International Space Station Environmental Control and Life Support System Phase III Water Recovery Test Stage 9 Final Report

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TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ACD	Architectural Control Document
AEM	Aerotolerant Eutrophic Mesophilic
CDR	Critical Design Review
CHeCS	Crew Health Care System
CMIF	Core Module Integration Facility
CMS	Core Module Simulator
EEF	End-use Equipment Facility
ECLSS	Environmental Control and Life Support System
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
GLS	Gas Liquid Separator
HPA	High Purity Air
IR/GLS	Infrared Cell/Gas Liquid Separator
ISS	International Space Station
MSFC	Marshall Space Flight Center
ORU	Orbital Replacement Unit
PCWQM	Process Control Water Quality Monitor
PDR	Preliminary Design Review
POST	Predevelopment Operation System Test
SCMT	Sodium-n-Coconut Acid-n-Methyl Taurate
SSF	Space Station Freedom
SPA	Solid Phase Acidification
TIC	Total Inorganic Carbon
TOC	Total Organic Carbon
UCS	Urine Collection System
UP	Urine Processor
USOS	United States On-Orbit Segment
VCD	Vapor Compression Distillation
VRA	Volatile Removal Assembly
WP	Water Processor
WRM	Water Reclamation and Management
WRT	Water Recovery Test

1.0 Introduction

A test has been completed at NASA's Marshall Space Flight Center (MSFC) to evaluate the latest water recovery system design for the United States On-Orbit Segment (USOS) of the International Space Station (ISS) with higher fidelity hardware and integration than has been achieved in previous Water Recovery Test (WRT) Stages. This test is referred to as WRT Stage 9. 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. This report summarizes the test objectives, system design, test activities and protocols, significant results, anomalies and lessons learned throughout the WRT Stage 9.

2.0 Background

The provisions of safe potable water to spacecraft crew members has been a requirement since the beginning of the U.S. manned space program three decades ago. The evolution of spacecraft water systems, from the stored chlorinated supplies used in the Mercury and Gemini programs through the Space Shuttle's iodinated fuel cell product water system, has been summarized previously (1).

To reduce the quantity of fresh water to be resupplied from the ground (as well as to reduce the quantity of wastewater to be returned to the ground or otherwise disposed of on-orbit) the ISS Water Reclamation and Management (WRM) System will reclaim water from a variety of wastewater 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 wastewater 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 Environmental Control and Life Support System (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" wastewaters or "stand-alone" subsystem testbeds.

Integrated ECLSS testing dedicated to WRM System has been conducted as part of the WRT series. The WRT was originally conceived as a nine-stage test (1,2) proceeding from open-loop "donor-mode" in which human test subjects generated wastewaters 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 (1,3). Recipient mode tests with a dual-loop system which was modified in accordance with ISS subsystem technology selections (4,5) were completed in 1991 (6). 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 Water Processor (WP) was completed in early 1992 (7). Additional single loop testing completed in late 1992 evaluated the impact of eliminating the WP presterilizer on Unibed® life and overall WP performance (8).

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

3.0 Test Description

3.1 Test Objectives

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 Water Recovery Test 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. Detailed requirements and objectives are provided in the Stage 9 Test Requirements (9).

3.2 Test Schedule

Test activities were conducted in several distinct operational modes. Prior to the start of formal test operations, the water recovery system underwent treatment procedures intended to establish baseline microbial cleanliness levels throughout those portions of the system in which microbial concentrations of 1 CFU/100 ml or less were intended to be maintained. These activities were similar to those conducted prior to Stage 4/5 (6), with the additional sterilization of the WP's Unibed® train and Volatile Removal Assembly (VRA). The sterilization methods were identical to previous WRT stages (6) and will not be discussed in this report.

The first operation of the WRM System occurred on Day 1 of Stage 9, when waste waters generated in the End-use Equipment Facility (EEF) were processed by the respective assembly. Exercising test subjects generated humidity condensate and used facility water to generate waste shower, handwash, oral hygiene waste and wet

2

shave waste which were subsequently processed through the WP. Test subjects also donated urine to be processed by the Urine Processor, the distillate of which could then be processed by the WP. Once a sufficient volume of product water had been produced by the WP, reclaimed water was utilized for urinal flush water. Reclaimed water was not utilized for showers, handwashes, or taste tests during Stage 9.

Test activities spanned the period from July 19, 1994 through December 21, 1994 and included a total of 116 test days. System checkout testing and sterilization began on July 19 and was completed on August 17. Stage 9 operations commenced on August 18 (Day 1) with the processing of waste waters and continued through December 21 (Day 116) when the test was completed. After completion of Stage 9 integrated test activities, the water processor was subjected to a viral challenge from January 23-27, 1995.

4.0 Test System Description

The WRT Stage 9 was conducted at the MSFC Core Module Integration Facility (CMIF) in Building 4755. A layout of the CMIF area is shown in Figure 4-1. The WP, Process Control and Water Quality Monitor (PCWQM), and Urine Processor (UP) assemblies were located adjacent to the EEF. Equipment dedicated to the generation and collection of various wastewaters were housed within the EEF and were interfaced to appropriate portions of the WRM System. The Urine Collection System (UCS) was also located inside the EEF. Adjacent to the EEF was a facility water supply dedicated to the purification of building 4755 tap water.

4.1 Water Recovery Test System

The WRT system consisted of a single water recovery loop that received inputs from the various waste sources. A simplified functional schematic of the water recovery system is provided in Figure 4-2. The water recovery system included assemblies and components for the purification of urine, Crew Health Care System (CHeCS) waste, humidity condensate, waste shower water, waste handwash water, waste oral hygiene, wet shave waste, ersatz animal condensate, and ersatz fuel cell water (deionized water). The Stage 9 water recovery system operated at a 4 crew production rate, processing an average of 110 lb/day of waste water. Product water provided by the WP was intended to meet the ISS potable water quality specification listed in Table 4-1. Sample ports were distributed throughout the water recovery system for the collection of water, air, and surface samples for off-line laboratory analyses. The general locations of these ports are listed in Table 4-2.

To achieve the Stage 9 objectives, several changes were made to the water recovery hardware, the test stand and the operational procedures from previous test stages. First, the Water Processor and Urine Processor from Stages 7 and 8 were replaced with the processors developed for use in the Boeing POST test. The technologies for each processor were the same as those used in Stages 7 and 8, however, several major improvements had been made to better reflect the flight design (see Sections

3

CONTROL ROOM

CORE MODULE SIMULATOR (ECLSS MODULE)

VCD

Urinal

AIR LOCK

END-USE EQUIPMENT FACILITY (EEF)

WP

PCWQM

WP

FACILITY WATER STORAGE
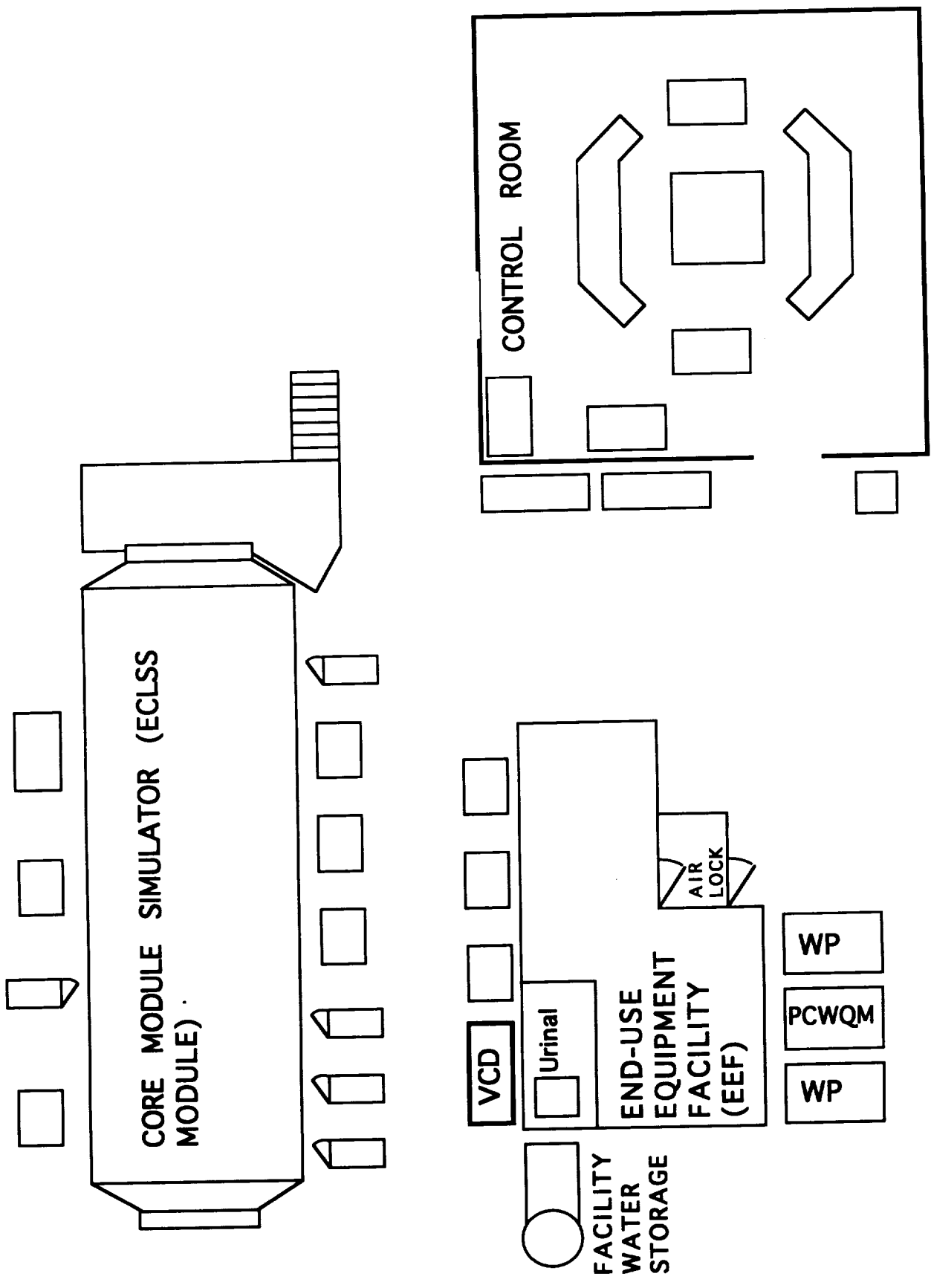
Figure 4-1. Stage 9 CMIF Test Area Layout
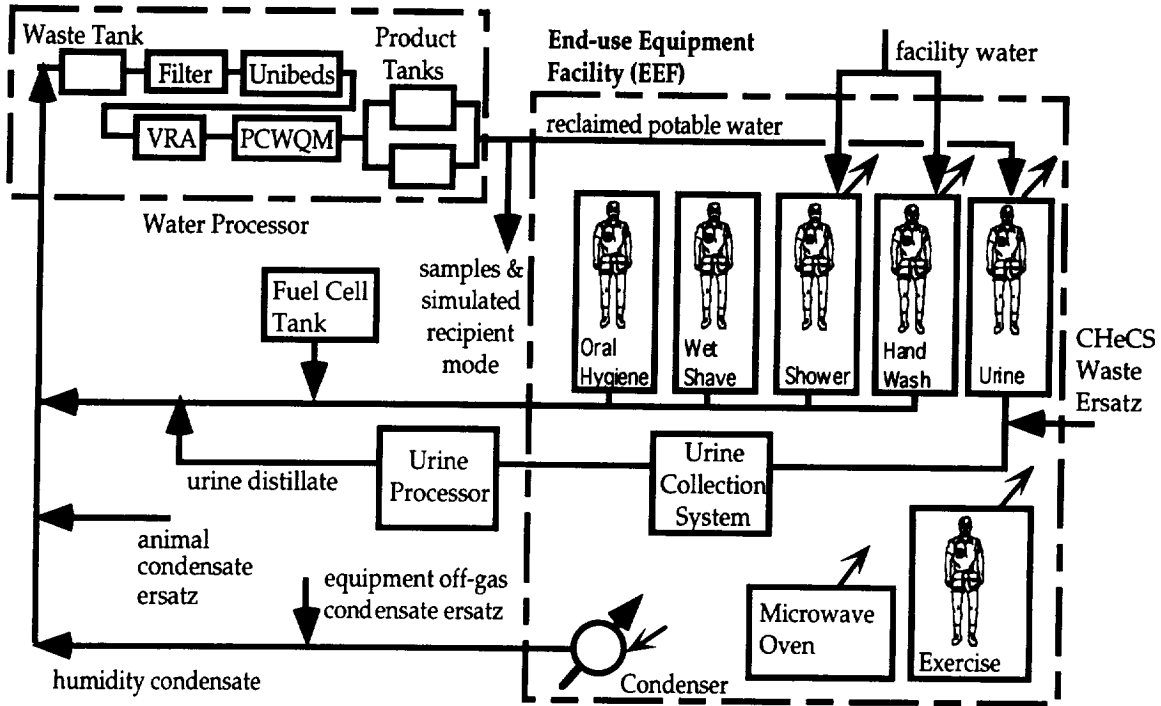
Figure 4-2. Water Recovery System Simplified Functional Schematic

4.1.2 and 4.1.4). Also, a "flight-like" PCWQM was integrated into the Water Processor, representing the first time this monitoring technology had been tested in an integrated system. The monitor measures Total Organic Carbon (TOC), iodine, conductivity and the pH of the product water. The data from the monitor is used to determine whether the water will be delivered to the product tanks or reprocessed by the water processor. This was also the first WRT test which included a "flight-like" urinal integrated with the urine processor. Detailed descriptions of each of these subsystems are given in Sections 4.1.2, 4.1.3, 4.1.4, and 4.2.

The composition of the waste waters that were generated in the EEF were altered to reflect new flight data as well as design changes due to the Space Station redesign. Specifically, the EEF laundry system was eliminated because the laundry system had been deleted during the Space Station redesign. CHeCS waste water, wet shave waste, and ersatz animal condensate were added as waste streams. Humidity condensate generated from exercising test subjects was collected as in previous test stages; however, before it was processed, an equipment off-gassing ersatz was added to each batch to bring contaminant levels up to those expected on ISS. Urine was collected in the EEF using a development-maturity Space Station urinal with automated urine pretreatment during collection. A detailed description of the EEF operation is given in Section 4.3.

5

Table 4-1. International Space Station Potable Water Quality Specification (10)

	Specification		Specification
PHYSICAL PARAMETERS		INORGANIC CONSTITUENTS continued	
Total Solids (mg/l)	100	Nitrate (NO3-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	CO2	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

Table 4-2. Water Recovery System Stage 9 Sample Ports

Sample Port	Description	Sample Port	Description
38	Facility Water Tank	124	Waste Water Feed Tank
19	Pretreated Urine Tank	134	Prefilter Effluent
84	VCD Brine Loop	125	Unibed® #1 Effluent
88	Internal Brine Tank	126	Unibed® Train Effluent
128	Urine Distillate	205	VRA Reactor Effluent
24	Humidity Condensate	201	VRA Phase Sep. Effluent
199	Waste Shower	127	VRA Effluent
200	Waste Handwash	122	WP Fill Tank
93	Shower Nozzle	120	WP Test Tank
94	Handwash Faucet		

The most significant difference between Stage 9 and previous stages was the level of integration between the water recovery hardware and end-use equipment. In previous testing, waste waters were generated one day and then mixed and processed as a batch the following day. This method gave the water system a mixed, nominal waste stream that reflected the waste water quantities and contaminant load expected on the Space Station, but did not take into account time-varying waste water mixes that would result from actual ISS operations. In Stage 9, hygiene waste streams (such as the shower, handwash, wet shave, and oral hygiene) were generated and immediately transferred to the WP feed tank. Humidity condensate was transferred 24 hours a day at rates that reflected varying degrees of crew activity (sleep, active hours, and exercise). Ersatz animal condensate was transferred at a rate that would provide the daily waste input according to ISS requirements. While urine was manually collected and transferred in previous test, in Stage 9 urine was collected and pretreated through the UCS and then sent directly to the Urine Processor feed tank. Urine distillate was transferred to the water processor feed tank when the urine processor was producing distillate. This operational approach resulted in daily variations in contaminant concentrations depending on the predominant waste stream in the WP waste tank at the start of and during processing, which better reflected the way waste water would be received by the water system on ISS. Any effects of this tighter integration on water system performance could now be assessed.

In addition to simulating ISS waste water inputs, product water outputs were also simulated to reflect a closed loop, recipient mode operation. Hygiene water use was simulated by synchronizing product water drains from the WP product tanks with input of shower and handwash waste water to the WP waste tank. All other "water consuming" uses such as crew drinking and oxygen generation water were summed together and drained from the product tank at predetermined times. Simulating a closed loop system allowed the WRM System control to be assessed without incurring the cost of a permanently manned chamber test. The water input and output of the system had to "balance" relative to the ISS maximum and minimum requirements. These issues will be further addressed in Section 5.1.1.

4.1.1 Water Recovery and Management System Automated Control Description

4.1.1.1 Water Recovery and Management System Control

To achieve the integration level discussed previously, the water recovery system as well as the test stand needed to be automated. The software was written in Labview for Windows (Version 3.0.1) because it was considered the most flexible, well developed, graphical user interface software control package available. The host computer was an IBM PC 486 with 66 Mhz clock speed, 64 MB RAM, and 503 MB hard drive. The system control logic was developed from discussions between MSFC and Boeing over several years pertaining to the WRM System control on ISS. Subsystem level control was developed using the most up-to-date defined control logic for each subsystem. For the UP and PCWQM this logic was defined at the

7

Critical Design Review (CDR) level. For the WP the control scheme was defined at the Preliminary Design Review (PDR) level. Because development hardware was used, some of the subsystem's control logic did not represent the flight control logic. Where this was the case, the system level controller acted as a subsystem controller, trying to emulate the control functions that were "flight-like" but not included in this fidelity hardware.

A detailed description of the control logic is given in Appendix A. The Stage 9 system control can be broken down into four functions; water management, WRM subsystem coordination, the PCWQM data interpretation, and the end-use equipment coordination. The water management function includes control of the rotation of product water tanks between fill and deliver modes, control of WP operations based on waste tank and product tank quantities, and the control of fuel cell water input to supplement water losses to the system. The goal of the water management function was to maintain product water and end-use equipment availability at all times. The product and waste water tanks were operated at a maximum usable capacity of 135 lb each. The waste tank effected the WRM operation based on 4 quantity setpoints. First, if the waste tank net quantity reached 30 lb, the WP was commanded to begin processing from Standby mode. If the waste tank net quantity reached 135 lb, the waste tank was isolated from the waste water distribution bus and all end-use equipment that fed water into the WP feed tank and the UP were commanded to shutdown. Thereafter the waste tank was opened to the waste water bus only when the tank level dropped below 127.5 lb net quantity. The WP was commanded to stop processing (Standby mode) when the waste tank reached 0 lb net quantity. The waste tank setpoints were taken from the WP PDR data package. They were selected to control the waste tank in a way that processed waste water as soon as it was available (allowing product water to be available as soon as possible) while preventing a shutdown of the WRM System and end-use equipment because the waste tank was filled to capacity.

The product tanks operated in a fashion similar to the waste tank. If a product tank was in fill mode (tank is open to the WP and is available to be filled with product water) and the tank's net quantity exceeded 108 lb at the end of a WP processing cycle, the tank was isolated from the WP and the product water bus. If the tank's contents reached its maximum usable capacity of 135 lb before the WP completed a process cycle, the WP was commanded to stop processing and the tank was isolated from the WP and the product water bus. This tank remained isolated until the second product tank in the deliver mode (tank was open to the product water bus and water in the tank was available for use) was emptied and isolated. At that point the full product tank was opened to the product water bus and was designated to be in the deliver mode. The second product tank was opened to the WP and was designated to be in the fill mode. When the water quantity in the deliver mode tank dropped below 30 lb and water usage stopped, the tank was isolated from the product water bus. If water usage did not stop by the time the tank net quantity fell to 0 lb, the tank was isolated from the WP and product water bus during water usage to protect the tank. At this point the tank cycle repeated. This product tank control

scheme was taken from the WP PDR data package and is designed to provide product water as soon as it was available. The control of the WP operation using waste and product tank setpoints as well as the product tank rotations from fill to deliver are considered to be part of the WP subsystem level control, but since it was not a part of the control software for the development WP used in Stage 9, this control was handled at the system level.

Fuel cell water ersatz (deionized, iodinated water) was added to the waste tank to maintain a total water quantity in the WRM System. The system control logic checked the total water quantity in the system (summation of the waste tank and two product tanks) and compared it to a set point every 24 hours. If the total water in the system was less than or equal to 260 lb, fuel cell water was added to the system through the waste bus until the total water quantity equaled 270 lb. The set point was checked at 6:00 a.m. every morning when water usage and waste water input were at a minimum. A computer model of the WRM System control was used to determine the quantity of water that needed to be maintained in the system in order to have water available for use at all times.

The WRM subsystem coordination function consisted of operational mode coordination between the WP, UP, and PCWQM. The UP normally operated independent of the rest of the WRM subsystems. Only if the WP waste tank reached maximum capacity did the system software inhibit the UP operation. The WP and PCWQM required coordination of operating modes. When the WP was cycled from Standby to Process, the PCWQM was commanded to begin analysis of the product water (Normal Operation mode). When the WP was cycled from Process to Standby, the PCWQM was commanded to stop the analysis of the product water (Standby mode). To maintain the accuracy of its sensors, the PCWQM performed a Recirculation mode every 24 hours and Calibration mode every 168 hours (Section 4.1.3). The system software coordinated each of these PCWQM operations so that they occurred on schedule with minimum impact to the WRM's ability to provide product water. For the first 22 days of the test, the PCWQM could only go into Recirculation or Calibration if the waste tank was at 0 lb net quantity and the time between the end of the last Recirculation and Calibration had been at least 24 hours and 168 hours, respectively. This criteria provided the least impact to the system by only allowing the PCWQM to conduct these modes when there was no possibility of the WP needing to process waste water. However, the criteria was too stringent, resulting in the PCWQM going several days beyond required intervals before a Recirculation and Calibration could be implemented. Since this could result in a degradation of the PCWQM performance, the logic was changed on Test Day 22. If the time between a Recirculation and a Calibration had reached the required interval, the PCWQM could transition into Recirculation or Calibration if the waste tank was at 0 lb net quantity or if there was a full, isolated product tank and a deliver tank available. Though this logic was more intrusive on the WP operation (occasionally preventing the WP from processing when waste water was available to process), it still preserved the function of maintaining water available for use at all

9

times by only allowing a Recirculation and Calibration if there was at least a day's supply of water available for use.

The PCWQM data interpretation function involved control of the WP reject valve. The reject valve was configured to deliver product water to the product tanks only when the VRA reactor temperatures had stabilized and the product water quality was acceptable. When the WP began a process cycle, the valve was in the reject position (diverting product water from the product tanks to the inlet of the WP). A control algorithm interpreted data from the PCWQM and controlled the reject valve of the water processor. Because there was no documentation to draw from, a simple averaging algorithm was used (Appendix A). The PCWQM data was averaged over a 30 minute time period and compared to the water quality specification for TOC, iodine, conductivity and pH to determine if the water met acceptance criteria. However, over the course the test, it was discovered that this control algorithm was unable to handle the operating characteristics of the PCWQM. Further discussion of this issue can be found in Section 5.1.2.

The end-use equipment coordination function involves the shutdown of the end-use equipment in the event that the waste water tanks (WP and the UP waste tanks) are full or the product tanks are empty. The conditions required to shut down each piece of end-use equipment are described in detail in Appendix A.

Stage 9 was not a test of the control software, but of the control logic and how the water system performance would be affected in the control scheme. To adequately test the software, it would have been necessary to write and organize the software to Space Station requirements, essentially resulting in the flight coded software. Because of the state of flux the software requirements were in during the development of this test as well as the fidelity of the hardware to be tested (this hardware was never designed to be controlled autonomously from a host computer) flight software was considered to be out-of-scope for this test.

4.1.1.2 Simulated Recipient Mode

To test the automated control system, the water system was operated in a closed loop (or recipient mode) fashion, where test subjects used the reclaimed water for hygiene uses as well as for drinking and food preparation. This is the only way to test the influence of crew activities on the water management control schemes and operational timelines of the subsystems. Since operating in recipient mode would have required additional costs as a result of having to verify the water quality prior to use, Stage 9 was operated in a simulated recipient mode.

There were two water loops that had to be closed in order to simulate a recipient mode operation: the hygiene loop and the crew and lab animal loop. To simulate the hygiene loop, facility water, which had been analyzed and approved by the medical monitor, was used to generate shower, handwash and wet shave waste waters. When a shower, handwash or wet shave was taken by a test subject, a flow

10

totalizer in the facility tank output line (CI40) indicated when and how much facility water was being used. The exact amount used in the shower, handwash, and wet shave was automatically and simultaneously drained from the WP product tank using the totalizer in the Product Tank drain line (RI40). For oral hygiene waste water, tap water was used to brush teeth 8 times per day (0.4 lb/toothbrush). The product tank was drained automatically (but not simultaneously to the actual oral hygiene waste inputs) every two hours starting at 8:00 AM until 2:00 PM to simulate the use of recycled water for brushing teeth.

To simulate the closure of the crew and lab animals loop, urine, humidity condensate and an animal condensate ersatz were input into the system. Urine collection was open to anyone and was collected 24 hours a day, though most of the urine was collected from 6:00 a.m. to 4:00 p.m. Although the humidity condensate for a 4 person crew was collected in the EEF over approximately 10 hours per day, the collected humidity condensate was delivered to the WRM System waste bus 24 hours a day to simulate the closed environment of the Space Station. The flow rates of humidity condensate were also varied throughout the day to simulate three different activity levels of the crew. These flow rates were 0.4 lb/hr for 8 hours (sleep), 0.5 lb/hr for 14 hours (active), and 6.9 lb/hr for 2 hours (exercise). An animal condensate ersatz was also pumped to the waste bus 24 hours a day at 0.33 lb/hr to simulate condensate input from the Research Animal Holding Facility (RAHF) on the Space Station. Details of the urinal, humidity condensate, and animal condensate operation and composition are given in Sections 4.2 and 4.3. To simulate output of water required for drinking and food preparation for the crew and drinking water for the animals, water was drained every two hours from the product tank from 8:00 AM until 6:00 PM. A schedule of the drinking water pulls and their quantity is provided in Table 4-3. The total water removed from the system for drinking included sample quantities. As can be seen from the table, adjustments were made to the quantity of product water removed for each pull during the test. These adjustments were made to balance the crew and lab animal loop as a result of lower than expected inputs and changes in sampling quantities. Also included in the scheduled drains of the product tank was 8.28 lb/day of oxygen generation water.

Table 4-3. Schedule of Drinking Water Pulls

Test Day	Quantity/pull Mon.- Fri. (lb/pull)	Total per day Mon. - Fri. (lb/day)	Quantity/pull Sat. & Sun. (lb/pull)	Total per day Sat. & Sun. (lb/day)
1-20	7	42	8	48
21-27	6	36	7	42
28-116	5.5	33	7	42

Crew Health Care System (CHeCS) waste as well as Extravehicular Activity (EVA) wastes were also simulated. An additional 700 ml of water was pulled from the product tank daily to simulate sampling for CHeCS. Every seven days, 4600 ml of

ersatz CHeCS waste was input into the system through the urinal. EVA water use was initially done as part of the drinking water tank drains described earlier, however, this did not reflect how actual EVA water would be removed and input back into the system. Therefore, beginning on Test Day 29, EVA inputs and outputs were done every twelve days. At the beginning of an EVA day, 19.3 lb of product water was drained from the product tank to simulate water collected for drinking (2.6 lb), sublimator use (16.6 lb), and cooling water for the Liquid Cooled Ventilation Garment (LCVG) (0.1 lb). After 8 hours, 4.2 lb of urine was dumped into the urinal and 7 lb of waste Extravehicular Mobility Unit (EMU) condensate ersatz was dumped into the hygiene sink. These water quantities and frequencies were designed to simulate a 2-crew EVA performed 30 times per year.

All activities involved with simulating recipient mode were performed manually until Test Day 43, when the scheduled drinking water drains as well as the hygiene water balance were automated. Automated control for the animal and humidity condensate inputs were implemented on Test Day 56. CHeCS and EVA inputs remained manual throughout the test.

4.1.2 Urine Processor Description

The Vapor Compression Distillation (VCD-V) unit was used to process urine/flush water collected in the EEF and CHeCS waste. Distillate was delivered to the WP for processing. The UP sensor data and the quality of the distillate produced was analyzed in order to assess the UP's performance.

Pretreated urine and flush water were received periodically in the Pretreated Urine Storage Tank (TK1) from the predevelopment urinal and pretreatment hardware. The design ratio of urine to flush water in pretreated urine was 3 parts urine to 1 part flush water by volume. Oxone® (a potassium monopersulfate salt) and sulfuric acid were added to the urine stream in the proper quantities for chemical and microbial stabilization prior to processing (Table 4-4). The urinal is described in Section 4.2.

Table 4-4. Urine Pretreatment

Pretreatment Chemicals	(g/liter urine)	(g/liter pretreated urine)
Oxone®	5.0	3.75
H2SO4	2.32	1.74

A schematic of the VCD-V is shown in Figure 4-3. The wastewater is circulated through the distillation unit by a four section peristaltic fluids pump (PU1). The feed section of the pump discharges waste water to the inner surface of the evaporator drum 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 conductivity sensor K1 (vk01). Water with a conductivity above the setpoint of 150 µmhos/cm is routed back to the recycle loop for reprocessing. Condensate with a

conductivity below 150 μmhos/cm is delivered as distillate. Excess wastewater feed is returned through a 22 liter recycle filter tank (25 micron filter) 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 DC motor via a magnetic fluid-sealed direct-drive coupling. The entire evaporation/compression/condensation process takes place between 90-110°F by operating the subsystem at 0.5-0.8 psia. Based on a control scheme of purging every 10 minutes, a purge valve is activated to remove non-condensable gases from the condenser. Any water condensed in the purge stream is separated from the non-condensable gases by a static membrane gas/liquid separator (WS1). This water is then sent to the product water line, while the non-condensable gases are vented to the atmosphere. The purge pump (PU2) is the same design as the fluids pump. This test was the first integrated test which included the UP flight design purge pump.
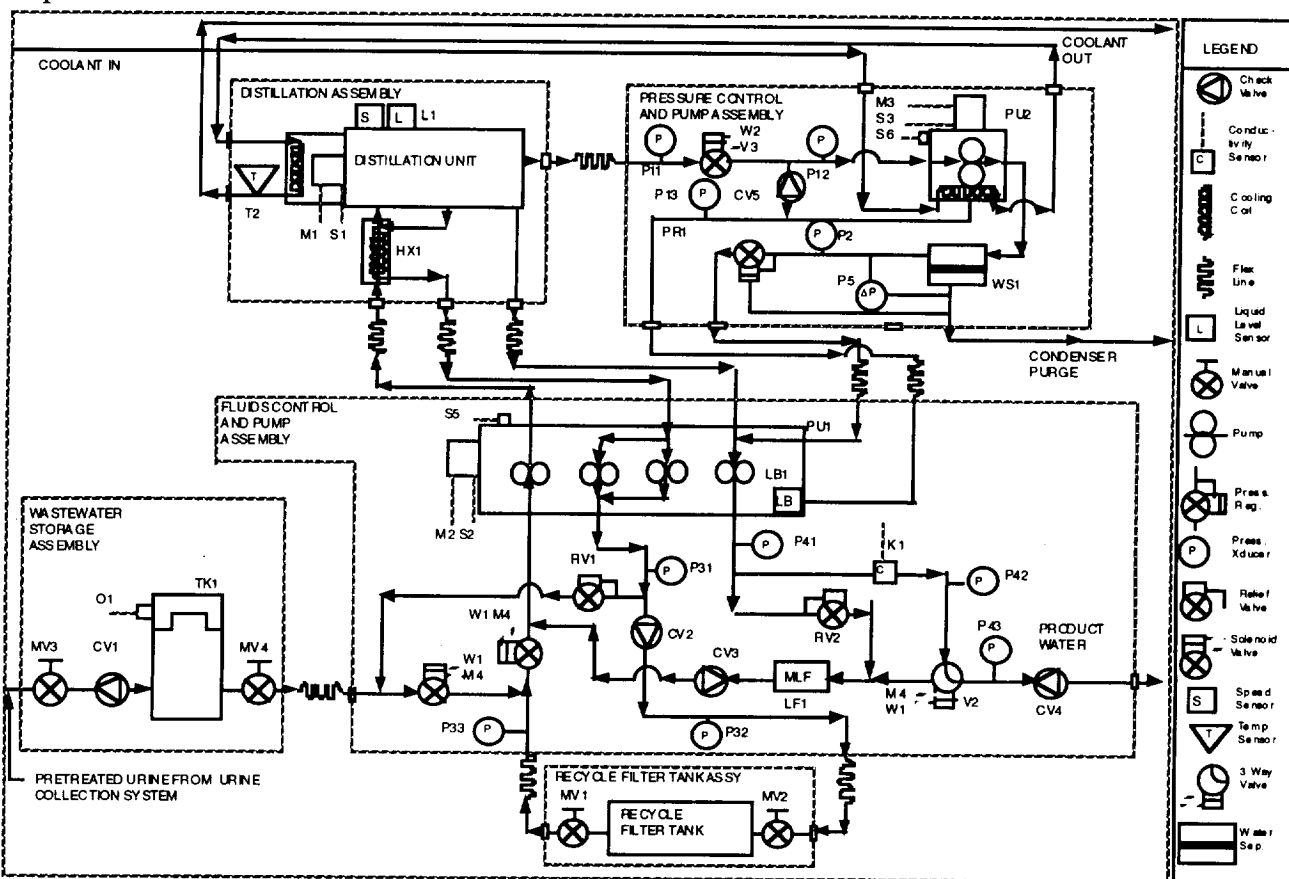
Figure 4-3 Vapor Compression Distillation (VCD-V) Subsystem Schematic

4.1.3 Process Control Water Quality Monitor Description

The VRA effluent water quality was analyzed by the PCWQM. The PCWQM provides on-line water quality monitoring for TOC (ptc1), iodine (pin1), pH (po20) and conductivity (pc21). Figure 4-4 provides a schematic of the hardware. The iodine and conductivity sensors are located in the WP process line, while TOC and
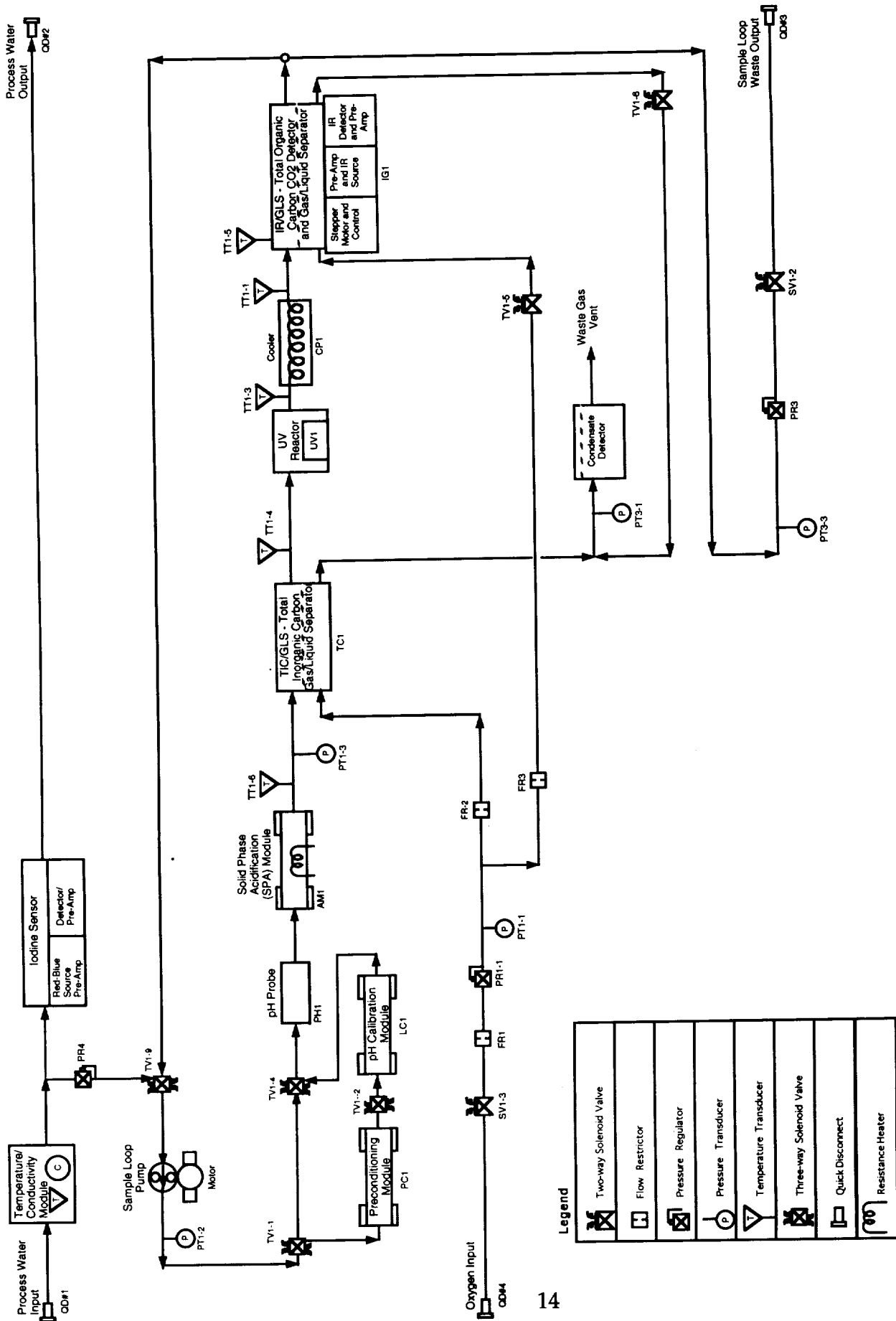
Figure 4-4. Process Control Water Quality Monitor (PCWQM) Schematic

14

pH are measured in the PCWQM sample loop. The sample loop is a 1 ml/min stream taken from the process line. The pH is measured initially. The stream is then acidified by the Solid Phase Acidification (SPA) module, which contains resin designed to impart chemicals into the water that will effect a drop to <4 pH. Acidification drives the Total Inorganic Carbon (TIC) to carbon dioxide, which is subsequently removed by a gas/liquid separator (GLS) membrane referred to as the TIC/GLS. The TIC/GLS uses oxygen gas as the carrier gas for the carbon dioxide. As the carbon dioxide is removed, the stream is also saturated with oxygen, which diffuses across the membrane and is subsequently used for the oxidation of organics by the ultraviolet (UV) lamp to carbon dioxide. The stream finally passes through a second gas/liquid membrane integrated with an infrared (IR) detector cell (IR/GLS). Carbon dioxide diffuses through the membrane until equilibrium is established between the carbon dioxide in the water and the carbon dioxide in the IR cell. The concentration of carbon dioxide is determined by measuring the adsorption of infrared light in the cell. The TOC concentration is then calculated based on correlations with the equilibrium carbon dioxide concentration. After the TOC measurement, the sample stream is returned to the ion exchange bed influent. The sample loop also includes the calibration loop, which contains valving whereby the pH calibration module can be placed in line during Calibration mode. Valving is also available to recirculate the sample loop during Recirculation mode.

The PCWQM has four software modes; Standby, Normal, Recirculation and Calibration. During Standby, the PCWQM sensors and effectors are off while the software awaits a command. When requested, the PCWQM will transition to Normal, where all sensors are operational and the sample stream is pumped from the WP process line for pH and TOC measurement in the sample loop. Calibration mode is requested by the PCWQM software every 168 hours (7 days). During Calibration mode, the sample stream is diverted through the pH calibration module, which is designed to maintain an effluent pH of 3.8 and contains the same resin as the SPA module. The pH sensor is then calibrated to the module's effluent pH to determine the pH offset. The pH offset is added to the sensor's measurement to compensate for calibration drift. Additionally, the System TIC level of the sample loop is measured by turning off the UV lamp (to prevent oxidation of organics to carbon dioxide). The carbon dioxide measured by the IR/GLS should thereby represent the system's background TIC not removed by the TIC/GLS.

Recirculation mode is requested every 24 hours. During Recirculation the pH of the SPA module is measured to determine if adequate acidification is being performed. If the SPA module effluent pH is above 3.8, the PCWQM software calculates the required temperature of the module effluent to effect a 3.8 pH. The higher temperature serves to increase the concentration of chemicals imparted into the sample stream by the SPA resin, thus lowering the pH. Next the System TOC of the PCWQM sample loop is measured by recirculating the sample loop stream through the UV lamp for 90 minutes until the organics originating in the WP product water are oxidized and removed via the TIC/GLS. The System TOC is equal to the TOC measured minus the System TIC calculated during Calibration mode, and is

attributed to the TOC inherent to the sample loop. The TOC reported during Normal mode is the TOC measured in the IR/GLS minus the System TIC and System TOC.

4.1.4 Water Processor Description

A schematic of the WP is shown in Figure 4-5. The function of the WP was to process a waste stream consisting of humidity condensate, animal condensate ersatz, urine distillate, waste shower water, waste handwash water, waste wet shave, waste oral hygiene, and ersatz fuel cell water to potable water quality specifications (Table 4-1) and to provide storage and delivery of the potable water as necessary. Waste water was received from the EEF into a 316L stainless steel bellows tank pressurized from 2-4 psig. The waste water was pumped from the waste tank using a gear pump located at the inlet of the WP. The process stream first passed through a 0.5 micron depth filter where particulates were removed to prevent premature saturation of the Unibed® train. The Unibed® train followed the filter and consisted of two Unibeds® in series. Each Unibed® was identical, containing various adsorbents and ion exchange resins designed for removal of a particular group of contaminants expected in the process stream. Adsorbents were geared towards removing non-ionic organics while the resins removed ionic species. An iodinated resin was located at the inlet of each Unibed® to control microbial growth in the Unibeds® by imparting a 2 ppm residual iodine level in the process stream. Table 4-5 lists the adsorbents and resins and their order and quantity in the Unibed®. Conductivity sensors located at the inlet (wc41) and outlet (wc42) of each Unibed® were used to monitor the performance of the bed and determine when bed saturation had occurred.

Effluent from the Unibed® was post-treated by the VRA for removal of low molecular weight, polar organics not effectively removed by adsorption and ion exchange, and also for final sterilization of the product water. The VRA utilized two regenerative heat exchangers to reclaim heat generated in its catalytic reactor, which operated at a temperature of 260 to 265°F. A stoichiometric excess of oxygen for the oxidation reaction was added to the process stream via a gas sparger located at the reactor inlet. The reactor used catalytic oxidation to oxidize the organics to carbon dioxide and/or to organic compounds that can be removed by phase separation or ion exchange. The reactor catalyst and substrate used during Stage 9 were developed at Hamilton Standard; Stage 9 represented the first test of this reactor modification in an integrated system. Effluent from the reactor returned through the heat exchangers to reclaim heat generated in the reactor and was then degassed with a hollow fiber membrane phase separator. The phase separator removed waste gases generated in the reactor, consisting mainly of carbon dioxide and oxygen not consumed in the oxidation reaction. The effluent from the phase separator was then treated with an ion exchange bed (200 cc of MCV-RT, 12775 cc of IRN-78, 200 cc of IRN-150, 200 cc of IRN-77, and 200 cc of MCV-RT) for removal of any organic acids or other ionic contaminants generated in the reactor and to impart

16
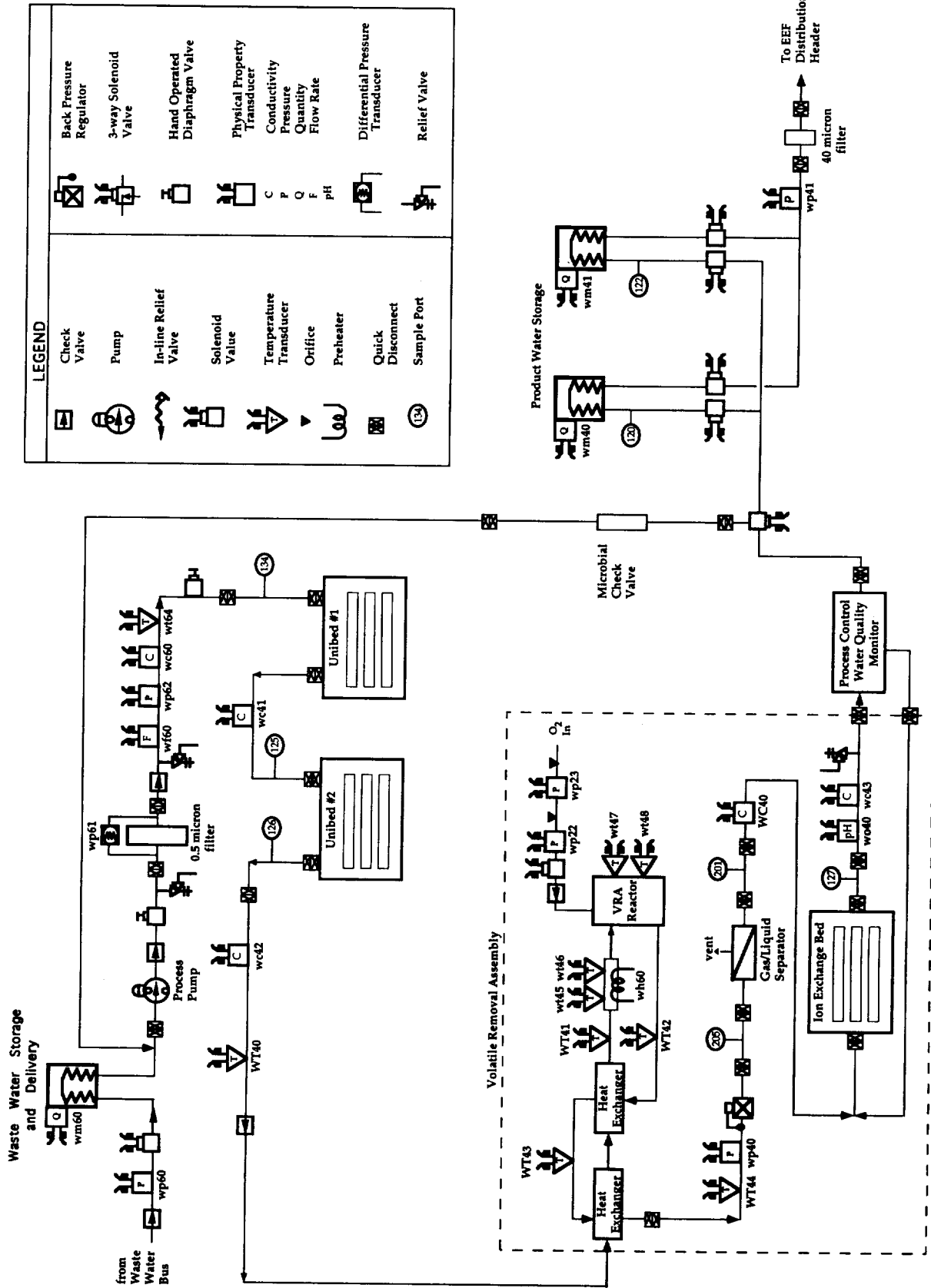
Figure 4-5. Water Processor Schematic

Table 4-5. Unibed® Media (in direction of flow)

Media	Media Quantity (cc)			Description of Media
	Stage 9	Stage 8	Stage 7	
MCV-H		200	200	high temperature iodinated anion exchange resin (Umpqua Research)
MCV-RT	200			room temperature iodinated anion exchange resin (Umpqua Research)
IRN-150	9750	5310	5310	mix of IRN-77 and IRN-78, a strongly basic anion exchange resin (Rohm and Haas)
IRN-77	695	200	200	strongly basic cation exchange resin (Rohm and Haas)
IRA-68	4275	1580	1580	weakly basic anion exchange resin (Rohm and Haas)
580-26	4630	2820	2820	activated carbon produced from coconut shell (Barneby Cheney)
APA	1325	1640	1640	activated carbon produced from bituminous coal (Calgon)
XAD-4	1325	1640	1640	polymeric adsorbent (Rohm and Haas)
IRN-150	200			mix of IRN-77 and IRN-78, a strongly basic anion exchange resin (Rohm and Haas)
IRN-77	200			strongly basic cation exchange resin (Rohm and Haas)
MCV-H		200	200	iodinated anion exchange resin (Umpqua Research)

Unibed® Dimensions: Stages 7 and 8 - 3 tubes, dia. of 3 in, length of 39 in, capacity of 13560 cc
Stage 9 - 5 tubes, dia. of 3 in., length of 39 in., capacity of 22600 cc

a nominal residual iodine level (1-4 ppm) in the product water for microbial control. Two 316L stainless steel bellows tanks were used to store the product water while awaiting use.

The WP had four operational modes; Process, Reject, Standby, and Shutdown. During Process mode, the WP was processing waste water through the Unibeds® and VRA. Reject mode was used when the water quality of the VRA effluent (as measured by the PCWQM) exceeded specifications or when the temperatures of the VRA reactor were below the minimum setpoint. Under these conditions, product water was returned to the waste tank and reprocessed. During Standby mode, the feed pump was off while the VRA reactor was maintained at temperature.

4.2 Urine Collection System

A predevelopment urinal was used to collect urine, reclaimed flush water and CHeCS waste water. The design ratio of urine to flush water in pretreated urine was 3 parts urine to 1 part flush water by volume. The schematic for the UCS is shown in Figure 4-6. The fan/separator turned on when the urinal cover was moved from the top of the funnel.

When the separator reached the correct operating speed (3500 rpm), a light would indicate that the urinal was ready to accept donations. A counter on the urinal subassembly indicated the total number of donations. This could be compared to the log maintained by the donors after each use. After each donation the donor manually added 80 to 100 ml of flush water to the urinal. The fan drew air through the urinal hose at 10 cfm. At the entrance to the fan/separator, Oxone® was injected into the urine stream (5 g/liter of waste) based on pressure activation from the separator. The Oxone® pretreatment system consisted of a holding tank for chemicals, an injection pump, and controls. The separator, operating at 14,000 rpm, separated the air from the liquid. The sulfuric acid (2.3 g/liter of waste) was injected downstream of the unit by a facility-provided metering pump. This was also done based on the separator operation. Once the liquid and air were separated, the liquid was delivered to the UP waste water storage tank. The air flowed into an odor/bacteria filter before being exhausted to the EEF environment.
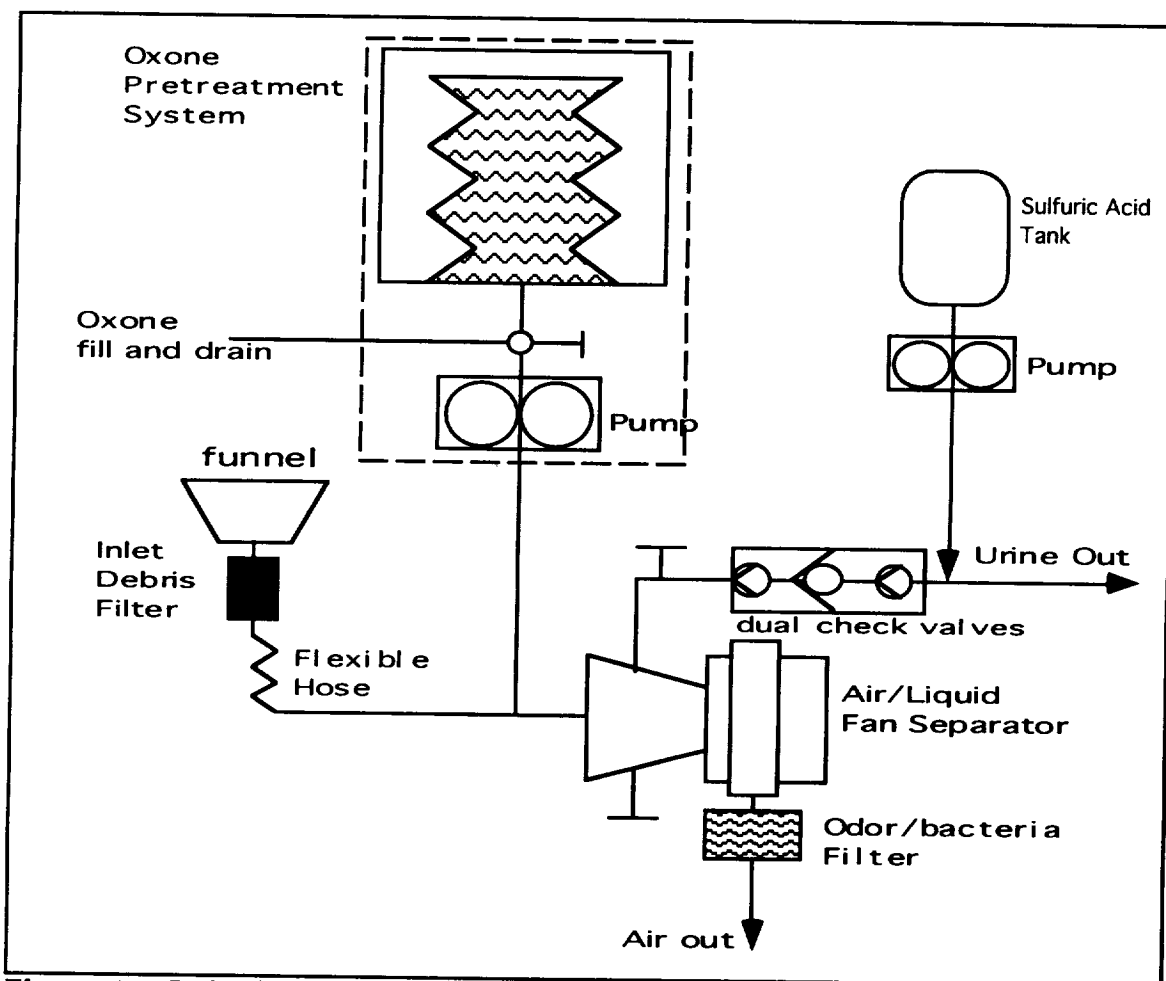
Figure 4-6. Urinal Collection System Schematic

4.3 End-Use Equipment Facility

Equipment dedicated to the generation and collection of various wastewaters was housed within the EEF and was interfaced to appropriate portions of the WRT

system. The EEF is a positive pressure 100K clean room located in Building 4755 north high bay facility adjacent to the Core Module Simulator (CMS). A controlled environment was required to ensure that the various wastewaters fed to the water recovery system were representative of the actual effluents and did not contain extraneous contamination introduced from the general facility environment. Make-up air was provided by continuous feed of facility high purity air (HPA), approved by the MSFC Environmental Health Office. The concentration of carbon dioxide within the EEF was continually monitored (DG20, DG22) and the feed rate of HPA was adjusted to ensure that carbon dioxide concentration was maintained below a maximum of 1.2%. EEF equipment included a shower, handwasher, four pieces of exercise equipment, microwave oven, and the urinal. The exercise equipment was used by human test subjects to generate a metabolic moisture load on the air through increased perspiration and respiration. The water vapor in the EEF was also derived from evaporation at or in the shower, handwasher, and the microwave. This water vapor was condensed by a condensing heat exchanger and collected by means of a drip pan and drain line to one of two stainless steel tanks. As one tank was being filled with condensate, a small pump located near the second tank pumped out the condensate collected from the previous day over a 24 hour period at flow rates that reflected the various levels of activity expected on Space Station. At the end of the 24 hour period, approximately one liter of an equipment off-gassing ersatz was added to the collected humidity condensate to bring organic levels up to those expected on ISS. The composition of this ersatz was based on analyses of condensate generated on Spacelab and Space Shuttle missions. The composition of the ersatz is shown in Table 4-6. The tanks were rotated so that the condensate collected from the previous day could be delivered to the waste bus of the water system while the empty tank was being used to collect the present test day's condensate. An EEF internal schematic is shown in Figure 4-7. The EEF floor plan is shown in Figure 4-8.

