430), HS took an action to investigate the diaphragm and vane pump technologies further to determine which technology will be carried through the prototype design with the external gear and piston pump during this phase. Presently, all four pump technologies will be carried forward to a prototype design.

Parallel to the trade study and prototype development effort, the original process pump design was to be tested using 17-4 stainless steel gears. In previous testing, these gears had shown an operational life approximately an order of magnitude longer than other gear materials used in this design, but a test stand failure had caused premature failure of the pump. This test was intended to determine the actual life of these gears to see if they showed promise for meeting the requirements of the ISS. However, since Howden Fluid Systems did not respond to the Statement of Work issued by HS in a timely fashion, the pump will not be on test until April 1996, which is one month prior to the scheduled completion of this phase of the development effort. Technically, it was agreed in the meeting by HS, Boeing, and MSFC, that the Howden pump had little hope of showing a significant improvement in life compared to the other gear materials. Therefore, it was recommended both from a technical and programmatic perspective that the Howden pump test be dropped from the tasks of Phase 1. This recommendation was reviewed with the Space Station ECLSS Manager and he concurred with this decision.

4.1.2 Mostly Liquid Separator ²

The Mostly Liquid Separator (MLS) is another integral part of the WWORU within the ISS WP. The MLS removes free gas from waste water prior to storage. The MLS design will remove approximately 10% by volume of free gas.

Water processor waste water contains free gas along with other materials which cause foaming. If the gas is not removed the system can become "gas-locked" which results in the degradation of the system's performance. HS has developed the MLS where free gas is separated, collected, and vented to the cabin; and the waste water is stored or drawn into the processor by the process pump.

HS built an initial MLS unit to remove free gas from the inlet waste water of the Potable Water Processor (PWP). This MLS used a series of low speed paddles which created the forces to separate the fluids, and a high speed screen coalescer which entrained droplets from the gas vent flow. The unit was tested using deionized water with varied inlet gas content. These studies gave a positive indication of the MLS unit feasibility.

After SSF redesign to ISS, the Potable and Hygiene Water Processors were combined into a single water processor. The MLS, with a single water processor, would have to

treat waste water loaded with soap. Since the paddle design aggravated the foaming problem, a design change was necessary. The paddle and screen design was replaced with a series of cylindrical disks. This design was tested using clean (deionized) water, soap and water, and shower water with varied free gas concentrations. Although there were modifications incorporated into the MLS design during testing, results indicated that the design concept provided gas/liquid separation and insignificant foaming.

The primary purpose of the MLS tests was to further develop the MLS technology, characterize its performance, and define its operating requirements. The four main objectives to develop the next generation MLS from the requirements of the ISS WP were:

- To map the performance of the MLS within the expected operating conditions of the Space Station Water Processor. This effort first focused on identifying the lowest rpm at which the separator would operate without water carry over into the gas outlet line for the full range of inlet flow rates. As the MLS was designed to operate with a constant rpm, the lowest possible rpm suitable for all flow rates would then be selected as the operating value. It was believed that minimizing the rpm would lower power consumption and minimize any detrimental turbulences within the MLS. Using this rpm, the amount of air carried over in the water outlet lines was measured for each inlet flow rate and for various percentages of air in the inlet stream. This performance mapping procedure was repeated using clean water, soap and water, and shower water.
- To demonstrate the insensitivity of the MLS unit to gravity. This was accomplished by orienting the MLS in various positions and then mapping its performance.
- To identify potential enhancements to the design or operation of the MLS. Observations made during development testing resulted in frequent modifications to the MLS and test rig.
- To evaluate the extended performance characteristics of the separator. The purpose of this test gathered experience on how the MLS works in near-continuous, long term operation using "real" water.

A new MLS design was created that was sized to operate over the full 60 to 960 pounds per hour (lb/hr) inlet flow range and that utilized an improved control mechanism to regulate gas venting. MLS units were built and tested to demonstrate acceptable performance at high inlet flow rates (up to 960 lb/hr), under a variety of water conditions. The success of the development program was aided by the use of a translucent plastic MLS which provided visual observation during operation. Performance mapping indicated that acceptable performance can be achieved at 1900 rpm for any water condition with 0% - 14% air in the inlet stream. Several hardware modifications were made during the course of the program to improve performance, the majority were successful. Test results suggested that maintaining a near-constant backpressure and rpm within the MLS was of prime importance in providing acceptable performance.

The MLS unit is shown in Figure 4.1-2. The prototype MLS units, built and tested, contained all of the features of the flight unit except for a flight-style motor, which was replaced with a variable speed, external, direct drive motor.

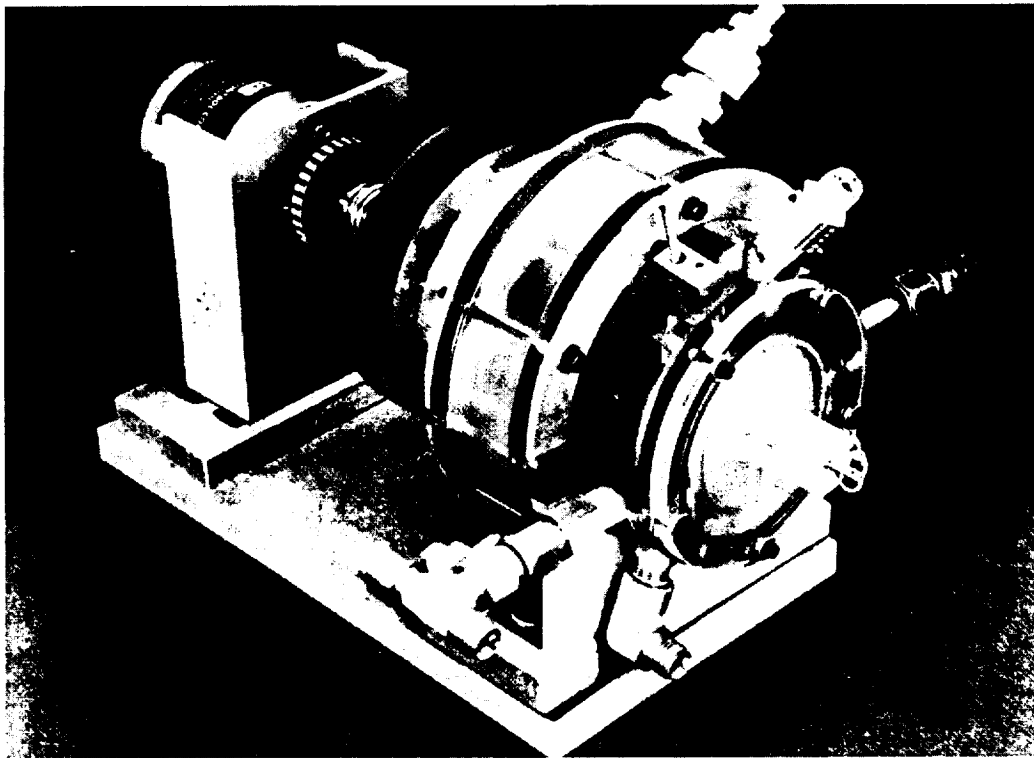


Figure 4.1-2 Mostly Liquid Separator

The motor spins a hollow center shaft mounted on journal bearings. A series of disks are attached to the shaft extending radially outward to a diameter approximately 1/4 inch from the inside diameter of a cylindrical housing. Each disk has a series of slotted holes extending through the disk near its center. The shaft has slots cut into its outside diameter so that the space between some of the disks near the center of the stack is vented to the shaft's center. The end of the shaft is open to a level control valve arrangement that connects to the gas vent.

In operation, a mixture of water and air enters the unit tangentially near the motor end of the housing. The mixture is forced to spin around the housing centerline as it follows the cylindrical housing wall. Initial separation occurs in this portion of the housing with the water moving to the outside and the air bubbles moving toward the centerline. The partially separated mixture then enters the disk portion of the housing where the centrifugal action of the spinning disks forces the water to the housing wall, forming a water ring that is maintained in motion by contact with the outer edge of the spinning disks. The air moves to the center line and flows through the holes in the disks towards the slots that connect to the center of the shaft. As the control valve opens, gas is vented from the separator. The water moves along the outer wall of the housing and exits tangentially, allowing recovery of some pressure head. Water level in the water ring is maintained by the action of the control valve. A control piston

pushes on the control valve element with a force that is proportional to the height and spinning velocity of the water ring. As the water level increases, the static pressure at the outer diameter increases with respect to the centerline pressure due to increased depth and due to an increased rotational velocity resulting from greater contact area on the rotating disks. This difference in pressure creates the level control force and is balanced against a spring to determine the vent valve position.

The Extended Performance Test (EPT) was conducted for 296.5 hours, frequently running 24 hours per day. Inlet flow was held at 60 pph, inlet air was held at 14%, and the MLS ran at 1900 rpm. No difficulties or unusual conditions were noted.

The final observations concern the modifications made to the MLS hardware:

- The diaphragm seal needs to be flat and requires minimal force to seal. A 0.031 inch thick Fluoroelastomer was used.
- The end disk, with paddles removed and enlarged vent holes, improved the air carryover performance.
- A dynamic seal was necessary to prevent water leakage past the Rulon journal bearing.
- The flat disks, with vent holes modified into slots to reduce the air flow restriction, improved air carryover performance.
- The inclusion of an end disk in the first or second disk position (nearest the inlet) improved performance.
- Repositioning the disk assembly shaft's vent holes two positions further away from the inlet improved water carryover performance.
- The new backpressure valve did not provide a constant backpressure that was independent of inlet flow.
- The current fault detection magnets and proximity switches did not provide the necessary sensitivity for proper operation.
- The air primarily vented at discrete times, rather than continuously. When this occurred, the backpressure would momentarily go to 0 pounds per square inch (psi), and the depth of the water ring would increase as the gas was vented. The rpm would consequently change in response to the changing depth of the water ring. It was concluded that the interaction of each of these responses resulted in the relative instability seen at times in the operation of the MLS unit, and that this instability affected the air carryover performance. Consequently, it was concluded that transient backpressure fluctuations need to be minimized or eliminated and the backpressure needs to be held constant for all inlet flow rates.
- Use of a single 1/2 inch ball valve to regulate backpressure resulted in dramatic improvement in the air carryover performance of the MLS.

The following conclusions were drawn regarding the performance of the MLS:

- The performance of both MLS units met the design requirements.
- No performance degradation was noted after an extended duration performance evaluation.
- Higher flow rates required a higher rpm to prevent water carryover.
- The percentage of air that is carried over into water outlet lines increases with increasing rpm and inlet flow.
- An acceptable operating speed is 1900 rpm.
- The inlet chamber and inlet disks both affected air carryover performance when the MLS was oriented horizontally.
- Backpressure instability will adversely affect air carryover performance.
- The diameter of the main water outlet line may need to be increased to help ensure that backpressure can be independent of inlet flow.
- The use of a translucent plastic housing was a significant aid in testing.

The current MLS development effort will implement design changes to solve some of the short comings discovered in the previous development effort. The most significant design changes that will be incorporated are as follows:

- Because of the sensitivities to back pressure, inlet flow rate, and rpm fluctuations, changes to test rig as well as to the MLS design will be incorporated. Back pressure will be improved by using a water accumulator to provide a stable back pressure on the MLS. The diameter of the outlet line of the MLS has been increased to remove sensitivities to inlet flow rate (resulting in internal changes in back pressure). A constant speed direct drive motor is being used for this effort to remove any loss in rpm due to loading of the discs when input flow rates increase.
- To further improve water carryover in the air side, a redesign of the shaft and air solenoid valve was undertaken. The shaft is now hollow, with the outlet port for the air located internal to the shaft. This design shields the outlet from any splashing which occurs at the control valve end of the MLS (the original location of the air outlet port) and should therefore improve separation performance.
- The control valve was redesigned to improve sensitivity and provide adequate control during MLS operation.

The design was completed in February of 1996. Manufacturing will begin in February 1996 with testing of the redesigned MLS to start in the fall of 1996.

4.1.3 Volatile Removal Assembly ³

The Volatile Removal Assembly (VRA) Reactor is an integral part of the Space Station WP. The WP is used to generate potable quality water from a variety of waste waters generated on the Space Station. The VRA reactor is located in the Catalytic Reactor Orbital Replacement Unit (ORU) which is downstream of the two Unibeds[®]. Its purpose is to oxidize volatile organics which are not easily removed by multifiltration technology (ion exchange and adsorption). The VRA Reactor uses gaseous oxygen along with a noble metal catalyst to oxidize the organics. This reaction produces a combination of organic acids and carbon dioxide which are subsequently removed by a downstream phase separator and an ion exchange resin bed. The reactor operates at relatively low temperatures, approximately 265 degrees Fahrenheit (°F), and also sterilizes the water that flows through it.

In August 1991, the predevelopment potable water processor, containing a VRA reactor with a carbon substrate, was delivered to MSFC and subsequently tested. This testing indicated a degradation in reactor substrate over time, which would eventually cause an unsatisfactory operating life. HS continued development efforts to improve the reactor's performance life. These efforts resulted in the use of a new substrate material, alumina, designed to improve the reactor's life. The second system, the Predevelopment Water Processor, used this new reactor material and was delivered in August 1992 for further testing at MSFC.

In a parallel effort, the improved reactor design and 250 cc of the raw catalyst were delivered to Michigan Technological University (MTU) to develop performance characteristics for a mathematical model of the VRA Reactor. The mathematical model used empirical data gathered by in-house MSFC testing of the referenced VRA Reactor. The catalyst was received on July 20, 1994 and the VRA Reactor was received on August 18, 1994. A more detailed discussion of this effort is included in Section 4.3.2.

4.1.4 Process Control Water Quality Monitor

The purpose of this task was to procure a development unit Process Control Water Quality Monitor (PCWQM) to be utilized in the Stage 9 Water Recovery Test. The WP design for the Space Station Water Reclamation and Management (WRM) Subsystem employs a PCWQM to verify acceptability of water prior to use. An integrated test involving a flight-like PCWQM was necessary to verify that the design of the PCWQM can be integrated with the WP.

The PCWQM was refurbished with the necessary flight-like sensors and components so that it could be successfully integrated and operated in the Water Recovery Test (WRT) Stage 9. Astro International delivered one PCWQM that utilized the sensor technology proposed for the flight design of the PCWQM. The operations manual and other applicable documentation were also included in this procurement. A discussion of the PCWQM performance may be found in the ISS ECLSS Phase III Water Recovery Test Stage 9 Final Report, Technical Memorandum (TM)-108498. ⁵

4.1.5 Urine Pretreatment ⁴

There are several problems and considerations for the proper collection, storage, and processing of urine in a microgravity environment for long duration manned spacecraft missions such as the Space Station. Urine processing for water reclamation usually requires the addition of chemicals to fix the urea, provide microbial control, and minimize urine particulate formation. Because there is minimal use of flush water, the additive chemicals must also eliminate particulate deposits within the equipment and plumbing which can cause premature failure to hardware and systems.

Urine pretreatment, as presently defined for the Space Station program for proper downstream processing of urine, is a two-part chemical treatment of 5.0 grams (g) of OXONE[®] Monopersulfate compound and 2.3 milliliters (mL) of sulfuric acid (H₂SO₄) per liter of urine. A new method of introducing the OXONE[®] portion into the two-phase urine/air flow stream of the Space Station urine processor has been successfully tested and evaluated. The feasibility of this innovative method has been established for purposes of providing a simple, convenient, and safe method of handling a chemical pretreatment. During a real time test collection of 750 pounds of urine, OXONE[®] introduced into the processors urine/air flow, upstream of the Fan/Separator, has demonstrated the following advantages:

- Eliminated urine precipitate buildup on internal hardware and plumbing.
- Minimized odor from collected urine.
- Virtually eliminated airborne bacteria.

This study program and test demonstrated only the addition of the proper ratio of OXONE[®] into the urine collection system.

The program was divided into three major tasks: (1) a trade study, to define and recommend the type of OXONE[®] injection method to pursue further; (2) the design and fabrication of the selected method; and (3) a test program using high fidelity hardware and fresh urine to demonstrate the method feasibility.

The trade study was conducted to define different forms and methods for introducing OXONE[®] into a urine system. OXONE[®] was considered in liquid, solid, paste, and powdered forms. The results from the trade study recommended a solid tablet in a bag suspended in the urine/air flow stream. These OXONE[®] tablets would slowly dissolve at a controlled rate providing the proper concentration in the collected urine.

To implement the solid tablet in a bag approach, a design concept was completed with prototype drawings of the urine pretreatment prefilter assembly. A successful fabrication technique was developed for retaining the OXONE[®] tablets in a fabric casing attached to the end of the existing Space Station Waste Collection System urine prefilter assembly. The final pretreatment prefilter configuration held sufficient OXONE[®] in a tablet form to allow normal scheduled daily (or twice daily) change out of the urine filter depending on the use rate of the Space Station urine collection system.

The test to prove the concept was conducted using the Urine Fan/Separator assembly that was originally used in the STS-52 Design Test Objective (DTO) urinal assembly. The Fan/Separator was installed into a portable urine collection test assembly for real time collection of urine. Urine collection continued over a 2-month period with a total of 40 batches of urine collected. Each batch consisted of approximately one day of urine collection with a fresh pretreatment prefilter installed at the beginning of the day. Based on a mass balance of urine collected and OXONE® tablets used, an average pretreatment ratio of 5.2 g of OXONE® per liter was obtained. This meets the test program goal of a minimum average of 5.0 grams per liter (gm/l). Also, a post test teardown of the test hardware (including the urine separator and downstream urine check valve) showed that OXONE® alone does an excellent job of eliminating undesirable urine particulates in the system. The collection reservoir also maintained a 4.5 pH average.

Other related tests were conducted to demonstrate the actual minimum ratio of OXONE® to urine that will control microbial growth. The results of this test indicated that at 3.0 gm/l there was limited control and above 4.0 gm/l microbial growth was prevented over 7 days. A microbial air sampling test (at 10 cubic feet per minute (cfm) air entrainment flow) of the Urinal Fan/Separator indicated that sample points within the urine collection system and at the outlet did not contain microbes over the detection limits of 12 Colony Forming Units per cubic meter (CFU/m³). Air samples at the urine funnel showed that men's bathroom air entering the system was as high as 193 CFU/m³.

An effective method of dispensing sulfuric acid to the waste stream is currently under investigation. A solid tablet has been developed using potassium bisulfate to hold the sulfuric acid in the tablet. Potassium bisulfate is already a part of the Oxone® so no additional chemicals would be added, only a slightly larger amount of that salt. This tablet would be added to the string Oxone® tablets already in the filter so that the urine pretreatment chemicals would be added once or twice daily with the filter. No additional maintenance would be required for the pretreatment. Testing to prove this method is planned for the near future.

4.2 Stage 9 Water Recovery Test ⁵

The provisions of safe potable water to spacecraft crew members has been a requirement since the beginning of the US manned space program three decades ago. Spacecraft water systems have evolved from stored chlorinated supplies used in the Mercury and Gemini programs to the Space Shuttle's iodinated fuel cell product water system.

To reduce the quantity of fresh water to be resupplied from the ground (as well as to reduce the quantity of waste water to be returned to the ground or otherwise disposed of on-orbit) the ISS WRM System will reclaim water from a variety of waste water sources for reuse. Through reclamation and reuse, a given mass of water may be used repeatedly. Resupply of fresh water and return (or disposal) of waste water is thus reduced to that necessary to compensate for the inefficiencies of the reclamation processes.

The development of the ISS WRM System has been supported through integrated ECLSS testing at MSFC. This testing, which began in 1986 and has continued through ISS Preliminary and Critical Design phases, has been conducted with development potable and hygiene water reclamation assemblies which were integrated with end-use equipment. Man-in-the-loop testing of these integrated systems has provided early performance data on "heart-of-the-subsystem" technologies in environments that would have otherwise been impossible to reproduce with artificially prepared "ersatz" waste waters or "stand-alone" subsystem testbeds.

Integrated ECLSS testing dedicated to the WRM System has been conducted as part of the WRT series. The WRT was originally conceived as a nine-stage test proceeding from open-loop "donor-mode" in which human test subjects generated waste waters from non-recycled water to closed loop "recipient-mode" in which reclaimed water was returned to test subjects for reuse and subjective assessment. Data collected from early WRT stages, combined with the passing of ISS program design review and restructuring milestones, necessitated the revision of the WRT plan. Donor mode tests, with a dual-loop (potable and hygiene) water recovery system were completed in 1990. Recipient mode tests, with a dual-loop system, which was modified in accordance with ISS subsystem technology selections, were completed in 1991. Donor and recipient mode testing, with a single loop system representative of the restructured ISS baseline and modified to utilize the current available technology for the WP, was completed in early 1992. Additional single loop testing, complete in late 1992, evaluated the impact of eliminating the WP presterilizer on unibed life and overall WP performance.

In 1993, the Space Station Program went through the most extensive redesign since the program began in the mid 1980s. When the redesign was concluded in late 1993, SSF was completely redesigned and was renamed International Space Station. As part of the redesign, Boeing's Predevelopment Operational Systems Test (POST) for the WRM System was deleted and replaced with the WRT Stage 9.

The WRT Stage 9 was conducted at NASA/MSFC to evaluate the latest water recovery system design for the United States On-Orbit Segment (USOS) of the ISS with higher fidelity hardware and integration than has been achieved in previous WRT stage testing. Potable and urine processing assemblies were integrated with end-use equipment and operated for 116 days. The overall integrated configuration of the test system included a single water recovery loop that was automated and controlled from a central computer. The Water Recovery System, Stage 9 simplified functional schematic is shown in Figure 4.2-1.

The main objective of Stage 9 was to operate higher fidelity Water Recovery hardware, integrated to reflect the ISS USOS configuration, in an automated system level control scheme. Previous WRT stages at MSFC had successfully demonstrated that the WRM System technologies could produce potable grade water from the various waste streams expected on the Space Station. Stage 9 allowed the assessment of the water recovery technologies under system operational constraints and conditions that would be expected on the Space Station.

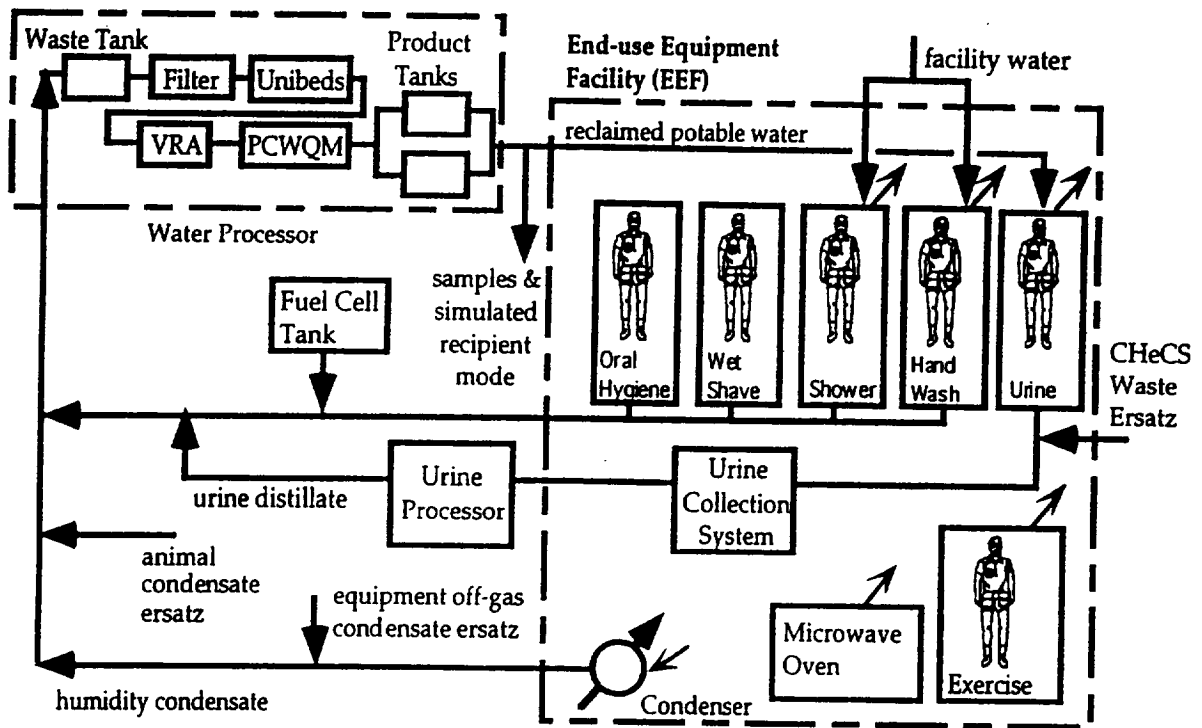


Figure 4.2-1 Water Recovery System Simplified Functional Schematic

Analysis of the WRT Stage 9 test data resulted in a number of conclusions and recommendations. These conclusions and recommendations are given in the following paragraphs.

The control logic for the WRM System and simulated recipient mode performed well throughout Stage 9. Based on the Stage 9 data, the water management control logic is considered to be sufficient to maintain product water availability and waste water storage capability aboard the ISS. However, the PCWQM data interpretation algorithm was unable to respond to the dynamics of the WP or PCWQM performance. Additional studies are recommended to develop control algorithms that are better suited for interpreting the PCWQM data. As the ISS operational scenarios are better defined, the WRM System control logic should be tested using computer modeling techniques.

The predevelopment urinal functioned effectively in collecting urine and providing pretreated urine to the Urine Processor (UP). Air entrained in the pretreated urine stream created start-up difficulties for the Vapor Compression Distillation-V (VCD-V) though this phenomenon is not expected to be significant in microgravity. The VCD-V was able to produce distillate meeting water quality requirements while incurring no hardware anomalies.

The PCWQM Total Organic Carbon (TOC) and conductivity sensors performed well throughout Stage 9. The iodine and pH sensor data was not consistent with that reported by the Boeing laboratory, requiring a further assessment of these sensors. Gas in the product water led to an inconsistent pH measurement, which subsequently led to erroneous calibration and recirculation modes. The presence of gas in the sample loop also caused channeling which potentially reduced the life of the Solid Phase Acidification (SPA) module.

The PCWQM sample loop experienced a high delta pressure anomaly during the test which raised concern regarding the tubing size in the sample loop and the effect of gas on the PCWQM. The small tubing size (0.040 inch diameter) used in the PCWQM sample loop was at great risk of particulate blockage. Since this was also the suspected cause of failure in the ECLSS Flight Experiment that utilized similar size tubing, analyses should be conducted to ensure particulate contamination does not lead to a PCWQM failure. The high delta pressure anomaly could also have resulted from paste resistant to flow, thus creating a high pressure drop. The effect of gas on the SPA module and the PCWQM pH sensor emphasized the sensitivity of the PCWQM performance to the presence of the free gas in the product water and the need to develop a flight design WP phase separator and validate its performance.

The TOC Monitor Deletion study determined that no correlation can be established between reactor effluent conductivity and on-line product water TOC. The most feasible approach to a real-time assessment of the VRA performance is with on-line TOC monitoring. An alternative approach is batch TOC analysis subsequent to product water generation, though it would not provide water quality verification prior to use. This batch approach accepts the risk that VRA performance degradation will not present a critical safety hazard as a result of product water consumption prior to TOC analysis.

The ISS integration and operational modes simulated in Stage 9 reduced the life of the WP filter. Additional filter surface area will be required to enable the filter to meet the throughput requirement. No measurable impact to the Unibed® life was observed between Stages 7, 8, and 9 with regard to ionic contamination loading. The identical contaminant loading rates achieved in the tests indicated that a shelf life of up to 22 months has no detectable effect on the Unibed® performance.

The VRA reactor transient temperature anomaly was seen in all previous tests at MSFC and was considered unacceptable for the efficient operation of the VRA reactor. Control and heater configuration design changes will be required to eliminate this transient anomaly.

Viral testing was conducted on the WP to verify its ability to meet the ISS specification of <1 Plaque Forming Unit per 100 milliliters (PFU/100 mL). No viruses were detected downstream of the Unibed® train, indicating adsorption of the viruses by the Unibed® adsorbents. The high temperature, oxidation environment of the VRA was expected to provide an additional barrier for the viruses. Based on these results, the ability of the WP to remove viruses from the waste water appeared to be excellent.

The automated operation had no apparent effect on the WP product water quality. On-line PCWQM data detected two phenomena related to the performance of the VRA. First, a TOC spike at the beginning of each process cycle was determined to consist of organics leaching off of the IRN-78 resin located in the ion exchange bed. Replacing the IRN-78 resin with IRA-68 resin could potentially minimize if not eliminate these leachates without impacting the life expectancy of the ion exchange bed. Second, an increase in product water TOC occurred due to a degradation in catalyst performance over the course of a processing cycle. The cause of this degradation appears to be catalyst poisoning due to the slow desorption of oxidation products in the reactor and/or the contamination of the catalyst with compounds that occupy reaction sites without being readily oxidized. Overall, the effect of the TOC rise on product water quality was minimal, though further studies of this phenomenon are recommended to ensure that the WP will be able to reliably produce water meeting the ISS water quality requirements.

4.3 Analytical Model Development

Recycling the water aboard the ISS involves a series of treatment processes to convert waste water to potable (drinking) water. Figure 4.3-1 below is a simplified schematic of the WRM System. It shows the source points for water and the collection bus which feeds into the water processing assembly. The various waste streams treated by the ISS water processor include: 1) urine distillate; 2) waste shower/handwash water; 3) humidity condensing heat exchanger (CHX) condensate; 4) oral hygiene and wet shave waste; 5) mixture of animal condensate and evaporated urine; 6) fuel cell product water; and 7) Extravehicular Mobility Unit (EMU) condensate.

