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SVHSER 7236

(NASA-CR-171815) DEVELOPMENT OF A PREPROTOTYPE TIMES WASTEWATER RECOVERY SUBSYSTEM Final Report (Hamilton Standard, Windsor Locks, Conn.) 195 p HC A09/MF A01 N85-12480
CSCL 13B G3/45 Unclas 24450

DEVELOPMENT OF A PREPROTOTYPE
TIMES
WASTEWATER RECOVERY SUBSYSTEM

BY

GEORGE J. ROEBELEN, JR.

AND GERARD F. DEHNER

PREPARED UNDER CONTRACT NO. NAS 9-15471

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HAMILTON STANDARD

DIVISION OF UNITED TECHNOLOGIES CORPORATION

WINDSOR LOCKS, CONNECTICUT

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LYNDON B. JOHNSON SPACE CENTER

HOUSTON, TEXAS

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ABSTRACT

A three-man wastewater recovery preprototype subsystem using a hollow fiber membrane evaporator with a thermoelectric heat pump to provide efficient potable water recovery from wastewater on extended duration space flights has been designed, fabricated, and tested at one-gravity. Low power, compactness and gravity insensitive operation are featured in this vacuum distillation subsystem. The tubular hollow fiber elements provide positive liquid/gas phase control with no moving parts, and provide structural integrity, improving on previous flat sheet membrane designs. A thermoelectric heat pump provides latent energy recovery. Application and integration of these key elements have solved problems inherent in all previous reclamation subsystem designs.

FOREWORD

This report has been prepared by the Hamilton Standard Division of United Technologies Corporation for the National Aeronautics and Space Administration's Lyndon B. Johnson Space Center in accordance with Contract NAS 9-15471, "Development of a Urine Water Recovery Subsystem".

Appreciation is expressed to the NASA Technical Monitor, Mr. H. Eugene Winkler of Lyndon B. Jonson Space Center, for his guidance and advice.

Hamilton Standard personnel responsible for conduct of this program were Messrs. Harlan F. Brose, Program Manager, George J. Roebelen, Jr., Project Engineering Manager, and Gerard F. Dehner, Senior Experimental Engineer. Appreciation is expressed to Messrs. Gilbert N. Kleiner, Project Engineering Supervisor, Edward O'Connor, Project Analytical Engineer and William Perkins, Project Electrical Engineer.

SUMMARY

A three man wastewater recovery preprototype subsystem has been designed, fabricated, and successfully acceptance tested by Hamilton Standard. Low power, compactness, and gravity insensitive operation are featured in this vacuum distillation subsystem that combines a hollow fiber membrane evaporaor with a thermoelectric heat pump. Application of these key elements have solved problems inherent in previous reclamation subsystem designs. The hollow fiber elements provide positive liquid/gas phase control with no moving parts other than the wastewater recirculating pump, a condensate removal pump and accumulator, and a condensate cooling pump. Tubular membranes provide structural integrity, improving on previous flat sheet membrane designs. Thermoelectric heat pumps provide efficient heat recovery, as well as eliminate moving parts and equipment noise associated with a vapor compressor. Over 850 hours of operation processing pretreated urine and pretreated wash water with solids concentrations reaching 37% have been completed. The rate of production of high quality potable water averaged 1.0 kg/h (2.2 lb/h) at 29.0 VDC throughout the testing.

The subsystem was successfully integrated with a microprocessor based controller which permitted complete automatic control, and a CRT display which provided a colored display of subsystem flow and key operating and performance parameters. All control modes, anomoly situations, and failure shutdown operations were demonstrated.

A computer analytical model of the TIMES has been developed; the parametric outputs from this model compared closely with experimentally obtained parametric data.

INTRODUCTION

The Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES) was conceived in 1977 to provide a water recovery subsystem with minimum mechanical complexity and positive liquid/gas phase separation. Low power consumption, automatic operation, compactness, and gravity insensitive operation are characteristics of this vacuum distillation subsystem that combines a hollow fiber membrane evaporator with a thermoelectric heat pump that provides latent heat recovery.

Program Objective

The basic objective of this program is to design, fabricate, and acceptance test a three man urine water recovery preprototype subsystem to be integrated with other individual technologies in the area of regenerative life support and evaluated as a part of a Regenerative Life Support Evaluation (RLSE) program at NASA/JSC.

Program Duration

This final report encompasses all work performed during the period January, 1978 through December, 1981.

Specifications

The basic specification requirements for the TIMES are:

Capable of processing of urine, urinal rinse water, and shower concentrated brine of three crew members for 180 days without resupply.

Scheduled maintenance is allowable.

Capable of recovering at least 95% of the water as potable quality water.

Total dry weight to be less than 136.1 kilograms (300 pounds), total volume to be less than 0.80 cubic meters (28.25 cubic feet).

Specific energy requirements to be less than 334.4 watt hours per kilogram (152 watt hours per pound) of product water from non-concentrated raw urine at 26.5 VDC power supply.

Expendable requirements to be less than 11.8 kilograms (26 pounds) to process 1814.4 kilograms (4,000 pounds) of raw urine.

Process rate to be at least 0.77 kilograms (1.7 pounds) per hour of product water from non-concentrated urine at nominal 29 VDC power supply to the thermoelectric regenerator after thirty days of eight hours per day operation.

Water loss rate from vacuum purging to be less than 0.014 kilograms (0.03 pounds) per hour.

Process water quality shall exceed the standards recommended by the National Academy of Science - National Research Council Committee on Toxicology in their Report of the Panel on Potable Water Quality in Manned Spacecraft, August, 1972.

Basic Description

The TIMES, as illustrated in Figure 1, consists of a pretreat section, a processing section, a postfiltration section, and a control and display.

The pretreat section collects wastewater, mixes it with a pretreat solution, and supplies the mixed solution to a recycle loop. In the recycle loop wastewater is circulated through a recycle tank, a heater on the hot side of a heat pump, a hollow fiber membrane evaporator, and back to the recycle tank. The separation of the water from the waste solids occurs in the hollow fiber membranes as water diffuses through the membranes and evaporates as steam from the outer side of the membrane walls. The steam is condensed in a porous plate heat exchanger phase separator on the cold side of the heat pump. Heat is transferred from the condenser to the heat exchanger by the thermoelectric heat pumps, recovering latent heat energy. Condensate is pumped out of the condenser and through a postfiltration section. The TIMES is an independent subsystem, with four functional interfaces to the vehicle:

Wastewater Input
Power Input
Clean Water Output
Heat Rejection

The TIMES is designed to produce microbiologically safe potable water by a sequential application of definite control procedures. Control procedures designed into the subsystem include chemical pretreatment, pasteurization, distillation, and final bacteria filtration. Under all conditions, the chemical pretreatment fixes the urea and acts to kill bacteria in the waste storage area and the recycle loop. During steady state operation, the wastewater is maintained at a pasteurization temperature. The evaporator hollow fiber membranes provide a positive barrier to passage of bacteria from the hot wastewater recycle loop into the steam chamber and the condenser during the distillation process. Bacteria filters in the postfiltration module prevent the migration of any bacteria which might form in the condensate line.

A microprocessor based controller is used to monitor the various sensor outputs and supply the required actuation and sequencing signals for the various pumps and valves to provide automatic operation and control for each of the preset operational modes. In addition, the controller supplies inputs to a cathode ray tube (CRT) display module that displays subsystem flow schematics in multi-colors for each of the various operating modes. A keyboard located at the CRT display module allows operator control and monitoring of the subsystem.

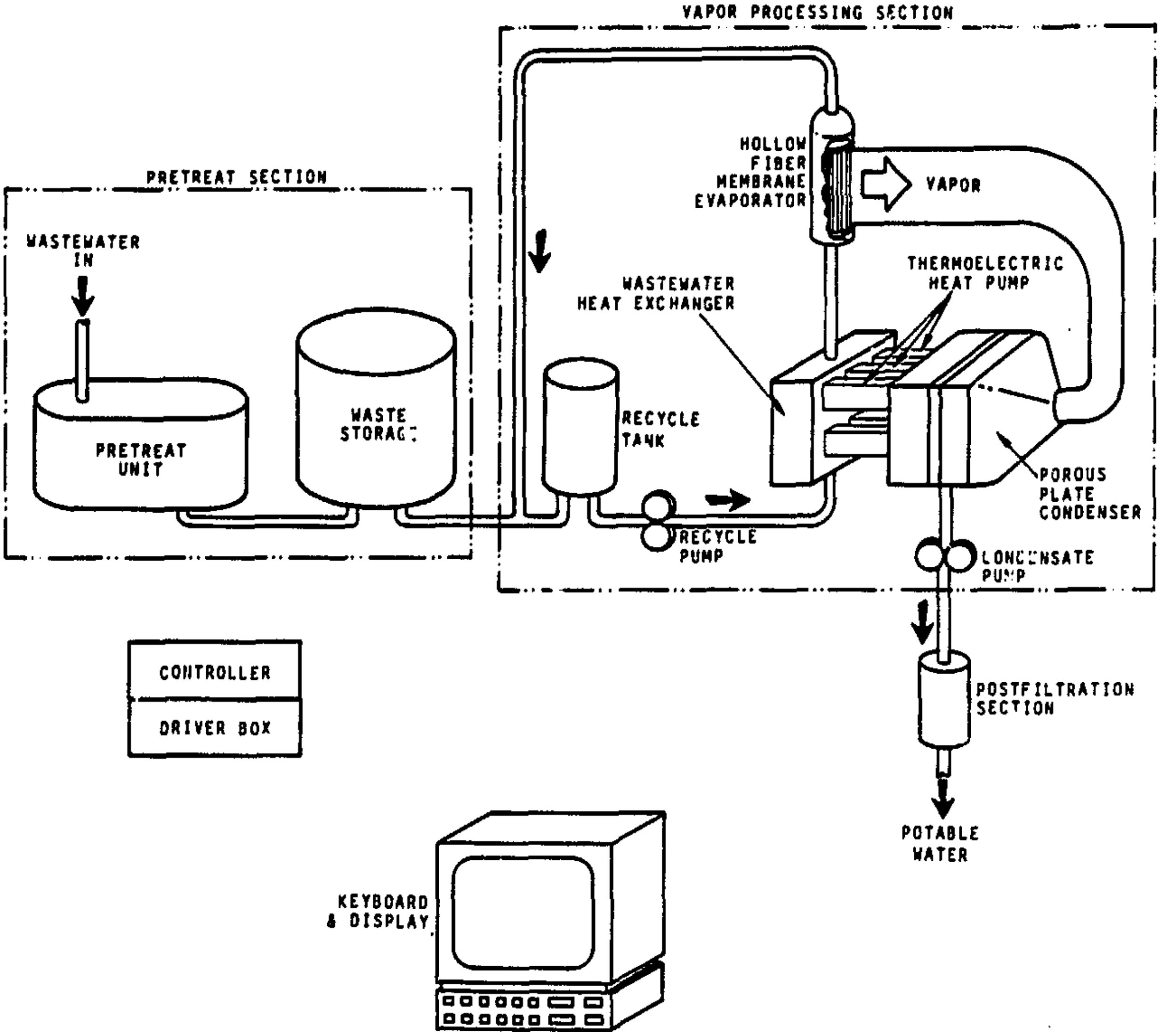

FIGURE 1
TIMES BASIC SCHEMATIC

CONCLUSIONS

The preprototype TIMES subsystem has been demonstrated to meet or exceed all requirements for producing potable water from urine and wash water as defined by the Statement of Work for Development of a Urine Water Recovery Subsystem per NASA Contract NAS 9-15471 thru Modification 9S.

From a hardware standpoint the TIMES integrates proven components to produce an extremely simple design exhibiting very competitive weight, power, and volume. The TIMES consistently produces high quality water and has been demonstrated to be capable of being maintained, when necessary, with safety and within acceptable crew time limitations.

This approach to wastewater recovery utilized by the TIMES is particularly advantageous because it produces microbiologically safe potable water by providing positive separation between processed and unprocessed water through a sequential application of definite control procedures. At each component and interface, the chance of entrance or growth of bacteria was considered for planned start-up and shutdown modes, as well as for shutdown due to loss of power. These procedures designed into the subsystem include chemical pretreatment, pasteurization, distillation, vapor duct liquid entrapment, and final bacteria filtration. This combination of features combined with a microprocessor-based controller provides a completely automatic subsystem having a potential for long life with high reliability and efficiency.

RECOMMENDATIONS

The test results and studies of this program have demonstrated that a TIMES wastewater recovery subsystem can be designed to meet water recovery requirements for long-term space missions or for extended on-orbit operations to avoid launch and resupply penalties.

In order to optimize the overall design it is recommended that:

- The temperature control and water quality improvement changes studied during this program be implemented.
- Start-up/shutdown procedures be studied to improve fluid isolation conditions during non-destructive failure shutdown to allow immediate restart upon correction of the failure shutdown condition. The resulting changes to the hardware should be implemented.
- Methods for automatically calculating and displaying solids concentration in the subsystem recycle tank be studied and implemented.
- Methods for recycle tank dumping and recharging while installed in the subsystem be studied and implemented.
- Methods for on-orbit and ground refurbishment of membranes to extend membrane performance levels be studied and tested.
- Methods for optimizing pretreatment usage rate by monitoring recycle and waste tank pH levels be studied and implemented.
- Conduct additional endurance testing to accumulate more processing time on the membranes to determine if a life limitation exists under actual operating conditions with urine and wash water.

The present preprototype TIMES should be used as appropriate for evaluating the above optimization recommendations. It is further recommended that a flight prototype TIMES be designed, fabricated and tested utilizing the information learned from conducting the program reported herein and from the results of the above optimization effort.

NOMENCLATURE

AC	Alternating Current
AISI	American Iron And Steel Institute
AMS	Aerospace Material Specifications
BTU	British Thermal Unit
°C	Degrees Centigrade
cc	Cubic Centimeters
cm	Centimeter
CRT	Cathode Ray Tube
DC	Direct Current
°F	Degrees Fahrenheit
ft^3	Cubic Feet
g	Gram
gal	Gallon
GFE	Government Furnished Equipment
h	Hour
HFM	Hollow Fiber Membrane
HZ	Hertz
in	Inch
in^3	Cubic Inches
K	Degrees Kelvin
kg	Kilogram
kg/h	Kilograms Per Hour
kPa	Kilopascal
l	Liter
lb	Pound
lb/h	Pounds Per Hour
m	Meter
m^3	Cubic Meters
meq	Milliequivalent
mg	Milligram
min	Minute
ml	Milliliter
pH	Negative Log Of Hydrogen Ion Concentration
P/N	Part Number
ppb	Parts Per Billion
ppm	Parts Per Million
psi	Pounds Per Square Inch
psia	Pounds Per Square Inch Absolute
psid	Pounds Per Square Inch Differential
RLSE	Regenerable Life Support Evaluation
sec	Second
STP	Standard Temperature And Pressure
TED	Thermoelectric Device
TER	Thermoelectric Regenerator
TIMES	Thermoelectric Integrated Membrane Evaporation Subsystem
UV	Ultraviolet
V	Volts
VAC	Volts Alternating Current
VDC	Volts Direct Current
W	Watt
W-h/kg	Watt Hours Per Kilogram
W-h/lb	Watt Hours Per Pound
ΔP	Differential Pressure
ΔT	Differential Temperature
μmho	10^{-6} mhos

SUBSYSTEM DESCRIPTION

The TIMES utilizes a vacuum distillation process for reclaiming water from waste fluids, primarily urine. The subsystem includes wastewater collection and pretreatment, wastewater distillation, and product water postfiltration functions. Figure 2 is a simplified schematic of the design.

Wastewater, pretreated to inhibit urea breakdown and to provide bacteria control, is heated to a pasteurization temperature of 66°C (150°F) within a wastewater heat exchanger in contact with the hot junction surfaces of a thermoelectric heat pump. The heated wastewater then passes through a tubular hollow fiber membrane (HFM) evaporator module. The outside surfaces of the membrane tubes are exposed to low pressure. Water diffuses through the tube walls and evaporates as steam at the tube outer surfaces. Other liquid and dissolved solid constituents of the wastewater remain within a recycle loop. The heat of evaporation is provided by the hot wastewater stream circulating in the recycle loop. The slightly cooled and concentrated wastewater is returned to a recycle tank, passed through a filter to remove any particulate matter that might be present in the loop, and pumped back to the heat exchanger where it is reheated and recirculated.

Liquid evaporated as steam from the hollow fiber membrane evaporator is made up by the automatic introduction of preheated, pretreated wastewater from the waste storage tank. The solids concentration in the recycle loop gradually increases until 95 percent of the original water content has been removed and a solids concentration of approximately 40 percent has been reached. At this point the recycle tank and filter are removed and replaced with fresh units and the process is continued.

The evaporated steam is condensed to water on a chilled porous plate surface thermally contacting the cold junction surfaces of the thermoelectric heat pump. The chilled porous plate acts like a sponge and the condensate passes through the porous plate into a thermally conducting water passage between the porous plate and thermoelectric heat pump cold junction contact sheet. This passage is a flow path in a process thermal control cooling loop discussed later in this section. The condensed water is then drawn into an accumulator where it is collected prior to delivery to a postfiltration module.

The tubular hollow fiber membrane design allows the wastewater liquid feed to operate at atmospheric pressure while the steam passage operates at the steam saturation pressure. Free and dissolved gases contained in the hot recirculating wastewater stream pass through the membrane with the steam and increase the total pressure in the steam passages. Periodically these non-condensables are removed from the subsystem by venting the steam passages to vacuum so as not to inhibit steam flow from the evaporative membrane surfaces to the condensing porous plate.

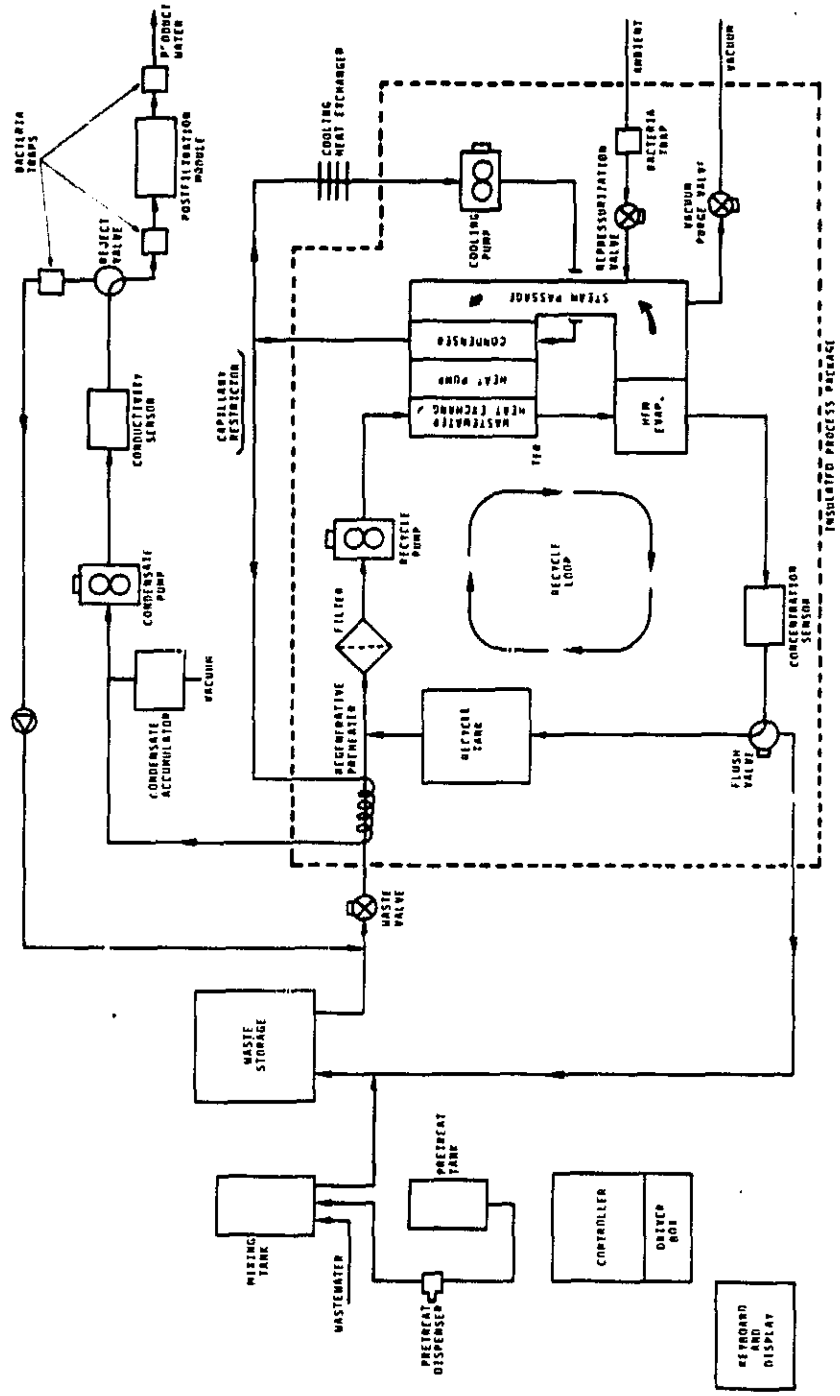

FIGURE 2

TIMES SIMPLIFIED SUBSYSTEM SCHEMATIC

A spring loaded condensate accumulator, referenced to vacuum, provides a suction at the outlet of the condensate removal line. To prevent the outlet suction from causing excessive condensate vaporization at the porous plate, a capillary restrictor, whose function is to automatically produce a compensating variable pressure drop, is located in the condensate removal line. The compensating variable pressure drop occurs when steam starts to form in the condensing passage due to a suction lower than the saturation pressure. The steam is withdrawn through the capillary restrictor where the volume of the steam is many times greater than an equivalent mass of liquid water. The flow rate of the liquid water through the capillary causes an insignificant pressure drop whereas the steam causes enough pressure drop to backpressure the condensing passage and prevent any additional steam from forming at the porous plate.

Withdrawal of water from the condensate accumulator is accomplished by energizing the condensate pump when the accumulator is 75 percent full, as measured by the condensate accumulator diaphragm position. The pump stops when the accumulator is emptied to 25 percent capacity.