Table 4-6. Equipment Off-gassing Ersatz

Contaminant	Concentration	Units
ammonium	37	mg/l
propylene glycol	375	mg/l
isopropyl alcohol	370	mg/l
chloride	13	mg/l
zinc	160	mg/l
acetic acid	90	mg/l
formic acid	70	mg/l
formaldehyde	100	mg/l
caprolactam	125	mg/l
2-butoxyethoxyethanol	17	mg/l
4-hydroxy-4-methyl-2-pentanone	15	mg/l

Urine from test subjects was collected and pretreated in the EEF Urinal. A description of the Urinal is provided in Section 4-2. An ersatz designed to reflect the

chemical makeup of the waste water expected from the Crew Health Care System (CHeCS) was input into the water system every seven days through the urinal. The composition of this waste stream is shown in Table 4-7.

Table 4-7. Crew Health Care System (CHeCS) Waste Formulation

Contaminant	Vol. (ml)[1]	Contaminant	Vol. (ml)[1,3]
Phosphoric acid, 3M	1.05	Chloride	18
Sodium Hydroxide, 0.2M	1398	Nitrite	18
Di-amine propionic acid-HCl, 0.0003M	1053	Nitrate	18
Hydrochloric acid, 0.02M	1053	Sulfate	18
Pyridine-2,6-Dicarboxylic acid, 0.006M	690	Sulfur	18
Acetic acid, 0.05M	690	Iodine	18
Sodium acetate, 0.05M	690	Ammonium	18
4-(2-Pyridylazo) Resorcinol, 0.0002M	483	Potassium	18
Acetic acid, 1M	483	Magnesium	18
Ammonium hydroxide, 3M	483	Calcium	18
Hydrazine sulfate[2]	45	Barium	18
Hexamethylenetetramine[2]	45	Iron	18
Potassium dihydrogen phosphate[2]	0.05775	Copper	18
Phosphoric acid, 3M	0.00385	Nickel	18
Potassium dihydrogen phosphate, 0.025M	0.00012	Zinc	18
Disodium hydrogen phosphate, 0.025M	0.5	Cadmium	18
Potassium dihydrogen citrate, 0.05M	0.5	Manganese	18
Potassium chloride, 0.01M	5	Arsenic	18
Ammonium chloride, 9.4E-05M	2	Chromium	18
Sodium hydroxide, 6M	0.7	Lead	18
Nitric acid, 0.2M	18	Mercury	18
		Selenium	18
		Silver	18

[1]Add chemicals to 5096 ml water
[2]The concentration of the hydrazine sulfate solution should be 10 g/liter.
 The concentration of the hexamethylenetetramine solution should be 100 g/liter.
 The concentration of the potassium dihydrogen phosphate solution should be 0.5 mg/liter
[3]The concentration of the solutions in the right hand column should be 0.1 mg/liter

Each of the hygiene waste inputs (shower, handwash, oral hygiene, and wet shave) was generated as in previous test stages. Each waste stream was pumped directly to the WP waste tank (wa60) as it was generated. Vented tanks were installed in each waste stream line to allow air bubbles to escape because the WP did not have a "flight-like" inlet ORU (which contains an air/water separator).

An animal condensate and fuel cell water ersatz were also used in this test. The tanks for each of these waste streams were located just outside the EEF. The animal condensate ersatz was metered into the waste bus 24 hours a day. The composition
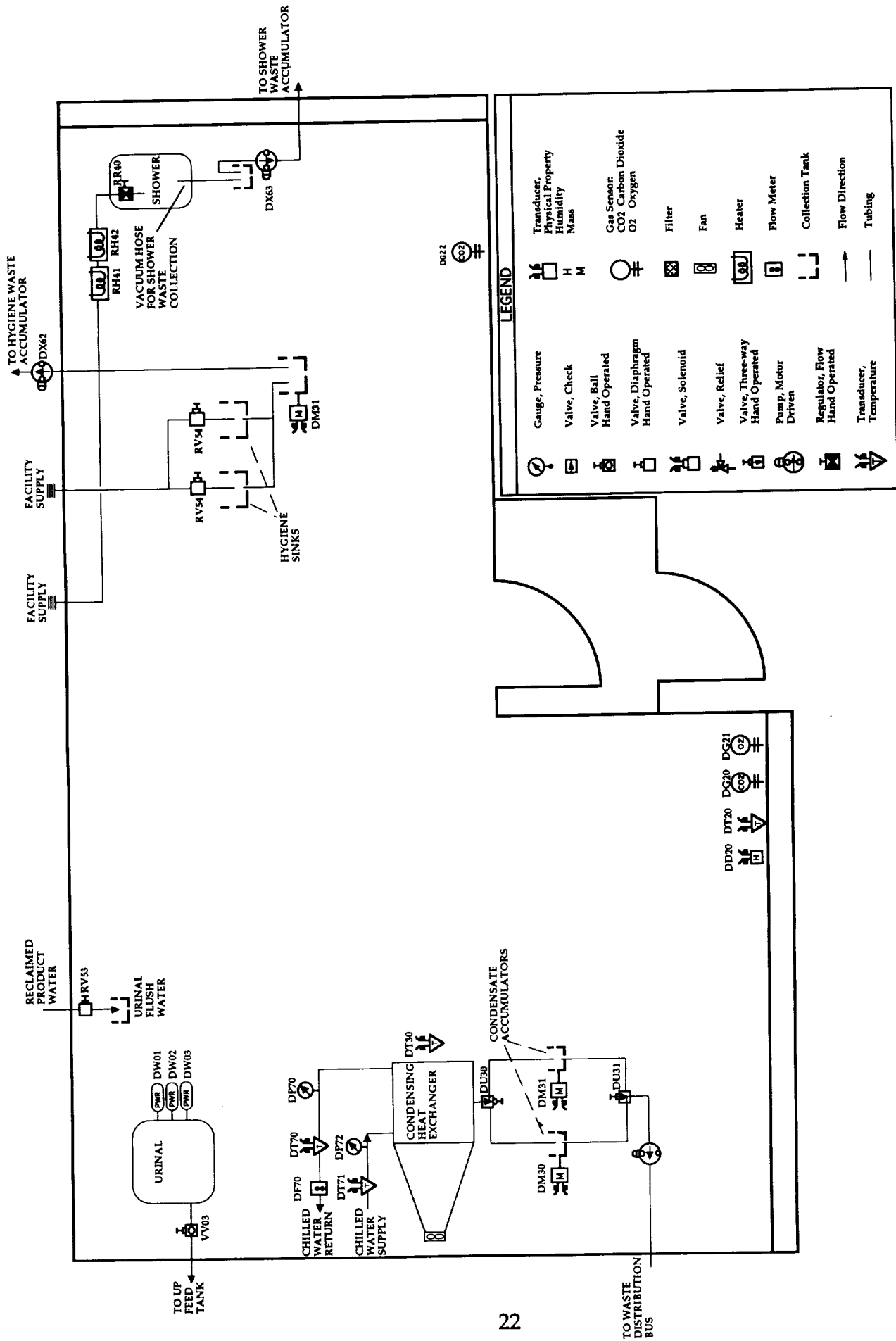
Figure 4-7. Stage 9 End-Use Equipment Facility Internal Schematic
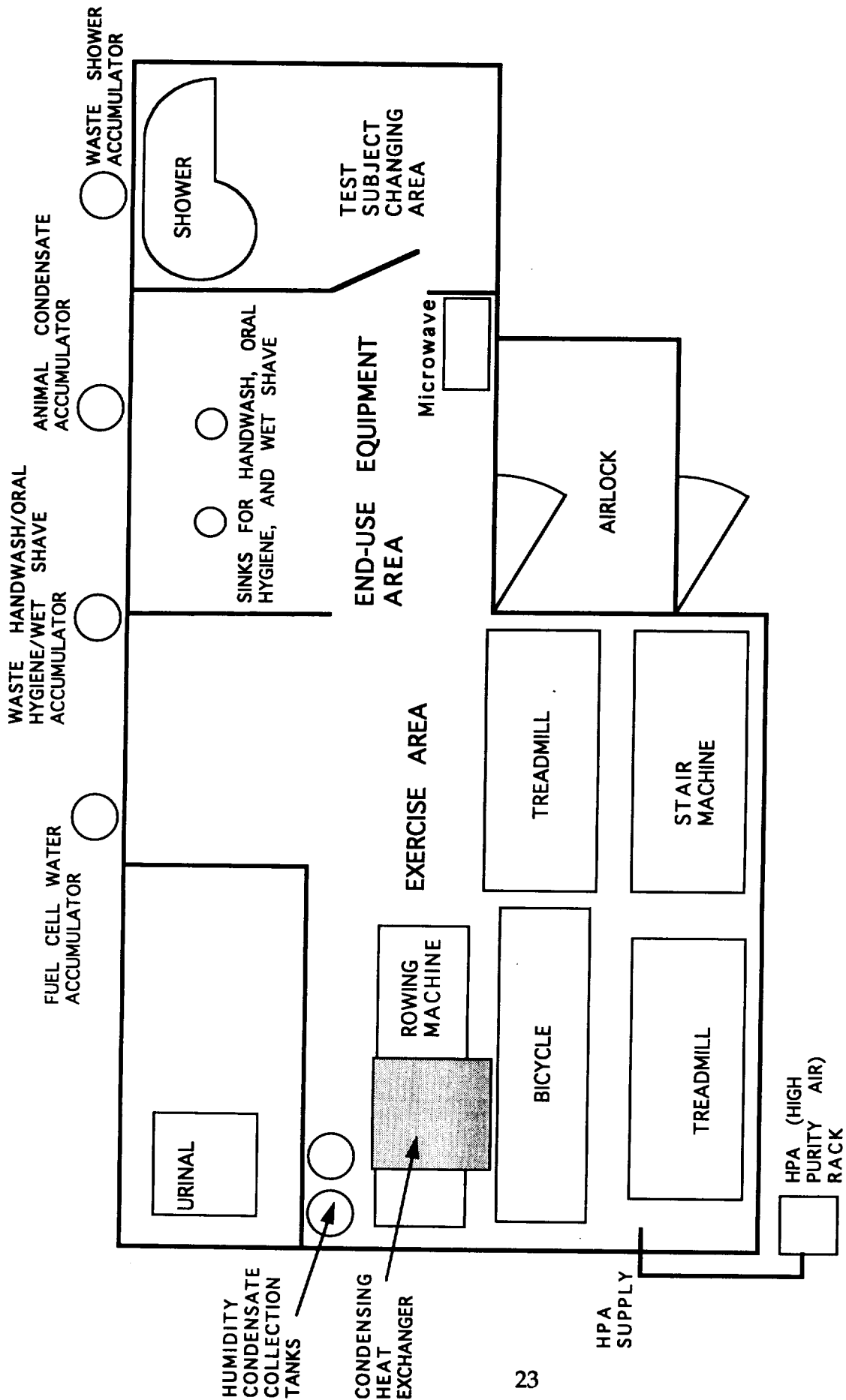
Figure 4-8. Stage 9 End-use Equipment Facility Floor Plan

of the animal condensate ersatz is shown in Table 4-8. The fuel cell water ersatz was simply facility water, and was added to the WP as needed (Section 4.1.1.1).

Table 4-8. Ersatz Animal Condensate

Contaminant	Concentration	Units
Nickel	600	ug/liter
Phosphate	17000	ug/liter
Phenol	50	ug/liter
Bis(2-ethylhexyl) phthalate	70	ug/liter
Acetaldehyde	300	ug/liter
Ammonium	590000	ug/liter
Benzoic Acid	850	ug/liter
Urea	1170	ug/liter
Protein	6080	ug/liter
Acetone	10100	ug/liter
2-Propanol	11500	ug/liter
Ethylene Glycol	14000	ug/liter
Acetic Acid	24400	ug/liter

During Stage 9, there was an average of 22.2 test subjects per day. Test subjects were asked to exercise, shower and/or handwash, donate urine, shave, and brush teeth as required by the test procedure on each day. Each test subject exercised approximately 60 minutes per day. The cleansing agents listed in Table 4-9 were used in accordance with Protocol B and the Stage 9 test requirements (9,11) and are consistent with the current flight design. Average cleansing agent usage was 1.3 grams/person per handwash and 5.6 grams/person per shower.

Table 4-9. EEF Cleansing Agents

Shower/Handwash:	Formulation: 6503-45-4
Ingredient sodium-n-coconut acid-n-methyl taurate (SCMT) (24% active)	(% by weight) 98.65
formaldehyde (Formalin, 37% active)	0.10
lecipur 95-f (soybean lecithin)	0.50
luviquat FC-500 (polyquaternium 16)	0.75
Shaving Cream Colgate	
Toothpaste: Crest (Regular flavor)	

4.4 Facility Water Supply

Facility water was provided by the on-site treatment of Redstone Arsenal tap water to meet the water quality specifications listed in Table 4-10. A schematic of the facility water treatment system is shown in Figure 4-9. Tap water was processed through two mixed bed deionizers followed by a Nanopure II laboratory water purification system (Barnstead Thermolyne, Dubuque, IA). The Nanopure II processed the water to a nominal resistivity of 18 Mohm-cm. The water was then directed to a 200 gallon stainless steel tank (CT01) which was vented through a sorbent bed and a microbial filter. The temperature of each batch of water fed to this tank was raised to 195°F by recirculating the water through an external heater. After the batch of water had been maintained at 195°F for a minimum of 4 hours, the heater was turned off and cooling water flow to a heat exchanger in the recirculation loop was turned on to lower the temperature of the batch of water to approximately 131°F. Iodine was then added to the batch of water until a residual iodine level of 3 mg/l was reached. The water was checked periodically throughout the test insure a 1 mg/l residual iodine level was maintained in the tank. Acceptable water was delivered from the tank to the appropriate use points as required.

The facility water supply has been verified in previous testing to provide acceptable water quality throughout the test operations. No significant anomalies were encountered related to the facility water supply during Stage 9, therefore the performance of the facility water supply will not be addressed in this report. A summary of facility water quality data obtained through Stage 9 is provided as Table 4-10.

5.0 Water Recovery and Management System Test Results and Lessons Learned

During Stage 9, the WRM System processed 12728 lb of total feed with 12300 lb of potable water produced and 138 lb lost as brine. This leaves 290 lb unaccounted for during Stage 9 which is well within the load cell error. The WRM System water recovery was calculated to be 99%. The following sections will discuss the overall performance of the WRM System during Stage 9.

5.1 System Control

Although the Stage 9 test was not intended to provide a comprehensive assessment of the WRM System control scheme, some important findings were discovered in implementing the tested control algorithms. Because this test was only able to address a limited number of operational scenarios, any assessment of the control scheme using Stage 9 data can only conclusively identify problems with the control scheme. The successful results achieved in the Stage 9 test are not necessarily universal to all nominal or off-nominal operational conditions. A more comprehensive assessment of the control scheme would best be done using computer modeling techniques.

25

LEGEND

⧓	Microbial Check Valve
⊡	Valve, Ball Hand Operated
⊟	Valve, Diaphragm Hand Operated
⊘	Pump, Motor Driven
🔄	Transducer, Flow
Ⓣ	Transducer, Temperature
◁	Transducer, Pressure
▦	Filter
◎	Heater
Ⓢ	Sample Port
RD	Rupture Disc
⫴	Quick Disconnect
↑	Flow Direction Tubing
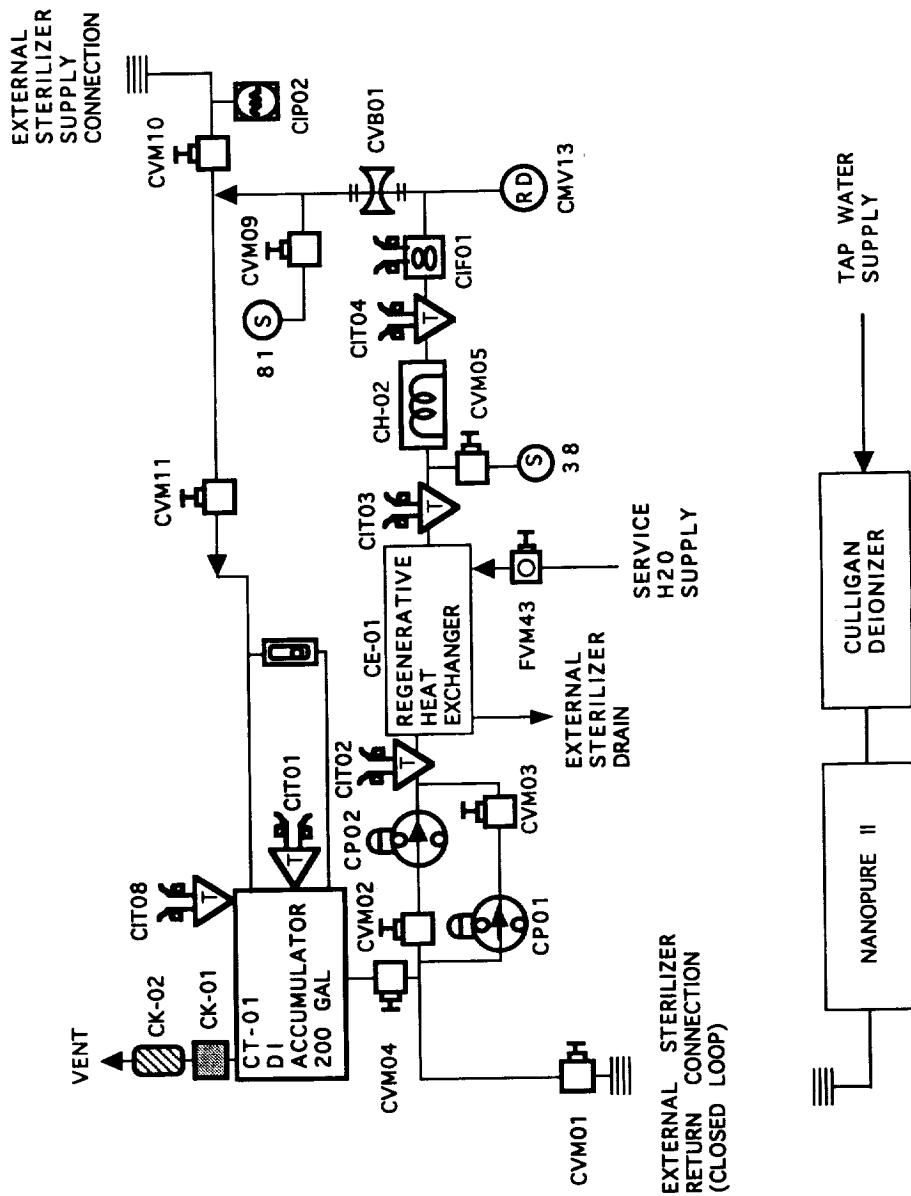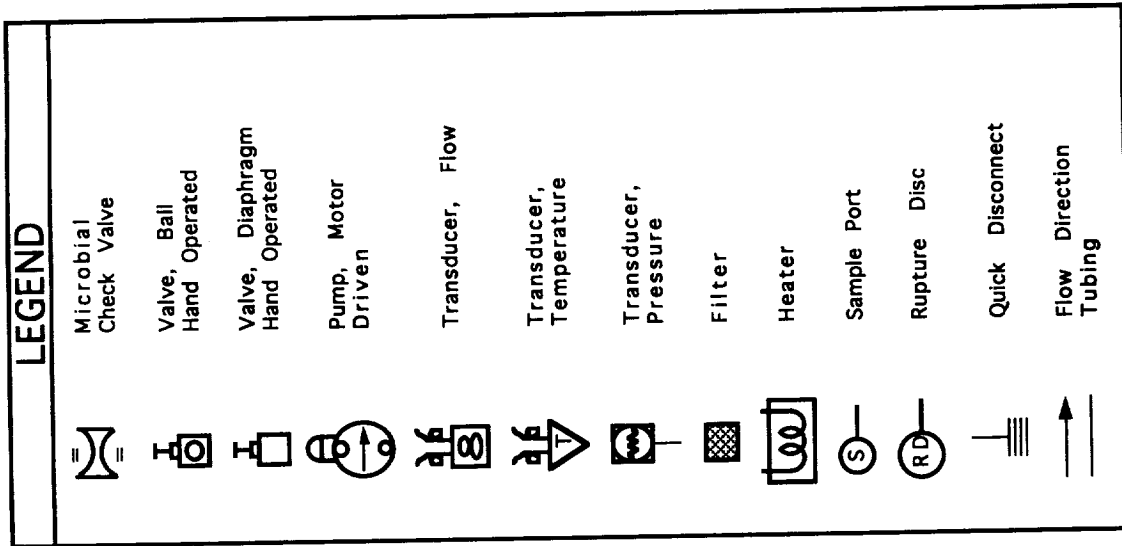
Figure 4-9. Stage 9 Facility Water Supply System Schematic

26

Table 4-10. Facility Tank Water Quality Summary (Port 38)

PARAMETER	UNITS	SPECIFICATION POTABLE	DETECTION LIMIT	TIMES DETECTED / SAMPLED	DETECTED [1] AVERAGE	MAX	MIN	STANDARD DEVIATION
PHYSICAL PARAMETERS:								
Ph	S.U.	6.0-8.5	0.0 - 14.0	82/82	6.35	7.50	3.20	0.72
Conductivity	µmho/cm	See note 2	1	81/82	2.68	7.00	1.70	0.83
Turbidity	NTU	1	0.1	69/82	0.34	1.10	0.10	0.21
CATIONS:								
Ammonium	mg/L	0.5	0.05	0/3	****	****	****	****
Potassium	mg/L	340	0.05	0/3	0.09	0.09	0.09	0.00
ANIONS:								
Chloride	mg/L	200	0.04	3/3	0.11	0.16	0.08	0.04
Fluoride	mg/L	See note 2	0.02	2/3	0.03	0.03	0.03	****
Nitrate	mg/L	10	0.1	0/3	****	****	****	****
Sulfate	mg/L	250	0.15	3/3	0.60	0.70	0.48	0.11
METALS:								
Aluminum	mg/L	0.05	0.02	0/3	****	****	****	****
Arsenic	mg/L	0.01	0.05	0/3	****	****	****	****
Barium	mg/L	1	0.001	2/3	0.003	0.004	0.002	0.001
Cadmium	mg/L	0.005	0.001	0/3	****	****	****	****
Calcium	mg/L	30	0.05	2/3	0.064	0.067	0.061	0.004
Chromium	mg/L	0.05	0.005	0/3	0.006	0.006	0.006	0.000
Copper	mg/L	1	0.005	0/3	****	****	****	****
Iron	mg/L	0.3	0.005	2/3	0.006	0.006	0.006	****
Lead	mg/L	0.05	0.01	0/3	****	****	****	****
Magnesium	mg/L	50	0.05	0/3	****	****	****	****
Manganese	mg/L	0.05	0.001	0/3	****	****	****	****
Nickel	mg/L	0.05	0.005	1/3	0.007	0.007	0.007	****
Selenium	mg/L	0.01	0.05	0/3	****	****	****	****
Silver	mg/L	0.05	0.002	0/3	****	****	****	****
Zinc	mg/L	5	0.005	0/3	0.002	0.002	0.002	0.000
BACTERICIDE								
Iodine Residual	mg/L	1 min, 4 max	0.1	62/62	2.12	2.60	1.50	0.232
Iodine Total	mg/L	15	0.1	62/62	3.10	3.50	2.80	0.149
CARBON:								
Total Organic Carbon	mg/L	0.5	1	0/39	****	****	****	****
Total Inorganic Carbon	mg/L	See note 2	1	0/39	****	****	****	****
Total Carbon	mg/L	See note 2	1	0/39	****	****	****	****
MICROBIAL:								
AEM Plate Count/2 Day	CFU/100 mL	1	1	11/48	1.4	3.0	1.0	0.7
R2A Plate Count/7 Day	CFU/100 mL	1	1	9/48	1.2	2.0	1.0	0.4

1 Averages based on samples in which detectable concentrations were measured and do not account for samples in which detectable concentrations were not found.
2 No requirement. Conductivity, fluoride, total carbon, total inorganic carbon, & specific organics will be measured and reported for information.

27

5.1.1 Simulated Recipient Mode

In order to assess the performance of the WRM hardware and control scheme under the flight operating conditions (the primary objective of the Stage 9 test), the performance of the simulated recipient mode had to be assessed. Only during correct operation of the simulation could the WRM hardware performance and control scheme be assessed.

The requirements that define "correct operation" of the simulation for assessing the hardware performance are different than the requirements for assessing the WRM control scheme performance. In assessing hardware performance, the simulation only needed to deliver waste water to the WRM hardware at proper flow rates and quantities. However, to assess the control scheme, it was necessary for hygiene waste water inputs and product tank outputs to be synchronized and the mass in and out of the system to be balanced within ISS specifications.

The data was reviewed to see if all waste streams pumped into the waste tank were done so at the proper flow rates. The data indicated that the two metered waste streams (humidity condensate/equipment off-gas ersatz mixture and the animal condensate ersatz) flowed into the WP waste tank at the proper flow rates throughout the test. The animal condensate flow rate (DF31) averaged 2.63 ml/min (required flow = 2.5 ml/min) and the humidity condensate/equipment off-gas ersatz flow rate (DF30, DF32) averaged 3.61 ml/min for 14 hours to simulate active crew, 50.8 ml/min for 2 hours to simulate exercising crew, and 3.34 ml/min for 8 hours to simulate a sleeping crew (required flow rates of 3.78 ml/min, 52.3 ml/min, 3.0 ml/min respectively). There were excursions due to operator error but these were few and insignificant.

Shower waste water was delivered to the WP waste tank at an average of 0.32 lb/min. Waste water from the handwash (handwash, wet shave, oral hygiene) was delivered at an average flow rate of 0.22 lb/min. These flow rates are lower than the derived flight maximum flow rates (shower maximum flow rate = 2.35 lb/min, handwasher maximum flow rate = 0.93 lb/min), though they are not considered an unreasonable simulation of ISS flow rates. The impacts associated with operating at the maximum shower and handwash flow rates on water management are discussed in Section 5.1.2. All other waste stream flow rates (CHeCS waste, urine, urine distillate, fuel cell water) were considered representative of flight.

Waste stream quantities per day were also compared to the expected flight values. Table 5-1 lists the average quantity for each waste stream during Stage 9, the nominal value expected on the ISS, and the acceptable range for that stream on ISS. Appendix B contains plots of the daily waste water and product water quantities for the key waste streams. There were test days when some of the waste streams were outside the acceptable range. An acceptable level of pretreated urine/flush water was the most difficult to achieve, with 40 of the 116 test days below 6.9 lb/day (Figure B-3). Shower waste quantity was less than 16 lb/day on 13 of 116 test days and above

28

24 lbs per day on 37 days (Figure B-1). Because the maximum and nominal shower waste quantities were the same, exceeding the maximum shower quantity on 32% of the test days was considered to be acceptable. Humidity condensate/equipment off-gas ersatz mixture was below 16.04 lb/day on 6 of 116 test days (Figure B-4). General hygiene waste (handwash, wet shave, oral hygiene) was below the minimum level of 32 lb/day on 7 of 116 test days (Figure B-2). Animal condensate ersatz and CHeCS waste ersatz were within acceptable ranges throughout the test. The quantity of fuel cell water used during the test is dependent on the deficit between water into and out of the WP tanks during the test. The average fuel cell water input per day was higher than the nominal value because of the lower than expected input of urine and humidity condensate, as well as the errors in the totalizers that controlled the input and output of hygiene water.

As described in Section 4.1.1.2, the recipient mode simulation consisted of the crew and lab animal loop and the hygiene loop. Table 5-2 shows the product water uses and waste water inputs that were defined as the crew and lab animal loop. The average values for all waste streams fell within the ISS acceptable range, however, the drinking water and sample quantity averaged 0.94 lb higher than the maximum acceptable ISS quantity. The difference can be attributed to inclusion of EVA water in the drinking water pulls for the first 28 days of the test (see Section 4.1.1.2 and Figure B-6). To assess how well the crew and lab animal loop simulation balanced, the difference between daily inputs and outputs were compared to the difference between the ISS maximum and minimum values (Figure B-7). Only 10 days of the 116 test days were outside the ISS acceptable range (ISS input - output = -13.1 to 66.6 lb/day). All 10 off-nominal days were the result of outputs exceeding inputs by more than 13.1 lb. Three of the off-nominal days were caused by operator error which resulted in extra water being dumped from the product tanks (Test Days 43, 95, 104). Even though the balance was within specification for most of the test, the crew and lab animal loop ran at a deficit for 76 of the 116 test days, resulting in the increase in fuel cell water input as discussed earlier. The effect this had on the performance of the WP will be discussed in Section 5.5.

The hygiene loop simulation was assessed for mass balance and synchronization between waste water inputs from facility and water drained from the product tank. Because of several problems with the system software as well as inexperience in operating a simulation of this type, the hygiene loop simulation was neither balanced or synchronized for the first 8 days of the test. Test days 9-43 and 52-99 showed excellent balance (< ± 5.0 lb) between the quantity of water drained to simulate hygiene use and the quantity of facility water input for hygiene use. During days 44-51, more product water was drained from the system than was added as waste water input because of an error in the facility water totalizer (CI40) that was used to control the simulation. The totalizer was re-zeroed on Test Day 51 and the balance was restored. CI40 drifted 2 more times from day 51 to day 99 but the calibration was adjusted, resulting in only 1 or 2 days of small imbalances. On Test Day 100, the balance of the waste water inputs to product tank drains was lost until the end of the test. Review of the sensor data shows error in both the facility water

Table 5-1. Average Waste Stream Quantities During Stage 9

Waste Stream	Average from Stage 9 (lb/day)	ISS nominal (lb/day)[1]	ISS acceptable range (lb/day)[1]
Shower	23.2	24	16-24
General Hygiene	33.5	42.7	32-46.7
handwash		36	32-40
wet shave		3.5	0-3.5
oral hygiene		3.2	0-3.2
Pretreated urine/flush water	10.2	17.65	6.9-22.4
CHeCS Waste	1.44	1.44	0-1.44
Humidity Condensate/Equipment off-gas ersatz mixture	22.5	23.5	16.04-57.56
Animal Condensate[2]	7.7	7.92	N/A
Fuel Cell Water	11.51	3.72	N/A

1. All nominal values and acceptable ranges for the waste streams were taken from the ECLSS ACD rev E unless noted and are based on a 4 person crew.
2. Values were derived from data given in U.S. Segment Specification SSP41162A

Table 5-2. Crew and Lab Animal Loop Inputs and Outputs to the WRM

Waste Water Inputs	Average from Stage 9 (lb/day)	ISS nominal (lb/day)[1]	ISS acceptable range (lb/day)[1]
Humidity Condensate/Equipment off-gas ersatz mixture	22.5	23.5	16.04-57.56
Metabolic condensate		20.4	13.88-53.6
Hygiene Latent condensate		2.8	2-3.6
Food prep latent condensate		0.32	0.16-0.36
Animal Condensate[2]	7.7	7.92[2]	N/A
Urine/Flush water	10.2	17.65	6.9-22.4
CHeCS Waste	1.44	1.44	0-1.44
Product Water Outputs			
Drinking Water and Samples	44.9	41.28	22.76-43.96
Drinking water		14.24	2-15.6
Food prep water		6.68	3.6-8
Animal Drinking Water[2]		7.34	N/A
Wet Trash		3.2	0-3.2
CHeCS Sample		1.54	N/A
O_2 Generation		8.28	N/A

1. All nominal values and acceptable ranges for the waste streams were taken from the ECLSS ACD rev D unless noted and are based on a 4 person crew.
2. Values were derived from data given in U.S. Segment Specification SSP41162A

totalizer (CI40) and the Product Tank totalizer (RI40), resulting in more water drained from the system than was input through hygiene use.

The synchronization of the waste water input and the corresponding product tank drains to simulate closed loop usage was also assessed. Test days 1-43 were simulated manually. This resulted in the WRM System "seeing" the input of waste water into the WP waste tank before water was removed from the product tank (an order of events that is backwards from what would be expected if the hygiene loop were actually closed). The delay between input of the waste water and draining of the product tank was anywhere from 15 minutes to several hours depending on when the test director checked the facility water totalizer and drained the corresponding amount of water from the product tank. Once the hygiene loop simulation was automated on day 44, the product water drain was initiated as soon as the facility water totalizer (CI40) registered an increase. Because there was a delay between the use of facility water and the delivery of the hygiene waste water to the WP waste tank, the WRM System "saw" the product tank drain begin before the waste water input occurred (reflecting a more accurate order of events than the simulation did in days 1-43). The delay between the start of the product tank drain and the start of waste water input to the WP waste tank after automation was 7-15 minutes for showers and 2-10 minutes for the handwasher. These delays were considered insignificant given the slow dynamics of the WRM System.

The lack of synchronization in the first 43 days of the test was assessed to determine the effect on the WP's ability to process waste water in a timely manner. The delay in draining product water from the tank until after the waste water was delivered to the waste tank could result in the WP not having a product tank to fill during processing. This would occur by filling the waste tank above its setpoint to initiate WP processing while the product tanks remained in a deliver and isolate mode only because the product water corresponding to the waste water generated had not been drained. Once the product water was drained after the "artificial" delay, the tank would transition to fill mode and the water processor would begin processing. These artificial delays could allow a significant amount of waste water to collect in the waste tank, resulting in a more aggregate waste water processed by the WP than would be achieved in an actual closed loop system. In order to verify that the closed loop simulation was not compromised in this manner, the daily maximum waste tank quantities for Test Days 1-43 were compared to Test Days 44-116 (when the hygiene waste water input was correctly synchronized to the product tank drains). Table 5-3 shows the distribution of maximum waste tank quantities per day for the Test Days 1-43 and 44-116. As can be seen from the table, during Test Days 44-116 the waste tank quantity actually reached high levels more often than during Test Days 1-43, indicating that any waste water buildup that occurred as a result of the lack of synchronization of the hygiene waste inputs and product tank drains was insignificant.

31

Table 5-3. Distribution of Maximum Waste Tank (wa60) Quantities Before and After Hygiene Loop Automation

WP Waste Tank Maximum Quantity (lb)	Test days 1-43 (% days)	Test days 44-116 (% days)
>100	2.7	6.1
>90	16.2	14.3
>80	27.02	42.8
>70	48.6	71.4
>60	67.6	91.8
>50	86.5	95.9
>40	100	100

5.1.1.1 Conclusions and Recommendations

The Stage 9 recipient mode simulation did not perform perfectly. Though the simulation was "balanced" per ISS requirements over 94% of the test, the balance ran on the negative side for most of the test. This resulted primarily from lower than normal input of urine to the system as compared to the simulated consumption of water by the crew. A negative balance around the crew could be expected to occur periodically aboard the ISS but would eventually be offset by positive balances. The effect this consistently negative balance had on the simulation was an increase in the daily input of fuel cell water above the nominal value.

The hygiene loop had problems with balance as well as synchronization. Due to sensor drift, the quantity of hygiene inputs and outputs were not always the same. Also, the hygiene inputs were not correctly synchronized with the hygiene water dumps from the product tanks until Test Day 44. These errors in the simulation affect the ability to assess the WRM control algorithms. However, the operating conditions were not altered significantly enough to affect the ability to assess the WRM hardware performance.

The recipient mode simulation was considered adequate during the entire test to assess the performance of the WRM hardware under ISS operating condition. The below normal urine input and above normal fuel cell water input is factored into the assessment of the WP performance. However, an assessment of the WRM control can only be made from Test Days 52 to 99. Only during this time frame was the simulation balanced and synchronized sufficiently to assure that any control anomalies were the result of the WRM control logic and not from the simulation itself.

5.1.2 Water Recovery System Control

Given the results from recipient mode simulation assessment, only the data from Test Days 52 to 99 were used in the performance analysis of the WRM control logic.

32

The management function was assessed to determine if the product water availability and waste tank storage capability was maintained at all times. Water was unavailable for immediate use during 5 of the 48 days reviewed. Of those five days, two were caused by communication errors between the WP and the host computer (Test Days 55 and 58) and therefore did not result from a failure of the control logic. Water availability was lost on Test Day 96 because of an operator error which occurred on Test Day 95 that dumped an additional 30 lb of water from the product tank. Because this error caused the crew and lab animal loop simulation to be extremely out-of-balance on Test Day 96, the failed simulation caused the loss of available product water, not the WRM water management function. The last two days (Test Day 77 and 92) were unable to provide water continuously because the WP was being maintained. During Test Day 77, the WP was shutdown to replace the WP software with an updated version, resulting in the delivery tank becoming empty 30 minutes before the fill tank was full and able to deliver water. A failure of the heater element in the VRA reactor on Test Day 91 caused a 24 hour shutdown of the WP while troubleshooting and maintenance was performed. The shutdown resulted in water being unavailable for 11.6 hours on Test Day 92. Though shutdowns for maintenance will obviously occur aboard the ISS, water availability can not be expected to be maintained during those shutdowns. Under these circumstances, the fuel cell water stored aboard the ISS would be used if water was needed.

Also through the water management function, the water level in the WP waste tank was maintained low enough so that end-use equipment was never commanded to shutdown because the waste tank was full during nominal operations. Some end-use equipment shutdowns occurred because of high temperature failures in VRA which automatically isolated the waste tank from the waste water bus. This logic was internal to the WP and is not considered representative of the ISS flight control. The high temperature failures in the VRA are discussed in Section 5.5. The only time the waste tank actually reached its maximum capacity and shut down the end-use equipment was Test Day 92 because of the VRA heater failure on Test Day 91. As stated earlier, the system cannot be expected to operate nominally during a 24 hour shutdown of the WP.

In order to apply these results to the ISS, the relevance of the simulation to actual operating conditions as well as the state of the water tanks must be assessed. The simulation assumed a 4-person crew, all working and sleeping at the same time. The Stage 9 "crew" used water for a 12 hour period each day, with the majority of water used in the first six hour period of the work day. With this operating scenario, the WRM was able to process water faster than the overall usage rate, allowing water to be available at all times. The nominal water usage for ISS is 107.9 lb/day with a maximum usage of 132.4 lb/day if an EVA is performed. As long as the water usage per day is below the maximum allowed for the ISS and the usage rate is below the WP process rate of 15 lb/hr, product water will be available at all times. However, the water usage rate could exceed the WP process rate (i.e. 132.4 lb over an 8.8 hour period or less). This should not affect product water availability

because of the high process rate of the WP. As long as there is a sufficient time period where water is not being used (at least 8.8 hours for 132.4 lb/day), the WP has a high enough process rate and sufficient product water storage capacity to have more than a day's supply of water available at the beginning of the next day. Therefore, the WRM should be able to provide product water at all times.

The problem with a high usage rate is in waste water storage capacity. The ISS nominal waste water input to the WP waste tank is 98.1 lb/day with a maximum input of 240.8 lb/day. An input of 240.8 lb/day would occur under the following conditions: the maximum input of hygiene water and humidity condensate, the balance of input to output on the previous day was at the maximum deficit resulting in the addition of 32.31 lb of fuel cell water, and the UP produced 65.3 lb of urine/CHeCS waste distillate (40 lb of urine stored in the UP urine tank, 22.4 lb maximum input of urine per day, and 10.1 lb of CHeCS waste processed by the UP at 90% water recovery). Of the 240.8 lb/day, 121.3 could be put into the waste tank within 50 minutes. This would require the shower and handwash usage, UP operation, and fuel cell water addition to occur simultaneously at the maximum flow rates until all the hygiene water had been used for the day. This would also have to occur during the crew exercise period so that the maximum input of humidity condensate would occur. If this happened when the waste tank was at its maximum capacity with the WP in Standby (30 lb), then at the end of the 50 minutes, the WP waste tank would have to contain from 138.8 to 151.3 lb of waste water, 3.8 to 16.3 lb greater than its capacity (depending on how long it took for the VRA temperatures and PCWQM measured water quality to stabilize so that the WP was transitioned from Reject to Process state). Therefore, with this control scheme, there is a possibility that waste water storage capability could be lost for up to 3 hours.

The control logic of the WRM subsystem coordination function performed as expected. The mode transition of the WP from Standby to Process was tracked very well by the PCWQM. Failures that occurred were the result of communication errors and not related to the logic. After the criteria that determined when the PCWQM could go into Recirculation and Calibration mode was changed on Test Day 22, the PCWQM went into Recirculation and Calibration modes an average of 25.8 hours and 170.1 hours, respectively, following the completion of the previous mode. The only problem with this logic was that the time interval between the respective modes was set from the completion of the previous mode to the initiation of the next mode. For example, a Recirculation mode that ended at 8:00 p.m. one day was intended to be initiated at 8:00 p.m. the following day. Because PCWQM Recirculation mode lasted for about 2.3 hours, each Recirculation would start 2.3 hours later in the day than the previous one. Eventually this would result in a Recirculation taking place during the normal operating time of the WP, and therefore not allow the WP to enter process even though sufficient waste water had collected in the waste tank. Though this never interfered with the availability of product water, the impact to the WP operation could be reduced by changing the

time interval between these modes from the start of the previous Recirculation mode to start of the next Recirculation mode.

The system software interpreted data obtained from the WP and the PCWQM to determine if the WP should be in Process or Reject mode. As mentioned previously, the WP was maintained in Reject mode if the VRA reactor temperatures (wt47, wt48) were below the minimum setpoint. Furthermore, PCWQM data was used by the system control logic to determine if the WP product water was of acceptable quality. If unacceptable, the system control kept the WP in Reject mode until the water quality was acceptable. Water quality data provided by the PCWQM was compared to the potable water quality specification to determine if the water was acceptable. Initially the potable water quality specifications provided in Table 5-4 for TOC, iodine, conductivity and pH were used as the setpoints for determining acceptable water quality. However, the PCWQM reported data that regularly exceeded the water quality specification values. Because a major objective of Stage 9 was to evaluate an automated water management system, the control setpoint range was extended for these parameters to allow for a more representative WP production rate. Table 5-4 provides the revised range for the PCWQM parameters. Analysis conducted after the test showed that the iodine and pH levels reported by the PCWQM were inaccurate and, according to laboratory results, actually did meet the water quality specification. Further discussion of the PCWQM pH and iodine data is provided in the PCWQM performance discussion, Section 5.4.1.

Table 5-4. Water Quality Acceptance Setpoints

Parameter	Units	Water Quality Requirements	Stage 9 Revised Setpoints
Total Organic Carbon	ug/l	500	1000
Conductivity	umhos/cm	10	10
Iodine	mg/l	1-4	1-7
pH	pH units	5-8	0.1-8.5

The operating characteristics of the WP presented difficulties for the PCWQM data interpretation function. A TOC spike (Section 5.5) occurred at the beginning of each process cycle that exceeded the TOC specification for approximately 2 hours. Since the averaging technique installed before the test was not developed to address the dynamic nature of a TOC spike, difficulties were encountered during the transition from Reject to Process. A redesign of the ion exchange bed that would eliminate or minimize the TOC spike would likely resolve this problem. If this approach is not feasible, alternative control scenarios will be developed to better address the TOC spike.

Despite relaxing the water quality requirement (Table 5-4), acceptable water quality was achieved in 23 of 40 product water tanks, not including those tanks filled following the replacement of an ion exchange bed or during the TOC Monitor Deletion study (see Sections 5.5.2 and 5.4.2 - excessively high TOC levels required the

PCWQM data interpretation function to be disabled for the continued production of water). Of the 23 tanks that met the water quality requirements, 20 tanks received water that exceeded the TOC requirement of 500 ug/l at some point in the processing cycle. Unacceptable water quality in the product tanks (Port 120) was normally due to high TOC levels which could have been reduced by using a more stringent criteria for accepting product water, especially when dealing with the TOC spike.

5.1.2.1 Conclusions and Recommendations

The water management logic of the Stage 9 test worked very well. Waste water was received and processed in a timely manner and product tanks were rotated from fill to deliver modes efficiently so that, during the nominal conditions of the Stage 9 test, product water was always available for use and waste water storage was always available. How these successful results apply to the myriad of conditions that can be expected aboard the ISS is difficult to assess. An assessment of worse case conditions show that the water management scheme in Stage 9 would be able to provide product water at all times but an end-use equipment shutdown could result because of loss of waste water storage capability. The loss of waste water storage as a result of the worse case conditions described earlier could easily be rectified by lowering the waste tank setpoint that triggers the WP to process from 30 lb to 10 lb, allowing more available capacity in the tank. However, this would result in an increase in power usage as a result of more frequent cycling of the WP between Processing and Standby modes. Given the low probability of this operating condition occurring, a logic change to handle it that results in less efficient operation of the WRM would not be justified. Therefore, 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. As the ISS operational scenarios are better defined, the water management control logic should be tested using computer modeling techniques.

WRM subsystem coordination was successfully achieved during Stage 9. The only recommended improvement is to initiate a PCWQM Recirculation mode 24 hours following the start of the previous Recirculation mode, rather than at the completion of the previous mode. The same logic would apply to the time interval between Calibration modes.

The PCWQM data interpretation algorithm was unable to respond to the dynamics of the WP or PCWQM performance. The test results did indicate that the water meeting the ISS requirements in the product tanks (Port 120) could be achieved while delivering water to the tanks that at times did not meet the ISS water quality requirement. Since the ISS water quality requirement is established for water delivered to the crew (i.e., water in the product tanks), the control approach should be geared toward insuring acceptable water quality in the product tanks, rather than in the VRA effluent. An integrated response to the PCWQM data would seem most feasible whereby degraded water quality would be acceptable if past history on the tank's water quality indicates that overall water quality will be acceptable.

Additional studies are recommended to develop control algorithms that are better suited for the dynamic product water quality and PCWQM performance.

5.2 Urine Collection System

5.2.1 Performance

The urinal collected and pretreated 1330 lbs of urine, flush water and CHeCS waste during the test. An pretreated urine delivered to the UP maintained an average pH of 2.3. The average power (DW01, DW02, DW03) consumed by the urinal when it was operating was 148 Watts. During Standby, 13 Watts were required to operate the sensors. The urinal provided the required pressure to deliver the liquid to the UP feed tank. The separator operated nominally throughout the test, though anomalies related to test stand operation did occur. The separator flooded twice during the test because the on/off switch did not function properly and once due to improper configuration of the test stand. After being flooded, the separator bearings became corroded and, while it did not affect the test, will need to be replaced before additional testing. The bearings used for the flight unit may need to be sealed so that any inadvertent flooding will not damage the bearings.

Figure 5-1 shows a typical operating period. At each donation, the pressure across the separator (vp05) increased between six and nine psig. At the end of the donation the pressure difference began decreasing and continued to decay until the next donation.
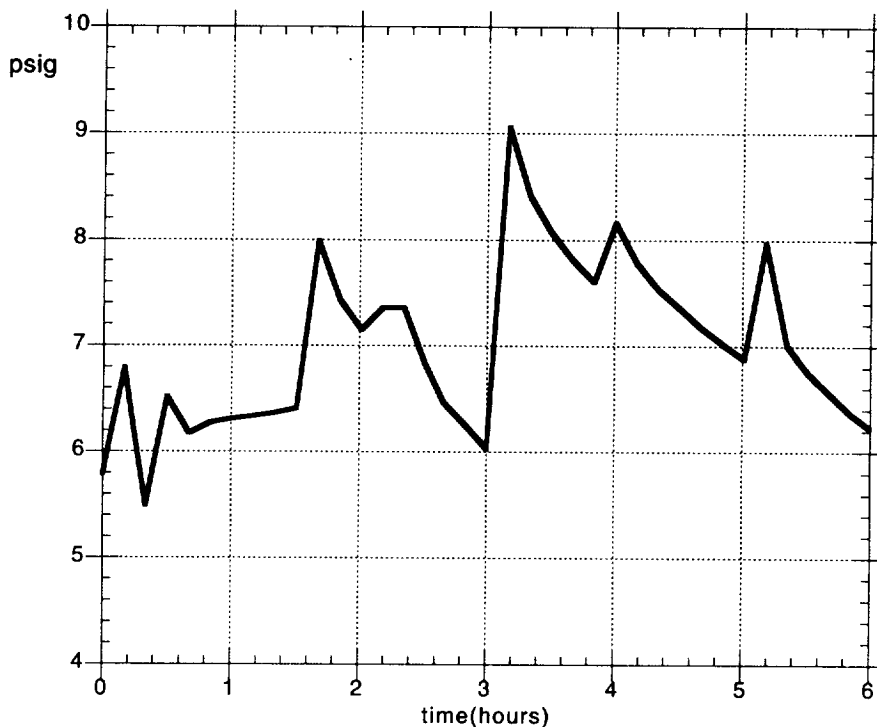
Figure 5-1 Urinal Operating Pressure (November 1, 1995)

The amount of air entrained was not measured during this test, but the operating pressures seen at the start-up of the UP indicated there was some air in the urinal outlet (See Section 5.3.1). The presence of air in the urinal outlet was expected, though every effort will be made in future development work to reduce the amount of air inclusion in the urinal outlet.

5.2.2 Conclusions and Recommendations

This was the first time the predevelopment urinal had been tested at MSFC and the first time it had been integrated into a water recovery system. The urinal adequately collected, pretreated and transferred urine to the urine processor. Because of the separator flooding during the test, it should be refurbished with new bearings before any new integrated tests are planned for this unit. While no significant anomalies occurred, the air entrained in the pretreated urine stream did affect UP performance. This effect should be negligible in microgravity because the air should stay dispersed in the UP feed tank. If necessary, modifications to the urinal separator design (such as adjusting the position of the pitot tube) could minimize the volume of air transferred to the UP feed tank.

5.3 Urine Processor

A total of 1126 lbs of pretreated urine/flush water and 152 lbs of CHeCS waste water was processed by the UP during 242 hours of operation with 1140 lbs of distillate delivered to the WP waste feed stream. The UP produced urine distillate that regularly met the water quality requirements for the urine processor. The UP recovered 91% of the pretreated urine and CHeCS waste water. This recovery rate is similar to previous testing conducted with the VCD-V. Differences in water recovery are generally due to the timing of the replacement of the brine tank.

5.3.1 Performance

The VCD-V production rate is shown in Figure 5-2 and indicates when the brine recycle filter tank changeout occurred during the test. Tank changeout occurred when the throughput of urine to the VCD-V reached approximately 400 lb. The required processing rate for the ISS is 4.5 lb/hr, which the VCD-V averaged during the test. The production rates were determined by dividing the amount of water processed in a batch by the number of hours the VCD-V was in operation, including Start-up, Normal and Reprocessing modes. The production rates decreased over time as the solids concentration built up in the recycle loop. The rate went back up each time the brine tank was replaced.

Figure 5-3 shows the condenser temperature calculated from the operating pressure (based on saturated steam correlations) during the nominal processing of a batch of pretreated urine. This is typical of the operating temperature curves for the VCD-V.

Figure 5-4 shows start-up and operating temperatures measured at the outlet of the compressor (vt01) on Test Day 28 and indicates the temperature close to the gears. The temperature spiked above the alarm set-point of 200°F due to the excessive load on the compressor while processing the air entrained in the pretreated urine (hours 0-5). The air

in one-g stays at the top of the feed tank. During Stage 9, the feed tank outlet was also located at the top of the tank. Therefore, air entered the VCD-V at the beginning of each batch. This left the compressor with dry air to compress rather than steam, thus the gears received no cooling or lubrication from the steam. After the air was evacuated, the temperature dropped and a normal temperature curve was observed (hours 5-8). This anomaly happened repeatedly over the test.
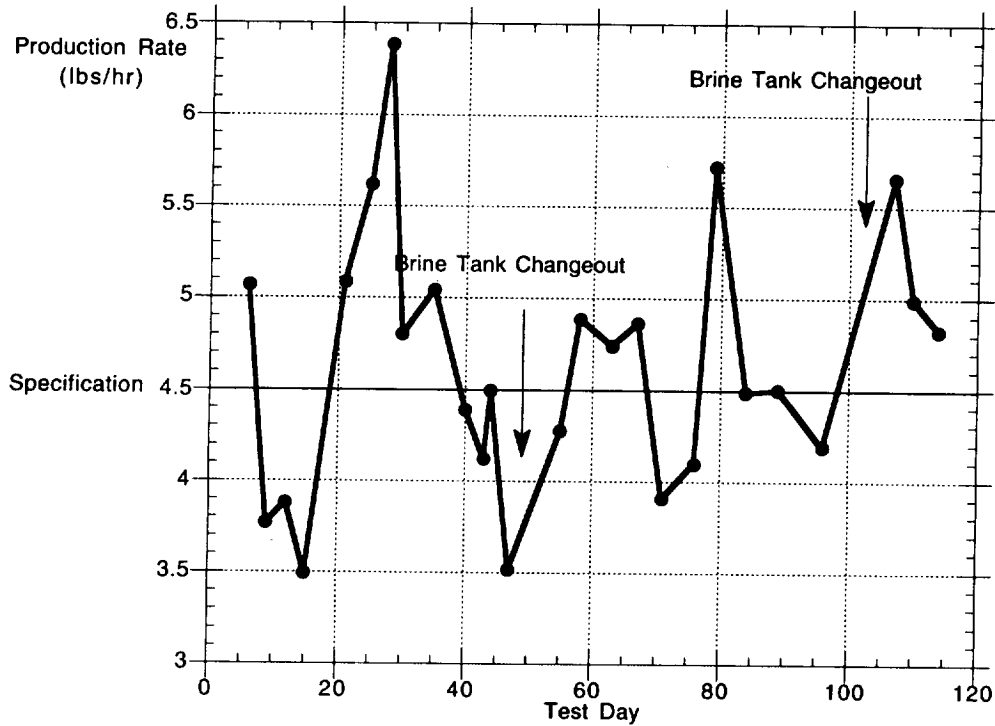
Figure 5-2 WRT Stage 9 VCD-V Production Rate

The condenser pressure (vp01) also showed these start-up and operating trends (Figure 5-5). During start-up, due to the large volume of gas in the feed tank (hours 0-5), the pressure in the still increased significantly over a short period of time, subsequently increasing the load on the purge pump and compressor. When the air was removed by the purge pump, the operating pressures returned to those typically seen with the VCD-V in previous testing (hours 5-8).