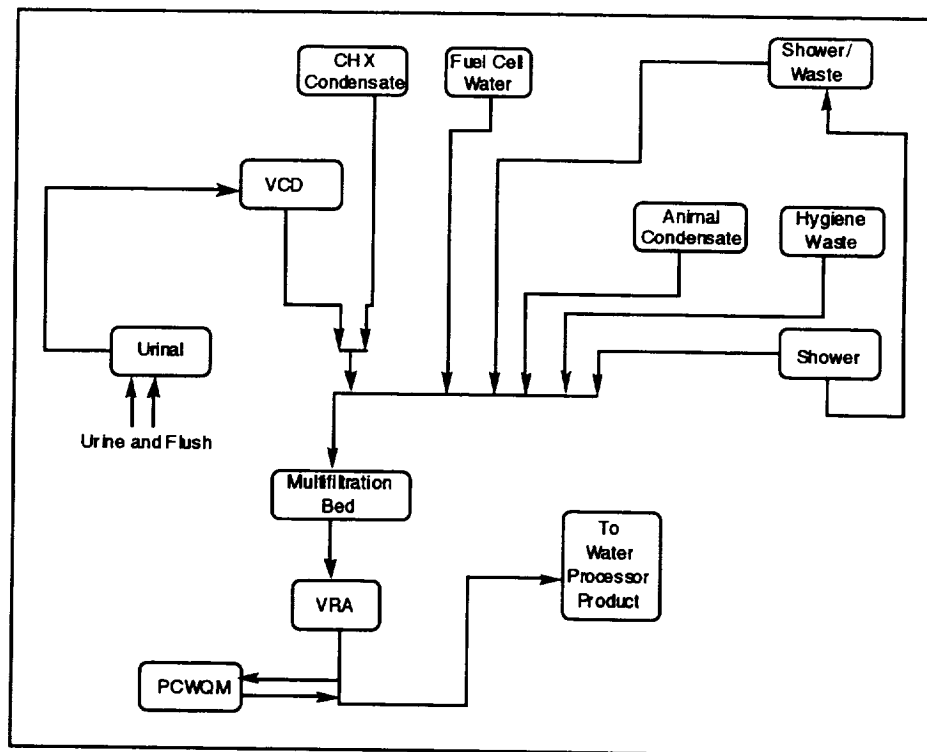


Figure 4.3-1 Simplified Schematic of Water Processing System for ISS

Once the water reaches the water processor bus, it first passes through a 0.5 micron filter to remove particulate matter (dirt, urine particulates, system contamination, etc.). Next in the sequence, ion exchange resins and adsorption media are combined in multifiltration beds (MFB) for removal of ionic and organic compounds. These beds remove specific organic compounds and ion contaminants. Catalytic Oxidation technology incorporated into the VRA follows the MFB to remove low molecular weight organics not efficiently eliminated via MFB adsorption. The water is tested via the PCWQM and, if it meets the defined quality requirements, it is distributed back to the end use points for recycling.

Water Recovery system analytical models are being developed for the water processor multifiltration beds and the VRA reactor. When completed, these computer models will have the capability to predict performance of these components for varying input conditions and thus reduce the amount of testing that is currently required.

4.3.1 Multifiltration Beds ⁶

A schematic of a multifiltration bed is shown in Figure 4.3-2. The MFB model was developed to enable engineers to predict the impact of changing process variables on the performance of the multifiltration bed. The model will also be used to simulate laboratory and pilot scale experiments. Process variables such as the time variable influent contaminant concentrations (including number and type of contaminants), empty bed contact time, sequence of the ion exchange resins and adsorbents (including number and type) within a multifiltration bed or multiple beds, and competitive interactions among ions and adsorbates can be evaluated with the model.

The first phase of testing focused on verification of the model for a surrogate of the waste shower and handwash stream, termed "ersatz" water. An ersatz water was made up to mimic the TOC adsorption capacity of the actual waste shower and handwash water as it exists after exiting the waste tank storage and pre-filter (see Figure 4.2-1). A TOC isotherm was performed to verify that the TOC adsorption capacity of the ersatz water was similar to that of the actual waste shower and handwash water. Once verified as a suitable surrogate in this manner, the ersatz was treated as an unknown mixture for modeling efforts. Waste shower and handwash water is the most prevalent and most contaminated waste stream in the ISS, and contains the component sodium-N-methyl-N-"coconut oil acid" taurate (SCMT) which is "soap" used for hygiene purposes. Consequently, it was assumed that if the performance of the ion exchange and adsorption processes could be predicted accurately for this waste stream using the MFB model, then the model should be able to predict the performance of the MFB in treating other waste water streams or their mixtures. A full scale multifiltration bed experiment was performed using the ersatz shower and handwash waste stream. The combined ion exchange and adsorption model was verified by comparing the model predictions to empirical data.

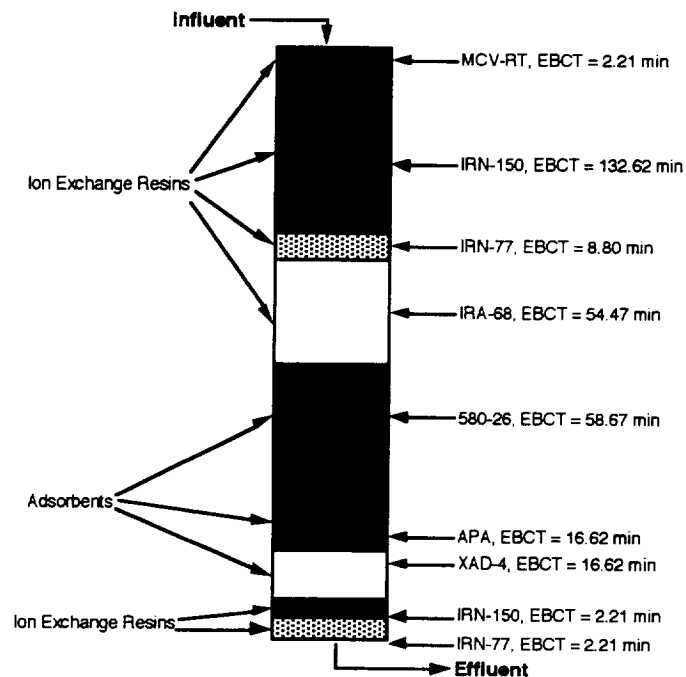


Figure 4.3-2 Multifiltration Bed Schematic

The ion exchange model development includes multicomponent equilibrium as well as external and intraparticle mass transfer. Binary isotherms were conducted to determine separation factors for the ions of interest on each resin. Multicomponent isotherms were conducted and used to validate the multicomponent equilibrium description. Kinetic studies were performed to determine external and intraparticle mass transfer parameters and/or validate the application of literature correlations and validate the multicomponent fixed bed model.

The adsorption model was developed to predict the removal of individual target compounds and TOC from mixtures of unknown composition. The Fictive Component Analysis (FCA) was developed to describe the competitive interactions between individual known target compounds and the unknown background matrix making up the overall mixture TOC concentration. TOC and known individual target compound isotherms were performed on all the adsorbents and used to determine the Fictive Component (FC) concentrations. Column studies were performed on all the adsorbents and compared to model calculations to obtain intraparticle mass transfer correlations for the wide range of adsorbing contaminants expected in the ISS waste stream and to verify the fixed bed model.

The multifiltration bed model was designed for the Microsoft Windows™ environment with a Graphical User Interface (GUI) to maximize user-friendliness. The Microsoft Windows interface was used because of its built-in file and hardware control features which frees the analyst from concerns over printer drivers and other machine issues and allows more attention to the computational algorithms. The GUI consists of a front-end shell written in Visual Basic™ (Trademark Microsoft Corporation 1981 - 1995, All rights reserved) that calls Formula Translator (FORTRAN) computer program language subroutines in order to perform calculations.

4.3.1.1 Ion Exchange Modeling

Ion exchange resins are insoluble matrices containing fixed charged sites which exchange ions for aqueous phase ions. The main types of ion exchange resins are natural mineral ion exchangers, synthetic inorganic ion exchangers, and synthetic organic ion exchangers. The resins investigated in this work are synthetic organic ion exchange resins which are comprised of polymer chains crosslinked with divinylbenzene (DVB). Fixed functional groups contained within the matrix provide charged exchange sites as shown in Figure 4.3-3. Ion exchange resins have been compared to a plate of spaghetti (polymer chain) cooled to the point of sticking (crosslinking) together.

The fixed exchange sites can be positively charged (anionic exchange resins), negatively charged (cation exchange resin), or amphoteric (capable of exchanging both cations and anions depending on pH). Ion exchange resins are grouped by their functional exchange site characteristics. Ion exchange resins can be strong or weak: strong acid cation (SAC); weak acid cation (WAC); strong base anion (SBA); or weak base anion (WBA). This distinction is based on the functional pH ranges of the resins.

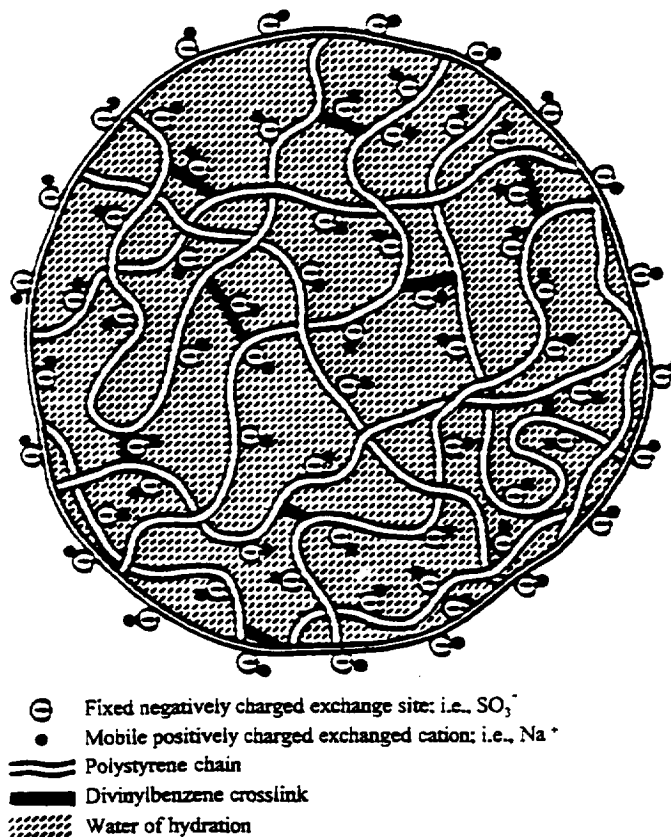


Figure 4.3-3 Schematic of Hydrated Strong Acid Cation Resin

The total number of exchange sites per unit of resin is the total exchange capacity and is independent of the experimental conditions. The apparent capacity depends on experimental conditions, such as pH and solution concentrations, and is usually lower than the total capacity. The capacity of a resin also depends on the presaturant ion such as hydrogen or sodium since the density is different for each form of resin.

Total resin capacities and physical properties for each of the resins were experimentally determined. Fitted apparent capacities were also determined using the binary Langmuir equation. Both the total capacities and apparent capacities are comparable to the reported manufacturer's capacities.

Binary isotherms were performed on SAC (IRN-77), SBA (IRN-78), WBA (IRA-68), mixed bed (IRN-150), and iodinated (MCV-RT) ion exchange resins. Separation factors/equilibrium exchange constants for IRN-77, IRN-78, and IRA-68 resins were determined from the binary isotherms. The separation factors for the IRN-77 and IRN-78 resins were able to describe equilibrium for the IRN-150 resin by coupling the water formation reaction with the binary Langmuir equilibrium expression for each ion.

When the separation factors determined from binary isotherms were used, the multicomponent Langmuir equilibrium expression predicted six-component isotherm data for the IRN-77 and IRN-78 resins. The multicomponent predictions were within approximately 10% error for liquid phase predictions and approximately 50% for solid phase predictions.

A multicomponent isotherm with the IRA-68 resin was conducted to validate the Langmuir multicomponent equilibrium description for WBA resins. The preliminary model calculations showed promising results. However, more multicomponent equilibrium experiments are needed to verify the multicomponent Langmuir equilibrium expression for WBA resins.

The Langmuir multicomponent equilibrium expression was able to predict the ion exchange in the ersatz water for IRN-77 resin, but overpredicted the amount of ion exchange for the IRN-78 resin. The separation factor determined for SCMT could be underpredicted, or fouling of the anionic resin by the negatively charged SCMT and organic contaminants may have caused the observed decrease in resin capacity.

The ersatz isotherms with IRN-77 did not indicate resin fouling. Fouling of SAC resins by organics, especially by polar and anionic organics, is not usually a problem because the functional groups of SAC resins are negatively charged. The ammonium ersatz isotherm data for IRN-77 resin showed an increased resin capacity for ammonium. A decrease in competition or an increase in capacity could account for this observation. It is possible that binding to soap (SCMT), present in the ersatz water, could decrease the liquid phase concentration of ammonium causing an apparent increase in solid phase concentration.

4.3.1.2 Adsorption Modeling

The fixed bed adsorption model includes multicomponent equilibrium and both external and intraparticle mass transfer resistances. Single solute isotherm correlations were developed to predict single solute isotherm parameters for the components of interest. The single solute isotherm parameters were used in the multicomponent equilibrium description to predict the competitive adsorption interactions occurring during the adsorption process. Multicomponent isotherms were used to validate the multicomponent equilibrium description. Column studies were used to develop and validate external and intraparticle mass transfer parameter correlations for components of interest. The fixed bed model was verified using the shower/handwash ersatz water.

There were two overall objectives for the MFB adsorption model. The first objective was to predict the performance of the adsorption beds in series in the MFBs for removing TOC from the shower and handwash waste water. The second objective was to predict the removal of target compounds in the MFB.

The fixed bed model used in this study assumed both pore and surface diffusion were intraparticle transport mechanisms and plug flow was the axial transport mechanism. It is named the Pore and Surface Diffusion Model (PSDM). Figure 4.3-4 illustrates the adsorption and diffusion mechanisms incorporated into the PSDM.

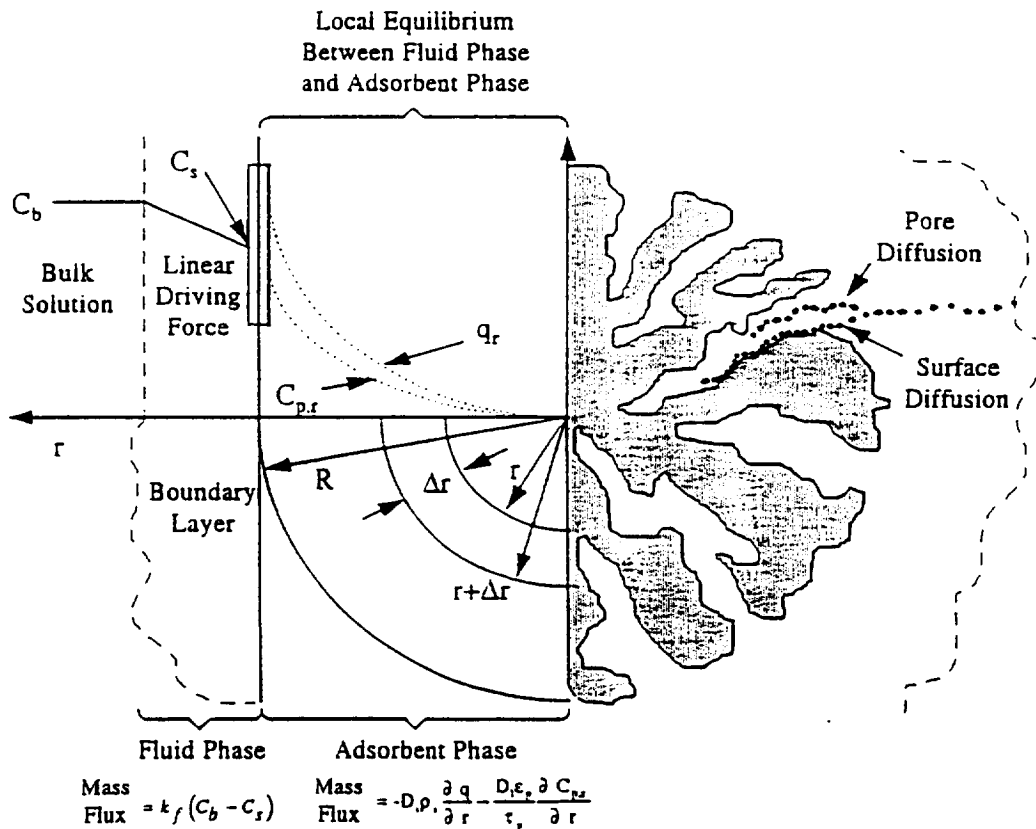


Figure 4.3-4 PSDM Mechanisms

The assumptions and mechanisms that are built into the model are:

- Plug-flow conditions exist in the bed (axial and radial dispersion are neglected).
- The hydraulic loading is constant.
- Single solute adsorption equilibrium is represented by the Freundlich isotherm equation.
- Ideal adsorbed solution theory incorporating the Freundlich isotherm equation describes the multicomponent adsorption equilibrium.
- Local adsorption equilibrium exists between the solute adsorbed onto the adsorbent particle and the solute in the intraparticle stagnant fluid. (The rate of sorption onto the adsorbent surface is much faster than the diffusion rate.)
- A linear driving force approximation describes the liquid-phase mass transfer flux at the exterior of the adsorbent.
- Intraparticle mass flux is described by surface diffusion and/or pore diffusion.
- There are no solute-solute interactions during the diffusion and/or pore diffusion.

A fixed bed adsorption model employing the FCA was developed for use in modeling the adsorption processes within the Space Station MFB. This modeling approach was chosen because it can predict the TOC breakthrough as well as target compound breakthrough from the MFB in an unknown mixture. The modeling approach was verified using the shower/handwash ersatz water.

The three adsorbents currently included in the MFB design were evaluated in this study. Those adsorbents were 580-26 GAC, APA GAC, and XAD-4 resin. The waste shower and handwash ersatz water included SCMT, trichloroethylene (TCE), toluene, m-xylene, 1,2,4-trichlorobenzene (TCB), and naphthalene as its adsorbable components. These components represent a distribution of weakly to strongly adsorbing compounds. SCMT was included since it is reported to account for over 60% of the TOC in the actual waste shower and handwash water. The ersatz water also contained ions representative of the actual waste shower and handwash water.

Single solute isotherm data was available for each of the adsorbates in the ersatz water on each of the MFB adsorbents. The isotherm data was obtained over a concentration range of approximately 10 micrograms per liter ($\mu\text{g/L}$) to 10 milligrams per liter (mg/L) and described using the Freundlich isotherm equation. The isotherms on the 580-26 and APA activated carbons were all linear on a log-log plot and the Freundlich equation fit the data well. The single solute isotherm on the XAD-4 resin exhibited some curvature on a log-log plot. For this reason, the XAD-4 resin Freundlich parameters were dependent on the concentration range fit.

The single solute isotherm data for each adsorbent was correlated using the Polanyi theory. Polanyi correlations were developed for each adsorbent using the molar volume of the compound as the correlating physical parameter, and the compound's aqueous solubility was used in determining the adsorption potential. The data was correlated so that Freundlich isotherm parameters for compounds other than TCE, toluene, m-xylene, 1,2,4-TCB, and naphthalene could be estimated. The error in the correlation could possibly be removed by refining the correlation for different compound classes. The use of different physical property correlating factors (other than molar volume) could also result in a better correlation.

A TOC isotherm was performed on the actual waste shower and handwash water to determine its TOC adsorption capacity. The isotherm revealed, as expected, that the waste shower and handwash water was a multicomponent mixture with a nonadsorbing TOC fraction. Unfortunately, this was the only isotherm data obtained for the actual waste shower and handwash water.

Isotherms were performed on each of the adsorbents using the ersatz water. The isotherms were analyzed for TOC and the individual constituents of the water. The FCA was applied to this isotherm data to determine the TOC and tracer FC for each adsorbent. The FCs were determined from fitting the isotherm data in a manner which would facilitate beds in series modeling of the different adsorbents. The FCA was able to accurately fit the TOC isotherms for each of the adsorbents. This indicated that the TOC FC used in Ideal Adsorbed Solution Theory (IAST) calculations accurately simulated the TOC adsorption capacity of the ersatz water.

The FCA was also able to fit the tracer isotherms well for each of the adsorbents. The tracer FCs were tested in IAST calculations to see if the equilibrium of the other ersatz water constituents could be predicted based on the tracer fit. The results indicated that as the adsorbability of the compound increased, the accuracy of the model prediction to the data decreased. The model generally did a good job of predicting the equilibrium for TCE, toluene, and m-xylene. The equilibrium description consistently over predicted the reduction in capacity for 1,2,4-TCB, naphthalene, and SCMT in the system. It was likely that the reduction in capacity was observed for naphthalene and 1,2,4-TCB since the strongly adsorbing compounds were already accounted for in the mixture by the FC because a weakly adsorbing compound was fit. The reduction in capacity for SCMT was overpredicted because SCMT made up such a large percentage of the overall TOC of the mixture. A component must make up a small amount of the TOC in the mixture because its adsorption potential is already accounted for by the FC. The fits and predictions were more accurate for the XAD-4 resin than for either of the activated carbons.

Column experiments were performed on each of the adsorbents using the ersatz water. The breakthrough curves for each of the known ersatz water constituents were fit on a single solute basis using the PSDM to determine the optimum fluid residence time in the packed bed and the surface to pore diffusion flux ratio (SPDFR) for each compound. The fitting results were used to develop correlations for prediction of fluid residence time in the packed bed and SPDFR for other target compounds on each adsorbent. The results indicated that pore diffusion was the controlling mass transfer mechanism for both 580-26 and APA GACs. Surface diffusion was approximately 5

times more important than pore diffusion in describing the mass transfer for the XAD-4 resin. The mass transfer parameter correlations were used to predict the mass transfer parameters for the FCA.

The TOC FCs were used in the PSDM to predict the TOC breakthrough from each of the adsorption columns. The results indicated that the model slightly overpredicted the capacity of the columns for TOC adsorption. The model calculations involved using the 6 TOC FCs determined from fitting the TOC isotherms in fixed bed calculations.

The tracers FC were used in the PSDM with the known constituents of the ersatz water to predict breakthrough of those compounds. The model calculations used the target compound and the 5 tracer FCs determined from fitting the tracer isotherms in fixed bed calculations. The results were then compared to the experimental data to test the model. The model predictions were best for the weakly to moderately adsorbing compounds. As the strength of the adsorbing compound increased, the accuracy of the PSDM prediction consistently decreased. This is due to the mass transfer parameters and tracer FC used in the system. The mass transfer parameters and tracer FC could be tuned to better predict the breakthrough of the stronger compounds.

One experiment was performed using a series of adsorbents and ion exchange resins set up in the same configuration as the actual MFB design. This experiment was also performed with the ersatz water. The breakthrough of TOC and target compounds from the verification MFB was predicted with the fixed bed model and compared to the breakthrough data. The model predicted the TOC breakthrough slightly before the experimental data. The model did a good job of predicting the SCMT breakthrough. The breakthrough prediction began slightly after the data but was steeper than the data indicating that the mass transfer parameters used for the SCMT could use some fine tuning to get a better prediction. The model predicted TCE breakthrough occurred about 15% earlier than the data. The error appears to be due to the mass transfer parameters. The predicted breakthrough of toluene is significantly later than the experimental data. However, it is difficult to determine if the error is due to mass transfer parameters or capacity since only part of the breakthrough curve was observed during the experiment. The error in the MFB verification column predictions may have occurred since the SCMT was held up for some time period in the ion exchange resins but it was not held up in the experiments where the mass transfer parameter correlations were determined. This error could be corrected by tuning the mass transfer parameters for this situation. These results have shown that the FCA used in conjunction with the PSDM can predict breakthrough of both TOC and target compounds from the MFB. However, this verification was only on ersatz water.

4.3.2 Volatile Removal Assembly Reactor ⁷

Recovery of waste water streams for potable use onboard space-based installations, such as the ISS, is paramount for long term missions in space. Although carbon adsorption and ion exchange can remove a majority of the pollutants in such streams, weakly adsorbing organic compounds must still be removed to make the water potable. One method of removing these organic compounds is via catalytic oxidation. A catalytic reactor system known as the VRA was designed to perform such an operation. The VRA is a co-current bubble column which uses gas-phase oxygen as

the oxidant over a catalyst consisting of a noble metal on an alumina substrate. In Earth-based testing, the VRA is run in an upflow mode. In zero gravity the gas phase will be moved only under the influence of the water's drag forces. Therefore, the residence time of the gas and liquid phases may be slightly altered. Before the design and operating conditions for the VRA are finalized, a numerical model incorporating mass transfer, contacting patterns, and the multicomponent reaction kinetics should be developed and tested to predict the reactor's performance.

Heterogeneous catalysts can be used effectively in oxygen purged packed bed reactors to remove aqueous organics at elevated temperatures. Conversions of formic acid are quite high in a trickle bed reactor and ethanol can be readily oxidized to acetic acid in either an upflow or downflow packed bed reactor. Numerous studies have been reported for oxidation of single components through packed beds, mostly in downflow trickle bed reactors. A thorough review revealed no studies on the multiphase oxidation of multicomponent streams. A small number of studies were found on the mass transfer characteristics of co-current upflow packed bubble columns (also known as flooded bed reactors). The extension of earlier models to a multicomponent mixture and the determination of the necessary parameters are described in the following.

A flooded bed reactor is a reactor in which a continuous liquid phase and a disperse gas phase flow co-currently through a fixed bed of catalyst particles while the reaction takes place. The rate at which this reaction occurs is a function of the mass transfer rates for the reactants, internal (pore) mass transfer, and the actual surface reaction rate. Figure 4.3-5 represents the external mass transfer processes occurring for a single catalyst particle within the reactor. Figure 4.3-6 shows a schematic diagram of the bench scale reactor system.

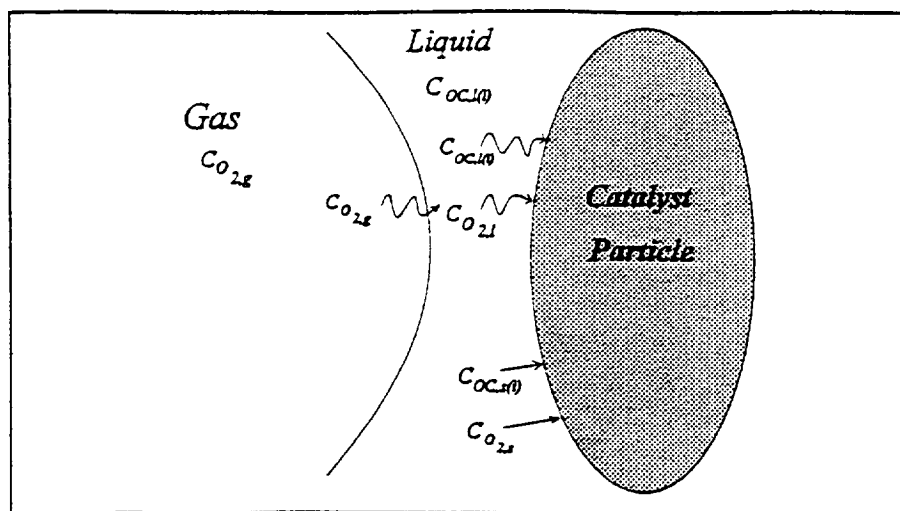


Figure 4.3-5 Mass Transfer Process for a Single Catalyst Particle

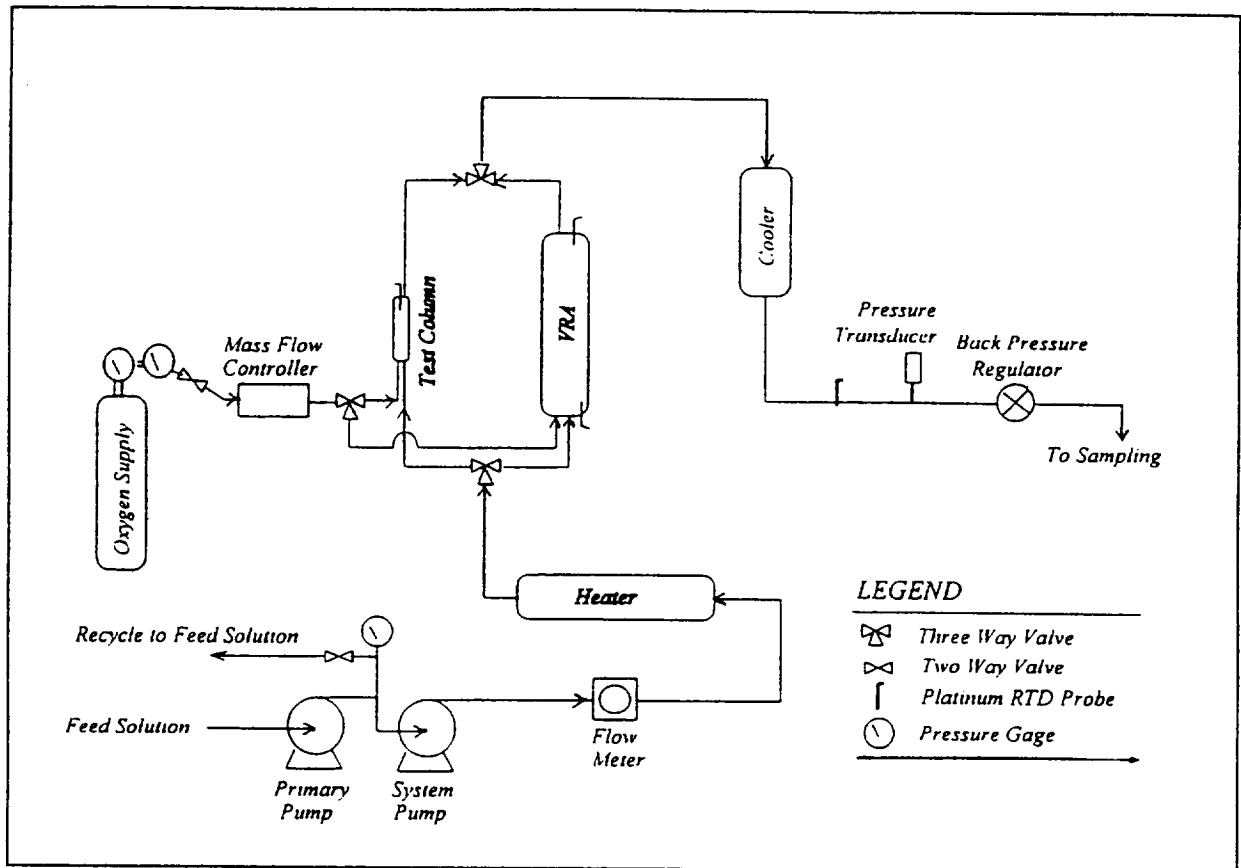


Figure 4.3-6 Schematic Diagram of Bench Scale Reactor System

As the continuous phase, the liquid generally covers the catalyst particle. The gas phase (in the form of bubbles) forces its way between the liquid covered particles. The key steps in the mass transfer process are the transfer of the reactant (oxygen) from the gas to the liquid and of all the reactants from the liquid to the catalyst particle surface. The other reactants in the aqueous phase are the dilute aqueous organic contaminants (OC). The basic transport and reaction steps in this three phase reaction are as follows: (1) transport of oxygen from the bulk gas phase to the gas-liquid interface; (2) equilibrium partitioning of oxygen at the gas-liquid interface; (3) transport of oxygen from the interface to the bulk liquid; (4) transport of the OC and oxygen from the bulk liquid to the catalyst surface; and (5) diffusion and reaction of the reactants inside the catalyst pellet.