Process thermal control is provided by means of a cooling loop. The condensed product water is recirculated from the condensing passage, through a cooling heat exchanger where heat is rejected, and back to the condensing passage. This cooling effect reduces the heat pump cold junction temperature and thus limits the amount of heat pumped to the hot junction contacting the wastewater recycle loop heat exchanger. A temperature controller senses HFM evaporator inlet temperature and regulates flow of the cooling pump.

Product water delivered by the condensate pump passes through a conductivity sensor. If unacceptable product water conductivity is detected, a three-way reject valve, which normally delivers the product water to the postfiltration module, automatically swtiches and transfers the water back to the waste storage tank outlet.

Acceptable product water is filtered in a postfiltration module that contains charcoal and ion exchange beds to remove odor and trace amounts of dissolved ammonia. The polished product water is then pumped to the vehicle potable water storage tank for crew use.

DESIGN SUPPORT TESTING

CONFIGURATION VERIFICATION

Objective

The objective of this test program is to demonstrate the TIMES process prior to the design and fabrication of the TIMES hardware using a scale model setup to attempt to uncover problem areas that might not be apparent during subsystem analytical examination.

Discussion

A 1/6 scale model setup was assembled and tested to verify plumbing configurations and further demonstrate process suitability.

The TIMES, as illustrated in Figure 3 contains a loop that circulates wastewater that is heated to the controlled process temperature by the hot junction of the thermoelectric elements in contact with the wastewater heat exchanger. The heated wastewater flows through the inside diameters of the hollow fiber membranes with a portion of the water permeating through the membrane walls and evaporating as steam from the membrane outer surfaces. The wastewater from the inside diameters of the hollow fiber membranes returns to the wastewater heat exchanger for reheating, and the steam from the outer surfaces of the membranes flows to the condenser plate in contact with the cold junction of the thermoelectric elements where it is condensed. The condensate is removed for posttreatment and storage.

Figure 4 shows the 1/6 scale model hollow fiber membrane evaporator and thermoelectric regenerator combination. All elements and orientations of the final design except the porous plate are included. Figure 5 depicts the configuration test setup. Refer to Appendix A for the Design Support Test Plan section of the Master Test Plan. The configuration verification testing was run in an oven so that ambient temperature could be adjusted to minimize condensation of product water vapor on the transparent uninsulated plastic surfaces.

Results

Assembly of the 1/6 scale model setup was completed, and the major packaging configuration and fluid line locations were verified. No problems were uncovered with the actual process. It was decided that precise parametric data could be obtained more efficiently by waiting for the completion of the development component hardware rather than by expending additional effort with the scale test hardware.

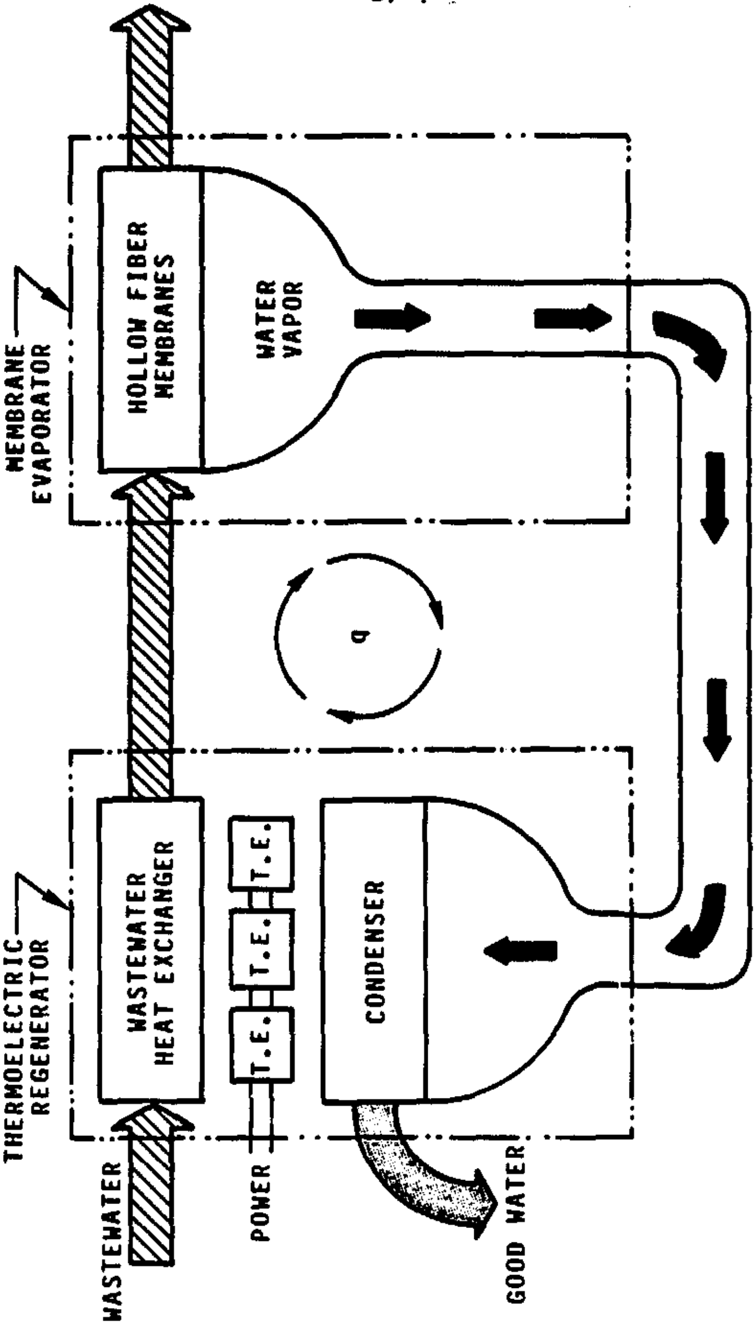

FIGURE 3
TIMES PROCESS

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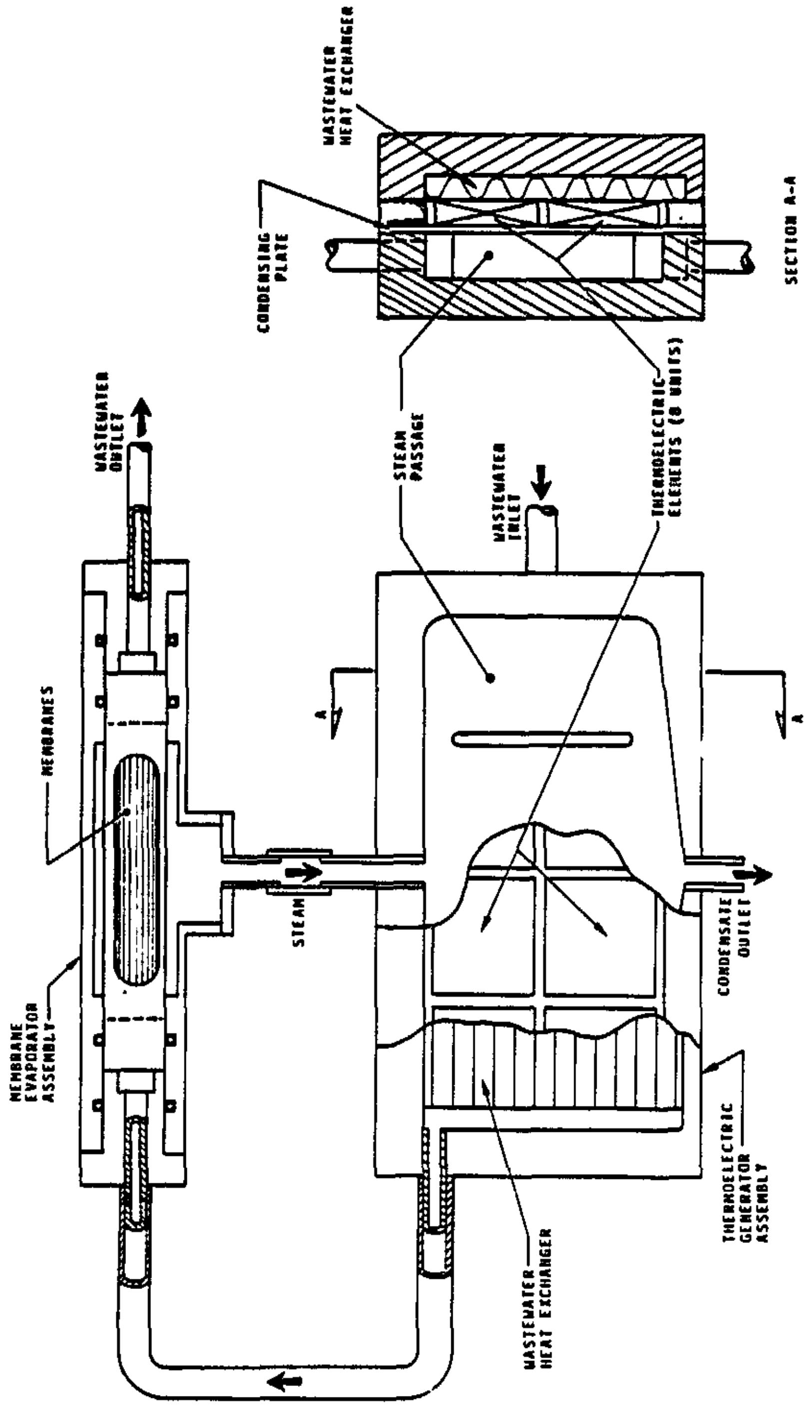

FIGURE 4
EVAPORATOR/REGENERATOR

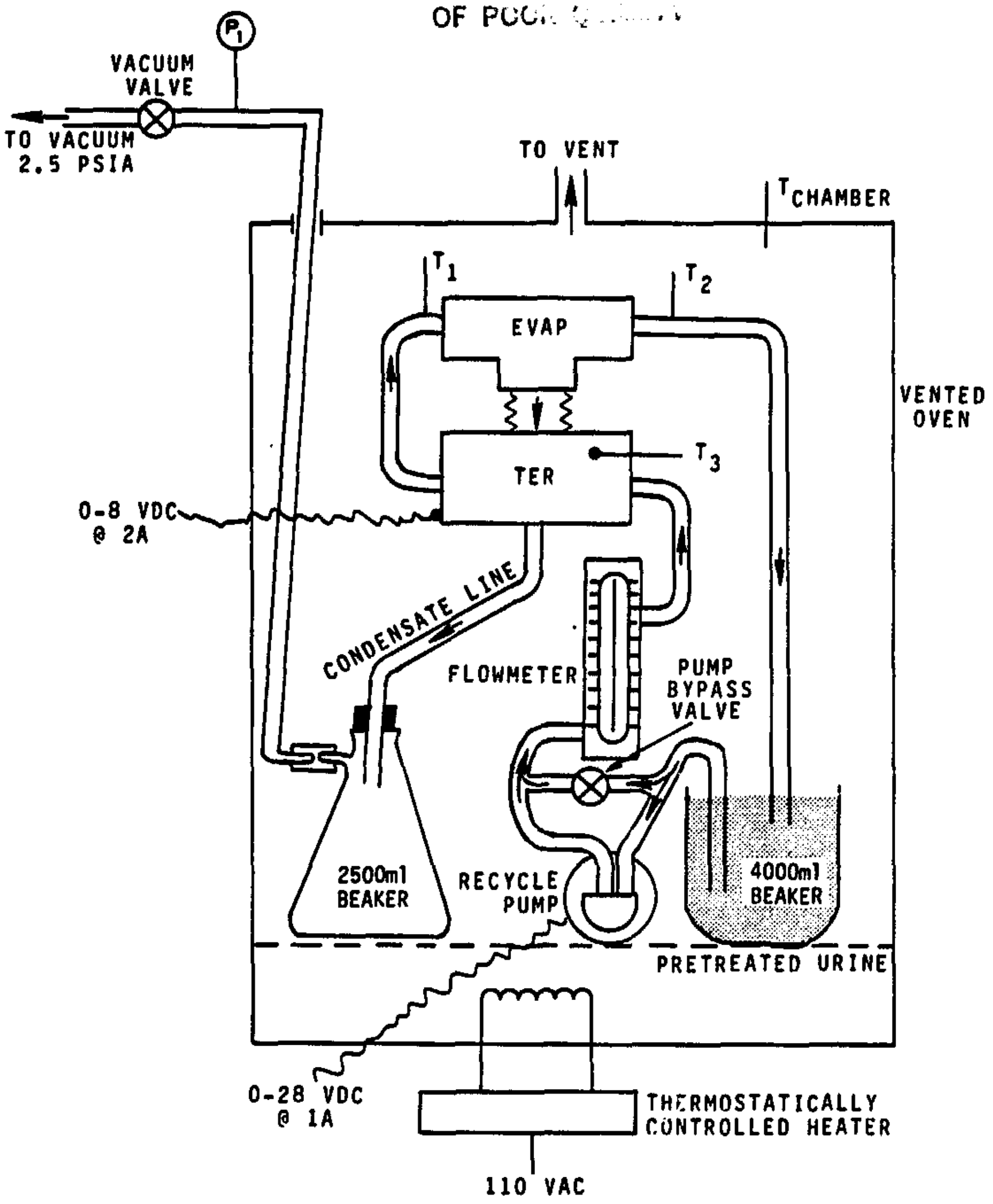

FIGURE 5

SUBSYSTEM PACKAGING CONFIGURATION
TEST SETUP

MATERIALS CORROSION/DEGRADATION

Objective

The objective of this test program is to evaluate and demonstrate suitable corrosion/degradation resistance of materials to be used in the TIMES for exposure to chromic acid pretreated wastewater.

Discussion

All materials and joining processes that were anticipated for use in the chromic acid pretreated wastewater loop were identified and are as follows:

Titanium per AMS 4901 with an electron beam weld joint
Titanium per AMS 4901 with a fusion weld joint
Stainless steel per AISI 347 with a nickel braze joint
Polysulfone, annealed and non-annealed, solvent wiped
Amicon T640 membrane potting compound
Viton V747-75 o-ring material

Each of the materials and joining processes is described in available literature as having excellent corrosion/degradation resistance to moderately concentrated chromic acid.

A 66°C (150°F) pretreated urine bath test setup as illustrated in Figure 6 was assembled. Pretreated urine was added during the testing to maintain bath level. Solids levels ranging from 4 to 40 percent were obtained during the testing, and pH level was maintained between 4 and 6. This test sequence was designed to simulate actual subsystem exposure conditions for a minimum of 180 days.

Figure 7A shows the AMS 4901 titanium with an electron beam weld joint, before testing and after 270 days immersion in the test bath. No corrosion or deterioration of any kind is evident under 10X magnification.

Figure 7b shows the AMS 4901 titanium with a fusion weld joint, before testing and after 270 days immersion in the test bath. No corrosion or deterioration of any kind is evident under 10X magnification.

Figure 8a shows the AISI 347 stainless steel with a fusion weld joint, before and after 270 days immersion in the test bath. No corrosion or deterioration of any kind is evident under 10X magnification.

Figure 8b shows the AISI 347 stainless steel with a nickel braze joint, before and after 270 days immersion in the test bath. No corrosion or deterioration of any kind is evident under 10X magnification.

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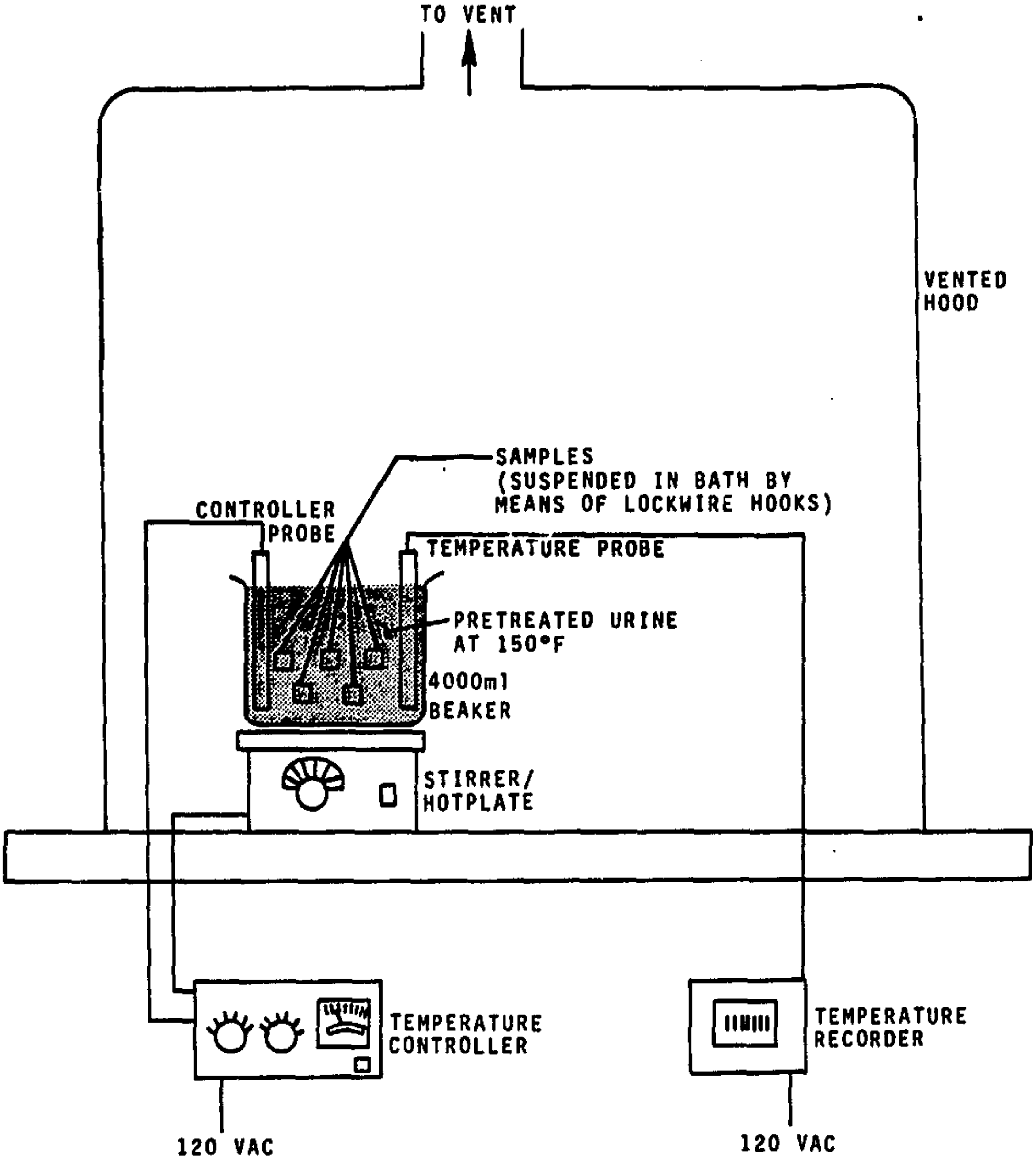
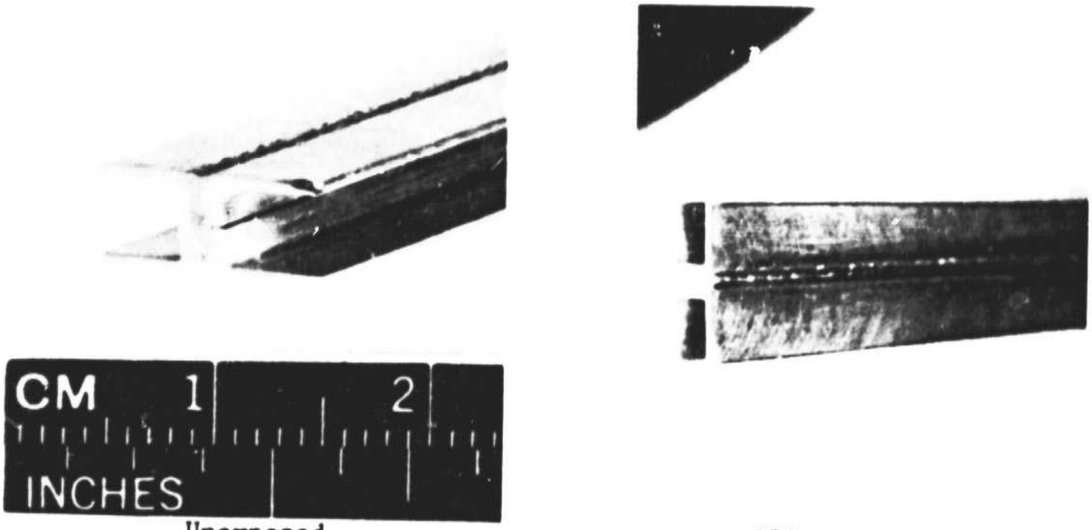