The anomalous start-up temperatures and pressures are assumed to be one-g related because the air would not collect in one area of the feed tank on-orbit. This was demonstrated during the ECLSS Flight Experiment when the air in a bellows tank was observed to stay entrained rather than collect in one area of the tank (12). A VCD flight experiment planned for May 1997 should validate this start-up behavior.

39
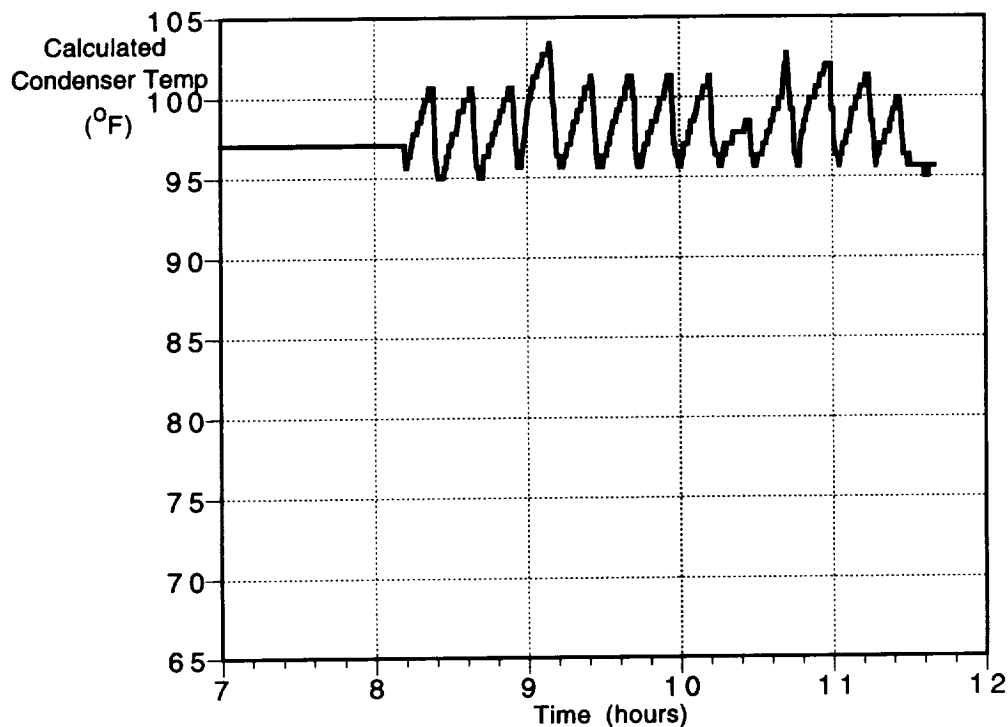
Figure 5-3 Calculated VCD-V Condenser Temperature (Test Day 28)

5.3.2 Water Quality

The water quality specifications for the VCD-V distillate along with the average water quality data measured throughout the test are shown in Table 5-5. In general, the water quality was considered nominal for the VCD-V. No differences in water quality were attributed to adding CHeCS waste or to the automated addition of pretreatment chemicals. The conductivity, pH and TOC were very near the averages seen when processing manually pretreated urine with the VCD-V during Life Testing in 1993 and 1994 (13).

Table 5-5 WRT Stage 9 Water Quality Data for VCD-V Distillate

Parameter	Spec.	Average	Units	No. of Samples
Conductivity	<150	59.9	umho/cm	19
pH	3-8	3.94	pH units	19
Total Organic Carbon	<50	21.1	mg/L	19

5.3.3 Conclusions and Recommendations

The VCD-V performed adequately during Stage 9. There were no anomalies which could be directly or indirectly linked to the overall system operating control. The high temperatures seen on start-up of each batch of urine are attributed to air in the feed tank. This is considered to be a one-g phenomenon and is not expected on-orbit. However, a flight experiment is planned to address these concerns. The mechanical and electrical

40
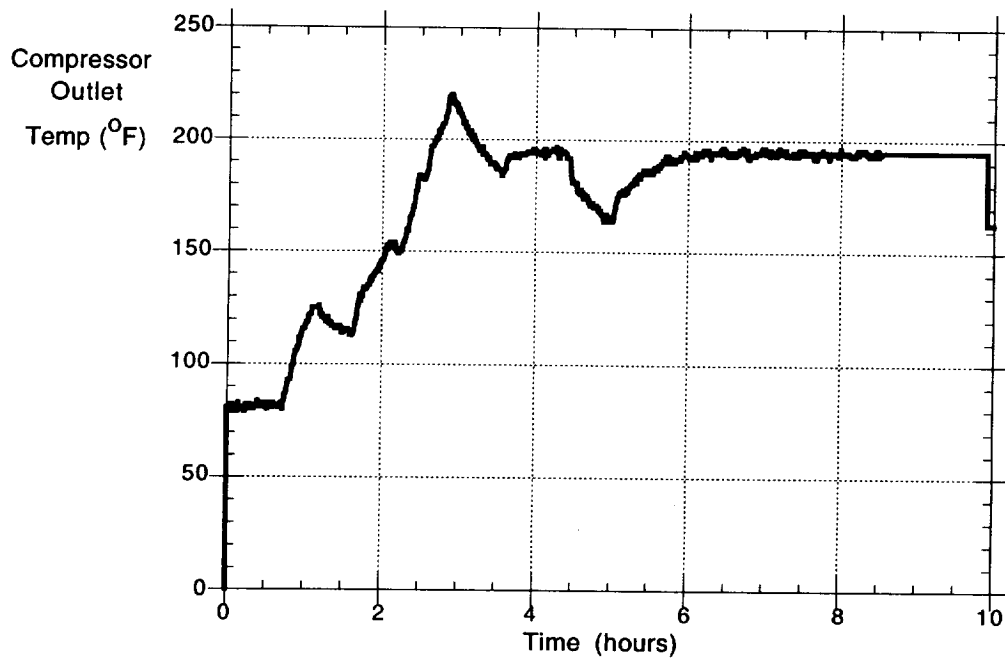
Figure 5-4. VCD-V Compressor Outlet Temperature (Test Day 28)
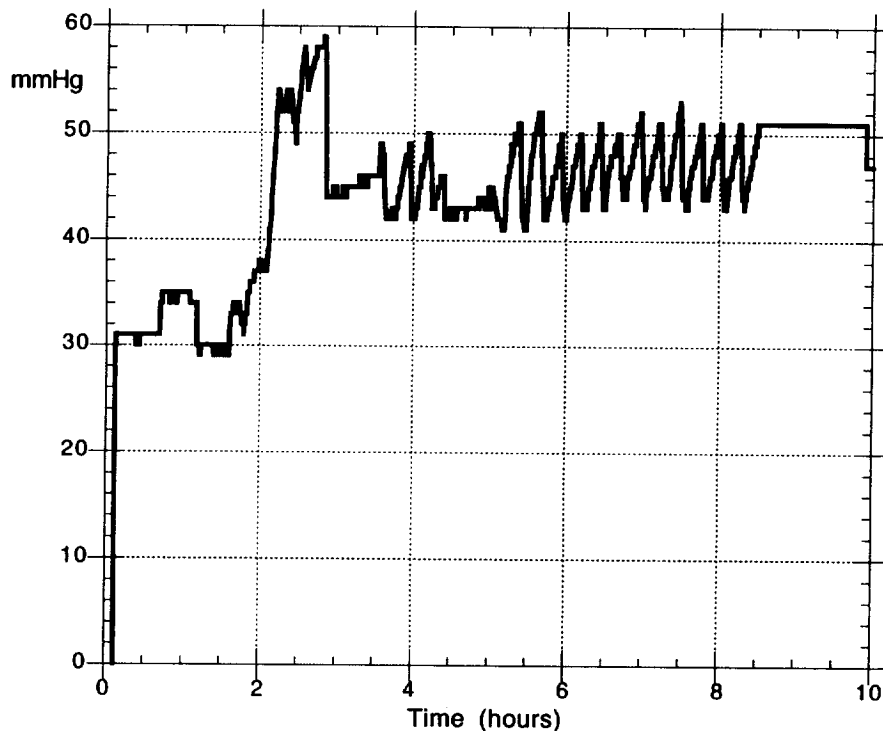
Figure 5-5. VCD-V Condenser Pressure (Test Day 28)

performance was nominal and comparable to earlier testing, including Life Testing with the VCD-V. The water quality was always within required limits. The VCD-V's performance added more confidence in the hardware's ability to produce water meeting

41

the required specifications. This was the first time that a predevelopment urinal and automatic urine pretreatment hardware has been integrated in a WRM test. The success of this integration made this test very useful for future development efforts.

5.4 Process Control Water Quality Monitor

5.4.1 Performance

Performance analysis of the respective PCWQM sensors was accomplished by comparing analytical data of samples pulled from the VRA effluent with the PCWQM data. Iodine data was also analyzed by comparing the analytical results on Product Tank samples (Port 120) with PCWQM data generated over the time period that a specific tank was filled.

The PCWQM performance assessment also includes an evaluation of the Calibration and Recirculation modes. During these modes parameters were determined that were used to calibrate the pH sensor and make appropriate adjustments to the measured TOC. The performance evaluation will address the success of these modes and the subsequent impact on the sensor performance.

5.4.1.1 Iodine Sensor Performance

Due to funding constraints associated with the Stage 9 test, limited analysis of the iodine concentration in the VRA effluent was performed. The results of these analyses are included as Figures 5-6 and 5-7. An observed step increase in the iodine data is related to the VRA and will be addressed in Section 5.5.2. The data shows that the PCWQM iodine sensor (pin1) read consistently higher than the residual iodine reported by the Boeing Laboratory, which is measured by the leuco crystal violet analysis technique. In fact, the PCWQM iodine sensor was consistently in agreement with total iodine analysis results, suggesting that the sensor may have been reading residual iodine (I_2) and iodide (I^-). However, design development data provided by Astro indicates that the infrared wavelength utilized by the sensor should not be significantly adsorbed by iodide. Figure 5-8 presents the interference with the sensor's wavelength by iodide determined by testing conducted at Astro (14). This plot compares the adsorbance of a 5 ppm iodine solution with 0 ppm potassium iodide and 0.82 ppm potassium iodide, and shows no significant impact due to the presence of iodide. The blue and red LEDs mentioned in the plot are the light emitting diodes that generate the light source from which the adsorbance through the cell is measured. According to this data, the nominal iodide level in the WP product water of 0.7 mg/l should have a negligible effect on the sensor reading. Studies conducted at the Boeing Laboratory on the iodine sensor support Astro's findings. This data leaves open the possibility that other contaminants in the water may be interfering with the sensor data. However, the low levels of conductivity and total organic carbon indicate the presence of only trace levels of other contaminants. Organic species were also investigated by Astro to determine relative interference with the measurement of iodine. This data also indicates that

42
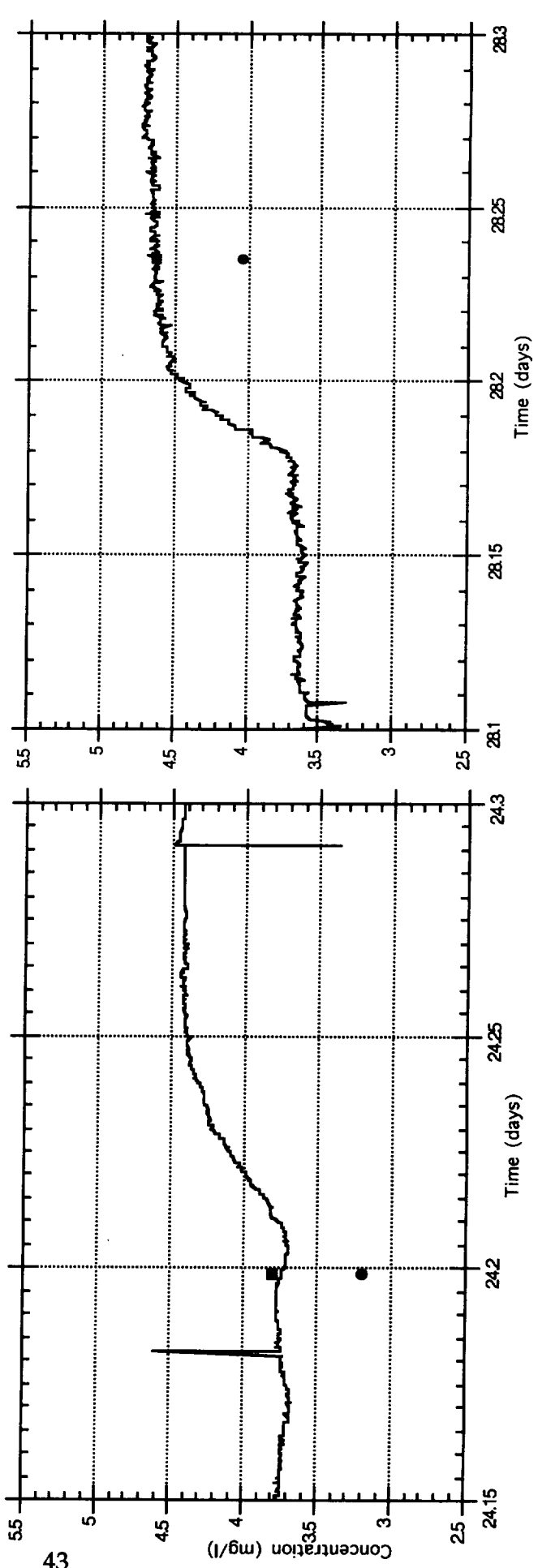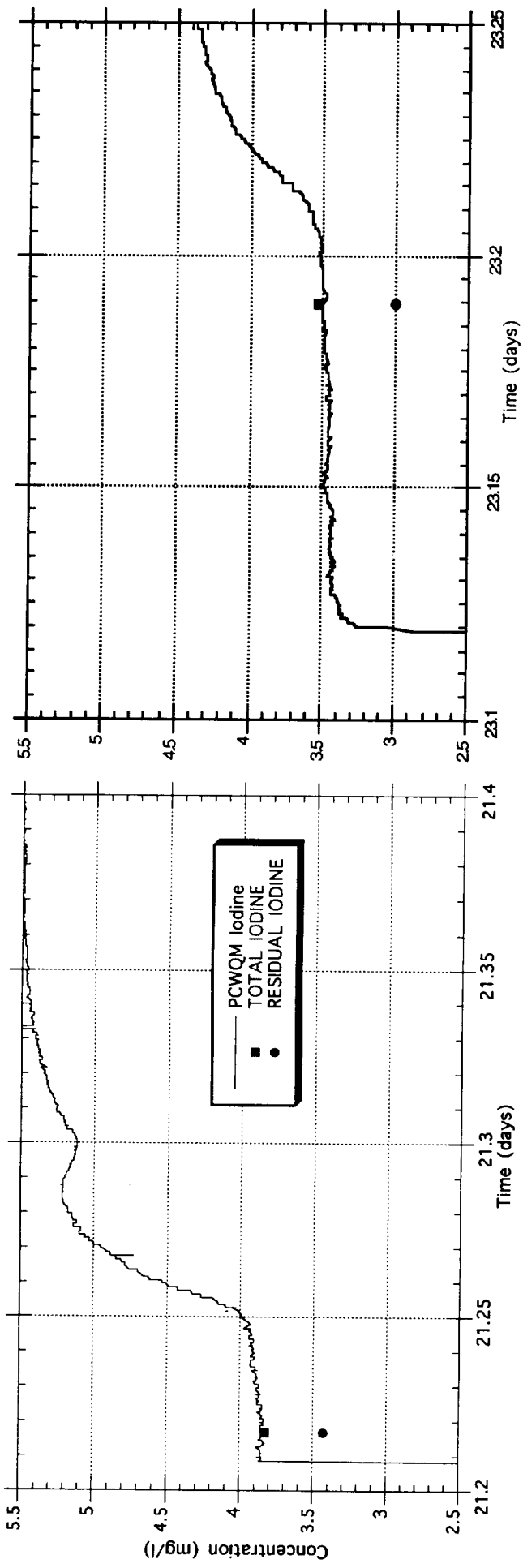
Figure 5-6. PCWQM Iodine and Laboratory Results, Days 22-29
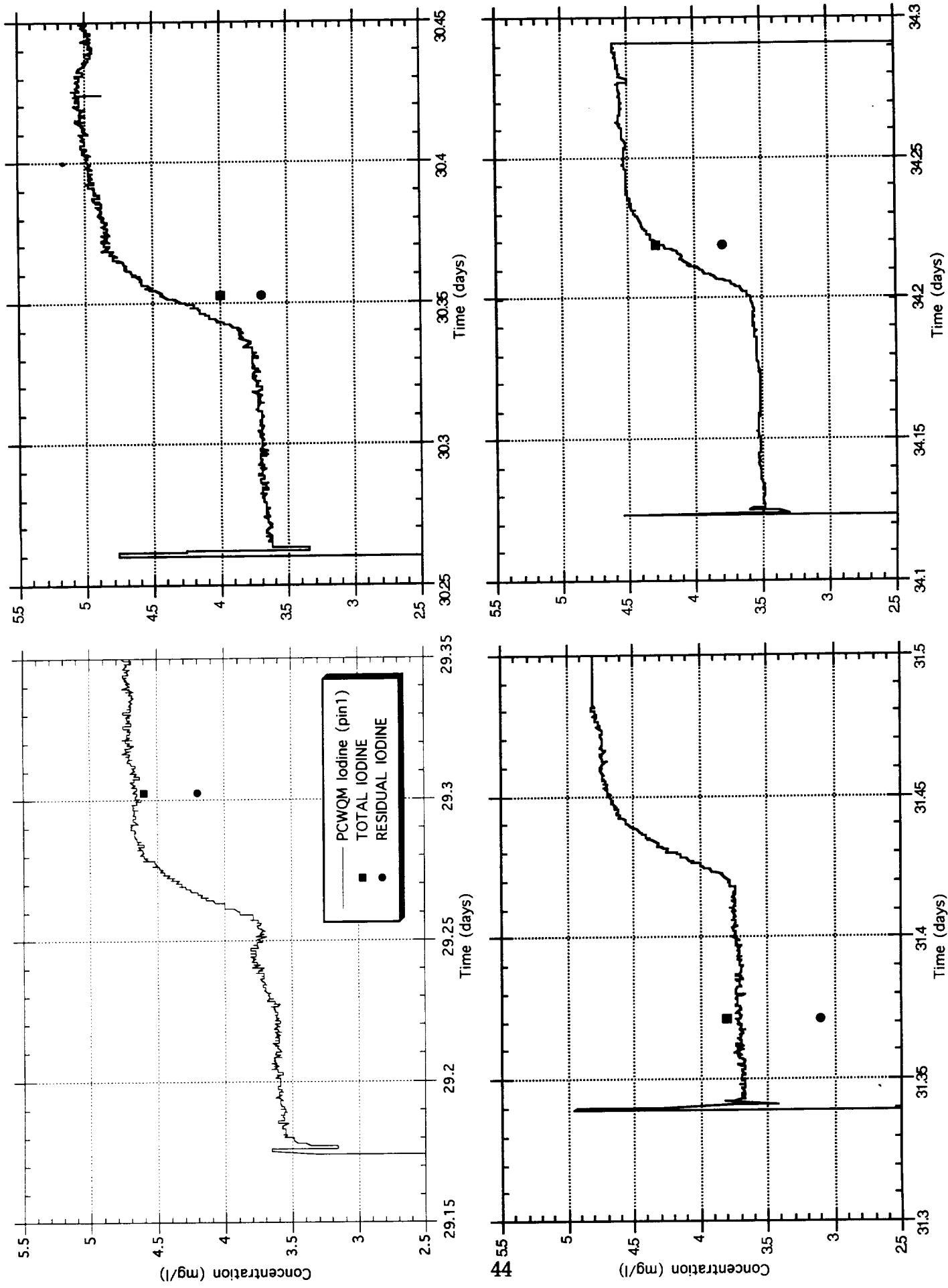
Figure 5-7. PCWQM Iodine and Laboratory Results, Days 30-35

44

LED's Relative Intensity
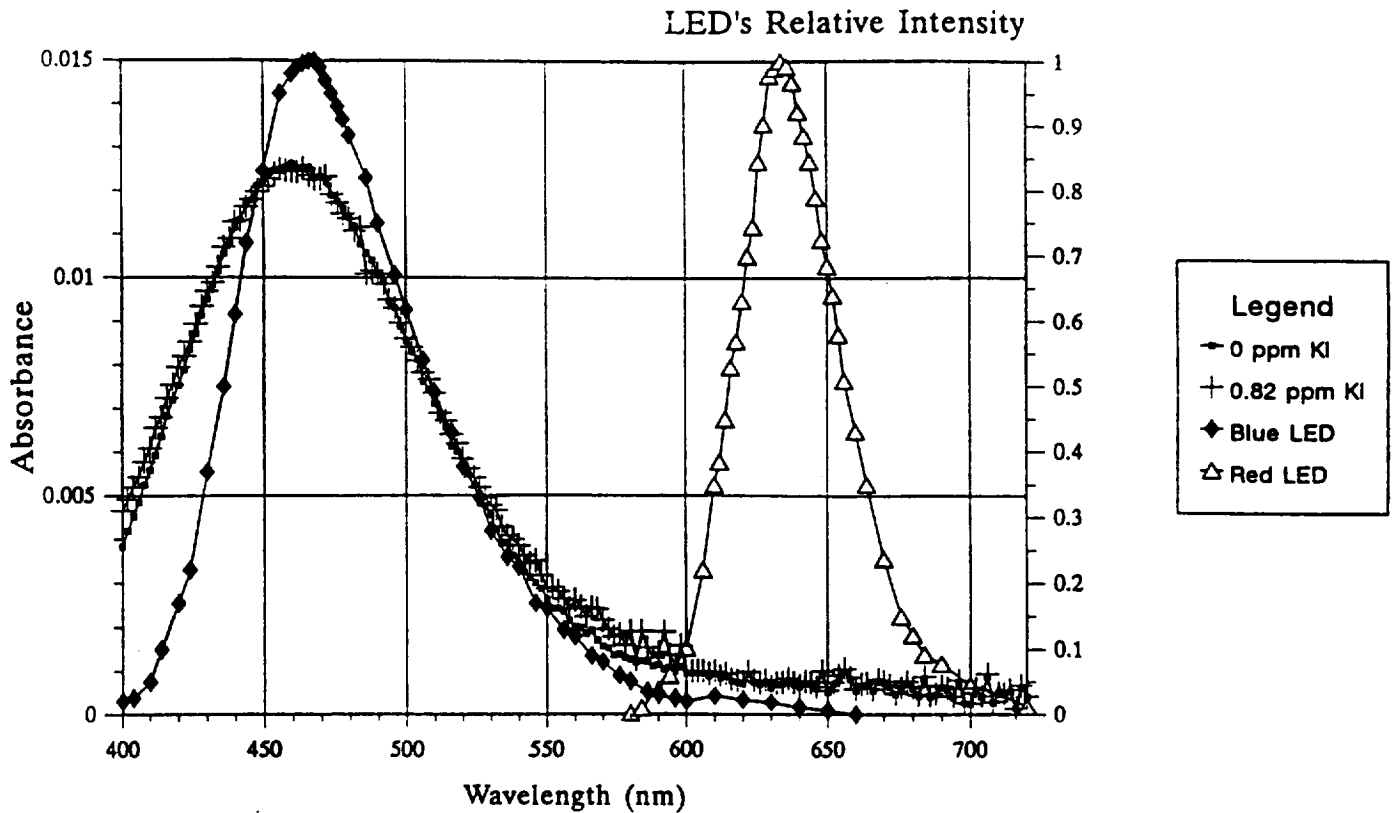
Actual Spectroscopy Data -vs- Published LED Relative Intensities
5 ppm Iodine in De-Ionized Water
Measured with 10cm Cell

Figure 5-8. Impact of Iodide on Measurement of Iodine via Adsorbance

the organic species present in the product water should not significantly interfere with the iodine measurement (14).

The iodine sensor was evaluated after the test to provide further information regarding its performance. The sensor reported an iodine level of -0.07 mg/l for deionized water and reported an iodine level of 2.45 mg/l for a solution that was also measured analytically to be 2.45 mg/l. Additional samples were taken to address concerns that residual iodine could be degrading in the Stage 9 samples before they were measured by the lab. These samples were taken in the same dark bottles used for the Stage 9 iodine samples and refrigerated. The analytical iodine measurement was 2.18 mg/l 6 hours later and 2.28 mg/l 24 hours later. This data indicates that residual iodine may be degrading despite sampling techniques designed to minimize this effect. However, no correlation could be established between the hold time for the iodine samples taken during Stage 9 and the difference between the PCWQM iodine sensor and the analytical data (from a data set of 10 samples).

5.4.1.2 Conductivity Sensor Performance

A comparison between the PCWQM conductivity sensor (pc21), the WP product water conductivity sensor (wc43) and laboratory data show excellent agreement

(Figure 5-9). Insignificant statistical variances between the data sources exist, thus validating the acceptability of the PCWQM conductivity sensor.
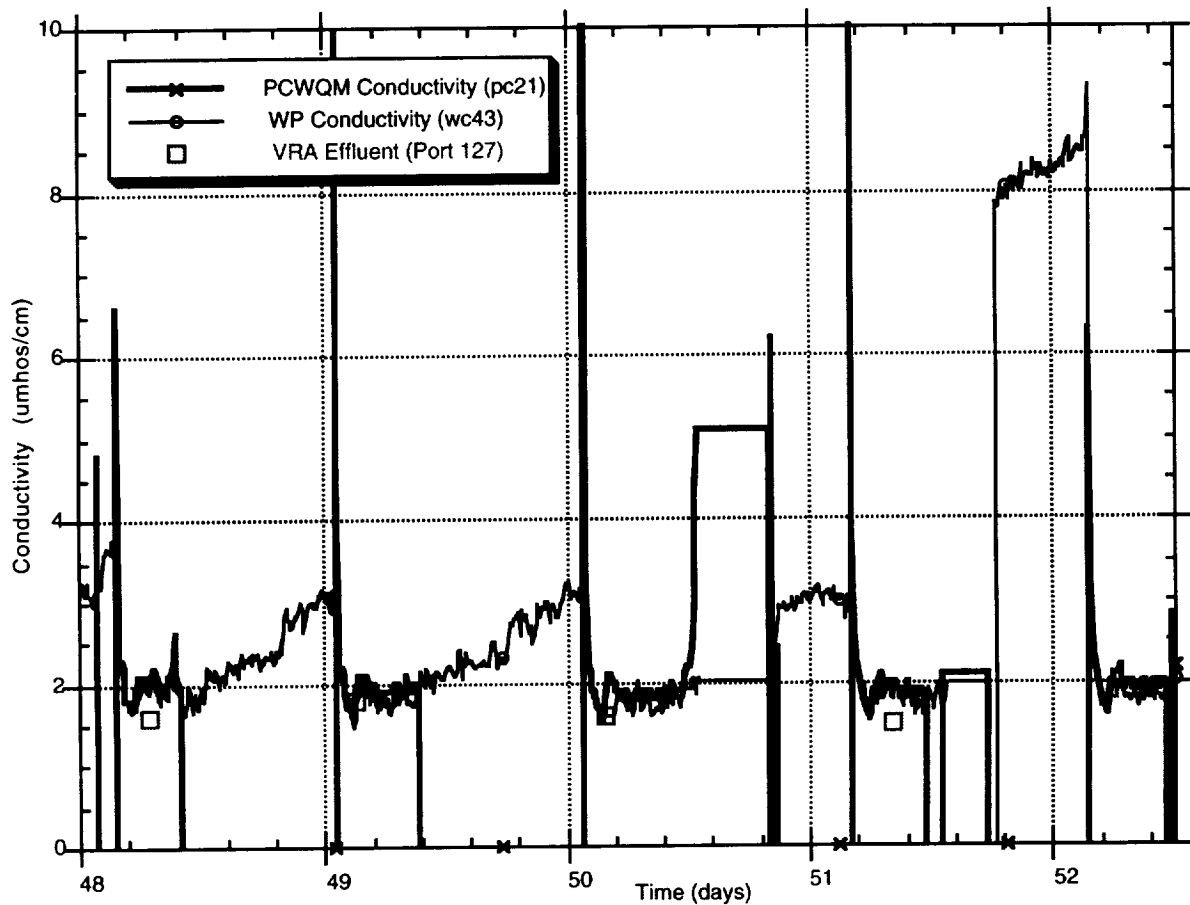
Figure 5-9. Comparison Between PCWQM, WP, and Laboratory Conductivity

5.4.1.3 Total Organic Carbon Monitor Performance

The PCWQM TOC sensor data (ptc1) was compared with the results of the product water (Port 127) analysis performed by the Boeing Laboratory. The average of the difference between each pair of data was 75 ppb, with the standard deviation of the differences being 58. The Boeing TOC method is reported to be accurate within 10%, which equates to an average of ±42 ppb for the data reported, while the design requirement for the TOC sensor is ±50 ppb. The data comparison included a lag time of 25 minutes between the time the sample was taken and the PCWQM sensor data time stamp to account for the time required by the water to flow through the sample loop (15 minutes) and reach equilibrium across the IR/GLS membrane.

Online TOC data also provided insight into operational tendencies of the VRA not previously known. These tendencies included a TOC spike that occurred at the beginning of each processing cycle and a TOC rise that occurred during certain cycles due to the presence of 2-propanol in the VRA influent. An example of these

phenomena is provided in Figure 5-10. A detailed discussion regarding the TOC data is provided in Section 5.5.2.
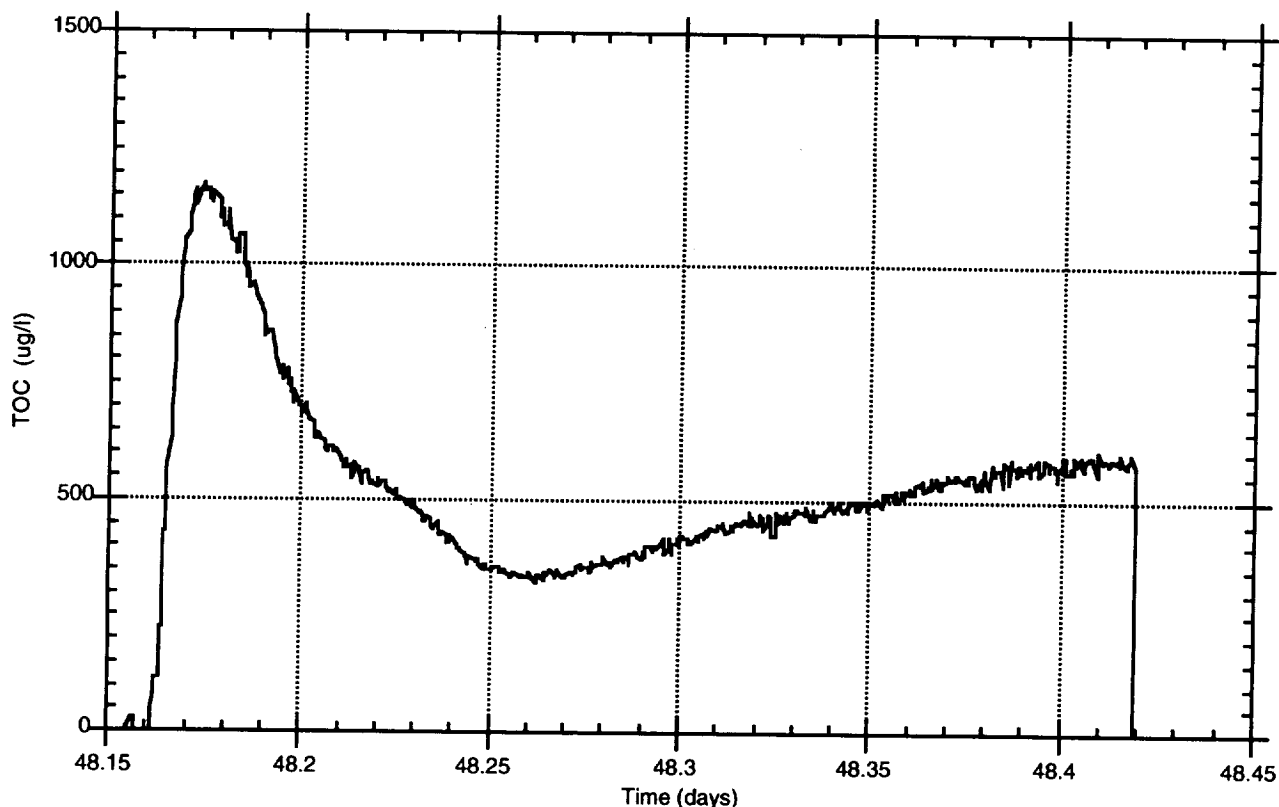
Figure 5-10. Characteristic TOC Sensor Output

The characteristic TOC spike observed during a processing cycle adversely affected the PCWQM's average TOC accuracy. Samples taken before the product water TOC had stabilized (approximately 2 hours) yielded lab data that tended to be more variant when compared to the PCWQM TOC data. If these data points are eliminated, the difference between the PCWQM data and Boeing lab data drops to an average of 54 ppb with a standard deviation of 51.

This loss in accuracy is due to the fact that the actual product water TOC is changing faster than the time required for the CO_2 in the sample loop (oxidized TOC) to reach equilibrium with the CO_2 in the IR Cell. This equilibrium is driven by the transport of the CO_2 across the membrane and the concentration gradient between the CO_2 in the IR Cell and the sample loop water. Approximately 15 minutes are required for product water to pass from the sample loop influent to the IR/GLS, where the TOC is measured. At the GLS membrane, CO_2 from the water must diffuse across the membrane and disperse in the IR Cell where it is measured. The amount of time required for this last step varies depending on the difference between the CO_2 concentration in the water and in the IR Cell. This time was assumed to be 15 minutes when determining the sensor's statistical accuracy, which is sufficient for minor changes in TOC. However, experimental data from Astro shows that approximately 50 minutes are required to reach equilibrium after a step change in

47

TOC influent. The product water TOC curve exhibited by the WP at the beginning of a process cycle is similar to a step change driven by the time required to flush the organics (approximately two hours) through the ion exchange bed and the PCWQM. Unlike a step change, however, the decrease in TOC is actually more gradual. The output of the PCWQM TOC monitor during this transition is thus a function of the time required for the CO_2 to reach equilibrium in the IR Cell while the TOC in the product water is decreasing.

Compounding the TOC accuracy problem were PCWQM software errors that resulted in PCWQM system shutdowns on most days during the TOC spike. The shutdowns resulted in the IR Cell being purged of all CO_2, which subsequently delayed the time required to reach equilibrium with the product water CO_2 once PCWQM Normal mode was reestablished. Furthermore, the PCWQM is only required to measure TOC levels up to 1500 ppb. Above this level, the software initiates a purge of the cell. This procedure also occurred several times due to high TOC levels in the product water, resulting in further delays with reaching equilibrium in the IR Cell.

Two additional points should be made regarding the performance of the PCWQM and application of the results to the flight design. First, though the data generated does not provide absolute verification of the TOC monitor's accuracy, its ability to report on the product water TOC trend has been verified. The monitor has shown that approximately 2 hours are required for the product water TOC to reach steady state, a finding validated with laboratory data. This data can be further used to determine how long the WP should be maintained in Reject mode (if there is reason to prevent methanol, ethanol, and trimethylamine from entering the product tanks) and is now being used to determine if WP design modifications can prevent the high TOC levels.

Second, the PCWQM design includes a TOC predictor function (ptc2). This software function predicts a final TOC based on the slope of the actual TOC curve. This function was used early in the test with limited success (Figure 5-11), but a mathematical error in the function kept initiating a PCWQM software failure. The predictor function was turned off on Test Day 20 to eliminate further software failures. The data obtained indicates the predictor function estimated the equilibrium TOC approximately 30 minutes before the measured TOC reached this point. Further studies will be required to fully assess the worth of this technique.

5.4.1.4 pH Sensor Performance

A comparison between the PCWQM pH sensor (po20) and laboratory data shows significant variance. The average difference between the two data points (out of 70 samples) was 1.3, while the standard deviation was 0.7. The PCWQM data (average of 5.4) was consistently lower than the laboratory results (average of 6.7). The internal pH calibration will be discussed in the PCWQM Calibration Mode performance.

48
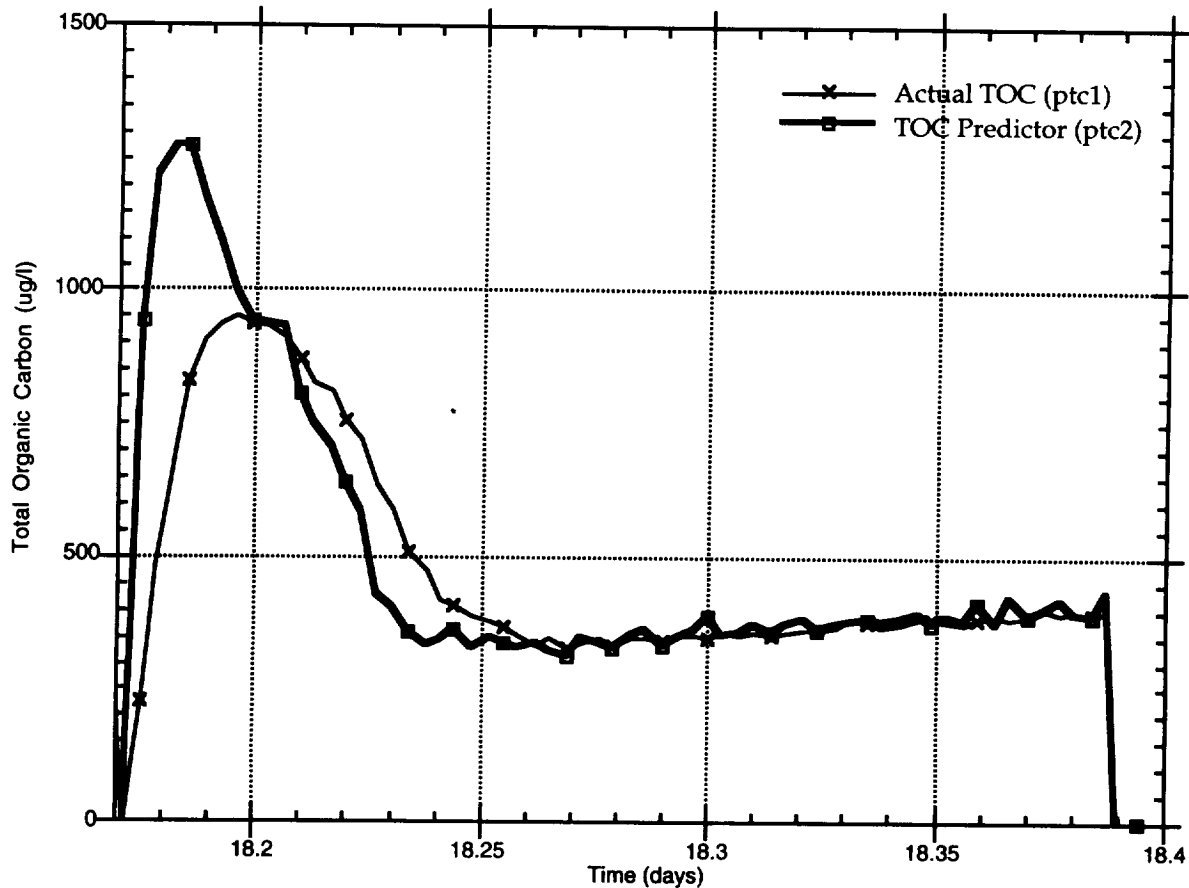
Figure 5-11. TOC Predictor Results

The pH sensor output exhibited extreme variance on occasion (see Figure 5-12). According to Astro, this abnormal output has been observed previously due to the presence of gas bubbles in the sample loop. During Stage 9, gas bubbles would be introduced as oxygen by the VRA oxygen sparger. If not sufficiently removed by the VRA phase separator, the oxygen gas could be pumped into the PCWQM sample loop, thereby causing the observed sensor output. Physical observations of bubbles in the VRA effluent were observed when taking samples downstream of the VRA phase separator and the VRA ion exchange bed. The WP is required to remove all free gas from the product water, primarily because of the problems associated with crew consumption of water with free gas in microgravity. Based on the pH sensor performance, the likelihood that free gas is present in the product water is high. Furthermore, the PCWQM design interface requirements state that no free gas will be present in the product water coming from the VRA. The pH sensor design is based on the assumption that gas bubbles will not be present to interfere with the pH measurement. The erroneous data obtained from the pH sensor during these periods adversely affected the overall pH performance as well as the performance of the Calibration and Recirculation modes (see following discussion). Accordingly, the VRA design should insure adequate removal of free gas.

49
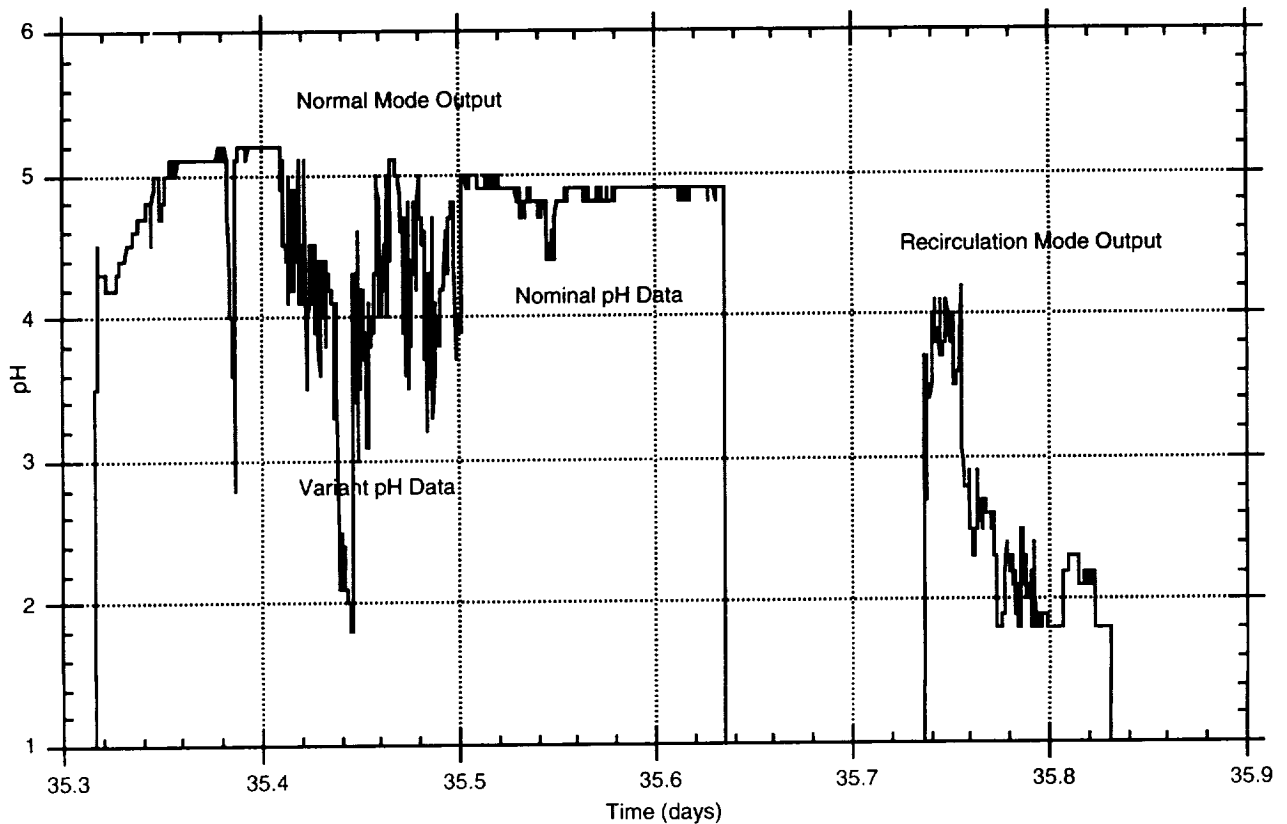
Figure 5-12. PCWQM pH Sensor Data

5.4.1.5 Calibration Mode Performance

Twenty-one calibrations were performed during the test, including six that were manually initiated. The key performance parameter to be addressed is the pH offset, which is added to the pH measured by the sensor to obtain the reported pH. During Calibration mode, a 10 minute purge of the IR Cell (with oxygen) and the sample loop (with WP product water) and a 1 minute built-in-test (BITE) are conducted. Next, flow is diverted through the pH calibration module for 10 minutes to achieve a stable effluent pH. The pH is then measured during the next five minutes and the pH offset is determined assuming the calibration module effluent pH to be 3.86. For example, if the average pH measured during the five minute measurement cycle is 4.0, the pH offset would be -0.14. Table 5-6 summarizes the pH data obtained during the measurement cycle. Based on the Calibration mode results, the pH sensor calibration varied significantly during the test. The average pH offset (taking the absolute value of all pH offset data) was determined to be 0.28, excluding data obtained during anomalous Calibration modes (due to the presence of gas bubbles). The instability of the calibration was much higher than that observed during tests at the Astro facility, where the pH sensor calibration has shown to vary less than 0.1 units over extended test periods. However, these tests were conducted under more ideal conditions, while during Stage 9 the influent water and environmental conditions were less controlled. As a result, the effluent pH of the calibration

50

Table 5-6. PCWQM Calibration and Recirculation Results

Calibration Day	Time	Recirculation Day	Time	Last SPA pH	SPA Htr Stp	pH Offset	SPA Flow	System TOC	System TIC
				3.847	33.24	0.1672	72.51	106.477	-0.667
0	1826	1	1707	3.660	15.00	-0.0889			
8	755	9	641	3.830	20.86	0.0108		40.400	1.800
8	755	13	2149	3.970	30.88	0.0108		59.100	1.800
8	755	14	22	3.840	32.83	0.0108		55.100	1.800
		15	557	4.027	44.15				
16	1729	16	442	3.820	45.15	-0.2320	85.14	20.600	5.470
16	1729	21	128	3.694	15.00	-0.2317	2.66	37.734	5.468
16	1729	22	346	3.683	15.00	-0.2317	3.22	37.834	5.468
23	1800	23	557	3.647	15.00	-0.1535	3.84	29.700	13.262
23	1800	25	817	3.557	15.00	-0.1535	4.39	25.093	13.262
23	1800	26	1754	2.894	65.00	-0.1535	5.96	25.649	13.262
		27	2019	2.900	65.00	-0.1535			13.262
23	1800	28	50	3.577	53.86	-0.1535	6.65	23.186	13.262
23	1800	28	50	3.577	19.00	-0.1535	6.65	23.186	13.262
23	1800	29	526	3.861	22.03	-0.1535	7.27	32.096	13.262
30	1837	31	748	2.508	47.03	-0.1588	7.92	15.787	16.730
30	1837	31	748	2.508	20.00	-0.1588	7.92	15.787	16.730
30	1837	32	959	3.031	15.00	-0.1588	8.53	21.092	16.730
		33	1219	3.815	15.76	-0.1588			16.730
30	1837	34	1648	3.839	17.70	-0.1588	10.01	26.068	16.730
30	1837	35	2135	3.823	18.84	-0.1588	10.79	26.029	16.730
30	1837	36	156	2.632	65.84	-0.1588	11.42	15.194	16.730
30	1837	36	156	2.632	20.00	-0.1588	11.42	15.194	16.730
37	1915	37	415	3.669	15.00	-0.2824	12.20	14.612	14.699
		39	631	3.700	15.00	-0.2824			14.699
37	1915	40	853	3.645	15.00	-0.2824	13.56	14.359	14.699
		41	1913	3.600	15.00	-0.2824			14.699
37	1915	42	2226	3.167	15.00	-0.2824	14.95	22.388	14.699
37	1915	43	439	3.701	15.00	-0.2824	15.90	28.557	14.699
44	1950	45	1255	3.938	21.92	0.0735	17.19	27.410	15.493
44	1950	46	2010	3.757	19.76	0.0735	17.88	19.054	15.493
		47	2206	2.000	66.77	0.0735			15.493
44	1950	48	22	3.175	35.51	0.0735	19.16	24.752	15.493
44	1950	48	22	3.175	20.00	0.0735	19.57	24.752	15.493
52	251	51	2019	4.164	38.21	0.4211	20.91	25.789	6.083
52	251	52	2116	4.395	67.97	0.4211	21.51	23.309	6.083
52	251	52	2116	3.500	20.00	-0.2337	21.55	23.309	4.062
52	251	53	1951	3.327	15.00	-0.2337	22.17	24.597	4.062
52	251	54	2209	3.313	15.00	-0.2337	23.20	22.615	4.062
52	251	55	27	2.102	62.00	-0.2337	23.34	16.038	4.062
52	251	55	27	3.102	20.00	-0.2337	23.34	16.038	4.062
52	251	56	2039	3.761	18.05	-0.2337	23.96	27.984	4.062
52	251	57	2255	3.763	16.19	-0.2337	24.62	24.155	4.062
52	251	58	445	2.684	15.00	-0.2337	25.32	33.574	4.062
59	2329	60	700	5.021	72.00	0.9294	25.92	32.627	7.326
59	2329	62	1824	5.012	72.00	0.9294	27.54	41.404	7.326
59	2329	62	1824	5.012	20.00	0.9294	27.54	41.404	7.326
59	2329	63	2041	5.015	77.00	0.9294	28.16	22.724	7.326
64	751	63	2041	3.501	20.00	-0.1903	28.19	22.724	2.813

Table 5-6. PCWQM Calibration and Recirculation Results (cont'd)

Calibration Day	Time	Recirculation Day	Time	Last SPA pH	SPA Htr Stp	pH Offset	SPA Flow	System TOC	System TIC
64	751	65	643	3.906	28.57	-0.1903	28.82	31.509	2.813
64	751	66	900	1.996	85.57	-0.1903	29.89	26.112	2.813
64	751	66	900	1.996	22.00	-0.1903	29.89	26.112	2.813
64	751	69	2045	3.770	77.52	-0.1903	31.72	45.940	2.813
64	751	69	2045	3.770	24.00	-0.1903	31.72	45.940	2.813
71	630	70	2303	3.190	15.00	2.0010	32.31	19.485	1.041
71	746	70	2303	3.190	15.00	0.1128	32.35	19.485	-0.740
71	746	71	119	4.208	35.40	0.1128	32.98	34.433	-0.740
71	746	72	335	4.138	52.32	0.1128	33.60	36.680	-0.740
71	746	74	1008	4.128	68.70	0.1128	34.22	39.687	-0.740
		75	1241	4.158	86.58	0.1128			-0.740
71	746	76	2042	4.191	106.12	0.1128	35.83	38.067	-0.740
71	746	76	2042	3.300	15.00	0.1128	0.00	38.067	-0.740
78	854	77	1011	4.031	26.54	-0.3985	0.65	48.372	16.900
78	854	78	1227	3.503	15.00	-0.3985	1.28	25.140	16.900
78	854	79	11	3.700	15.00	-0.3985	1.96	18.570	16.900
78	854	80	310	3.502	15.00	-0.3985	2.61	12.174	16.900
78	854	82	817	3.481	15.00	-0.3985	3.21	24.262	16.900
78	854	83	1033	2.178	15.00	-0.3985	3.98	3.102	16.900
78	854	84	1250	2.796	15.00	-0.3985	4.58	13.087	16.900
85	943	85	1943	5.392	94.60	1.9819	5.20	48.101	1.787
86	756	86	1012	3.702	15.00	0.2779	5.78	37.303	-0.326
		87	1229	3.200	15.00	0.2779			0.000
		89	2006	4.462	48.11	0.2779			0.000
86	756	90	2220	4.250	70.60	0.2779	7.60	32.631	0.000
		90	2220	3.204	20.00	0.2779			0.000
86	756	92	1128	4.204	40.00	0.2779	8.56	38.889	0.000
93	831	93	1158	1.722	15.00	-2.4038	9.30	50.188	0.000
94	811	94	1423	3.816	15.80	-0.4314	9.72	31.981	7.934
95	812	95	1900	3.875	19.56	-0.4318	10.39	27.815	9.460
95	812	96	2117	3.814	20.25	-0.4318	11.17	32.048	9.460
95	812	97	3	3.784	19.44	-0.4318	12.17	44.714	9.460
95	812	98	219	2.468	15.00	-0.4318	12.75	41.640	9.460
95	812	100	748	2.554	15.00	-0.4318	13.77	42.153	9.460
95	812	100	748	2.554	15.00	-0.4318	14.20	42.153	9.460
95	812	101	1416	2.879	15.00	-0.4318	14.93	52.973	9.460
102	1346	102	2250	3.655	15.00	-0.6094	15.71	31.308	10.626
102	1346	103	106	3.558	15.00	-0.6094	16.34	19.452	10.626
102	1346	104	334	1.768	15.00	-0.6094	17.46	33.105	10.626
102	1346	106	1752	2.223	15.00	-0.6094	18.05	30.455	10.626
102	1346	107	2013	3.773	15.00	-0.6094	18.96	37.724	10.626
102	1346	108	2305	2.051	15.00	-0.6094	19.44	27.258	10.626
109	1632	108	2305	2.051	15.00	-0.0865	19.90	27.258	21.091
109	1632	110	1750	4.254	37.69	-0.0865	20.65	11.572	21.091
109	1632	111	2005	3.059	15.00	-0.0865	21.53	10.554	21.091
109	1632	113	1743	4.279	38.95	-0.0865	22.14	13.418	21.091
109	1632	115	923	4.012	49.53	-0.0865	22.86	9.327	21.091
116	310	116	937	4.138	32.45	0.7737	24.46	12.479	17.557
116	310	117	926	4.948	89.83	0.7737	24.60	6.155	17.557

module varied more than expected, subsequently affecting the calibration of the sensor. This performance anomaly did not cause the anomalous pH output obtained during the test by itself, however, it certainly contributed to the overall degradation in sensor performance. Potential modifications to the PCWQM design may improve the performance of the calibration module. First, the pH calibration module volume will be increased to the size of the SPA module, both of which contain the same resin material. This larger volume should result in an output more stable and less dependent on the influent conditions. If improved performance is not observed with this change, no attempt will be made to calibrate the pH sensor during operation. Testing conducted at Astro showed that the sensor maintained adequate calibration over a 60 day period, though verification of this performance in an integrated test environment would be required. In the flight design, the sensor would require replacement every 60 days with the SPA module.

The PCWQM software correctly interpreted the calibration data so that the pH sensor would read a calibration module effluent of 3.86. Though the module effluent pH varied from one Calibration to another, the stability during an individual measurement cycle did not vary significantly. Of the 17 Calibration modes during which data was available, no variance or minimal variance in the data occurred during 13 modes. However, on Test Days 44, 59, 71, and 116, the standard deviation was too high to yield a believable pH offset. These variances could have occurred due to the presence of gas in the sample loop, as discussed previously in the pH sensor performance. On the days in question, the pH sensor data prior to the Calibration mode was extremely variant, indicating that there was gas in the system affecting the sensor performance. The effluent pH measured during Calibration was low for the days in question, thus the pH offset was high when attempting to compensate for the erroneous reading. This error would then be added to the pH measured during Normal mode, reporting an erroneously high pH.