By taking the 5 basic transport and reaction steps into account along with an appropriate reactor model, the behavior of a flooded bed reactor can be determined. To derive an appropriate model to describe the flooded bed reactor, primary simplifying assumptions are made as:

- Isothermal reactor operation - Since the concentration of the contaminants is very low, the heat generated by the oxidation reactions has a negligible effect on the water temperature.

- Axial dispersion in the gas phase is negligible - The bubbles would tend to move forward as self-contained units. Little backmixing would be possible.
- Conditions are uniform in the radial direction - The liquid is evenly dispersed in the radial direction, and there is no "channeling".
- Gas and liquid flow rates are constant throughout the reactor - This is the standard steady state assumption (no accumulation).
- Mass transfer resistances in the gas phase are negligible so that equilibrium exists at the gas-liquid interface - The diffusion rate in the gas phase is several orders of magnitude higher than the liquid phase.

Axial dispersion models take into account the diffusion of the components in the axial direction, whereas plug flow models typically assume axial dispersion is negligible.

A multiphase, multicomponent reactor model was developed for the oxidation of dilute contaminants in water. Over the range of temperatures and flow rates examined, the experimental data for the destruction of chlorobenzene, ethanol, dimethylsulfoxide (DMSO), formaldehyde, and urea were used to calculate the single component overall reaction rate constants. The resulting data for each compound was fit to the Arrhenius equation and the individual activation energies determined. The activation energies obtained for the raw catalyst fell within the range which is generally ascribed to pore diffusion limited for ethanol, external mass transfer limited for formaldehyde and chlorobenzene, and surface reaction limited for urea and DMSO. By running the experiments at different particle sizes, it was possible to qualitatively identify that the bigger catalyst size is largely internal mass transfer limited, and this is directly lumped into the overall rate constant determined.

The multicomponent plug flow model developed was applied to a five component mixture and gave predicted results close to actual experimental results for urea, chlorobenzene, and ethanol over the range of conditions. The deviations between the model and experiments were well within the range of experimental error. The results for formaldehyde showed the reaction rate to be determined totally by the rate of mass transfer. DMSO has been determined to be a weak catalyst poison, and as a result the conversions were always lower than predicted, which may affect the results for other compounds. By incorporating the appropriate mass transfer correlations and scale up parameters, this model allowed the testing of other reactor configurations and contaminant mixtures.

4.4 Life Testing

4.4.1 Subassembly Life Testing

4.4.1.1 Urine Processor Assembly ⁸

The purpose of the test is to provide for long duration operation of the VCD ECLSS subsystem at normal operating conditions to determine the useful life of ECLSS hardware. A complete VCD subsystem is being tested to determine life characteristics of mechanical components under actual on-orbit conditions.

The VCD Urine Processor Assembly V A (VCD-V A) is a phase-change water recovery subsystem developed for space application to reclaim water from urine and other Space Station waste waters. The VCD process recovers the latent heat of condensation by compressing the water vapor to raise its saturation temperature and pressure, and then condenses it on a surface that is in thermal contact with the evaporator. The resulting heat flux from the condenser to the evaporator, driven by this saturation temperature difference, is enough to evaporate an equal mass of water from waste water so that the only additional energy required is that necessary to compress the water vapor and overcome any mechanical and thermal inefficiencies.

A simplified schematic of the VCD-VA is shown in Figure 4.4-1. The waste water is circulated through the distillation unit by a four section peristaltic fluids pump. The feed section of the pump discharges waste water to the inner surface of the evaporator drum (still) at a higher rate than the distillation rate. The vapor is first compressed and then condensed. The condensate is collected in the condenser, pumped out of the distillation unit, and passed through a conductivity sensor. Unacceptable water, that does not meet conductivity specifications, is routed back to the recycle loop for reprocessing. Good quality condensate is delivered as product water. Excess waste water feed is returned through a recycle filter tank by the second and third sections of the fluids pump. Having two pump sections pumping water out assures the rate out is always greater than the rate in, which avoids flooding the still.

The condenser/evaporator drum is rotated by a brushless direct current (DC) motor, by way of a magnetic coupling, to maintain the fluid evaporator liquid/vapor interface in microgravity. The entire evaporation/compression/condensation process takes place at a lower than normal temperature by operating the subsystem at near vacuum. Periodically, a purge valve is activated to remove noncondensables (gases) from the condenser.

The VCD design has continued to evolve over 20 years. Since it was first introduced, changes and improvements have included changes in the peristaltic fluids pump, various improvements on sensor hardware, changes in the shape of the distillation unit to a tapered drum, and improvements to the compressor. The materials used have been upgraded to withstand the harsh environment in which the subsystem must operate.

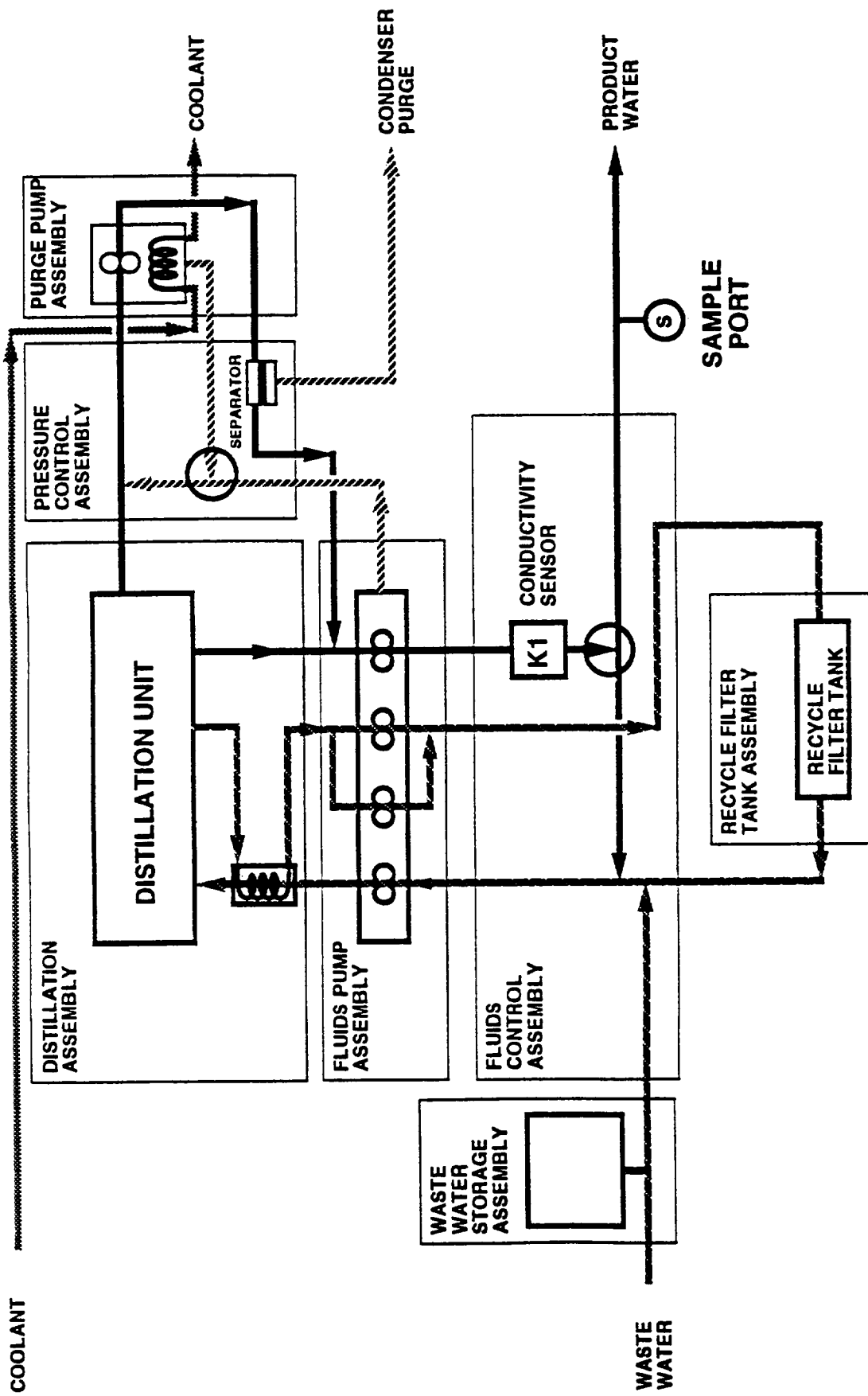


Figure 4.4-1 VCD-VA Simplified Schematic

According to the established procedure, the VCD-VA is run approximately 6 hours a day during scheduled workdays. The VCD-VA has continued to run well throughout Life Testing and has provided useful data on the wear and tear of components. A summary of VCD life test anomalies is provided in the following paragraphs.

The fluids pump failed after 51 days of testing. The failure was determined to be similar to that which occurred during checkout at the hardware supplier. A flex spline in a gear reduction mechanism of the fluids pump drive shaft failed in both cases. It was determined that the failure may have resulted from a slight horizontal misalignment introduced into the pump during retrofit at the hardware vendor. The hardware supplier has implemented use of a new alignment jig during hardware assembly to provide the proper alignment. This jig will be used for flight hardware assembly.

A second pump problem was related to the tubing used in the peristaltic purge pump. This pump uses the same tubing as the fluids pump although it pumps a two-phase mixture which is mostly gas. This application was found to cause tube spalling which results in the air/water separator to become clogged with tube material flakes. The initial resolution suggested by the hardware supplier was to add a filter downstream of the pump to prevent air/water separator clogging; however, there are other design solutions such as alternate tubing material. Eventually, modifications to the VCD will be made which will include the appropriate design change. An inspection of the air/water separator is made every 30 days to avoid build up of materials.

During the last half of 1995, the VCD-VA experienced increasing problems such as excessive noise, increasing temperature, and high current loads. Also, slippage of the drum at startup was occurring more often. To correct the problems and to determine which parts were wearing out, the VCD-VA was disassembled for repairs, which were completed during the week of January 15, 1996.

The following conditions were noted upon disassembly of the VCD-VA:

- An o-ring seal was missing between the condenser end plate and the drum. There was no indication of liquid leakage, however, so the metal-to-metal contact apparently provided a good seal.
- Some slight corrosion was evident between the condenser end plate and the drum spokes.
- The urine injection tube had a small "blob" of solids (1/8" to 1/4" thick) around the end of the tube. This material was hard and was removed as a "chunk". The opening of the injection tube was not restricted.
- The compressor gears showed some wear, with a gap of 0.013" to 0.0165" rather than the desired 0.006", but there were no chips or missing teeth. There was a coating of vespel lubricant dust on components of the pump. Examination under a microscope also showed metallic particles on the vespel gear.
- The drive belt from the compressor to the drum was stretched about 14%.

The compressor gears had operated for an estimated 4831 hours, and the drive belt for a similar length of time. The condition of the gears and drive belt indicates that they had reached the end of their useful life and they were replaced. Upon reassembly and startup the VCD-VA showed unusual behavior and shut down after about one hour. The unit was restarted and operated as expected. The problem reappears after a period of no operation (such as over a weekend). Investigations are continuing to determine the cause of the problem and the best solution.

4.4.2 Microbial Check Valve ⁹

The Microbial Check Valve (MCV) is intended for use on the ISS in the water processor recycle loop, and will provide a microbial barrier to that portion of the water recovery system. A life test will provide information which will help lead to the most economical MCV replacement scenario on the ISS.

Four MCVs will be used in the test. The first three will be used in the water circulation portion of the test, and a fourth will be placed on the shelf, in the vicinity of the water circulation test, for shelf life testing. Water will be circulated through each of the first 3 MCVs daily (five days per week), for three years, or until all three of the MCVs fail.

Due to unexpected regulatory concerns from the Environmental Protection Agency (EPA), the project was suspended pending EPA approval.

4.4.3 Water Distribution Plumbing ¹⁰

The need for the Water Degradation Study (WDS) originally stemmed from the 1991 Space Station restructure baseline design which called for the water lines to be launched wet and to be undisturbed until the activation of the water recovery and management system for an extended period of time. This "launch-wet-and-wait" scenario fueled concern over whether the biocidal iodine would break down during extended storage, leaving the distribution lines vulnerable to microbial growth, biofouling, and microbial-induced corrosion. These concerns prompted engineers and scientists to investigate the change in water quality under long-term storage conditions.

The WDS is being conducted as an engineering demonstration activity. As a demonstration, the study emphasizes geometric and material similarity with space station water distribution lines. Because the test fixtures are relatively expensive, the budget for this activity has precluded the use of replication. The WDS lends credibility to its results by allowing comparisons among tubes of similar material, initial water quality, or exposure time.

The WDS consists of a total of 34 tubes that are configured as straight sections, 10 feet long, with valves at each end as illustrated in Figure 4.4-2. These tubes are grouped into two batches, designated Batch 1 and Batch 2. Within each batch, the tubes are grouped into sets according to exposure time. All tubes are stored vertically in a rack until their exposure time is completed.

Thus far, the WDS has clearly demonstrated that it is possible to store water in a stainless steel or titanium distribution system for up to 3 years without significant levels of microbial growth. The WDS has shown that the microbial integrity of the water can be maintained even after iodine depletion, if the quality of the water and tubes are carefully controlled during the filling. Although some parameters, such as pH, conductivity, iodine, iron, nickel, and TOC have been shown to violate their specified limits during extended storage, the absence of biofilm growth would enable the lines to be ready for use following a simple flushing operation. Furthermore, the WDS suggests that the water flushed from the system would be easily reconditioned by the space station's water processor for use as potable water.

Data from the WDS suggests that there is an interaction between iodine and nickel that results in depletion of up to 10 parts per million (ppm) iodine within 3 to 6 months. Viewed another way, the WDS suggests that an initial iodine concentration of 10 ppm may be insufficient to maintain iodine levels above the specified 2 ppm minimum for any extended period of time. Of course, if iodine is indeed being consumed through some interaction with stainless steel or with a nickel-rich lubricant, avoiding these materials could increase the longevity of biocidal iodine in the distribution lines. Results from batch 2, expected in early 1996 and 1998, should provide insight into iodine longevity in an all-titanium system without the nickel-rich valve lubricant.

Despite the rapid decrease in iodine concentrations, no bacterial growth has been detected in the water stored in the tubes. Extremely low levels of bacteria were isolated on only four samples with no correlation between the occurrences. These events could possibly be attributed to contamination during sampling or sample handling due to the nature of the bacteria that were isolated, common organisms found in the environment. The early depletion of iodine suggests that optimization of the initial iodine levels may be needed to maintain an active biocide concentration in a "launch-wet-and-wait" scenario.

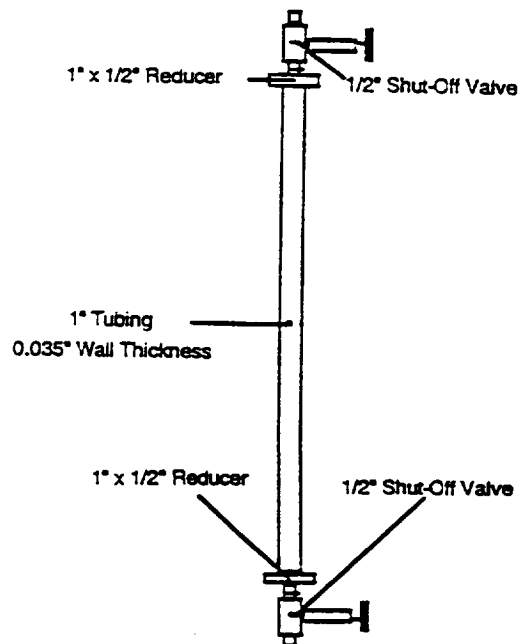


Figure 4.4-2 Tube Configuration

4.5 ECLSS Flight Experiments

4.5.1 Vapor Compression Distillation Preliminary Design ¹¹

The VCD Waste Water Processor (WWP) technology was selected for use as the Urine Processor Assembly (UPA) for the SSF as a result of performance demonstrated during the Comparative Test conducted at the MSFC in 1989 and 1990. Following selection, the design process continued through a Space Station Critical Design Review (CDR) which was held in August 1994.

Following completion of the Space Station CDR, the UPA was placed on hold as a result of the restructure of the Space Station program from SSF to ISS. The new schedule for the restructured program called for a delay in the completion of the UPA with work not restarting until October 1997. As a result of this delay an opportunity was created to conduct a flight experiment that would provide a means by which operation of the technology in zero gravity could be demonstrated and the risks of its ISS future use greatly reduced.

The VCD Flight Experiment was developed in a two step process. The first step (funded by the Space Station Program Office under TTA's), the Preliminary Design Study, was to produce a design that could be implemented in either the SPACEHAB, Spacelab, or Russian MIR flight vehicles. As work progressed the flight vehicle was identified to be the SPACEHAB. Therefore, the design documentation focused on the experiment being performed on the SPACEHAB flight vehicle. The second step (funded by NASA Headquarters Code U) will be the completion of the final design through the flight and flight data interpretation.

The VCD WWP concept is illustrated in Figure 4.5-1. The concept uses a phase change process to efficiently recover product water from waste water feed. A key characteristic of the process is the recovery of the latent heat of condensation from the product water. This recovery is accomplished by compressing water vapor to raise its saturation temperature and then condensing it on a surface which is in thermal contact with the evaporator. This results in heat transfer from the condenser to the evaporator. To achieve phase separation in microgravity, the evaporator/condenser and product water collector are rotated. This imparts sufficient centrifugal force on the fluids to achieve phase separation.

The primary focus of the VCD Flight Experiment is subsystem performance. NASA has recognized the need for water recovery from waste water and has been developing VCD WWP technology for space applications since the early 1960s. Key aspects of VCD WWP technology have been verified with over tens of thousands of hours of testing. Significant improvements have been made in water production rates, water quality, specific energy, pump designs, packaging, maintainability, and Control/Monitor Instrumentation (C/MI) throughout the development history. However, an important element lacking from previous subsystem development efforts is actual flight testing. Consequently, important goals of the VCD Flight Experiment are the demonstration and validation of the VCD WWP technology, as well as the investigation of system performance, in microgravity.

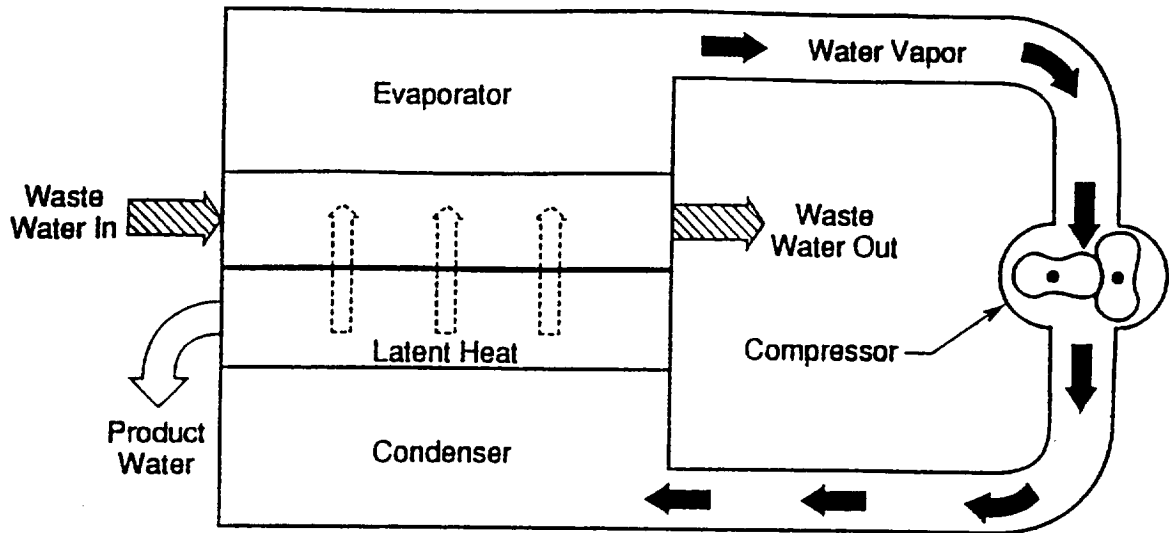


Figure 4.5-1. VCD Concept

To achieve the goal of abating or avoiding problems associated with integrating VCD WWP hardware onboard ISS, a flight experiment utilizing a full-sized VCD Waste water Recovery System must be conducted. The VCD WWP and associated experiment support equipment should reflect, to the maximum extent possible, the design of VCD WWP hardware currently developed and intended for use aboard the Space Station.

The following are the general objectives of the VCD Flight Experiment:

- Verify the readiness of VCD WWP technology for utilization in space, including the validation of; VCD waste water processing concept, interaction of components and parts, quality and quantity of product water, and efficiency of the VCD WWP process.
- Verify ground-based analyses of the VCD WWP components and processes. Include the validation of; VCD WWP components sensitivity to the launch environment, and VCD WWP components and processes sensitivity to the microgravity environment on an integrated basis.

Specific flight experiment objectives which support these general objectives are:

- Verify integrated hardware operations. This includes evaluating the water production rate, water quality, power consumption, dynamic loads, all possible mode changes, free/entrained gas addition at various rates, and dry system start-up with evacuated recycle filter tank.
- Characterize waste water droplet/film behavior during normal start-up and shutdown, during normal operation, during emergency (e.g., power loss) shutdown and restart, and during shutdown following emergency shutdown.
- Examine the effects of precipitates in recycle filter tank.
- Confirm gas/liquid separator performance.

Concentration on these specific objectives will identify operational risks, problems, or anomalies which may impact actual implementation of the VCD WWP in space operations.

The objectives of the Preliminary Design Program were to define the experiment test plan that, if successfully performed, accomplishes the program objectives stated above; and to develop and document a design through a Preliminary Design Review (PDR) that can be efficiently implemented into hardware and qualified for flight that can implement the specified experiment test plan.

The VCD Flight Experiment will provide extensive data, that when compared to Earth-based test data, will verify the readiness of VCD WWP technology for application to ISS or other long-duration missions. The successful implementation of the PDR shows that a VCD Flight Experiment can be implemented within the resource constraints of the available flight vehicles that will accomplish the program goals. Figure 4.5-2 presents a photograph of the VCD Flight Experiment Mockup.

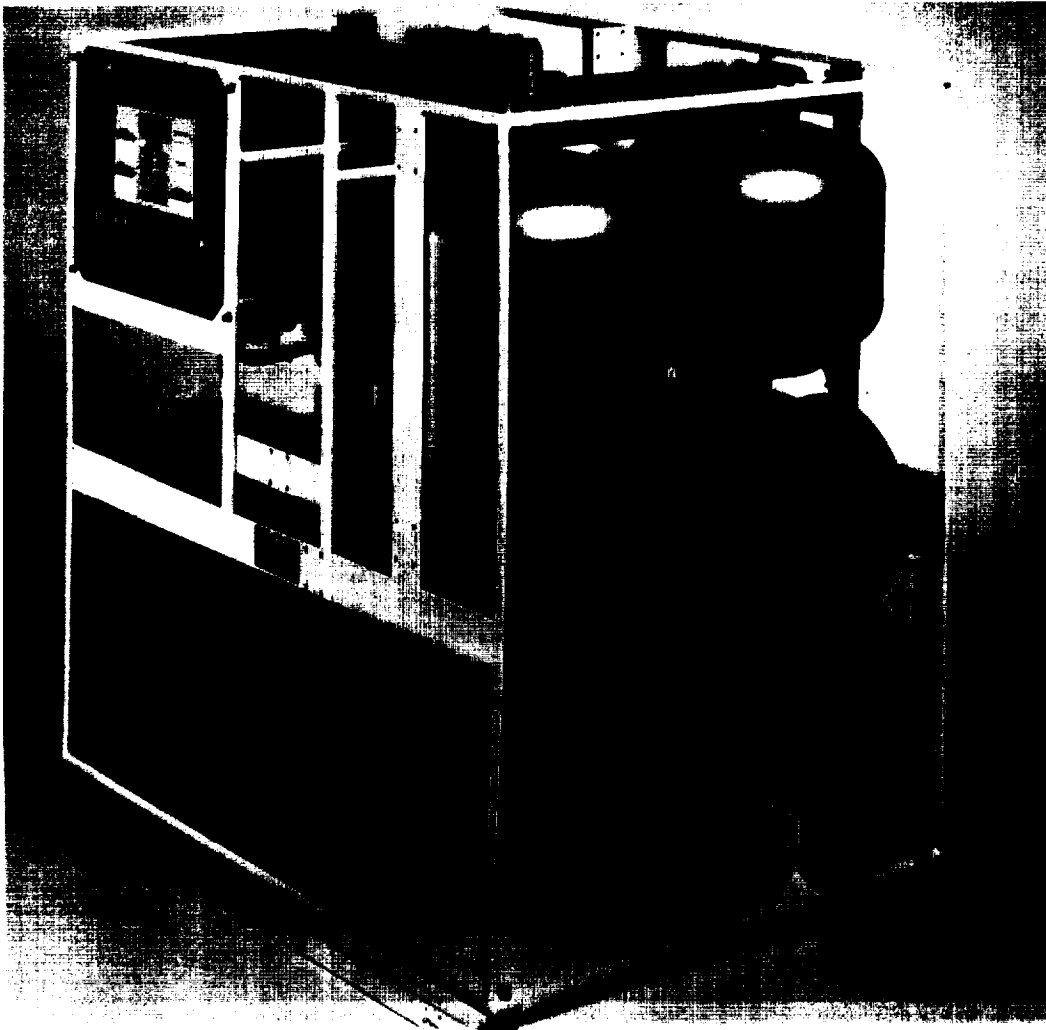


Figure 4.5-2 VCD Flight Experiment Mockup

4.5.1.1 Enhanced Urine Ersatz Development ¹²

The VCD Flight Experiment was designed to investigate critical issues associated with operating a VCD-based waste water processor under microgravity conditions. The goal of the VCD Flight Experiment was to minimize future development and implementation risks by evaluating the microgravity sensitivity of the VCD waste water processor components on an integrated basis. The experiment will verify the readiness of this technology for use in space and substantiate planned closed-loop water recovery for ISS.

Two approaches were used in deriving the chemical formulation of the process fluid: (1) development of a synthetic urine ersatz based upon the composition of raw human urine; and (2) use of reconstituted (diluted) concentrated pretreated human male urine as the process fluid. The concept of using a synthetic urine ersatz was aborted due to potential biological degradation and the absence of precipitated solids in concentrated solutions. Preliminary results (i.e., surface tension, density, conductivity, and precipitation characteristics) of the reconstituted concentrated pretreated urine justified its selection as the process fluid for the VCD Flight Experiment. Hence, concentrated pretreated urine at 0.15 grams solute/gram solution (solute weight fraction) was recommended as the process fluid stock solution.

Standard laboratory benchtop tests demonstrated that the physical characteristics and physical properties of the approved fluid conform with the NASA specifications. Specifically, it was capable of providing waste water carryover via conductivity measurements. The vapor pressure, surface tension, and viscosity of the fluid were 22.0 millimeters of Mercury (mm Hg), 46.7 dynes per centimeters (dynes/cm) and 0.924 Centistokes, respectively, at 25 degrees Centigrade (°C). The quantity of precipitates in the urine ersatz brine increased with increased solute weight fraction (i.e., solids concentration).

The favorable results of the benchtop tests raised expectations for a successful performance test in Life System Incorporated's (LSI) VCD-VI test unit. However, this did not occur due to the absence of visible precipitated solids in the concentrated brine. It was postulated that storage of the urine at relatively high temperatures (i.e., 78° to 82° F) for an extended period of time prior to the performance test led to its chemical degradation as evidence by the formation of mold on its surface. Tests are planned to validate the use of the concentrated urine as the process fluid.