FIGURE 6

CORROSION TEST SETUP

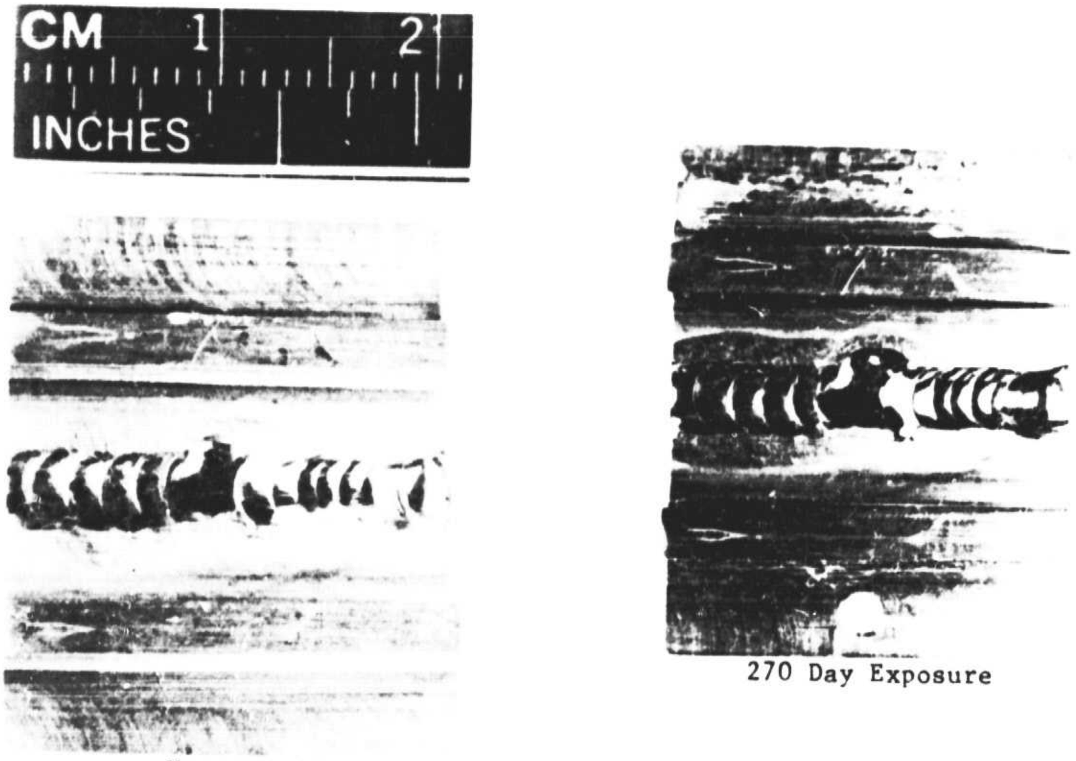


Unexposed

270 Day Exposure

FIGURE 7a

TITANIUM PER AMS 4901
ELECTRON BEAM WELD JOINT

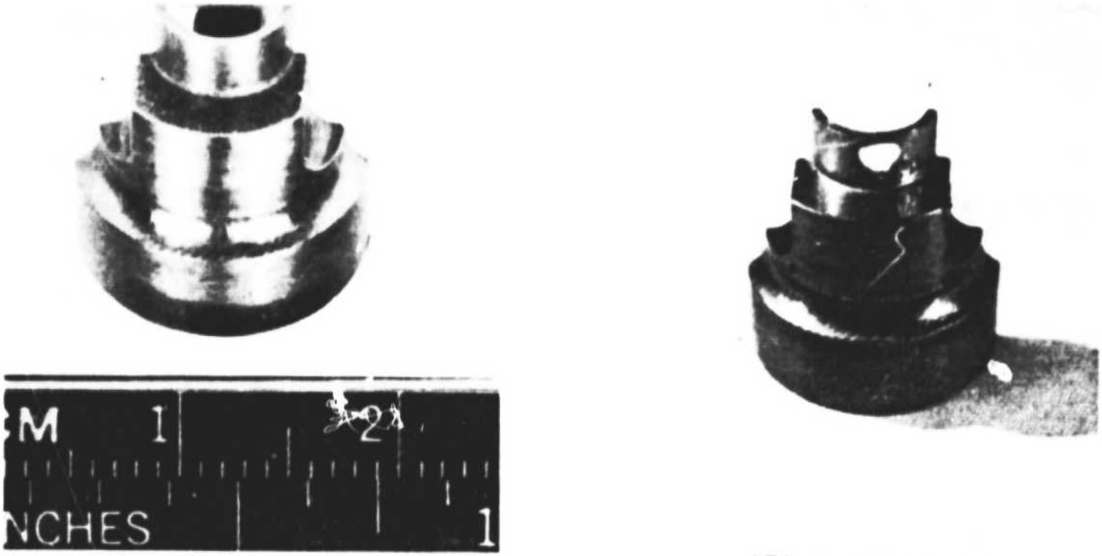


270 Day Exposure

Unexposed

FIGURE 7b

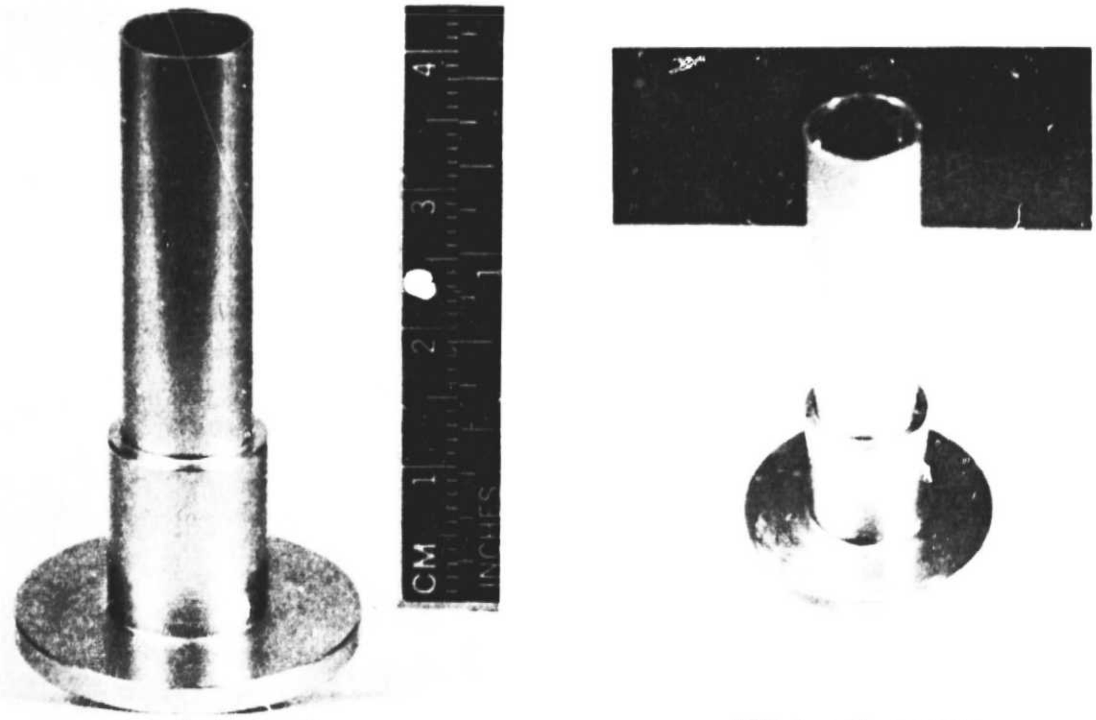
TITANIUM PER AMS 4901
FUSION WELD JOINT



Unexposed **270 Day Exposure**

FIGURE 8a

STAINLESS STEEL PER AISI 347
FUSION WELD JOINT



Unexposed **270 Day Exposure**

FIGURE 8b

STAINLESS STEEL PER AISI 347
NICKEL BRAZE JOINT

Figure 9a shows four samples of polysulfone after 210 days immersion in the test bath. Sample 1 is non-annealed, sample 2 was annealed at 166°C (330°F) for 4 hours after machining, sample 3 went through the anneal cycle prior to machining, and sample 4 was annealed before and after machining. All four samples were dipped in the bonding solvent, methylene chloride, and air dried overnight before being placed in the test bath. No crazing was observed in any of the samples after the solvent dip. Crazing can occur in polysulfone if excessive internal stress exists when the material is exposed to a solvent; the anneal is designed to reduce internal stress but, as evidenced by our samples, the material was stable as received and had negligible stress introduced during machining. Examination of all four samples under 10X magnification showed no detectable deterioration.

Figure 9b shows a potted membrane header consisting of polysulfone hollow fiber membrane stubs potted into a polysulfone shell with Amicon T640 membrane potting compound, after 210 days of immersion in the test bath. No detectable deterioration in either the materials or the bonding joint was observed under 10X magnification.

Figure 9c shows a length of a Viton V747-75 (MIL-R-83248 CL1 TYI) o-ring after 210 days of immersion in the test bath. No detectable deterioration was observed under 10X magnification and no measurable changes in durometer were detected.

Emission spectrographic analysis of the solid residue collected from the test bath has indicated the presence of the following elements in the indicated concentration ranges:

> (The instrument categorizes the content of each element of the sample into the following ranges that are specified as a percent of the total sample.)

Major (15 to 100% range): Na, Cr
Minor (5 to 20% range): Ni
Present (1/2 to 2% range): Mg, P, Ca
Trace (0.1 to 1% range): Mn, Si, Cu

The results are predictable except for the high nickel concentration. The high nickel concentration is attributable to the high purity nickel wires that were used to suspend the samples in the bath; the wire eventually corroded away and were replaced with AISI 304 wires. Therefore, an additional fall-out from this test program is the fact that high purity nickel is unacceptable for exposure to 150°F pretreated urine.

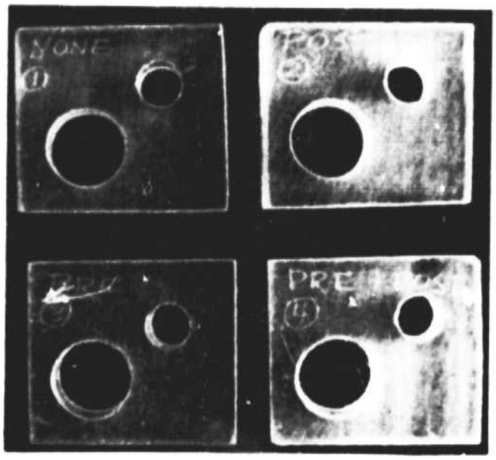


FIGURE 9a
POLYSULFONE

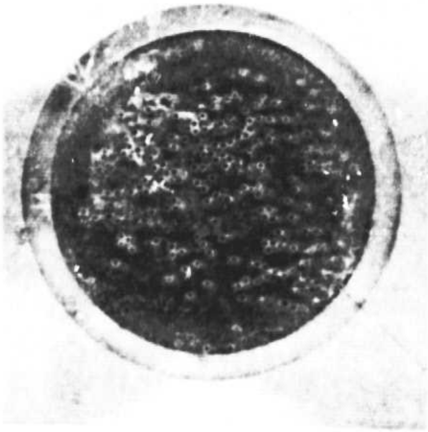


FIGURE 9b
T640 POTTED MEMBRANE HEADER

FIGURE 9c
VITON O-RING

Summary

Testing has demonstrated the suitability of the following materials for use in chromic acid pretreated urine at 66°C (150°F) for a minimum of 210 days.

- Titanium per AMS 4901
  - Electron beam welded
  - Fusion welded

- Stainless steel per AISI 347
  - Fusion welded
  - Nickel brazed

- Polysulfone bonded with a methylene chloride solvent-- annealed at 166°C ± 2.8°C (330°F ± 5°F) for 4 hours

- Amicon T640 membrane potting compound

- Viton V747-75 (MIL-R-83248 CL1 TYI)

Based on these results the tested materials have been demonstrated to be capable of exceeding the mission requirement of 180 days.

DEVELOPMENT COMPONENT TESTING

1/3 SCALE THERMOELECTRIC REGENERATOR/HOLLOW FIBER MEMBRANE EVAPORATOR EVALUATION

Objective

The objective of this task is to evaluate the performance of the thermoelectric regenerator/hollow fiber membrane evaporator combination using hardware consisting of one full size regenerator module (three modules are required for the full size subsystem) coupled with a full size evaporator containing membrane surface area equivalent to 1/3 of that anticipated for the full size subsystem.

Discussion

The 1/3 scale thermoelectric regenerator/hollow fiber membrane evaporator assembly was installed in the vented oven as described by Figure 10. This assembly simulates the subsystem insulated process package illustrated in Figure 2. Refer to the Subsystem Description section of this report for a description of the process package operation.

Prior to the start of the test air was flowed through the porous plates to demonstrate that the plates were dry. At the end of the test a bubble-point check showed the plate to be completely wetted and capable of sealing against a gas pressure differential of 46.9 kPa (6.8 psi). A porous plate flow test with a fully wetted plate yielded water flow rates plotted in Figure 11. At a porous plate pressure differential of 3.4 kPa (0.5 psi), projected flow capability for the full TER assembly would be 5.6 kg/h (12.4 lb/h) which is approximately six times the required throughput capacity.

The data obtained during transient start-up and run of the 1/3 scale TER/HFM assembly is contained in Appendix B, Development Component Test Data, and plotted in Figure 12. During the first 15 minutes of the test, the recycle fluid temperature drop across the HFM averaged approximately 4.7°C (8.5°F), the magnitude of the temperature drop indicating the throughput or water evaporated. Comparing this to the 2.8°C (5°F) design condition indicates margin on HFM throughput.

This initial testing of the Evaporator/Regenerator combination indicated that the hardware as configured performed properly for 10 to 15 minutes after start-up but performance quickly decayed and eventually stopped within 30 minutes after start-up. Testing with the TER removed and a water cooled condensing coil substituted indicated that the performance rate can be made to fully recover by momentarily applying a vacuum source downstream of the water cooled condensing coil. Applying the vacuum upstream of the water cooled condensing coil results in no recovery of performance.

The series of tests with the water cooled condensing coil indicates that the noncondensible gases in the system are being swept to the condensing areas by the steam flow; the steam is removed by condensation and the noncondensible gases are left in the condensing chamber to build up and eventually blanket the condensing surfaces. Exposure of the chamber to vacuum for a short period of time vents the accumulated noncondensible gases and allows continuation of the steam condensation.

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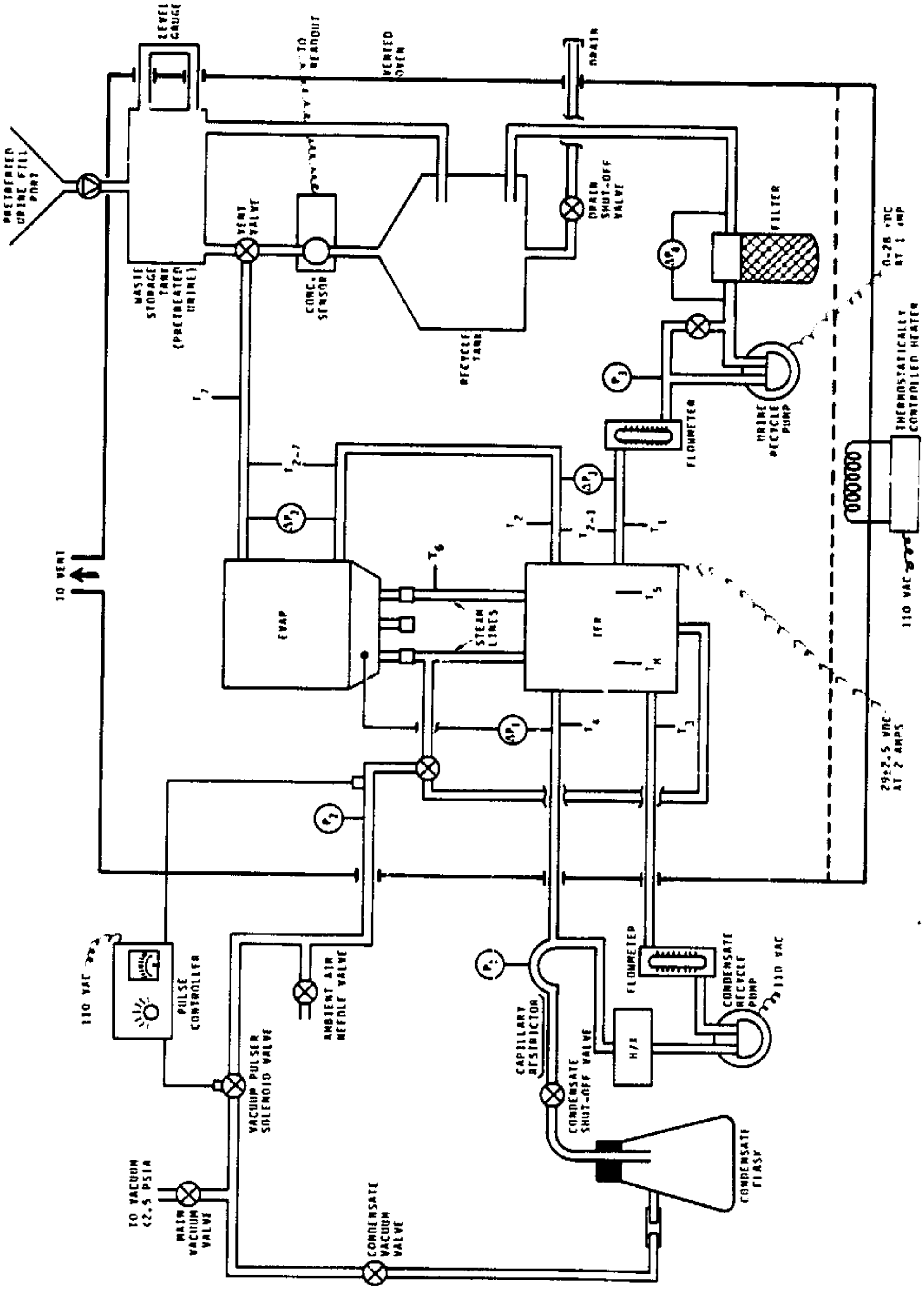

FIGURE 10
TER/EVAP DEVELOPMENT COMPONENT TEST SETUP

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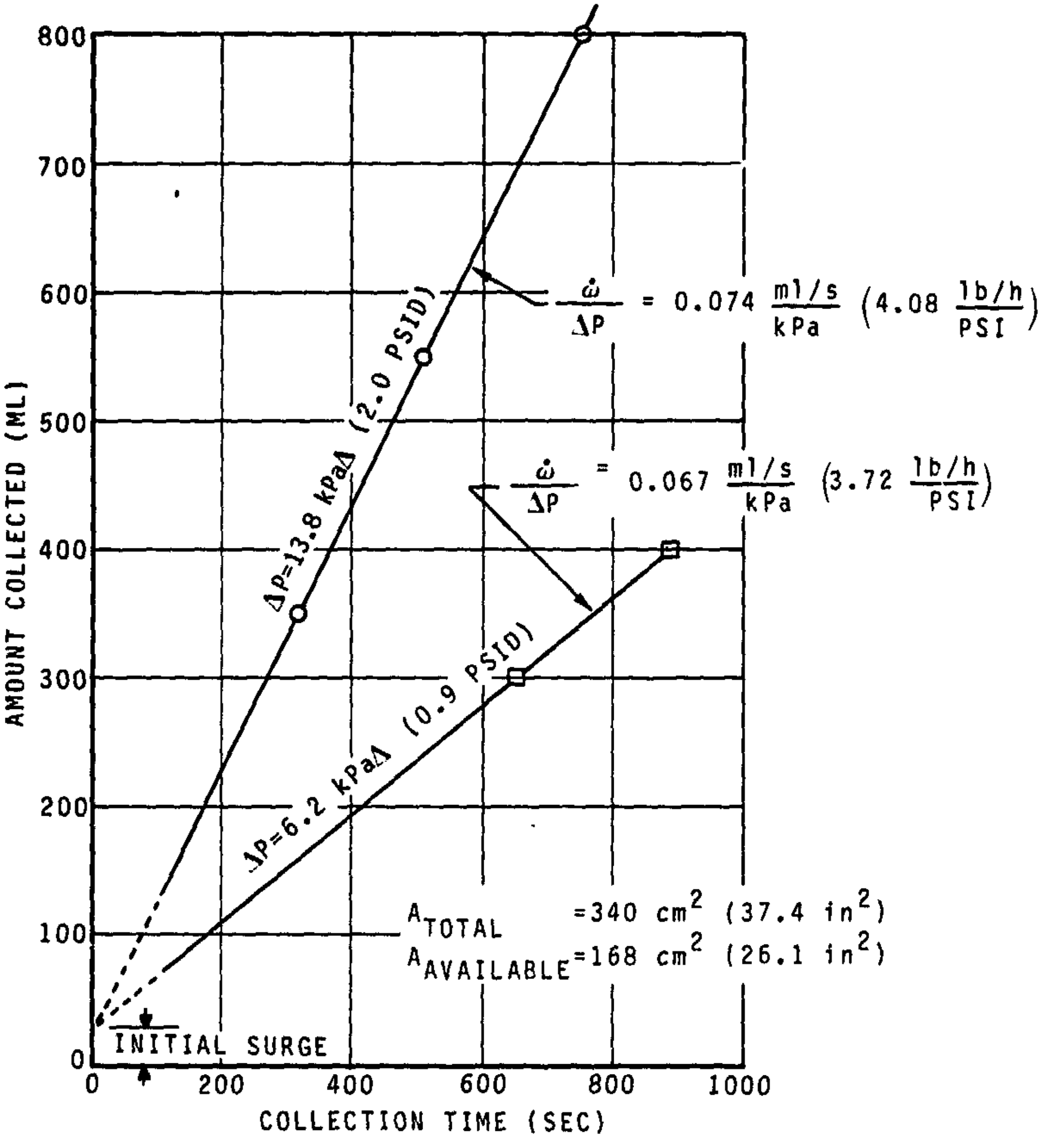

FIGURE 11
TIMES POROUS PLATE FLOW

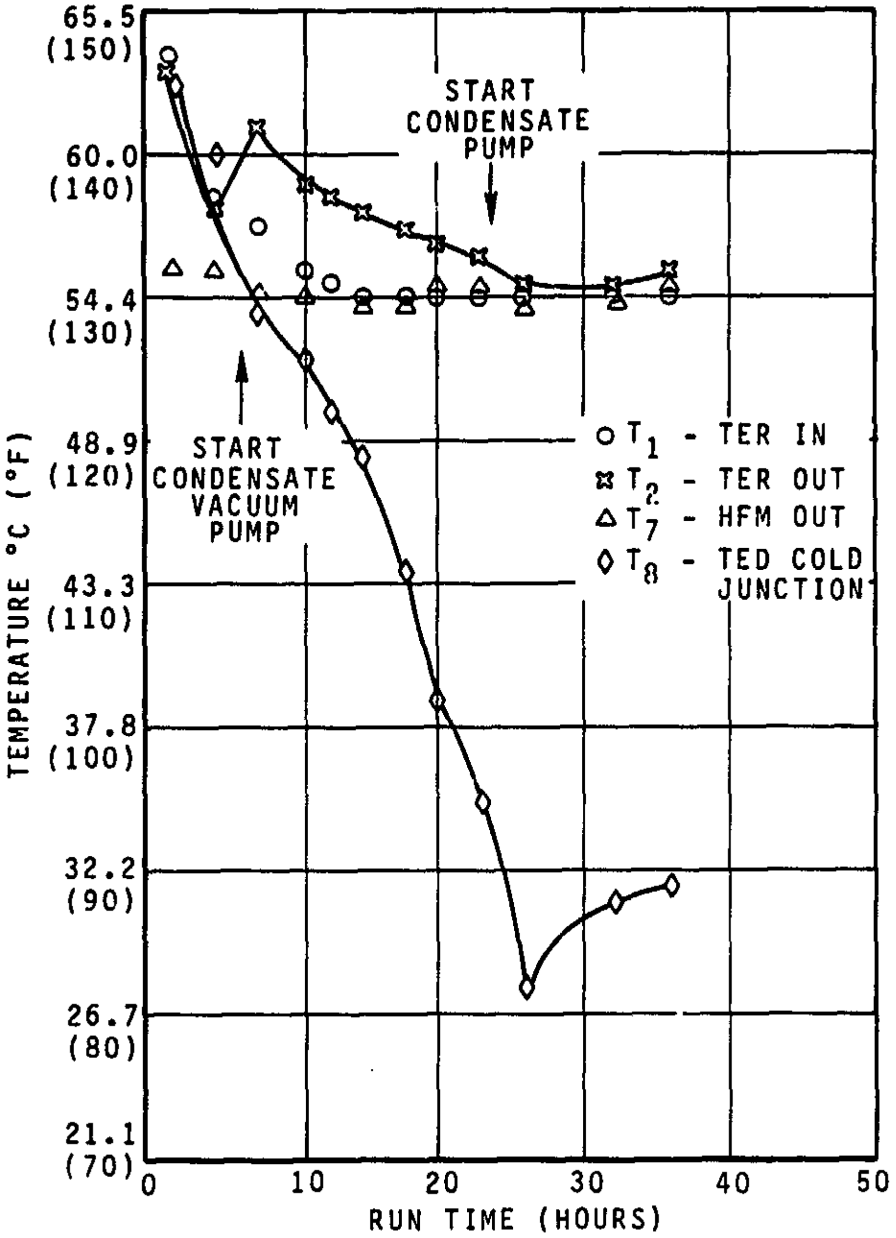

FIGURE 12
TIMES 1/3 SCALE TEST RESULTS

The TER design was modified to add ports in the condensing chambers for the removal of the noncondensible gases. Testing of the development hardware with the modified TER demonstrated that removing noncondensible gas directly from the TER vapor passages produces a configuration that maintains the HFM temperature drop above 2.8°C (5°F) during steady state operation. The temperature differentials across the membranes, the urine heat exchanger, and the thermoelectric elements were as anticipated, and the condensate water delivery rate checked out to verify the thermal balance of the subsystem. The removal/bleed rate of the noncondensible gas/water vapor was approximately 2.7×10^{-5} kg/h (6×10^{-5} lb/h).