A summary of the System TIC values calculated during the Calibration mode are available in Table 5-6. The average value was 8.2 with a standard deviation of 6.9. These results are consistent with those obtained at the Astro facilities.

5.4.1.6 Recirculation Mode Performance

Over the course of the test 91 Recirculation modes were completed by the PCWQM, each lasting 136 minutes. As mentioned previously, Recirculation mode served to measure the System TOC level and to verify that the SPA module was adequately acidifying the sample loop. Verification of the SPA module performance was accomplished by measuring the SPA module effluent pH via the PCWQM pH sensor, and, if necessary, adjusting the SPA Heater Setpoint to effect the desired pH output. As with the Calibration mode, the pH measured during Recirculation was very stable except for when gas bubbles were present in the sample loop. The SPA Heater Setpoint was calculated by the following equation:

SPA Heater Setpoint = Previous Value + [(SPA pH-3.8)/0.02]

The last term in the equation represents the temperature adjustment based on the difference between the SPA pH and the desired pH of 3.8. If the pH was higher than that desired, the SPA Heater Setpoint was increased; subsequently the higher SPA temperature would result in a lower pH. Numerous performance anomalies occurred resulting in an erroneously high SPA Heater Setpoint. The anomalies can be attributed to two separate causes. First, as discussed previously, high pH offset values were derived during Calibration mode throughout the test. This anomaly resulted in a high SPA pH measured (due to the addition of the high pH offset). To compensate for a high SPA effluent pH, the PCWQM software would increase the SPA heater setpoint. This anomaly occurred on Test Days 51, 52, 60-63, 85, 89-92, and 116.

Second, gas bubbles in the system resulted in the calculation of an erroneously low SPA pH, usually between 2.0 and 2.6, resulting in a large negative temperature adjustment. For example, if a SPA pH of 2.0 is used in the SPA Heater Setpoint calculation, the calculated temperature adjustment (to be added to previous SPA Heater Setpoint) is -90.0. An error in the SPA Heater Setpoint calculation resulted in the absolute value of the temperature adjustment being added to the previous setpoint when the temperature adjustment was above a setpoint value defined in the PCWQM software. The end result was an erroneously high SPA Heater Setpoint. This anomaly occurred on Test Days 26, 31, 36, 47, 55 and 66. The temperature adjustment setpoint value was increased after Test Day 69 so that the anomaly did not occur again. A software update on Test Day 95 corrected the software error, and the anomaly was not repeated for the remainder of the test.

High SPA Heater Setpoints were also calculated on Days 13-16 and 71-76. These values were due to the expended life of the SPA module and represented the software's attempt to increase the SPA life by increasing the heater's temperature setpoint. The measured life of the SPA (85 and 36 liters) was significantly less than the design requirement of 140 liters of throughput. Testing conducted at Astro's facilities have shown the SPA life to be approximately 200 liters. The second SPA may have been expended more quickly due to the anomalous SPA Heater Setpoint calculations. The higher temperature would have succeeded in driving off more chemicals from the SPA resin, thus expending it's acidification capability more quickly. However, this explanation cannot account for the first SPA module, thus indicating that other factors may have impacted the life of the SPA. The most plausible explanation is channeling, whereby flow through the SPA is restricted to only a portion of the resin. This results in expending the resin in the flow path more quickly while leaving a portion of the resin unused. The suspected presence of gas bubbles in the PCWQM sample loop coupled with information obtained from Astro regarding the impact of gas on the SPA module indicates that the channeling may have occurred due to the accumulation of gas in the SPA module. Degradation of the resin may have occurred between manufacturing and use, though the testing conducted at Astro has not indicated this to be a concern. Further testing of the SPA

module will be conducted to verify that this module will meet its design life requirements.

No anomalies were associated with determining the System TOC level. The average concentration was 28 ug/l with a standard deviation of 12 ug/l. These values were consistent with those obtained during development testing at Astro.

5.4.1.7 Performance Anomalies

On Test Day 87, the PCWQM could not initiate Norm mode due to a PM10PH error. This error occurs when the pressure downstream of the sample loop pump (pp21) exceeds the critical setpoint during high flow (5 ml/min) conditions. The high flow rate is used to purge the sample loop immediately before Norm mode. The critical pressure setpoint at the high flow rate was originally set at 55 psig. During attempts to initiate Norm mode on Test Day 88, a PM10PL error also occurred, indicating the pressure was also exceeding the critical setpoint of 30 psig for nominal flow conditions (1 ml/min). To troubleshoot the anomaly, the SPA module was replaced with tubing. No errors occurred when the PCWQM was transitioned to Norm mode. This indicates that the pressure drop across the SPA contributed to the high pressure after the sample pump. However, after replacing the SPA module with a new unit, the error persisted. After installing another new SPA module, the error continued. The critical pressure setpoint at the high flow rate was increased to 90 psig and Norm mode was initiated without error. Because of the potential risk to the GLS membranes involved with pressurizing the sample loop to 90 psig, on Test Day 91 the pump speed during high flow states was reset from 5 ml/min to 1 ml/min, effectively eliminating the risk of high system pressures. Though this change extended the time to purge the sample loop, the effect is not considered significant. The anomaly did not repeat itself after this modification.

Based on this information, the most plausible explanation for the anomaly is a pressure spike occurring due to a high pressure drop in the sample loop. A plot of the sample loop pressure shows the pressure drop from the pump effluent to the SPA module effluent increasing on Test Day 80 and continuing to increase until Test Day 87 when Norm mode could not be initiated (Figure 5-13). The pressures returned to normal on Test Day 89 after the anomaly was resolved. The components in this line include two 3-way solenoid valves, the pH sensor, the SPA module, and a temperature sensor. Since replacing the SPA module with the tubing eliminated the error, the SPA obviously caused or contributed to the high pressure drop. Astro has reported difficulty with air accumulating in the SPA module and creating excessive pressure drops. This pressure drop has also occurred with unused SPA modules if not properly filled with water prior to use, which may explain why the pressure drop anomaly occurred with the unused SPA modules during the troubleshooting on Test Day 89. Considering the data supporting the presence of gas bubbles in the sample loop, the accumulation of air in the SPA is a feasible theory. The likelihood that air could cause the pressure drop due to surface tension is unlikely. However, if gas accumulated in the SPA module, the resin surrounded

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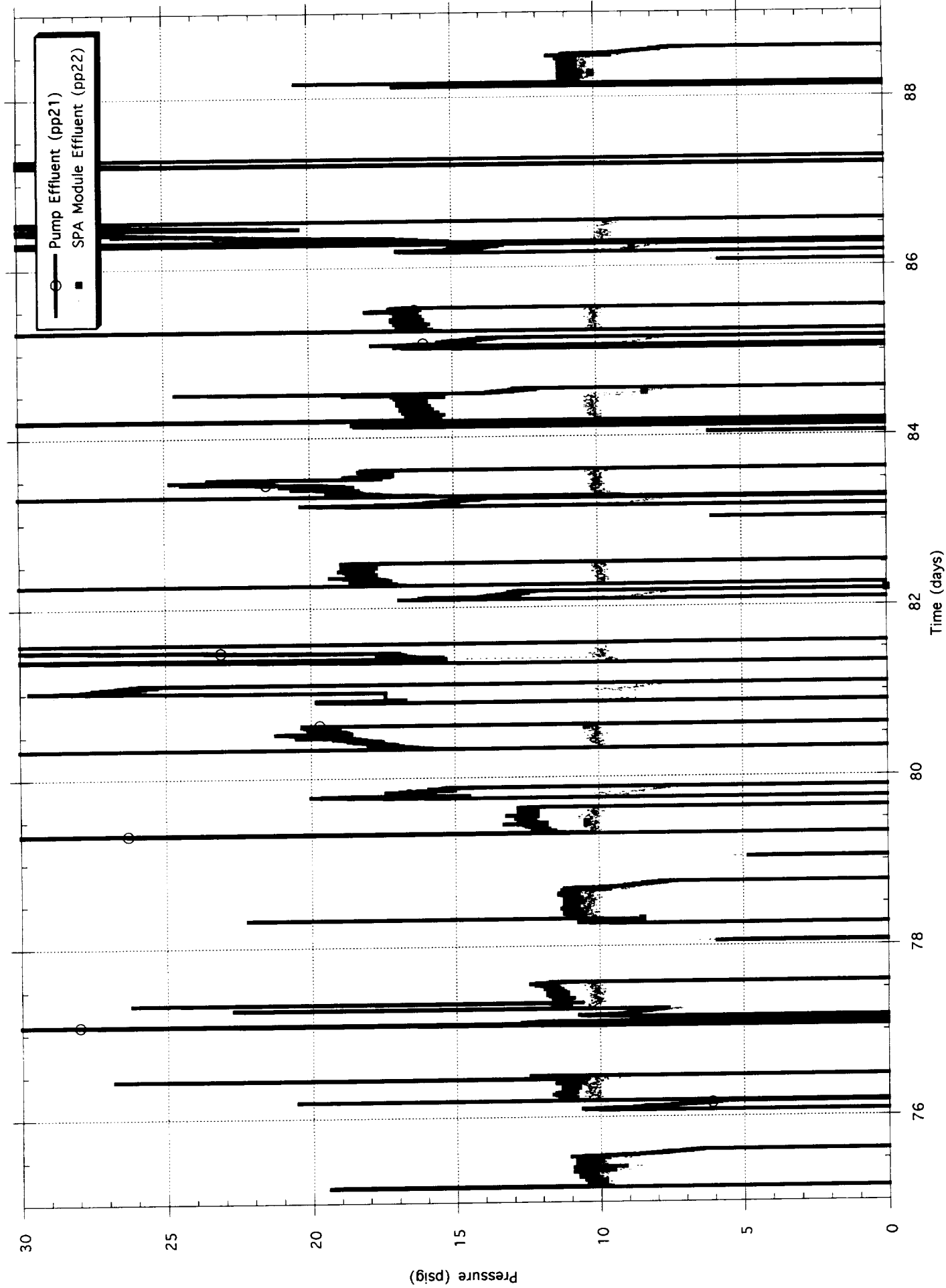
Figure 5-13. PCWQM Sample Loop Pressure, Test Days 75-90

56

by the gas could become dry. Information provided by Umpqua and Astro indicate that a "dry" resin would become a paste that would be resistant to water flow. In this event, the observed pressure drop could occur.

Another possibility is that a particulate entered the sample loop and created the excessive pressure drop by becoming lodged in the tubing or one of the components. The nominal tubing size in the sample loop is 0.040 in, or 1016 microns. The valves and pH sensor have a flow path diameter of 760 microns, while the SPA module has a 40 micron filter at its inlet and outlet to prevent downstream particulate contamination. At the temperature sensor downstream of the SPA module, the tubing size decreases to 0.011 in, or 279 microns. The WP is required to remove all particulates greater than 40 microns in the product water, though it is not inconceivable for a series of particles less than 40 microns in size to impede flow through an area larger in diameter, or for particulates larger than 40 microns to have contaminated the product water and subsequently the PCWQM sample loop. If a particulate did become trapped in the sample loop, the observed error would have been caused by the combination of the pressure drop by the particulate and that inherent to the SPA module. The particulate would have been expelled after the allowed pressure drop was increased to 90 psig.

Software errors resulting in a shutdown of the PCWQM system occurred almost daily. The primary error was a memory allocation error that resulted in the HIRES Program Ending. This error occurred almost every day (but rarely more than once/day), normally in the first 30 minutes of Normal mode. Modifications to the PCWQM software prior to any further testing should eliminate this anomaly. This anomaly has no bearing on the PCWQM flight design since the Stage 9 PCWQM software was provided by Astro, while the flight design software will be developed by the Boeing Company, the ISS Prime Contractor.

On Test Day 9 test personnel observed a delay associated with the PCWQM data acquisition. The initial observation occurred when personnel observed that the data acquisition system would record a PCWQM mode transition several minutes after it had already occurred. Further analysis verified that there was a delay between when data was generated by the PCWQM and when it was recorded by the data acquisition system. To investigate this anomaly, a terminal was installed between the PCWQM computer and the RS232 line that transmitted data to Labview for data acquisition. The terminal showed that the PCWQM data transmittal was being slowed by the data acquisition software, rather than the PCWQM software. Further analysis indicated the error was occurring due to the accumulation of executable software in the data acquisition buffer, which served to slow down the frequency at which Labview pulled data from the PCWQM buffer. Once this data was actually sent from the PCWQM software, the time stamp given by the data acquisition system was incorrect due to the time spent in the PCWQM buffer. The capacity of the data acquisition buffer was increased after Test Day 14, thus the delay in data acquisition became less significant. Increasing the buffer capacity prevented the accumulation of data in the buffer. The issue was completely resolved on Day 35 by programming

57

Labview to erase the buffer after it acquired each data point, thus preventing any data accumulation. Because Labview used the information obtained via data acquisition to make software commands, some events were postponed while waiting for the data. However, no significant impact on the performance of the PCWQM or WP was incurred due to this anomaly.

5.4.2 TOC Monitor Deletion Study

One objective of the Stage 9 test was to evaluate the feasibility of assessing WP product water quality without on-line TOC monitoring. This modification to the PCWQM design was investigated as an ISS cost saving measure and to reduce the complexity of the subsystem. The most plausible alternative to detecting the failure of the VRA to oxidize the influent organic load was with an on-line conductivity sensor (WC40) located between the VRA reactor and the ion exchange bed (see Figure 4-5). This approach assumes a definable relationship can be established between the oxidation of alcohols to organic acids and bicarbonate (which can be measured via conductivity) and the product water TOC. In the reactor, alcohols (primarily ethanol and 1-propanol) are oxidized initially to their respective organic acid (acetic and propionic). A percentage of the organic acids are then further oxidized. Conductivity could potentially detect variances in the reactor's performance as reflected in the concentration of organic acids, which are ionic. Figure 5-14 illustrates the correlation between ionic conductivity and the concentration of acetic and propionic acid. This plot shows that a change in the organic acid concentration results in a measurable change in conductivity. Two phenomena occurred during the test that were used to assess this issue. The first phenomenon was the TOC rise (Figure 5-10) whereby on numerous test days the product water TOC exceeded the ISS water quality specification of 500 ppb (Section 5.5.2). Second, VRA conditions were deliberately altered on Test Days 93-101 to simulate a "VRA failure" scenario. This was accomplished by dropping the reactor operating temperature and thus degrading the reactor performance. These days were evaluated to assess any trends in the reactor effluent conductivity.

Figure 5-15 provides a comparison between reactor effluent conductivity (WC40) and product water TOC (ptc1) on Days 40 through 42, which exhibited an obvious TOC rise. On Days 40 and 42 the reactor effluent conductivity also increased initially, though on Day 40 the conductivity tailed off at the end of the processing cycle. On Day 41 the conductivity is relatively stable throughout the processing cycle. Similar results were observed on other test days where the TOC rise was observed. On Days 96 through 99, the reactor temperature was set at 200 to 205 $^{\circ}$F. On Day 96 and the first half of Day 97, the conductivity increase appeared to track the TOC increase. From this point and throughout the remainder of the low temperature VRA test, the conductivity maintained a stable level of approximately 30 umhos/cm despite changes in the VRA temperature and the TOC data (Figures 5-16 and 5-17). Based on this data, the reactor effluent conductivity appears to be unable to monitor the increasing TOC during a processing cycle.
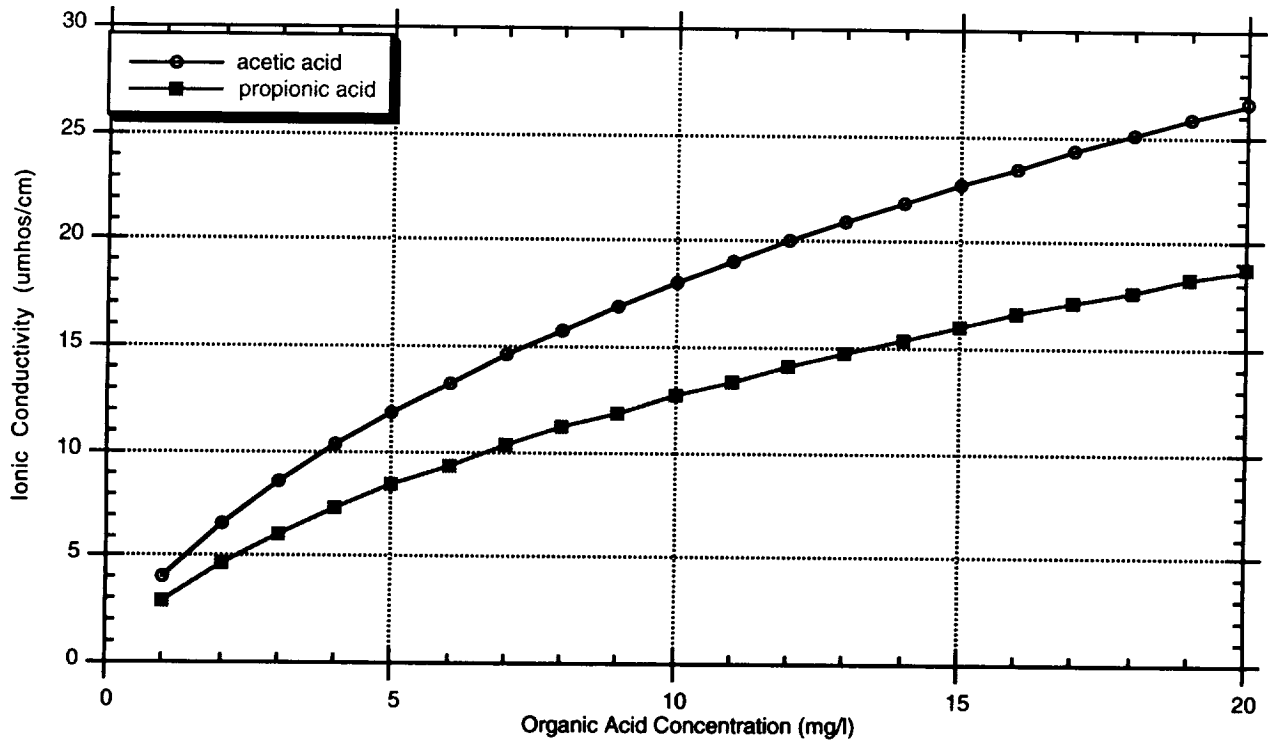
Figure 5-14. Ionic Conductivity for Acetic and Propionic Acid

The overall conductivity level was evaluated throughout the test to determine if there were any absolute differences depending on the VRA temperature or the presence of a TOC rise. Nominally, the conductivity was approximately 20 umhos/cm. During the VRA low temperature test, the conductivity increased to 30 umhos/cm after 4 1/2 days probably due to the decreased oxidation of organic acids. On Days 89 and 90, the conductivity dropped to approximately 10 umhos/cm when the reactor temperature was increased to 270 to 275 °F. This data indicates absolute conductivity can be used to track significant variances in VRA performance. However, on Days 55 through 65, 85, 108 and 109, the conductivity also reached 30 umhos/cm without any change to the VRA operating conditions or any corresponding change to the product water TOC. Though VRA performance variations may effect changes in the effluent conductivity, changes in the effluent conductivity do not necessarily indicate a variation in the VRA performance.

In summary, correlating product water TOC to reactor effluent conductivity is not feasible. Though the oxidation of some alcohols can be tracked via TOC and conductivity, monitoring this reaction in a multicomponent feed stream by conductivity before the water is treated by the ion exchange bed is difficult. Further, organics such as 2-propanol yield oxidation products (acetone) that cannot be measured via conductivity, thus any performance degradation in this area would not be detected. Based on the data generated during this test, the only feasible approach to real-time monitoring of the VRA performance is with an on-line TOC monitor.
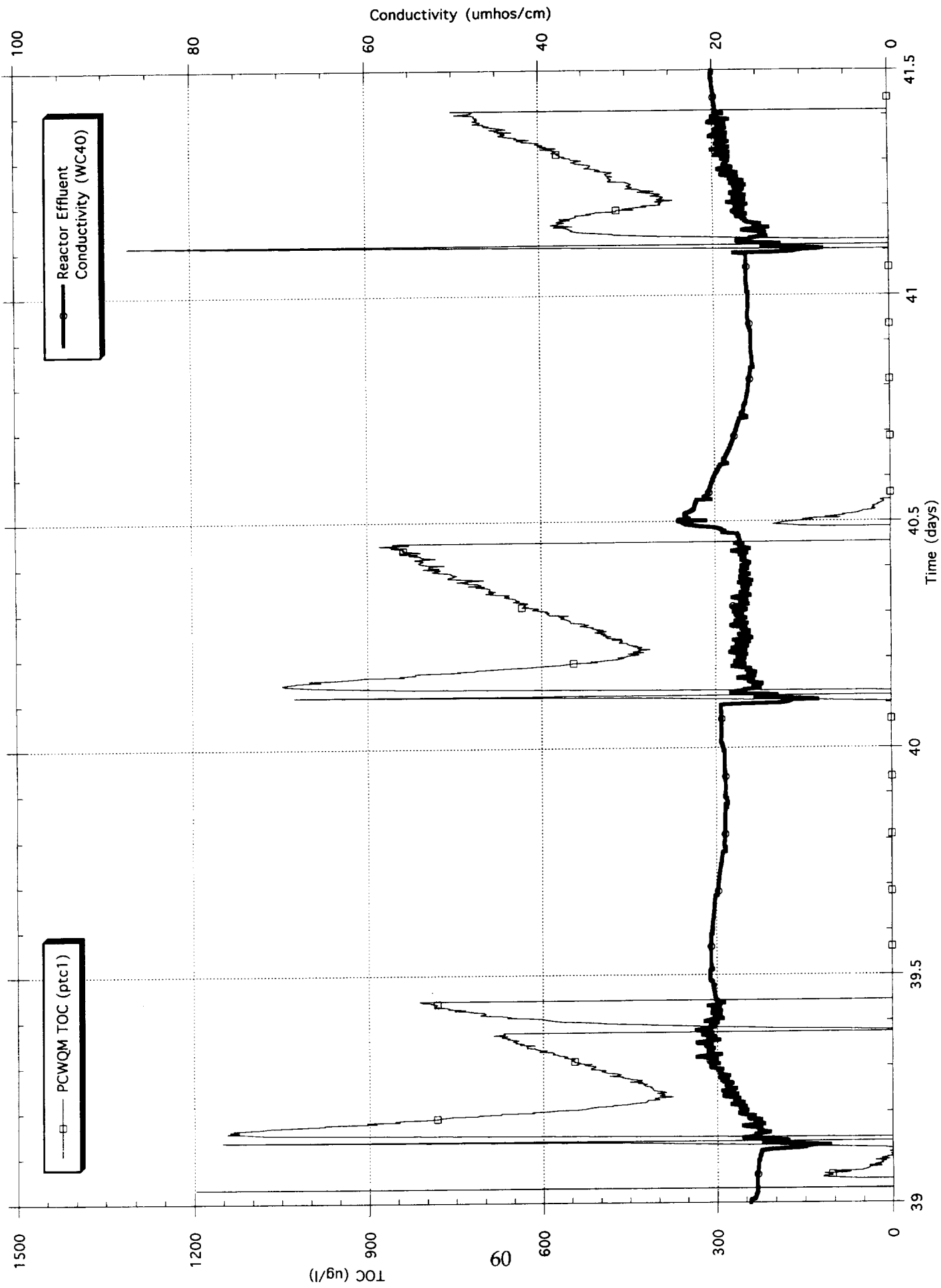
Figure 5-15. PCWQM TOC vs Reactor Effluent Conductivity, Days 40-42
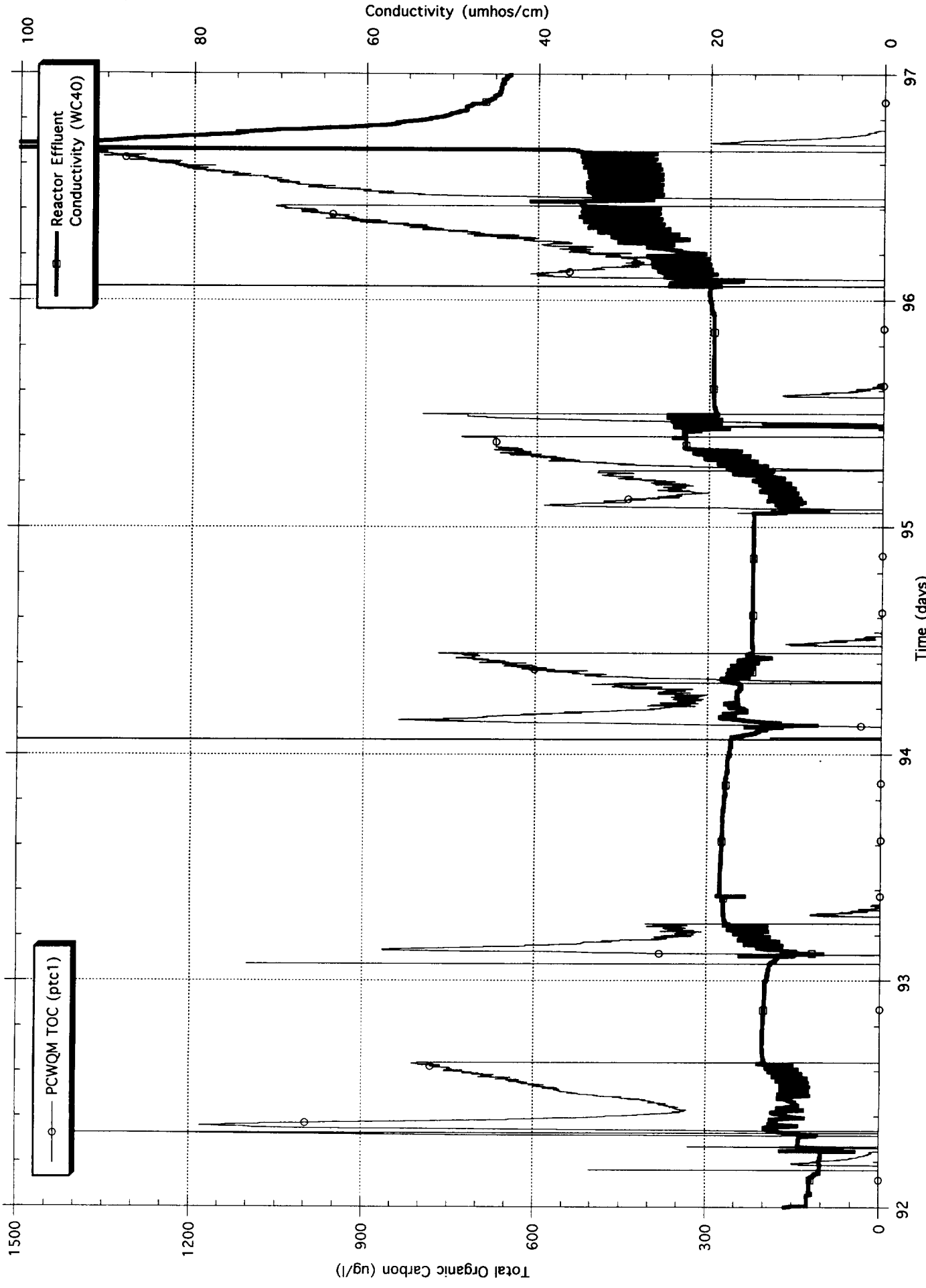
Figure 5-16. PCWQM TOC vs Reactor Effluent Conductivity, Days 93-97
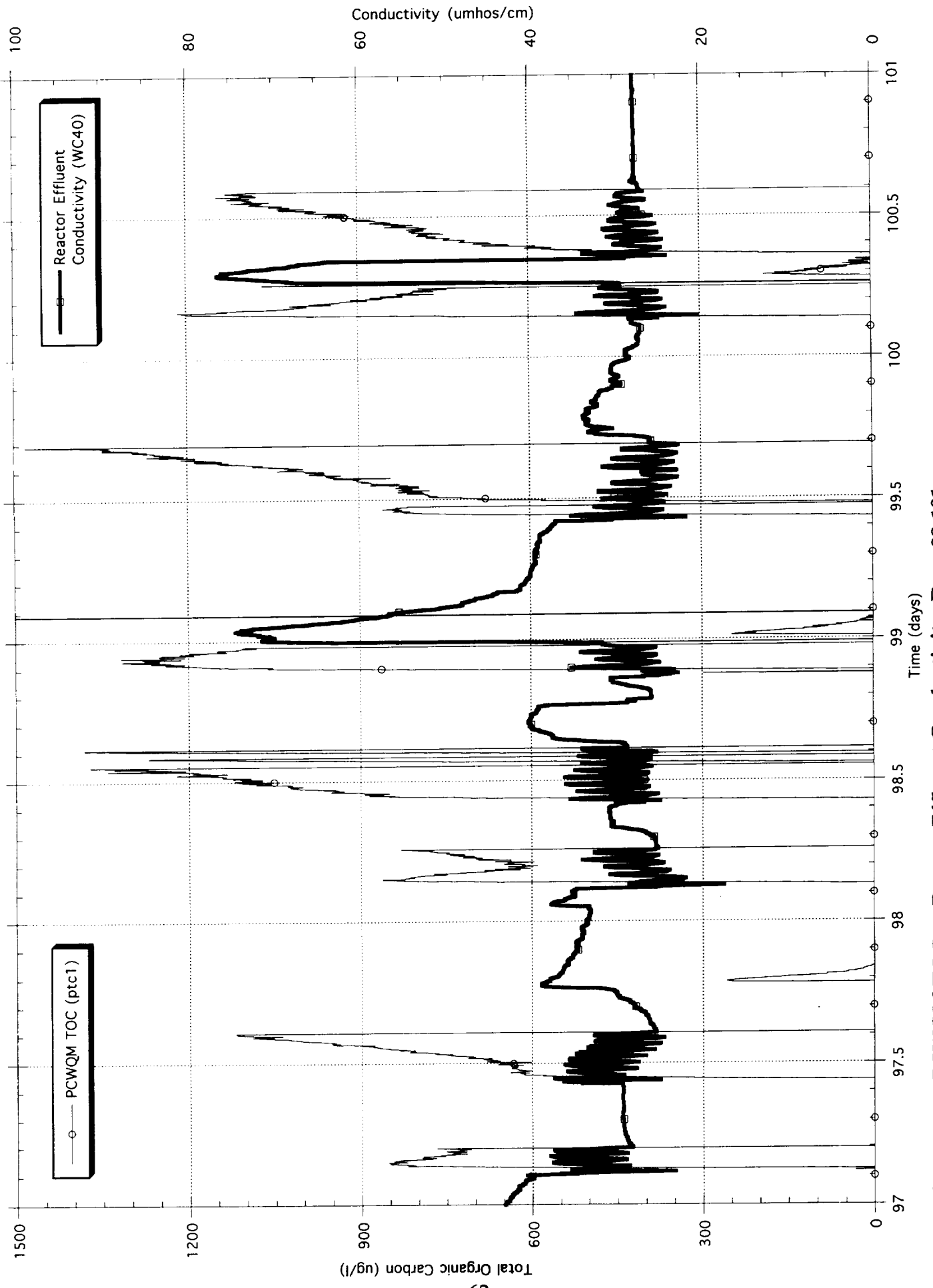
Figure 5-17. PCWQM TOC vs Reactor Effluent Conductivity, Days 98-101

62

An alternative approach to on-line TOC monitoring is batch TOC analysis subsequent to product water generation. Due to the time required to complete water quality analyses, this approach accepts the risk that VRA performance degradation will not present a safety hazard as a result of product water consumption prior to TOC analysis.

5.4.3 Conclusions and Recommendations

On-line monitoring of iodine provided information regarding aspects of the VRA performance not previously known. The iodine sensor reported data higher than that measured analytically. Development and verification data on the sensor shows that it should not measure interference from iodide or any other contaminants potentially present in the WP product water. Data related to the degradation of iodine in the product water samples was inconclusive, thus a further assessment will be required to better define the performance of this sensor.

Further studies are recommended to evaluate the TOC monitor's response to a dynamic TOC input. However, data obtained during steady state conditions verifies that the PCWQM provides comparable results to those obtained in the laboratory. Furthermore, the PCWQM provided useful data on the characteristic product water TOC output. This data can be used to determine the optimum WP control scenario and as a basis for potential design modifications.

The PCWQM conductivity sensor performance was excellent throughout the Stage 9 test. The pH sensor data obtained during the test did not compare favorably with the laboratory results, though acceptance test data verified the accuracy of this sensor. Additional testing is required to determine the reason for this discrepancy. Gas in the product water appeared to create difficulty for the pH measurement, which subsequently affected the results of the Calibration and Recirculation modes. Further impact to the pH calibration occurred due to the instability of the pH calibration module, probably due to the variant influent conditions compared to those used in development testing. This anomaly may be resolved by utilizing a larger module in future designs. The presence of gas in the sample loop also appeared to adversely affect the life of the SPA module, apparently creating a channeling effect due to the accumulation of gas in the module.

Pressure anomalies during the test raise concern regarding the tubing size in the sample loop. This same tubing size was recently used in a flight experiment that experienced anomalous performance potentially due to particulate blockage in the tubing (15). Acceptance procedures presented at the PCWQM Critical Design Review detail the steps taken to minimize the potential for particulate contamination during hardware assembly, though further analysis should be conducted to insure that all appropriate measures have been taken. The presence of gas bubbles in the sample loop and information provided by Astro and Umpqua indicate that the SPA module could be effecting a high pressure drop after the SPA resin becomes dry. This possibility drives the need to verify the adequate performance of a "flight-like"

WP phase separator. Further, a better understanding of the mechanisms of the SPA resin should be obtained, especially regarding the response of the material to gas accumulating in the module. This information could be used to develop a SPA resin more resistant to environmental conditions that created the anomalous Stage 9 performance.

Based on test data, 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 approach accepts the risk that VRA performance degradation will not present a safety hazard as a result of product water consumption prior to TOC analysis.

5.5 Water Processor

5.5.1 Performance

During Stage 9 the WP operated for 795 hours in Processing mode, 83 hours in Reject mode and 1789 hours in Standby mode while processing 12590 lb of waste water. The WP's average power consumption (WW40, WW41) during Processing, Standby, and Reject Mode was approximately 511 watts, 134 watts, and 586 watts respectively. This equates to a specific power consumption of 55 W-hr/lb. This is lower than the Stage 8 specific power consumption of 65 W-hr/lb because the deletion of the laundry waste significantly reduced the WP duty cycle.

In order to assess the effects of ISS integration and control on the performance of the WP, component expendable rates and effluent water quality from Stage 9 were compared to previous single loop integrated tests. Table 5-7 shows the throughput of the WP expendables throughout Stages 9, 8, and 7 (7,8). The filter throughput significantly decreased in Stage 9 from previous tests. This decrease in filter life was the result of the end-use equipment integration during Stage 9. In Stages 7 and 8, all waste streams were collected in accumulators throughout the day. At the end of the day, each waste stream was added to an interim tank in the proper proportions and mixed. This mixture was then pumped though a 105 μm screen to the WP waste tank at the start of each test day. Because all waste water streams were filtered through the same screen, including laundry waste (highest particulate load of all waste streams), a filter cake developed rapidly on the screen. The filter cake effectively increased the screen's performance by decreasing the effective micron rating and removing a higher particle load upstream of the WP filter. This extended the WP filter life well beyond the ISS requirement of 3750 lb throughput. In Stage 9, as in the ISS configuration, waste streams were filtered separately, each using a different 105 micron screen. As a result, a filter cake did not develop on the screens, and a higher particulate load flowed downstream to the WP filter than in previous tests. This effectively shortened the life of the filter to below the ISS throughput

64

requirement. These results indicate that additional filter surface area will be required to meet ISS throughput requirements.

Table 5-7. Expendable Throughputs for Test Stages 9, 8, and 7

Expendable	Average Throughput (lb)		
	Stage 9	Stage 8	Stage 7
Filter	2513	6647[1]	4798[2]
Unibed®	5539	2385	2216
VRA Ion Exchange Bed	9156[2]	6716[2]	4605[2]

1. Only 1 filter was loaded during Stage 8
2. Expendable was never loaded throughout the test

Although Table 5-7 indicates a significant increase in Unibed® throughput from Stages 7 and 8 to Stage 9, it should be understood in the proper context. Unibed® saturation is determined by conductivity breakthrough, which is governed by the total quantity of ion exchange resin in the Unibed®. Stage 9 Unibeds® were 40% larger and contained 2.1 times more ion exchange resin than the Unibeds® used in Stages 7 and 8 (see Table 4-5). This increase in ion exchange resin, coupled with the increase in fuel cell water throughput discussed earlier resulted in the increase in Unibed® life in Stage 9 from previous tests. To verify that the Unibed® expendable rate from Stage 9 was comparable to Stages 7 and 8, the contaminant loading rate on the ion exchange resin was calculated based on the contaminant levels of the individual waste streams during each test. The average loading rate for Stage 9 was 36 mg of ionic contaminant/cc of ion exchange resin. This was virtually identical to the loading rates for Stage 7 (35 mg ionic contaminant/cc IX resin) and Stage 8 (36 mg ionic contaminant/cc IX resin). Based on the contaminant load data, the ISS operational conditions did not adversely affect Unibed® life.

These contaminant loading rates also give some indication of how shelf life affects Unibed® performance. Stage 7 Unibeds® were manufactured approximately 7 months prior to use in the test. Stage 8 Unibeds® were installed approximately 2 weeks after manufacturing while the Stage 9 Unibeds® were installed 22 months after manufacturing. The virtually identical contaminant loading rates as well as the comparable Unibed® effluent water quality (see Section 5.5.2) from each test indicate that a shelf life of up to 22 months has no detectable effect on the Unibed® performance.

Temperature data in the VRA indicated that an anomalous condition occurred in the reactor during transition from Standby to Process. Figure 5-18 shows the temperature of the pre-heater outlet (wt45), the water temperature in the reactor inlet endcap (wt47), and the water temperature in the reactor outlet endcap (wt48). During Standby (no flow through the reactor), the pre-heater is turned off and the temperature of the reactor is maintained by controlling the water temperature in the outlet endcap of the reactor (wt48). As a result, the pre-heater outlet temperature

(wt45) and the reactor inlet temperature (wt47) degraded during Standby. During transition from Standby to Process, the pre-heater is activated as water begins to flow through the system. The initial water to enter the reactor is relatively cold (190-220°F), and the reactor heater is unable to compensate for this before the temperature at the outlet begins to fall well below the minimum operating temperature of the reactor (260°F). Until the reactor outlet temperature is above the minimum operating temperature, the reactor heater is powered on. During this time, the water entering the reactor has been heated to the nominal reactor temperature. The combination of the hot water entering the reactor and reactor heater powered on to raise the temperature of the reactor outlet resulted in the temperature at the reactor outlet exceeded nominal levels. On several occasions, the temperature exceeded the setpoint (wt48>280°F) resulting in a shutdown of the WP. Even if the reactor temperature did not rise above 280°F, the temperature shifts are significant and result in loss of reactor temperature control during the transition.

The WP phase separator did not effectively remove the free gas from the product water to the ISS specification level (no free gas at standard temperature and pressure). The amount of gas in the product water was not quantified, however, gas bubbles were observed in samples taken from the phase separator effluent (Port 201). As discussed previously, this free gas significantly impacted the performance of the PCWQM (Section 5.4.1). The ambient temperature phase separator used during Stage 9 and its location in the VRA is not the proposed flight design. The flight design phase separator will be a high temperature membrane separator located between the two regenerative heat exchangers so that the product water can be degassed at elevated temperature. Because of these differences, no conclusions can be drawn from the performance of the Stage 9 phase separator with regard to the performance of the flight phase separator. However, the failure of the Stage 9 separator to completely remove the free gas in the system and the effect free gas appears to have on the performance of the PCWQM indicate the criticality of the phase separator performance on the ISS integrated water system.

5.5.1.1 Viral Challenge Test

At the conclusion of the integrated testing, the WP underwent a viral challenge to verify its ability to meet the ISS specification of <1 Plaque Forming Unit (PFU) per 100 ml. Stage 9 was the first time the WP had been intentionally challenged with viruses. Waste water was seeded with four bacterial viruses so that each was at a concentration between $1 \times 10^{7.5}$ and $1 \times 10^{8.5}$ PFU/100 ml (16). Bacterial viruses were used to avoid any safety concerns associated with human viruses and were selected to represent specific human viruses that would be considered dangerous and likely to be found in waste water. The challenge was run for 5 days with no viruses detected downstream of the Unibed® train (17), indicating adsorption of the viruses by the Unibed® adsorbents. The VRA is expected to provide an additional barrier for the viruses due to its high temperature, oxidative environment, though its ability to remove viruses was not tested due to the performance of the Unibeds®.
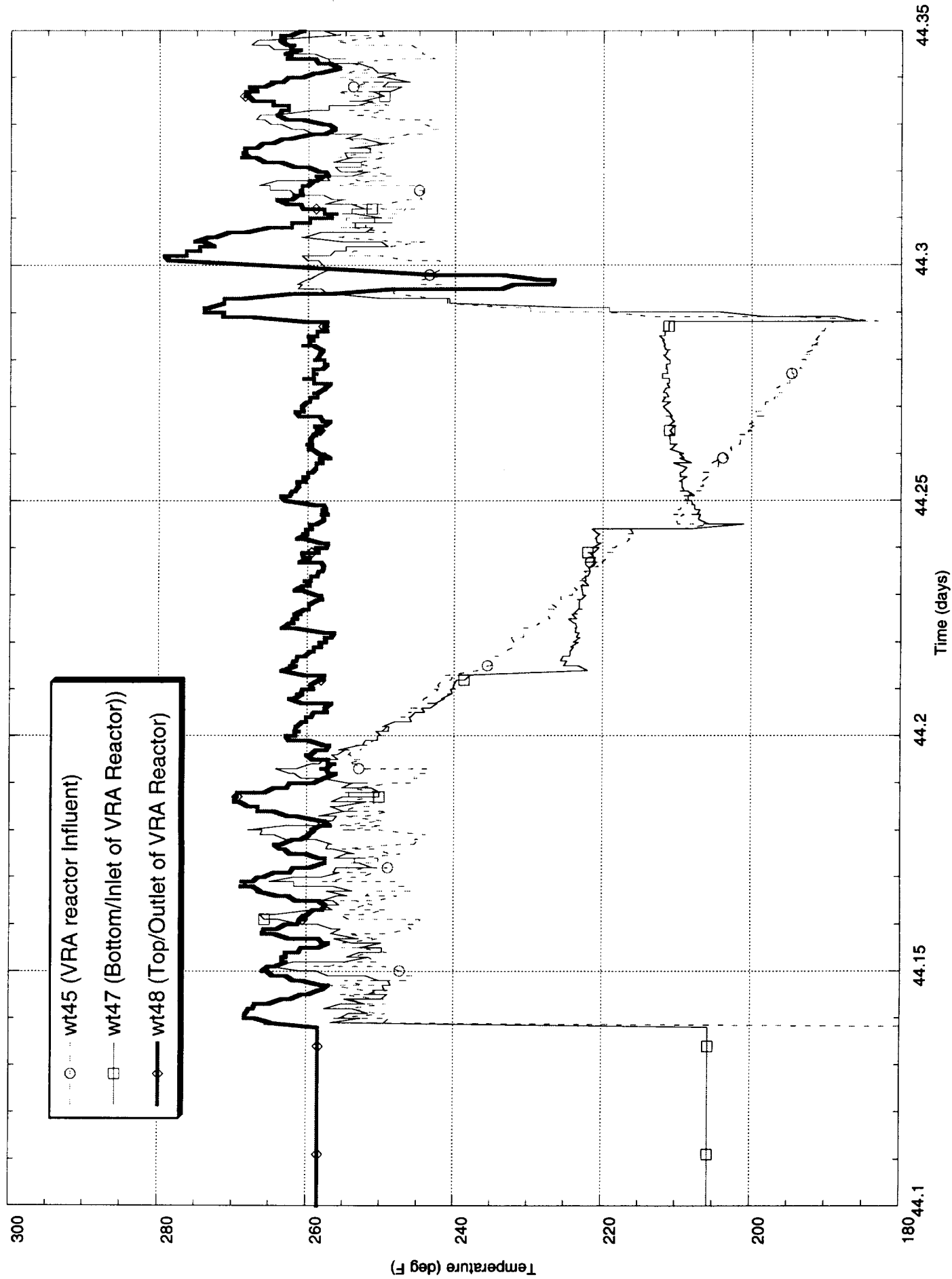
Figure 5-18. VRA Reactor Temperatures

These findings indicate that the WP has an excellent capacity for reducing the disease hazards posed by viruses in the water being processed for potable use aboard the ISS.

5.5.2 Water Quality

Table 5-8 shows a comparison of the Stage 9 water quality data at various points throughout the WP with Stages 7 and 8. Changes in the integration and control scheme from Stages 7 and 8 resulted in changes in product water quality as well as contaminant loads of the various WP components. Higher conductivity and TOC levels were observed in Stage 9 primarily due to sample timing rather than an actual increase in contaminant load to the WP. During Stages 7 and 8 the nominal waste stream contained only 26% shower/handwash waste water, which is the most contaminated waste stream. In Stage 9, the average percentage of shower/handwash waste water in the WP waste tank when the samples were taken was 35.8%, thus contaminant concentrations in the waste tank were higher in Stage 9 than in Stages 7 and 8. TOC levels were also higher as a result of the Equipment off-gas ersatz and the animal condensate ersatz which were added for the first time in Stage 9. This contributed significantly to the increased levels of 1-propanol, 2-propanol, and ethylene glycol shown in Table 5-8. Urea levels in the waste water were significantly lower in Stage 9 than in the previous stages. Much of this decrease can be attributed to the deletion of the laundry waste stream, which was the largest contributor of urea in the waste water.

There were some differences in the Unibed® train effluent water quality in Stage 9 from previous tests. The higher TOC in Stage 9 was the result of the alcohols added to the EEF humidity condensate through the equipment off-gas ersatz. The Stage 9 conductivity was lower due to the absence of residual levels of various ionic contaminants that were detected in previous tests. The most plausible explanation for this improvement is the addition of IRN-150 and IRN-77 ion exchange resin and the removal of MCV resin at the outlet of the Stage 9 Unibed®. In Stages 7 and 8, carbon sorbent and MCV resin were at the outlet of the Unibed®. The sorbent manufacturers have indicated that low levels of ions could wash off the sorbent material (specifically sulfate and potassium). This "washing" of the sorbent with the addition of iodide from the MCV resin resulted in the slightly higher conductivity levels in Stages 7 and 8. The IRN-150 and IRN-77 in the Stage 9 Unibed® outlet would remove any ions that were washed from the sorbent material, resulting in lower conductivity levels.

68

Table 5-8. Comparison of Stage 9, 8, and 7 WP Water Quality Data

Waste Tank (Port 124) Parameter	Units	Potable Specification	Stage 9 Detection Limit	Stage 9 Times Detected/ Sampled	Stage 9 Detected Average*	Stage 7/8 Detection Limit	Stage 8 Times Detected/ Sampled	Stage 8 Detected Average*	Stage 7 Times Detected/ Sampled	Stage 7 Detected Average*
Conductivity	umho/cm	N/A		18/18	408.80		61/61	388.4	44/44	401.25
pH	S.U.	6.0-8.5	0.0-14.0	18/18	7.03	0.0-14.0	61/61	6.6	44/44	6.61
Total Organic Carbon	mg/L	0.5	1	18/18	211.70	1	61/61	187.6	44/44	156.65
1-propanol	mg/l	N/A	0.03	18/18	3.10	0.1	9/13	0.2	27/44	0.69
2-propanol	mg/l	N/A	0.04	18/18	8.00	0.2	2/13	0.3	9/44	0.29
acetone	mg/l	N/A	0.05	18/18	2.30	0.035	****	****	****	****
ethanol	mg/l	N/A	0.04	15/18	7.49	0.1	12/13	4.6	41/44	7.90
ethylene glycol	mg/l	N/A	0.25	4/18	1.20	0.25	1/13	0.3	15/44	0.42
methanol	mg/l	N/A	0.05	18/18	3.13	0.41	2/13	0.9	9/44	1.26
urea	mg/l	N/A	0.5	6/16	4.67	0.1	13/13	13.1	23/28	13.28
Total Inorganic Carbon	mg/L	N/A	1	18/18	12.53	1	60/61	11.5	44/44	8.68
Total Bacteria Count	CFU/100mL	1								
AEM Plate Count/2 Day	CFU/100mL		1	15/15	8.90E+08	1	60/61	1.02E+09	****	****
R2A Plate Count/7 Day	CFU/100mL		1	15/15	1.06E+09	1	61/61	3.55E+09	17/17	1.06E+08
VRA Influent (Port 126)										
Conductivity	umho/cm	N/A		68/77	1.99		58/58	5.3	44/44	4.65
pH	S.U.	6.0-8.5	0.0-14.0	77/77	7.11	0.0-14.0	58/58	7.8	44/44	8.05
Total Organic Carbon	mg/L	0.5	1	60/66	13.30	1	55/58	5.5	45/45	4.92
1-propanol	mg/l	N/A	0.03	57/65	3.03	0.1	****	****	8/43	0.85
2-propanol	mg/l	N/A	0.04	56/65	5.78	0.2	****	****	21/43	0.38
acetone	mg/l	N/A	0.05	39/65	1.23	0.035	****	****	****	****
ethanol	mg/l	N/A	0.04	62/65	10.51	0.1	****	****	38/43	7.71
ethylene glycol	mg/l	N/A	0.25	28/47	1.12	0.25	****	****	1/43	2.51
methanol	mg/l	N/A	0.05	64/65	1.15	0.41	****	****	15/43	0.73
urea	mg/l	N/A	0.5	57/61	3.67	0.1	****	****	39/43	3.76
Total Inorganic Carbon	mg/L	N/A	1	0/68	****	1	1/58	1	0/45	****
Residual Iodine	mg/L	15	0.1	0/17	****	0.1	0/12	****	****	****
VRA Effluent (Port 127)										
Conductivity	umho/cm	N/A		80/80	2.12		58/58	4.1	42/42	3.37
pH	S.U.	6.0-8.5	0.0-14.0	81/81	6.66	0.0-14.0	58/58	7.0	42/42	7.10
Total Organic Carbon	mg/L	0.5	0.2	69/77	1.60	0.2	58/58	0.56	47/47	0.66
1-propanol	mg/l	N/A	0.03	32/37	0.19	0.1	****	****	1/43	3.21
2-propanol	mg/l	N/A	0.04	4/37	0.14	0.2	****	****	0/43	****
acetone	mg/l	N/A	0.05	28/37	0.37	0.035	****	****	****	****
ethanol	mg/l	N/A	0.04	5/37	1.25	0.1	****	****	5/43	1.76
methanol	mg/l	N/A	0.05	25/37	5.10	0.41	****	****	12/43	1.03
urea	mg/l	N/A	0.5	0/18	****	0.1	****	****	0/43	****
Residual Iodine	mg/L	15	0.1	6/6	3.63	0.1	58/58	2.2	43/43	2.67
Product Tank (Port 120)										
Conductivity	umho/cm	N/A		51/51	2.25		49/49	5.5	32/32	4.51
pH	S.U.	6.0-8.5	0.0-14.0	51/51	6.27	0.0-14.0	49/49	6.9	32/32	6.93
Total Organic Carbon	mg/L	0.5	0.2	42/42	0.48	0.2	49/49	0.56	28/32	0.57
1-propanol	mg/l	N/A	0.03	33/42	0.17	0.1	****	****	0/7	****
2-propanol	mg/l	N/A	0.04	3/42	0.06	0.2	****	****	0/7	****
acetone	mg/l	N/A	0.05	28/42	0.23	0.035	****	****	0/30	****
ethanol	mg/l	N/A	0.04	0/42	****	0.1	****	****	3/7	0.54
ethylene glycol	mg/l	N/A	0.25	0/42	****	0.25	****	****	0/5	****
methanol	mg/l	N/A	0.05	28/42	0.27	0.41	****	****	0/7	****
urea	mg/l	N/A	0.5	0/42	****	0.1	****	****	0/7	****
Residual Iodine	mg/L	15	0.1	51/51	3.30	0.1	49/49	2.2	32/32	2.41
Total Bacteria Count	CFU/100mL	1								
AEM Plate Count/2 Day	CFU/100mL		1	8/42	1.1	1	4/49	1	22/93	1.9
R2A Plate Count/7 Day	CFU/100mL		1	16/41	1.4	1	9/49	1.30	34/93	43.9

* Averages are based on on the samples in which detectable concentrations were measured and do not account for samples in which detectable concentrations were not found.