5.0 AIR REVITALIZATION SYSTEMS

5.1 Component Design and Development

5.1.1 Trace Contaminant Control Subsystem Catalyst Poisoning Investigation ¹³

The Trace Contaminant Control Subsystem (TCCS) developed for the Space Station utilizes palladium (Pd) on alumina (Al_2O_3) catalyst for oxidizing organic contaminants in Space Station cabin air. A series of tests were designed and conducted to study the poisoning effects of miscellaneous chemical compounds on the catalyst. A detailed schematic of the catalyst testing apparatus is shown in Figure 5.1-1.

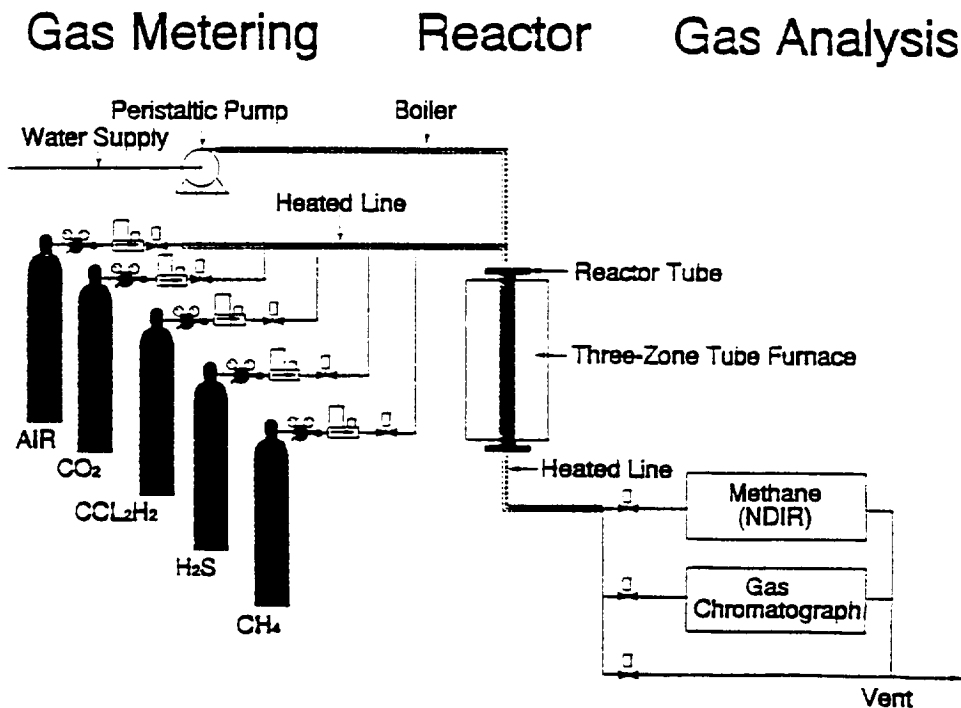


Figure 5.1-1 Schematic of the Catalyst Testing Apparatus

This investigation determined the following:

- The effects of halocarbon (dichloromethane, Freon 113, and Halon 1301) and inorganic (ammonia and hydrogen sulfide) catalyst poisons on methane oxidation activity.
- The regenerability of the catalyst used in the TCCS.

Experimentation to achieve these objectives included the following:

- The catalyst efficiency for methane oxidation (the most difficult organic molecule to oxidize), both in pure air and air containing poisons.
- The by-products of halocarbon, inorganic sulfide, and ammonia oxidation.
- The products of pure air oxidation (baseline).

Ten ppm dichloromethane in air was injected into the catalyst bed at 400°C at a gas hourly space velocity of 8000 per hour and 40% relative humidity (based on ambient). The catalyst rapidly poisoned dropping to 15% methane conversion after 20 hours. No additional degradation was observed after 20 hours (this is still a high enough conversion rate to meet Space Station specifications). Upon exposure to "clean" air, the catalyst slowly recovered. After 100 hours with "clean" air, the catalyst conversion of methane was approximately 90% that of the fresh catalyst. Additional poisoning/recovery cycles (8 total) showed similar degradation and recovery profiles (no significant additional degradation). Figure 5.1-2 summarizes the three month cyclic poisoning test with CH_2Cl_2 , showing all eight poisoning regeneration cycles.

These experiments were performed to show catalyst recovery from a poisoned state. Tests were performed at various temperatures and stages in the cyclic poisoning (150 to 400 °C, 95 hours into the poisoning cycle, and 102.5 hours into the regeneration cycle). There was little difference in the catalyst activity at 400 °C. Following the ramp experiment, the catalyst was exposed to "clean" air at 400 °C and recovered to 90% methane oxidation.

One ppm hydrogen sulfide in air was injected into the catalyst bed at 400 °C (Figure 5.1-3), a gas hourly space velocity of 8000 per hour, and 40% relative humidity (based on ambient). The catalyst rapidly poisoned dropping to 60% methane conversion after 23 hours. The catalyst did not regenerate significantly when exposed to "clean" air at 400 °C. In initial tests, the hydrogen sulfide was adsorbed by the hot stainless steel reactor wall used in the test rig. A quartz sleeve was installed to overcome this phenomenon. The adsorption of hydrogen sulfide by stainless steel may ensure that the Space Station catalyst is not poisoned by the compound, but further work is required to be certain. Additionally no significant generation sources of sulfides, other than minimal human metabolic products, exist on the station.

The by-products of chemical oxidation in the TCCS catalyst were investigated. The by-products produced through the oxidation of dichloromethane were formaldehyde (0.45 ppm at operating temperature) and hydrogen chloride (16 ppm at operating temperature). No detectable phosgene or chlorine gas was produced as a by-product of dichloromethane oxidation. The by-products produced through the oxidation of hydrogen sulfide were sulfur dioxide (0.6 ppm at operating temperature) and hydrogen sulfate (0.3 ppm at operating temperature). No detectable carbon monoxide or formaldehyde was observed.

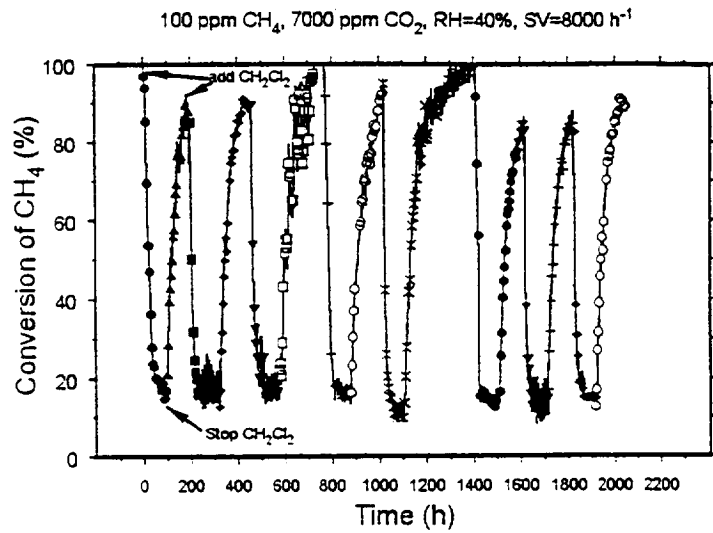


Figure 5.1-2 Cyclic Poisoning Test using Dichloromethane

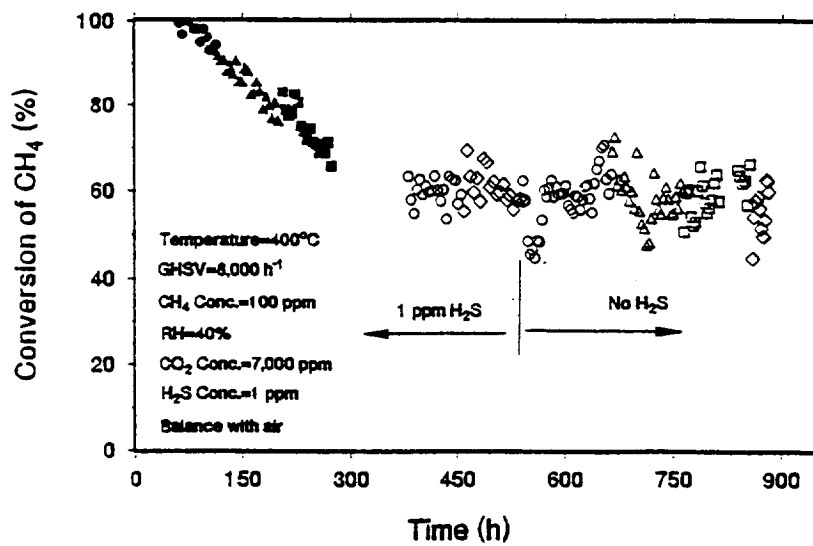


Figure 5.1-3 Baseline Performance Test using Hydrogen Sulfide

A study of the poisoning effects of Halon 1301 was also performed. At 10 ppm Halon in air, catalyst efficiency dropped to 65% in 100 hours (an initial rapid decrease to 70% followed by slow stabilization). The reaction rate was 16 times lower than with fresh catalyst. The catalyst regenerated to an acceptable level, but still had an activity four times lower than fresh catalyst.

A fresh load of catalyst was exposed to 1 ppm Freon 113 (R-113) in air. At that level, catalyst activity dropped by a factor of 5 in 17 hours with little additional depletion after 17 hours. At 10 ppm Freon, the catalyst activity dropped by a factor of 10 in 68 hours. The steady state was reached after 100 hours. Regeneration increased the catalytic activity by a factor of 4 showing that the Freon has less poisoning potential than dichloromethane.

A study of the reaction by-products of ammonia was performed to determine if undesirable nitrogen oxides will be produced should ammonia break through the TCCS carbon bed. In this study, the catalyst was exposed to 10 ppm ammonia in air. The ammonia did not affect the catalyst's ability to oxidize methane, and only nitrogen and nitrogen oxide were observed as reaction products of ammonia oxidation (i.e. no nitrogen dioxide was observed).

5.2 Oxygen Generation Systems

5.2.1 Static Feed Electrolyzer ¹⁴

The Static Feed Electrolyzer (SFE) Oxygen Generator uses electrolysis to generate oxygen from water (Figure 5.2-1). The process incorporated by the SFE involves the vaporization of water through a membrane into an aqueous potassium hydroxide (KOH) electrolyte. Oxygen (O₂) is generated at the anode and hydrogen (H₂) is generated at the cathode. Both outlet gases are saturated with water vapor. Because the electrolysis process is not 100% efficient, some heat is generated and must be controlled by the feed liquid flow. For each kilogram of water processed 0.89 kilograms (kg) of O₂ and 0.11 kg of H₂ are produced.

Because the ISS O₂ generator was changed from continuous to cyclic operations, the SFE-IVA required modifications. The SFE-IVA had been provided by LSI for use in the POST. The contract issued for this conversion included hardware and software modifications to incorporate cyclic operation and to implement performance approaches identified as necessary by the comparative test.

A refurbishment program has been established to upgrade the SFE for independent subsystem testing and for use in the Integrated Air Revitalization Test (IART). Refurbishments addressed design problems identified in previous testing. Problems identified were cell flooding, aerosol buildup, excessive thermal swings, and the Thermal Control Assembly (TCA) pump.

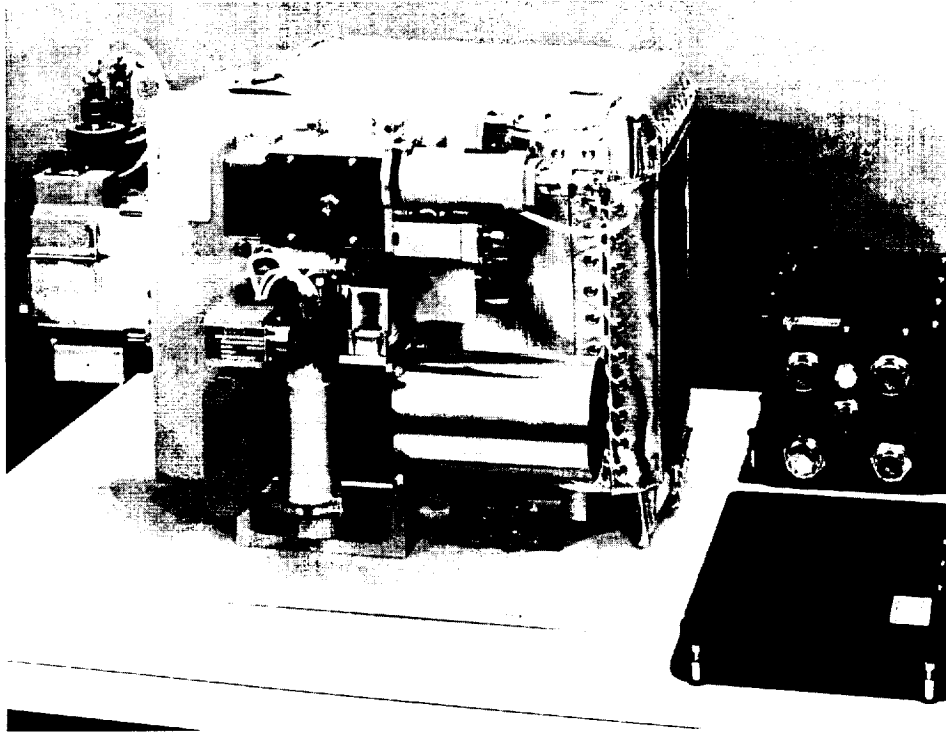


Figure 5.2-1 SFE Oxygen Generator

Cell flooding was alleviated by improving the humidity control in the Electrochemical Module Assembly (EMA) and by circulating an electrolyte feed instead of a water feed. By adding filter cells to the EMA, aerosol residue was eliminated from the O₂ and nitrogen (N₂) streams and will not build up on the regulator poppets. Excessive thermal swings were fixed by improving the TCA and modifying the control software.

Additional problems were discovered and addressed in the refurbishment program. The Pressure Control Assembly (PCA) was redesigned to fix the tendency of the SFE to pressurize improperly during start-up. PCA improvements prevented movement of the electrolyte caused by pressure variations in the O₂ and H₂ streams. By using N₂ for the initial pressurization, the long start-up time was reduced. An ion exchanger and a deiodinator were added to the design to prevent contamination of the electrolyte by the intake water.

After refurbishment was completed, the SFE-IVA' was tested extensively at the LSI facility. Checkout, shakedown, break-in, design verification, cyclic endurance, and parametric testing were conducted with the goal of verifying that the subsystem could operate in the cyclic mode. This testing began February 21, 1995 and was concluded on April 28, 1995. Total test time was 48 days with 14 days of continuous operation. Subsystem performance during this testing was nominal with no significant anomalies.

The SFE-IVA' was shipped to MSFC on May 2, 1995 and installed in the CMS in Building 4755. Initial subsystem startup occurred on June 22, 1995 with independent subsystem testing continuing until November 29, 1995. Total test time during this period was 26 days total with 15.6 days of continuous operation. Subsystem performance during this testing was nominal except when anomalies occurred.

During the testing at MSFC, four anomalies occurred as shown in Table 5.2-1. Each of these anomalies resulted in the subsystem being shipped back to LSI for repair. The first two anomalies were caused by operator error and quality control problems. The third anomaly was a software problem and was resolved by raising the filter cell set point temperature. The fourth anomaly was a hardware problem associated with loose fastener inserts (keenserts) at the module-to-interface plate location. Repeated assembly/disassembly to resolve the last anomaly resulted in LSI informing MSFC that they could not deliver an operable subsystem for subsequent Integrated Air Revitalization testing at MSFC.

Table 5.2-1 Anomaly* Summary

No.	Date Observed	How Manifested	Immediate Cause	Root Cause Summary
1	7/7/95	Low P2 Alarm	Liquid blocked H ₂ filter/barrier cells	Feed core leak caused by hot spot in cell resulting from multiple out-of-tolerance operations and conditions
2	8/19/95	P1 failed to reach operating pressure during Standby to Normal transition	Liquid on H ₂ regulator seat	<ul style="list-style-type: none"> • Nondetected feedcore leak from Anomaly No. 1 • Insufficient compression in replacement fluids insulation plate • Insufficient epoxy in passage of replacement fluids insulation plate
3	10/20/95	High P2 Alarm	Liquid in O ₂ filter/barrier cells	Condensation of water vapor in O ₂ filter/barrier cells due to overcapacity operation, followed by inadvertent application of high N ₂ pressure during dry-out attempt
4	11/29/95	Low P2 Alarm	Sudden loss of O ₂ pressure	Small amount of residual liquid (from prior disassembly) in O ₂ regulator and/or loss of seal at module-to-interface plate location due to loose fastener inserts (keenserts)

* Event that caused automatic shutdown with its root cause not fully explainable at time of occurrence and prevented restart and/or continued operation without returning unit to LSI for analysis and repair.

Conclusions based on testing of the SFE-IVA' include:

- All test requirements and goals were met except for the goal of 30 days of total run time at MSFC (26 days achieved). Cyclic operation was successfully demonstrated with an accumulated run time of 1189 orbital cycles.

- Considering the extent of modifications made to the hardware, the budget constraints, and the fact that MSFC was checking out a new facility, the anomalies encountered should not have been unexpected.
- Lessons learned from these anomalies will be applied to the SFE flight experiment program.
- None of the anomalies experienced indicate problems with the SFE technology's ability to meet ISS requirements.
- Test data shows that the hardware performed well for extended periods between anomalies.

5.2.2 Solid Polymer Electrolyzer ¹⁵

The Solid Polymer Electrolyzer-Oxygen Generation Assembly (SPE-OGA, originally designated the Liquid Feed Solid Polymer Electrolyzer (LFSPE) Oxygen Generation Subsystem), was designed and built by HS in the late 1980s, and was designed to safely and efficiently generate oxygen and hydrogen, under pressure, using a 12-cell liquid feed Solid Polymer Electrolyzer (SPE) water electrolyzer. The system participated in the SSF ECLSS Technology Demonstration Program, and a follow-on program in November 1990.

The HS SPE (Figure 5.2-2) safely generates O₂ and H₂ gas through the electrolysis of water. The oxygen gas is generated and delivered at ambient pressure directly to the environment, while the hydrogen is generated at slightly elevated pressure for possible delivery to a carbon dioxide (CO₂) reduction system. The SPE includes all valves, regulators, sensors, and other controls for safe operation of the system.

The cell stack is a liquid anode feed water electrolyzer consisting of 18 SPE water electrolysis cells assembled in a bipolar arrangement between two compression end plates. In the electrolysis process, liquid water is fed to the anode, or oxygen compartment, where it is electrolyzed to produce gaseous oxygen, hydrogen ions (H⁺), and electrons. The H⁺ ions, or protons, are transported across the ion exchange membrane and the electrons travel through the external electrical circuit to the cathode. These protons are fully hydrated and deliver water to the cathode side of the membrane. The electrons combine with the protons to form gaseous hydrogen at the cathode. Excess water is pumped through the anode compartment to remove heat generated by the electrolysis process.

The oxygen/water stream exiting the electrolysis cell stack enters a shell and tube liquid-to-liquid heat exchanger to reject waste heat from the electrolysis reaction and to reduce the dew point of the oxygen gas. The two-phase stream then enters the oxygen/water phase separator to deliver water free oxygen to the oxygen delivery system while oxygen free water is returned to the water recirculation loop. The phase separator assembly consists of two stages. In the first stage six hydrophilic membranes allow water to wick through but, because of their high bubble point, the membranes will not allow gas to flow through. The fluid exiting the two-phase cavity is mostly gas with a small amount of water carry-over. The fluid is directed to the second

stage, or "polishing" section of the separator. The polishing section contains a hydrophilic and hydrophobic membrane, where the remaining water is returned to the water recirculation loop. The oxygen gas is delivered to the oxygen delivery system through the hydrophobic membrane. Because the hydrophobic membrane has a high water intrusion pressure (an attribute similar to the bubble point of a hydrophilic membrane), the oxygen gas is delivered free of any liquid water. The operating pressure of the water recirculation loop is lower than the water intrusion pressure of the hydrophobic membrane under all operating conditions.

Water exiting the oxygen/water phase separator is delivered to a metal bellows accumulator which serves as a feed tank for the electrolysis cell stack and an expansion volume for the water recirculation loop during the system start-up transient. Water is returned to the electrolysis cell stack by a gear pump driven by a brushless DC motor. The water is polished with a deionizer bed to ensure the water is free of any ionic contamination (cation and anion) that would be detrimental to cell life. A conductivity sensor located immediately downstream of the deionizer bed monitors water quality and performance of the deionizer bed. Water flow to the module is monitored by a flow switch located immediately upstream of the cell stack.

The oxygen gas produced in the SPE electrolyzer is free of hydrogen, with purity of 99.5% or greater typically measured. Since the SPE has been designed to operate with hydrogen pressure always greater than oxygen pressure, redundant combustible gas sensors located at the oxygen outlet interface constantly monitor the oxygen for hydrogen. A pressure sensor initiates a shutdown should an obstruction occur in the delivery line, and a relief valve provides redundancy in the event of a failed pressure sensor.

The hydrogen/water exiting the cell stack is mostly hydrogen gas by volume with a small amount of liquid water present from protonic pumping in the ion exchange membrane. The hydrogen/water phase separator employs two cavities, each containing a hydrophilic and hydrophobic membrane, and is similar in design and operation to the polishing section of the oxygen/water phase separator. The hydrogen gas passes through the hydrophobic membranes to the hydrogen valve manifold containing the pressure control system, and the water is delivered to the "stripper" section of the phase separator. The stripper section contains four electrochemical hydrogen pumps that remove dissolved hydrogen from the water before it is returned to the water recirculation loop. The electrochemical hydrogen pump uses an SPE membrane and electrode assembly similar to the electrolysis membrane and electrode assembly. The degassed water is subsequently delivered to one of two metal bellows accumulators after dropping in pressure through a negative bias back pressure regulator referenced to hydrogen.

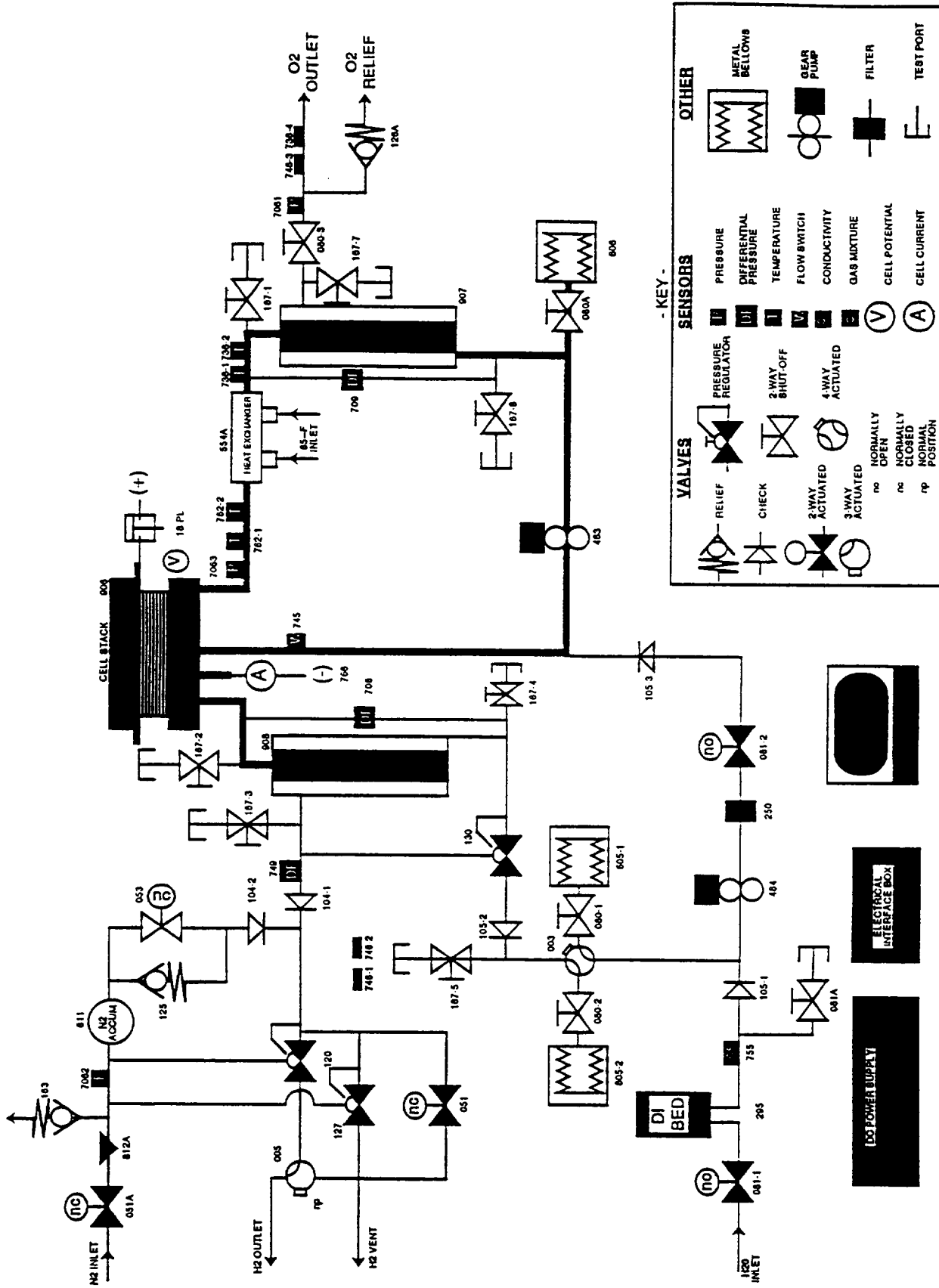


Figure 5.2-2 SPE Schematic

Several problems were noted with the SPE during the Technology Demonstration Program tests. These problems were:

- Water carry-over from the hydrogen phase separator during start-up transient conditions
- Rising cell potentials while operating the system with water from the reverse osmosis (RO) water processor
- Inadequate priming of the recirculation water loop pump
- Inaccurate flow sensor readings for the recirculating water loop
- Inadequate heat rejection from the recirculating water loop heat exchanger due to higher than expected cell potentials
- Failure of the three-way solenoid valves which divert the flow of generated gas to either a delivery or vent interface
- Blistering of hydrophobic membrane material in the oxygen phase separator, inhibiting gas transport
- Frequent alarm conditions triggered by the hydrogen sense cell of the hydrogen phase separator assembly
- Failed electrical contactor for the 4-way ball valve, resulting in incomplete valve travel
- Failed current control isolation board, resulting in reduced current to the electrolysis module and, hence reduced gas output

HS addressed and corrected the above deficiencies, and incorporated additional hardware and software changes. These additional changes were made to meet the ISS requirements. These changes included:

- Generation of oxygen while on the light side of the space station orbit (set at 53 minutes)
- Variable oxygen generation rates (7.4 pounds per day (lb/day) \pm 10 lb/day adjustable)
- Space Station nitrogen interface reduced to 100 pounds per square inch absolute (psia) maximum

The contract requirements instructed HS to:

- Conduct a baseline test of the as-received system to determine the status of key system components

- Refurbish the system to incorporate design changes as necessary to correct system deficiencies, and provide variable oxygen generation rates and cyclic system operation
- Test the effectiveness of the design changes
- Provide field support of the unit once returned to NASA/MSFC

Refurbishment of the Oxygen Generation Assembly (OGA) began in September 1994. The entire system was disassembled to the component level, with each item separately bagged to preserve cleanliness. Modifications performed during refurbishment included:

- The hydrogen phase separator assembly was modified to incorporate dual hydrophilic-hydrophobic cavities. Proper fluid separation at all operating conditions was observed thus eliminating water carry-over.
- The 12-cell electrolysis cell stack was refurbished to an 18-cell configuration to accommodate thermal efficiency at ambient temperature.
- The recirculating water loop was modified to correct inadequate pump priming at system startup, and to correct for loss of pump prime during system shutdown. In addition, a thermal flow switch was installed to monitor the water flow rate to the stack. A liquid-to-liquid heat exchanger was added to reject waste heat from the water electrolysis process.
- The failed 3-way solenoid valve was refurbished to ensure proper operation in an enclosed environment without over heating.
- The oxygen phase separator was refurbished providing a blister free membrane capable of transporting gas with little condensation (utilizing "X" membrane material versus the "S" material of the first design). The unit was installed separate from the stack-manifold assembly.
- Since a Failure Mode and Effects Analysis showed sufficient fault detection, a problematic Hydrogen Sense Cell was removed from the subsystem.
- A mechanical contactor on the 4-way Ball Valve was replaced with a 6 amp replacement.
- A failed current control isolation board for the electrolysis power supply was replaced.
- The subsystem was reconfigured to operate in a cyclic mode with a variable oxygen generation rate. The software was set-up to allow for a 6.66 to 8.14 lb/hr oxygen production rate with variable light side operation from 50-60 minutes, and variable dark side operation from 40-30 minutes.

- Since the space station nitrogen pressure was reduced to 100 psia maximum, the subassembly was reconfigured to meet this specification.

The refurbished SPE was subjected to an acceptance test program at HS. The purpose of the acceptance test was to verify the effectiveness of the refurbishment by demonstrating elimination of operational deficiencies present in the original system, and operation of the system at various oxygen generation rates and in a cyclical manner. After successfully completing a thorough check-out test, including proof pressure and leakage testing, anomaly verification testing, and mode/state transition testing, the unit operated for 743 hours, including 693 hours in the cyclic mode of operation. With a simulated orbit of 90 minutes, the system completed approximately 460 cycles of light side/dark side operation.

The NASA Liquid Feed Solid Polymer Electrolyzer Test Plan required the unit to operate in cyclic mode for 30 test days total. Included in the 30 day requirement was 14 consecutive days of testing at a nominal production rate (7.4 pounds of oxygen per day (lbs oxygen/day)). Also required were two sets of two consecutive test days each at a 6.66 lb oxygen/day production rate, and an 8.14 lb oxygen/day production rate.