Testing with the pressure controlling capillary restrictor on the condensate removal line showed that this configuration operates extremely well, with a typical product water (condensate) production rate at 26.5 VDC thermoelectric voltage with unconcentrated urine of 5 ml/minute. This rate translates to 0.90 kg/h (1.98 lb/h) for the full size subsystem.

Results

Testing of the thermoelectric regenerator/hollow fiber membrane evaporator assembly with the capillary tube restrictor has been run with the thermoelectric elements at 26.5 VDC and at 29.0 VDC with urine recycle loop solids concentrations up to 21%.

The membranes were tested for processing rate after approximately 240 hours of operation (the equivalent of 30 8-hour days) using non-concentrated urine at 29 VDC. The processing rate was 3% lower than the specification requirements and the membrane area of the full size unit was increased accordingly.

Product water removal pressures were investigated and it was determined that a pressure range between 10.3 (1.5) and 13.8 kPa (2.0 psia) would provide the required product water removal rate and allow the accumulator to be sized for this range while still allowing a reasonable margin for mechanical tolerances.

Product water samples have been analyzed and except for slightly elevated organic carbon levels and ammonia levels, the product water appeared acceptable. These impurities will be removed by the posttreatment charcoal bed and ion exchange resin bed, respectively.

URINE LOOP RECYCLE PUMP

Objective

The objective of this task is to performance and endurance test the urine loop recirculation pump prior to incorporation into the subsystem. The pump is to be run continuously in pretreated urine at varying solids concentrations for a period of 90 days.

Discussion

This test was performed to verify the durability of the Micropump P/N 12A-31-316-80647 for use in the TIMES subsystem. The pump was run in pretreated urine at 66°C (150°F) for a period of 90 days at which time the pump was leakage and performance tested, and subjected to disassembly and visual inspection to determine the 90 day degradation.

The endurance test setup is shown in Figure 13, and the pump leakage and pump performance test setups are shown in Figure 14. Endurance testing was run using 66°C (150°F) pretreated urine with a solids concentration ranging from 4 to 40%. Table 1 summarizes the test results. As can be seen from the test results, the flow degradation after 90 days is 36%, resulting in a flow value of 152 kg/h (336 lb/h). This value exceeds the 136 kg/h (300 lb/h) value assumed as the required subsystem flow. The loss in flow was attributed to internal leakage.

Figure 15 shows the gears and end faces of the pump. The diameter of the drive gear shaft has been worn from 0.318 cm (0.125 inch) to 0.267 cm (0.105 inch) and the driven gear shaft from 0.318 cm (0.125 inch) to 0.292 cm (0.115 inch). This wear could be reduced by selecting a harder shaft material, but the "off-the-shelf" shaft is sufficiently durable to meet our subsystem requirements. The end faces show a wear pattern with very little removal of material.

Results

Based on the endurance testing performed during this task, it may be concluded that the selected urine loop recirculation pump will perform as required for a minimum of 90 days continuous operation.

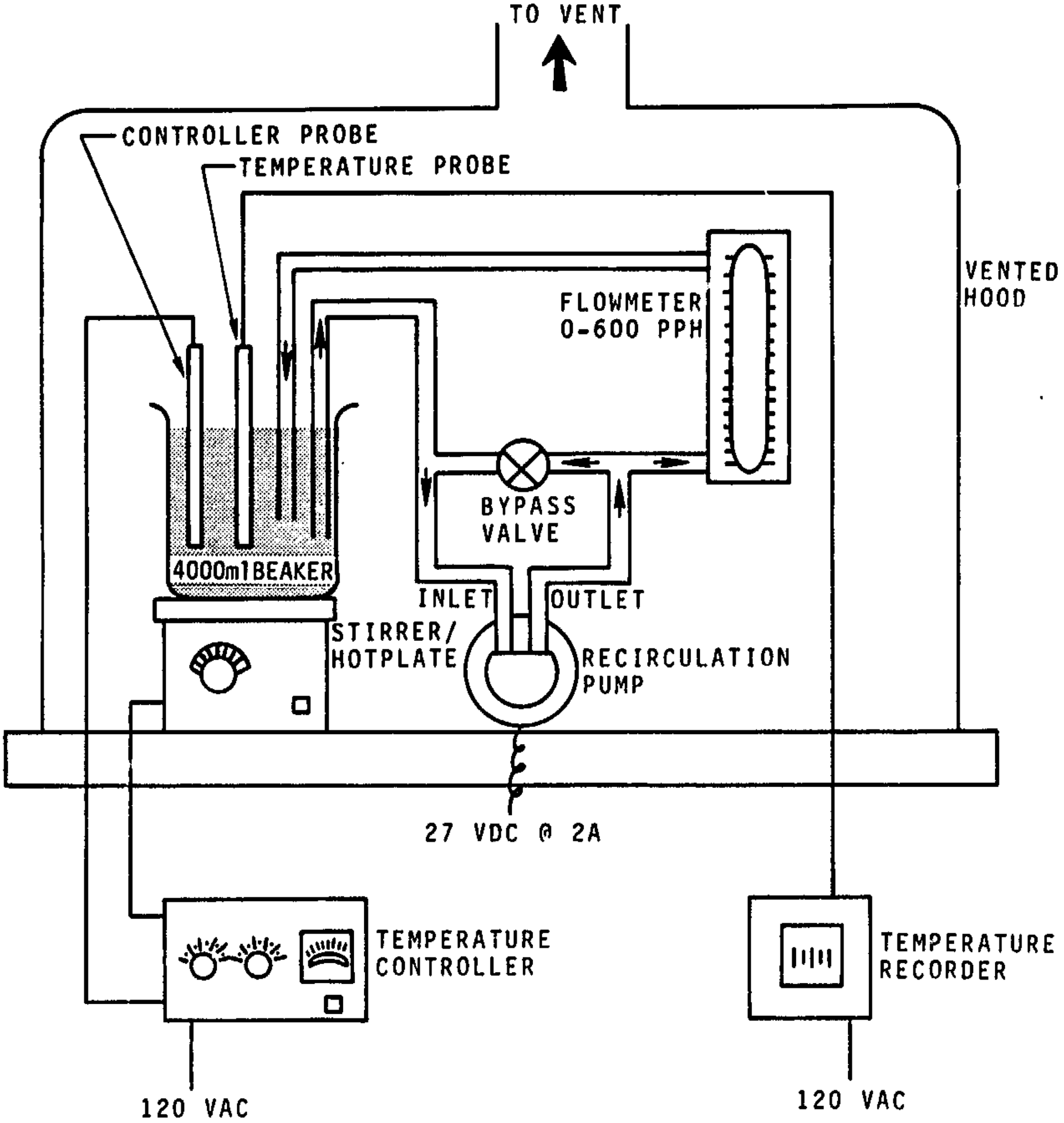

FIGURE 13
URINE LOOP RECIRCULATION PUMP TEST SETUP

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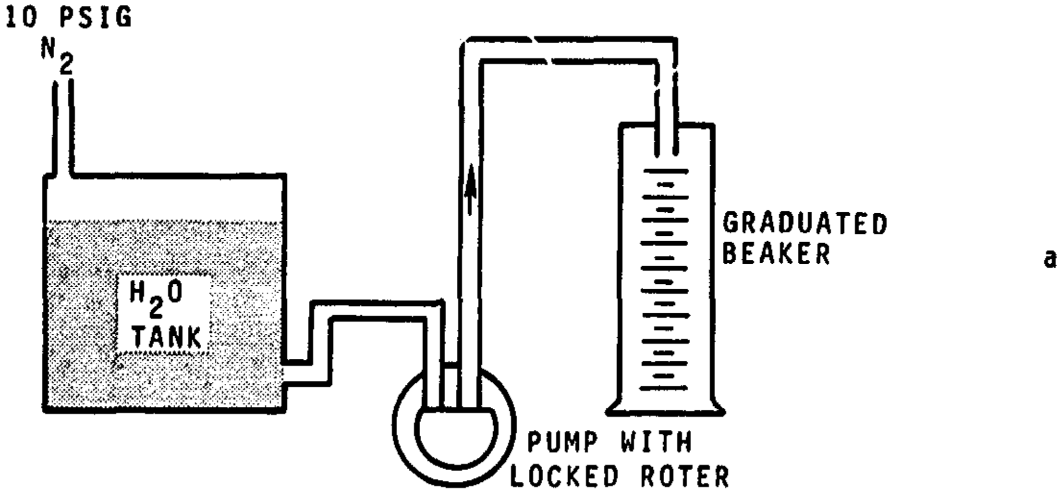
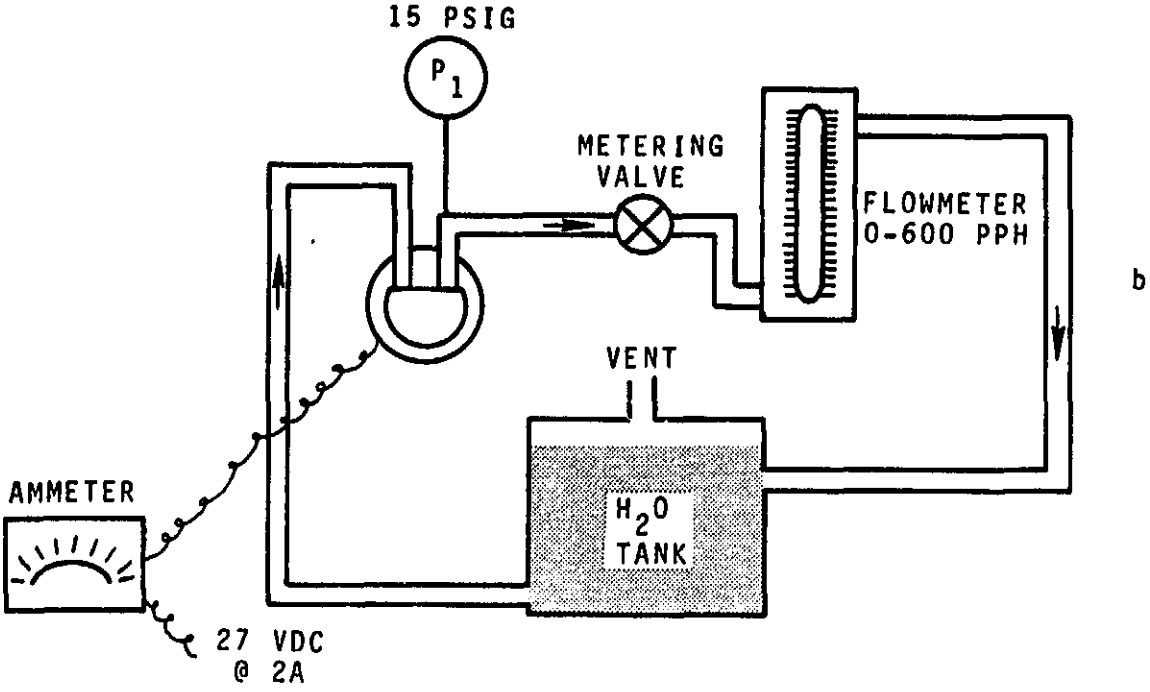


Pump Leakage



Pump Performance

FIGURE 14

URINE LOOP RECIRCULATION PUMP
LEAKAGE AND PERFORMANCE SETUP

Table 1
URINE LOOP RECIRCULATION PUMP LEAKAGE AND PERFORMANCE

Operating Pump Time (Days)	Flow kg/h @ 103.4 kPa (lb/h @ 15 psid)	Degradation (%)	Pump Current Amps @ 27 VDC	Locked Rotor Internal Leakage kg/h @ 69.0 kPa (lb/h @ psid)
0 (new)	238 (525)	---	1.30	12.2 (27)
49	217 (478)	9	1.30	50.3 (111)
90	152 (336)	36	1.05	56.2 (124)
Subsystem Specification	136 (300)	---	---	---

FIGURE 15a

DRIVE AND DRIVEN GEARS
AT 0 DAYS

FIGURE 15b

DRIVE AND DRIVEN GEARS
AT 90 DAYS

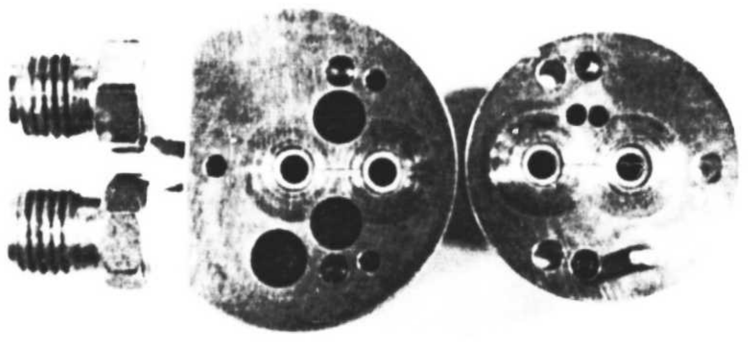


FIGURE 15c

VISUAL DEGRADATION
URINE LOOP RECIRCULATION PUMP

SUBSYSTEM DESIGN

The preprototype TIMES subsystem has been designed to conform with all requirements of NASA Statement of Work for Development of a Urine Water Recovery Subsystem, November 1977, contained as Exhibit A in NASA Contract NAS 9-15471, Urine Water Recovery Subsystem.

OVERALL SUBSYSTEM REQUIREMENTS

General Design Requirements

The operational lifetime for individual components and the overall subsystem is 6 months minimum, occurring anytime within 2 years of hardware delivery to NASA. Scheduled maintenance, including replacement of individual parts, is an allowable approach. Provisions are incorporated to provide external buffered analog signals to allow remote monitoring and/or recording of all subsystem sensor outputs.

Specific Design Requirements

Specific design requirements are:

> Capable of processing of urine, urinal rinse water, and shower concentrated brine of three crew members for 180 days without resupply.
>
> Capable of recovering at least 95% of the water as potable quality water.
>
> Total dry weight to be less than 136.1 kg (300 lb), total volume to be less than 0.80 m^3 (28.25 ft^3).
>
> Specific energy requirements to be less than 334.4 W-h/kg (152 W-h/lb) of product water from nonconcentrated raw urine at 26.5 VDC power supply.
>
> Expendable requirements to be less than 11.8 kg (26 lb) to process 1814.4 kg (4000 lb) of raw urine.
>
> Process rate to be at least 0.77 kg/h (1.7 lb/h) of product water from nonconcentrated urine at nominal 29 VDC power supply to the thermoelectric regenerator after thirty days of eight hours per day operation.
>
> Water loss rate from vacuum purging to be less than 0.014 kg/h (0.03 lb/h).

Process water quality shall exceed the standards recommended by the National Academy of Science - National Research Council Committee on Toxicology in their Report of the Panel on Potable Water Quality in Manned Spacecraft, August, 1972.

Test Facility Services

Facility services available at JSC for the TIMES subsystem are:

Power 29 ± 2.5 VDC
115 VAC, 1 Phase, 60 Hz
115 VAC, 1 and 3 Phase, 400 Hz

Water pumped nitrogen with pressure selectable to 3448 kPa (500 psia)

Industrial distilled water (0.5 megohm-cm)

Chilled water at 7.2°C (45°F)

Hydrogen with pressure selectable to 204.8 kPa (15 psig)

Space vacuum simulation

SUBSYSTEM ANALYSIS

The bulk of the subsystem analysis activity occurred during the preliminary design and design phases of the TIMES program. Subsequent support activity provided component redefinition during development and then evaluation of unit test performance at the end of the program.

As part of the preliminary design activity, trade studies were conducted and focused on the systems configuration and sizing. In particular, these studies evaluated the pressure control scheme, the temperature control scheme, a heating insulation study, and sizing of the thermoelectric regulator (TER), hollow fiber membrane (HFM), and the pumps and tanks. With these results, the thermal control study defined in detail the dynamic control characteristics, and the system performance information was used to generate the system operating logic. As the basis for defining the system operating characteristics, a system computer program was generated and approximately one hundred program cases were run to provide the basic trade study curves and parametric information. Subsequent development activity modified the value of some of the parameters, but the initial preliminary design effort provided a valid baseline for performance-based decisions. Figure 16 outlines the scope of the computer program and Analysis Memo 78-92 defines it in detail. (The Analysis Memos are contained in Appendix C.) The program cases are listed in Memo 78-107 and the results are documented in Memo 78-104.

The most significant trade studies involve the schematic selection of the temperature control and evaporator pressure control schemes. In the TIMES process, the heat required to vaporize the wastewater in the evaporator is drawn from the wastewater flow in the recycle loop. The heat is then recovered and pumped back into the recycle loop as the purified steam condensed on the porous plate in the TER. In addition to the process heat, which is conserved, there is heat addition due to the power required for the heat pump, and there is heat leak from the hot recycle loop. Even if the heat leak were exactly balanced with the pumping power required at 26.5 VDC, the heat pump inefficiencies at 29 and 31.5 VDC would cause net heat addition to the system. Therefore, an active thermal control scheme is required. Cooling could be implemented either in the hot recycle portion of the loop or in the cold condensate portion. If the cooling is accomplished in the recycle portion, the heat pump must pump the process heat plus the excess heat to be rejected. With cooling accomplished on the condensate side, only the process heat need be pumped. Since there is a power penalty associated with pumping the heat, it is desirable to pump the minimal amount of heat. Therefore, the system design objective should be to minimize heat leak on the recycle portion of the loop and provide all the heat rejection on the cold condensate portion of the loop. This logic provided the basic thermal control scheme in which the package is heavily insulated and in which cooling is accomplished by recirculating the condensate through an external air-cooled heat exchanger. As can be seen in the computer runs, the most efficient operation occurs with high evaporator temperature. However, there is a tendency with excessive temperature for the urea to break down into ammonia. Since it was believed that 71.1°C (160°F) should be the upper operating limit, 65.6°C (150°F) was selected as the control set point so that excursions could be tolerated. The control trade study then selected a proportional integral control scheme and defined the constants for that scheme.