69

An interesting phenomenon occurred in the Unibed® train effluent with regard to ethylene glycol, propylene glycol, and urea. Figures 5-19, 5-20, 5-21 show the levels of ethylene glycol, propylene glycol, and urea in the Unibed® train effluent (port 126) for Stage 9 and Stage 7. High levels of urea, ethylene glycol, and propylene glycol were in the effluent of the Unibed® train at the start of the test. As processing continued, the levels of all three of these components gradually decreased until urea was at a significantly lower level, and propylene and ethylene glycol were below detection limit. The levels remained low for all three contaminants until the first Unibed® was saturated and replaced on Test Day 51. After the Unibed® changeout, the levels immediately increased to a significantly higher concentration, which was slightly lower than the concentrations at the start of the test. This phenomenon is not considered to be caused by the ISS operational configuration because these trends were also observed in the Stage 7 data. Data from the Unibed® influent (port 124) indicates that the influent contaminant level also decreased over time. Insufficient data was collected during Stages 7 and 9 to determine the cause of this phenomenon and how it relates to the influent contaminant levels. Though interesting, this phenomenon did not effect the VRA's ability to remove these contaminants from the product water. In order to determine the reason for these contaminant level fluctuations, a detailed study of Unibed® performance is required.
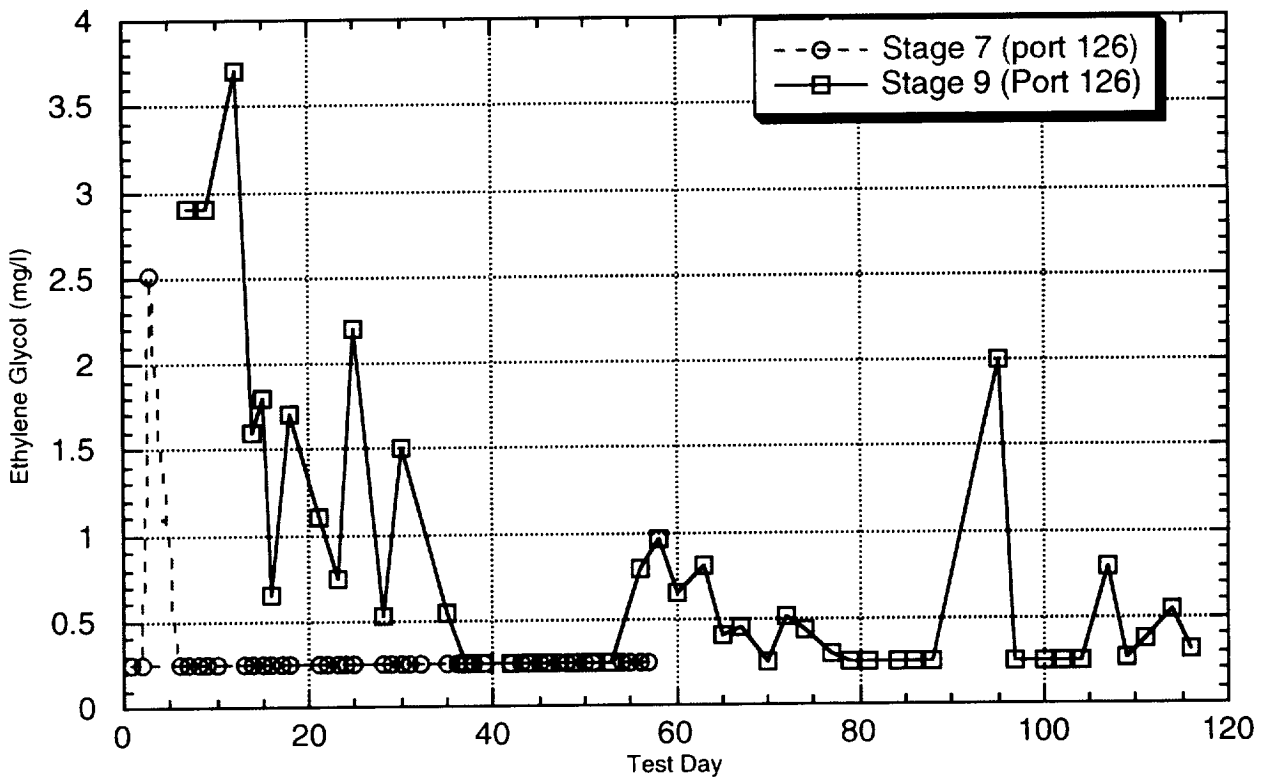
Figure 5-19. Unibed® Effluent Ethylene Glycol Levels

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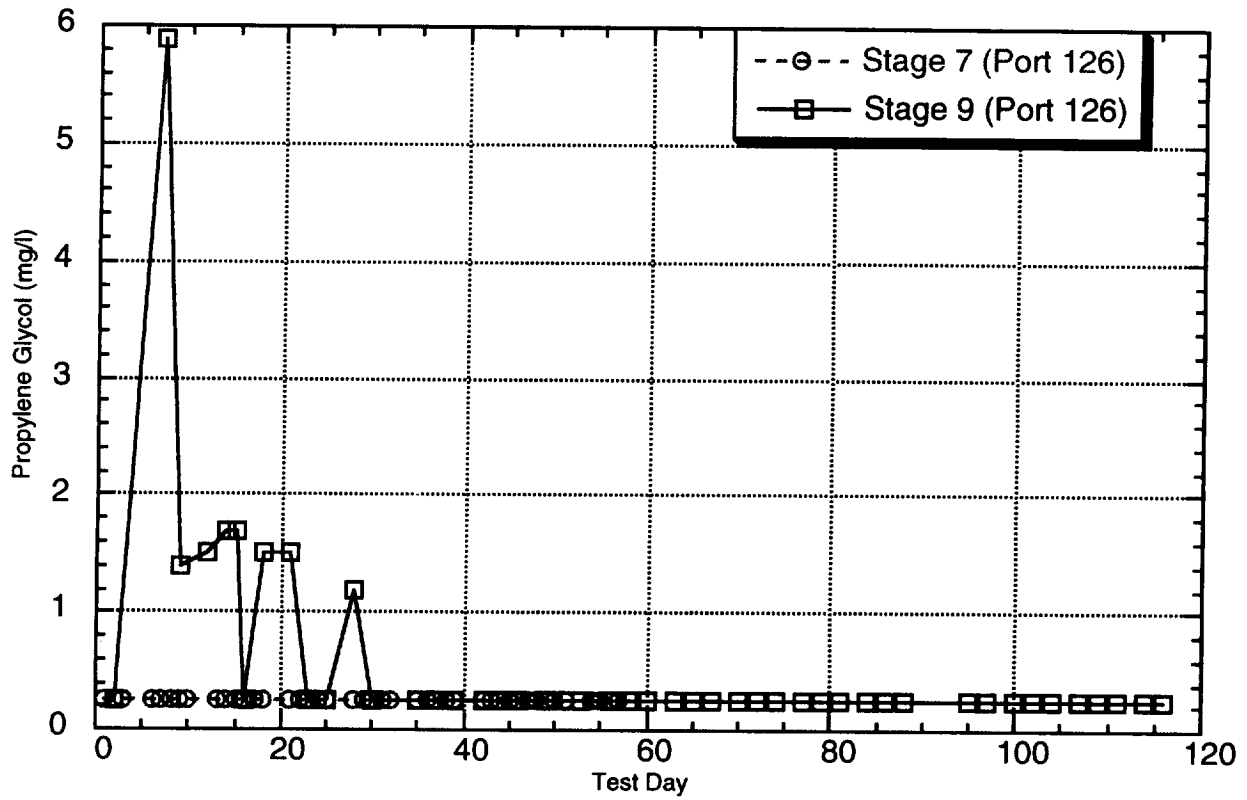
Figure 5-20. Unibed® Effluent Propylene Glycol Levels
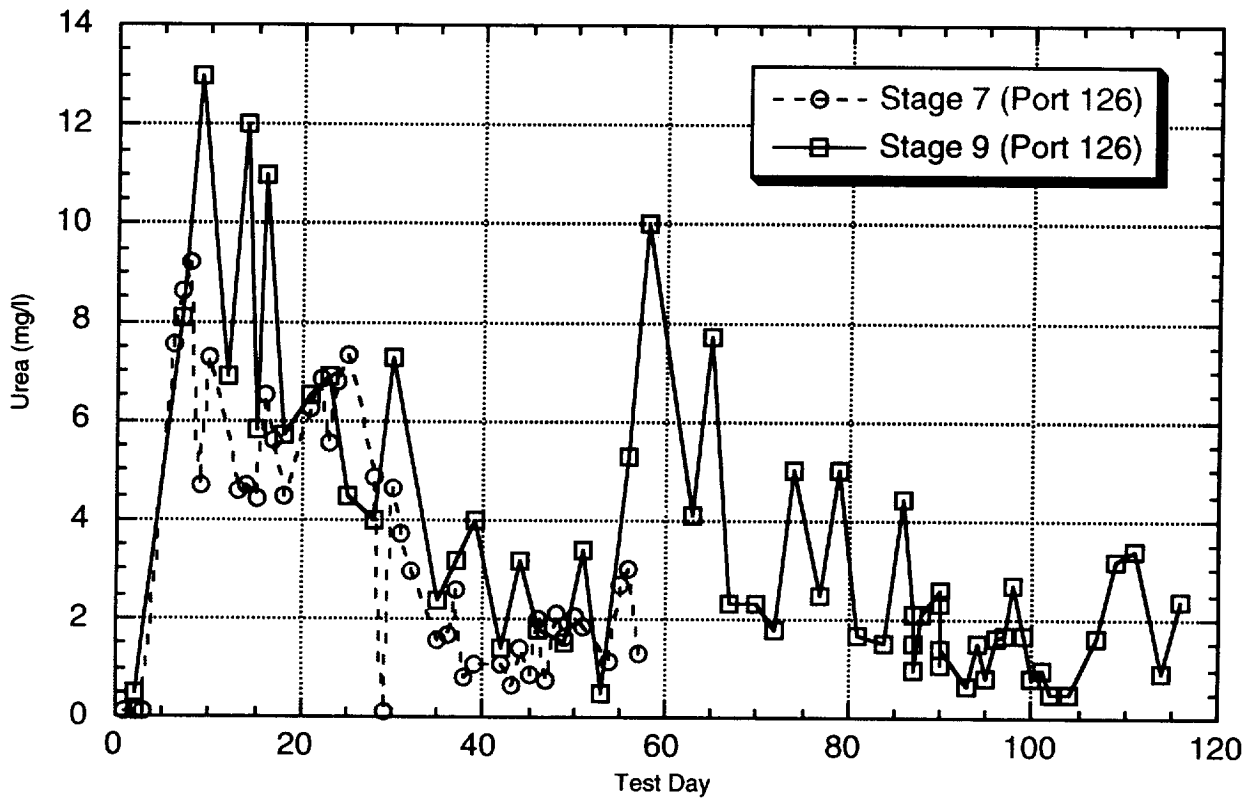
Figure 5-21. Unibed® Effluent Urea Levels

71

The water quality of the VRA effluent and in the product tanks was comparable to previous test results, though variant data was obtained on iodine and TOC (Table 5-8). The higher iodine levels in the product water were due to the use of a Room Temperature iodinated resin in the ion exchange bed as opposed to the High Temperature resin used during Stages 7 and 8. The room temperature resin is designed to impart a residual iodine level of 2.5 to 4.5 mg/l at 65 to 75 °F. A plot of PCWQM iodine data (pin1) on a given day shows a steep increase in iodine levels after approximately two hours of processing (see Figure 5-22). An analysis of other sensor data indicated that the iodine increase coincided with a temperature increase in the VRA heat exchanger influent (WT42), which subsequently led to a temperature increase in the VRA effluent (pt20). The source of the temperature variance is the VRA assembly, which contains a volume of ambient temperature water downstream of the reactor after any extended time in Standby mode. After processing begins, the water temperature downstream of the reactor (WT42) increases as the high temperature water from the reactor moves downstream. The initial temperature observed at the PCWQM ranged from 71 to 76 °F, while the final temperature ranged from 76 to 83 °F. The iodine increase occurred as the higher temperature water passed through the MCV resin located at the outlet of the VRA ion exchange bed. Though the delta temperature on a given day was nominally less than 10 °F, this effected an iodine increase of approximately 1.2 mg/l each day.
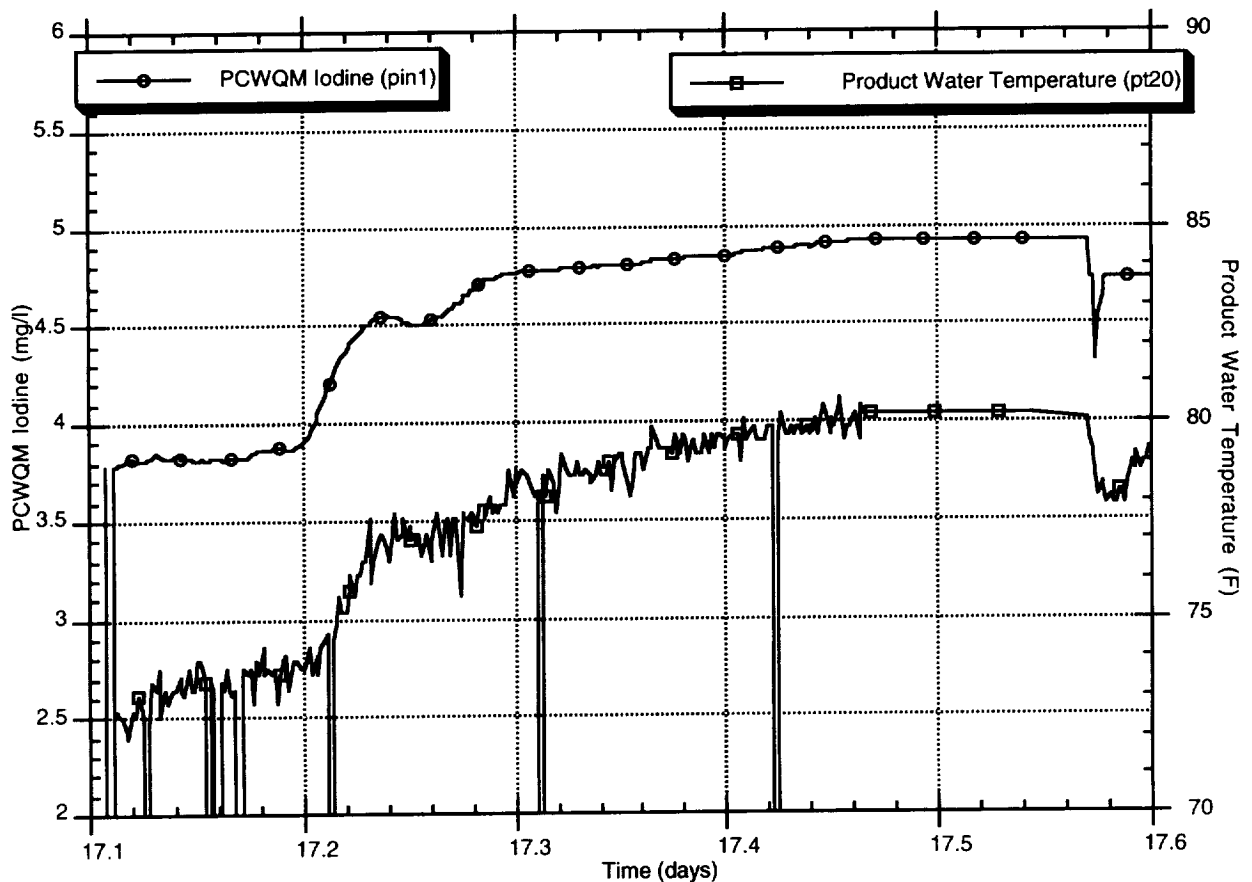
Figure 5-22. Product Water Iodine vs Temperature

72

Accordingly, the iodine levels exceeded the water quality specification of 4 mg/l in 7 out of 51 product water tanks tested. Since test data indicates that the higher iodine levels are not necessary for microbial control (Table 5-8), lower iodine levels are recommended to improve the palatability of the product water. This would be accomplished by returning to the High Temperature resin as utilized in Stages 7 and 8. The temperature increase in the product water is not an issue, since it does not exceed the product water temperature requirement of 70-113 °F. Note that this phenomenon has likely occurred in previous testing but was not detected without on-line monitoring, nor was it of the same magnitude due to the use of the high temperature MCV resin.

The high average TOC value in the VRA effluent was primarily due to the thermal degradation of the IRN-78 resin used in the ion exchange beds. This degradation results in the accumulation of organic contaminants in the ion exchange bed that are flushed out of the bed following installation of a new bed or after Standby mode. The TOC monitor's response to this phenomena is a "TOC spike" and is illustrated in Figure 5-10. The transition period required to flush the contaminants out of the ion exchange bed was approximately 2 hours after Process mode was initiated. The high product water TOC levels were not as significant on split cycle days (test days in which the processing cycle was "split" two cycles) during the second processing cycle (Figure 5-23), indicating that the beds must be maintained in Standby longer than approximately 4 hours for any significant effect to occur. Test data also shows the TOC is significantly higher after an ion exchange bed is replaced (Figure 5-24), which is expected due to the higher concentration of organics in the resin and the lengthy period the bed has sat without use. High effluent TOC levels were observed in the product water following the installation of a new ion exchange bed for the first 65 to 110 lb of throughput. The repeated spikes observed on Test Day 23 after an ion exchange bed changeout represent when the PCWQM IR cell was purged because the measured TOC level exceeded 1500 ppb. This effect was first observed in Stage 9, as this was the first test in which the ion exchange bed was replaced during the test. During Stages 7 and 8, the leaching only occurred at the beginning of the test and was erroneously attributed to the VRA phase separator (7).

Samples were pulled in the product water (Port 127) during a TOC spike on Days 14, 15 and 18 and after replacing an ion exchange bed on Days 23 and 107 (Table 5-9) to determine the organics contributing to the effect.

The available data indicates that the primary contributor to the TOC spike is methanol, with trimethyl amine and ethanol also detected in the VRA effluent immediately following the replacement of an ion exchange bed. Methanol was also detected in 28 out of 42 product water tanks at an average concentration of 270 ppb (Table 5-8), while ethanol was undetected in the 42 product water tanks. Discussions with the ion exchange bed vendor, Umpqua Research, indicate that the IRN-78, a strong base anion exchange resin, can impart the methanol and trimethylamine to the water. Information provided by Umpqua states that the hydroxyl radical (OH-)

73
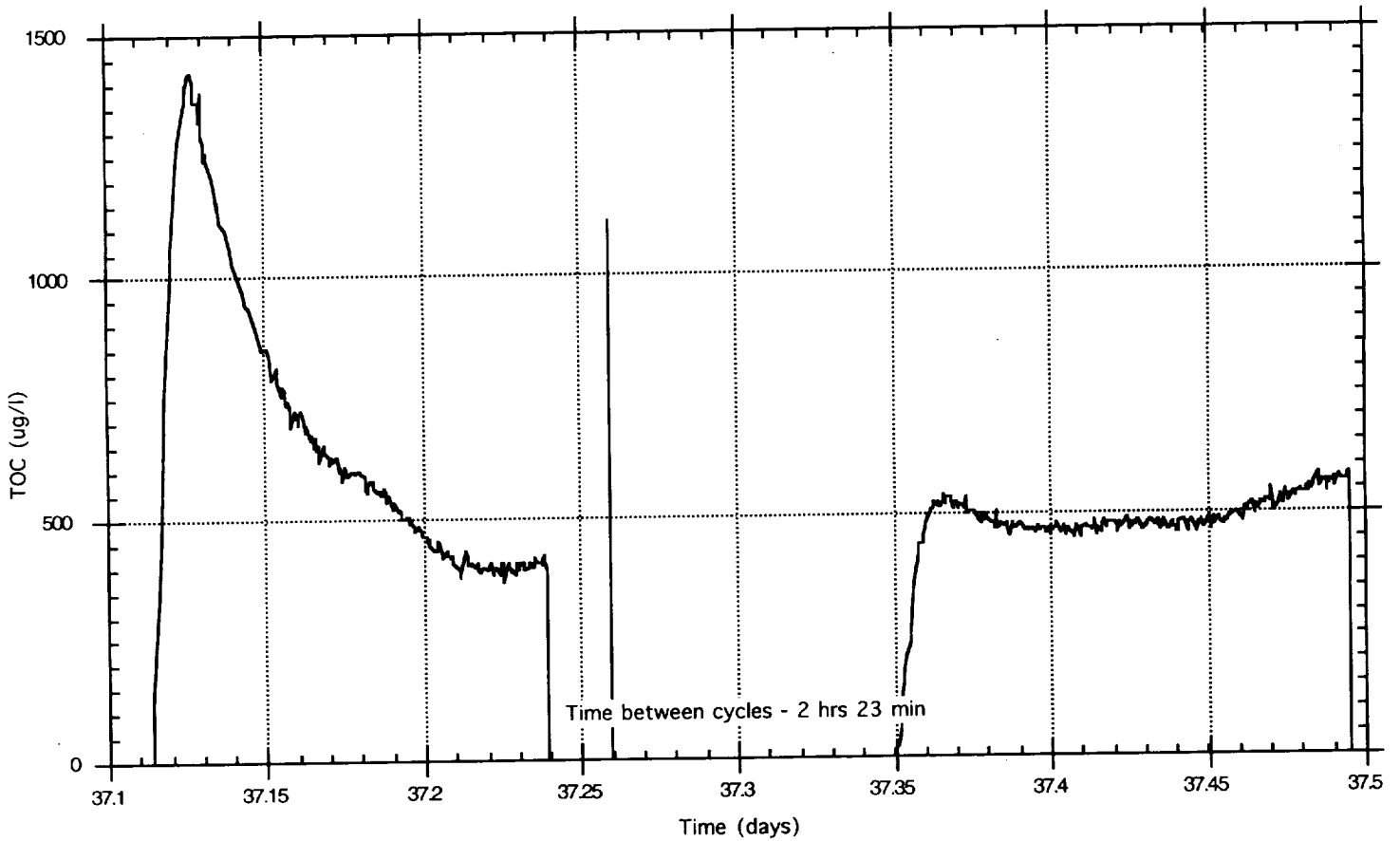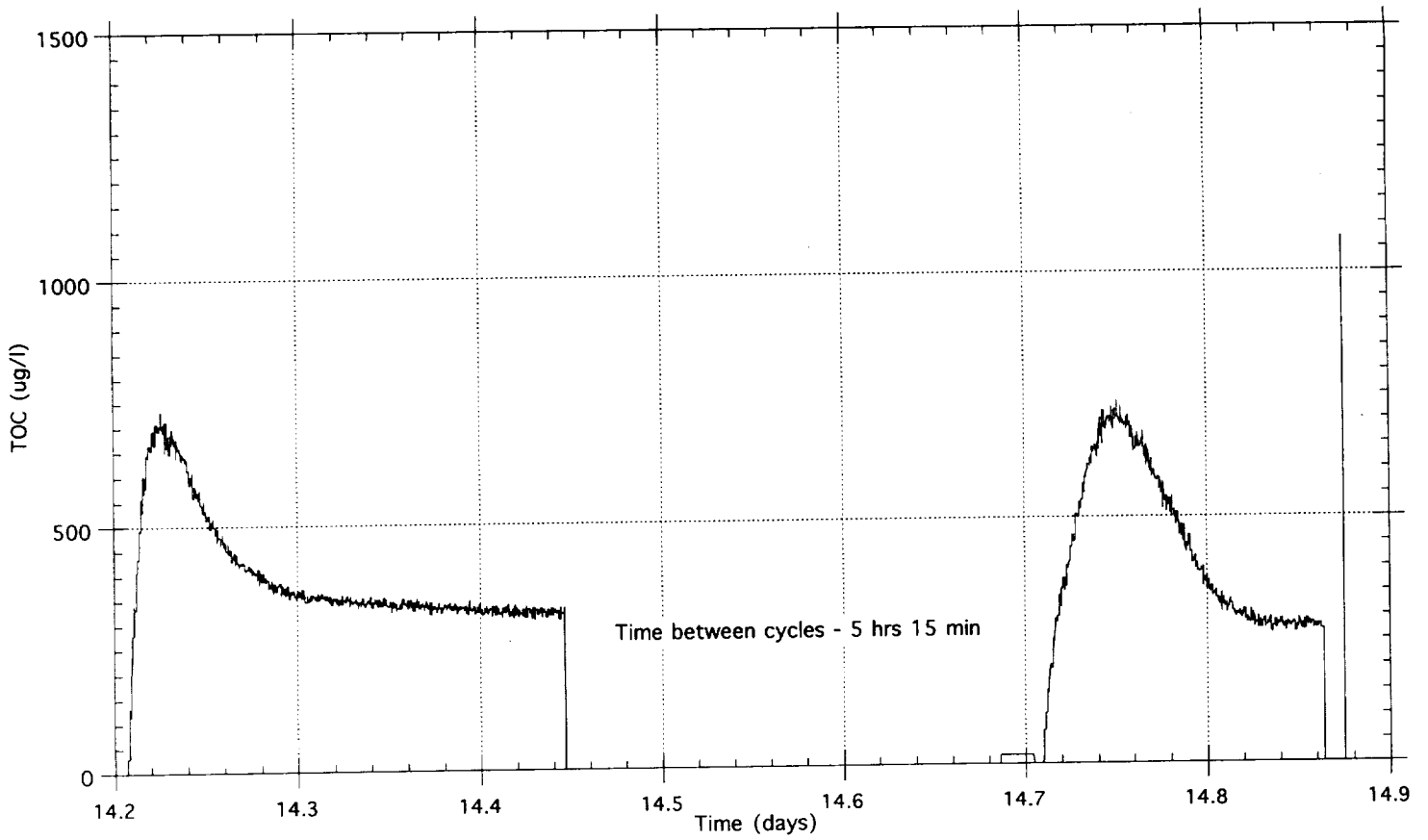
Figure 5-23. Product Water TOC on Split Cycle Processing Days
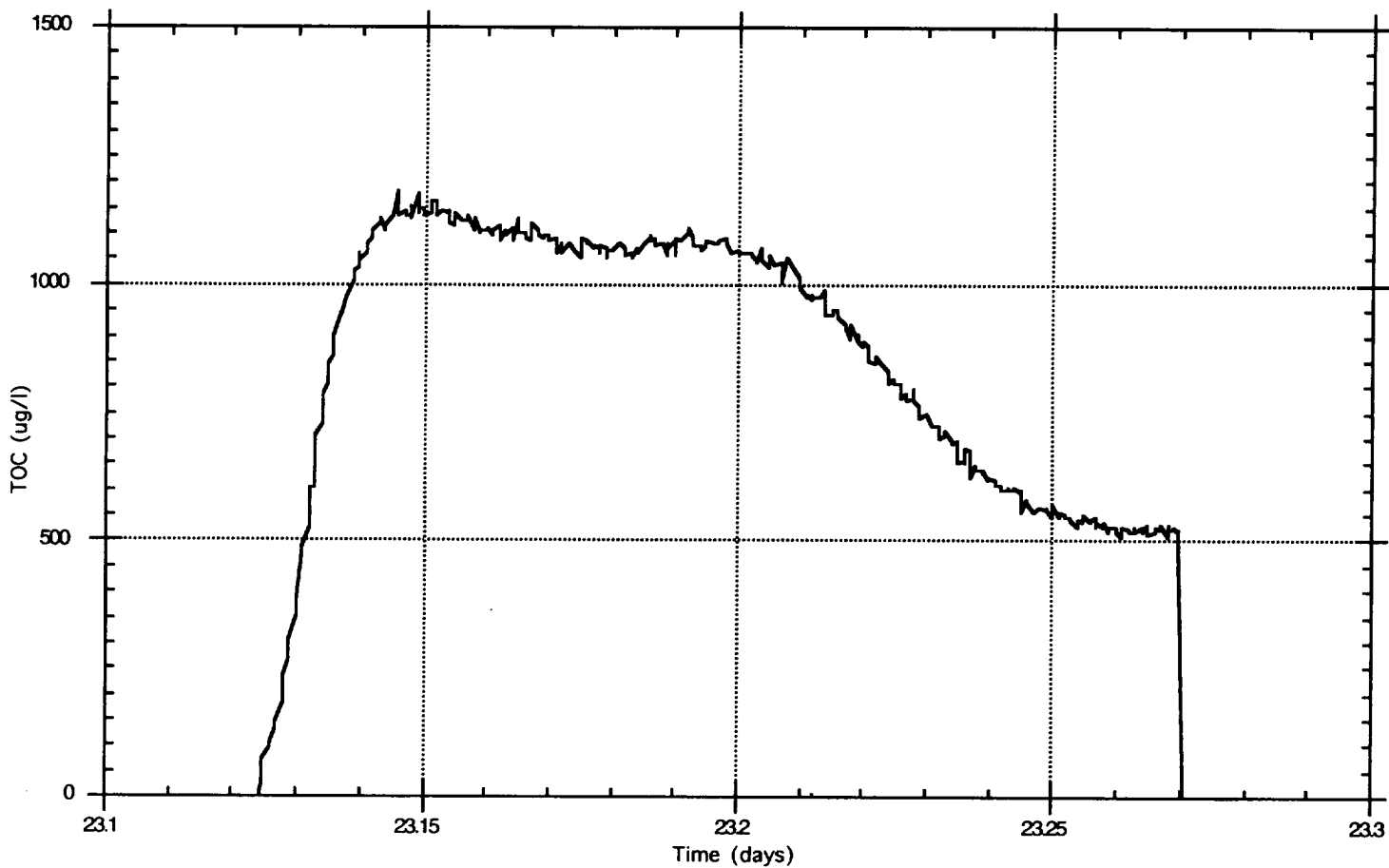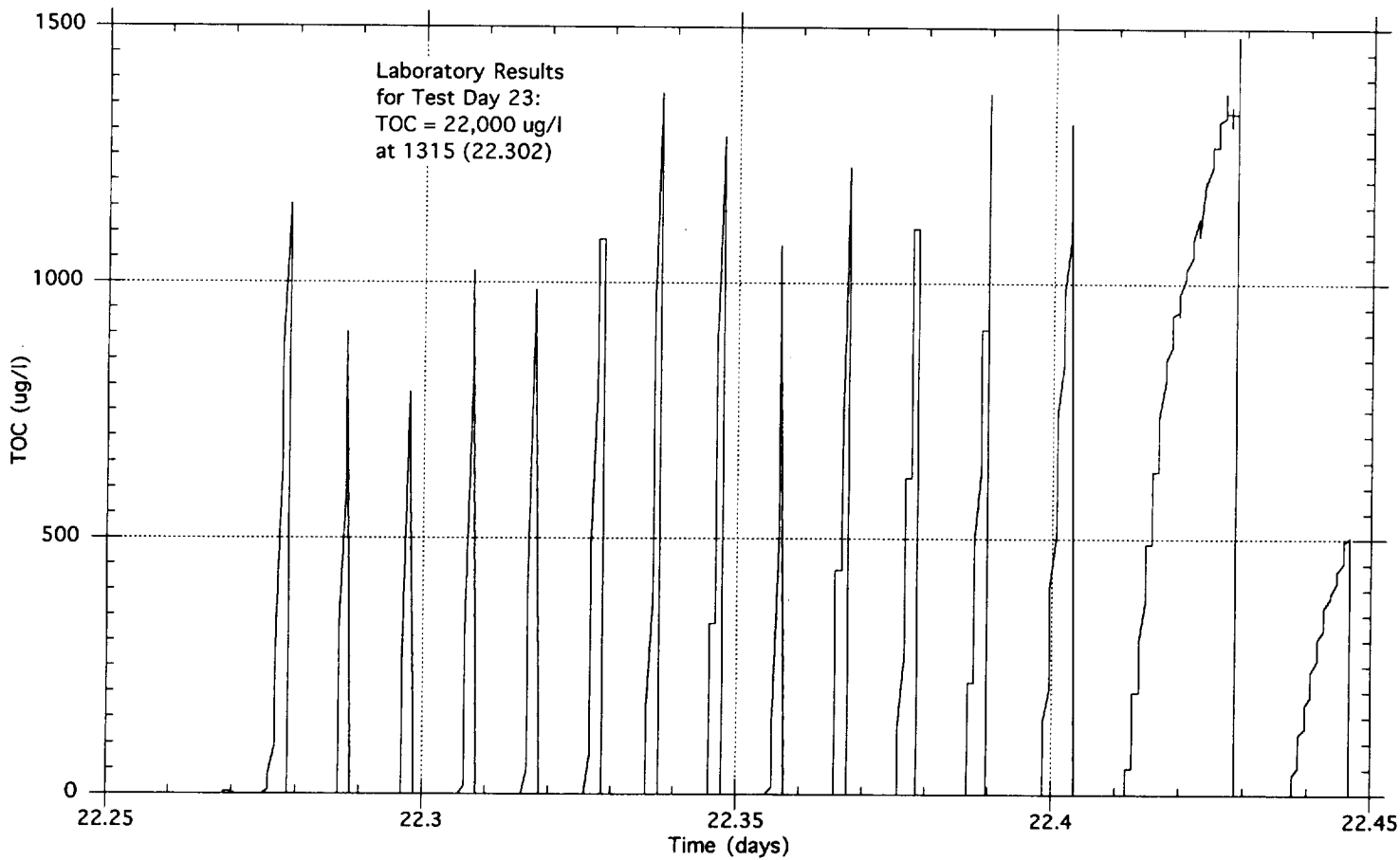
Figure 5-24. Product Water TOC Following Ion Exchange Bed Replacement

75

Table 5-9. Analysis of TOC Spike Constituents

Test Day	Time	Methanol (ppb)	Ethanol (ppb)	Trimethyl amine (ppb)	Measured TOC (ppb)	Characterized TOC (ppb)
14	1021	1240	ND	NA	1100	465
15	0959	2610	ND	NA	1700	979
18	0912	1290	ND	NA	1300	484
23	1314	23200	2700	NA	19700	10109
107	807	630	ND	240	250	380
107	1143	91000	2500	75	38000	35500
108	1235	1200	350	ND	450	630

ND-not detected   NA-not analyzed

will react with the quaternary amine group of the strong base anion exchange resin liberating trimethylamine and methanol:

$$RCH_2N(CH_3)_3{}^+OH^- \longrightarrow RCH_2OH + N(CH_3)_3$$
trimethylamine

$$RCH_2N(CH_3)_3{}^+OH^- \longrightarrow RCH_2N(CH_3)_2 + CH_3OH$$
methanol
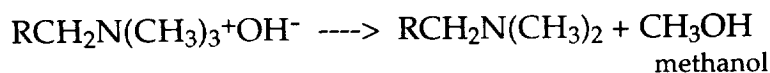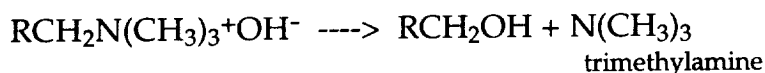
The source of ethanol is unknown. Although a toxicological assessment of the data has not been done, the relatively quick disappearance of methanol and ethanol in the VRA effluent allays concern regarding its long term effect on product water quality. Modifications to the ion exchange bed design could potentially eliminate the TOC spike, if necessary. This design change would consist of replacing the IRN-78 with IRA-68, a weak base anion exchange resin. The functional group of the IRA-68 resin is a tertiary amine that does not have a fixed charge. This resin undergoes ion exchange reactions under specific pH conditions during which it is never in the hydroxyl form, which is required to undergo the reaction described previously. Test data also indicates that the IRA-68 will provide better removal of acetic acid and bicarbonate (18, 19) and should therefore provide better performance as the primary resin in the ion exchange bed.

High TOC values were also achieved in the product water due to the TOC Monitor Deletion study on Test Days 93-101. As discussed previously the VRA temperature was deliberately lowered on these days to simulate a VRA failure, thus creating an artificially high TOC level. If the samples taken immediately after an ion exchange bed changeout are excluded, as well as those obtained during the TOC Monitor Deletion study, the average TOC concentration in the VRA effluent is 0.49 mg/l, which is comparable to previous testing.

The most significant issue related to the VRA performance was a gradual increase in the product water TOC over the course of a processing cycle. This phenomenon was first observed on Day 19 and became more prevalent as the Unibed® loaded. Samples were pulled to verify the PCWQM TOC reading (Figure 5-25) and to

determine the organics contributing to the rise. The resulting analyses indicated that acetone was the primary, if not sole, organic responsible. Table 5-10 compares the TOC contribution from acetone to the TOC increase recorded by the PCWQM for days when periodic acetone samples were taken. The data shows a definite relationship between the acetone and TOC increase. No other contaminants were identified in the product water (Port 120) that either increased or decreased during the TOC rise.
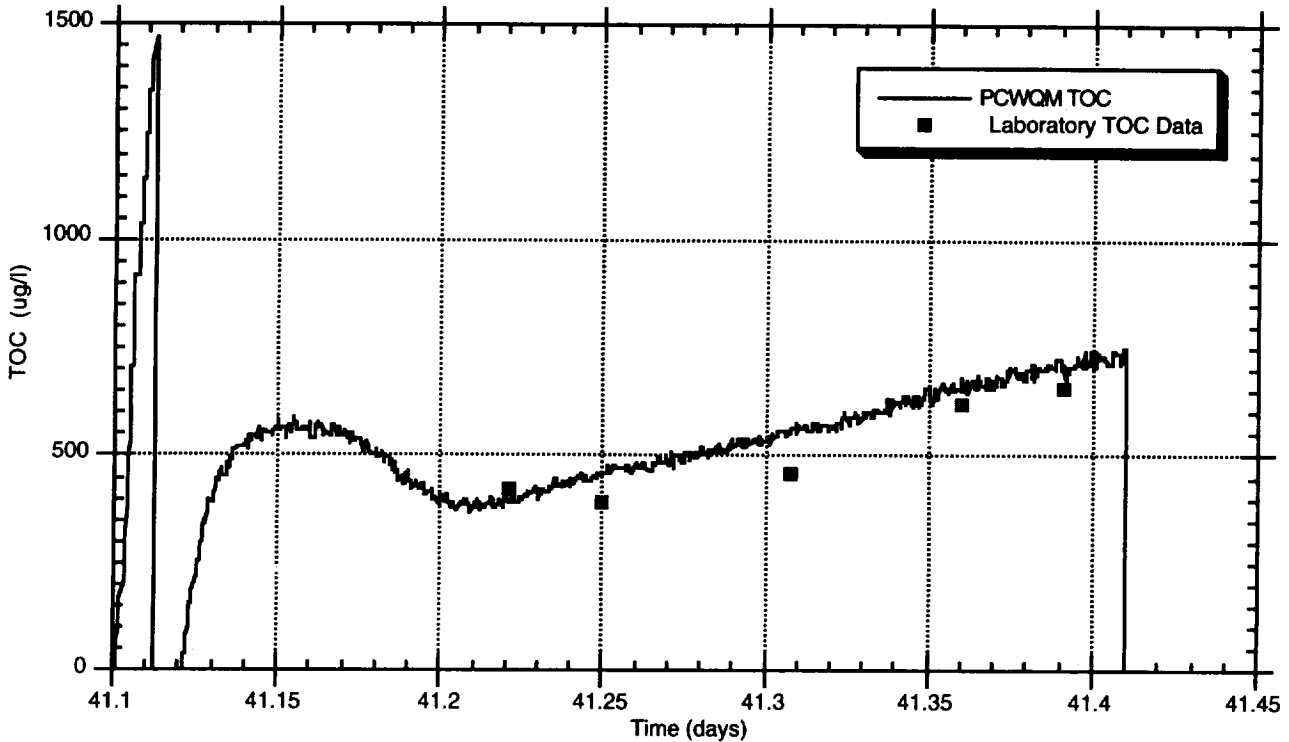
Figure 5-25. PCWQM TOC and Laboratory Results on TOC Rise

Table 5-10. Characterization of TOC Contributing to TOC Rise

Test Day	Time	PCWQM TOC (ppb)	delta TOC (ppb)	Acetone (ppb)	Acetone TOC Contribution	Acetone delta TOC (ppb)
42	1120	437	-	210	130	-
	1201	488	51	315	196	65
	1325	587	150	465	289	158
	1440	693	256	518	322	191
	1525	737	300	562	349	219
87	1522	260	-	137	85	-
	1845	350	90	294	183	97
90	1126	104	-	50	31	-
	1304	158	54	80	50	19
	1522	190	86	125	78	47
	1703	222	118	156	97	66

Acetone is present in the VRA effluent primarily as the oxidation product of 2-propanol, though it was also present in the VRA influent at lower concentrations. The reaction of 2-propanol to acetone occurs as follows:

$$OH \qquad\qquad\qquad O$$
$$H_3C\text{-}C\text{-}CH_3 + 1/2\ O_2 \longrightarrow H_3C\text{-}C\text{-}CH_3 + H_2O$$
$$H$$
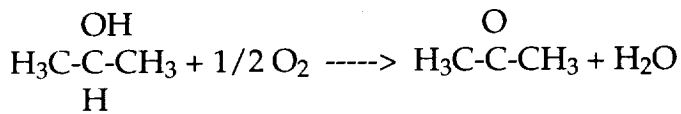
The relationship between 2-propanol, acetone and the TOC rise is further validated by observing the change in TOC rise based on the concentration of 2-propanol entering the VRA. The TOC rise ceases after a Unibed® is expended and replaced, and begins only after 2-propanol has broken through both Unibeds® and is actually present in the reactor influent. During the time required for 2-propanol to break through the Unibed®, no acetone was generated in the reactor and no TOC rise was observed in the product water (Figure 5-26). Furthermore, a general decrease in the concentration of 2-propanol in the VRA influent following Day 60 affected the TOC rise. Following Day 60 the slope of the curve decreased and did not return to that observed before the first Unibed® changeout, except during the TOC Monitor Deletion study when the reactor temperature was decreased. This change in the product water TOC can be tracked to the influent 2-propanol levels, which appeared to drop from approximately 7500 ppb to 5800 ppb on Test Day 62. The 2-propanol level further dropped to 4000 ppb around Test Day 100 (Figure 5-27). The decrease in 2-propanol would result in a decrease in acetone in the reactor effluent. The change observed in 2-propanol levels in the VRA influent was apparently sufficient to significantly affect the slope of the TOC rise in the VRA effluent.

Samples were also taken from the VRA influent (Port 126), the effluent from the reactor (Port 205) and phase separator (Port 201), and the VRA effluent (Port 127) to provide further information regarding this phenomenon. This data is summarized in Table 5-11. Though the concentration of organics in the VRA influent did not increase over the course of a processing cycle, a definite upward trend in the reactor effluent (Ports 205 and 201) concentration of acetone, acetic acid and propionic acid is observed. Acetic acid and propionic acid are oxidation products of ethanol and 1-propanol, respectively, both of which are detected in the VRA influent. This data indicates that the performance is related to the further reaction of oxidation products generated in the reactor.

The data summarized in Table 5-11 was used to estimate the conversion of acetone, acetic acid, and propionic acid in the VRA reactor. The acetone data assumed all 2-propanol is oxidized first to acetone and incorporates the acetone already present in the reactor influent. Higher conversion of acetone (72%) was achieved on Day 90 due to the higher reactor temperature of 270 to 275 °F, as opposed to the nominal 260 to 265 °F. The same calculation applies to the oxidation of 1-propanol to propionic acid. The conversion of acetic acid must take into account the contribution of ethanol and propionic acid, both of which are believed to be oxidized

78
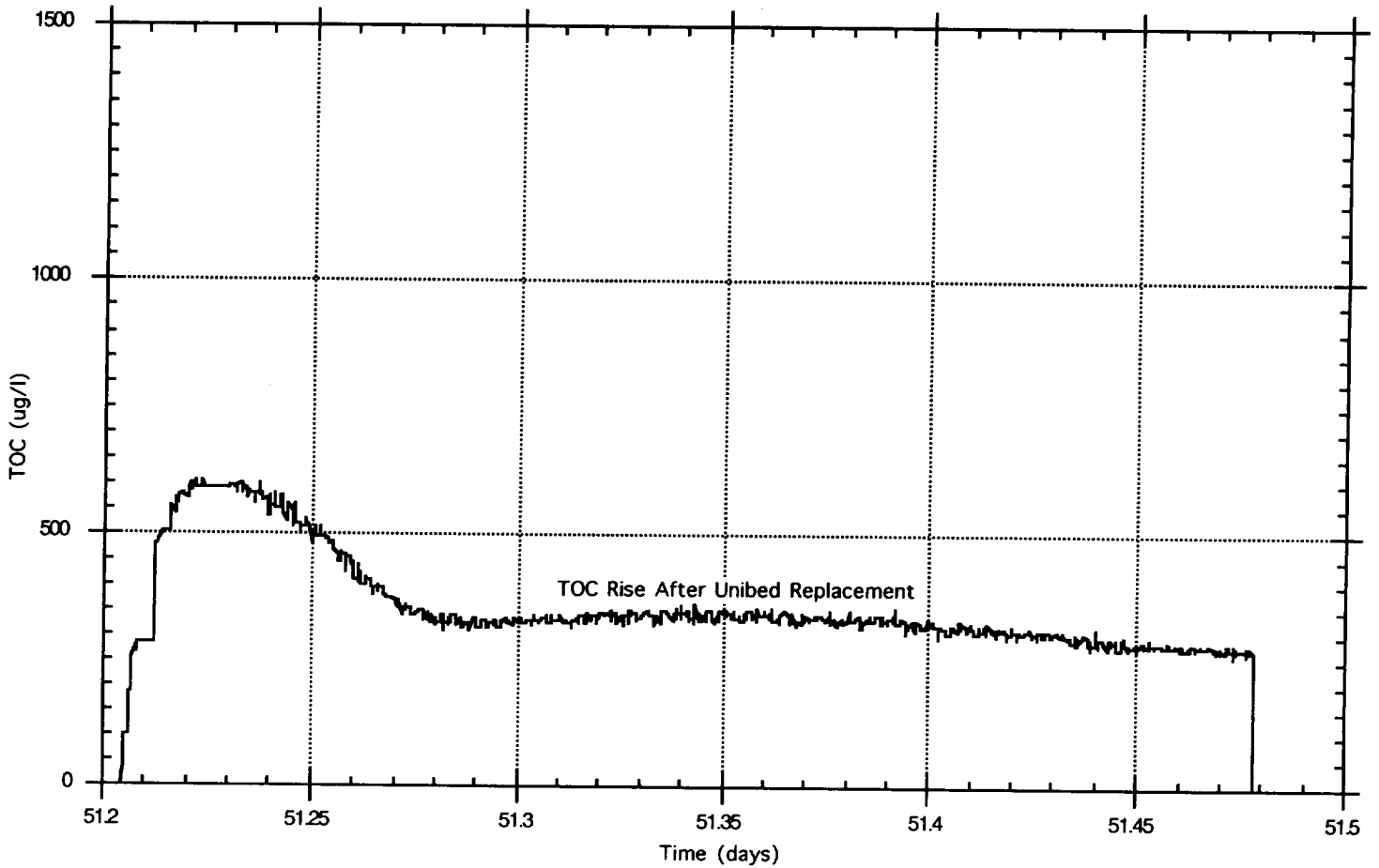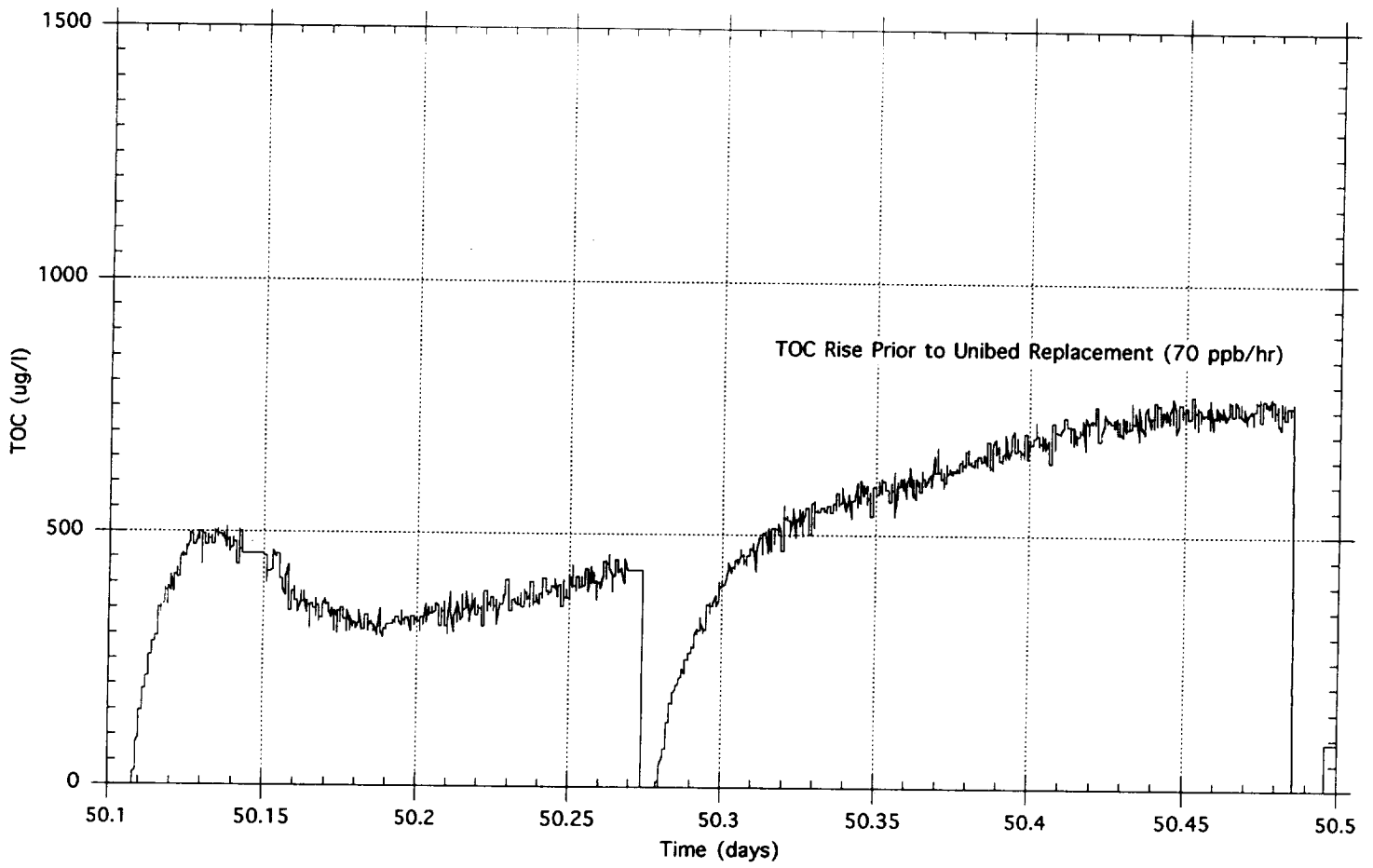
Figure 5-26. Product Water TOC Before and After Unibed Replacement

79
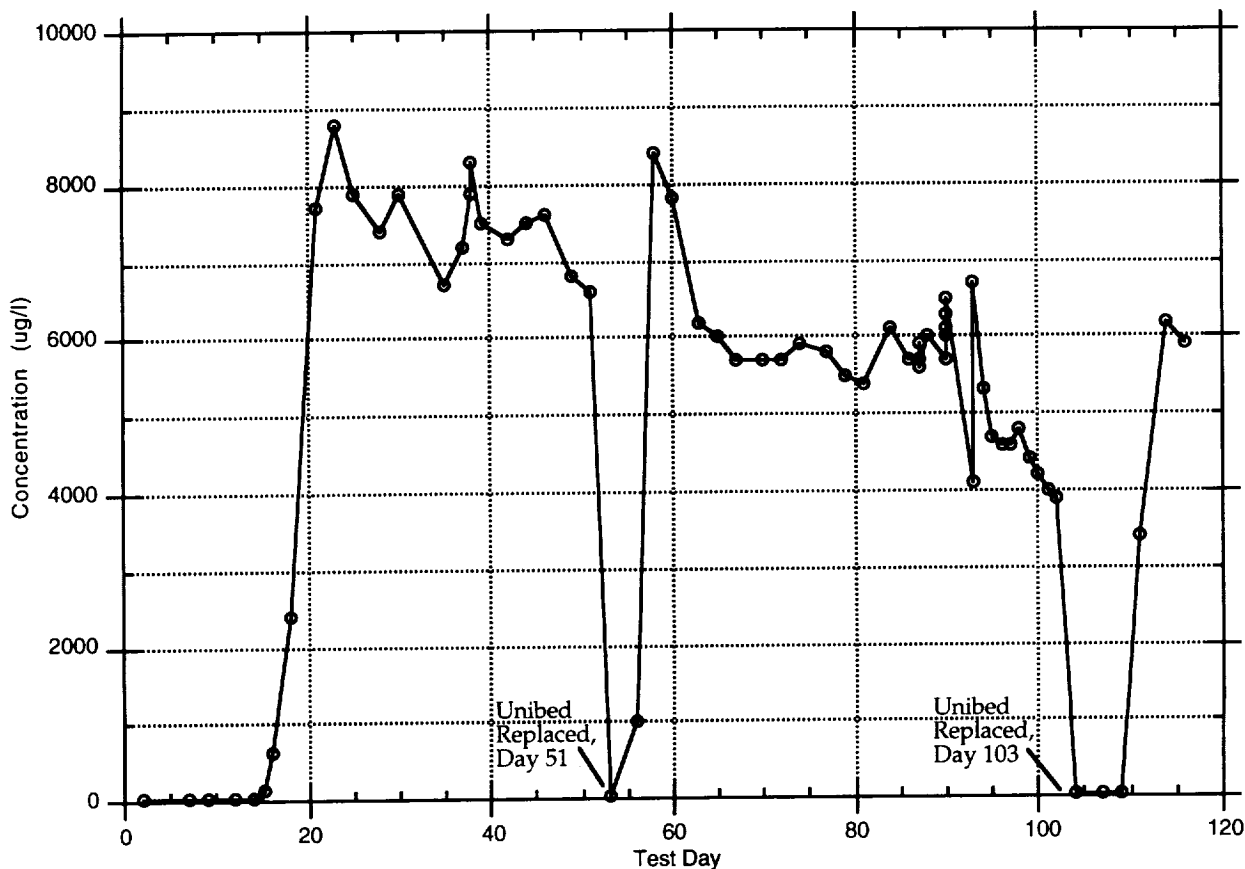
Figure 5-27. VRA Influent Concentration of 2-propanol

to acetic acid. Since neither ethanol or acetaldehyde was detected in the reactor effluent, it may be assumed that ethanol was converted either to acetic acid or to carbon dioxide and water. At the elevated temperatures on Test Day 90, the conversion of acetic acid ranged from 97% to 99%. The conversion data also shows a relative decrease in reactor performance over the course of a processing cycle. The data indicates that the reactor catalyst easily oxidizes low-molecular weight alcohols and aldehydes, but the subsequent conversion of organic acids and ketones presents more difficulty.

Michigan Technological University (MTU) is currently being funded by MSFC to develop a computer model of the Hamilton Standard VRA reactor. Data generated in the development of the model has potential application to an understanding of the reactor performance observed during Stage 9. MTU utilized small-column testing to determine the reaction rate for various organics. The shorter residence time used in small-column tests leads to a fractional conversion of the organics, as opposed to testing in the VRA reactor where the organic compounds studied were fully oxidized. Small-column testing (3.8 sec residence time) on the catalyst developed by Hamilton Standard showed an initial conversion of ethanol of 63%, which then decreased to a stable level of 20% after approximately 50 minutes (20).