The test ran for the prescribed 30 test days though not continuously (approximately 664 hours total). The 14 consecutive day requirement was achieved between the dates of August 23 and September 6, 1995. The two day requirement at a 6.66 lb oxygen/day production rate was met between September 11 and September 13, 1995. The two day requirement at 8.14 lb oxygen/day production rate was met between September 13, 1995 and September 15, 1995.

Overall the test went well. Anomalies were minor and the flight-like components, the cell stack, and phase separators, performed their function throughout the test. Several shutdowns occurred due to differential pressure transients at the hydrogen separator, but these were resolved by raising shutdown setpoints after evaluation of the effect on the separator.

The hydrogen phase separator transients were attributed to pressure regulators which do not track well at the low flow conditions observed during "night" cycle processing. As a result, when the system cycled from day to night or night to day, differential pressure spikes or troughs were observed. The retention of these regulators in the refurbishment was a design decision for economy, and the transients occurring as a result are less than two thirds of the recommended tolerance of the hydrogen phase separators according to HS.

Differential pressure transients also occurred in the oxygen separators but did not result in shutdowns during the test. One of the oxygen phase separator differential pressure shutdown setpoints was, however, adjusted prior to the start of the test.

Several other shutdowns were the result of a gradual failure of a volume sensor on a bellows accumulator tank. The sensor was part of the original SPE, and was first installed in 1989. The sensor was not replaced during refurbishment because no problems were linked to the sensor during the refurbishment process. High water shutdowns were not observed following sensor repair. A normally energized solenoid

nitrogen isolation valve, which was rebuilt during the refurbishment, also failed. It was repaired and offered no more trouble. These failed parts were both commercial off the shelf.

All data gathering objectives of the test were met with the exception of fatty acid, amine, oxidizability, and alkaline KOH analyses which were not performed. The analyses were not performed because no laboratory method existed for the analyses at the time of the test.

The lack of significant problems during the test allowed the test engineers to concentrate their efforts on the differential pressure transients in the phase separators. Analysis of the separators' performance has resulted in many recommendations for subsystem improvements. Some of these improvements have already been implemented by HS with good results, in preparation for planned life testing of the SPE.

5.3 Integrated Systems Testing ¹⁶

The ECLSS IART will be performed at MSFC. Testing of the ISS configuration of the Air Revitalization (AR) subsystem will be performed to provide data and gain knowledge of technical issues concerning operation and control to support the Space Station design and development. The ISS program ECLSS design includes oxygen generation, carbon dioxide removal, trace contaminant control, and atmosphere monitoring as the baseline AR design with scars included for carbon dioxide reduction. The TCCS will be included in the test but will not be challenged with an extensive list of contaminants until the follow-on phase. The test's primary purpose is to provide important data with respect to the AR subsystem's ability to control oxygen and carbon dioxide levels within ISS specifications, given crew metabolic profiles representative of predicted on-orbit operations incorporating day/night orbital cycle power saving measures. In addition, lessons learned from this test will be used to gain insight into the technical challenges to be faced by the technology ultimately selected for oxygen generation.

Hardware, data, instrumentation, and test requirements are outlined to support the test objectives of subsystem checkout followed by a minimum 14-day closed door integrated test. Process sampling requirements are included to provide additional data to assess the performance of the subsystems during the test.

The IART is scheduled to begin February 1996. A final test report will summarize the results. The major objectives for the IART are:

- Demonstrate simultaneous operation of oxygen generation, carbon dioxide removal, trace contaminant control, and atmosphere monitoring hardware under remote automatic control in the Core Module Simulator (CMS) with closed doors for a minimum of 14 days (7 days uninterrupted).
- Simulate metabolic oxygen consumption and carbon dioxide generation of 4 crew members inside closed door chamber with transient metabolic profiles representative of typical Space Station operational activity timelines.

- Provide performance data on oxygen generation, carbon dioxide removal, and atmosphere monitoring subsystems for controlling partial pressures of oxygen and carbon dioxide for a crew of four.
- Demonstrate capability of software for automatic control of oxygen partial pressure (ppO₂) through integration of the Major Constituent Analyzer (MCA) ppO₂ signal with oxygen generator production rate.
- Demonstrate day/night orbital cyclic operation of oxygen generation and carbon dioxide removal subsystems with signal from control system representative of day/night orbit.
- Demonstrate the oxygen generation subsystem operation with actual reclaimed water from the Integrated Water Recovery Test (Stage 9) as feed water for electrolysis.
- Determine the accuracy of the MCA water vapor measurement when integrated with a simulated length of sample delivery system tubing as compared to cabin water vapor concentrations measured directly by facility sensors.

A schematic showing the subsystems and major facility support hardware necessary for the test is shown in Figure 5.3-1. Subsystems include an oxygen generation assembly, a carbon dioxide removal assembly, an atmosphere monitoring assembly, and a trace contaminant control system. Facility support hardware includes a metabolic simulator, a vacuum chamber, a temperature and humidity control system, and an oxygen concentrator. Figure 5.3-1 also includes a mass balance for the test at average nominal 4 crew member metabolic levels. Ranges of metabolic levels will be varied between values representing sleep to exercise to test the ability of the system to control ppO₂ and carbon dioxide partial pressure (ppCO₂) levels within Space Station requirements.

5.3.1 Oxygen Generation

The SFE OGA (Figure 5.3-2), will be used to generate oxygen and hydrogen from reclaimed water from the Integrated Water Recovery Test. Under closed door operation, oxygen produced will be fed to the Temperature and Humidity Control system and hydrogen will be vented. The facility should also be capable of venting the oxygen under independent (open door) subsystem operation. The hardware will be a refurbished version of the SFE-IVA, modified, for day/night cyclical operation.

5.3.2 Carbon Dioxide Removal

The 4BMS Carbon Dioxide Removal Assembly (CDRA) (Figure 5.3-3), will be used to remove carbon dioxide from the Core Module Simulator atmosphere. Removed carbon dioxide will be vented to a simulated space vacuum, and regenerated air routed back to the CMS through the Temperature and Humidity Control (THC) System. The hardware will be the POST unit modified for day/night cyclic operation.

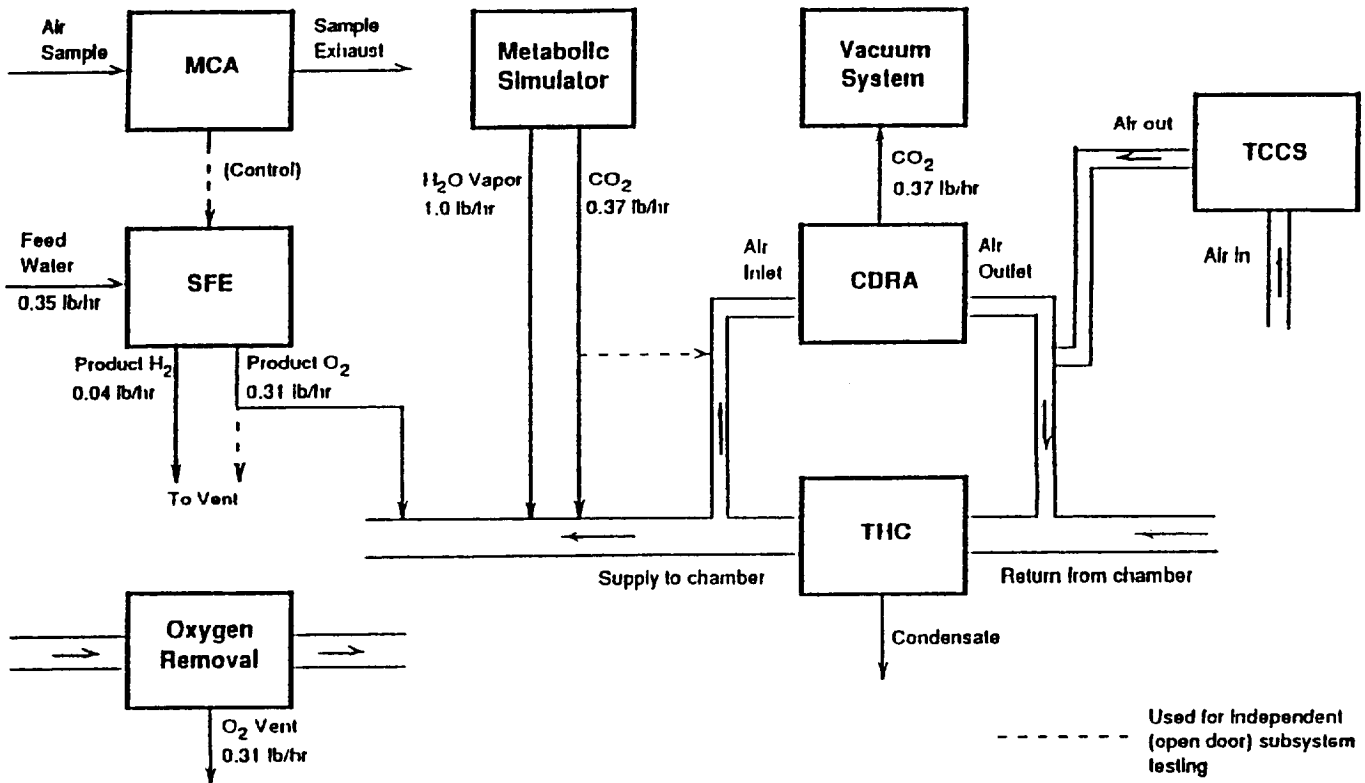


Figure 5.3-1 AR System Test Schematic and Average Mass Balance

5.3.3 Atmosphere Monitoring

The MCA (Figure 5.3-4), will be used to measure the partial pressures of oxygen, nitrogen, carbon dioxide, and water vapor inside the CMS. Oxygen partial pressure data will be used by the control system to adjust the level of oxygen production by the SFE to maintain proper oxygen partial pressures. The water vapor measurement will be compared to chamber humidity levels to determine the effects of the sample delivery system on accuracy of the MCA water vapor reading.

5.3.4 Trace Contaminant Control

The TCCS (Figure 5.3-5) will be operated in this phase of testing as part of the integrated AR configuration; however, the system will not be challenged with a range of contaminants until the follow-on phase of testing. The TCCS unit to be used in the test is the Life Test unit. Process air is drawn into the TCCS directly from the chamber atmosphere. TCCS exhaust air is returned to the chamber via the THC return duct (combined with the CDRA process air return).

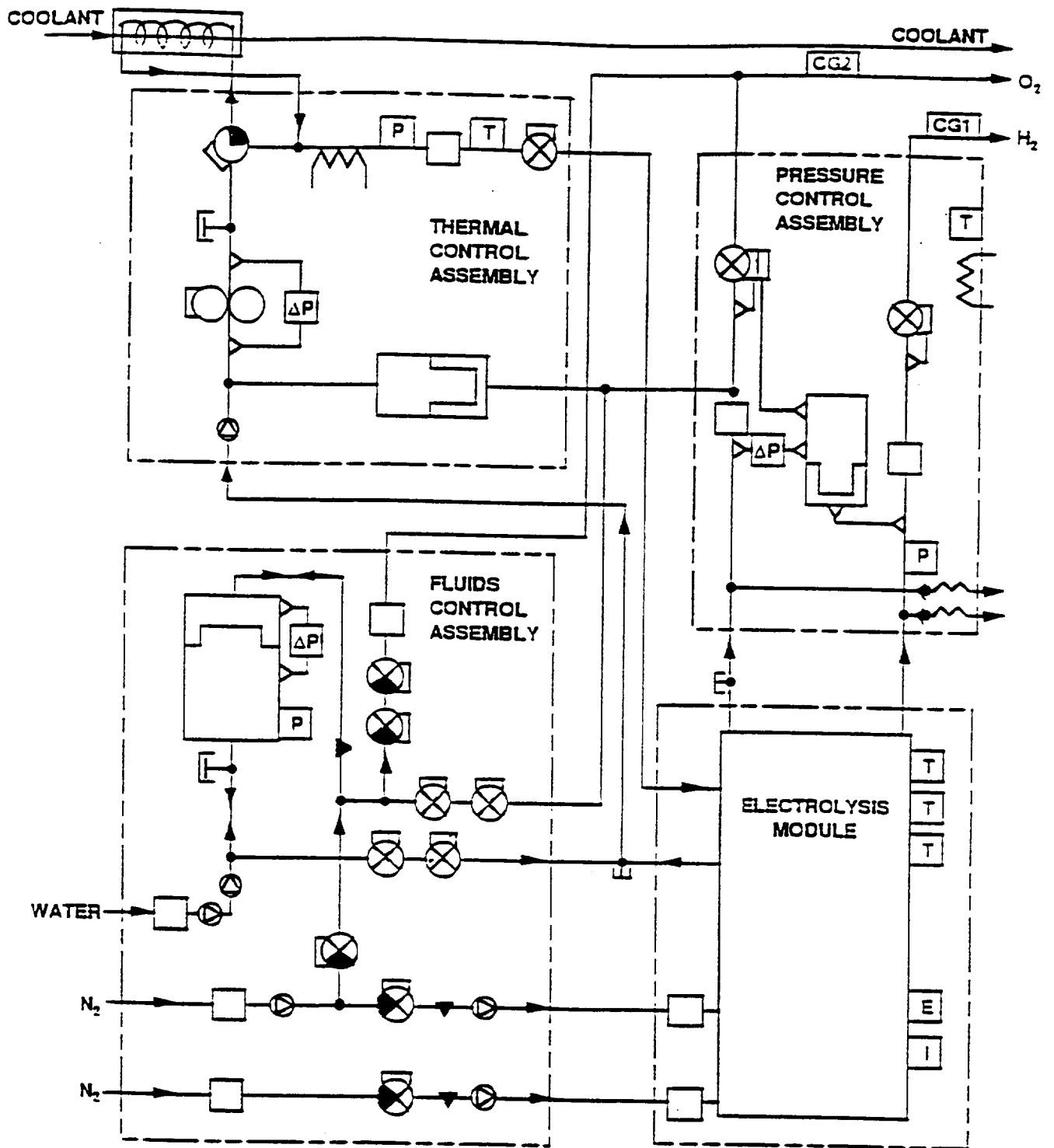


Figure 5.3-2 SFE Mechanical Schematic

CARBON DIOXIDE REMOVAL SUBSYSTEM

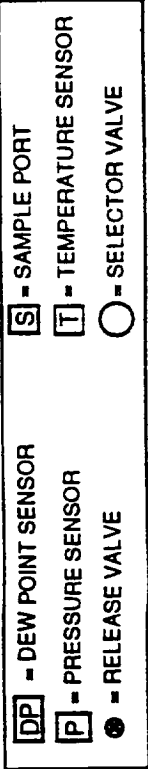
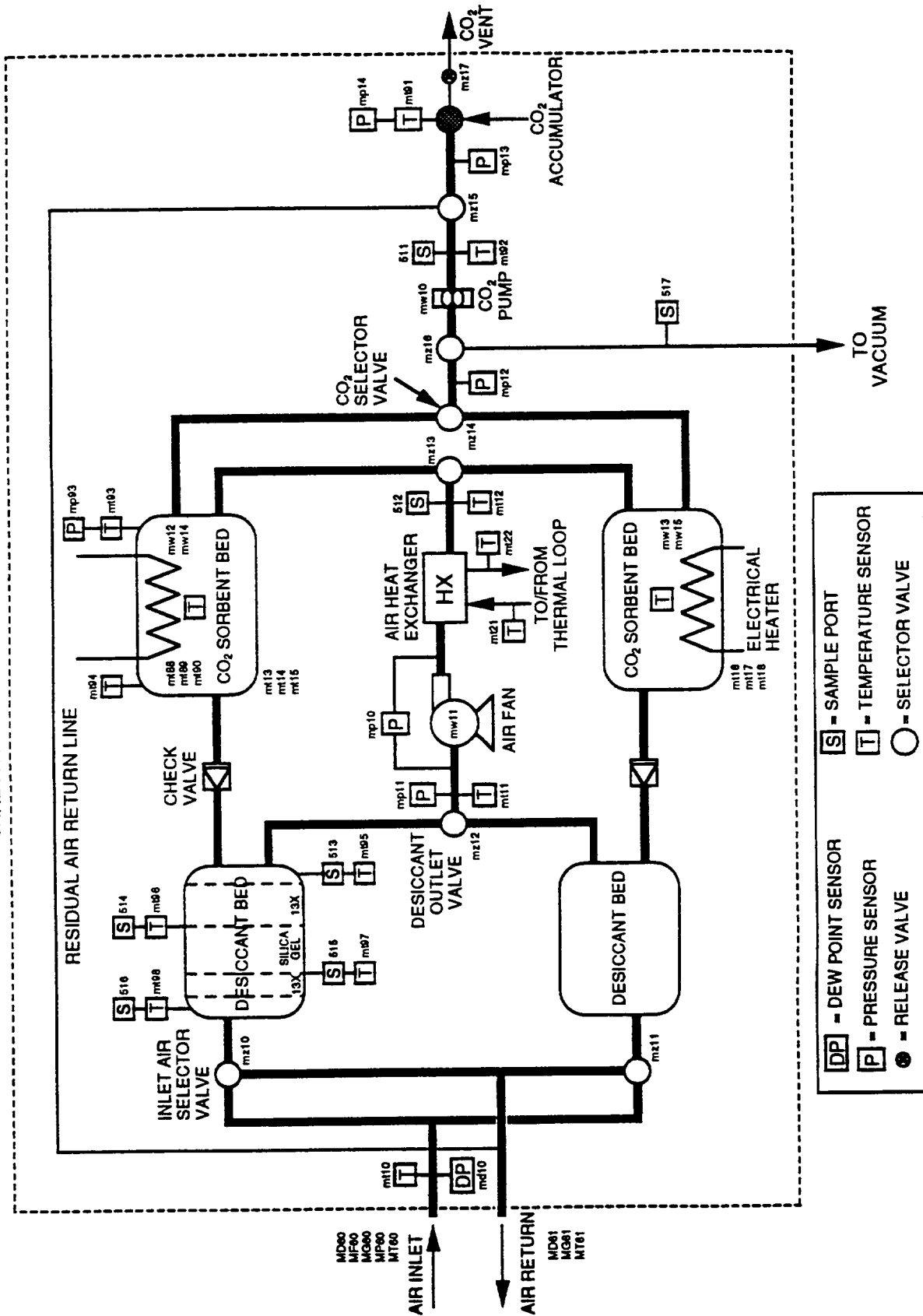


Figure 5.3-3 CDRA Mechanical Schematic

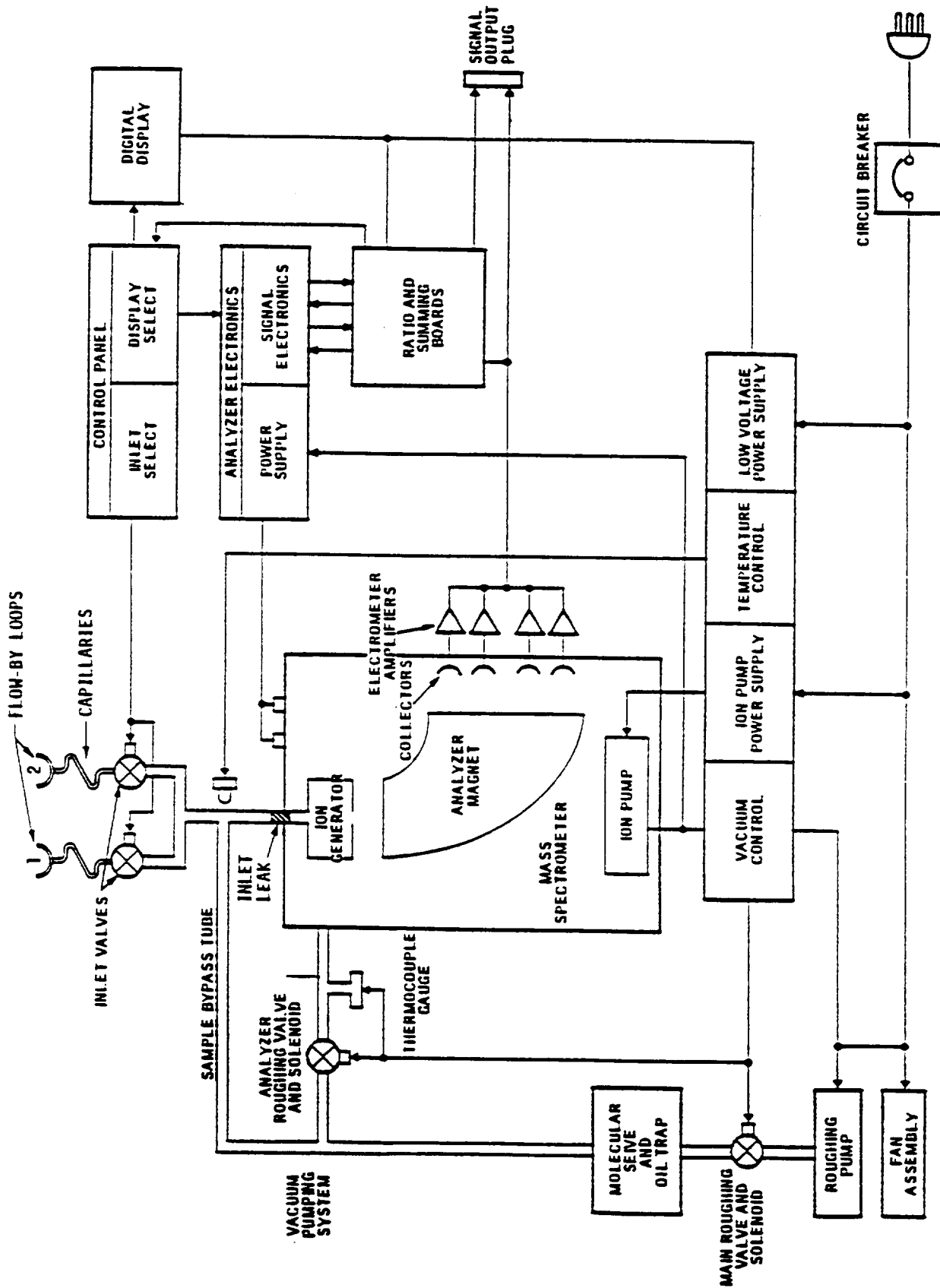


Figure 5.3-4 MCA Block Diagram

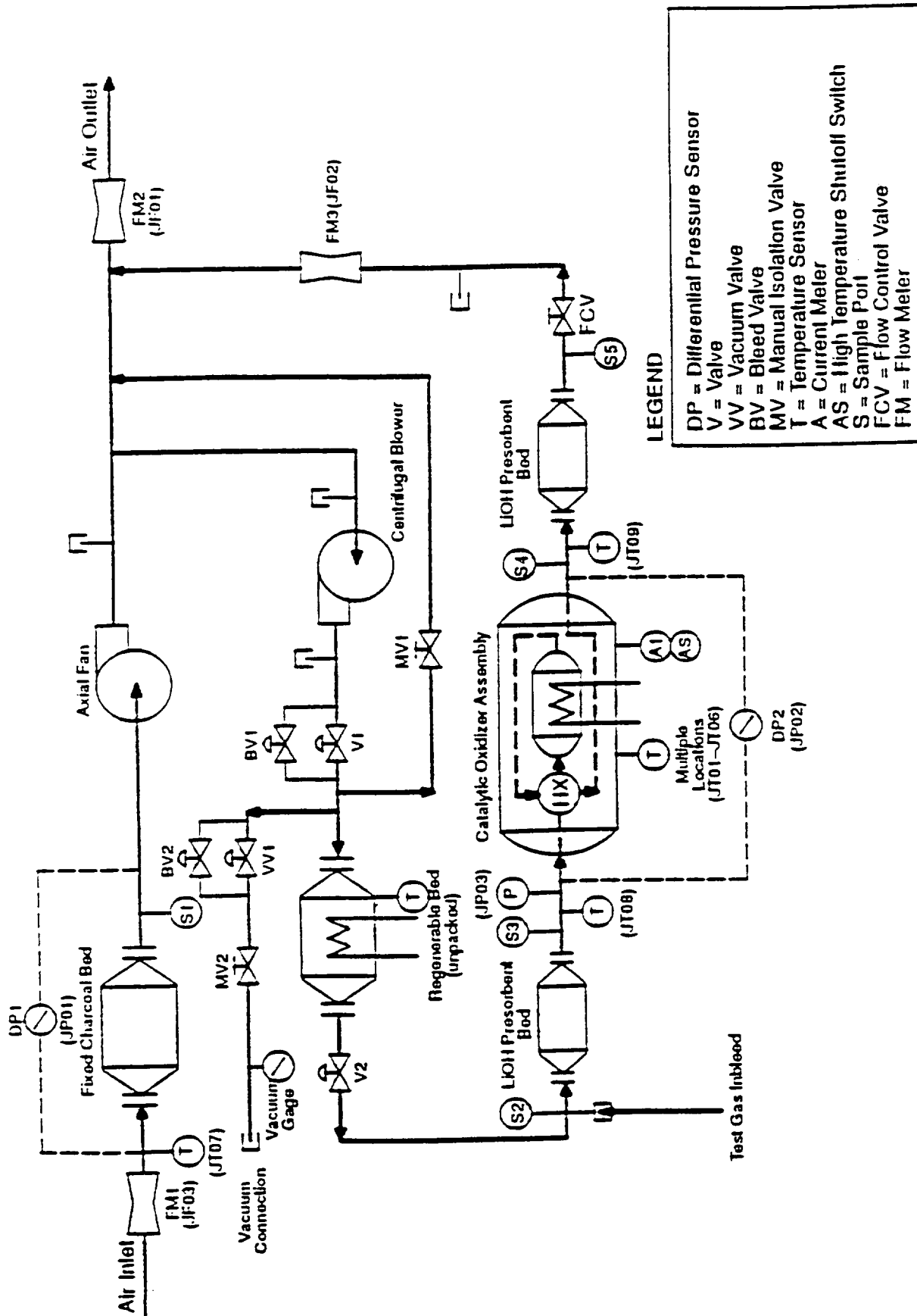


Figure 5.3-5 TCCS Mechanical Schematic

5.4 Analytical Model Development

5.4.1 Spacelab Charcoal Analysis

Atmosphere Revitalization systems analytical models being developed include TCCS and CDRA computer models. Charcoal returned from five Spacelab missions was analyzed and the resulting data utilized to upgrade the TCCS model. Data from testing molecular sieve material is being utilized to improve performance prediction methods for CO₂ removal and develop a molecular sieve computer model.

5.4.1.1 Spacelab Trace Contaminant Removal System Charcoal Analyses ¹⁷

Charcoal samples from two Spacelab Missions, International Microgravity Laboratory (IML) and Spacelab J mission (SLJ), were analyzed by Battelle Memorial Institute (BMI). The charcoal is a component of the Trace Contaminant Removal System (TCRS) of each Spacelab. The TCRS objective was to remove organic compounds from the Spacelab atmosphere.

The TCRS was configured with a canister, charcoal, and screens. The Spacelab tunnel blower provides flow through meters. The Spacelab tunnel blower provides a set flow rate of 4.8 cubic meters per hour (m³/hr). After each flight, the charcoal was divided into three sections: 1) 2.38 kg charcoal; 2) 1.81 kg acid treated charcoal; and 3) 338 g 2% platinum on charcoal. Each section had a screen as a partition. The sampling scheme analyzed the first section in segments to observe the adsorption capacity of the charcoal. The second and third sections would adsorb breakthrough compounds from section 1. It was hypothesized that compound concentrations would decrease as they passed through the bed. Calculating the total compound adsorbance along with the flow rate, would yield an ambient concentration.

The IML and SLJ samples were shipped from Kennedy Space Center (KSC). Upon examination, the IML and SLJ samples consisted of five individual samples per mission instead of the seven defined in the sampling procedure. Each of the five individual IML samples had been opened. Exposure to atmospheres, other than IML's, are unknown. Contamination from other than the IML atmosphere cannot be ruled out. The IML samples were transferred to borosilicate glass bottles and shipped to BMI. The SLJ sample set packaging was undisturbed and was also shipped to BMI. Upon receipt, BMI weighed and mixed each sample and analyzed them utilizing EPA methods.

Analysis of the charcoal samples was conducted by thermal desorption, trapping, and gas chromatography with simultaneous flame ionization and mass spectrometric detection. The target analytes were 1,1,1-trichloroethane, 1,2-dichloroethane, allyl chloride, benzene, carbon tetrachloride, chloroform, methylene chloride, toluene, vinylidene chloride, and vinyl chloride. Due to funding limitations, results were limited.

Initial attempts to analyze the samples failed as a result of the high concentrations of water in the charcoal samples. The high concentration of water resulted in freeze plugging of the chromatographic column, extinguishing the Flame Ionization Detector

(FID) flame, and vacuum failure of the mass spectrometer. Pre-purging the sample with dry helium prior to cryogenic trapping was attempted, however dry purge volumes as high as 2 liters failed to remove a sufficient quantity of the adsorbed water. A Perma Pure dryer was used to remove water vapor following thermal desorption. The technique was effective for all but sample number IML2, which contained the highest percentage of adsorbed water. Plugging of the chromatographic columns was evident for this sample. Experiments conducted with standards revealed that it also removed the polar organic compounds of interest. Results herein reflect only the non-polar target volatile organic compounds that may have been present in the charcoal samples.

The charcoal samples containing the highest water content were those fortified with phosphoric acid. Although charcoal is not normally hygroscopic, modification with phosphoric acid would be expected to allow retention of greater quantities of water vapor. The increased "wetness" of sample numbers IML2 and SLJ2 may also be responsible for the unexpectedly low retention of non-polar organic loading of the charcoal samples and is consistent with their location in the canister train shown in Figure 5.4-1. Most identified compounds are halogenated organic compounds indicative of "freons". Of particular interest is the relatively high concentration of bromotrifluoromethane (Halon 1301) in the IML charcoal samples. The compound, which is a fire extinguishing agent, is not a consistent component in the SLJ samples.