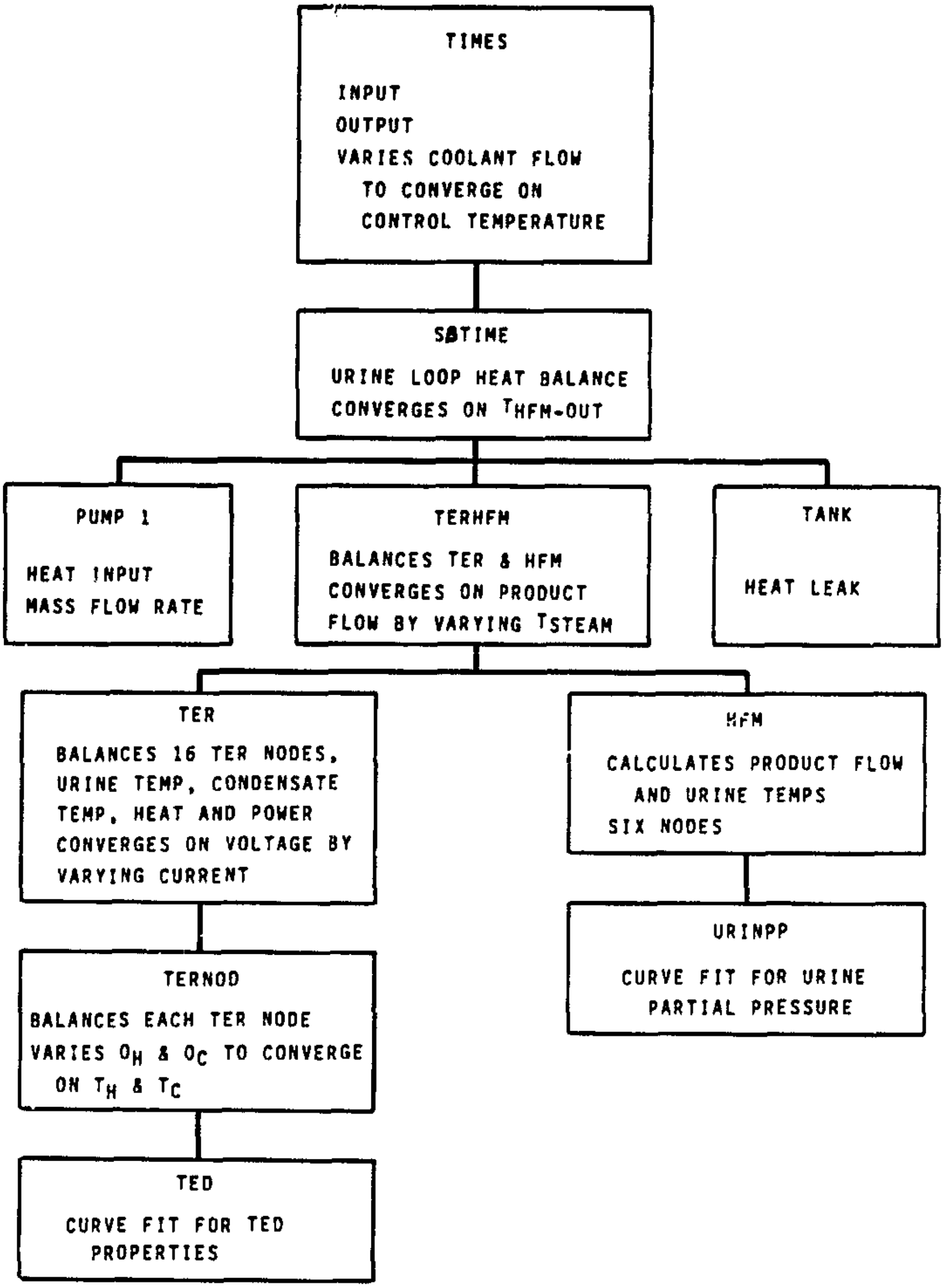


FIGURE 16
PROGRAM LISTING TREE FOR TIMES

With a condensate side cooling scheme, the temperature control interacts with the pressure control and water delivery schemes. To understand the interaction, the physics of the pressure control must be understood. The steam cavity pressure floats to balance the vapor flow through the HFM against the heat flow through the TER. The link between the two is the water pressure temperature-saturation relationship. Although not necessarily accurate, for purposes of basic understanding, the HFM can be considered to be permeable membrane. Thus the thoughput is proportional to the permeability and to the difference between partial pressure of urine and the partial pressure of water in the steam cavity. At a constant inlet temperature as the urine concentration increases, the saturation pressure of water in the recycle loop decreases. (Memo 78-93 contains the urine properties.) Since the driving pressure has decreased, the steam pressure in the steam cavity must also decrease to maintain throughput. Also, as the premeability changes, the steam cavity pressure floats to a new value to maintain throughput. This characteristic is particularly strong with Nafion in which the permeability is a function of the solids concentration. It can thus be seen that the steam cavity pressure and the water throughput will float as the solids concentration and permeability vary.

Steam in the steam cavity condenses on the porous plate which is thermally coupled to the cold junction of the thermoelectrics in the TER. Thus the cold junction assumes a temperature corresponding to the saturation pressure of the steam in the cavity. Since the hot junction of the thermoelectrics is equal to the urine temperature which is controlled to a fixed value, the steam saturation pressure-temperature relationship sets the temperature difference across the TER. The heat throughput of the TER is linked to the condensing steam flow via the latent heat of vaporization. As seen in Figure 17, for constant voltage the TER heat transfer/temperature difference performance characteristic is a linear relationship. As the heat flow decreases, the temperature difference increases. Considering the interrelationship between the TER and the HFM, the pressure dependence can be established. As the steam pressure decreases, the HFM throughput increases and the TER throughput decreases. Conversely, as the steam pressure increases, the HFM throughput decreases and TER throughput increases. Since steam pressure is the link between the two units, it must float or be controlled to balance the throughput. The steam and product water pressure is approximately 13.8-20.7 kPa (2-3 psia). Since the product water must be delivered to water tanks back pressured to 137.9 kPa (20 psia), the water delivery scheme interacts with the pressure control scheme.

As part of the preliminary design activity, several pressure control schemes were evaluated. They are as follows:

- Delivery Pump Speed Control - A pump's delivered pressure head is a function of rotating speed. Thus pump speed control can be used to indirectly control the condensate delivery pressure. However, since the delivery flow rates are small, 2.2-6.6 kg/h (1-3 lb/h product flow) and a tight control band 1.4 kPa (0.2 psi), was required, it was decided that this control scheme required an excessive sensitivity. It was therefore eliminated.

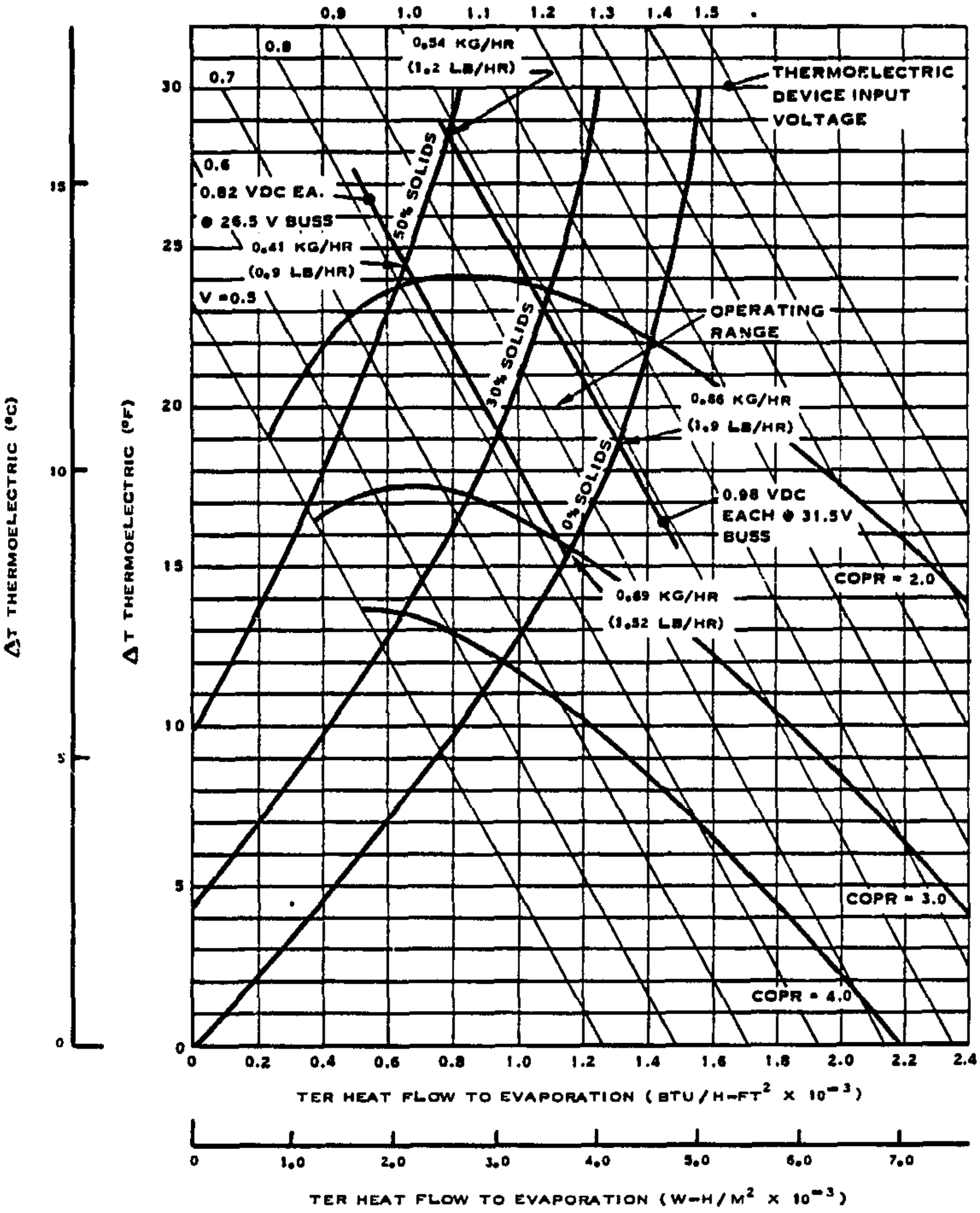


FIGURE 17
TIMES SUBSYSTEM PERFORMANCE MAP

- Product Water Pressure Regulator - This scheme would maintain the steam chamber pressure by controlling the water pressure downstream of the porous plate by means of a pressure regulator. This pressure regulator would be at the inlet to the water delivery pump. This scheme was rejected due to the cost and complexity associated with the pressure regulator.

- Constant Heat Pump With Control Bypass - This is essentially the same as the first scheme except that a controlled variable pump bypass would be utilized to control the feed pressure to the pump. Again, as in the first option, the control sensitivity would provide an excessive complication to the system.

- Accumulator - In this approach pressure control is maintained by utilizing as essentially constant pressure accumulator to provide the product water reference pressure. As the accumulator fills, liquid level sensor in the device turn the pump on and off to provide delivery to the external tankage. This approach utilizes extremely simple control logic. The accumulators are simple in construction, with springs providing the pressure set points. As an added feature, this approach has easily changeable set points. As a result, for hardware simplicity and for development program advantages, it was selected as the baseline pressure control scheme.

It was initially considered that a slight partial pressure of nitrogen, approximately 1.7 kPa (0.25 psi), might be needed to provide the pressure drop required to flow condensate through the porous plate. However, in development, it soon became apparent that the non-condensable gas concentrated above the plate, thereby choking steam flow. Diffusion calculations supported the contention that nitrogen or air blanketing the porous plate would provide drastic reduction in throughput. Several techniques of preventing this concentration were evaluated, including a recirculating steam flow. However, the selected approach utilized a burp control scheme to eliminate the non-condensables and a capillary tube to fine tune the back pressure control. The burp control vents the steam chamber on a periodic basis to eliminate the non-condensables. The vent rate is sized to maintain the steam losses less than the 0.014 kg/h (0.03 lb/h) maximum allowable. With the capillary tube, the accumulator pressure is set at approximately 1.7 kPa (0.25 psi) lower than the minimum expected steam pressure. The tube is then sized for a 1.4 kPa (0.2 psi) pressure drop at the maximum liquid flow and maximum accumulator pressure. For any other condition, the tendency is to provide a lower than required pressure upstream of the capillary. This would then cause flashing in the feed tube to the capillary. However, one percent flashing will create sufficient vapor to dramatically increase the capillary pressure drop. It will thus raise the upstream pressure to the saturation conditions, thereby tending to minimize flashing. Therefore, the capillary tube provides a self-regulating control scheme in which the condenser pressure is maintained at saturation conditions with significantly less than one percent flashing. This scheme worked successfully during development testing. As part of the preliminary design effort, approximately six cooling concepts were considered. Significantly later in the program, additional refinements were considered and will be dealt with in detail in the section entitled "Improved Temperature Control." Since it is described there, the cooling system trade studies will not be reported on at this point. The selected baseline cooling scheme was picked for its simplicity. It consisted of recirculation of the condensate through an external heat exchanger with temperature control achieved by modulation of the recycle flow. Thus the cooling was achieved at the most optimum point, namely, the condensing side of the TER. The external heat exchanger was sized to provide the required heat rejection utilizing the cabin circulation airflow of approximately 0.188 m/s (37 ft/min). This also corresponds to a natural convection heat flow in an earth gravity environment. Temperature control is achieved by varying the flow rate through the condenser section and through the heat exchanger. The flow variation was achieved by pulsing the fluid at various time intervals. As the urine temperature exceeded its 65.6°C (150°F) set point, the flow would be increased and conversely a decrease in temperature would prompt a flow decrease. The control logic was based on a proportional plus integral scheme. Difficulty in implementing the scheme was due to the very low flow rates required for cooling, less than 55.6 kg/h (26 lb/h). With the large heat exchanger and the low flows, there were very long time lags associated with this system. It worked adequately during development, but an improved scheme is desirable.

Once the schematic configuration was finalized the preliminary design studies were directed towards sizing the TER, HFM, heat exchanger, tanks, and pump. Thermoelectric devices have an optimum coefficient of performance (COP) for this application at approximately 0.8 VDC impressed voltage. Considering the 26.5 VDC minimum voltage available for the TIMES, an optimum thermoelectric module would consist of a series string of 32 thermoelectric chips. This then sizes the baseline TER module. As part of the optimization, computer analyses predicted the performance of two, three and four TER modules in conjunction with various permeabilities and areas for the HFM. Since two TER modules could not meet performance for any of the conditions studied, this configuration was eliminated as a viable option. Figure 18 shows the specific energy for three and four TER modules. As can be seen in that figure, for all cases, the specific energy with three modules is significantly less than with four modules. Since specific energy is the major criteria for design selection, three TER modules were baselined. Additionally, since the difference in power amounted to approximately 20 watts and the weight increase for the fourth module would be insignificant compared to the 20 watt power penalty, three modules were further validated. The basic requirement for the HFM sizing is that the subsystem be capable of delivering a product water flow of 3.8 kg/h (1.7 lb/h) from non-concentrated urine with a supply voltage of 29 VDC. The computerized sizing based on the Amicon membrane is shown in Figure 19. An area of 0.35 m^2 (3.75 ft^2) was initially accepted to provide performance with some margin. With the subsequent shift to the Nafion membranes, the unit was resized based on the same criteria.

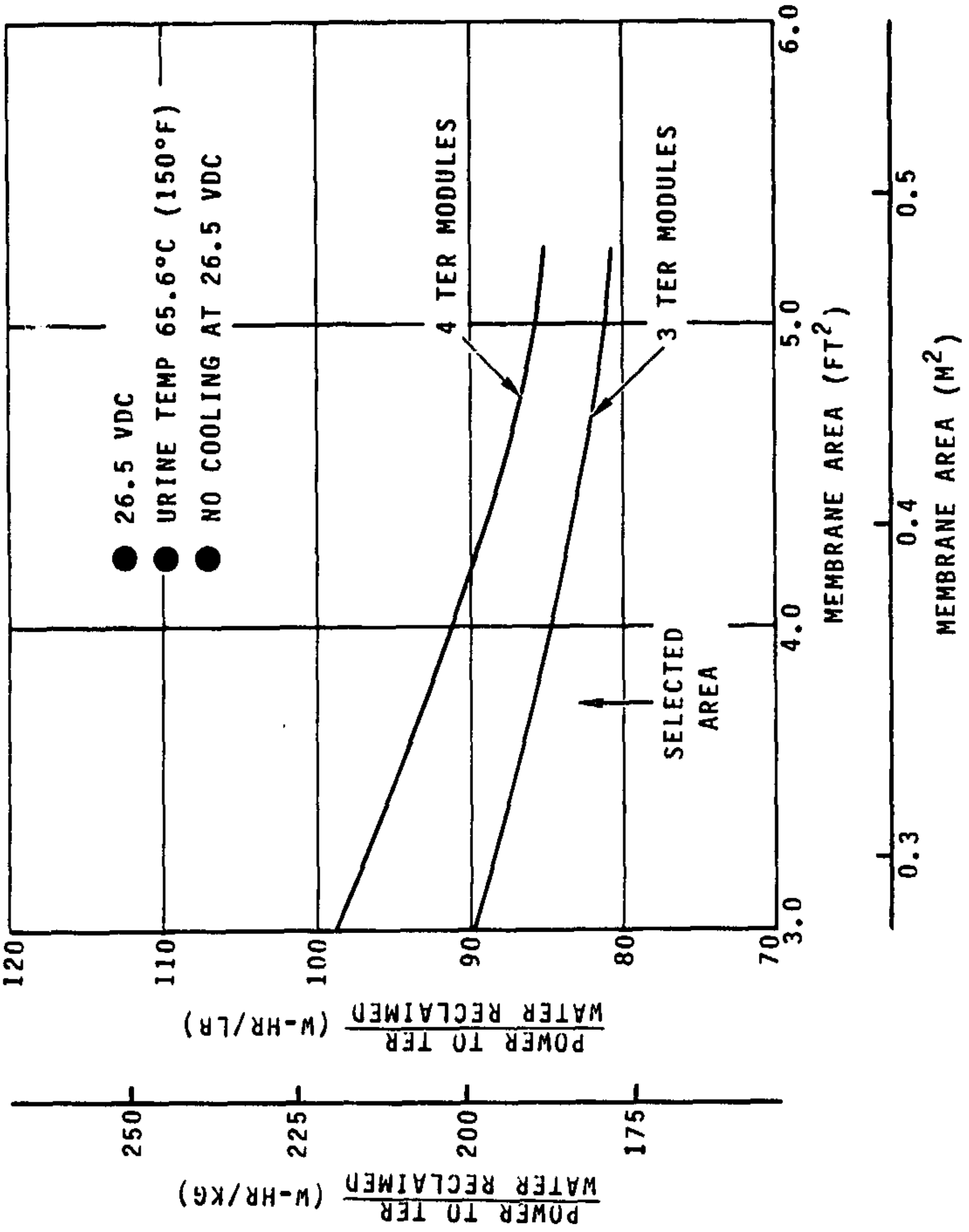


FIGURE 18
SPECIFIC ENERGY vs HFM AREA

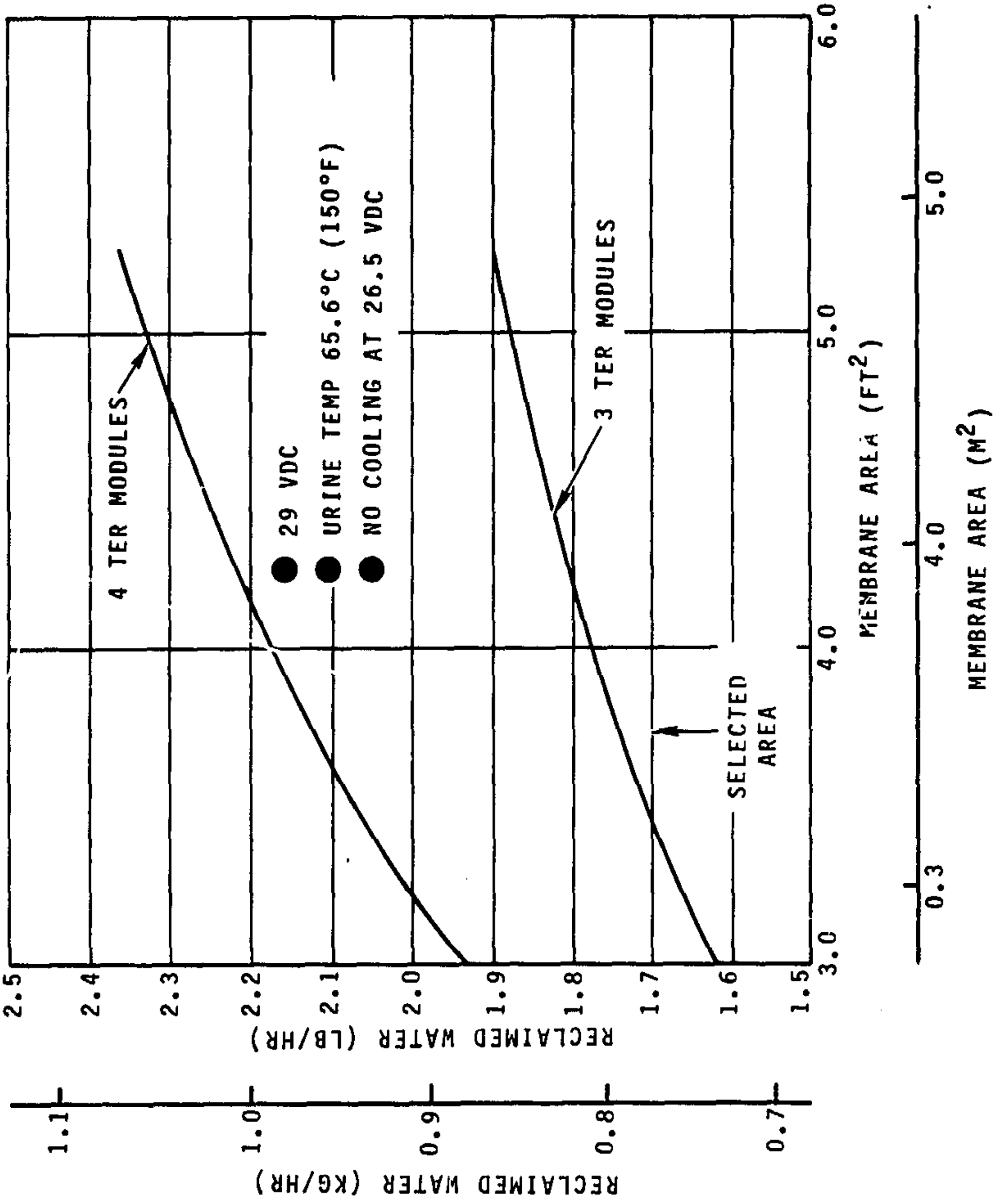


FIGURE 19
PRODUCT WATER vs HFM AREA

The basic water recovery and solids concentration model is used to determine the solids concentration at change-out to meet the 95 percent water recovery requirement. Figure 20 details the initial baseline water model which consisted of a mixture of urine, urine flush water, and brine. This is a total of 8.9 kg (19.65 lb) of water per day at a 3.1 percent solids concentration. This effect on final solids concentration can be seen in Figure 21, which shows the final solids concentration as a function of required recovery and the solids concentration in the raw feed. At the TIMES model of 3.1 percent solids concentration, the solids concentration in the recycle tank at change-out will be 39 percent to achieve an effective water recovery of 95 percent. As can be seen in the figure, the TIMES model is more stringent than that used for RLSE and not quite as stringent as using raw urine. The final solids concentration information was then used to size the system tankage. Figure 22 itemizes the size of each tank and the sizing rationale.