Table 5-11. Summary of TOC Rise Analytical Data

Test Day	Sample Port	Sample Time	Process Start	TOC (ppm)	TIC (ppm)	acetone (ppb)	% Conversion	methanol (ppb)	2-propanol (ppb)	ethanol (ppb)	1-propanol (ppb)	urea (ppb)	acetic acid	% Conversion	propionic acid	% Conversion	isobutyric acid
38	VRA Influent (126)	953	827	17.1	<1.0	<50		683	7900	11100	3660						
		1141	827	15.7	<1.0												
		1453	1409	15.5	<1.0												
		1754	1409	15.3	<1.0	72		1150	8330	11900	3840						
	Phase Separator Effluent (201)	945	827	4.76	4.83	4960	45.5	<50	<40	<40	100		4780	69.1	640	81.6	490
		1134	827	5.09	4.68	4190		<50	<40	<40	74		5390		830		520
		1457	1409	4.35	4.49	4530		<50	<40	<40	118		3240		540		430
		1747	1409	6.07	5.14	4770	41.1	<50	<40	<40	141		4560	75.6	810	82.9	430
42	VRA Influent (126)	927	811	14.4	<1.0												
		1145	811	14.7	<1.0												
		1517	811	16.6	<1.0												
	Phase Separator Effluent (201)	921	811	4.38	1.96	4216					61		3730		550		<400
		1140	811	4.38	1.96	4300					72		5610		1000		<400
		1512	811	6.87	2.27	4680					73		7490		1070		<400
	VRA Effluent (127)	1120	811	0.42		210		234	<40	<40	208						
		1201	811	0.39		315		210	<40	<40	203						
		1325	811	0.46		465		306	<40	<40	227						
		1440	811	0.62		518		218	<40	<40	210						
		1525	811	0.66		562		233	<40	<40	231						
87	VRA Influent (126)	1403	1229			1480		1380	5660	10100	3630	2110					
		1512	1229			1490		1300	5890	8850	3590	2140					
		1708	1229			1480		1300	5890	8560	3470	1490					
		1859	1229			1490		1880	5620	11100	3490	950					
	Reactor Effluent (205)	1347	1229			3560		<50	<40	<40	177	<500	7490		1570		<400
		1508	1229			4440		<50	<40	<40	156	<500	6240		1230		<400
		1704	1229			4490		<50	<40	<40	162	<500	6310		1820		<400
		1854	1229			4590		<50	<40	<40	151	<500	7820		2020		<400
	Phase Separator Effluent (201)	1342	1229			4110	41.0	<50	<40	<40	137	<500	6840	55.8	1640	63.4	<400
		1503	1229			4080	43.3	<50	<40	<40	127	<500	6390	54.4	1370	69.0	<400
		1700	1229			4210	41.5	<50	<40	<40	128	<500	6360	51.8	1780	58.4	<400
		1850	1229			4560	34.2	<50	<40	<40	157	<500	7840	51.6	2160	49.8	<400
	VRA Effluent	1522	1229			137		<50	<40	<40	150	<500					
		1845	1229			294		238	<40	<40	163	<500					
90*	VRA Influent (126)	1057	934			1650		2100	5980	13700	3800	2320					
		1133	934			1620		2080	5690	12600	3690	2590					
		1322	934			1750		505	6290	11000	3970	2320					
		1539	934			1650		276	6050	10600	3810	1070					
		1716	934			1750		648	6460	12100	4000	1440					
	Reactor Effluent (205)	1019	934			399		<50	<40	<40	<30	<30	<160		<400		<400
		1315	934			2020		<50	<40	<40	<30	<500	280		<400		<400
		1533	934			2250		<50	<40	<40	165	<500	420		<400		<400
		1712	934			2680		<50	<40	<40	121	<500	630		<400		<400
	Phase Separator Effluent (201)	1015	934			283	75.7	<50	<40	<40	<30	<500	<160	98.7	<400	75.7	<400
		1311	934			1890	72.0	<50	<40	<40	136		240	97.7	<400	72.0	<400
		1528	934			2110	67.1	<50	<40	<40	107		390	96.8	<400	67.1	<400
		1709	934			2610		<50	<40	<40	122		620		<400		<400
	VRA Effluent (127)	1126	934			<50		<50	<40	<40	172	<500					
		1304	934			80		<50	<40	<40	174	<500					
		1522	934			125		<50	<40	<40	188	<500					
		1703	934			156		<50	<40	<40	219	<500					

*VRA temperature set at 270 to 275 F on Test Day 90

81

This data is presented in Figure 5-28. Similar data was obtained for chlorobenzene. The data suggests a degradation in catalyst performance over time similar to the decreased conversion of acetone and the organic acids in Stage 9 (see Table 5-11). Since the MTU testing was conducted in a controlled environment, no inorganic poisons should be present to inhibit reactor performance, thus the degradation in catalyst performance should be attributed to the effect of the ethanol or chlorobenzene oxidation on the catalyst.
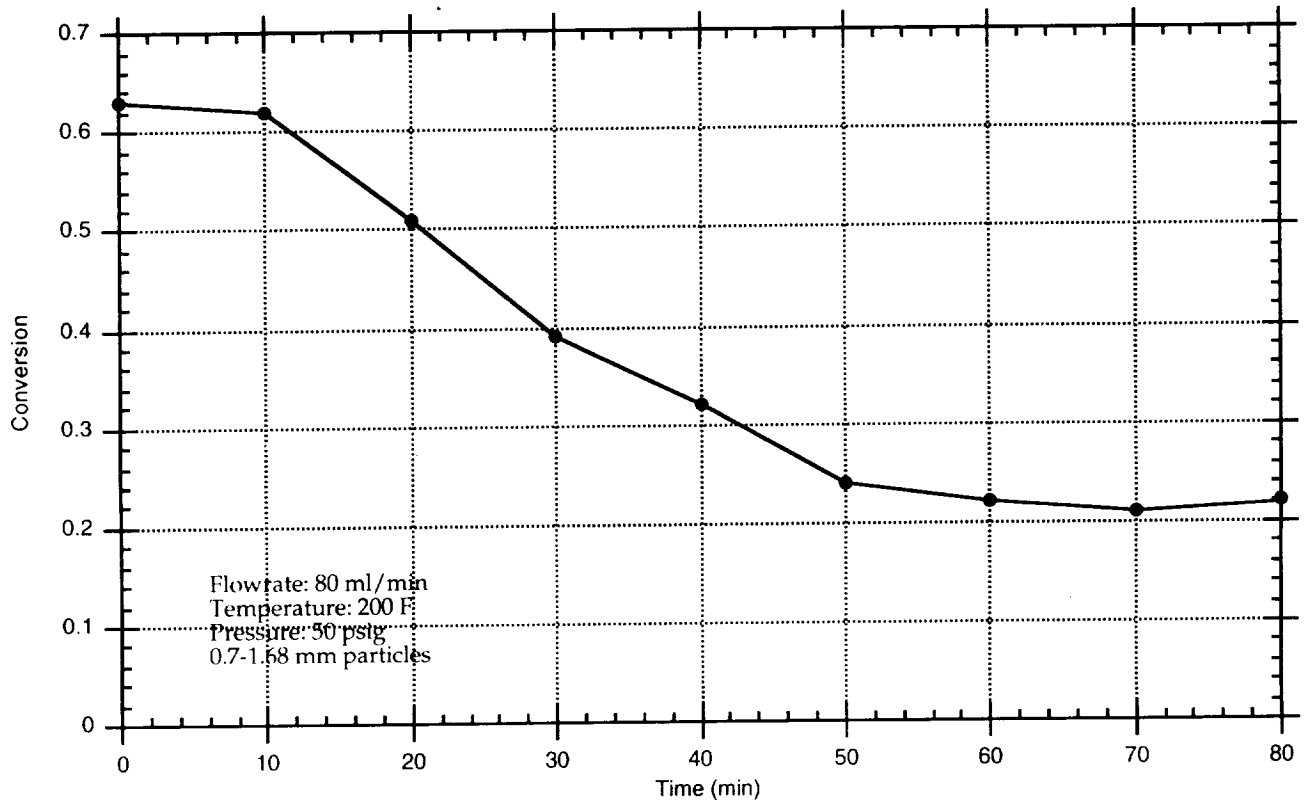
Figure 5-28. Conversion of Ethanol in Small Column Testing

Separate testing in the modeling effort with dimethyl sulfoxide indicated that it was acting as a catalyst poison. Dimethyl sulfoxide has been detected at low levels in the Unibed® effluent in previous testing. After processing a 300 ppb solution of dimethyl sulfoxide through a differential reactor for five hours, the reaction rate of ethanol and chlorobenzene was reduced by up to 50%. After running the poisoned catalyst in the presence of these same contaminants at a temperature of 270 °F, the conversion returned to within 10% of its original value. These results indicate that the effect of a poison during Stage 9 could have been reversed during Standby mode, when the reactor temperature was maintained between 160 and 210 °F for over 16 hours/day.

This data, coupled with that observed during Stage 9, suggests that the performance of the reactor catalyst may be inhibited during a process cycle due to catalyst poisoning. Catalyst poisoning would reduce the number of reaction sites, decreasing

the oxidation of the organic products (acetone, acetic acid, propionic acid) in favor of contaminants more easily oxidized (alcohols) or preferentially adsorbed. After processing is completed the temperatures maintained in the reactor during Standby would serve to "burn off" the poisons (similar to results observed by MTU with dimethyl sulfoxide), thus allowing the reactor to return to the previous day's initial performance. The catalyst poisoning could also occur as part of the oxidation of the alcohols, as was observed in the MTU data with ethanol and chlorobenzene. This poisoning, referred to as organic adsorption, occurs when any of the organics or products of oxidation are not readily desorbed, thus effectively serving as catalyst poisons by occupying catalyst sites. Again, an extended period in Standby mode at relatively high temperatures would serve to oxidize the organics, at which time they would be desorbed and flushed out of the reactor once Processing was initiated. Since the volume of the reactor is large and the alcohols are readily oxidized, the oxidation of alcohols appears to be unaffected by this degradation in performance. However, as shown in Table 5-11, acetic acid, propionic acid, and acetone are only partially oxidized during nominal operating conditions. Any performance degradation in the form of catalyst poisoning would thereby be observed by decreased conversion of these organics.

The magnitude of the TOC rise appears to be magnified by decreasing the reactor temperature. During the TOC Monitor Deletion study on Days 93-101, the relative slope of the TOC rise increased as the reactor temperature decreased. This data indicates that the reaction rate is a key parameter in the performance degradation. The lower reactor temperature would decrease conversion by slowing the reaction rate, thus decreasing the conversion of the oxidation products. The oxidation of the alcohols is mass transfer limited, therefore the lower reactor temperatures do not have a significant impact on their conversion. The testing conducted at MTU showed that ethanol levels similar to those observed during Stage 9 were completely oxidized in the reactor at 200 °F.

A total carbon balance across the reactor lends further credibility to the theory of catalyst poisoning by organic adsorption. Since carbon cannot be destroyed, the total carbon in the reactor influent must equal the total carbon in the effluent. On Test Days 93 through 101, total carbon analysis was performed on samples taken from the reactor influent and effluent. This data is summarized in Table 5-12 below. On Test Days 93, 95 and 98, a significant reduction in total carbon is observed, while on Days 97 and 100 no decrease in total carbon is observed. No other samples were pulled from the reactor influent during the test, though samples were pulled from the phase separator effluent on Days 38 and 42. Though inorganic carbon in the form of carbon dioxide will be removed in the phase separator, data on Days 93 through 101 indicates the overall reduction in total carbon across the phase separator is insignificant. Accordingly, the samples pulled from the phase separator effluent on Days 38 and 42 can be compared to the reactor influent data for a total carbon balance. This data, also provided in Table 5-12, shows a more significant decrease in total carbon across the reactor and phase separator.

83

Table 5-12. Total Carbon Levels

Test Day	Unibed Effluent (mg/l)	Reactor Effluent (mg/l)	Phase Separator Effluent (mg/l)	% Reduction (mg/l)
93	9.8	5.8	6	39
95	11	8.2	8	27
97	13	13.5	13	0
98	14	10.8	10	29
100	12	13	13	0
38	17.1		9.59	44
	15.7		9.77	38
	15.5		8.84	43
	15.3		11.21	27
42	14.4		6.34	56
	14.7		6.34	56
	16.6		9.14	45

Though inconclusive, the data indicates that either TOC or TIC may be retained in the reactor. The most likely explanation for this occurring is the adsorption of contaminants on the substrate or catalyst either before or after oxidation. The TOC would not be detected in any samples since it would be oxidized to TIC during Standby and flushed out of the reactor before any sampling occurred. The TIC would then by removed either via the phase separator as carbon dioxide or by the ion exchange bed as bicarbonate. Since the samples are only pulled periodically and the carbon dioxide and bicarbonate would be flushed out immediately upon processing, the likelihood that this phenomenon would be detected via sampling is low. This theory is not validated by the conductivity sensor WC40, which is located between the phase separator and the ion exchange bed. This sensor should measure bicarbonate as conductivity and thus detect a conductivity spike at the beginning of a processing cycle following a day where a TOC rise was observed. Though an increase in conductivity was observed on most test days, the magnitude of the increase renders the data inconclusive.

An alternative theory revolves around the mass transfer of contaminants in the catalyst substrate. The majority of oxidation reactions occurring at the catalyst sites are substantially faster than the rate at which contaminants diffuse to and from the reaction site. Accordingly, the majority of reactions are occurring at the entrance to the substrate pores, rather than in the internal pore structure. In this case, reaction products may accumulate in the film surrounding the external surface of the catalyst, creating a chemical equilibrium that limits the diffusion of reactants to the reaction sites.

On Days 89 and 90, a temperature increase of 10 °F resulted in approximately doubling the conversion of acetic acid, propionic acid and acetone. This data indicates that the conversion of these compounds is limited by their reaction rate, which is a function of temperature. If their presence in the reactor effluent becomes

an issue for the flight design, an increase in the reactor temperature could provide sufficient oxidation of these organics.

The acetic acid and propionic acid generated in the reactor are easily removed in the ion exchange bed, which contains strong base anion exchange resin for the removal of organic acids and bicarbonate. Acetone possesses no ionic characteristics; however, calculations show that it is reduced by approximately 94% between the phase separator effluent and the product water. The only component downstream of the phase separator designed for contaminant removal is the ion exchange bed, which contains IRN-78 resin for the removal of organic acids and bicarbonate. Though acetone is nonionic, experimental data has indicated that ion exchange resin has limited adsorption capacity. Acetone isotherms conducted at MTU indicated that the IRN-78 (12,775 cc) capacity for acetone (with no competition from other contaminants) is 2,900 mg. Since an estimated 200 mg of acetone passed through the bed each day, this capacity should be exceeded in less than 15 days if no other contaminants interfered with acetone adsorption. Considering the competitive effect of acetic and propionic acid and the fact that no acetone was observed breaking through the second ion exchange bed after 84 days of throughput, the likelihood of significant acetone adsorption on IRN-78 is very low.

Further calculations were performed to determine if the acetone could have volatilized into the gas phase (not removed via the phase separator). Based on Henry's Law, the calculations determined that a negligible mass of acetone could be removed by this process. Furthermore, no contaminants were identified in the reactor effluent that are known to react with acetone in order to effect its removal in the ion exchange bed. Further studies will be conducted on the ion exchange bed with acetone to determine the actual removal mechanism and to assess its impact on the WP performance.

The actual effect of the TOC rise on product water quality was not significant. Of the 105 test days operated at nominal VRA temperatures, the TOC rise exceeded the current ISS requirement of 500 ppb on 31 days. Of the 40 product water tank volumes corresponding to these days, the water quality specification was exceeded in 9 tank volumes, with the highest value being 690 ppb and the average being 480 ppb. A toxicological assessment of this data should be conducted. Further investigation should be conducted to provide an adequate understanding of the reactor performance in order to insure its acceptable performance on ISS.

Residual levels of 1-propanol were detected in the reactor effluent and product water throughout the test. These levels ranged from the detection limit for 1-propanol (<30 ppb) up to 310 ppb and appear to be a function of the level of 1-propanol in the VRA influent (Figure 5-29). This data indicates that 1-propanol, in contrast to ethanol and 2-propanol, is not completely oxidized to its primary product (propionic acid) in the reactor. Furthermore, the level of 1-propanol in the VRA effluent appears to be unaffected by the reactor temperature, whether the temperature was higher (Days 89-90) or lower (Days 93-101) than the nominal,
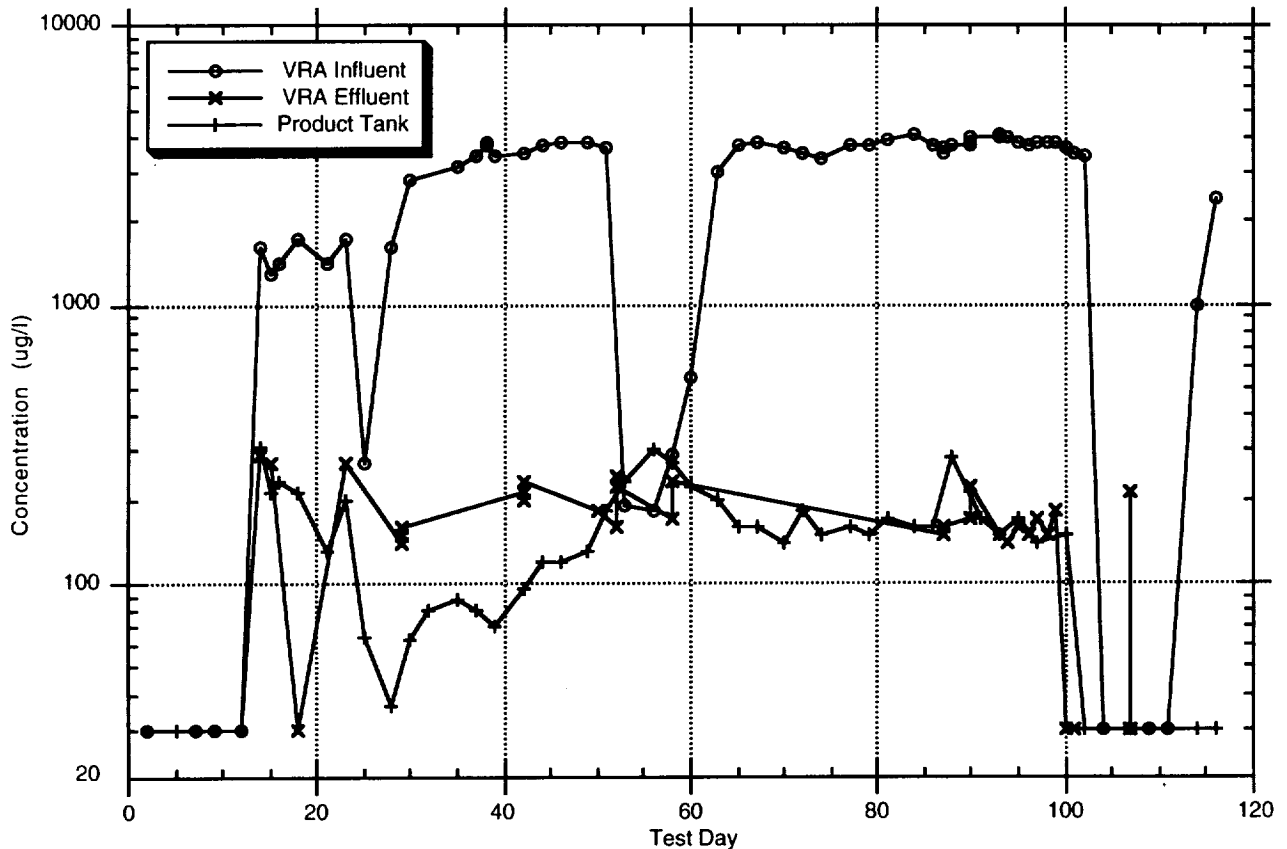
Figure 5-29. Removal of 1-propanol in the Water Processor

indicating the conversion of 1-propanol is mass transfer limited. Similarly ethanol levels, which were nominally below the detection limit in the VRA effluent, are unaffected by the lower temperatures on Days 93-101. This data concurs with the results of the reactor modeling at MTU, where small-scale reactor testing on various catalyst sizes indicated that the conversion of ethanol was also mass transfer limiting. In contrast, 2-propanol was affected by the lower reactor temperatures. During the TOC Monitor Deletion study, the concentration of 2-propanol in the VRA effluent ranged from 70 ppb at 205 °F to 310 ppb at 175 °F, compared to an effluent concentration of <40 ppb at nominal reactor temperatures. This data indicates that the conversion of 2-propanol is limited by the reaction rate on the catalyst, which is a function of temperature.

The detection of methanol and 2-propanol in the Stage 9 product water (when these contaminants were not detected in Stage 7) is not necessarily indicative of degraded water quality. During Stage 9, the detection limits developed by Boeing laboratory for several organics were lower than in previous stages. Therefore, their actual concentrations could be the same in both stages. As stated previously, methanol was suspected to be present in the product water for Stages 7, 8, and 9 due to the degradation of the resin in the ion exchange bed. Though the concentration of 2-propanol in the WP waste water was higher in Stage 9, insufficient data is provided

86

to indicate that its oxidation in the VRA did not effect a product water concentration as low as that achieved during previous tests. Considering the relative similarity between the TOC in the three stages, it is unlikely that the concentration of any specific organic detected in Stage 9 was significantly higher than those present in previous stages.

No significant difference in the WP microbial levels was observed between Stage 9 and previous test stages. The waste water microbial load was reduced from approximately 10^9 CFU/100 ml to 2×10^3 CFU/100 ml by the Unibed® media. This microbial level was effectively removed by the VRA. This data indicates that the automated delivery of waste water and the modifications to the VRA design did not adversely affect the WP's ability to reduce the waste water microbial load.

5.5.3 Conclusions and Recommendations

The most significant impact due to the Stage 9 hardware integration and automated operation was to the WP filter. The deletion of the laundry system coupled with the individual filtration of each waste stream prior to collection in the WP feed tank created a higher particulate load on the filter, thereby reducing its life below the ISS throughput requirement. 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 contaminant loading. The identical contaminant loading rates achieved in the tests indicate that a shelf life of up to 22 months has no detectable effect on the Unibed® performance.

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

The VRA phase separator did not perform well during the test. Gas was observed in samples pulled downstream of the reactor. More significantly, gas entering the PCWQM sample loop led to erroneous pH data, which subsequently affected the calculations for the pH offset and the SPA Heater Setpoint (Sections 5.4.1.5 and 5.4.1.6). Furthermore, gas entering the SPA module probably contributed to the anomalous pressure readings on Test Days 80-87. The performance of the phase separator is not a flight design issue, as the flight design phase separator has not yet been developed. However, the anomalous performance during Stage 9 emphasizes the need to develop the flight phase separator and validate its performance.

The automated operation had no apparent effect on the WP product water quality. The new VRA catalyst used in the Stage 9 test was effective at oxidizing the major contaminants as well as providing microbially sterile product water. The oxidation of acetone, acetic acid, and propionic acid (by-products of alcohol oxidation) in the reactor is of limited concern. The available test data indicates that some form of

87

catalyst poisoning is occurring in the VRA reactor to an extent that reactor performance tends to degrade over the course of a processing cycle. Inorganic contaminants known to be catalyst poisons have been detected at low concentrations in the VRA influent. However, test data generated at MTU and a total carbon balance across the reactor indicates the poison may be due to the slow desorption of the organics targeted for oxidation or their oxidation products. Since the organic acids generated in the oxidation reaction are removed in the ion exchange bed, their conversion in the reactor is of no concern. However, the generation of acetone is an issue, as it is not efficiently removed via the phase separator or the ion exchange bed resin. The disappearance of acetone downstream of the ion exchange bed cannot be explained at this time. However, if its removal is dependent on the presence of a specific contaminant in the reactor effluent or gas in the ion exchange bed, modifications to the WP design will be required to insure the consistent removal of this contaminant.

The methanol, ethanol, and trimethylamine leaching off the ion exchange bed will merit potential design modifications to minimize this phenomenon and its subsequent impact of WP water quality and control. 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.

6.0 Stage 9 Conclusions and Recommendations

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 UP. Air entrained in the pretreated urine stream created start-up difficulties for the 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 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 causes channeling which potentially reduced the life of the SPA module.

88

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 in dia.) used in the PCWQM sample loop is at great risk of particulate blockage. Since this is also the suspected cause of failure in the ECLSS Flight Experiment that utilized similar size tubing, analyses should be conducted to insure particulate contamination does not lead to a PCWQM failure. The high delta pressure anomaly could also have resulted from the presence of gas in the sample loop. Gas serves to dry the SPA resin resulting in a paste resistant to flow, thus creating a high pressure drop. The effect of gas on the SPA module and the PCWQM pH sensor emphasizes 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 contaminant loading. The identical contaminant loading rates achieved in the tests indicate that a shelf life of up to 22 months has no detectable effect on the Unibed® performance.

The VRA reactor transient temperature anomaly has been seen in all previous tests at MSFC and is 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 (PFU) per 100 ml. No viruses were detected downstream of the Unibed® train (17), indicating adsorption of the viruses by the Unibed® adsorbents. The high temperature, oxidation environment of the VRA is 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 appears to be excellent.

The automated operation had no apparent effect on the WP product water quality. Online 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

C-2

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 reactions 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 insure that the WP will be able to reliably produce water meeting the ISS water quality requirements.

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APPENDIX A

WATER RECOVERY TEST STAGE 9 CONTROL REQUIREMENT DOCUMENT

TABLE OF CONTENT

1.0 INTRODUCTION AND SCOPE

The Environmental Control and Life Support (ECLS) test program at the Marshall Space Flight Center (MSFC) is divided into phases beginning with the stand-alone ECLS subsystem bench tests (Phase I) in August, 1986. The Phase II program, which concluded in November of 1987, provided the first experience with an ECLS system that included four air revitalization and one urine processor assemblies operating in integrated fashion for periods of up to six days. The present Phase III program has expanded on the Phase II integrated test experiences by including the recovery of potable and hygiene water with man-in-the-loop. The Phase III Water Recovery Test (WRT) to date has evaluated the performance of a "dual-loop" water recovery system comprised of separate potable and hygiene water recovery subsystems operating in open-loop "donor" mode (Stages 1A, 2A, and 3A) and closed-loop "recipient mode (Stages 4 and 5). The WRT has also evaluated a "single-loop" water recovery system with one subsystem processing both hygiene and potable water waste streams in "donor" and "recipient" modes (Stages 7A and 7B) and without a pre-sterilizer (Stage 8).

The next "single-loop" test (Stage 9) will evaluate the latest water recovery system design for the United States On-Orbit Segment (USOS) of the International Space Station Alpha (ISSA) with higher fidelity hardware and integration than has been achieved in previous WRT Stages. The design and operation requirements for this test stage are defined in the Water Recovery Test and Facility Design Requirements: Water Recovery Test Stage 9. ED62 (05-94), January, 1994. This document defines the control requirements for the Water Recovery and Management (WRM) system to be tested during Stage 9.

2.0 REFERENCE DOCUMENTS

ED62 (05-94) Water Recovery Test and Facility Design Requirements: Water Recovery Test Stage 9. January, 1994.

3.0 SUBSYSTEM CONTROL DEFINITION

3.1 Water Processor

The Water Processor Shall accept ON, OFF, STANDBY, MANUAL, and SHUTDOWN commands. Figure 1 shows mode transitions of the WP. The mode commands are as follows: ON command provides automatic operation of the WP. It provides normal startup and heatup of the processor and reconfigures internal components to REJECT or PROCESS state as required based on process conditions and sensor data. OFF command mode shuts down the processor (usually for an extended period of time) in an orderly manner. STANDBY command mode maintains the processor in a "ready to run" state by

maintaining heater control. SHUTDOWN command shuts down the processor - usually for a short period of time. This command reconfigures the valves to isolate the processor. MANUAL command mode allows for manual activation of internal components while the processor is essentially in SHUTDOWN conditions. The MANUAL mode can only be accessed from the OFF mode and is manually selected.
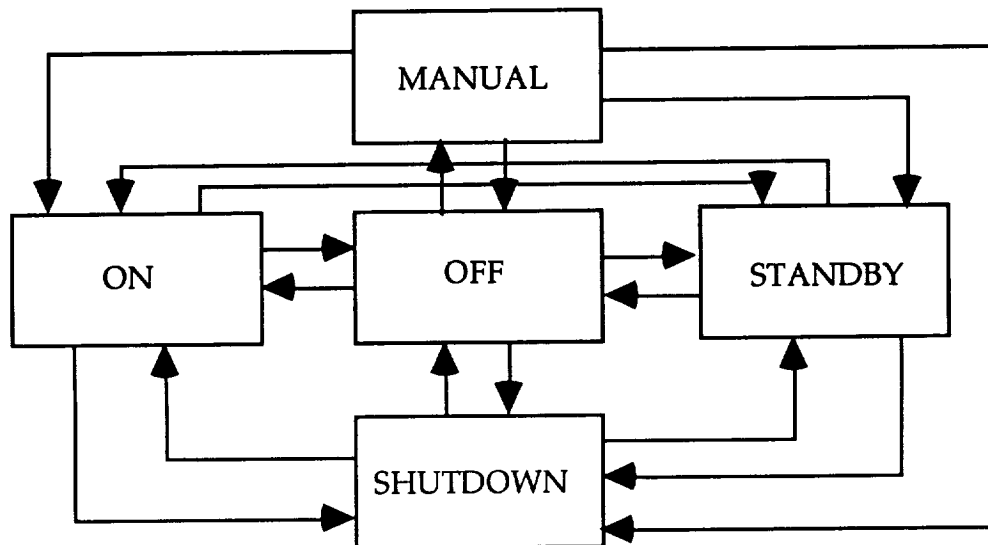
Figure 1. Water Processor Transition Diagram

Each mode has its own state commands that can be automatically selected or manually selected while the processor is in a certain mode. For example, in the ON mode, HEATUP, PROCESS, STANDBY, REJECT, FAIL/SHUTDOWN (F/S), or FAIL commands may be automatically selected by the controller as part of the normal control process or may be manually selected.

3.2 Process Control Water Quality Monitor

The Process Control Water Quality Monitor (PCWQM) has 8 operational modes. Figure 2 shows mode transitions of the PCWQM. The USER mode command places the PCWQM in manual operation. The STANDBY mode command brings all the sensors and effectors on-line with the exception of the UV lamp, pump, and isolation valves. The RECIRCULATE mode command flows water through the recirculation loop with the UV lamp on to measure background TOC levels and verifies that the TIC gas liquid separator is performing properly. The CALIBRATE mode command calibrates the pH sensor and verifies the operation of the TOC sensor. The NORM OP mode command allows the PCWQM to analyze the product water of the WP. The STOP mode command is a transition mode which place the PCWQM in STANDBY mode conditions. The OFF mode pulls power to the PCWQM. The OFF mode can be reached from all other

only for transition to
recirculation or
calibration mode

```
Off → Standby
Standby ↔ Calibrate (once/week)
Standby ↔ User
Recirculate (once/24 hrs)
User ↔ Norm Op
```

Override   Stop

| PCWQM can transition from any mode to
| Override, Stop, or Off. This is considered an
| unusual, yet allowable, transition.
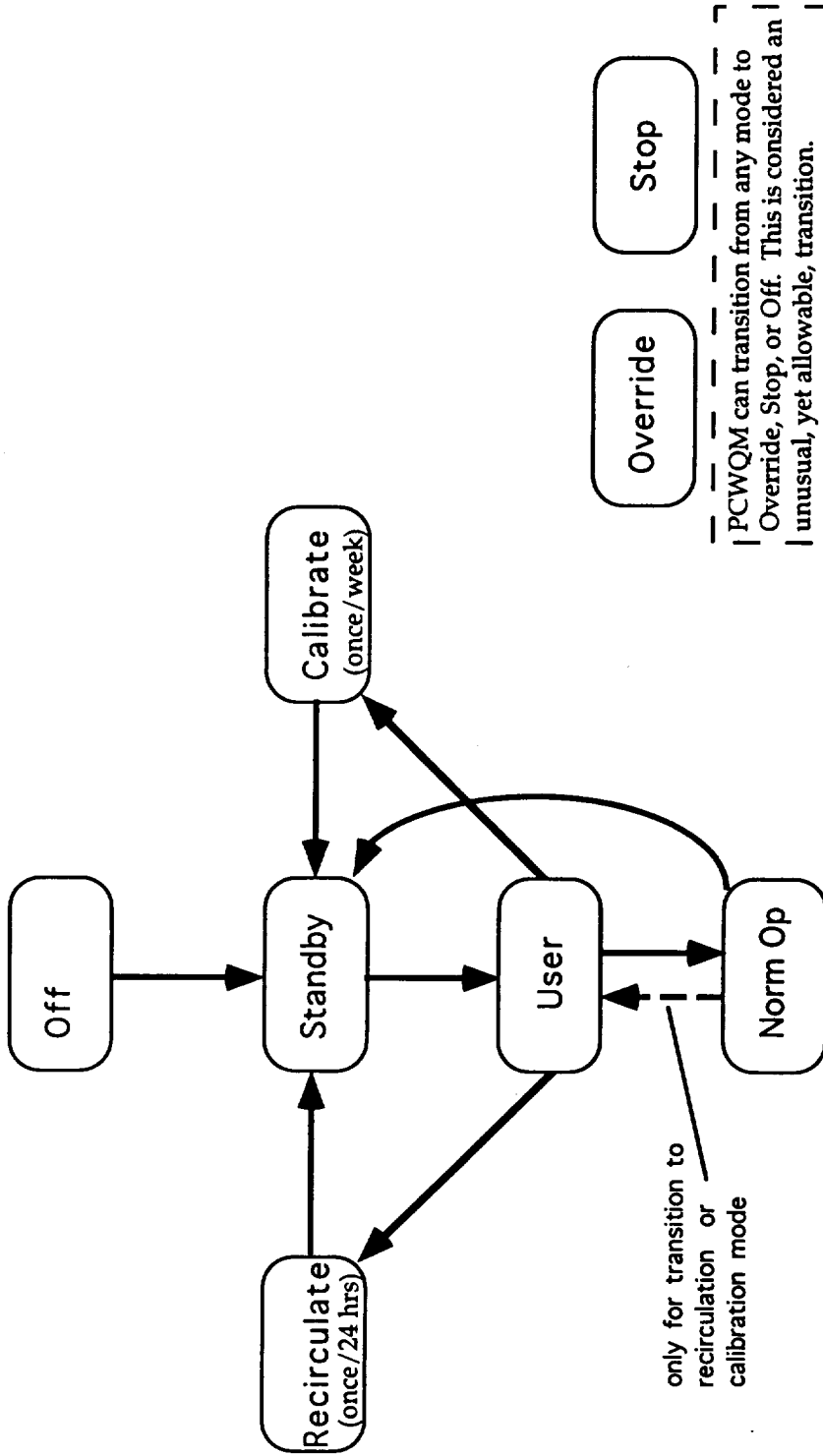
The PCWQM will transition into Standby mode when initially turned on. If an Override command is used, PCWQM will transition to Standby mode once Override is complete. When Recirculate or Calibrate mode is required, the System Software will transition the PCWQM from Standby to User mode and then to Recirculate or Calibrate. The PCWQM will automatically return to Standby once the mode sequence is complete. If the elapsed wait time for Recirculation or Calibration occurs during Norm Op, the System Software will transition the PCWQM directly to User and then to Recirculate or Calibrate from Norm Op. Once complete, the PCWQM will transition automatically to Standby mode. The System Software will transition the PCWQM from Standby to User to Norm Op when the WP is in Process mode. Once the WP transitions to Standby, the System Software will transition the PCWQM to Standby mode. In summary, the PCWQM will only transition from Standby to Norm Op and from Norm Op or Standby to Recirculate or Calibrate when requested by the System Software, each time going through User mode.

Figure 2:   PCWQM Mode Transitions

A-7

operational modes. The OVERRIDE mode allows the individual control of the PCWQM effectors.

3.3 Urine Processor

The UP shall accept OFF, SHUTDOWN, STANDBY, and NORMAL mode commands. Figure 3 shows mode transitions of the UP. The NORMAL command shall cause the UP to accept and process pretreated urine. The SHUTDOWN command shall result in a graceful shutdown of the system where no processing occurs and pretreated urine cannot be accepted. The STANDBY command shall cause the processor to enter a state where the pretreated urine storage tank can accept urine, but no processing occurs. If the pretreated urine storage tank (TK1) becomes full, the UP will automatically transition to NORMAL mode.
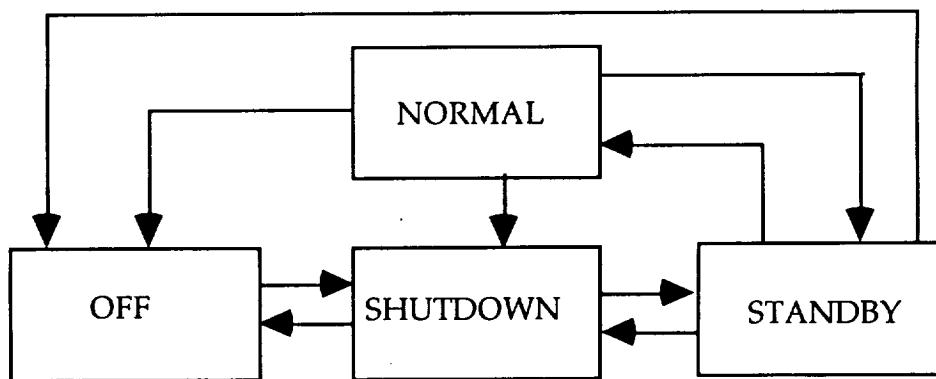
Figure 3. Urine Processor Transition Diagram

3.4 Urinal

There is no computer control interface between the Urinal and the system controller. The Urinal has an ON mode and an OFF mode which is commanded manually. The WRM system controller will give alarms that indicate when the urinal must be manually commanded from a mode.

3.5 Fuel Cell Tank

The Fuel Cell Tank shall accept an ON and OFF mode command. ON command mode allows the system controller to deliver fuel cell water to the WP if all operating conditions are met. The OFF mode command deactivates the Fuel Cell Tank.

3.6 End-use Equipment

3.6.1 Shower

The shower is not required to be controlled automatically from the system controller. The WP will isolate its Product Water Storage Tanks if there is insufficient water to start or complete a shower. If this occurs, an alarm shall be required to indicate use of the shower is prohibited.

3.6.2 Handwasher

The handwasher is not required to be controlled automatically from the system controller. The WP will isolate its Product Water Storage Tanks if there is insufficient water to start or complete a handwash. If this occurs, an alarm shall be required to indicate use of the handwasher is prohibited.

3.7 Waste Water Sources

3.6.1 Shower Waste Water

The transfer of shower waste water to the WP waste water storage tank shall be controlled by the system controller to prevent deadheading the pump. The WP will isolate its waste water storage tank if it is full. If this occurs, an alarm shall be required to indicate use of the shower is prohibited.

3.6.2 Handwash Waste Water

The transfer of handwash waste water to the WP waste water storage tank shall be controlled by the system controller to prevent deadheading the pump. The WP will isolate its waste water storage tank if it is full. If this occurs, an alarm shall be required to indicate use of the handwasher is prohibited.

3.6.3 EEF Humidity Condensate

The transfer of EEF Humidity Condensate to the WP waste water storage tank shall be controlled by the system controller to prevent deadheading the pump. The WP will isolate its waste water storage tank if it is full. If this occurs, an alarm shall be required to indicate that the transfer of condensate has stopped.

3.6.4 Animal Humidity Condensate

The transfer of Animal Humidity Condensate to the WP waste water storage tank shall be controlled by the system controller to prevent deadheading the pump. The WP will isolate its waste water storage tank if it is full. If this occurs, an alarm shall be required to indicate that the transfer of condensate has stopped.

4.0 WRM SYSTEM CONTROL DEFINITION

The water recovery system will include Fuel Cell Tank, UP, WP, PCWQM interfaced through storage and distribution assemblies and components, to end-use equipment items. Figure 4 shows the major system assemblies and the functional design concept.

4.1 System Definition

System level control of the WRM shall include but not be limited to the following:

a. Supervisory control during the transition between any two steady state operating modes such that it is conducted in a smooth and orderly fashion.

b. Ensure that the resulting steady state operating mode of each subsystem at the end of a system transition is appropriate for the system operating mode.

4.2 Steady State Modes

The system shall have four steady state operating modes:

a. OFF - In the OFF mode power is not applied to any WRM equipment

b. SHUTDOWN - The SHUTDOWN mode is characterized by power consumption by sensors only and lack of processing by the system.

c. STANDBY - In the STANDBY mode, the subsystems shall be at operating conditions with power applied but not processing.

d. PROCESS - In the PROCESS mode, the Subsystems can process wastewater if operating conditions are acceptable.

e. MANUAL - In the MANUAL mode, the subsystems can be transitioned to any operational mode manually for troubleshooting.

Table 1 shows the subsystem modes which correspond with the Integrated system operating modes. MANUAL mode is not shown in the table since each subsystem can be in any of its operational modes while the system is in MANUAL mode.
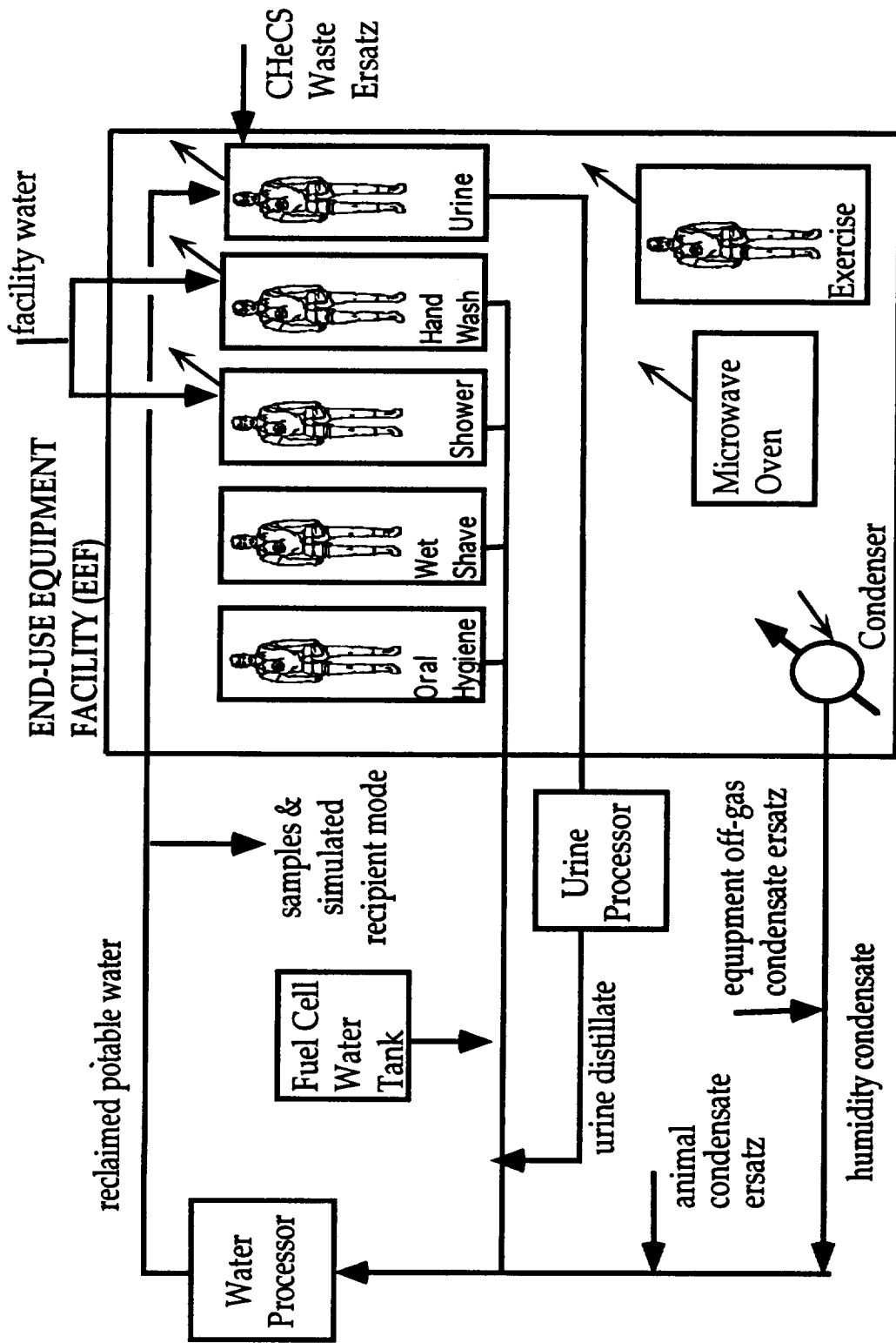
Figure 4. Stage 9 Simplified Functional Schematic

Table 1. WRT Stage 9 WRM System/Subsystem Operational Modes

SUBSYSTEM	WRM INTEGRATED SYSTEM MODES			
	OFF	SHUTDOWN	STANDBY	PROCESS
WP	OFF	IMMEDIATE SHUTDOWN	STANDBY	ON
PCWQM	OFF	STANDBY/ RECIR/CAL/ INITIALIZE	STANDBY/ RECIR/CAL/ INITIALIZE	all modes except OFF
UP	OFF	STANDBY	STANDBY	NORMAL/ STANDBY/ SHUTDOWN
Urinal	OFF	OFF	OFF	ON/OFF
Fuel Cell Tank	OFF	OFF	ON/OFF	ON/OFF

4.2.1 Mode Transitions

Figure 5 shows the allowed mode transitions for the WRM system. Figure 6 through 14 define the control steps necessary to complete the 9 mode transitions shown in Figure 5.

4.2.2 OFF Mode

In the OFF mode, the system controller is not required to monitor or control any equipment since all WRM equipment is in an unpowered condition.

4.2.3 SHUTDOWN Mode

In SHUTDOWN mode, the system controller must monitor sensors and actively control the PCWQM recirculation and auto calibration sequence while it is in STANDBY mode. Figure 15 shows a flow diagram that defines the control provided to the PCWQM during WRM SHUTDOWN mode.

4.2.4 STANDBY Mode

In STANDBY mode, the system controller must actively control the Fuel Cell water tank, the PCWQM, and the Shower wastewater, Handwash wastewater, animal condensate, and the EEF humidity condensate deliver systems. The system controller must monitor and control the WP Waste Water Storage (WWS) Tank and Product Water Storage (PWS) Tank configurations and control the input and deliver from and to the equipment end-items in the EEF. Figure 16 shows a flow diagram that defines the control provided to the WP tanks and equipment end-items during STANDBY mode. The input of Fuel Cell water

A-12
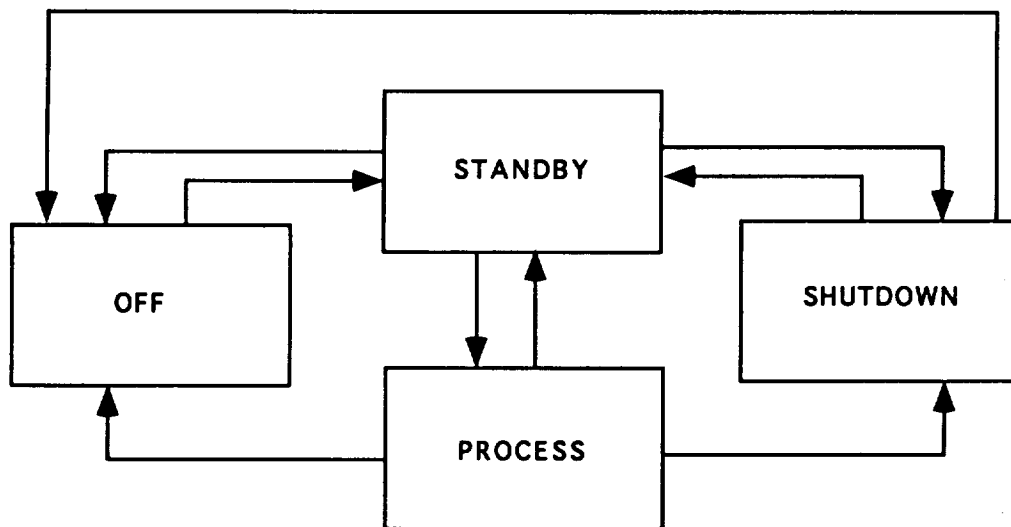
Figure 5. System Mode Transitions

```
                    ┌─────────────┐
                    │    Start    │
                    └─────────────┘
                           │
                           ▼
                 ┌──────────────────┐
                 │ Command  WP  to  │
                 │ STANDBY   mode   │
                 └──────────────────┘
                           │
                           ▼
                         ╱╲
                        ╱  ╲
                       ╱    ╲
                      ╱ Is WP╲
                     ╱ in     ╲
                    ╱ STANBY   ╲   no
                    ╲ mode     ╱──────────►
                     ╲STANDBY ╱
                      ╲state? ╱
                       ╲    ╱
                        ╲  ╱
                         ╲╱
                       yes│
                          ▼
                 ┌──────────────────┐
                 │ Command  Fuel Cell│
                 │ tank to ON mode  │
                 └──────────────────┘
                          │
                          ▼
        ┌──────────────────────────────────┐
        │ Start:      Shower - Go          │
        │             Handwasher - Go      │
        │             EFF Condensate       │
        │             Animal Condensate    │
        └──────────────────────────────────┘
                          │
                          ▼
                 ┌──────────────────┐
                 │ Transition  WRM to│
                 │ STANDBY   mode   │
                 └──────────────────┘
                          │
                          ▼
                    ┌─────────────┐
                    │    End      │
                    └─────────────┘
```
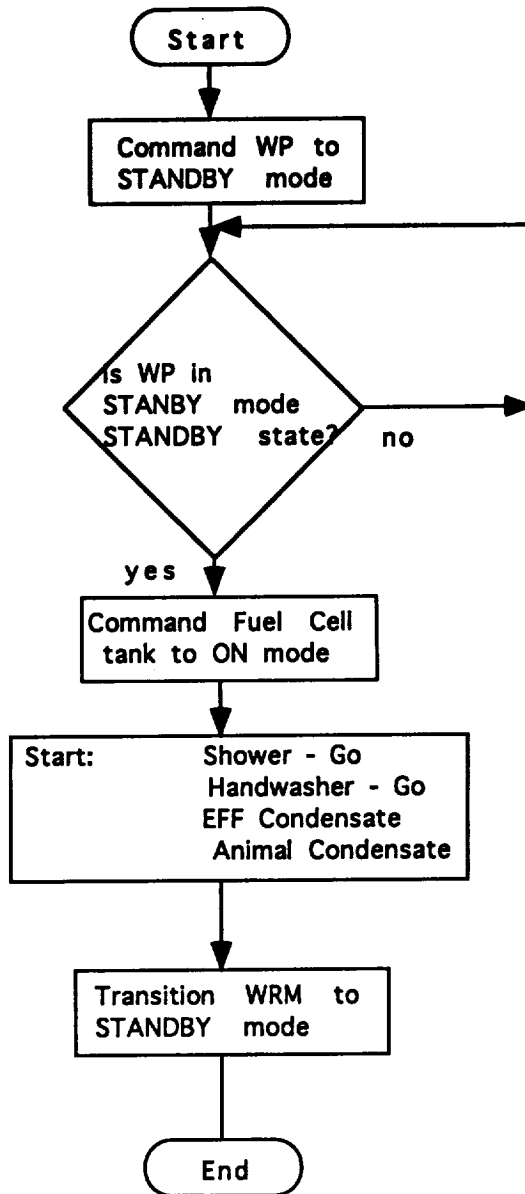
Figure 6.   System Mode Transition - SHUTDOWN to STANDBY
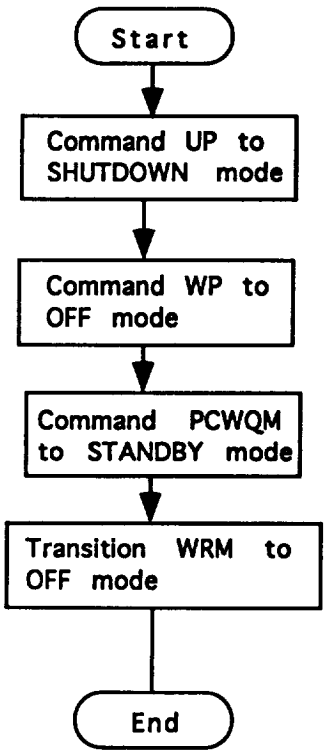
Figure 7. System Mode Transition - SHUTDOWN to OFF
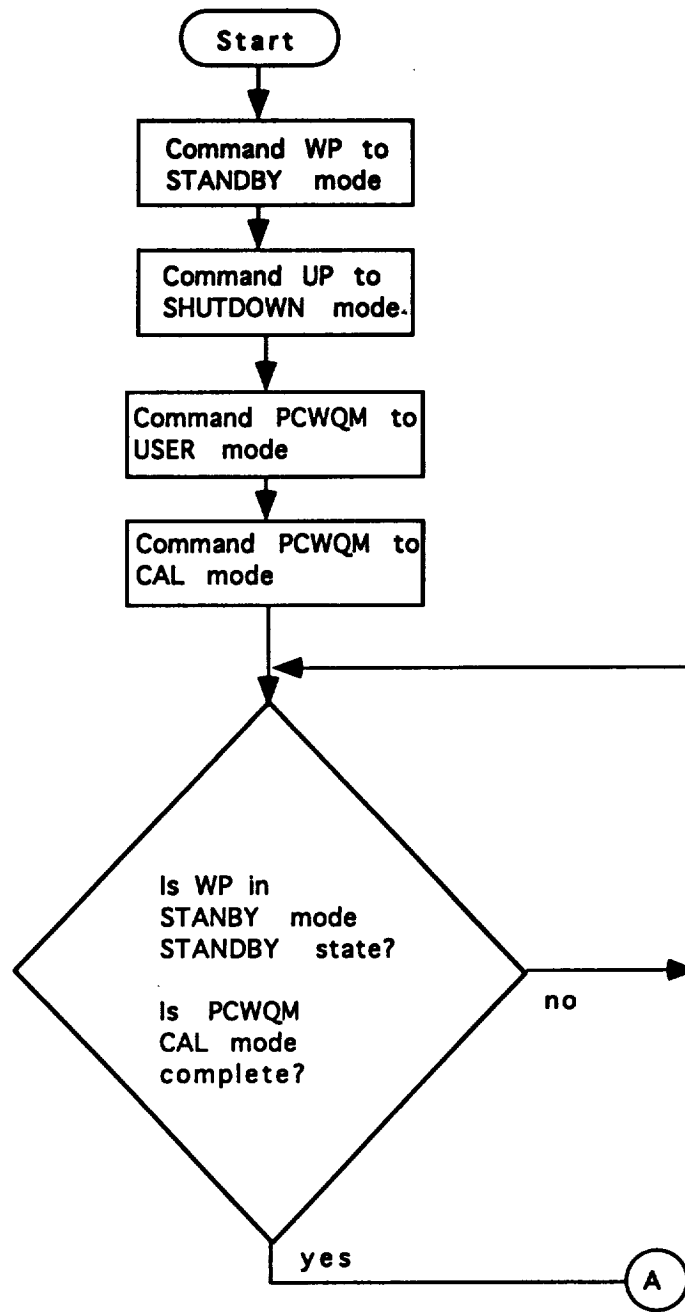
Figure 8. System Mode Transition - OFF to STANDBY

```
   ┌──────────────────┐      ┌──────────────────┐
A→ │ Command PCWQM to │ ───→ │ Command PCWQM to │ ←┐
   │ USER  mode       │      │ RECIR  mode      │  │
   └──────────────────┘      └──────────────────┘  │
                                      │             │
                                      ▼             │
                                  ◇ Is PCWQM ◇      │
                                  ◇ RECIR mode ◇ ──→┘  no
                                  ◇ complete? ◇
                                      │
                                    yes
                                      ▼
                             ┌──────────────────┐
                             │ Command Fuel Cell│
                             │ tank to ON mode  │
                             └──────────────────┘
                                      │
                                      ▼
                   ┌───────────────────────────────────┐
                   │ Start:     Shower - Go            │
                   │            Handwasher - Go        │
                   │            EFF Condensate         │
                   │            Animal Condensate      │
                   └───────────────────────────────────┘
                                      │
                                      ▼
                             ┌──────────────────┐
                             │ Transition  WRM to│
                             │ STANDBY   mode    │
                             └──────────────────┘
                                      │
                                  ( End )
```
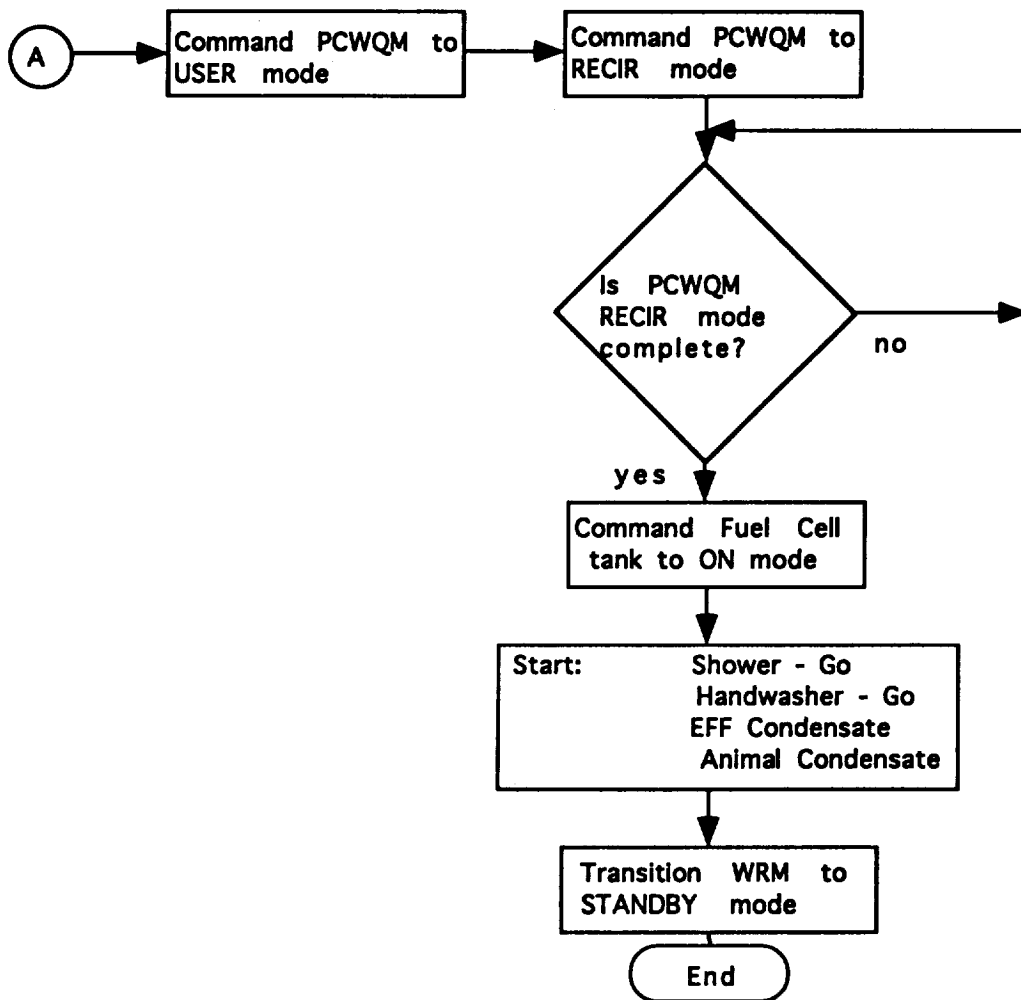
Figure 8.   System Mode Transition - OFF to STANDBY (continued)

```
                    ┌─────────────┐
                    │    Start    │
                    └──────┬──────┘
                           │
                           ▼
              ┌────────────────────────┐
              │ Command  Fuel  Cell     │
              │ tank  to  OFF  mode     │
              └────────────┬───────────┘
                           │
                           ▼
        ┌─────────────────────────────────────┐
        │ Shutdown:  Shower  -  No  Go         │
        │            Handwasher - No Go        │
        │            EFF Condensate            │
        │            Animal  Condensate        │
        └──────────────────┬──────────────────┘
                           │
                           ▼
              ┌────────────────────────┐
              │ Command  UP  to         │
              │ SHUTDOWN   mode         │
              └────────────┬───────────┘
                           │
                           ▼
              ┌────────────────────────┐
              │ Command  WP  to         │
              │ OFF  mode               │
              └────────────┬───────────┘
                           │
                           ▼
              ┌────────────────────────┐
              │ Command  PCWQM  to      │
              │ STANDBY   mode          │
              └────────────┬───────────┘
                           │
                           ▼
              ┌────────────────────────┐
              │ Transition  WRM  to     │
              │ OFF  mode               │
              └────────────┬───────────┘
                           │
                           ▼
                    ┌─────────────┐
                    │    End      │
                    └─────────────┘
```
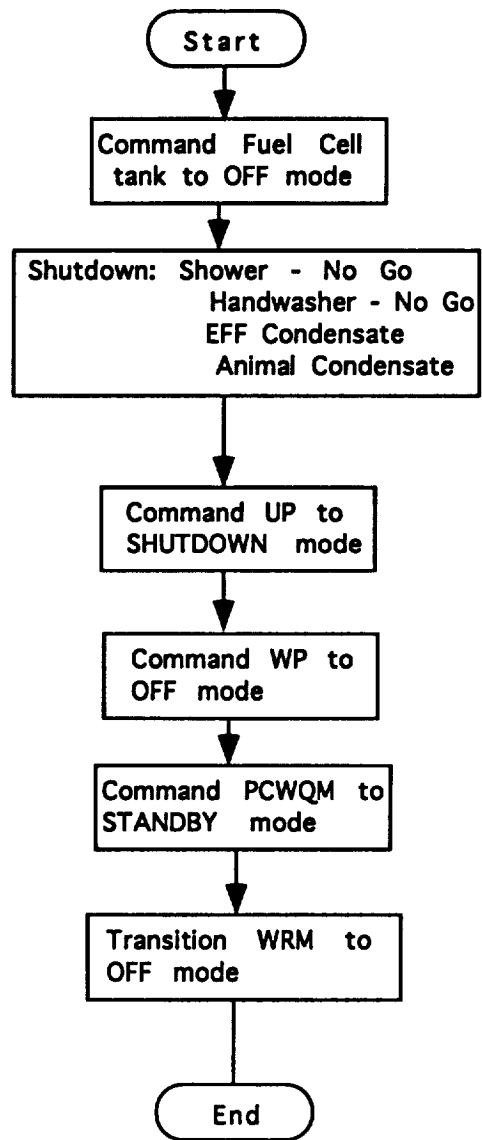
Figure 9.   System Mode Transition - STANDBY to OFF