5.4.1.2 Spacelab Charcoal Analyses for Target and Non-Target Organic Compounds ¹⁸

Chemical analysis of 31 charcoal samples were obtained from a scrubber used to filter ambient air onboard three Spacelab missions, United States Microgravity Laboratory (USML), Spacelab D (SLD2), and Spacelab S (SLS2). Analysis of the charcoal samples was conducted by thermal desorption followed by gas chromatography/mass spectrometry (GC/MS). All samples were analyzed using identical methods. BMI previously analyzed two Spacelab mission sample sets (IML and SLJ) using a method, which was unable to detect very volatile and/or very polar compounds. The method used for these analyses was able to detect compounds independent of their polarity or volatility.

The charcoal from two Spacelab missions that was analyzed previously by BMI was maintained in glass jars at room temperature from date of receipt. Also included in these analyses was a sample of clean activated charcoal provided by BMI that was stored with the previous samples from the date of receipt.

The analysis method used for these samples was thermal desorption coupled on-line to a GC/MS system. Unlike previous analyses, a dry purge was not conducted prior to thermal desorption, nor was a Nafion in-line dryer used to remove water vapor desorbed from the charcoal. The impact of water vapor on the analysis was significant, but was minimized by reducing the quantity of sample actually analyzed.

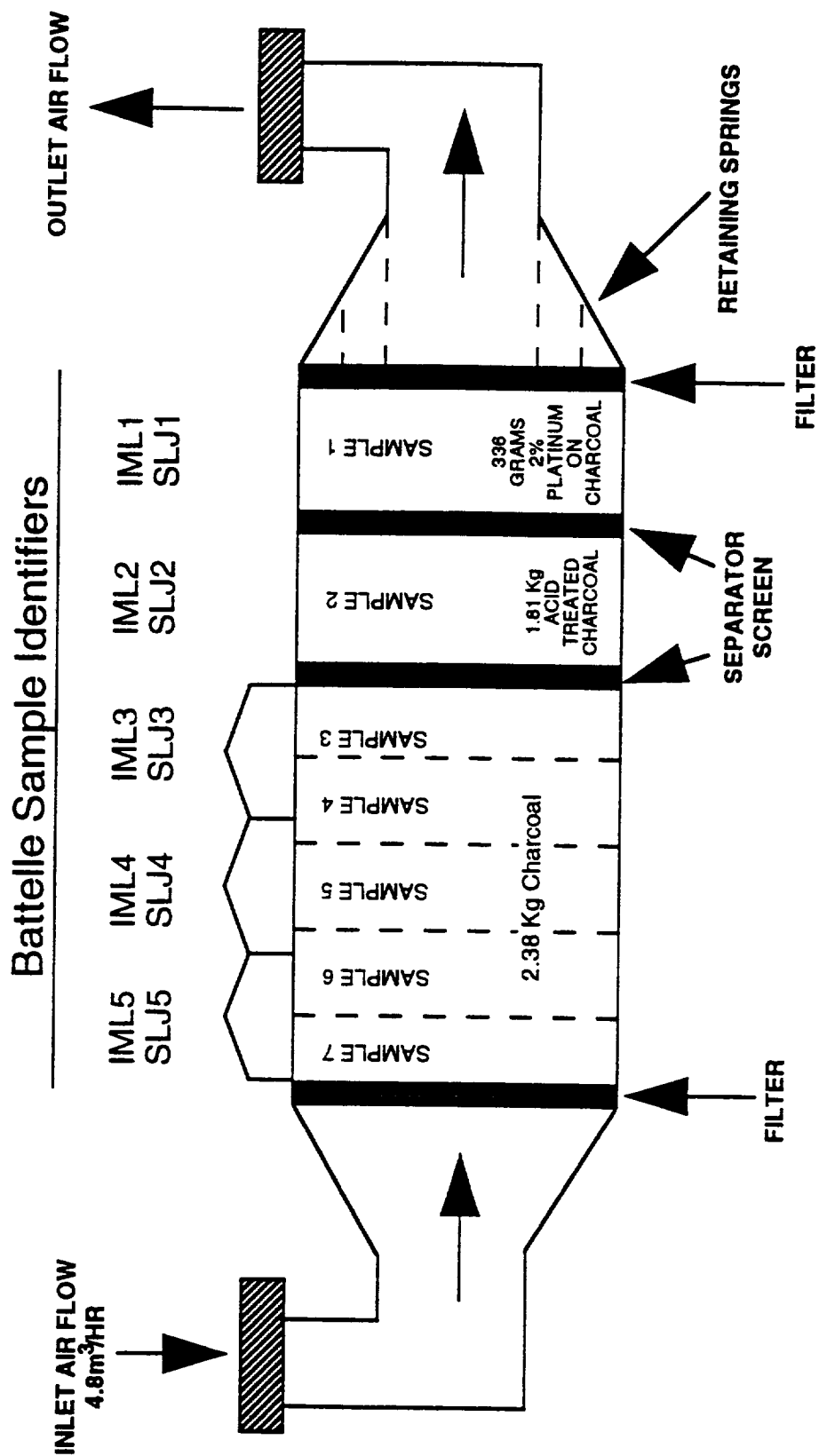


Figure 5.4-1 TCRS Configuration

To improve quantitative accuracy, standard mixtures were prepared containing known concentrations of selected compounds. The compounds were among the most abundant in previous scrubber charcoal analyses (including those conducted at BMI). This standard mixture was analyzed for purposes of calibration by direct splitless injection into the GC/MS system or, for purposes of estimating recovery, by spiking onto a charcoal sample followed by thermal desorption GC/MS. Initial trials using solvent based spikes onto previously desorbed charcoal samples were not successful because the solvent created excessive peak broadening rendering identification and quantification difficult. To overcome this problem, a pressurized gas standard was prepared. This gas standard was used for both direct injection to single point calibrate the GC/MS system, and for loading previously desorbed "blank" charcoal samples to estimate recovery.

The results obtained from the charcoal analyses represent a range of compounds and, in some cases, unusually high concentrations of polar compounds such as ethanol and acetone. The use of GC/MS to analyze a range of compounds is widely utilized for environmental analyses, however this approach becomes complicated for charcoal analyses because of the unusually high water loading. The first set of Spacelab charcoal samples did not show consistent water loading nor did these samples reveal the same concentration of non-polar compounds as determined in previous results. The remaining three sample sets showed a variety of polar and non-polar organic compounds.

5.4.2 Carbon Dioxide Removal System Computer Model ¹⁹

Adsorption involves the selective transfer of one or more solutes from fluid solutions onto and into solids. Physical adsorption is a surface phenomenon. When fluid is in contact with solid surface, molecules in the fluid phase spontaneously concentrate on the surface without any chemical change. At low temperature, adsorption is usually caused by intermolecular forces, such as Van der waal forces. The adsorption potential determines the strength with which any given molecule is adsorbed. The differences in the surface energy of the adsorbent and the properties of each kind of molecule cause differences in the amount adsorbed on certain kinds of surfaces, i.e., the selectivity. Separation of solutes in fluid mixtures can be accomplished through selective collection and concentration onto a solid surface.

Separation of gas mixtures by adsorption can be obtained by using either single column or multi-column configurations. However, for both processes the adsorbent column is alternately saturated and regenerated in a cyclic manner. One example of a continuous cyclic selective process is the Four-Bed Molecular Sieve (4BMS) used in ISS for the removal of CO₂ (Figure 5.4-2).

As shown in Figure 5.4-2, the actual CO₂ removal system for ISS consists of four beds. Two beds operate in the adsorption mode (a desiccant and CO₂ sorbent bed) while the other set of identical beds desorbs. The desiccant beds desorb through gas stripping while the sorbent beds are heated and subjected to a vacuum (e.g., the pressure and thermal swing process). Following the air flow path in Figure 5.4-2, cabin air laden with CO₂ and water enters at the system inlet, then enters desiccant bed (1), which consists of silica gel and 13X sorbent materials. The desiccant bed is

required to remove virtually all water from the air stream. The dry air is next pulled through the air blower, which overcomes the system pressure drop. A heat exchanger, the precooler, removes the heat of compression and heat of adsorption from the desiccant bed before the air enters the 5A sorbent which is responsible for removing the CO₂ from air. Following the precooler, the 5A bed (4) performs the primary system function of removing CO₂. The other 5A bed is concurrently desorbed with heat from embedded electrical heaters and allowed to vent to the vacuum of space. At the beginning of a new half cycle, the selector valves cycle to alternate the desorbing and adsorbing beds. Heated air from the hot, previously desorbing CO₂ sorbent bed, strips the downstream desiccant bed (3) of water, which is returned to the cabin in the return air stream. Note that in Figure 5.4-2, beds 1 and 4 operate concurrently to remove CO₂ while beds 3 and 2 desorb and recondition. The reverse is true when beds 3 and 2 operate to remove CO₂.

Because of the complexity of the process, the design of an efficient 4BMS CO₂ removal system mission depends on many mission parameters, such as duration, crew size, cost of power, volume, fluid interface properties, etc. A need for space vehicle CO₂ removal system models capable of accurately performing extrapolated hardware predictions is inevitable due to the change of the parameters which influences the CO₂ removal system capacity.

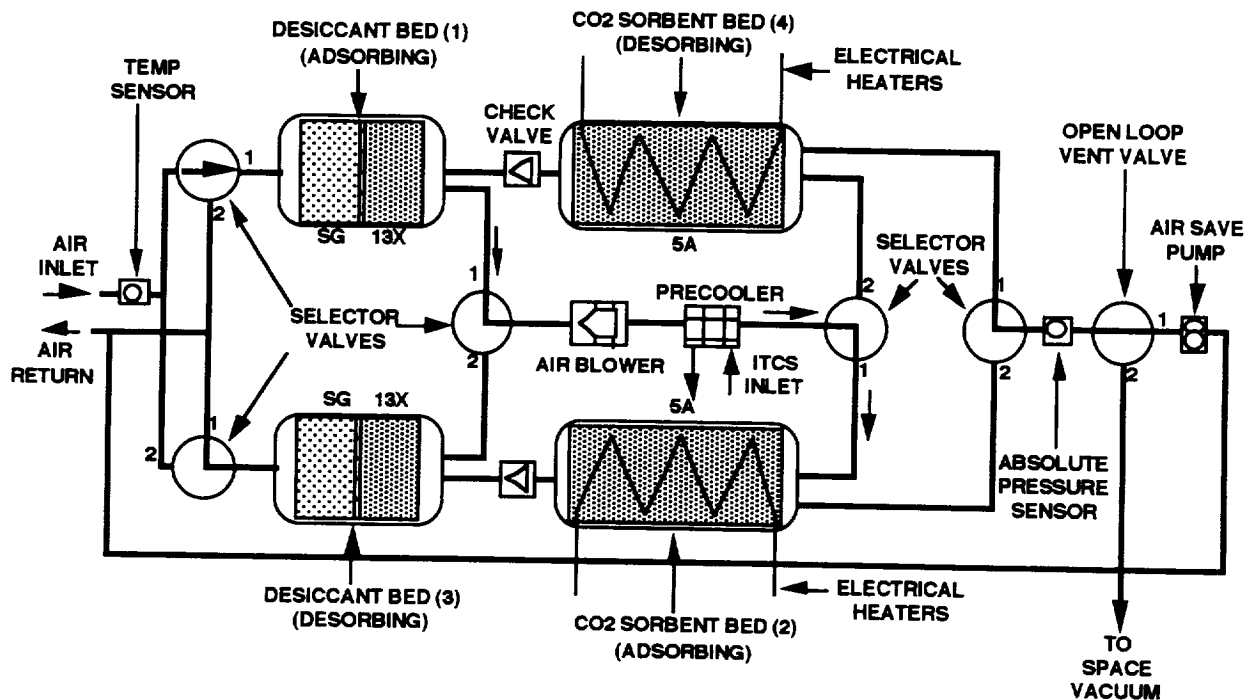


Figure 5.4-2 Four Bed Molecular Sieve Schematic

The purpose of this study was to: (1) investigate the mathematical techniques required for a model capable of accurate extrapolated performance predictions; and (2) obtain test data required to estimate mass transfer coefficients and verify the computer model. Models have been developed to demonstrate that the finite difference technique can be successfully applied to sorbents and conditions used in spacecraft CO₂ removal systems. The non-isothermal, axially dispersed, plug flow model with linear driving force for 13X and pore diffusion for silica gel were then applied to test data from a MSFC fixed bed column apparatus. A more complex model, a non-darcian model (2-dimensional) has also been developed for simulation of the test data. This model takes into account the channeling effect on column breakthrough.

5.4.2.1 Monodisperse and Bidisperse Diffusion Modeling

Mass transfer of solute from bulk gas to sorbed state is driven by equilibrium isotherms. The mass balance equation inside the sorbent material depends on the structure of the pellet. Monodisperse pore diffusion and bi-disperse pore diffusion are the two models used to predict the mass transport within the pellet. The diffusion mechanism for the two types of sorbents are illustrated in Figures 5.4-3 and 5.4-4. In general, the mass transfer mechanism of an adsorption process includes four steps: fluid-film transfer; pore diffusion; surface adhesion; and surface diffusion. Since the surface adhesion rate approximates the order of the collision frequency of the gas on the solid surface, which is much faster than the transport processes, equilibrium is assumed to be reached instantaneously at the interfaces. Adsorbates initially transfer from the bulk gas stream through an external film around the particles and reach the external surface of the particles. Molecules of adsorbate then diffuse into the pores of the particles, are adsorbed on the active sites, and then diffuse along the surface. Any of the steps can constitute the rate-controlling mechanism. The external mass transfer rate is defined in terms of an effective transfer coefficient as a linear driving force equation.

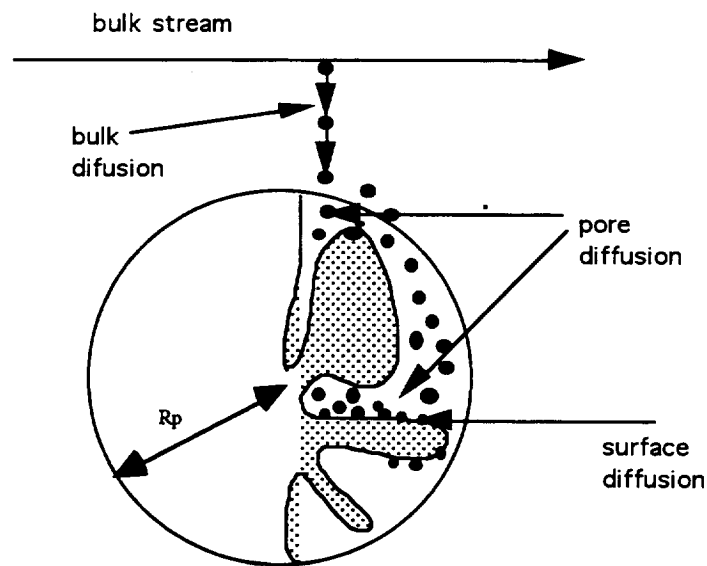


Figure 5.4-3 Intraparticle Mechanism of Diffusion for Monodisperse Sorbent

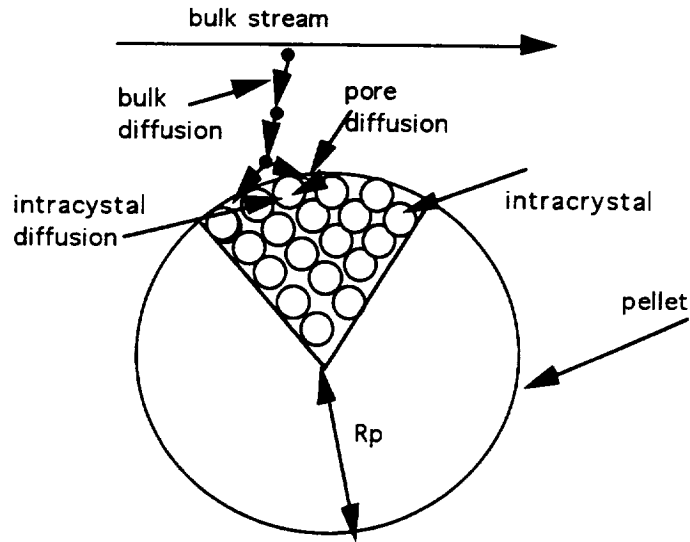


Figure 5.4-4 Intraparticle Mechanisms of Bidisperse-pore Sorbent

Results of the study are discussed below. Simulations were performed on an Alpha VAX computer. Experiments were performed on the insulated fixed-bed rig at MSFC. The sorbent is a 5A zeolite. Flow rates are scaled to match the superficial velocity in the 4BMS. Nitrogen is the carrier gas. Experiments begin with the column at ambient room temperature.

5.4.2.2 Thermal Effects Modeling

The time-sequence of simulation results in Figure 5.4-5 illustrate the significant thermal response of the column to a charge of CO_2 at a partial pressure of approximately 9 mmHg. The thermal wave caused by the heat of adsorption travels faster than and broadens the CO_2 front. For full saturation of the bed (an object of design), the thermal wave must exit the column.

The thermal model is validated by comparison with heating of the sub-scale column with an inert gas, shown in Figure 5.4-6. Nitrogen was heated to a temperature of 350°F and passed through an initially cold column. The markers are the measured temperatures at the inlet, midpoint, and exit of the column. The lines are the results from simulation.

5.4.2.3 Nitrogen Co-adsorption Effects Modeling

The importance of not neglecting the effect of nitrogen co-adsorption with CO_2 is shown in Figure 5.4-7. CO_2 in nitrogen at 6.2 mmHg was passed through an initially clean zeolite column. The gas at the column centerline was analyzed periodically at the column inlet, midpoint, and outlet. These results are compared with simulations that either included (solid lines) or neglected (dashed lines) the effect of nitrogen. Nitrogen clearly has a noticeable effect; however, the simulations that included N_2 adsorption over-predicted the effect slightly.

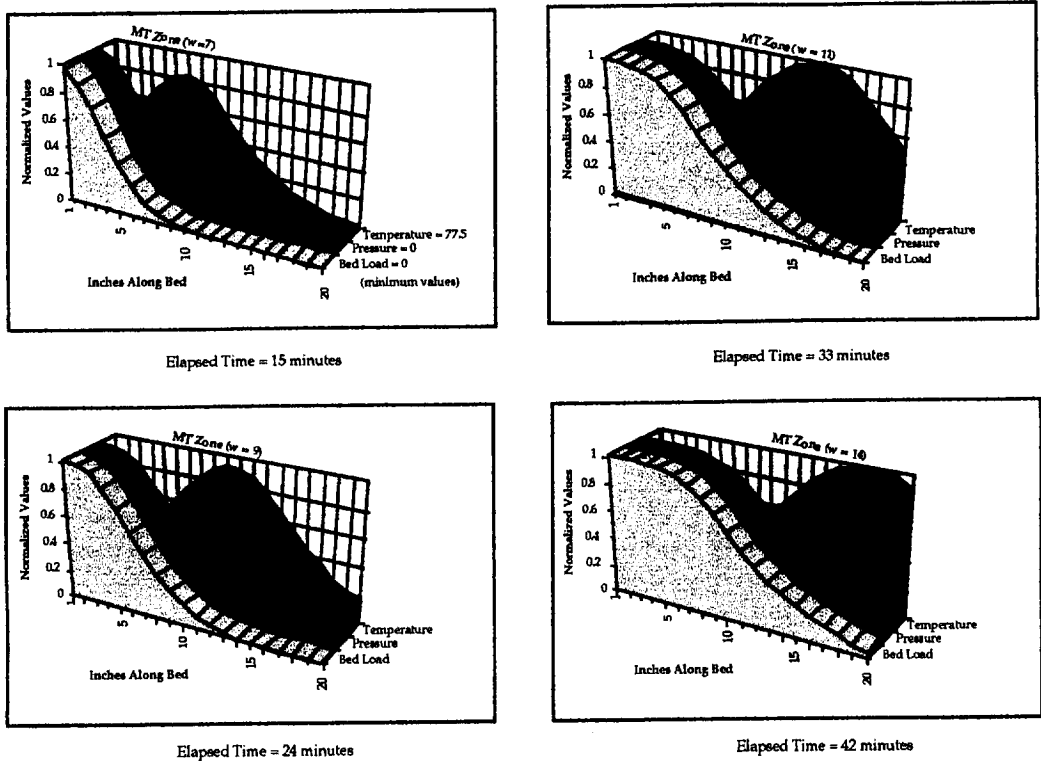


Figure 5.4-5 Single Component Mass and Heat Transfer Effects

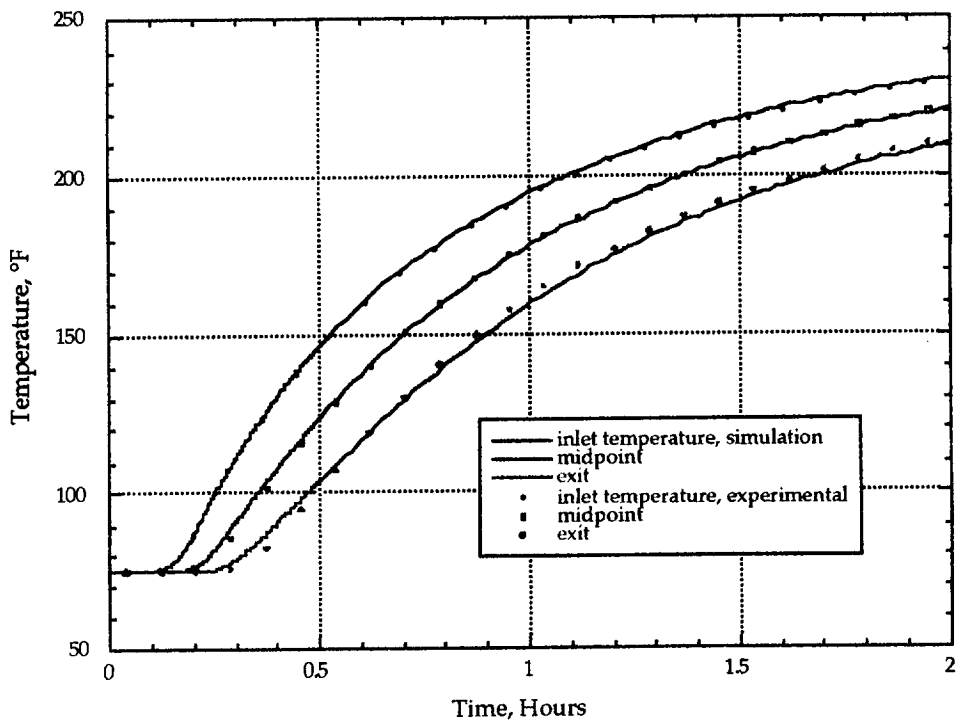


Figure 5.4-6 Thermal Validation of the Computer Model

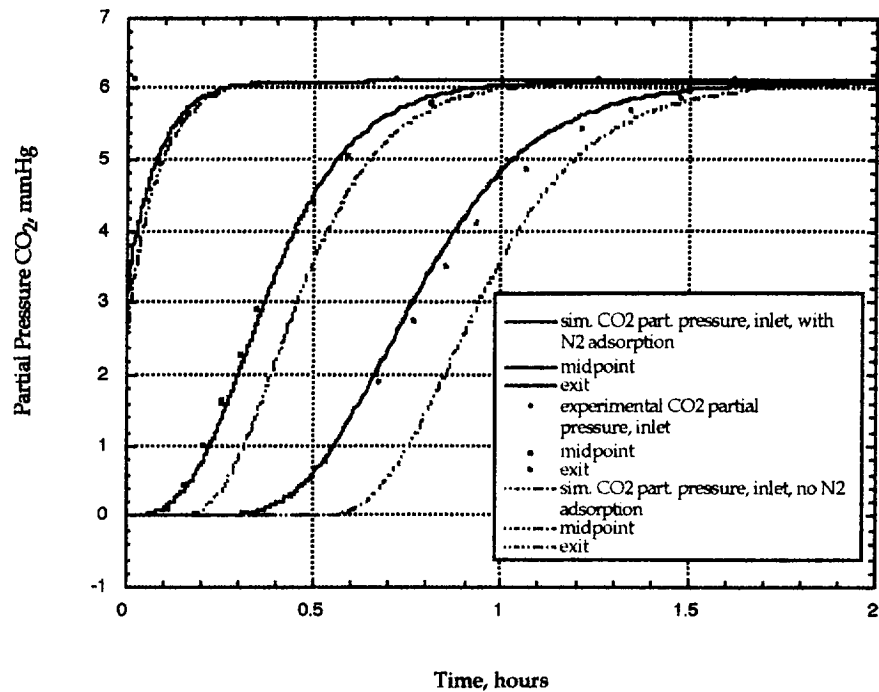


Figure 5.4-7 Mass Transfer Effects of Nitrogen Co-adsorption

The thermal sensitivity to N₂ co-adsorption is shown in Figure 5.4-8. The agreement is much better when the heat of adsorption of nitrogen is accounted. A dip in temperature occurs at 0.15 hours in both the test data and the simulation, due to N₂ displacement by CO₂. N₂ is seen to reduce the bed capacity and lower overall bed temperatures through desorption.

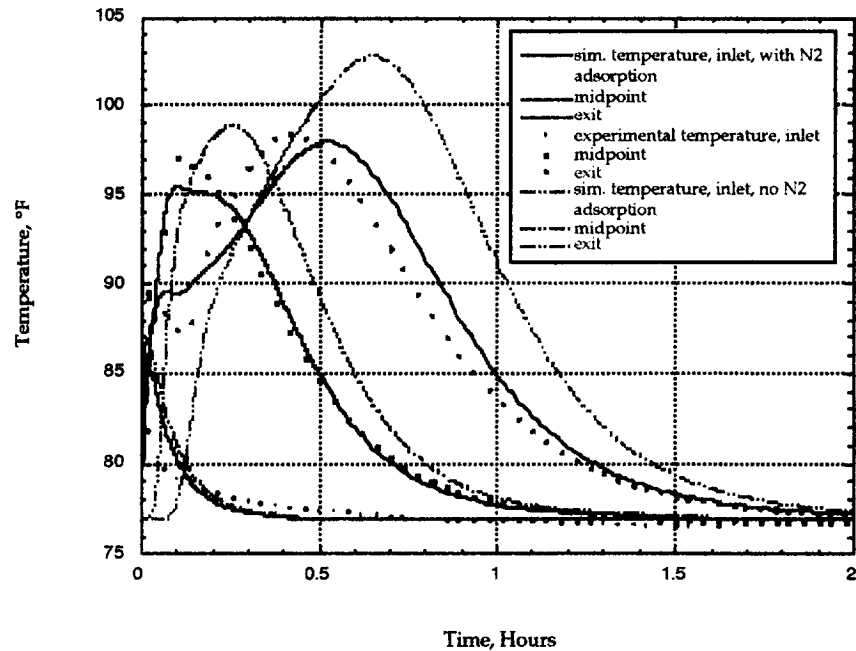


Figure 5.4-8 Heat Transfer Effects of Nitrogen Co-adsorption

5.4.2.4 Water Co-adsorption Effects Modeling

The interaction of water and CO₂ adsorption, and the effects of resulting heat generation, are shown in the simulation results in Figure 5.4-9. As illustrated by this time-sequence, the relatively weakly-adsorbed CO₂ initially saturates the sorbent downstream of the steep, slow-moving H₂O mass transfer wave. This results in two peaks on the thermal wave in the first figure (at 15 minutes). At 45 minutes, the thermal wave due to H₂O adsorption begins to drive CO₂ off the sorbent; by 105 minutes, the thermal wave effects are nearly complete. Finally, the H₂O is seen to completely displace CO₂ as it slowly moves down the column.

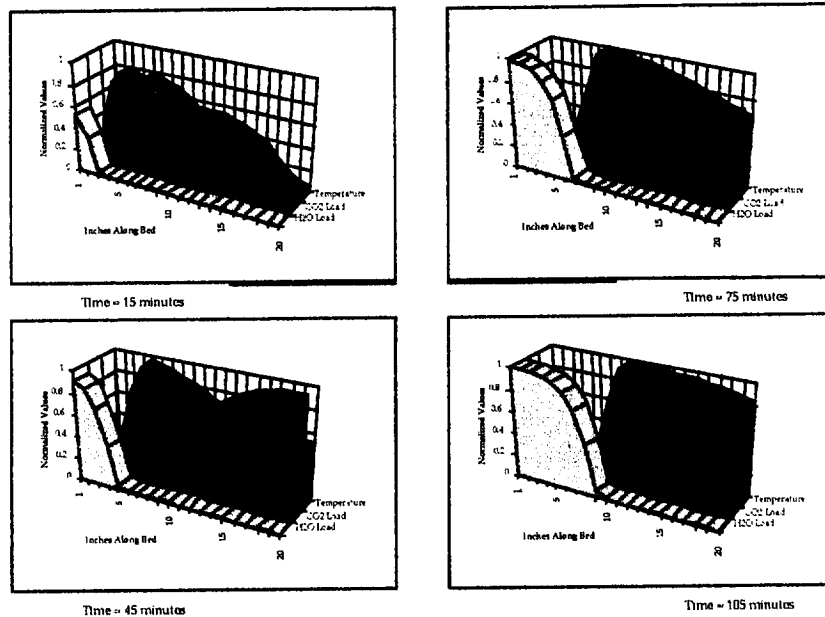


Figure 5.4-9 Effects of Water Co-adsorption

Verification of the model for CO₂/H₂O/N₂ co-adsorption shown in Figures 5.4-10 to 5.4-12. These three figures illustrate testing and simulation runs for adsorption of water at 6.3 mmHg and CO₂ at 2.89 mmHg in a carrier gas of nitrogen. All figures show test data as markers and simulation data as lines.