A heater trade study is presented in Memo 78-109. This provided the basic operating mode for the system during quiescent mode, sized the heaters, and sized the system insulation.

Based on the system sizes selected during preliminary design activity, the systems analysis design activity culminated in definition of the performance ranges and the initial operating logic. The performance ranges are defined on the flow chart in Figure 23 and the initial operating logic is defined in Memo 78-117. This is a compendium of the information that provided the basis for the system design.

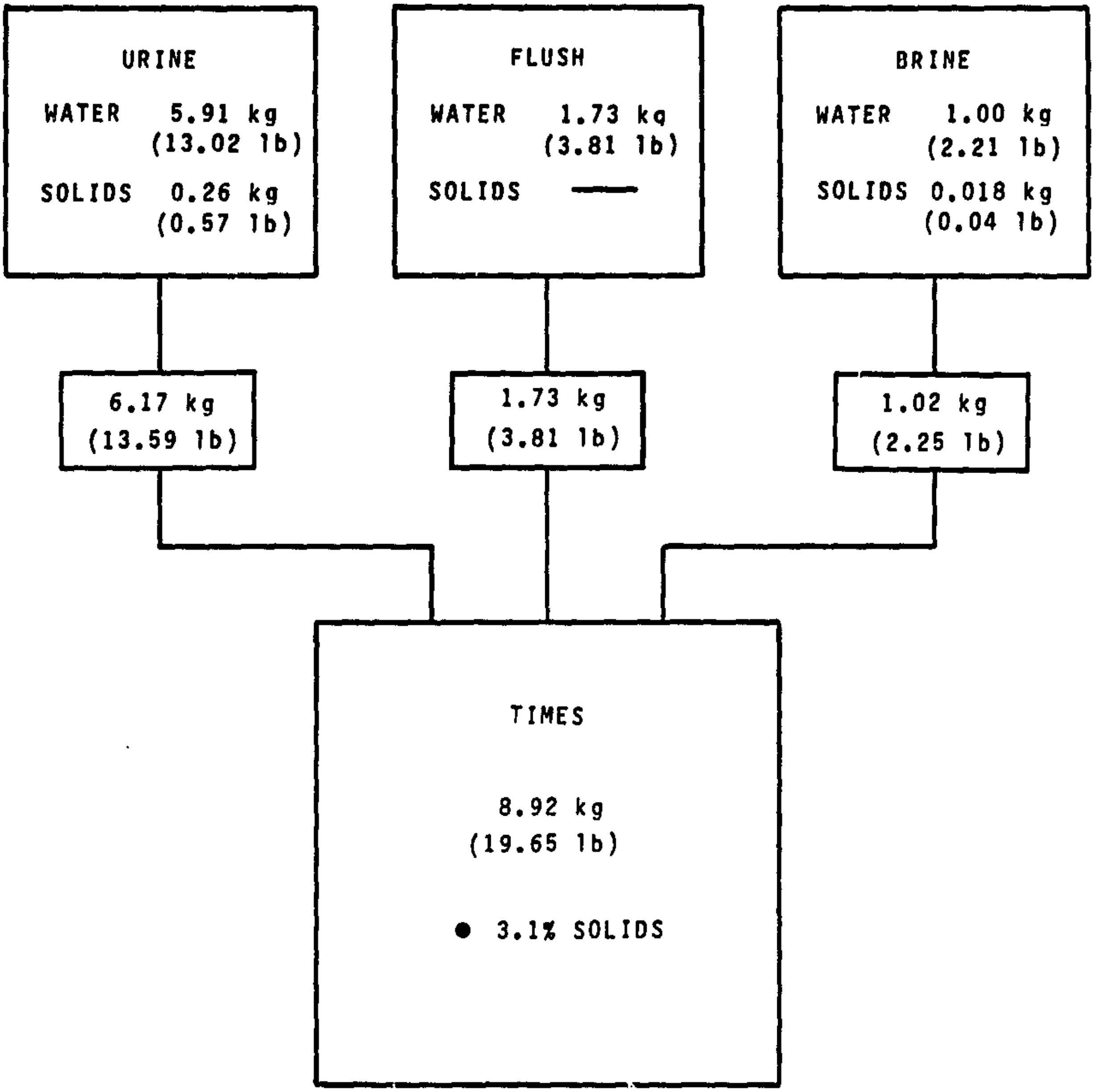


FIGURE 20
DAILY WATER RECOVERY

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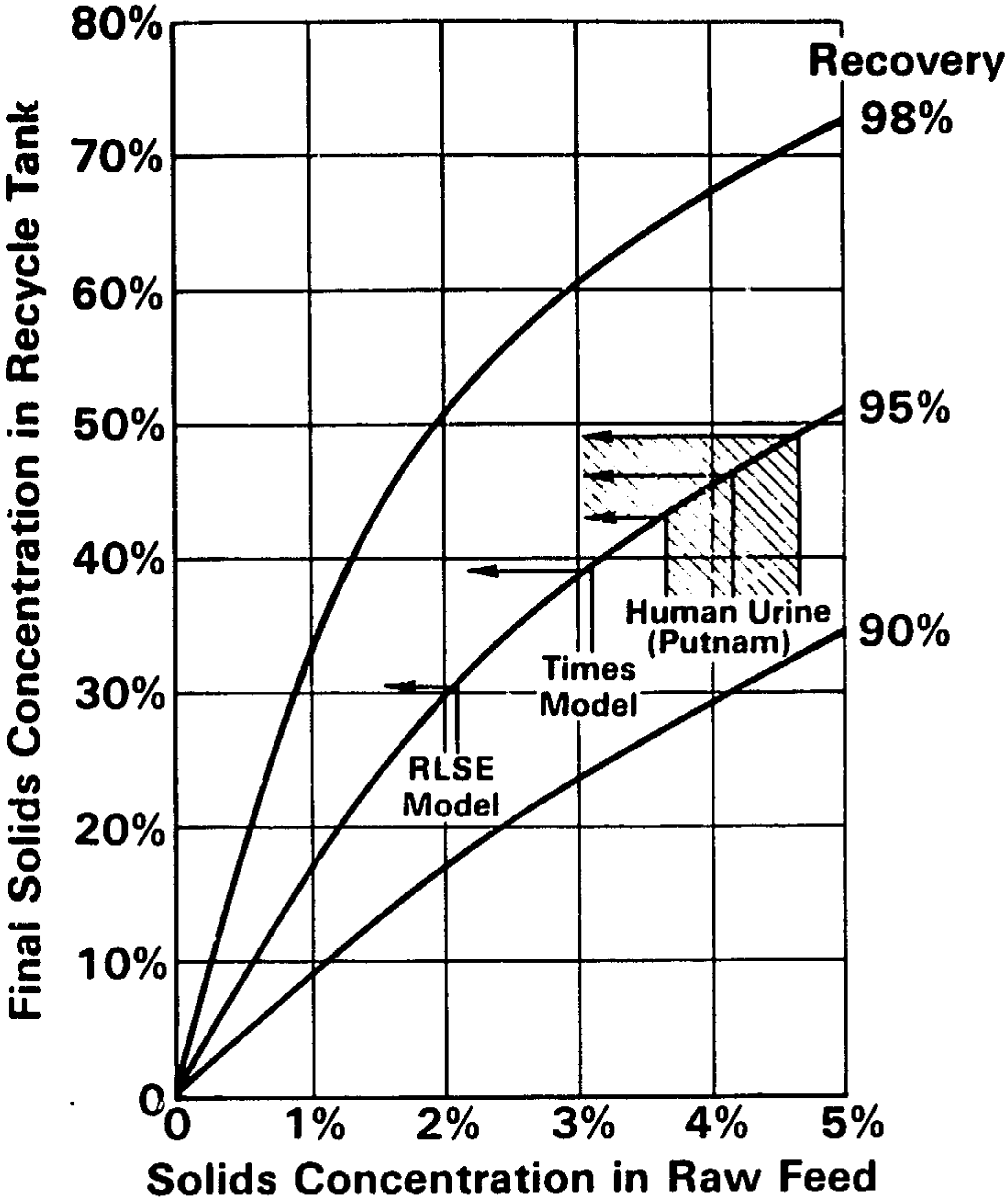
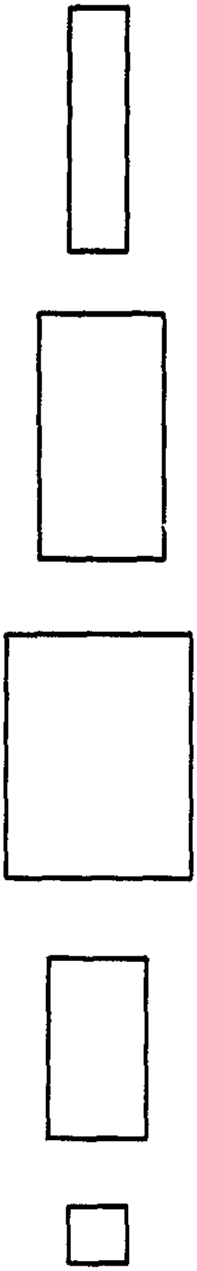


FIGURE 21
WASTEWATER SOLIDS CONCENTRATION
VS
WATER RECOVERY



HOLDING	1245 CM^3 (76 IN^3)	. 1.25 KG (2.75 LB) WASTEWATER . 7 PUMP-OUTS/DAY
PRETREAT	7212 CM^3 (440 IN^3)	. PROCESS 1816 KG (4000 LB) WASTEWATER
WASTE STORAGE	19668 CM^3 (1200 IN^3)	. 19.5 KG (43 LB) WASTEWATER . 2 DAYS & HOLDING TANK
RECYCLE	8850 CM^3 (540 IN^3)	. 3.6 KG (8.0 LB) SOLIDS . 15 DAY CAPACITY
ACCUMULATOR	164 CM^3 (10 IN^3)	. 0.5 MINUTE PUMP-OUT . 8-15 MINUTE DWELL

FIGURE 22

TANKS

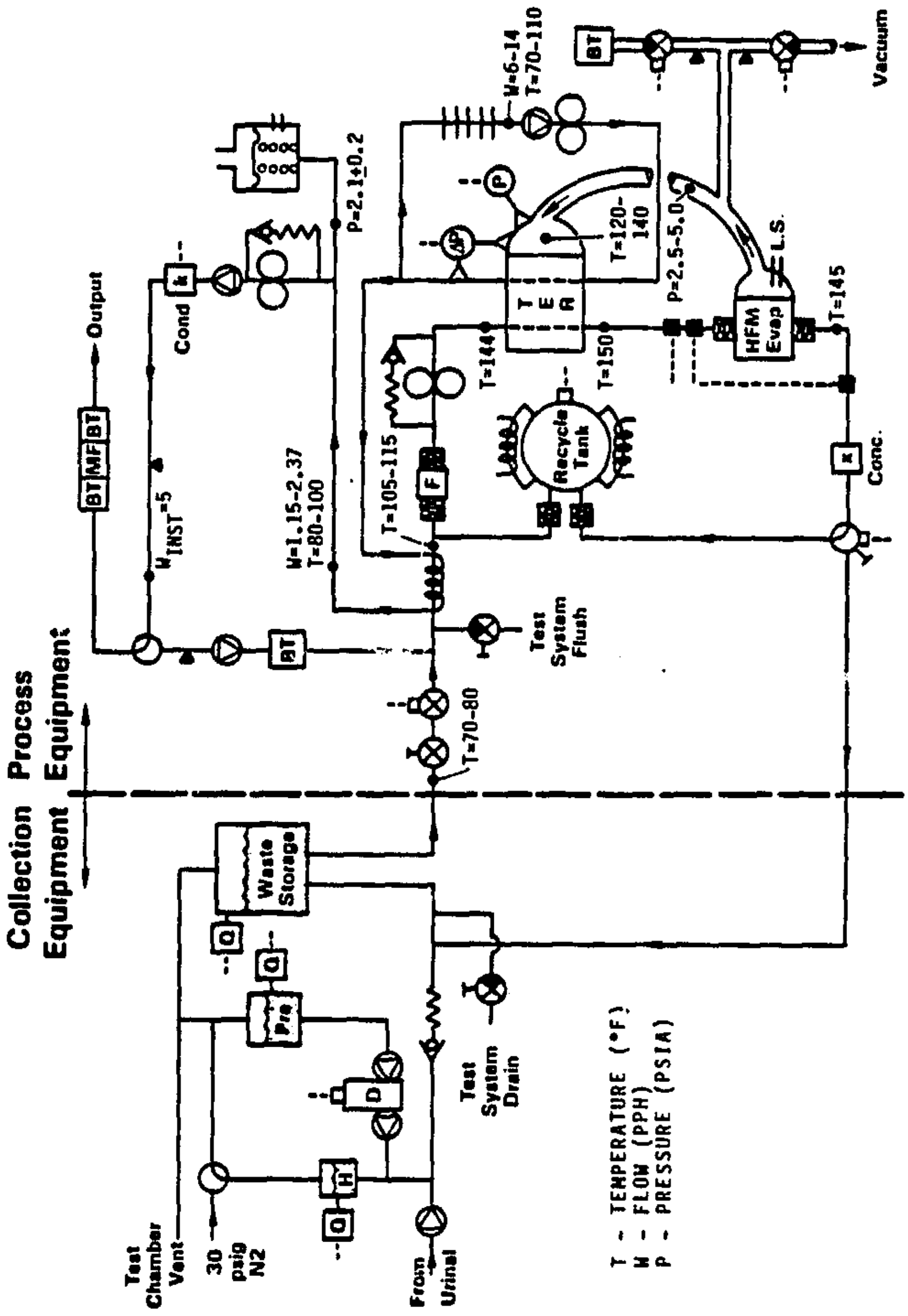


FIGURE 23
TIMES SCHEMATIC

HARDWARE DESCRIPTION

The basic preprototype TIMES subsystem, as described by the subsystem block diagram shown in Figure 24 and the subsystem parts list in Table 2, consists of a collection package, a process package, a controller, a driver box, a CRT display, a keyboard, a floppy disk drive, and an electrical harness set. Table 3 is a complete listing of all TIMES components. With the exception of the mixing tank, the pretreat tank, the waste storage tank, and the condensate cooling heat exchanger, the entire subsystem has been designed to operate in a zero-gravity as well as a one-gravity environment.

Package Description

The subsystem package arrangement less the CRT display, keyboard, and floppy disk drive is shown in Figure 25. The CRT display, keyboard, and floppy disk drive package arrangement is shown in Figure 26.

Collection Package

The collection package, whose overall dimensions are 43.8 cm (17.25 in) wide by 68.6 cm (27.0 in) deep by 63.5 cm (25.0 in) high with a volume of 0.191 m^3 (6.74 ft^3), contains the wastewater collection and pretreatment components and the posttreatment components. Table 4 is a collection package parts list, with the components plumbed as shown in the TIMES schematic, Figure 2. Components are grouped for the best compromise of simple plumbing and maintenance accessibility. The package frame consists of aluminum channel sections bolted together with simple support brackets and panels as required. All fluid and electrical interfaces terminate at the rear surface of the ackage.

Process Package

The process package, whose overall dimensions are 48.3 cm (19.0 in) wide by 63.5 cm (25.0 in) deep by 88.9 cm (35.0 in) high with a volume of 0.273 m^3 (9.62 ft^3), contains the processing components. Table 5 is a process package parts list, with the components plumbed as shown in the TIMES schematic, Figure 2. Components are grouped for the best compromise of simple plumbing, maintenance accessibility, and thermal isolation. The package frame consists of aluminum channel sections bolted together with simple support brackets and panels as required. The entire process package, with the exception of the condensate cooling heat exchanger item 211, is thermally insulated from ambient air. Additionally, the thermoelectric regenerator item 401, is thermally isolated from the process package interior ambient. All fluid and electrical interfaces terminate at the rear surface of the package.

Controller

The controller, whose overall dimension are 43.2 cm (17.0 in) wide by 43.5 cm (17.12 in) deep by 17.8 cm (7.0 in) high with a volume of 0.033 m^3 (1.18 ft^3), contains the microprocessor based control system. Signal conditioning and similar low level circuit functions are also contained within the controller that is shown in Figure 27. Logic level signals from the controller drive power control elements packaged within the separate driver box. The controller is located with the basic TIMES subsystem package as shown in Figure 25.

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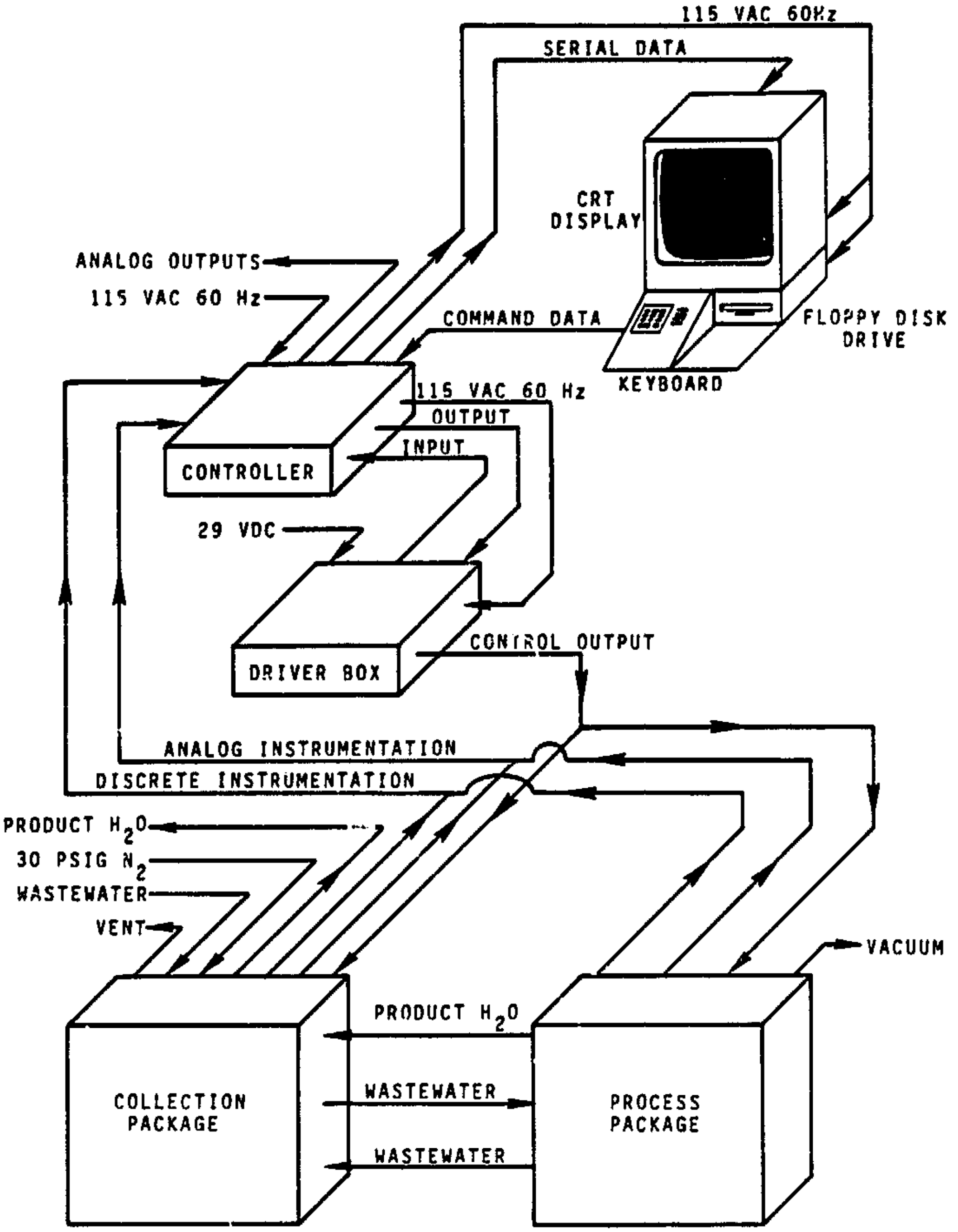

FIGURE 24
PREPROTOTYPE TIMES BLOCK DIAGRAM

Table 2
TIMES SUBSYSTEM PARTS LIST

Collection Package	SVSK97562
Process Package	SVSK96780
Controller	SVSK97811
Driver Box	SVSK97812
CRT Display	SVSK103179
Keyboard	SVSK103178
Floppy Disk Drive	SVSK103177
Electrical Harness	SVSK97814

Ref: TIMES Installation Drawing SVSK96787

Table 3
TIMES COMPONENT LIST

Item No.	Description	Part Number
100	Pretreat Metering Unit (incl. check valves)	SVSK97814
101	Manual Drain Valve	Whitey SS44S6
103	Waste Inlet Valve, Electrical	SVSK102756-103
104	Recycle Loop Flush Diverter Valve	SVSK102756-104
105	Input Check Valve	Circle Seal 232-T1-6TT-.1
106	Mixing Tank Expulsion Valve	SVSK102757-106
107	Relief/Check Valve, Feed Inlet	Circle Seal 232-T1-6TT-8
108	Reject Recycle Valve	SVSK102756-108
110	Septum, Condensate	SVSK96716
111	Septum, Multifilter Inlet	SVSK96716
112	Septum, Multifilter Outlet	SVSK96716
113	Manual Flush Valve	Whitey SS-44S6
114	Vacuum Control Valve, Control Pressure	Valcor V44700-124
115	Vacuum Control Valve, Raise Pressure	Valcor V44700-124
117	Check Valve, Condensate Delivery Pump	Circle Seal 232-T1-4TT-.1
119	Isolation Valve, Condensate	SVSK102757-119
121	Manual Isolation Valve, Multifilter	Parker 4Z-V66J-SS
122	Manual Isolation Valve, Process Pkg. Condensate	Parker 4M4Z-V4AR-SS
123	Manual Isolation Valve, Concentration Sensor Outlet	Hoke 7122G4Y
124	Manual Isolation Valve, Concentration Sensor Inlet	Hoke 7122G4Y
125	Restrictor, Orifice, Holding Tank	SVSK102805-125
126	Restrictor, Orifice, Concentration Sensor	SVSK102805-126