A-18

```
        ┌──────────┐
        │   Start  │
        └──────────┘
             │
             ▼
   ┌─────────────────────┐
   │ Command  Fuel  Cell │
   │ tank  to  OFF  mode │
   └─────────────────────┘
             │
             ▼
 ┌───────────────────────────────┐
 │ Shutdown:  Shower  -  No  Go  │
 │            Handwasher - No Go │
 │            EFF Condensate     │
 │            Animal Condensate  │
 └───────────────────────────────┘
             │
             ▼
   ┌─────────────────────┐
   │ Command  WP  to     │
   │ OFF  mode           │
   └─────────────────────┘
             │
             ▼
   ┌─────────────────────┐
   │ Transition   WRM  to│
   │ SHUTDOWN   mode     │
   └─────────────────────┘
             │
             ▼
        ┌──────────┐
        │   End    │
        └──────────┘
```
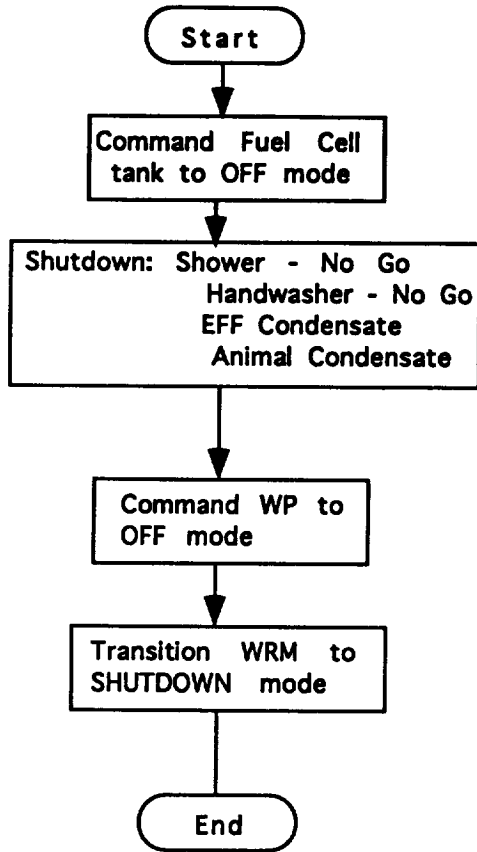
Figure 10.   System Mode Transition - STANDBY to SHUTDOWN

Figure 11.   System Mode Transistion- STANDBY to PROCESS

```
                    ┌─────────────┐
                    │    Start    │
                    └─────────────┘
                           │
                           ▼
                 ┌───────────────────┐
                 │ Command  Fuel  Cell│
                 │ tank  to  OFF  mode│
                 └───────────────────┘
                           │
                           ▼
         ┌──────────────────────────────────┐
         │ Shutdown:  Shower  -  No  Go      │
         │            Handwasher  -  No  Go  │
         │            EFF  Condensate        │
         │            Animal  Condensate     │
         └──────────────────────────────────┘
                           │
                           ▼
               ┌──────────────────────┐
               │ Command    Urinal     │
               │ to  OFF  mode  -  No  Go│
               └──────────────────────┘
                           │
                           ▼
               ┌──────────────────────┐
               │ Command  UP  to       │
               │ SHUTDOWN   mode       │
               └──────────────────────┘
                           │
                           ▼
               ┌──────────────────────┐
               │ Command  WP  to       │
               │ OFF  mode             │
               └──────────────────────┘
                           │
                           ▼
               ┌──────────────────────┐
               │ Command  PCWQM  to    │
               │ STANDBY   mode        │
               └──────────────────────┘
                           │
                           ▼
               ┌──────────────────────┐
               │ Transition  WRM  to   │
               │ OFF  mode             │
               └──────────────────────┘
                           │
                           ▼
                    ┌─────────────┐
                    │     End     │
                    └─────────────┘
```
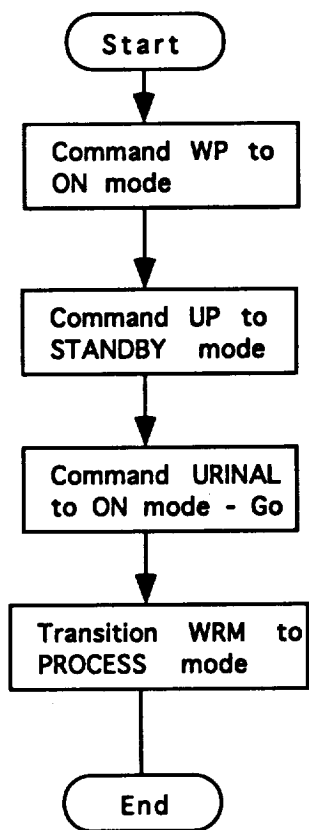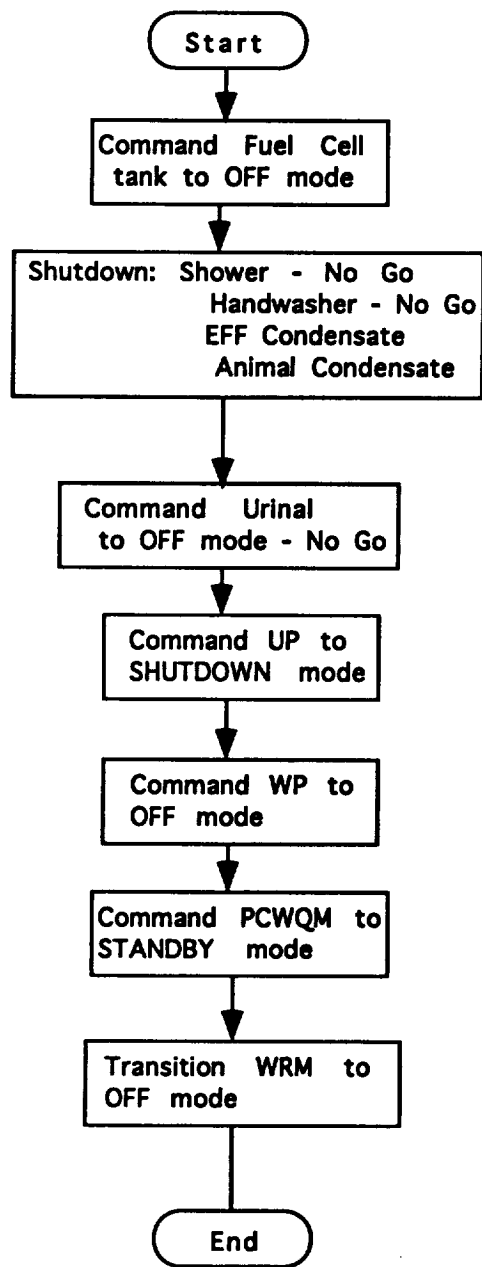
Figure 12.   System Mode Transition - PROCESS to OFF

```
                    ╭─────────╮
                    │  Start  │
                    ╰────┬────╯
                         │
                         ▼
              ┌────────────────────┐
              │ Command  Fuel  Cell│
              │ tank  to  OFF  mode│
              └─────────┬──────────┘
                        │
                        ▼
        ┌──────────────────────────────────┐
        │ Shutdown:  Shower  -  No  Go     │
        │            Handwasher  -  No  Go │
        │            EFF  Condensate       │
        │            Animal  Condensate    │
        └────────────────┬─────────────────┘
                         │
                         ▼
              ┌────────────────────────┐
              │ Command    Urinal      │
              │ to  OFF  mode  -  No Go│
              └───────────┬────────────┘
                          │
                          ▼
              ┌──────────────────────┐
              │ Command  UP  to      │
              │ SHUTDOWN   mode      │
              └──────────┬───────────┘
                         │
                         ▼
              ┌──────────────────────┐
              │ Command  WP  to      │
              │ OFF  mode            │
              └──────────┬───────────┘
                         │
                         ▼
              ┌──────────────────────┐
              │ Command   PCWQM      │
              │ to  STANDBY  mode    │
              └──────────┬───────────┘
                         │
                         ▼
              ┌──────────────────────┐
              │ Transition  WRM  to  │
              │ SHUTDOWN  mode       │
              └──────────┬───────────┘
                         │
                         ▼
                    ╭─────────╮
                    │   End   │
                    ╰─────────╯
```
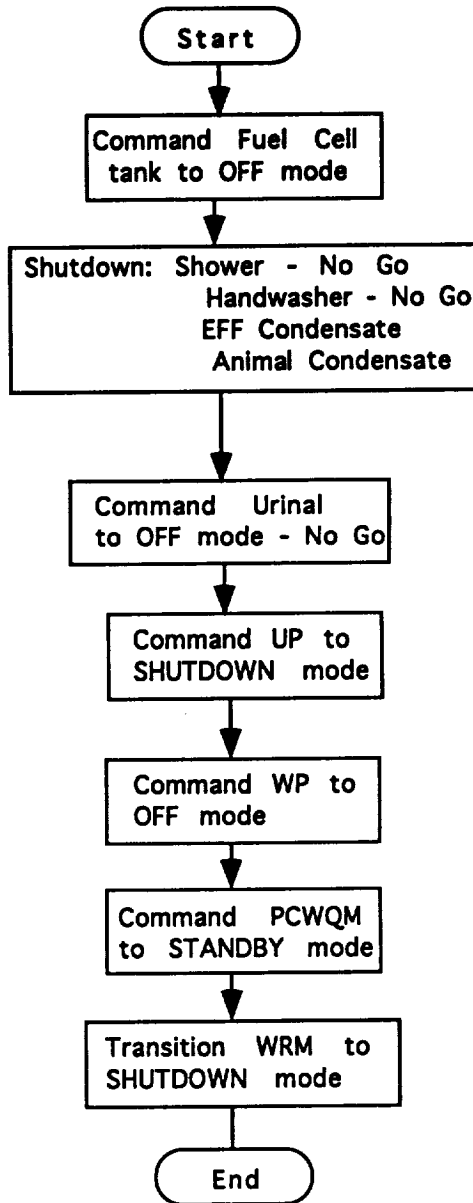
Figure 13. System Mode Transition - PROCESS to SHUTDOWN

```
                    ┌─────────────┐
                    │    Start    │
                    └──────┬──────┘
                           │
                           ▼
        ┌──────────────────────────────────┐
        │  Command  URINAL                 │
        │  to OFF mode - No Go             │
        └──────────────────┬───────────────┘
                           │
                           ▼
        ┌──────────────────────────────────┐
        │  Command  UP  to                 │
        │  SHUTDOWN  mode                  │
        └──────────────────┬───────────────┘
                           │
                           ▼
        ┌──────────────────────────────────┐
        │  Command  WP  to                 │
        │  STANDBY  mode                   │
        └──────────────────┬───────────────┘
                           │
                           ▼
        ┌──────────────────────────────────┐
        │  Command  PCWQM                  │
        │  to STANDBY  mode                │
        └──────────────────┬───────────────┘
                           │
                           ▼
        ┌──────────────────────────────────┐
        │  Transition  WRM  to             │
        │  STANDBY  mode                   │
        └──────────────────┬───────────────┘
                           │
                    ┌──────▼──────┐
                    │    End      │
                    └─────────────┘
```
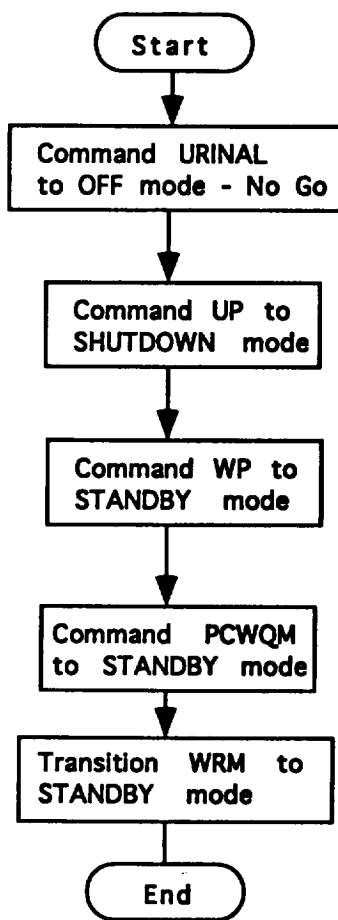
Figure 14.   System Mode Transistion- PROCESS to STANDBY
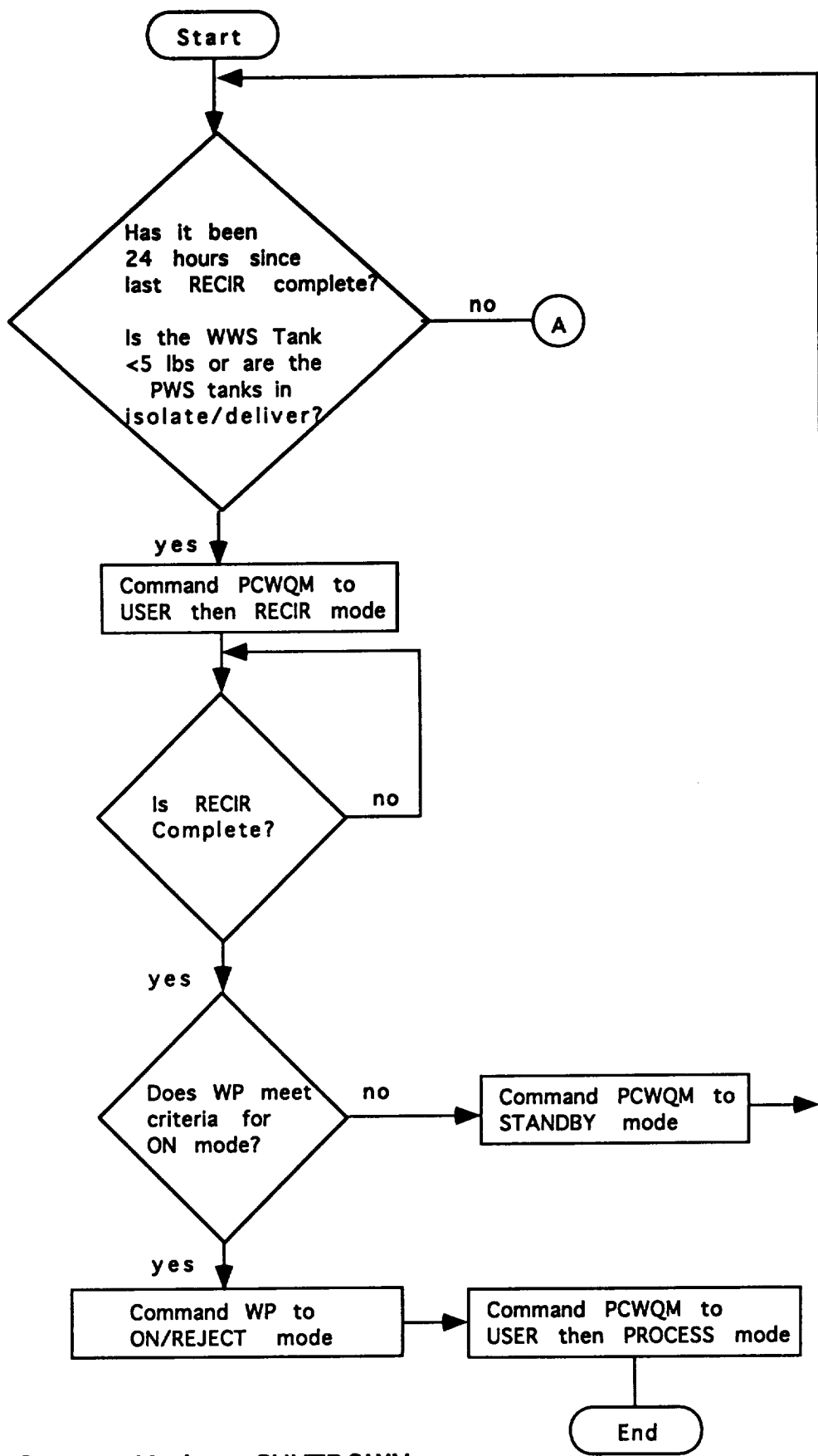
Figure 15. System Mode - SHUTDOWN

PCWQM

A-24
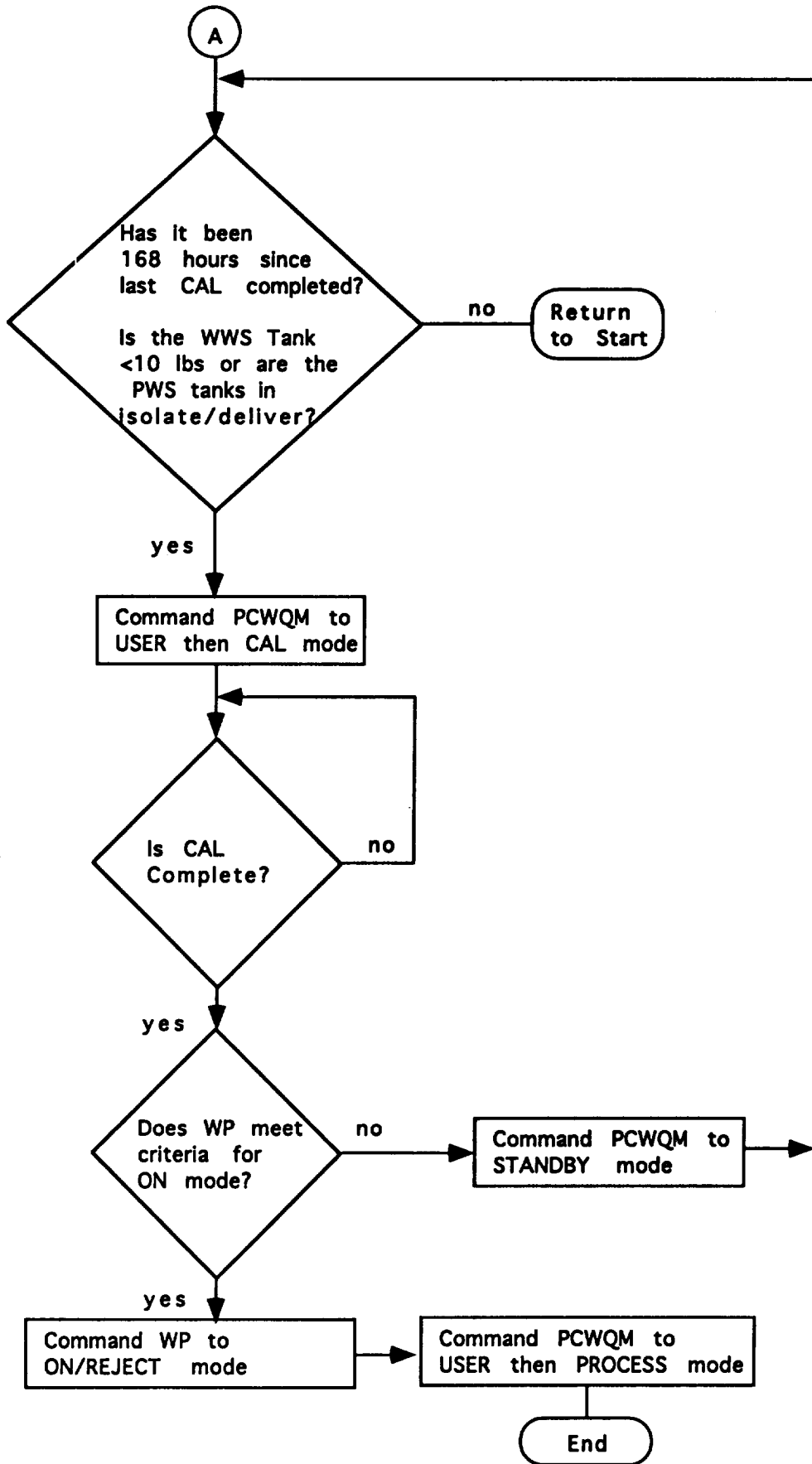
Figure 15. System Mode - SHUTDOWN (continued)

PCWQM   A-25

Start

Is WWS Tank configured to accept water? — **yes** →

Is a PWS Tank configured to deliver water? — **no** → **B**

no ↓

Is Fuel Cell Tank in OFF mode?

Is shower, Handwasher Animal Condensate EEF Humidity Condensate shutdown? — **yes** →

yes ↓ (PWS)

Is Fuel Cell Tank in ON mode?

Is shower, Handwasher Animal Condensate EEF Humidity Condensate on? — **yes** →

no ↓

Command Fuel Cell Water Tank to OFF mode

Shutdown: Shower - No Go
        Handwasher - No Go
        animal condensate
        EEF humidity condensate

no ↓

Command Fuel Cell Water Tank to ON mode

Start: Shower - Go
        Handwasher - Go
        animal condensate
        EEF humidity condensate

A

Figure 16.   System Mode - STANDBY

Water Management

A-26

Figure 16.   System Mode - STANDBY (continued)

Water   Management
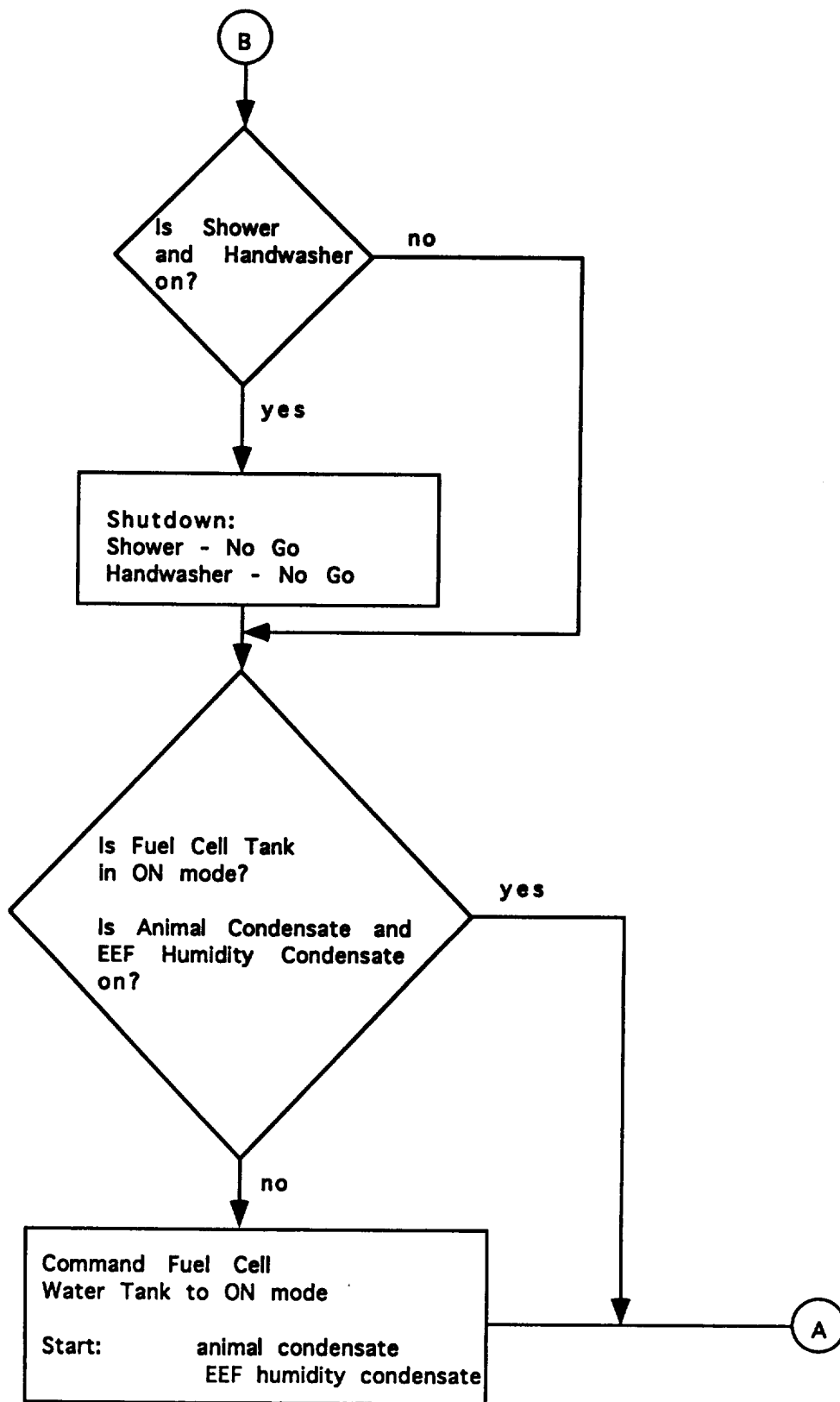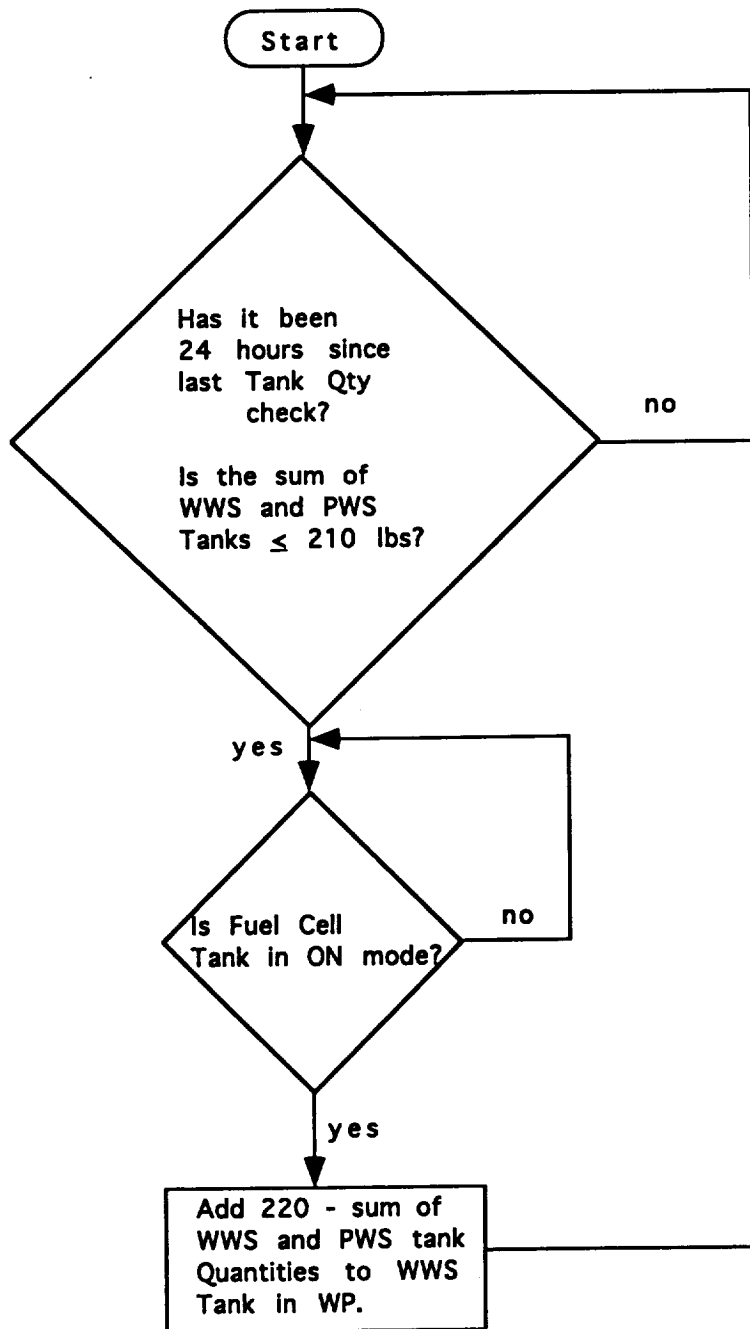
Figure 17. System Mode - STANDBY

Fuel Cell Tank

A-28

```
                    ┌─────────┐
                    │  Start  │◄──────────────────────────────────┐
                    └────┬────┘                                    │
                         │                                         │
                         ▼                                         │
                       ╱   ╲                                       │
                      ╱     ╲                                      │
                     ╱       ╲                                     │
                    ╱  Has it  ╲                                   │
                   ╱ been        ╲                                 │
                  ╱ 24 hours since ╲         no    ┌───┐           │
                 ╱ last RECIR complete╲───────────►│ A │           │
                ╱                       ╲          └───┘           │
                ╲ Is the WWS Tank       ╱                         │
                 ╲ <5 lbs or are the   ╱                          │
                  ╲ PWS tanks in      ╱                           │
                   ╲ isolate/deliver?╱                            │
                    ╲               ╱                             │
                     ╲             ╱                              │
                      ╲           ╱                               │
                       ╲    │    ╱                                │
                        ╲   │   ╱                                 │
                         ╲  │  ╱                                  │
                           yes                                    │
                            │                                     │
                            ▼                                     │
              ┌──────────────────────────┐                       │
              │ Command  PCWQM  to       │                       │
              │ USER  then  RECIR  mode  │                       │
              └────────────┬─────────────┘                       │
                           │        ┌──────────────┐             │
                           ▼        │              │             │
                         ╱   ╲      │              │             │
                        ╱     ╲     │              │             │
                       ╱       ╲    │              │             │
                      ╱  Is RECIR╲  no             │             │
                     ╱  Complete? ╲─┘              │             │
                      ╲           ╱                │             │
                       ╲         ╱                 │             │
                        ╲   │   ╱                  │             │
                          yes                      │             │
                           │                       │             │
                           ▼                       │             │
                         ╱   ╲                     │             │
                        ╱     ╲                    │             │
                       ╱       ╲    no  ┌──────────────────────┐ │
                      ╱ Does WP  ╲──────►│ Command  PCWQM  to  │ │
                     ╱  meet       ╲     │ STANDBY   mode      │─┘
                     ╲  criteria for╱    └──────────────────────┘
                      ╲ ON mode?   ╱
                       ╲         ╱
                        ╲   │   ╱
                          yes
                           │
                           ▼
         ┌──────────────────────────┐   ┌──────────────────────────┐
         │ Command WP to            │──►│ Command  PCWQM  to        │
         │ ON/REJECT    mode        │   │ USER then PROCESS  mode   │
         └──────────────────────────┘   └────────────┬─────────────┘
                                                      │
                                                      ▼
                                                 ┌─────────┐
                                                 │   End   │
                                                 └─────────┘
```
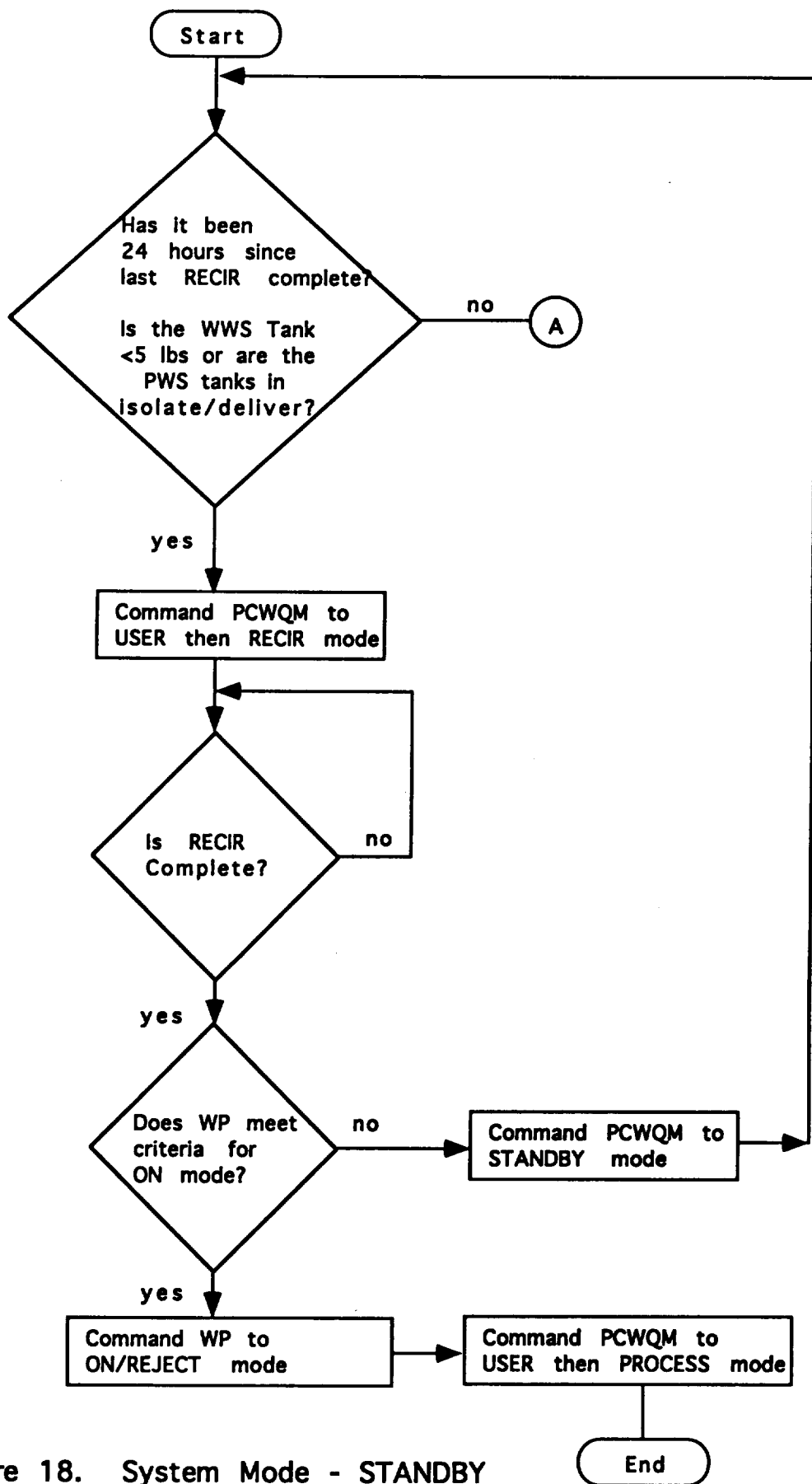
Figure 18.   System Mode - STANDBY

PCWQM   A-29

(A)

Has it been
168 hours since
last CAL completed?

Is the WWS Tank
<10 lbs or are the
PWS tanks in
isolate/deliver?

no → Return to Start

yes ↓

Command PCWQM to
USER then RECIR mode

Is CAL
Complete?

no

yes ↓

Does WP meet
criteria for
ON mode?

no → Command PCWQM to
STANDBY mode

yes ↓

Command WP to
ON/REJECT mode

→ Command PCWQM to
USER then PROCESS mode

End
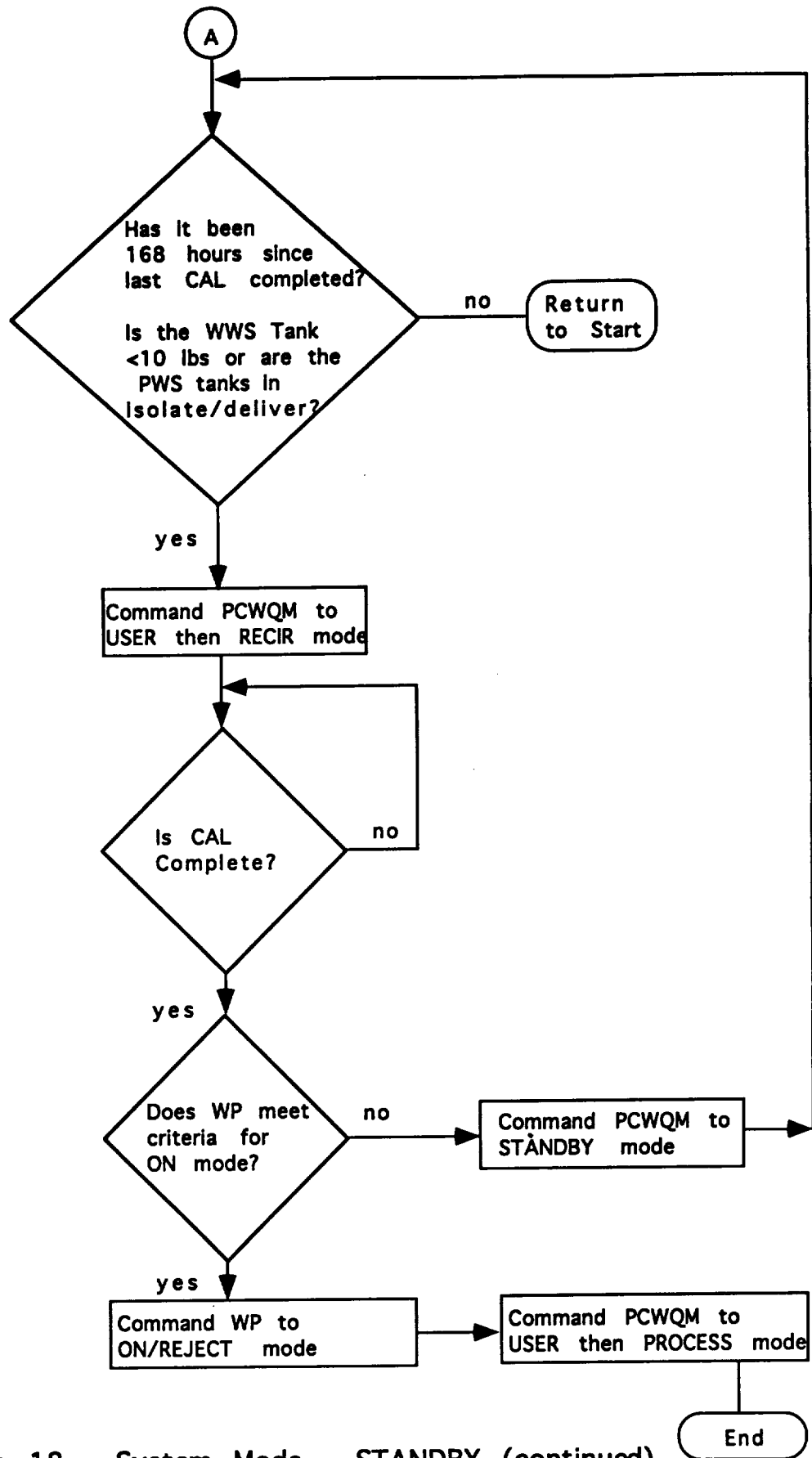
Figure 18. System Mode - STANDBY (continued)

PCWQM A-30

must be actively controlled during Standby mode and Figure 17 shows the control logic to be used. Figure 18 shows the control logic for the PCWQM auto calibration sequence while the WRM system is in STANDBY mode.

4.2.5 PROCESS Mode

In PROCESS mode, all active control that was provided in STANDBY mode must be provided with additional WP and PCWQM control. During WRM PROCESS mode, the UP operational mode must be controlled based on the configuration of the WP Waste Water Storage Tank and the Urinal must be controlled based on the UP feed tank (TK1). Figure 19 shows how the tanks, UP, Urinal, and equipment end-items will be managed during PROCESS mode. The added WP and PCWQM control will coordinate the operational modes of the PCWQM with the appropriate operational state of the WP. The system controller will also analyze the data generated by the PCWQM and command the WP to the appropriate operational state based on the analysis. Figure 20 and 21 shows the required WP and PCWQM control logic for the WRM PROCESS mode, while Figure 22 defines the PCWQM data analysis that will be performed by system controller. Figure 23 shows the control logic for input of Fuel Cell water into the WP during WRM PROCESS mode.
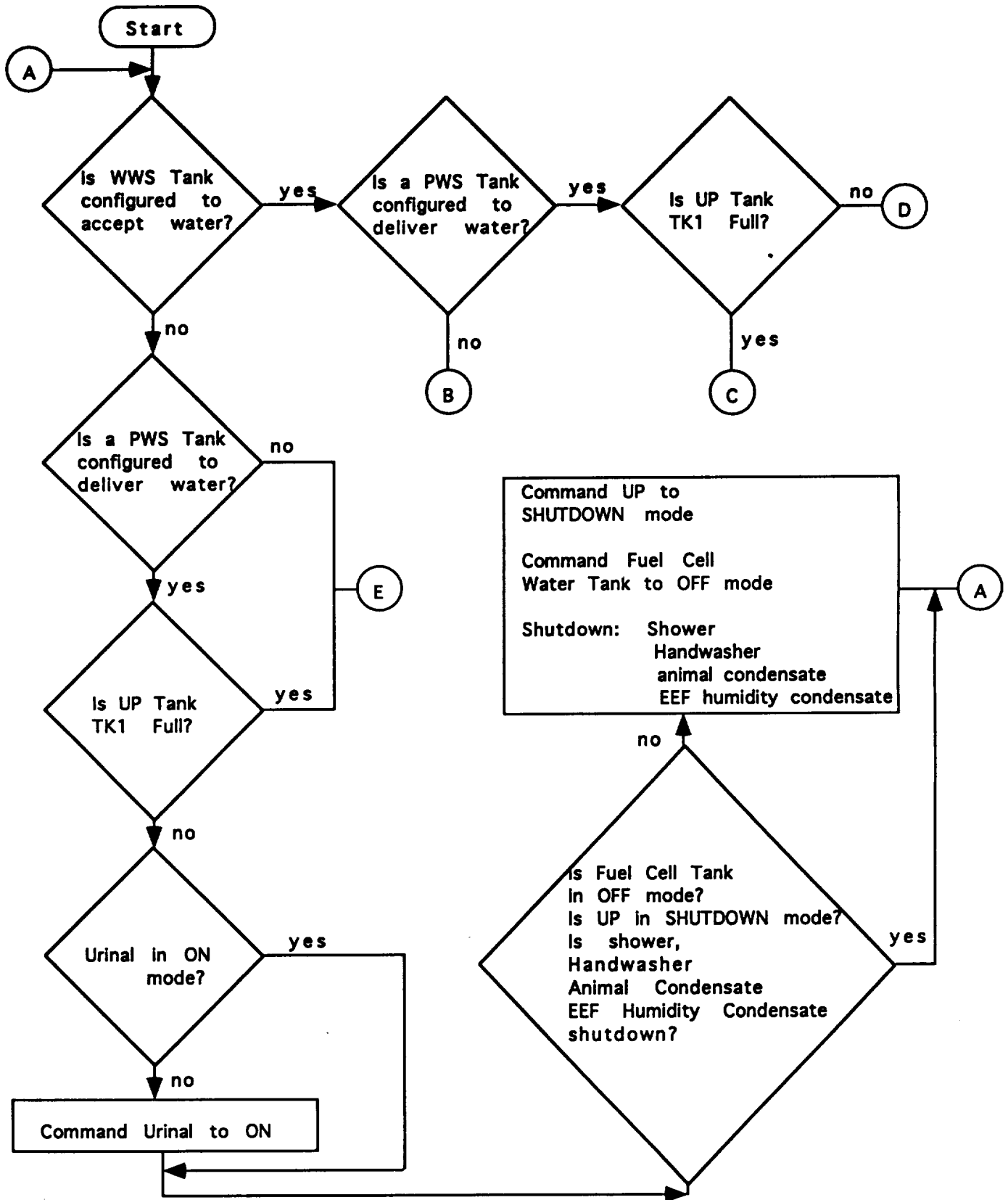
Figure 19.   System Mode - PROCESS
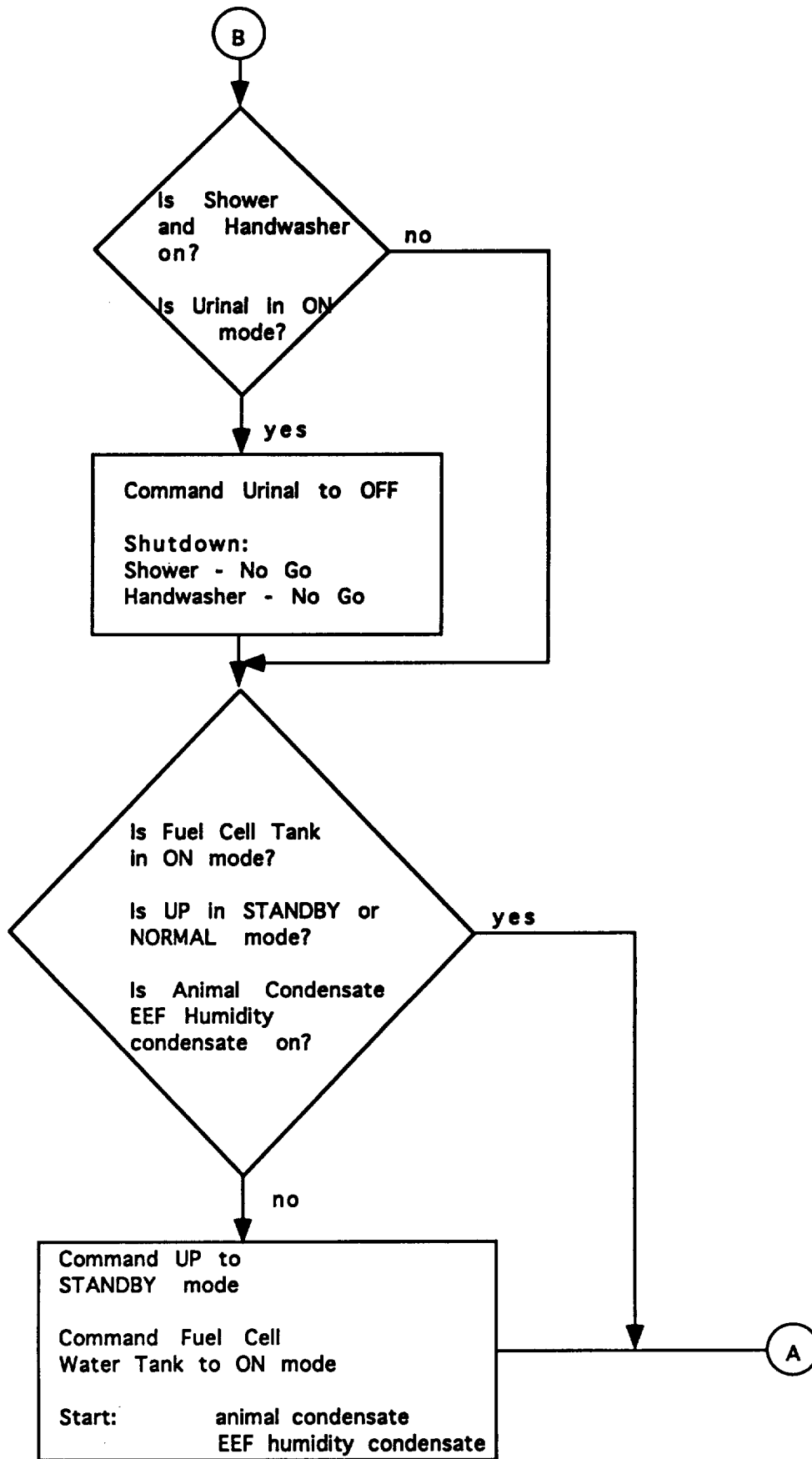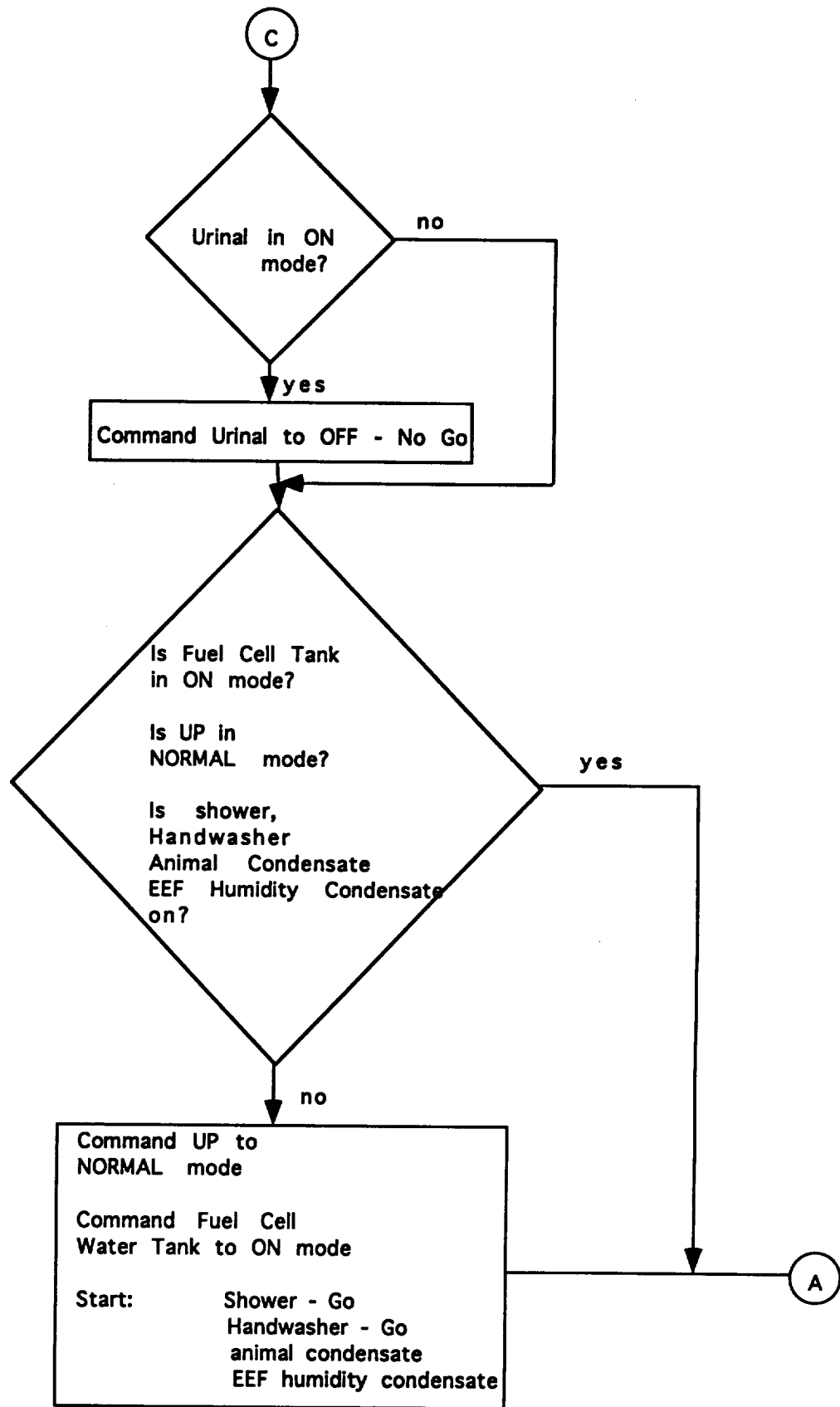
Water   Management   A-32

(B)

Is Shower and Handwasher on?