Figure 5.4.10 illustrates the "roll-up" phenomenon as adsorbed CO₂ is driven off by water, and the CO₂ partial pressure rises above the inlet level temporarily. The effect should be larger at the column outlet than midpoint as shown by test data.

Figure 5.4-11 shows the water breakthrough at the column midpoint and outlet. Also shown is the H₂O partial pressure of gas mixed by passing through glass beads downstream of the sorbent material. Note the mixed gas breaks through before the gas at the centerline, indicating that channeling is significant along the walls of the two-inch diameter column. Since the heater core of the 4BMS sorbent bed consists of channels roughly one-half inch in diameter, the channeling effect on CO₂ removal will be significant. The results of the two-dimensional model (not shown here) confirm that channeling has a significant effect on this adsorption process. Finally, Figure 5.4-12 shows the temperatures of the bed at midpoint and outlet.

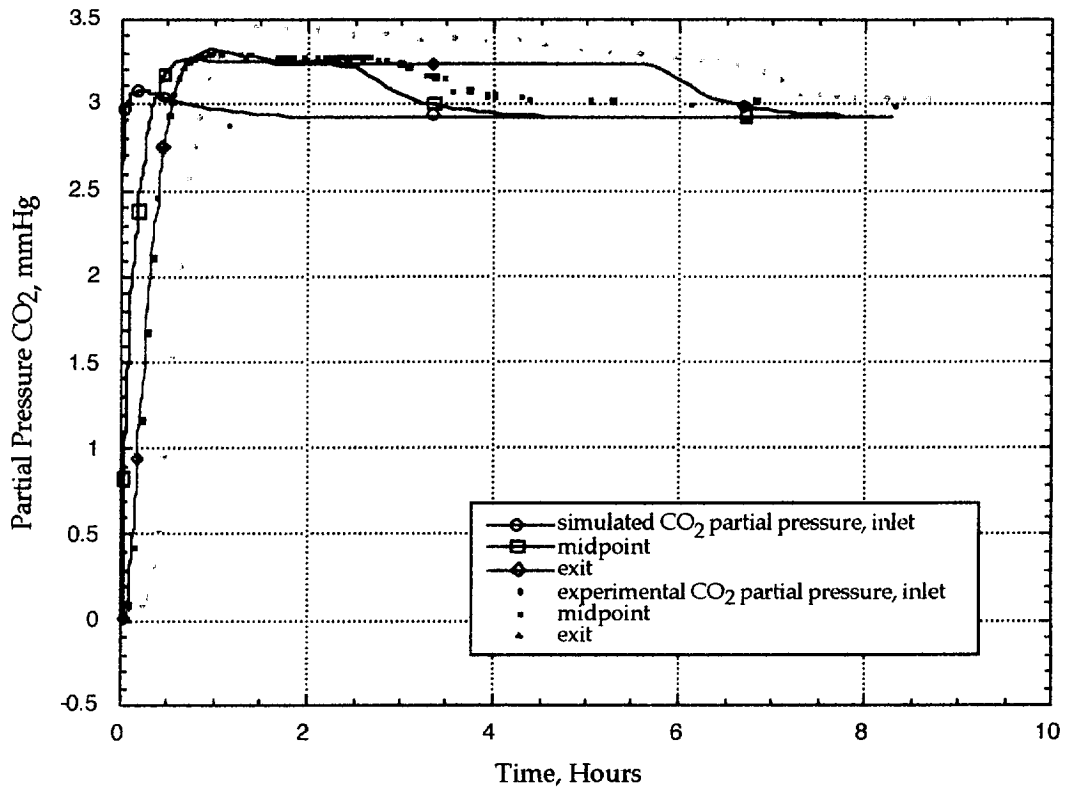


Figure 5.4-10 Mass Transfer of CO₂ for CO₂/H₂O/N₂ Co-adsorption

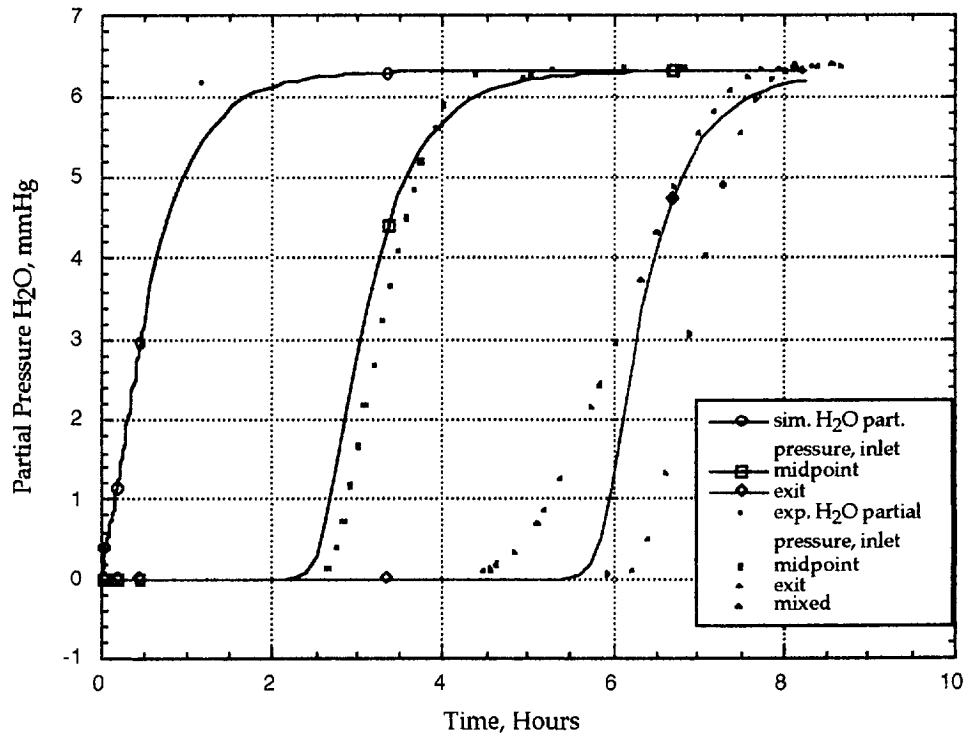


Figure 5.4-11 Mass Transfer of H₂O for CO₂/H₂O/N₂ Co-adsorption

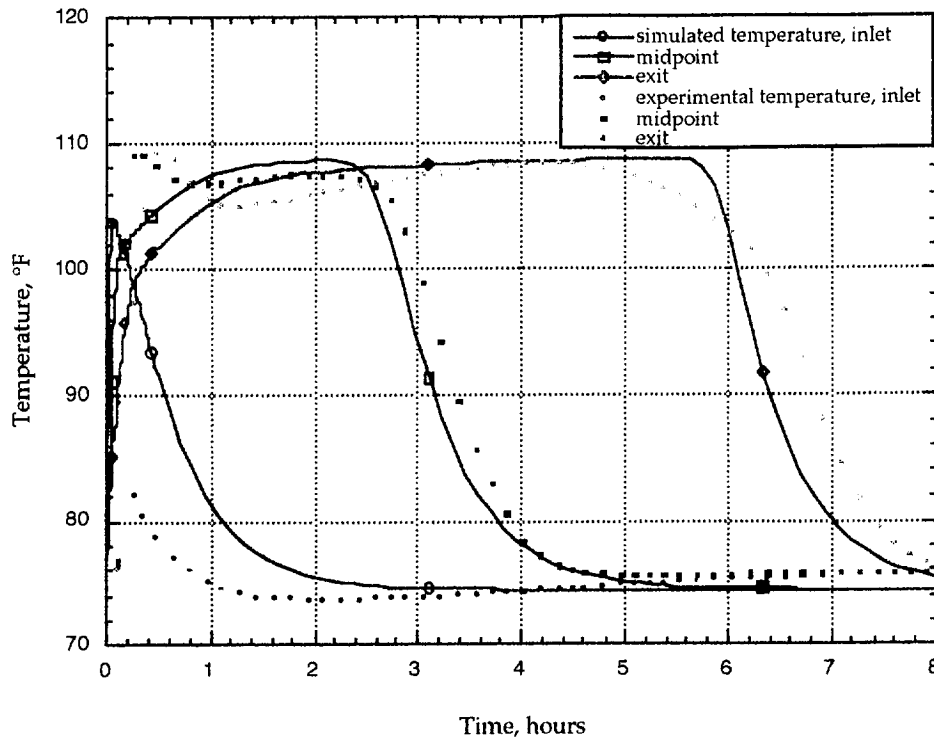


Figure 5.4-12 Heat Transfer Effects for CO₂/H₂O/N₂ Co-adsorption

Based on analytical and experimental investigation of convective flows in porous media the following conclusions are drawn:

- The experimental results from the laboratory scale-fixed bed adsorber are quantitatively consistent with the one-dimensional model at the column center. The average concentration of cross sectional bed obtained by test result deviates from the column center concentration appreciably. This indicates the strong effects of porosity variation along the radial direction of column bed on the temperature, concentration, and velocity field. These observations resulted in the decision to model the dynamic behavior of the column in two-dimensions.
- The two-dimensional model demonstrates the importance of non-darcian momentum and porosity variation on the flow distribution, concentration, and temperature in the radial direction of the bed. The two-dimensional model not only predicts the concentration and temperature profile at the column center well, but it also predicts the average concentration reasonably well.
- A linear driving force mass transfer model provides a reasonable fit to the experimental adsorption and desorption.
- The concentration of a key component, CO₂, is affected by the presence of the non-key component, N₂, in CO₂/N₂ adsorption. CO₂ effluent concentration overshoots its inlet concentration because of H₂O displacement (more easily adsorbed) component. The height of this roll-up is increased with the inlet concentration of H₂O component.

- Comparison of model results with test data shows the created models can be accurately used for modeling of the actual 4BMS.
- The two-dimensional model can be used to simulate the actual 5A bed of 4BMS, which contains an array of approximately 1/2 inch square channels, for porosity variation.
- The IAST equilibrium predicts the breakthrough curve much closer to the test data than the Lanmuir-Fredlitch theory for mixtures of CO₂/N₂ and CO₂/H₂O.

5.4.2.5 Adsorption Equilibria ²⁰

Single component adsorption isotherms required for the simulations are collected via static volumetric adsorption experiments. Isotherms are obtained for all adsorbent (13X and 5A zeolites and silica gel) and gas (N₂, CO₂, and H₂O) combinations over temperatures ranging from 0° to 250°C. Other physical properties of the adsorbents (e.g., porosity and thermal characteristics) are obtained through routine methods. Multicomponent experiments are performed to test the co-adsorption equilibrium prediction. Single and multicomponent testing is being performed at Ames Research Center (ARC). The family of adsorption equilibrium isotherms for CO₂ on Grace 13X zeolite is shown in Figure 5.4-13.

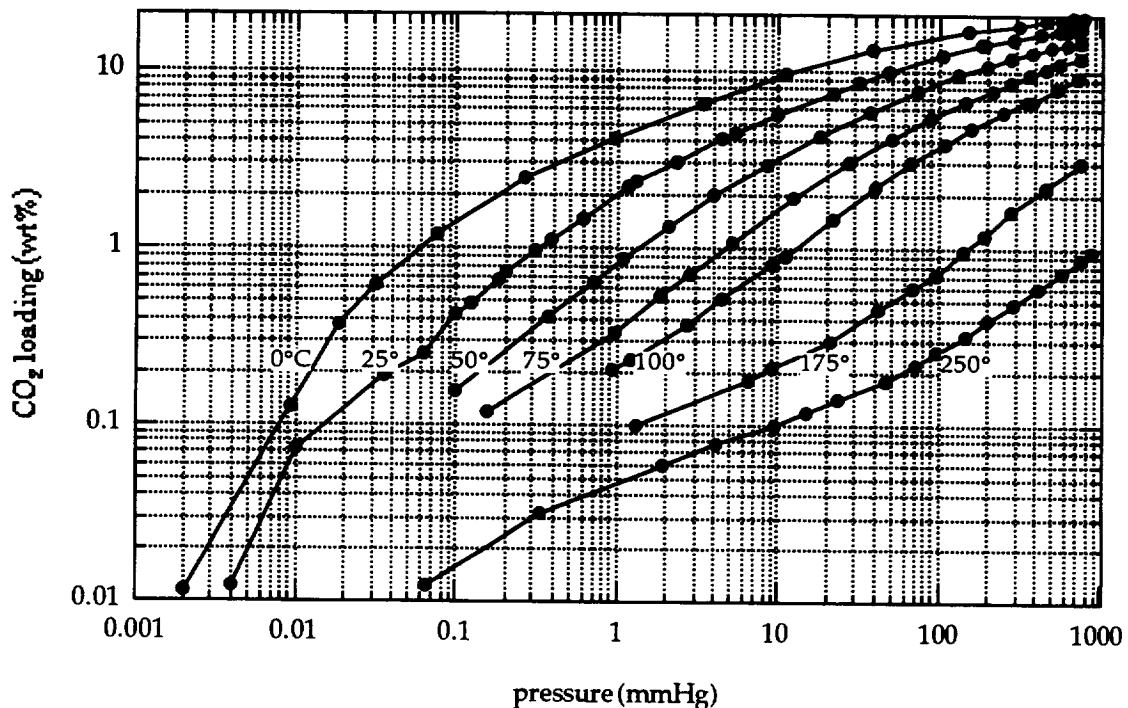


Figure 5.4-13 CO₂ Adsorption on Grace 13X Zeolite

5.4.2.6 Column Dynamics

Fixed-bed column tests are performed on a 20-inch long, 2-inch diameter insulated column. Gas samples are taken and temperatures are measured at four axial locations and at the exit. Samples are analyzed using a gas chromatograph equipped with a thermal conductivity detector. The experiments provide data for simulation verification and coefficients for lumped mass transfer terms in the model. Fixed-bed column tests are performed at MSFC.

5.4.2.7 Integrated 4BMS Model Development

Integration of the verified single-bed models described above is being performed at MSFC. The integrated model will be developed in two formats.

A standalone version is being developed featuring transportability to any computer platform with a FORTRAN 77 compiler. This version will utilize simplified heat exchanger and blower components and will be limited to bed configurations matching the existing 4BMS configuration.

Conversion of the single-bed models to CASE/A (Computer Aided System Engineering and Analysis)²¹ component models will follow development of the standalone 4BMS model. CASE/A, a graphical-based system-level computer modeling tool, will allow much greater flexibility in configuration of the sorbent models. The 4BMS CASE/A model will be developed using the graphical user interface and existing CASE/A components such as heat exchangers, valves, blowers, controllers, and timers. Other CO₂ removal system configurations can be readily developed based on the verified single-bed models in CASE/A to analyze candidate technologies for the evolutionary Space Station and future manned missions.

5.5 Life Testing

5.5.1 Carbon Dioxide Removal System ⁸

The ECLSS CDRA, 4BMS, utilizes the zeolite materials acting as sieves on a molecular scale to remove CO₂ molecules from air. The CO₂ molecules in the CO₂ enriched air are adsorbed to the zeolite 5A as the air flows through, and then released when the zeolite 5A undergoes a thermal/pressure swing process. The desorbed CO₂ is either released to the outside air, or collected in the accumulator tank for further processing. This process removes the excess CO₂ from the air in a confined environment.

The 4BMS system is shown in Figure 5.5-1. Major components are comprised of two pairs of desiccant and sorbent beds. The desiccant bed consists of a canister containing sorbent materials of silica gel and zeolite 13X. The carbon dioxide sorbent bed contains sorbent material zeolite 5A. Other components include a blower, a heat exchanger, a CO₂ pump, a CO₂ accumulator tank, four air selector valves, two CO₂

selector valves, and two check valves. Also, sensors with signal amplifiers measuring the temperatures, pressures, and dew point temperatures are used for controlling purposes. Among all components, the desiccant and sorbent bed materials are flight-like.

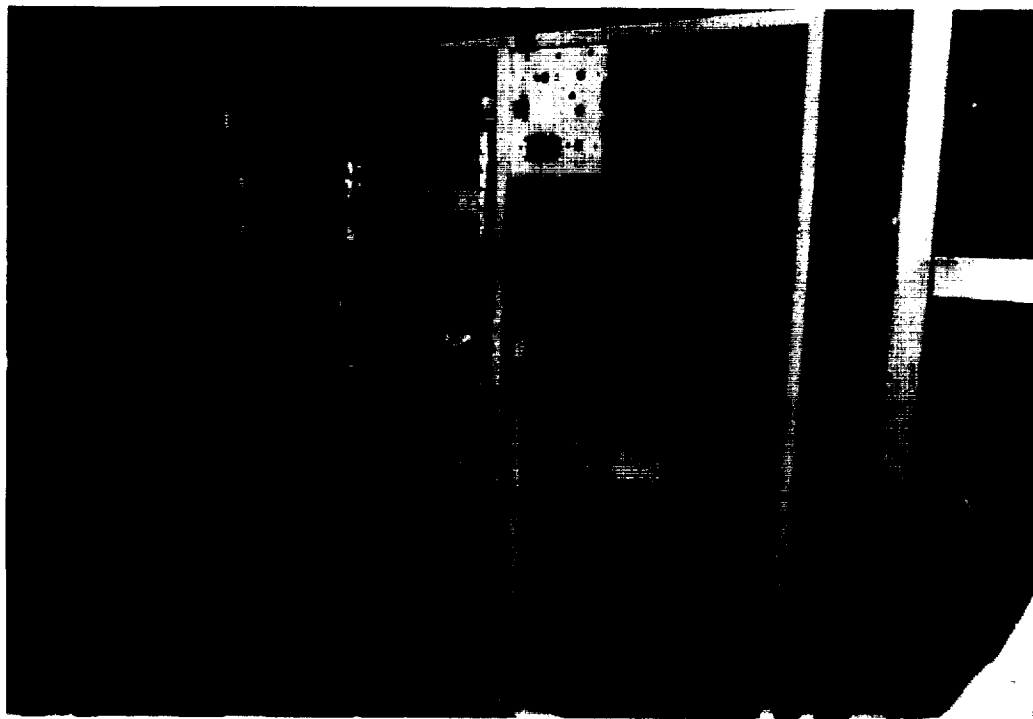


Figure 5.5-1 Four Bed Molecular Sieve

Since the Life Test initiation, the flight-like adsorbent material, cylindrical zeolite 5A, has displaced within the beds and produced small particles and dust. The particles and dust entered the system through the originally designed filters and caused premature blower failures. After the redesigned filtering system was installed, and particle flow was redirected to a bypass, the 4BMS subsystem ran nominally with minimum dust in the system. However, the dust is still being produced inside the sorbent beds and the majority of the dust is confined in the beds by the filters. Very small amounts of dust has passed through the filters, entered the system, and collected in the dust collection pipe.

Efforts have been made to resolve this dust problem. Both new and used adsorbent materials from the CO₂ sorbent bed have been analyzed by Scanning Electron Microscopy (SEM). The micrographs showed cracks on the used material but not on the fresh zeolite 5A. The dust composition, collected from 4BMS life testing, has also been analyzed with SEM and X-ray backscatter techniques. The results showed a consistent composition between samples indicating that the small particles and dust were physically breaking up and flaking off the zeolite 5A pellets. It has also been concluded that the adsorption and desorption process is not a dominant source of dust generation.

Among all the dust generation sources, the compression forces during the initial loading of the beds and those resulting from thermal expansion and contraction of the sorbent bed housing and heater core are considered most predominant. Since the dust generation continues, the vendor has proposed that in addition to the improved containment design the material geometry be changed from a pellet form to spheres. It is believed that the roundness of a sphere will be less likely to wear than the edges of a pellet. To assess the contributions of compressive forces and provide further data to support or deny the plausibility of a material geometry change, a bench-scale test was conducted on the two shapes of zeolite materials, cylindrical and spherical. The results showed that the spherical material is more prone to dust generation. A test conducted by AlliedSignal also showed that the performance of the spherical materials did not meet the CO₂ removal requirement. Thus, the sorbent material geometry will not be changed.

The most recent anomaly occurred when the 4BMS subsystem life testing restarted on November 20, 1995. It was running nominally with a lower power consumption of sorbent bed (2) (Refer to Figure 5.4-2). The temperature of sorbent bed (2) was also much lower than sorbent bed (4). After adjusting the variac to increase the wattage, there was still no significant improvement. It was concluded that some heater elements were burned out from the shutdown occurring on November 1, 1995. During this shutdown the system was locked in the heating mode of sorbent bed (2) and caused the heater elements to burn out. There are thirteen heater elements for the primary and secondary heaters. Only four primary heater elements are still good. The other primary heater elements and all secondary heater elements were open. The heater elements of sorbent bed (4) have also been checked. Only two secondary heater elements were open and the rest of the heater elements are all good.

Both beds will be sent to AlliedSignal to replace the heater core. A heater elements failure report will be requested when AlliedSignal replaces the heater elements. The current materials in these beds will be reused to preserve the life accumulated. AlliedSignal is preparing a cost proposal for this refurbishment.

Initial 4BMS life testing started January, 1993, with testing on the desiccant and sorbent materials. Total test time has exceeded 13,500 hours and there is no sign of material degradation. A flight-like blower is being fabricated and will be integrated into the existing test stand for operational life test after delivery. The control software, including the day/night operating cycle, will also be integrated to test functionalities.

5.5.2 Trace Contaminant Control System ²²

The purpose of the TCCS Life Test was to provide long duration operation of the ECLSS TCCS High Temperature Catalytic Oxidizer (HTCO) at normal operating conditions. Specifically, the test was designed to demonstrate thermal stability of the high temperature oxidizing catalyst. The TCCS life test was discontinued after 762 test days with no observed catalyst degradation.

A TCCS utilizing a 0.5% palladium on alumina catalyst is scheduled for use on the ISS for oxidizing trace organics in cabin air, yielding primarily CO₂ and H₂O. These products will be removed from the air stream, by other ECLSS components, prior to

the air stream's reentry into the cabin atmosphere. The organics to be oxidized will be introduced into the cabin as human metabolic products, and through off-gassing of materials used in ISS construction.

TCCS Life Testing utilized flight-like hardware built by Lockheed Missiles and Space Company. The axial fan and the low leg blower were both refurbished by the vendor prior to the beginning of the life test. The HTCO was fitted with additional thermocouples to more efficiently monitor internal temperatures. The flight-like test hardware was the HTCO assembly, and the palladium on alumina catalyst found within the HTCO housing. A TCCS simplified schematic is shown in Figure 5.5-2.

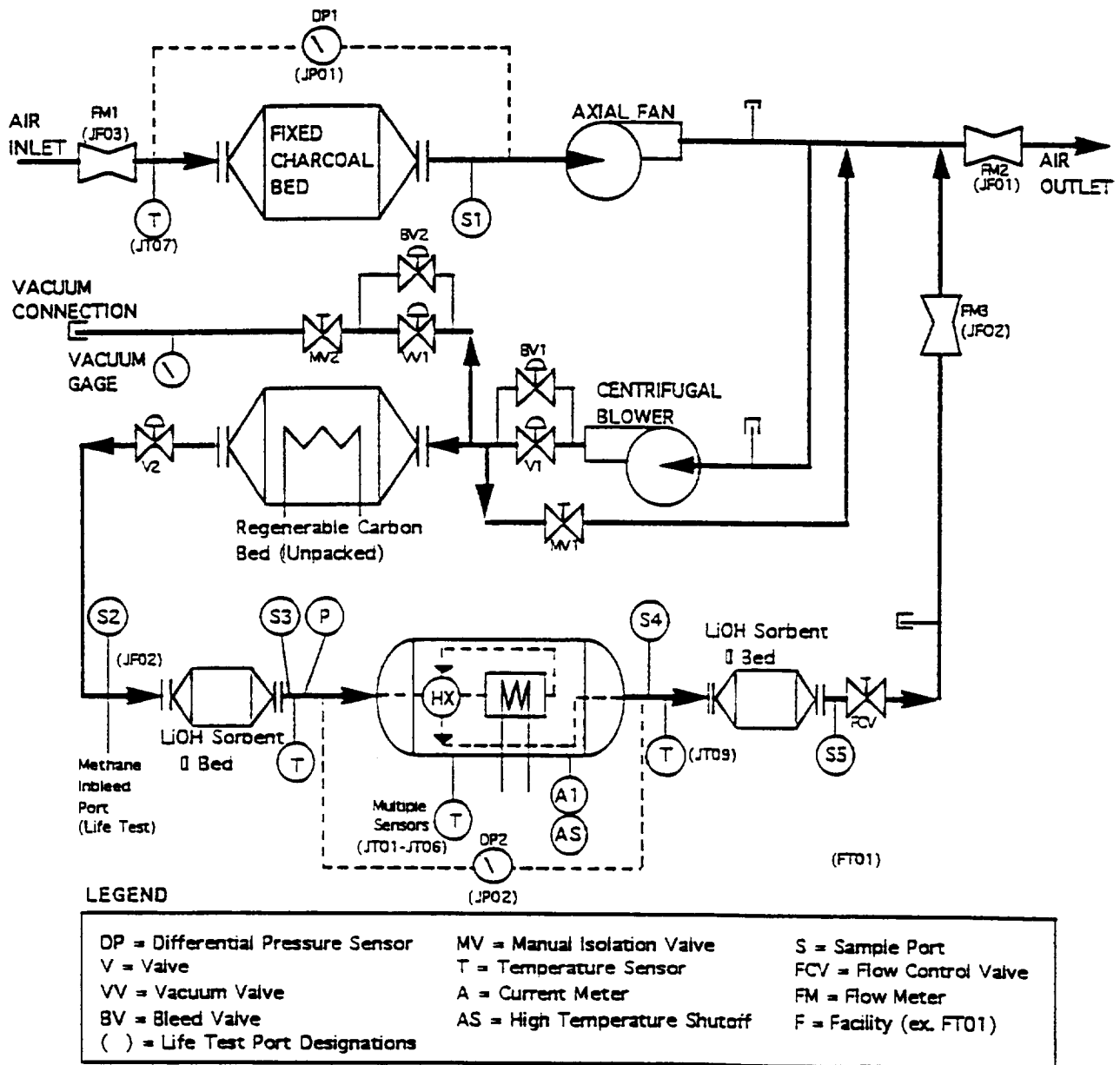


Figure 5.5-2 TCCS Schematic

In the TCCS catalyst life test, 3% methane in air was bled into an air stream in the catalytic oxidizer lower leg. This is just prior to the lithium hydroxide (LiOH) Presorbent Bed canister. The canister was used as a mixing chamber for this test, and was otherwise inoperable. The air stream methane concentration, as it left the presorbent canister, was approximately 90 ppm. The air stream then entered the H₂CO assembly (containing the palladium catalyst), where it passed through a heat exchanger, and then the catalyst bed. Within the bed, methane and other organic contaminants were oxidized. The air stream containing the oxidation by-products then left the bed, passed again through the heat exchanger (cooling somewhat as it gave up heat to the incoming air stream), and exited the assembly.

Life testing of the TCCS has provided much useful information. Above all, the test has shown that the H₂CO catalyst life is much longer than previously estimated. While the ISS logistics plan calls for catalyst replacement every 180 days, the Life Test has shown that, under non-poisoning conditions, the catalyst can remain effective in excess of two years and possibly much longer at the baseline temperature and flow conditions. This represents tremendous cost savings to the ISS program. In addition, preliminary catalyst poisoning test results have shown that a poisoned catalyst of this type can recover to a usable extent with increased heat and exposure to a non-poisoning atmosphere (Section 5.1.1).

5.6 Static Feed Electrolyzer Flight Experiment Preliminary Design ²³

In 1989 and 1990 a comparative test of electrolyzer technologies was conducted at the MSFC in Huntsville, Alabama. As a result of this test, LSI's SFE was selected for use on the SSF and proceeded through a Space Station PDR. Soon after completion of the PDR, the Space Station Program was restructured and further development of the O₂ generator was deferred. As a result of this deferral, SFE work was placed on hold.

The next significant event was the change from SSF to ISS. Of significance in this change was that the O₂ generator operation was changed from continuous to cyclic to match the light/dark cycle of the orbit which required modifications to the SFE hardware design and control software. The change from continuous to cyclic operation of the O₂ generation introduced a requirement that the O₂ generator be capable of rapid transitions from inactive operation (Standby Mode) to active operation (Normal Mode) so that maximum utilization of the 53 minute sunlight period of the orbit can be achieved. Because this requirement did not previously exist, all past emphasis was placed on long-term continuous operations.

Closure of the ISS OGA development was still deferred to later in the program. At this point it was recognized that it was possible to implement a Flight Experiment that would demonstrate the operation of an integrated SFE subsystem in microgravity and significantly reduce the risk of using the SFE on ISS.

This opportunity was identified by NASA and, with the sponsorship of MSFC within NASA, a Flight Experiment program was initiated. This program was structured as a two-phase process. The first phase (funded by the Space Station Program Office under TTA's) was structured to define the experiment and complete design work through a PDR. The second phase (funded by NASA Headquarters Code M) is to

implement the design documented by the Preliminary Design through a flight test in either the MIR, Spacelab, or SPACEHAB flight platforms. The SPACEHAB has been identified as the flight vehicle to be used. Figure 5.6-1 presents a photograph of the SFE Flight Experiment PDR Mockup.