Table 3 (Continued)
TIMES COMPONENT LIST

Item No.	Description	Part Number
127	Restrictor, Orifice, Filter	SVSK102805-127
128	Restrictor, Capillary, Condensate Delivery	SVSK102805-128
129	Restrictor, Capillary, Vacuum Control	SVSK102805-129
130	Check Valve, Condensate Recycle	SVSK102807
131	Manual Isolation Valve, Collection Pkg. Condensate	Parker 4M4Z-V4AR-SS
132	Manual Isolation Valve, Accumulator Vacuum	Parker 4Z-V66J-SS
133	Maintenance Quick Disconnect Valve--Recycle Tank	SVSK95685-221
134	Maintenance Quick Disconnect Valve--Filter	SVSK95685-221
135	Maintenance Isolation Valve, HFM Inlet	HOKE7115G6Y
136	Maintenance Isolation Valve, HFM Inlet	HOKE7115F4Y
137	Maintenance Isolation Valve, HFM Outlet	HOKE7115F4Y
138	Maintenance Isolation Valve, HFM Outlet	HOKE7115G6Y

Table 3 (Continued)
TIMES COMPONENT LIST

Item No.	Description	Part Number
200	Waste Storage Tank	SVSK96683
201	Pretreat Chemical Tank	SVSK96682
202	Pretreat Mixing Tank (Holding Tank)	SVSK96681
203	Recycle Tank	SVSK96710
204	Recycle Tank Heater	SVSK96710-7 (incl. on Item 203 Dwg.)
205	Product Water Bacteria Trap, Upstream	SVSK96720-103 (incl. on Item 206 Dwg.)
206	Multifilter	SVSK96720
207	Product Water Bacteria Trap, Downstream	SVSK96720-103 (incl. on Item 206 Dwg.)
208	Reject Recycle Bacteria Trap	SVSK96720-103 (incl. on Item 206 Dwg.)
209	Urine Preheater	SVSK97505
210	Filter	SVSK96795
211	Condensate Cooling Heat Exchanger	SVSK96791
212	Condensate Accumulator	SVSK96713
213	Ambient Air Bacteria Trap	SVSK96718

Table 3 (Continued)
TIMES COMPONENT LIST

Item No.	Description	Part Number
300	Quantity Sensor, Pretreat	GemXM 800-3-SS-SS-1-12 (incl. on Item 201 Dwg.)
301	Quantity Sensor, Mixing Tank	GemXM 800-3-SS-SS-1-12 (incl. on Item 202 Dwg.)
302	Quantity Sensor, Waste Storage	GemXM 800-3-SS-SS-1-12 (incl. on Item 200 Dwg.)
303	Concentration Sensor	H.F. Instruments Ltd. Model DRT-200 Sensor Module
304	TER Outlet Temperature Sensor	SVSK85443
305	Porous Plate Differential Pressure Transducer	Tavis Model P105, 0-2 PSID
306	Conductivity Sensor	SVSK97533
307	Recycle Tank Temperature Sensor	SVSK96710-8 (incl. on Item 203 Dwg.)
308	HFM Inlet Temperature Sensor	SVSK85443
309	HFM Outlet Temperature Sensor	SK85443
310	Filter Differential Pressure Transducer	Tavis Model P105, 0-4 PSID
311	Controller	SVSK97811
312	Quantity Sensor, Condensate	Bourns Model 5108, 5000ohm, 2.25" Travel, Linear Potentometer (incl. on Item 212 Dwg.)
313	Steam Pressure Transducer	Tavis Model P105, 0-16 PSIA
314	Evaporator Liquid Sensor	SVSK95637
315	Driver Box	SVSK97812 (including Item 303 and Item 306 Electronics)
316	HFM Differential Temperature Box	SVSK101112

Table 3 (Continued)
TIMES COMPONENT LIST

Item No.	Description	Part Number
400	Urine Recycle Pump	SVSK102747
401	Thermoelectrical Regenerator	SVSK95545
402	Hollow Fiber Membrane Evaporator	SVSK95638
403	Condensate Delivery Pump	SVSK102747
404	Condensate Recycle Pump	SVSK102788

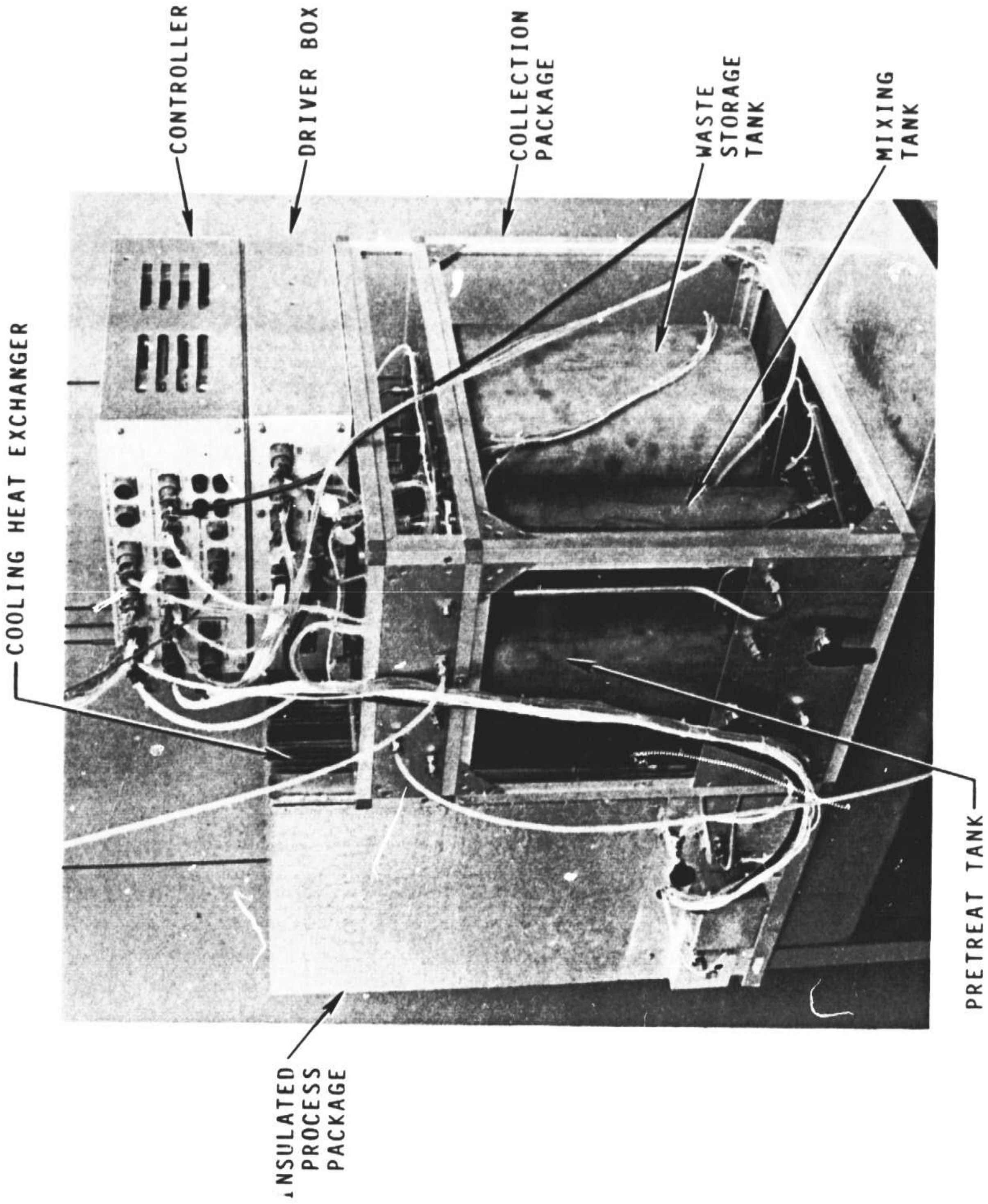

FIGURE 25
SUBSYSTEM PACKAGE ARRANGEMENT

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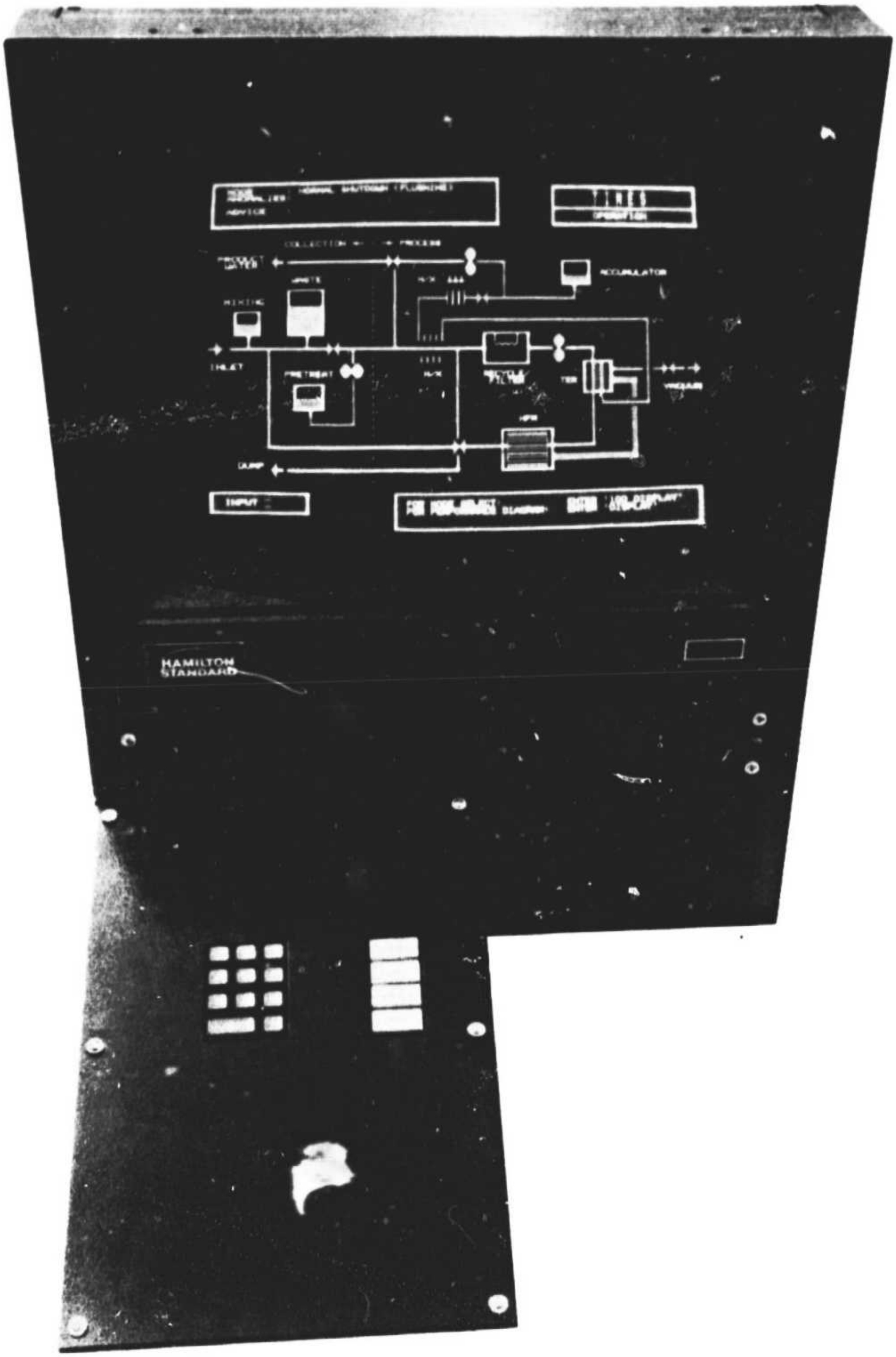

FIGURE 26
CRT DISPLAY, KEYBOARD, AND
FLOPPY DISK DRIVE

Table 4
COLLECTION PACKAGE SVSK97562 PARTS LIST

Item No.	Description	Part Number
100	Pretreat Metering Unit (incl. check valves)	SVSK97814
101	Manual Drain Valve	Whitey SS44S6
103	Waste Inlet Valve, Electrical	SVSK102756-103
105	Inlet Check Valve	Circle Seal 232-T1-6TT-.1
106	Mixing Tank Expulsion Valve	SVSK102757-106
107	Relief/Check Valve, Feed Inlet	Circle Seal 232-T1-6TT-8
108	Reject Recycle Valve	SVSK102756-108
110	Septum, Condensate	SVSK96716
111	Septum, Multifilter Inlet	SVSK96716
112	Septum, Multifilter Outlet	SVSK96716
113	Manual Flush Valve	Whitey SS-44S6
117	Check Valve, Condensate Delivery Pump	Circle Seal 232-T1-4TT-.1
119	Isolation Valve, Condensate	SVSK102757-119
121	Manual Isolation Valve, Multifilter	Parker 4Z-V66J-SS
125	Restrictor, Orifice, Holding Tank	SVSK102805-125
131	Manual Isolation Valve, Collection Pkg. Condensate	Parker 4M4Z-V4AR-SS
132	Manual Isolation Valve, Accumulator Vacuum	Parker 4Z-V66J-SS

Table 4 (Continued)
COLLECTION PACKAGE SVSK97562 PARTS LIST

Item No.	Description	Part Number
200	Waste Storage Tank	SVSK96683
201	Pretreat Chemical Tank	SVSK96682
202	Pretreat Mixing Tank (Holding Tank)	SVSK96681
205	Product Water Bacteria Trap, Upstream	SVSK96720-103 (incl. on Item 206 Dwg.)
206	Multifilter	SVSK96720
207	Product Water Bacteria Trap, Downstream	SVSK96720-103 (incl. on Item 206 Dwg.)
208	Reject Recycle Bacteria Trap	SVSK96720-103 (incl. on Item 206 Dwg.)
212	Condensate Accumulator	SVSK96713
300	Quantity Sensor, Pretreat	GemXM 800-3-SS-SS-1-12 (incl. on Item 201 Dwg.)
301	Quantity Sensor, Mixing Tank	GemXM 800-3-SS-SS-1-12 (incl. on Item 202 Dwg.)
302	Quantity Sensor, Waste Storage	GemXM 800-3-SS-SS-1-12 (incl. on Item 200 Dwg.)
306	Conductivity Sensor	SVSK97533
312	Quantity Sensor, Condensate	Bourns Model 5108, 5000ohm, 2.25" Travel, Linear Potentometer (incl. on Item 212 Dwg.)
403	Condensate Delivery Pump	SVSK102747
---	Frame	SVSK97562-100
---	Miscellaneous Fittings and Tubes	---

Table 5
PROCESS PACKAGE SVSK96789 PARTS LIST

Item No.	Description	Part Number
104	Recycle Loop Flush Diverter Valve	SVSK102756-104
114	Vacuum Control Valve, Control Pressure	Valcor V44700-124
115	Vacuum Control Valve, Raise Pressure	Valcor V44700-124
122	Manual Isolation Valve, Process Pkg. Condensate	Parker 4M4Z-V4AR-SS
123	Manual Isolation Valve, Concentration Sensor Outlet	Hoke 7122G4Y
124	Manual Isolation Valve, Concentration Sensor Inlet	Hoke 7122G4Y
126	Restrictor, Orifice, Concentration Sensor	SVSK102805-126
127	Restrictor, Orifice, Filter	SVSK102805-127
128	Restrictor, Capillary, Condensate Delivery	SVSK102805-128
129	Restrictor, Capillary, Vacuum Control	SVSK102805-129
130	Check Valve, Condensate Recycle	SVSK102807
133	Maintenance Quick Disconnect Valve--Recycle Tank	SVSK95685-221
134	Maintenance Quick Disconnect Valve--Filter	SVSK95685-221
135	Maintenance Isolation Valve, HFM Inlet	HOKE7115G6Y
136	Maintenance Isolation Valve, HFM Inlet	HOKE7115F4Y
137	Maintenance Isolation Valve, HFM Outlet	HOKE7115F4Y
138	Maintenance Isolation Valve, HFM Outlet	HOKE7115G6Y

Table 5 (Continued)
PROCESS PACKAGE SVSK96789 PARTS LIST

Item No.	Description	Part Number
203	Recycle Tank	SVSK96710
204	Recycle Tank Heater	SVSK96710-7 (incl. on Item 203 Dwg.)
209	Urine Preheater	SVSK97505
210	Filter	SVSK96795
211	Condensate Cooling Heat Exchanger	SVSK96791
213	Ambient Air Bacteria Trap	SVSK96718
303	Concentration Sensor	H.F. Instruments Ltd. Model DRT-200 Sensor Module
304	TER Outlet Temperature Sensor	SVSK85443
305	Porous Plate Differential Pressure Transducer	Tavis Model P105, 0-2 PSID
307	Recycle Tank Temperature Sensor	SVSK96710-8 (incl. on Item 203 Dwg.)
308	HFM Inlet Temperature Sensor	SVSK85443
309	HFM Outlet Temperature Sensor	SVSK85443
310	Filter Differential Pressure Transducer	Tavis Model P105, 0-4 PSID
313	Steam Pressure Transducer	Tavis Model P105, 0-16 PSIA
314	Evaporator Liquid Sensor	SVSK95637
316	HFM Differential Temperature Box	SVSK101112

Table 5 (Continued)
PROCESS PACKAGE SVSK96789 PARTS LIST

Item No.	Description	Part Number
400	Urine Recycle Pump	SVSK102747
401	Thermoelectrical Regenerator	SVSK95545
402	Hollow Fiber Membrane Evaporator	SVSK95638
404	Condensate Recycle Pump	SVSK102788
---	Frame	SVSK96789-100
---	Insulation	SVSK96789-200
---	Miscellaneous Fittings and Tubes	---

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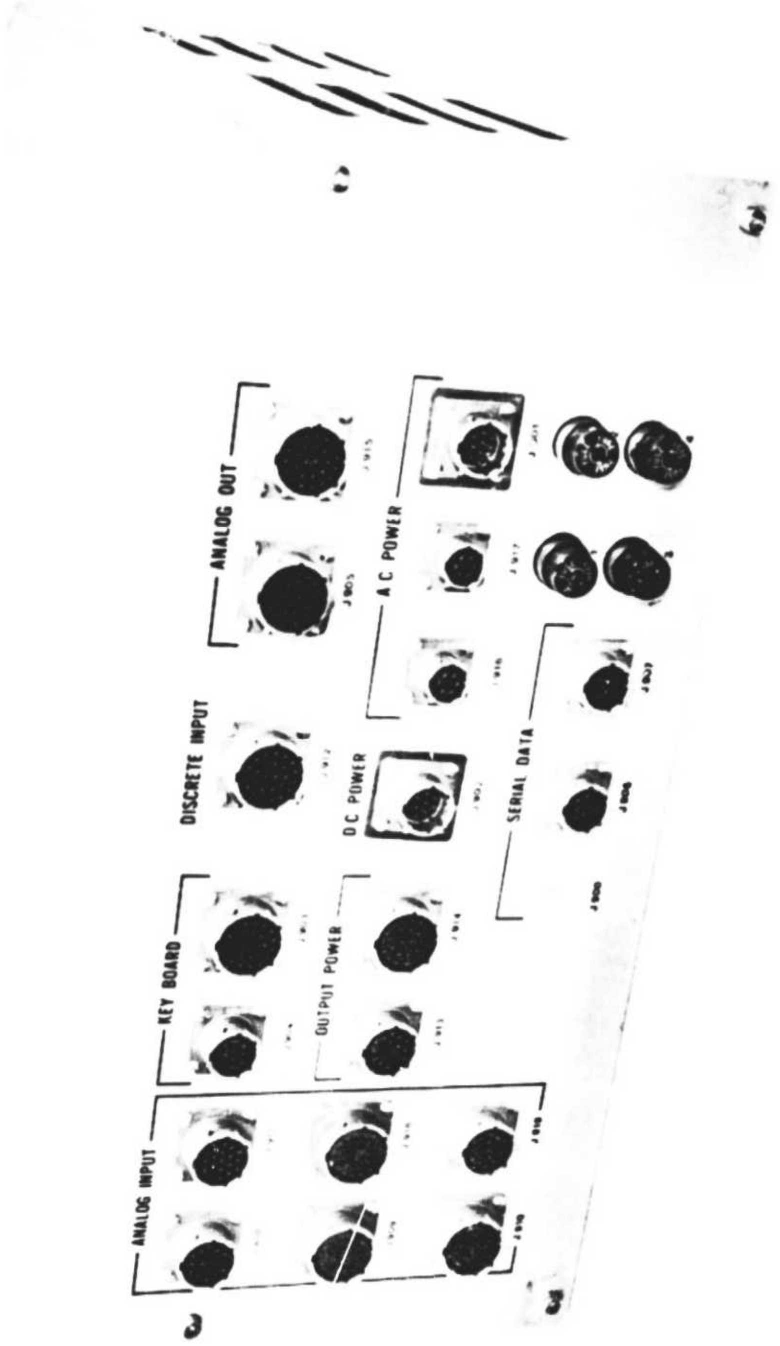

FIGURE 27
TIMES CONTROLLER

Driver Box

The driver box, whose overall dimensions use 4[illegible] cm (17.0 in) wide by 43.5 cm (17.12 in) deep by 13.0 cm (5.12 in) high with a volume of 0.024 m^3 (0.86 ft^3), interfaces with the controller and uses low power signals from the controller to actuate relays that switch AC and DC power, as applicable, to control the operation of the various subsystem component pumps, valves, etc. The driver box shown in Figure 28, also contains the electronic circuitry for conditioning the signals from the wastewater recycle loop concentration probe and the product water conductivity probe. The driver box is located with the basic TIMES subsystem package as shown in Figure 25.