Is Urinal in ON mode?

no →

↓ yes

Command Urinal to OFF

Shutdown:
Shower - No Go
Handwasher - No Go

Is Fuel Cell Tank in ON mode?

Is UP in STANDBY or NORMAL mode?

Is Animal Condensate EEF Humidity condensate on?

yes →

↓ no

Command UP to STANDBY mode

Command Fuel Cell Water Tank to ON mode

Start: animal condensate
                EEF humidity condensate

(A)

Figure 19.   System Mode - PROCESS (continued)

Water   Management   A-33
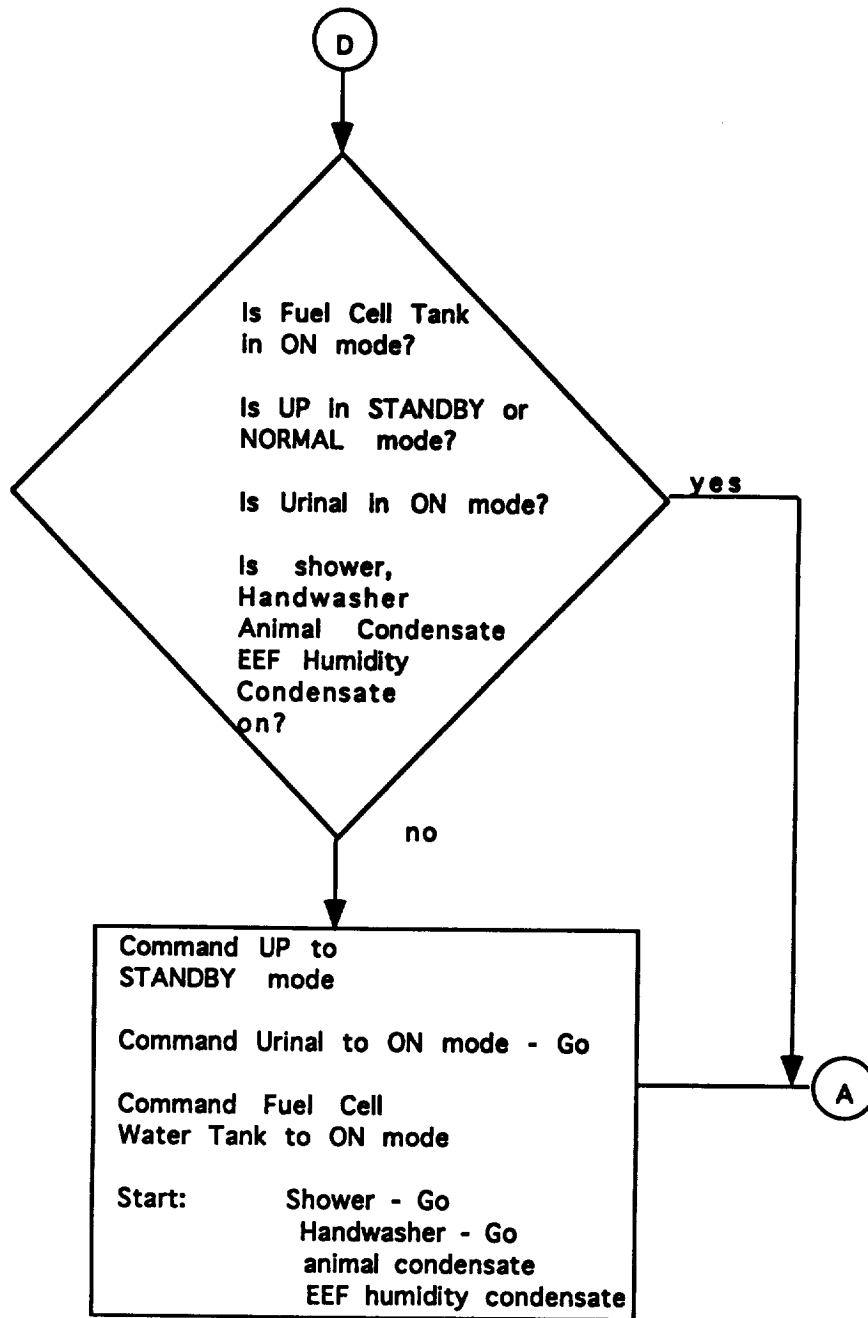
Figure 19. System Mode - PROCESS (continued)

Water Management

Figure 19. System Mode - PROCESS (continued)

Water Management

E

Is Fuel Cell Tank
in OFF mode?
Is UP in SHUTDOWN mode?
Is Urinal in OFF mode?
Is shower,
Handwasher
Animal Condensate
EEF Humidity Condensate
shutdown?

yes

no

Command UP to
SHUTDOWN mode

Command Urinal to OFF mode - No Go

Command Fuel Cell
Water Tank to OFF mode

Shutdown: Shower - No Go
        Handwasher - No Go
        animal condensate
        EEF humidity condensate

A

Figure 19. System Mode - PROCESS (continued)

Water Management

A-36
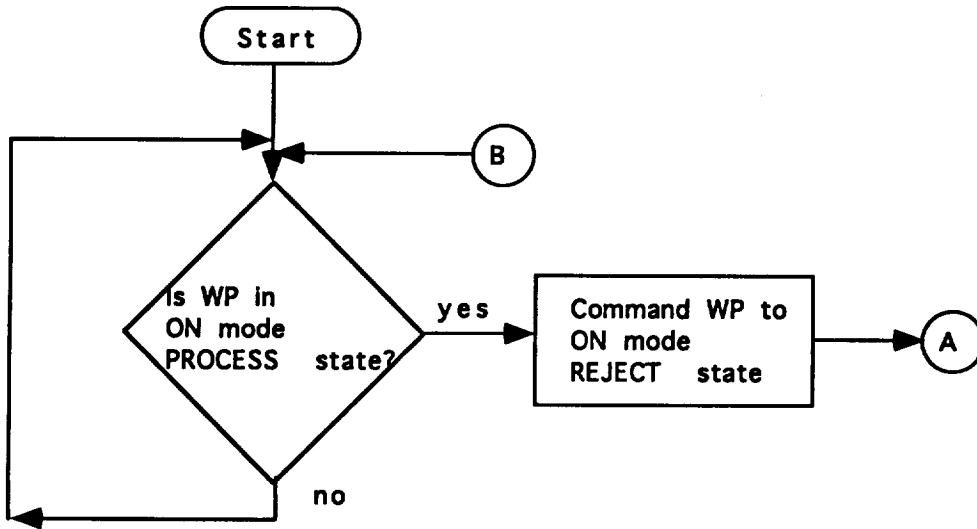
Figure 20.   System Mode - PROCESS
Water   Processor
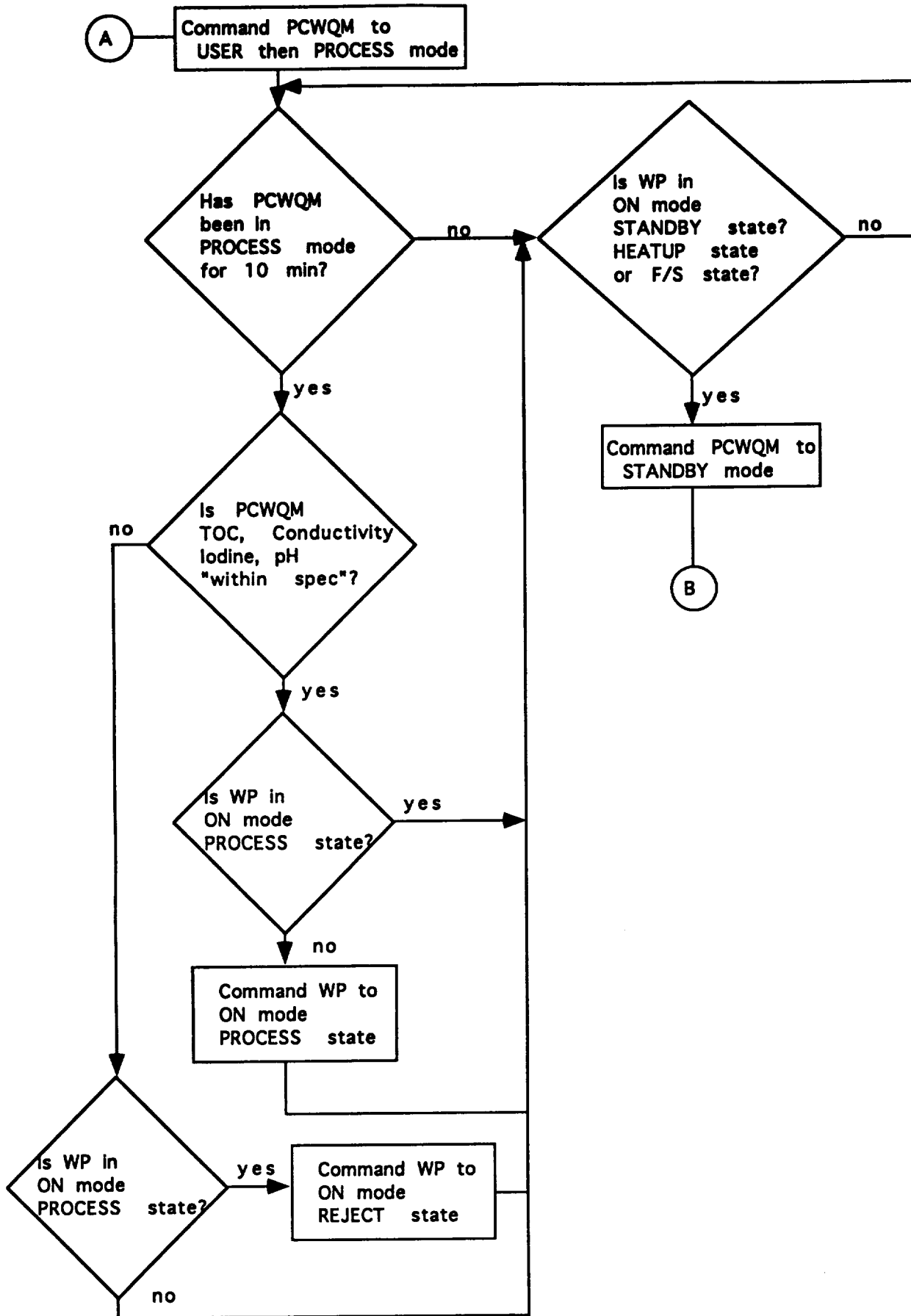
Figure 20. System Mode - PROCESS (continued)
Water Processor A-38
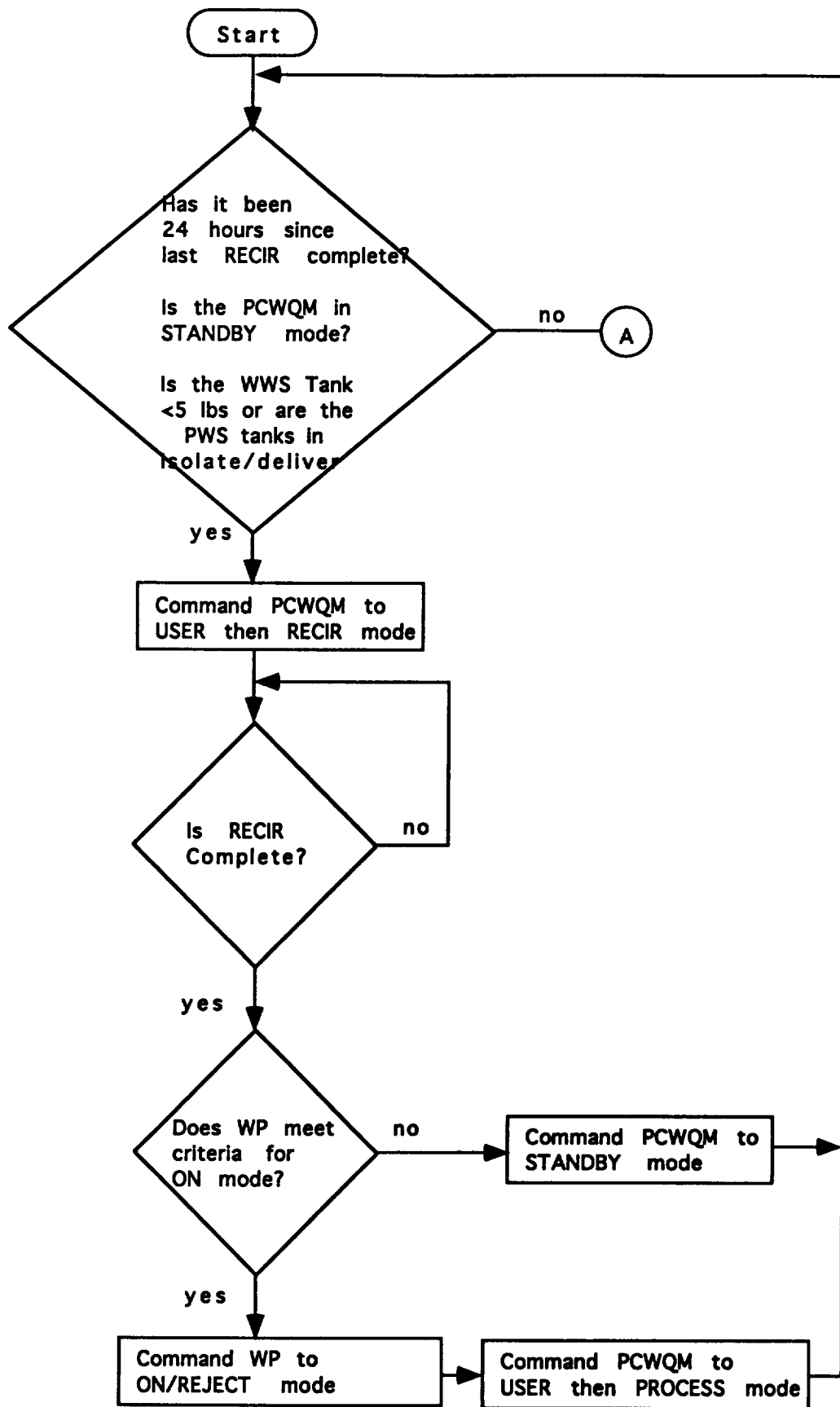
Figure 21. System Mode - PROCESS

PCWQM   A-39

A

Has it been 168 hours since last CAL complete?

Is the PCWQM in STANDBY mode?

Is the WWS Tank <10 lbs or are the PWS tanks in isolate/deliver?

no → Return to Start

yes

Command PCWQM to USER then CAL mode

Is CAL Complete? — no

yes

Does WP meet criteria for ON mode? — no → Command PCWQM to STANDBY mode

yes

Command WP to ON/REJECT mode → Command PCWQM to USER then PROCESS mode

Figure 21.   System Mode - PROCESS (continued)

PCWQM   A-40
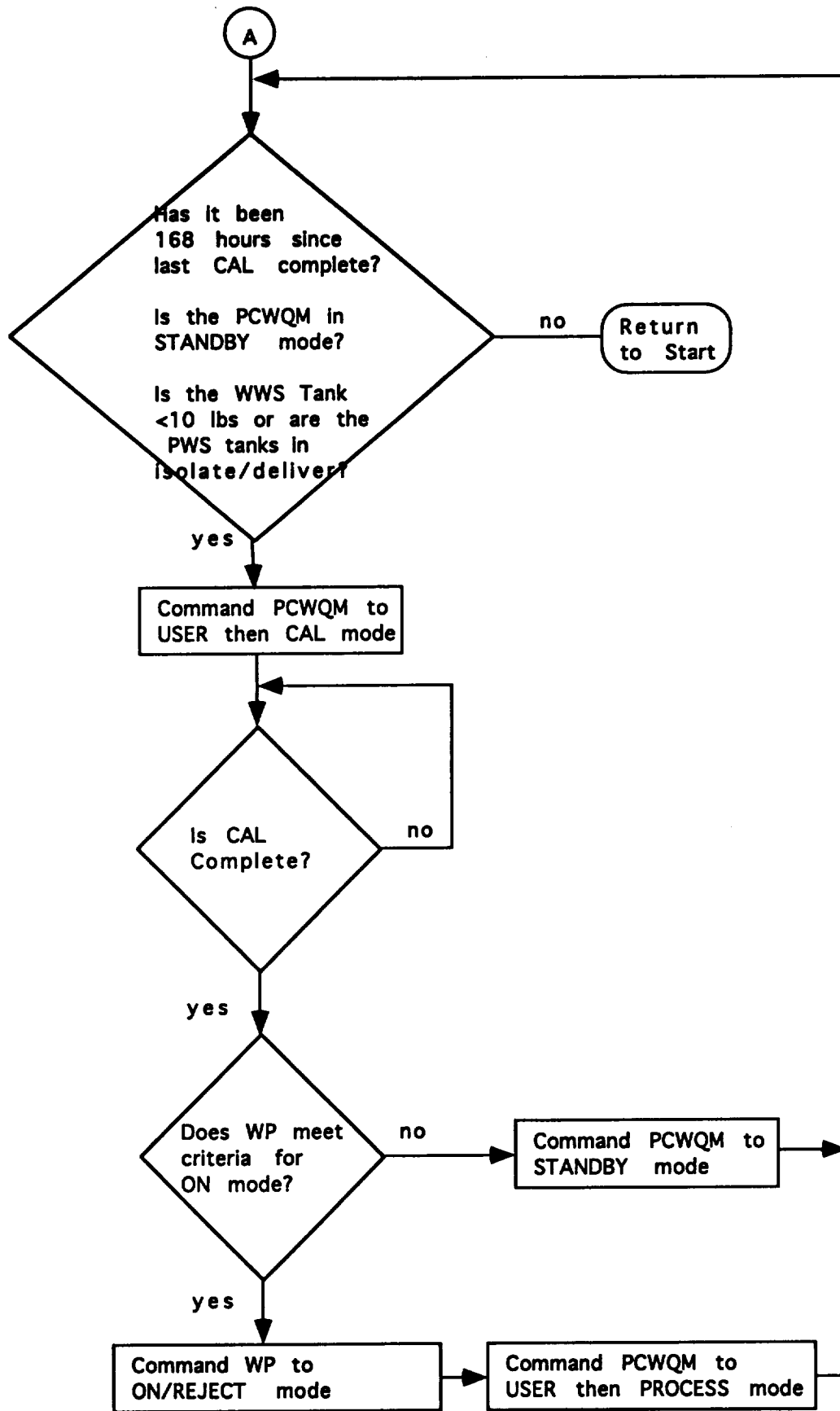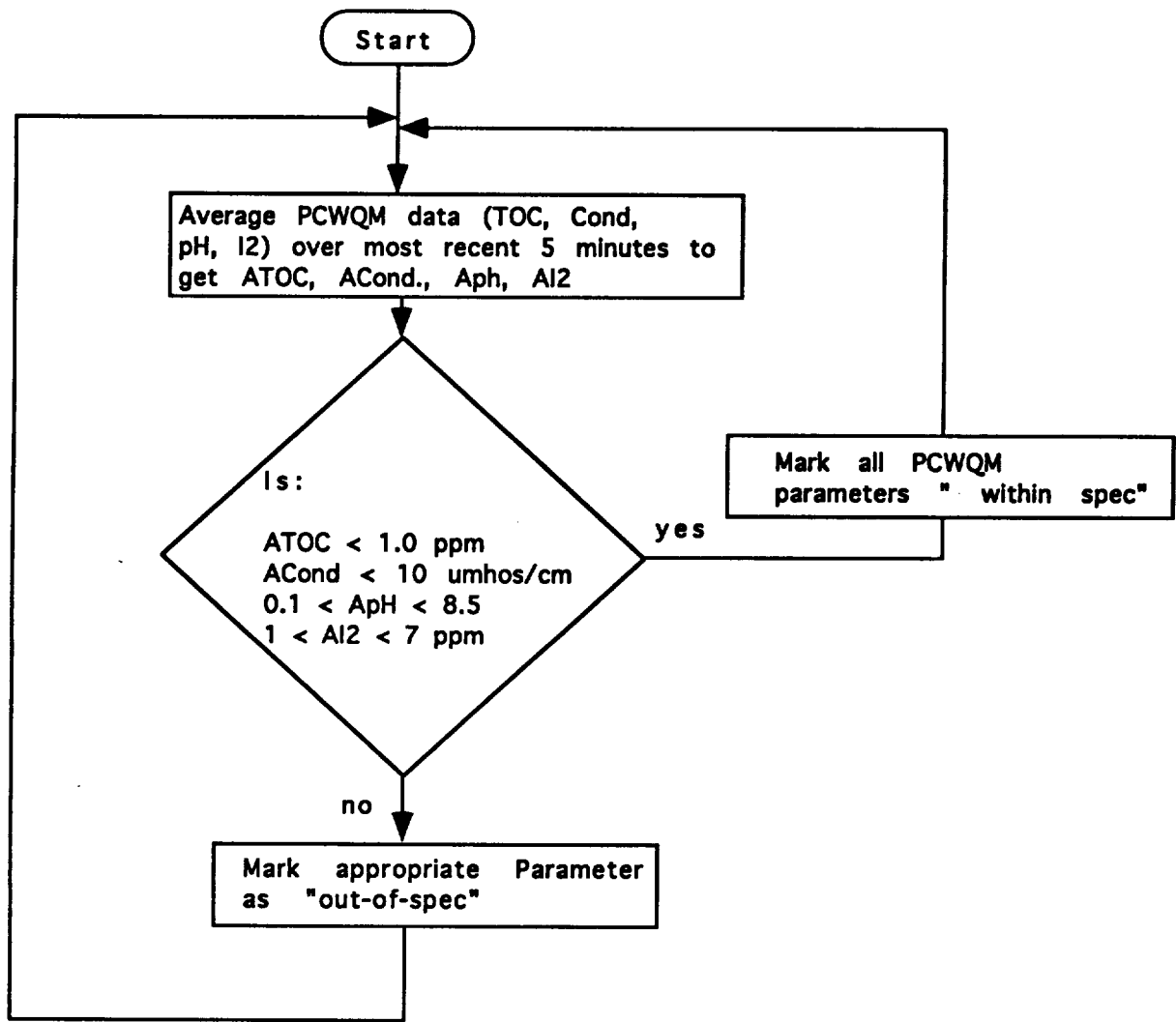
Figure 22. System Mode - PROCESS

PCWQM Data Analysis
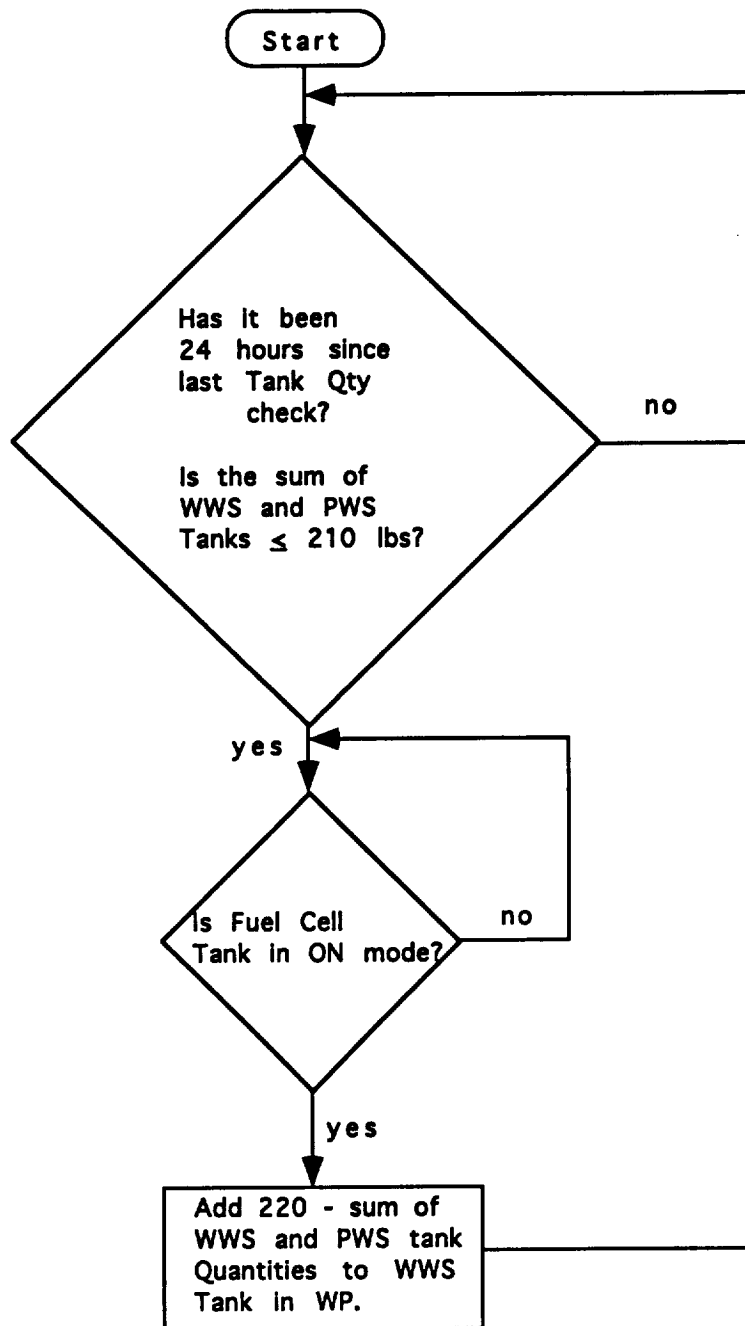
Figure 23. System Mode - PROCESS

Fuel Cell Tank

APPENDIX B

WRT STAGE 9
DAILY WASTE WATER QUANTITIES
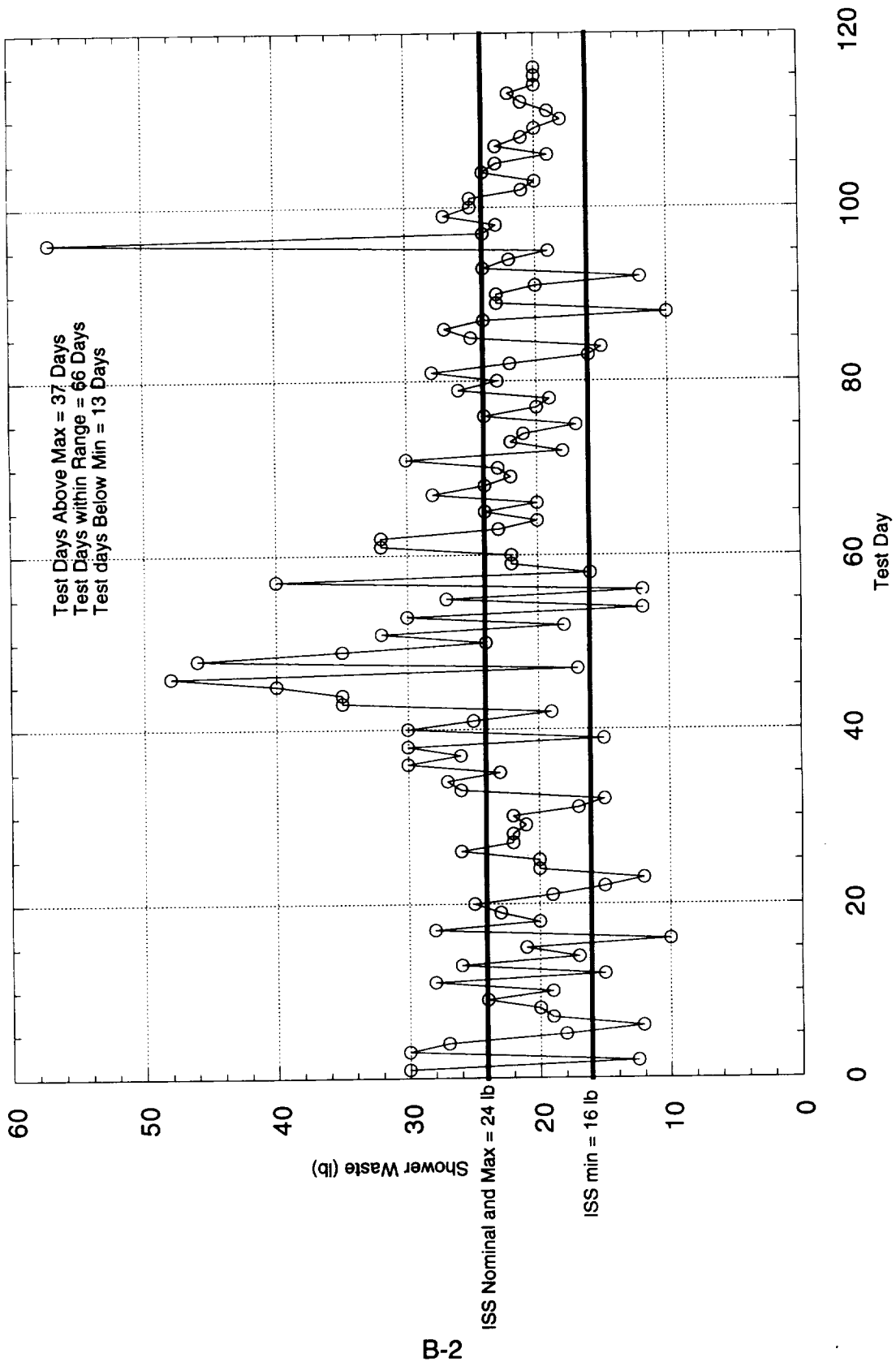
Figure B-1. WRT Stage 9 Shower Waste Daily Quantities
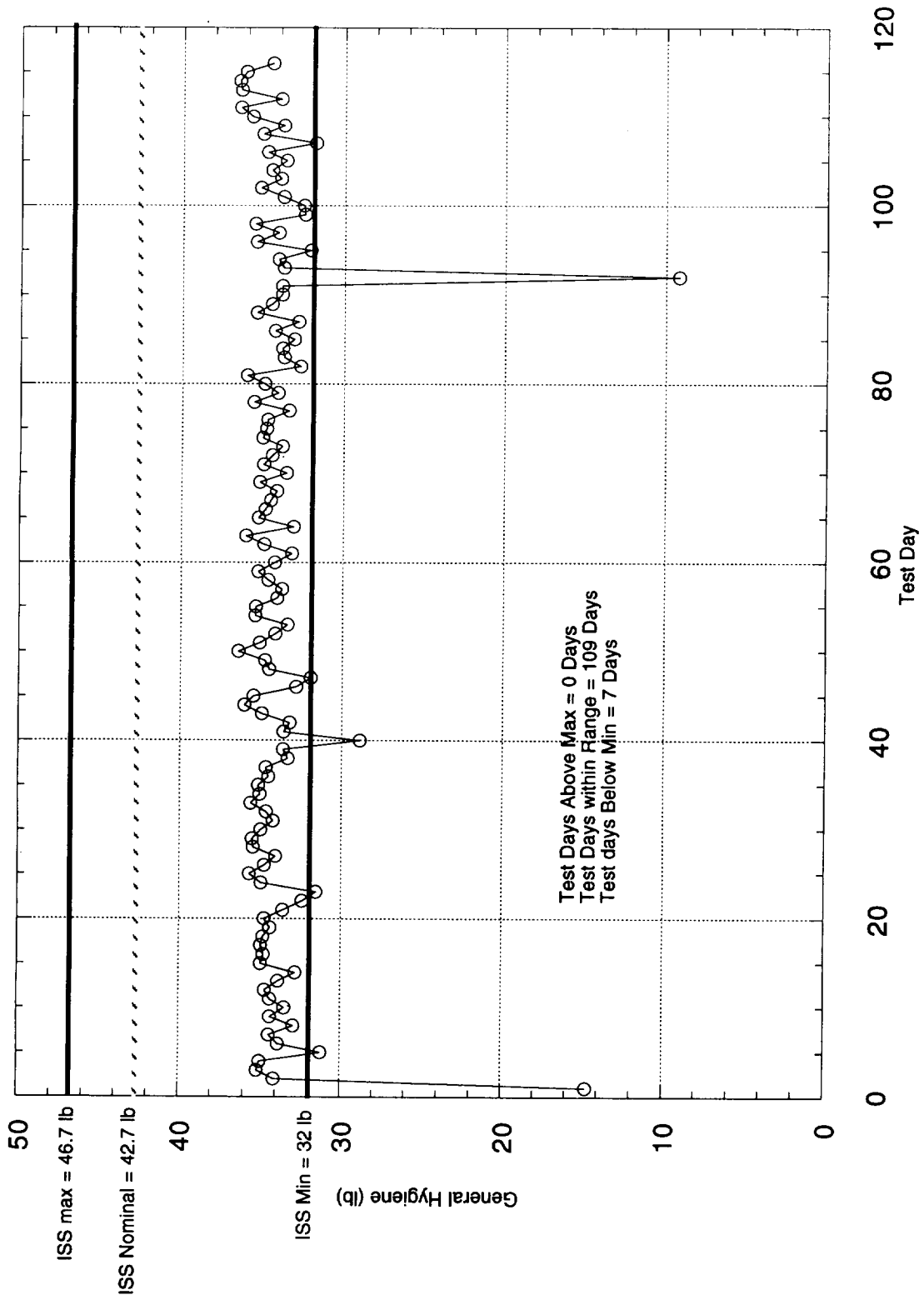
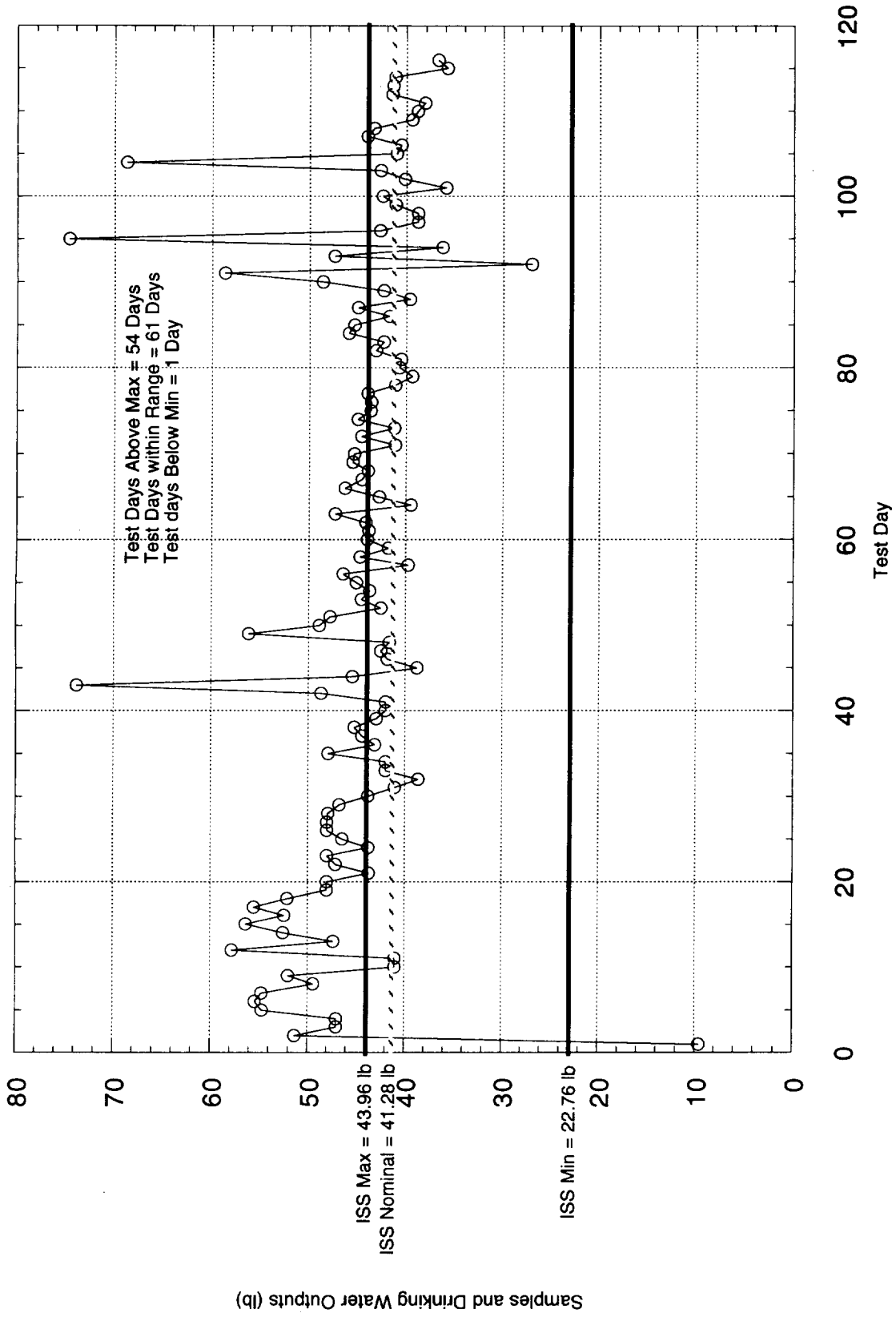Figure B-2.   WRT Stage 9 General Hygiene Waste Daily Quantities
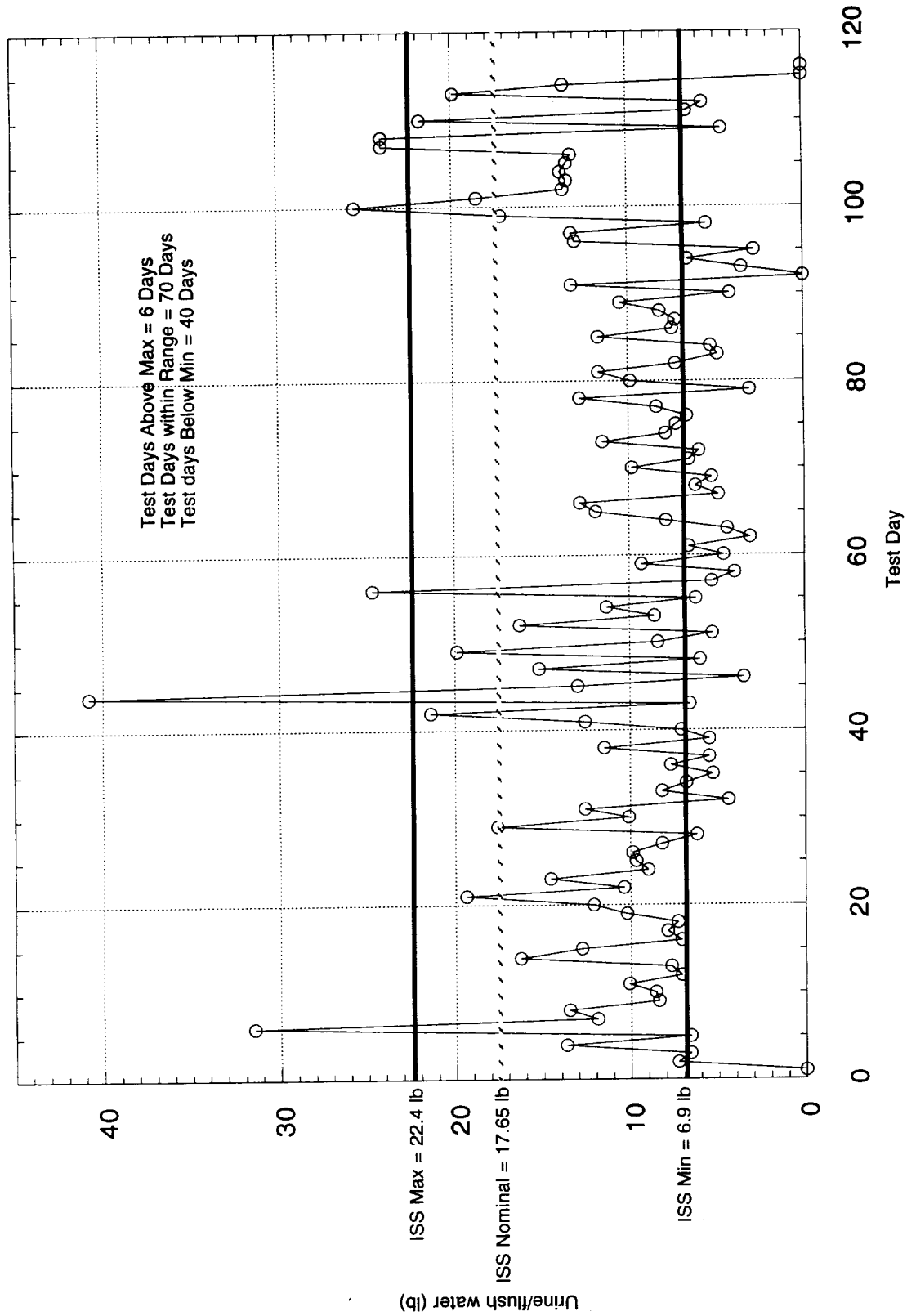
Figure B-3. WRT Stage 9 Urine/Flush Water Daily Quantities
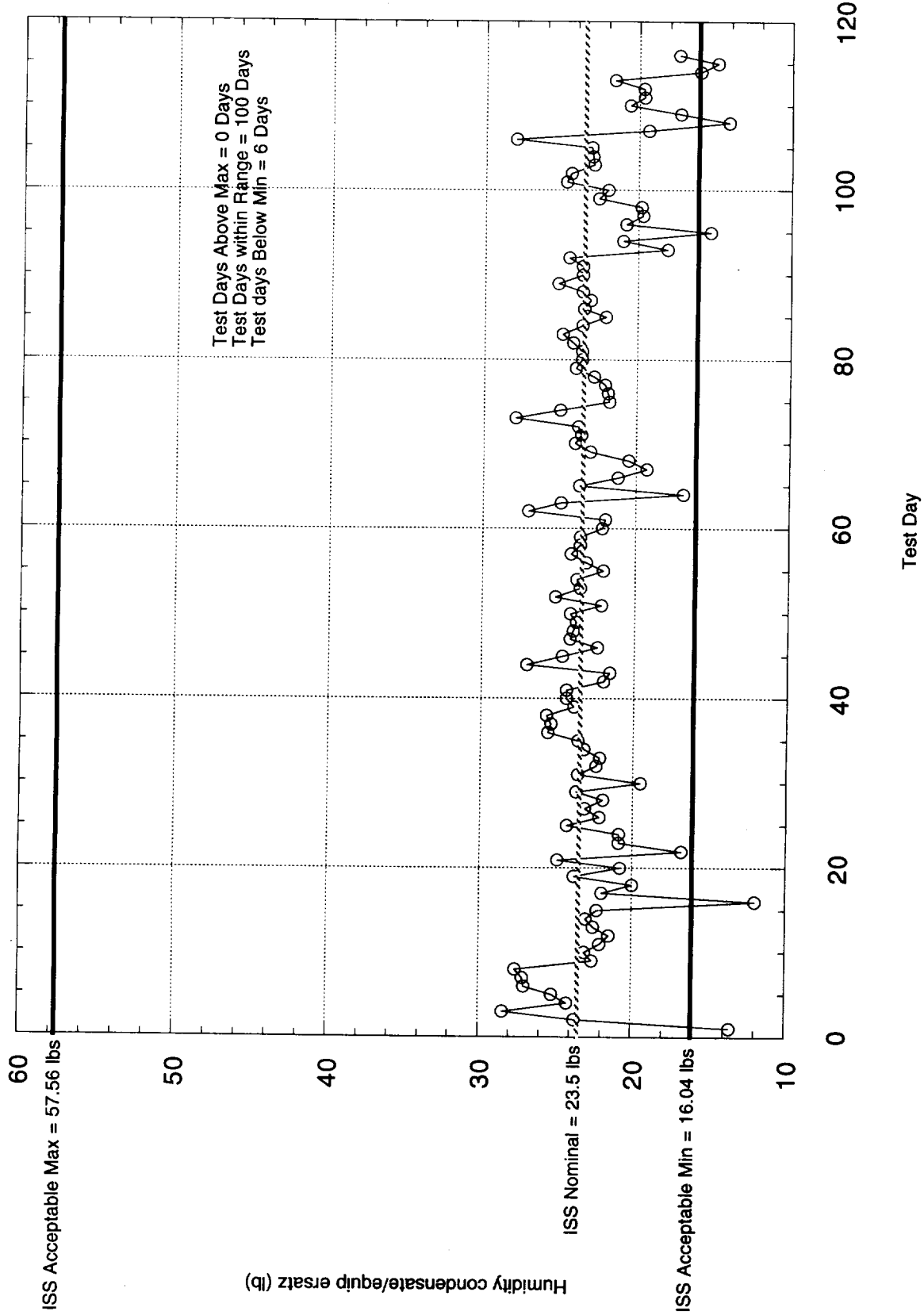
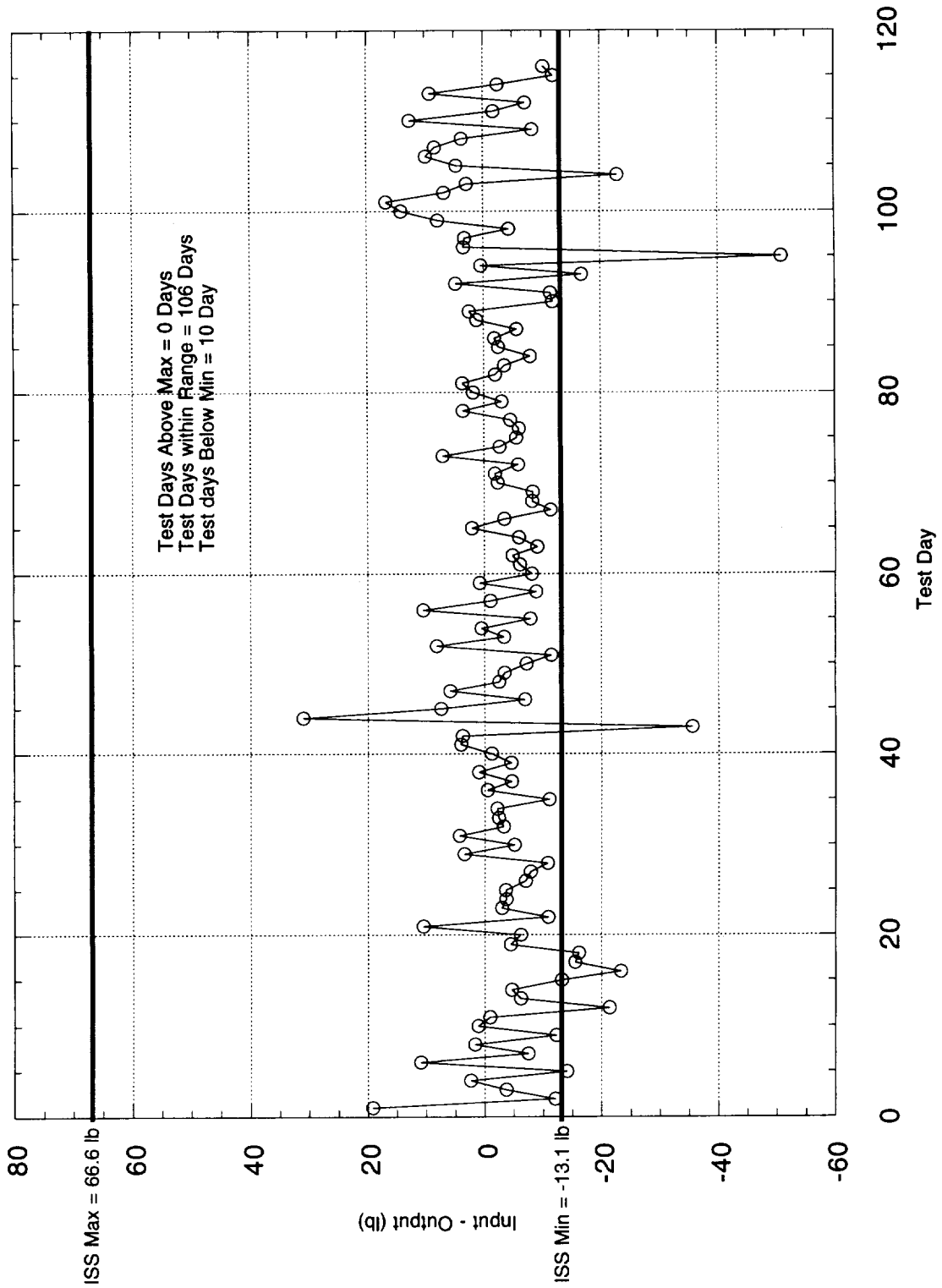Figure B-4. WRT Stage 9 Humidity Condensate/Equipment Ersatz Daily Quantities
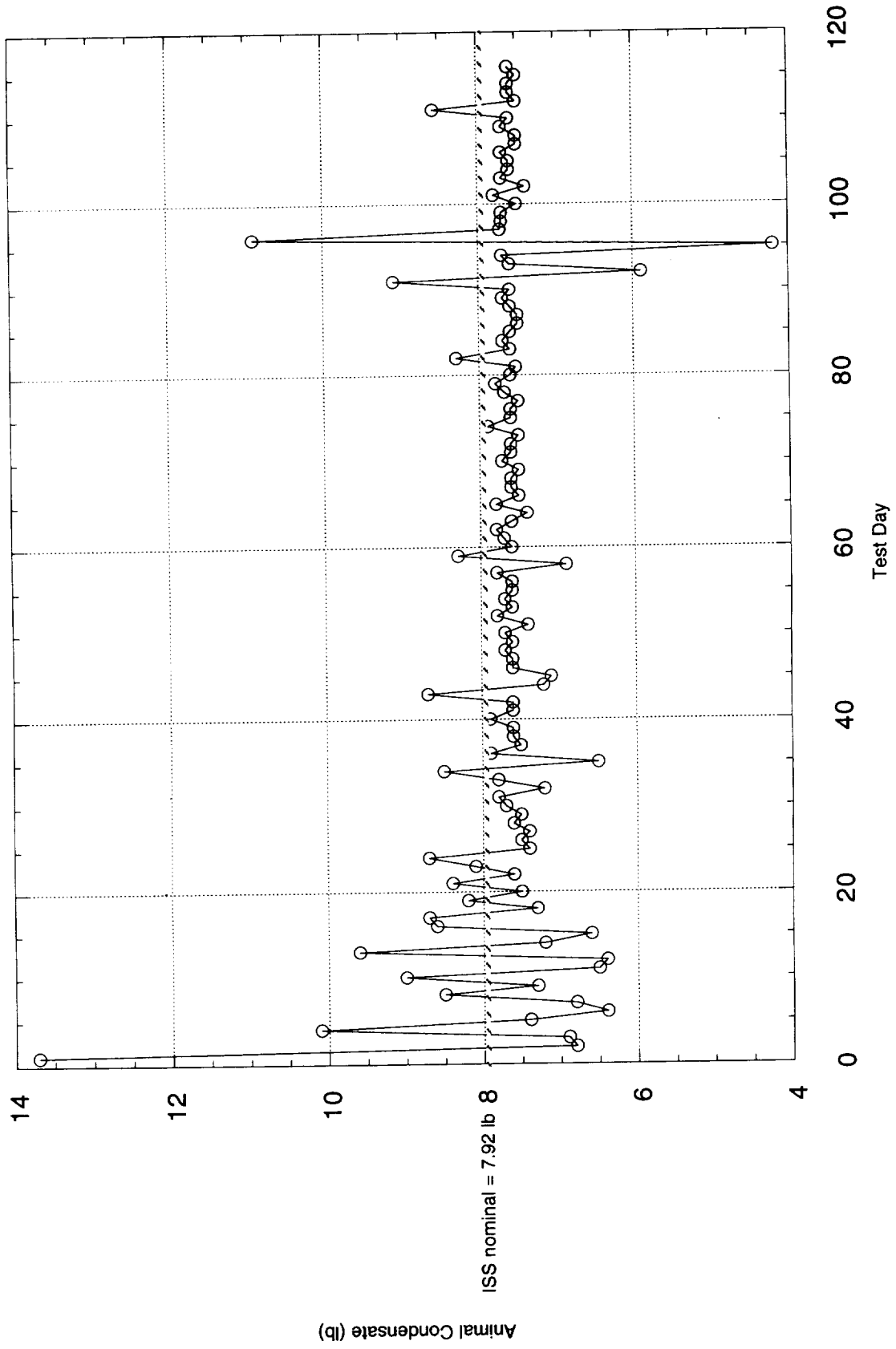
Figure B-5. WRT Stage 9 Animal Condensate Daily Quantities

Figure B-6. WRT Stage 9 Samples and Drinking Water Daily Quantities

Figure B-7. WRT Stage 9 Crew and Lab Animal Loop Daily Water Balance

Approval

International Space Station Environmental Control and Life Support System Phase III Water Recovery Test Stage 9 Final Report

D. Layne Carter, Donald W. Holder, and Cindy F. Hutchens

The information in this document has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This document, in its entirety, has been determined to be unclassified.

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8/30/95
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9/1/95
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13. ABSTRACT *(Maximum 200 words)*

A test has been completed at NASA's Marshall Space Flight Center (MSFC) to evaluate the latest water recovery system design for the United States On-Orbit Segment (USOS) of the International Space Station (ISS) with higher fidelity hardware and integration than has been achieved in previous Water Recovery Test (WRT) Stages. This test is referred to as WRT Stage 9. 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. This report summarizes the test objectives, system design, test activities and protocols, significant results, anomalies and lessons learned throughout the WRT Stage 9.

14. SUBJECT TERMS
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