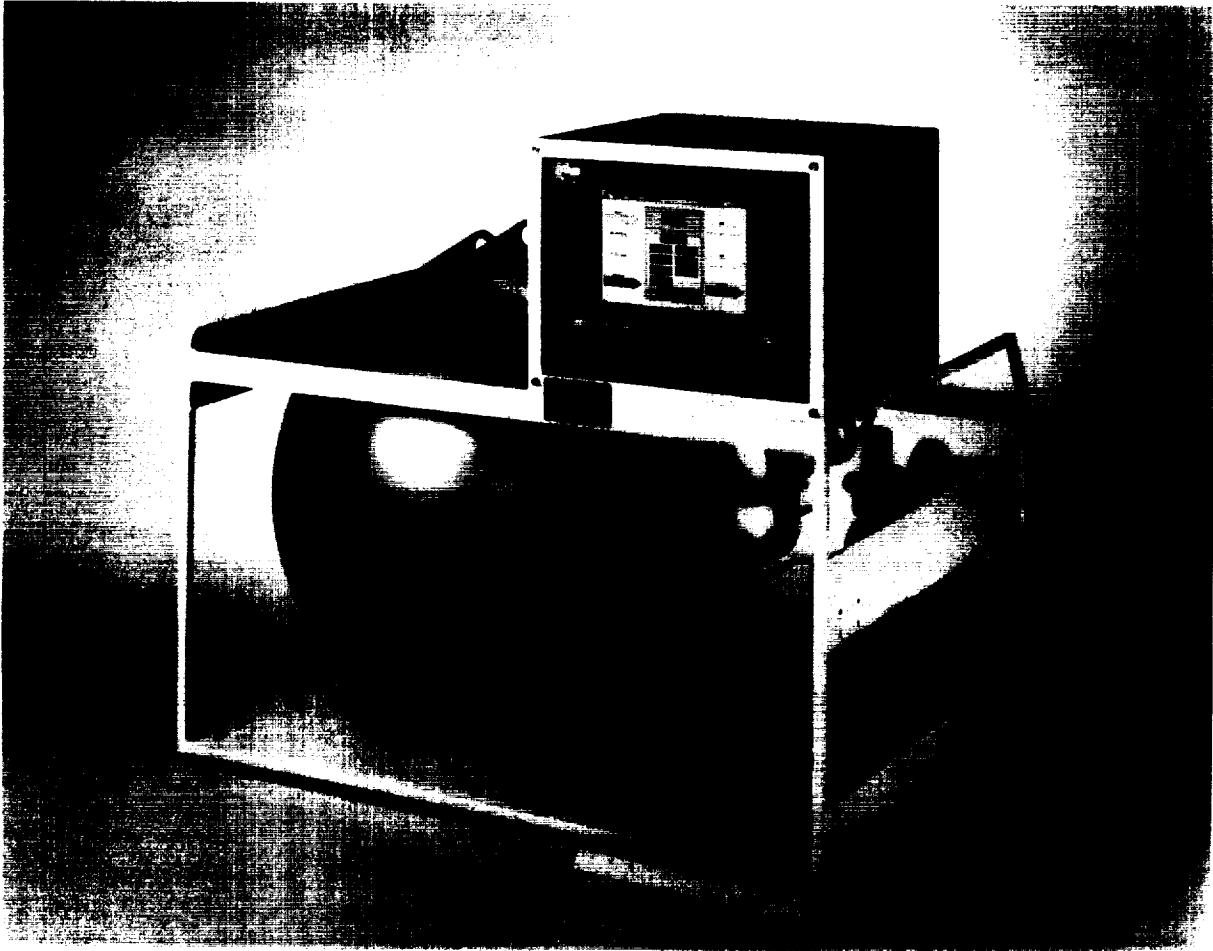


Figure 5.6-1 SFE Flight Experiment PDR Mockup

The overall objective of the SFE Flight Experiment is to demonstrate the readiness of the technology for use in long duration space missions as a water electrolysis based utility. Specifically, the objectives of the experiment are to:

- Evaluate the microgravity sensitivity of all SFE System components and processes on an integrated basis. This includes validation of ground-based analyses and multiple-cell configuration behavior.
- Verify the performance of the integrated SFE System in microgravity, which will validate: (1) the entire SFE concept at the systems level; (2) the interaction of component parts; (3) quality and quantity of product gases; and (4) the SFE efficiency.

The objectives of the Preliminary Design program were to define an experiment that, if successfully performed, accomplish the two overall program goals stated above and, to develop and document a design through a PDR that can be efficiently implemented into hardware and qualified for flight.

Extensive test data from operation of the upgraded SFE-IVA, designated the SFE-IVA' will be available to support the final design of the SFE Flight Experiment which will incorporate the new features being demonstrated by the SFE-IVA'. Modifications to this subsystem and a summary of test data was provided in Section 5.2.1 of this report.

The SFE Flight Experiment will provide extensive data, that when compared to Earth-based test data, will verify the readiness of SFE technology for application to ISS or other long-duration missions. The successful implementation of the PDR shows that an SFE Flight Experiment can be implemented within the resource constraints of the available flight vehicles that will accomplish the goals of the program.

6.0 MICROBIOLOGY

6.1 Assessment of Microbial Degradation of Space Station Materials ^{24, 25}

The degradation of materials by microbial attack is now accepted as a common occurrence. This hazard has been recognized in the Soviet/Russian space program. Numerous examples of attack of spacecraft materials have been documented. The goal of this task (Task A) was to assess the risk from microbial activities to candidate materials for the Space Station.

To assess the hazard for the Space Station, literature from the Russian space program and European Space Agency was reviewed. A collection of more than 70 papers were gathered in which either materials were determined to have been damaged by microbial attack, or human health hazards were reported because of the growth of microorganisms on surfaces in space habitats. The main focus was on the engineering problems rather than on the effects on crew health.

The Russian literature reports a wide range of materials attacked by bacteria and fungi. For example, on Salyut-6 thick fungal growth was observed on rubber straps. On Salyut-7 visible mold was observed on the hull, joints, and cables in the work area. Structural damage, including perforation of insulating material, was detected. The viewing window of the Soyuz transport vehicle was obscured by fungal growth. Degradation of polymeric materials, including epoxy enamels, by microbial activity, was also detected.

All of the publications reviewed for this report have been incorporated into a database, entitled MicroBase. This database was prepared to make the assembled literature easily accessible. All pertinent articles, books, and reports, which were located in the literature search, are in the database. Key words have been provided to facilitate easy location and cross-referencing of the data.

A major part of Task A was to test the susceptibility of candidate materials for the Space Station to microbial attack. No methods were available to either qualitatively or quantitatively assess the risk of material biodeterioration. A set of detailed protocols were developed for use in screening materials for susceptibility to microbial attack.

These protocols were applied to test seven candidate materials for susceptibility to microbial growth and degradation. The materials tested are polyimide foam, rubber-silicone sealant, teflon wire insulation, titanium tubing, a composite under development, a polyurethane coating, and polyurethane coating containing 1% fungicide.

Accelerated testing was performed at high humidity and high temperature. All seven materials developed large populations of bacteria and fungi within two weeks. SEM showed penetration of the non-metallic materials by microorganisms. Electrochemical Impedance Spectroscopy (EIS) was used to determine damage to the coatings and the composite. The materials showed damage due to attack by fungi within four weeks. Results for attachment studies of the two coatings indicate that there is no difference in the development of the microbial population between the polyurethane

coating without fungicide and the polyurethane coating containing 1% fungicide. Results indicated that the fungicide in the polyurethane coating failed to inhibit either attachment or growth of microorganisms at the concentration used (Figure 6.1-1 and 6.2-2).

The task was extended (Task B) to investigate the effect of lowering the temperature and humidity on the proliferation of microorganisms on surfaces of Space Station materials. In addition, electrochemical degradation studies initiated during Task A were continued to determine the long-term effect of microbial growth on candidate materials.

Results of Task B indicated the following:

- At ambient temperatures, all seven of the materials supported large microbial populations when the atmospheric humidity was permitted to fluctuate within a range of 40% to 80% Relative Humidity (RH).
- At ambient temperatures, maintenance of the atmospheric humidity within the range specified for the Space Station, 45% to 55% RH, resulted in a drop-off of the microbial population on the surfaces of all seven candidate materials.
- Scanning Electron Microscopy observations confirmed that on surfaces maintained at ambient temperature and 45% to 55% RH, microbial populations remained at extremely low levels.
- In assessing the efficacy of the biocide treatment for the polyurethane coating, it was conducted that the biocide is ineffective at the concentration specified for use. EIS analysis demonstrated that microorganisms overrode the biocide, resulting in deterioration of the protective coating.

The data obtained during Task B led to a number of conclusions. Humidity is the key to microbial growth on surfaces. Variation in humidity between approximately 40% and 80%, even at low temperatures, leads to massive growth on all surfaces tested. Conversely, if the humidity is maintained below 55% RH, the microorganisms die off. This is a surprising and important observation. Even when the surfaces are repeatedly challenged with microbial contamination, the number of microbes rapidly declines to low levels at humidities in the range of 45% to 55% RH.

The implications of these results are that, at temperatures close to ambient for the Space Station, if humidity is maintained at a "reasonable" 45% to 55%, then microbial survival and growth on candidate materials for the Space Station should be minimal.

Continuation of EIS analysis of the polyurethane coatings, with and without biocide additive, confirmed preliminary findings. The data from attachment studies show that the biocide, used at the concentration specified, does not prevent growth of microorganisms as intended. Furthermore, EIS data show that the polyurethane coating is highly susceptible to microbial attack. The microorganisms rapidly overrode the biocide additive and attacked the biocide-treated coating. Our analysis strongly indicates failure of the biocide.

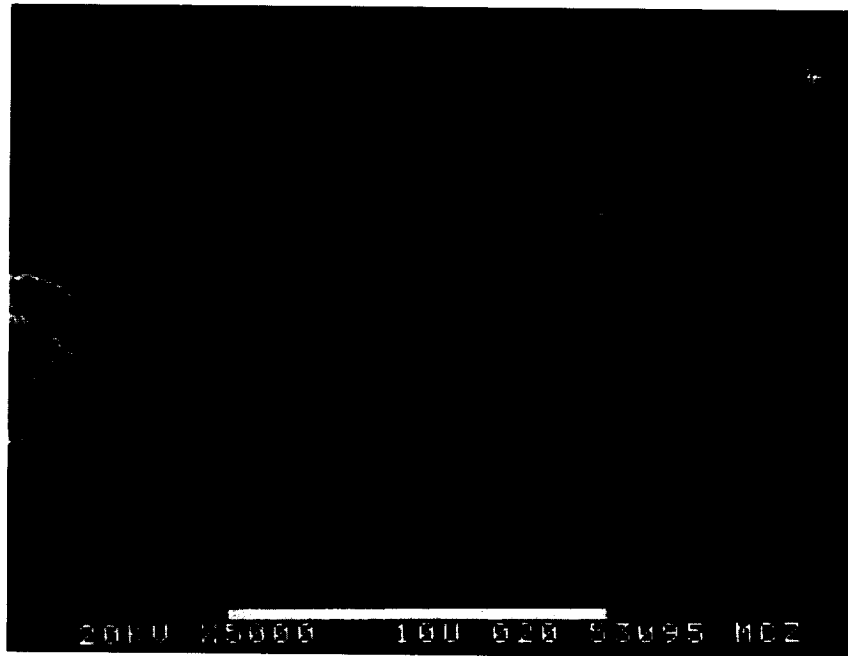


Figure 6.1-1 Microbial Colonization of Polyurethane Coating

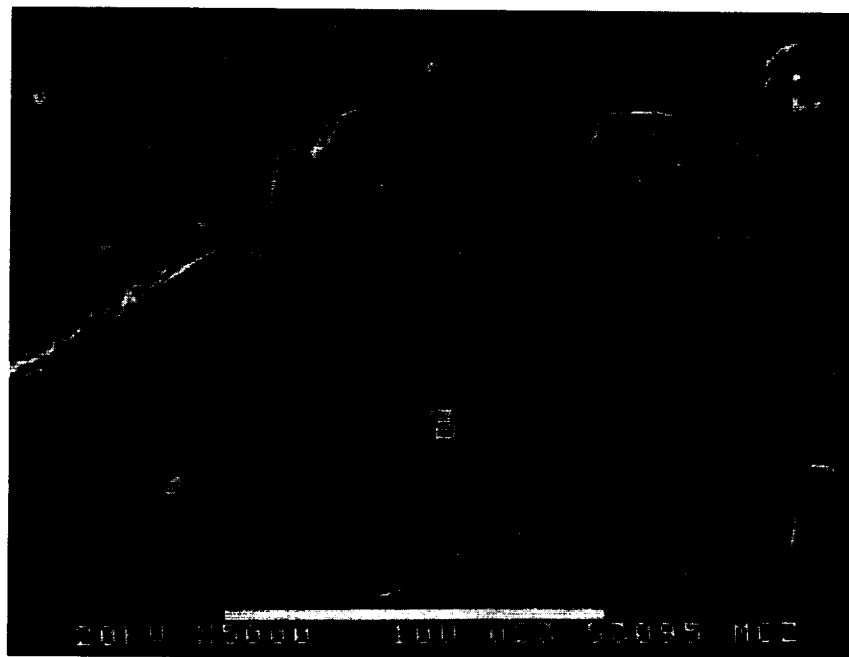


Figure 6.1-2 Microbial Colonization of Polyurethane Coating with Fungicide

6.2 Polymerase Chain Reaction Assessment ²⁶

The monitoring of spacecraft life support systems for the presence of health threatening microorganisms is paramount for crew well being and successful completion of missions. Development of technology to monitor spacecraft recycled water based on detection and identification of the genetic material of contaminating microorganisms and viruses would be a substantial improvement over current NASA plans to monitor recycled water samples that call for the use of conventional microbiology techniques which are slow, insensitive, and labor intensive. The feasibility of Polymerase Chain Reaction (PCR) technology was addressed for development of a microbial water quality monitor for use on the Space Station.

PCR is a genetic-based method in which a Deoxyribonucleic Acid (DNA) segment of the target microorganism is detected by enzymatic amplification of a single DNA segment to a million fold. The PCR procedure consists of three steps which is referred to as a cycle: (1) The double-stranded DNA is heat-denatured; (2) two primers (short single-stranded oligonucleotides, the nucleotide sequence which is located at the two ends of the target DNA to be amplified) are annealed at low temperature; and (3) the primers are enzymatically extended by DNA polymerase (TaqMan) at an intermediate temperature. An exponential increase of the target DNA occurs by repetition of each cycle. The PCR amplification is accomplished by using an instrument called a thermocycler which repeatedly changes the temperature of the PCR sample. The technique is relatively new; however, it is being used increasingly as a method of diagnosing and precisely identifying microbial contamination in environmental, clinical, and industrial samples.

The chemistry and molecular biology needed to utilize these probe-hybridization/PCR instruments must evolve in parallel with the hardware. The following issues of chemistry and biology must be addressed in developing a monitor:

- Early in the development of a PCR-based microbial monitor it will be necessary to decide how many and which organisms does the system need the capacity to detect. We propose a set of 17 different tests that would detect groups of bacteria and fungus, as well as specific eukaryotic parasites and viruses.
- To use the great sensitivity of PCR it will be necessary to concentrate water samples using filtration. If a lower limit of detection of 1 microorganism per 100 mL is required then the microbes in a 100 mL sample must be concentrated into a volume that can be added to a PCR assay.
- The TaqMan PCR product detection system is the most promising method for developing a rapid, highly automated gene-based microbial monitoring system. The method is inherently quantitative. NASA and other government agencies have invested in other technologies that, although potentially could lead to revolutionary advances, are not likely to mature in the next 5 years into working systems.
- PCR-based methods cannot distinguish between DNA or Ribonucleic Acid (RNA) of a viable microorganism and that of a non-viable organism. This may or may not be an important issue with reclaimed water on the ISS. The recycling system

probably damages the capacity of the genetic material of any bacteria or viruses killed during processing to serve as a template in a PCR designed to amplify a large segment of DNA (>650 pairs). If necessary vital dye staining could be used in addition to PCR, to enumerate the viable cells in a water sample.

- The quality control methods have been developed to ensure that PCRs are working properly, and that reactions are not contaminated with PCR carryover products which could lead to the generation of false-positive results.
- The sequences of the small Ribosomal RNA (rRNA) subunit gene for a large number of microorganisms are known, and they constitute the best database for rational development of the oligonucleotide reagents that give PCR its great specificity. From those gene sequences, sets of oligonucleotide primers for PCR and TaqMan detection that could be used in a NASA microbial monitor were constructed using computer based methods.

To develop a working microbial monitor using TaqMan PCR that will meet NASA's needs for ensuring water quality, work will need to proceed in concert in three different research areas: (1) a small, fully automated instrument with low power needs will need to be developed. Similar work for other government agencies to develop a PCR-based microbial monitor is being researched; (2) the chemistry and molecular biology needed to utilize a probe-hybridization/PCR instrument must evolve in parallel. Otherwise, it would require an additional two years to develop and optimize the PCR primers and TaqMan probes as well as determine quantitative relationships between the intensity of the TaqMan signal and the number of microorganisms in a sample; and (3) a system of water sample collection and contaminant concentration must be developed, and integrated with the actual monitor.

7.0 GENERAL TEST SUPPORT TASKS

7.1 Database

The Functional ECLSS Data System (FEDS) was implemented in 1990, and resides on the MINS2 VAX at MSFC. It stores data from all ECLSS testing performed at MSFC, and has supported all test reports for ECLSS hardware produced since that time. FEDS has served as a powerful analysis tool for the ECLSS hardware design engineers.

FEDS was established to track and maintain all sample schedules, analyses from independent labs for chemical and microbial parameters, predetermined parameter specifications to maintain water quality, sensor data, and analytical control samples. The database provides ECLSS engineers on-line access to analyze data and provides formatted reports, graphical, and statistical results. Menu driven interfaces allow the user to retrieve data on-line or extract test data to files. Real-time sensor data recorded during testing is available by downloading to spreadsheet format.

In 1994, a preload program was written to support direct transfer of data from Boeing Analytical Labs to FEDS, along with specific error-checking routines. This preload program was first used to support WRT Stage 9, which ran from August to December 1994. Regenerative testing supported since then includes SFE and LFSPE oxygen generators. Life testing has been supported constantly since November 1992. Other specific testing supported is described in Table 7.1-1. A total of 15,510 records were added during 1994 and 1995. A rewrite of the user manual is in work.

Table 7.1-1 Testing Supported by FEDS in 1995

Water Recovery Test (WRT)
<ul style="list-style-type: none">• System sterilization in preparation for Stage 9 WRT• Evaluation of the latest water recovery system design for the U.S. On-orbit Segment of the ISS, 9/15/94 to 4/15/95• Follow on testing to produce condensate for unibed modeling at MTU and to perform a viral challenge on Water Processor product water, 1/9/95 to 1/30/95• Verify the VCD can process simulated urine (ersatz) planned for processing in a VCD flight experiment, 2/27/95 to 4/1/95
Subsystem Life Test (LFT)
<ul style="list-style-type: none">• Life testing of the TCCS• Life testing of the VCD urine processor• Life testing of 4BMS carbon dioxide removal subsystem
Air Revitalization Test (ART)
<ul style="list-style-type: none">• Checkout test of the oxygen removal portion of the metabolic simulator• Checkout of the CDRA• Checkout of the CDRA with repacked desiccant beds• Independent performance test of the SFE oxygen generator• Independent performance test of the SPE oxygen generator
Water Degradation Study (WDS)
<ul style="list-style-type: none">• Continued Degradation Test #1 with stainless steel and titanium• Degradation study of water exposed to all titanium wetted surfaces

7.2 Boeing Analytical Laboratory Support

Boeing analytical laboratory support is essential to perform MSFC's Technical Task Agreements involving development testing of Space Station air and water systems. Unique capabilities have been enhanced under NASA Contract NAS8-50000, Schedule F, and NAS8-38250. Boeing provided test support for the Stage 9 Water Recovery Test, Life Testing, and are currently involved in pre-test activities for the upcoming IART.

Analysis and full characterization of water and air samples for both organic and inorganic contaminants involves both standard environmental methods (EPA, Standard Methods, etc.). Unique methods developed by the Boeing laboratory specifically for contaminants derived from human metabolic processes and equipment off-gassing are established by the MSFC's Analytical Control Test Plan and Microbiological Methods for Water Recovery Testing, (Version 3.2).²⁷ High volume sampling, from several different simultaneous tests, require analysis for numerous chemical and microbial parameters. Strict custody procedures and computerized sample and data management are in place to ensure and preserve sample identity, traceability, custody, tracking, and data reporting.

Boeing Analytical Services, has been performing this role since 1989. Boeing also provides unique microbiology capabilities established in conjunction with the University of Alabama in Birmingham. The lab has the ability to quickly turn around large volumes of data utilizing sophisticated instrumentation including a Fatty acid methyl ester (FAME) Gas Chromatography system used for microbe identification, in addition to a Vitek Biochemical Identification System, and Biolog Carbohydrate Utilization Identification System.

The Test Subjects for the Stage 9 Water Recovery Test and their physical examinations were provided by Boeing. Lab analysis confirmed the acceptability of the facility tank water for use by test subjects for hygiene purposes. To enhance Space Station waste inputs, Boeing prepared ersatz to simulate animal condensate, equipment off-gassing contaminants, and Crew Health Care System (CHeCS) wastewater. Boeing collected samples from designated ports and completed the specific analyses listed in the ISS potable water quality specifications (Table 7.2-1). This is necessary to confirm subsystem performance and verify in line sensors such as the PCWQM. Also, the TOC analysis provided valuable design information relative to the VRA in the water processor.

In preparation for the IART, Boeing provided the Integrated AR Test team consultation necessary to establish an on-line GC analysis capability for the AR test utilizing the existing Hewlett Packard GC previously purchased by Boeing as government property. Boeing supported the test team in equipment set-up, optimization, and calibration; designed an automated sampling system, including method development and verification; maintaining the software, and controls required to operate the instrument; writing a Standard Operating Procedure; and provided training to test personnel in the daily GC operation.

Boeing provided Method development for the SFE to analyze for low levels (ppm) of hydrogen in product oxygen, acetone, and alcohols, total aldehydes, nitrogen dioxide, ammonia, and carbon monoxide. Methods still under development are halo acids, total fatty acids, and amines. Method development for KOH in O₂ was evaluated to analyze for and quantify aerosol KOH in product oxygen samples from the SFE.

Life testing support included analysis of air and water samples from the TCCS, the VCD urine processor, and the 4BMS. These results provide invaluable data relative to subsystem performance, and verification of in-line sensor data.

Table 7.2-1 ISS Potable Water Quality Specifications

Specification	Specification		
PHYSICAL PARAMETERS	INORGANIC CONSTITUENTS (continued)		
Total Solids (mg/L)	100	Nitrate (NO ₃ -N)	10
Color, true (Pt/Co)	15	Potassium	340
Taste (TTN)	3	Selenium	0.01
Odor (TON)	3	Silver	0.05
Particulates (max micron)	40	Sulfate	250
pH	6-8.5	Sulfide	0.05
Turbidity (NTU)	1	Zinc	5.0
Dissolved Gas (free @ 37° C)	(a)	BACTERICIDE (mg/L)	
Free Gas (@ STP)	(a)	Residual Iodine (min)	1.0
INORGANIC CONSTITUENTS (mg/L)		Residual Iodine (max)	4.0
Ammonia	0.5	AESTHETICS	
Arsenic	0.01	CO ₂	15
Barium	1.0	MICROBIAL	
Cadmium	0.005	Total Count Bacteria/Fungi	100
Calcium	30	Total Coliform	ND
Chlorine (total)	200	Virus (PFU/100 mL)	ND
Chromium	0.05	ORGANIC PARAMETERS (µg/L)	(b)
Copper	1.0	Total Acids	500
Iodine (total)	15	Cyanide	200
Iron	0.3	Halogenated Hydrocarbons	10
Lead	0.05	Total Phenols	1
Magnesium	50	Total Alcohols	500
Manganese	0.05	Total Organic Carbon (TOC)	500
Mercury	0.002	Uncharacterized TOC (c)	100
Nickel	0.05		
NOTES:			
(a) No detectable gas using volumetric gas versus fluid measurement system. Excludes CO ₂ used for aesthetic purposes.			
(b) Each parameter/constituent MCL must be considered individually and independently of others.			
(c) Uncharacterized TOC equals TOC minus the sum of analyzed organic constituents expressed in equivalent TOC.			

8.0 ACKNOWLEDGEMENTS

The authors would like to acknowledge the following people from the MSFC Environmental Control and Life Support Branch/ED62 for their contributions: Robyn Carrasquillo, Layne Carter, Robert Erickson, Donald Holder, Cindy Hutchens, James Knox, Jay Perry, Monsi Roman, Mary Traweek, and Paul Wieland. The authors would like to thank the Development Test Branch/EL63 for their technical contributions, the staffs of Boeing Laboratory, Computer Science Corporation, and ION Electronics for their technical support.

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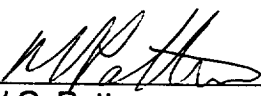
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International Space Station ECLSS Technical Task Agreement Summary Report

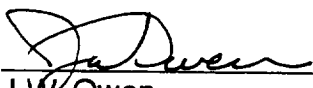
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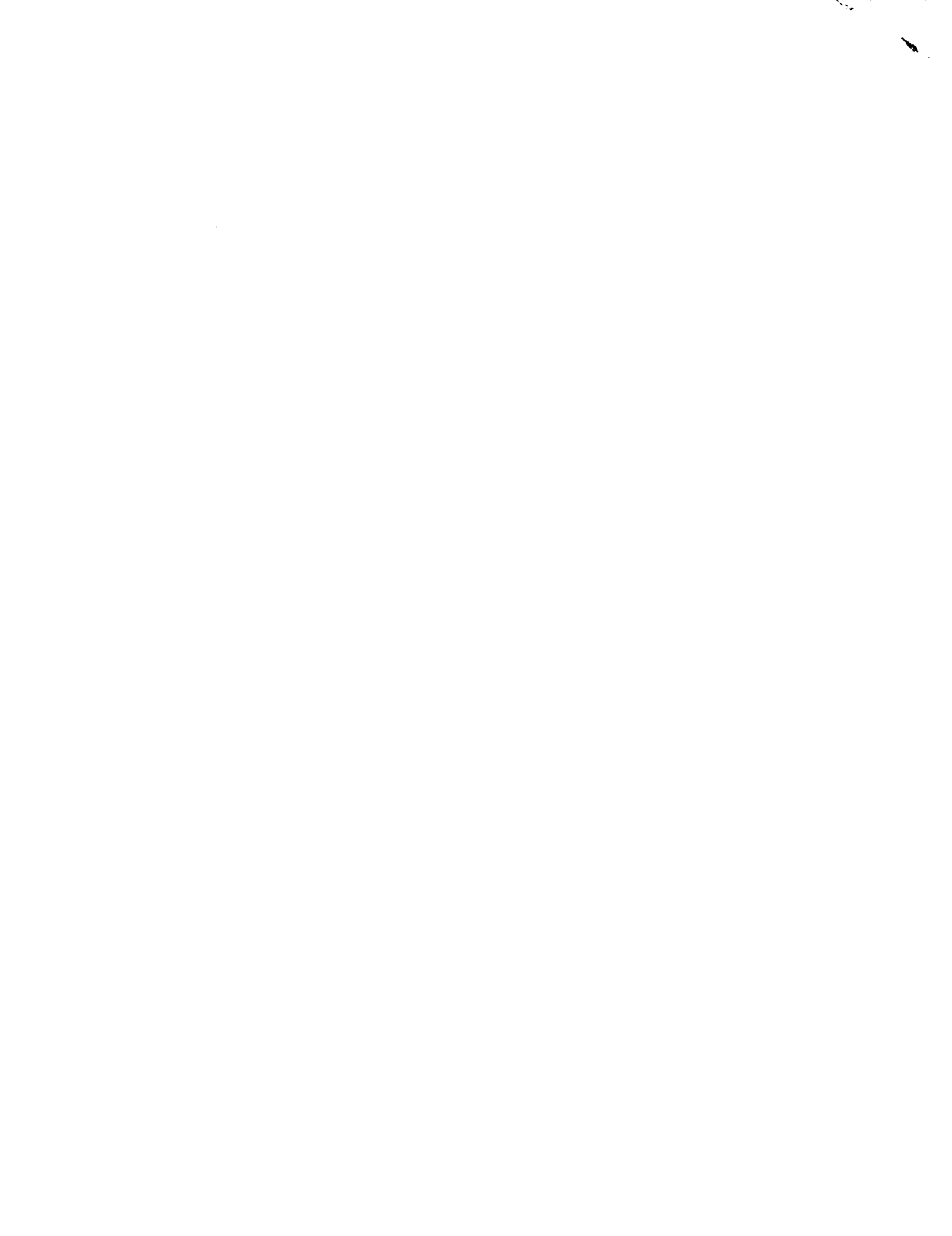
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE May 1996	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE International Space Station ECLSS Technical Task Agreement Summary Report			5. FUNDING NUMBERS	
6. AUTHOR(S) C. D. Ray and S. Minton-Summers, Compilers				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812			8. PERFORMING ORGANIZATION REPORT NUMBERS	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, D.C. 20546			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-108508	
11. SUPPLEMENTARY NOTES Prepared by Structures and Dynamics Laboratory, Science and Engineering Directorate				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A summary of work accomplished under Technical Task Agreement by the Marshall Space Flight Center (MSFC) documents activities regarding the Environmental Control and Life Support Systems (ECLSS) of the International Space Station (ISS) program. These MSFC activities were in-line to the designing, the development, the testing, and the flight of ECLSS equipment. MSFC's unique capabilities for performing integrated system testing and analyses, and its ability to perform some tasks cheaper and faster to support ISS program needs are the basis for the Technical Task Agreement activities. Tasks were completed in the Water Recovery Systems, Air Revitalization Systems, and microbiology areas. The results of each task is described in this summary report.				
14. SUBJECT TERMS Environmental Control, ECLSS, International Space Station, ISS, Water Recovery Test, WRT, Air Revitalization, IART, Microbiology Technical Task Agreement, TTA			15. NUMBER OF PAGES 103	
			16. PRICE CODE NTIS	
17. SECURITY CLASSIFICATION Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	



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