CRT Display, Keyboard, and Floppy Disk Drive

The CRT display, keyboard, and floppy disk drive, shown in Figure 26, are mounted in a GFE console and are arranged to integrate with the NASA/JSC Regenerative Life Support Evaluation program master control consoles. The keyboard key arrangement is shown in Figure 29. Use of this keyboard is discussed in detail in the Subsystem Analysis section.

Control and Display Description

Figure 30 is a control and display block diagram. The function of the control and display portion of the subsystem is to provide automatic control, 24 hour monitoring of subsystem product water output and conductivity, automatic shutdown, and subsystem performance monitoring.

The multi-colored cathode ray tube (CRT) display format shown in Figure 31 provides a continuous readout of system mode, any subsystem anomolies or advice system status, and operations instructions. Any one of six visual isplays of appropriate data can be selected. These are:

- Mode Selection Table (Figure 32)
- Operation Diagram (same as Performance Diagram except without performance data) - Performance Diagram (Figure 33)
- Performance Table With Limits (Figures 34 and 35)
- Performance Plot of Water Production Rate (Figure 36)
- Maintenance Diagram (Figure 37)

In addition, if an anomaly occurs, an anomaly readout together with an anomaly light, either white, yellow or red is displayed. White for a low level indication of abnormal occurrence, yellow for a caution, and red for a warning and indicating the fact that the system is automatically being shutdown. An audible alarm accompanies the red anomaly light.

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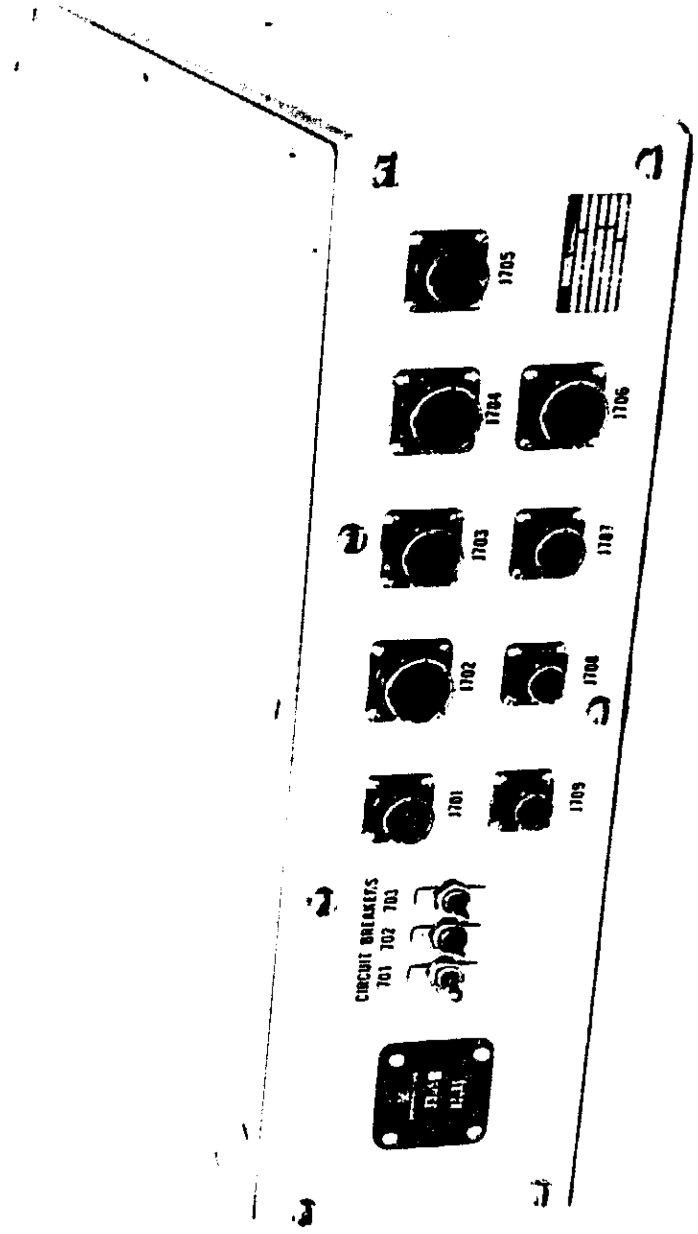

FIGURE 28
TIMES DRIVER BOX

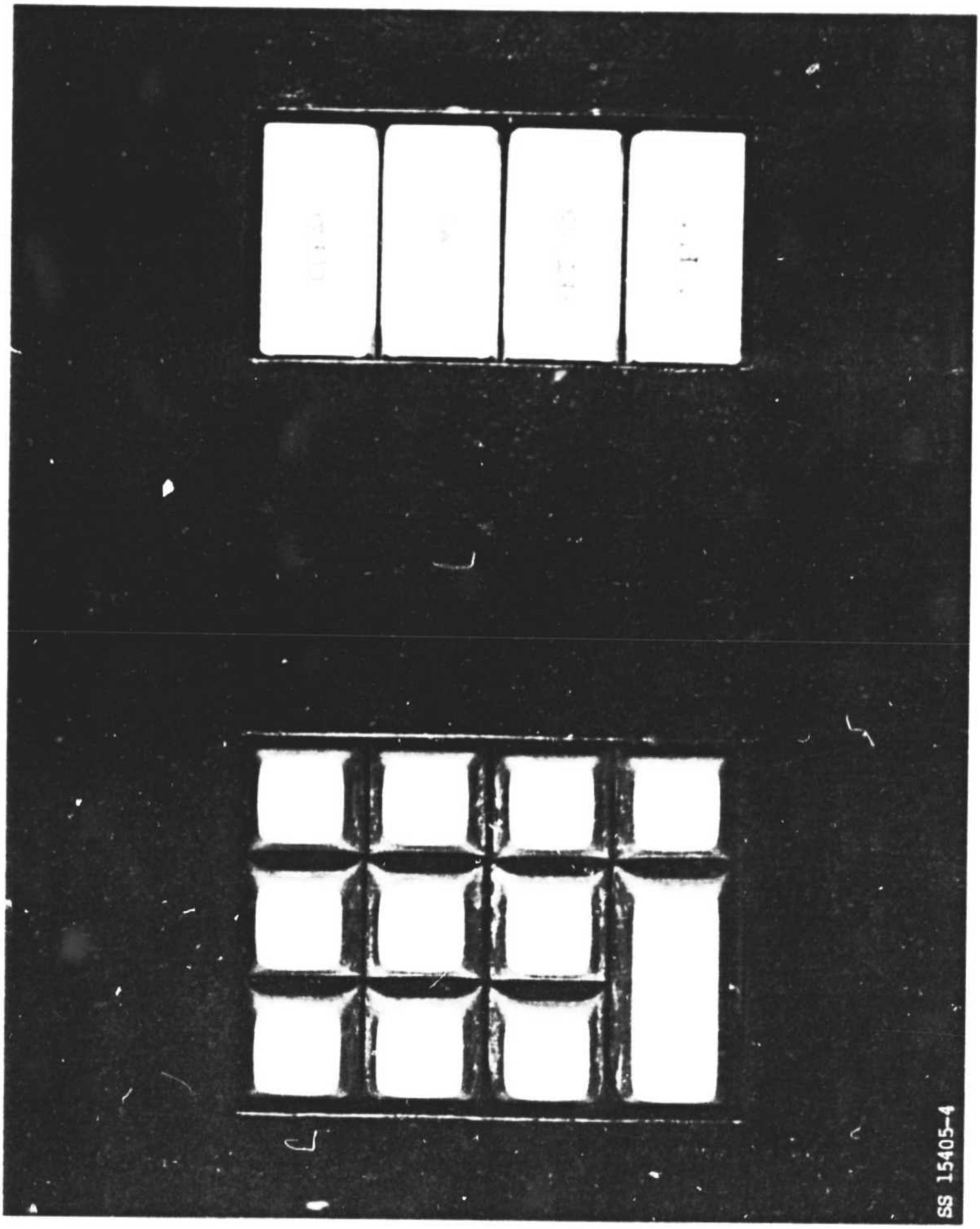

FIGURE 29
KEYBOARD

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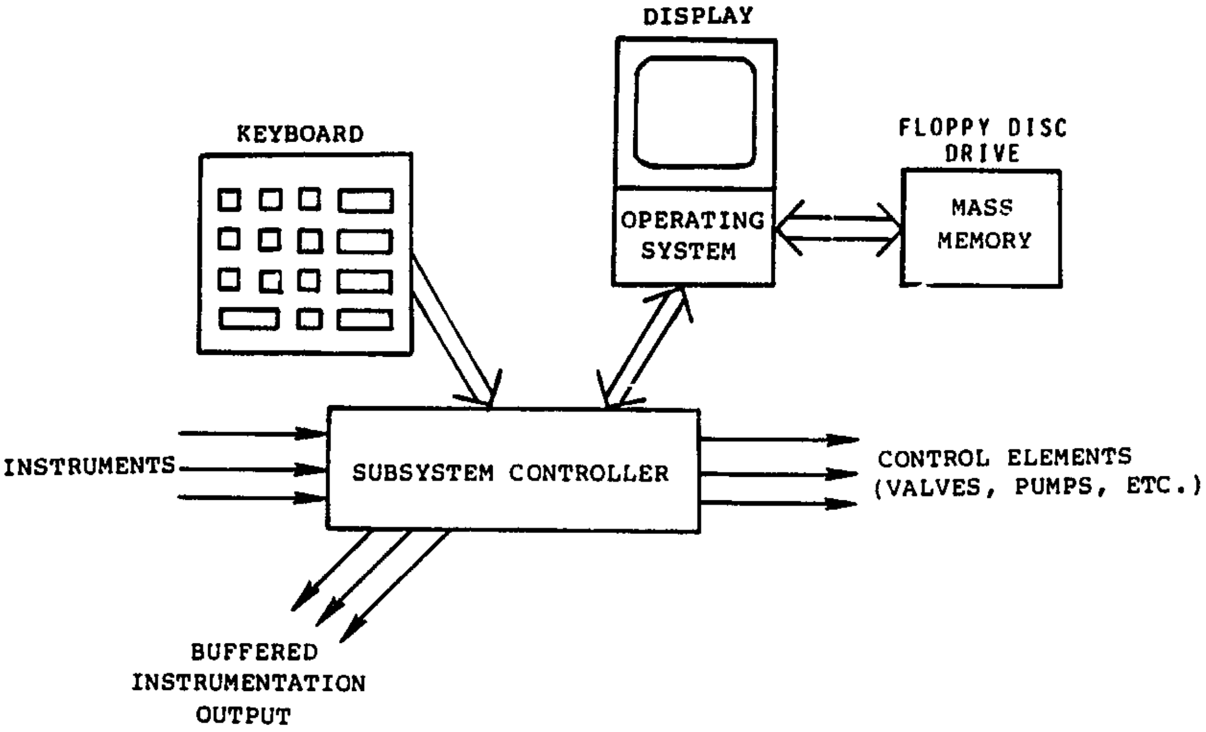


FIGURE 30
CONTROL AND DISPLAY BLOCK DIAGRAM

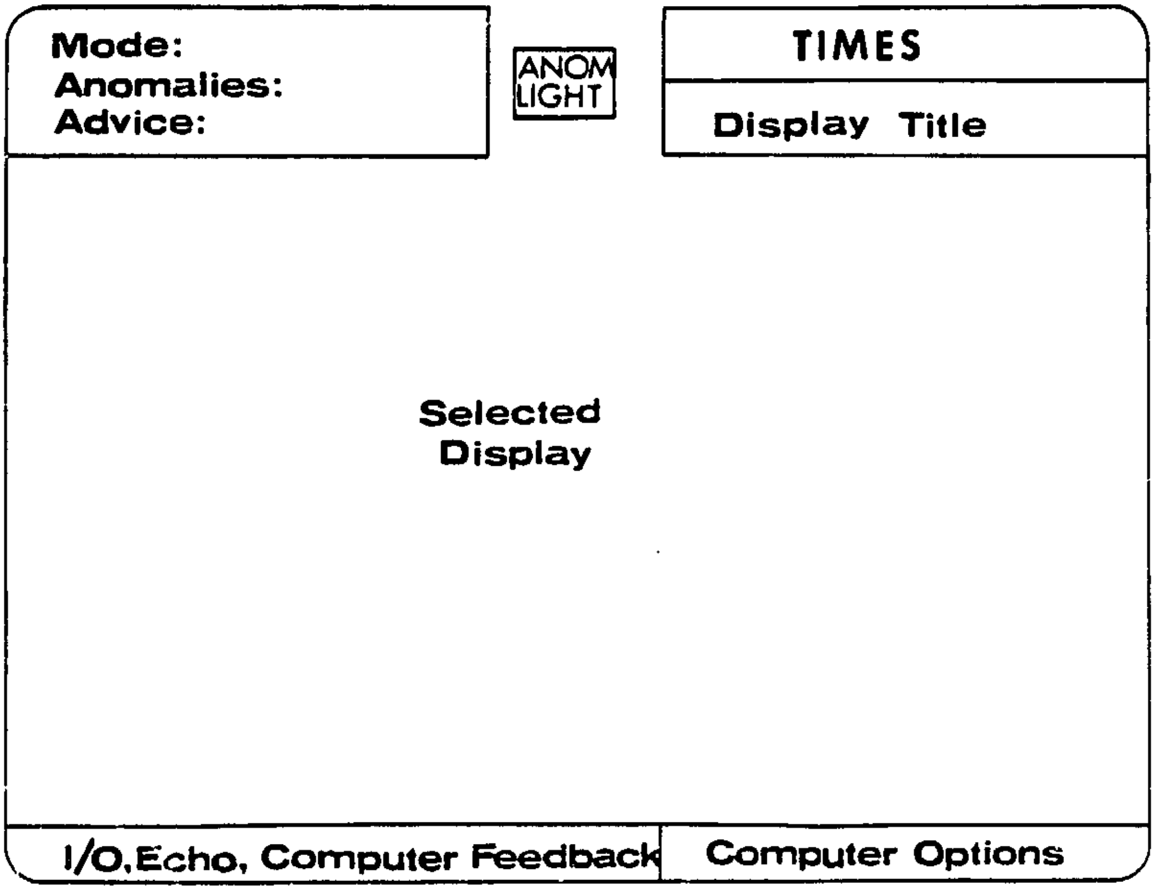
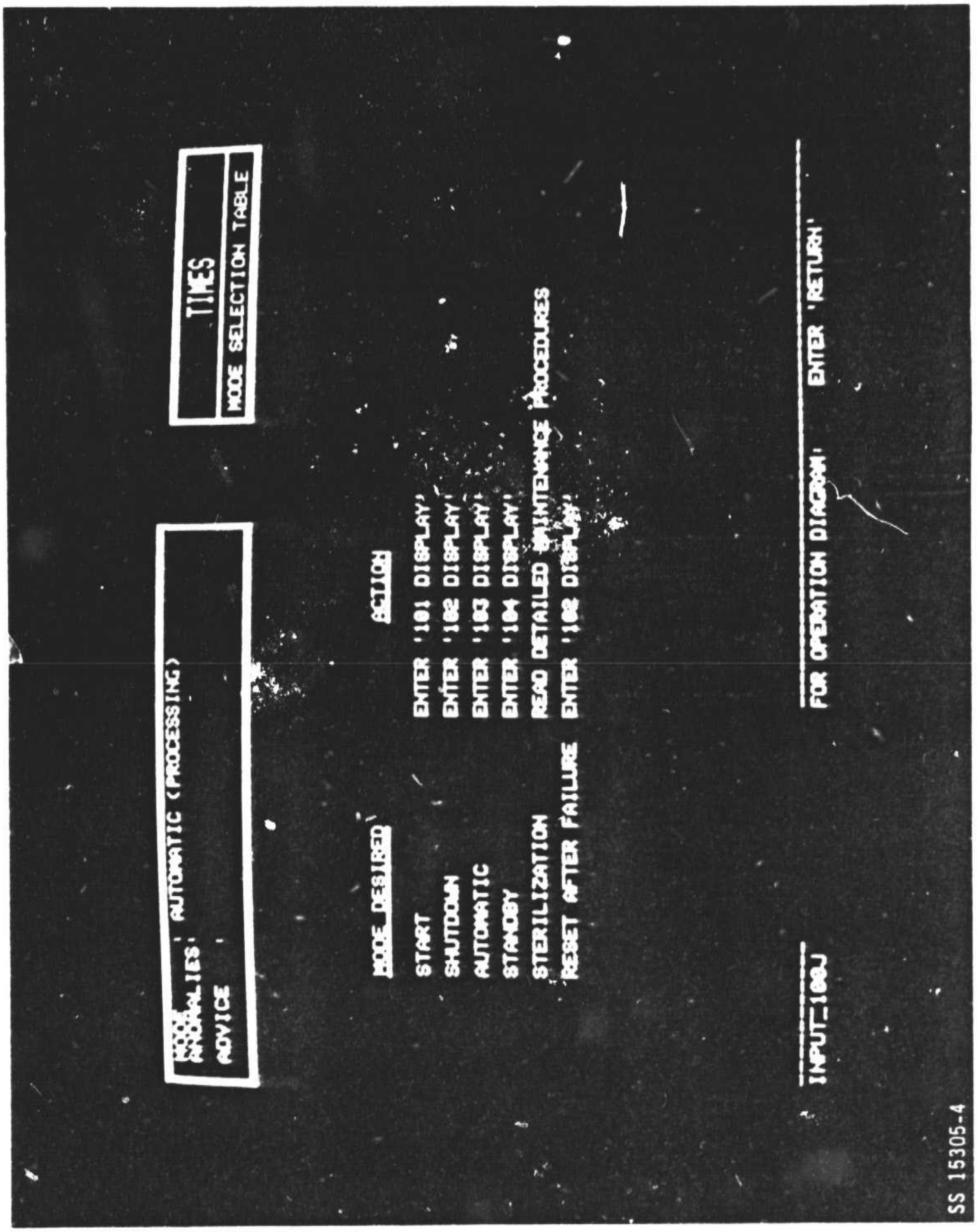


FIGURE 31
CRT DISPLAY FORMAT



TIMES

MODE SELECTION TABLE

MODE' AUTOMATIC (PROCESSING)

ANOMALIES'

ADVICE '

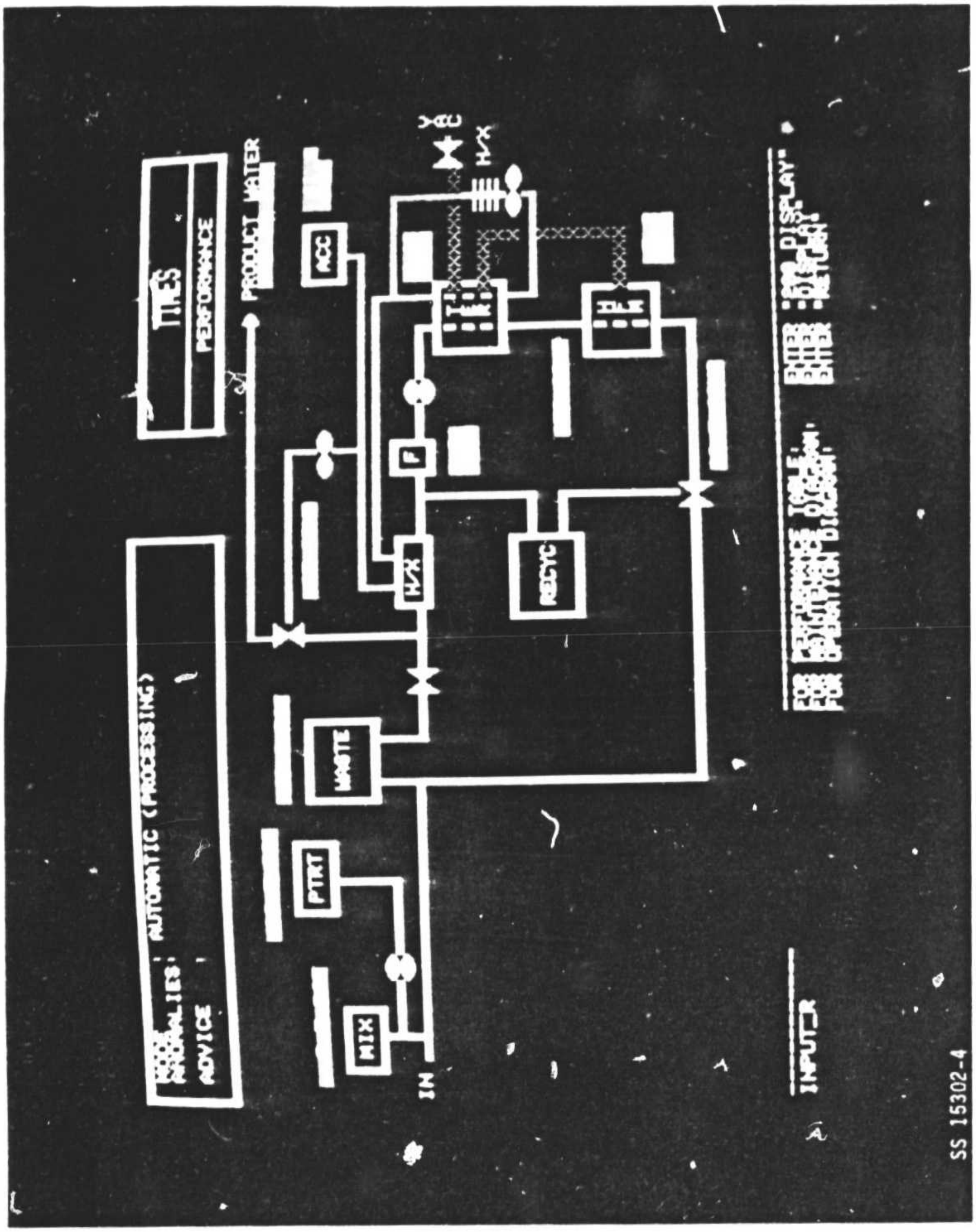
MODE DESIRED	ACTION
START	ENTER '101 DISPLAY'
SHUTDOWN	ENTER '102 DISPLAY'
AUTOMATIC	ENTER '103 DISPLAY'
STANDBY	ENTER '104 DISPLAY'
STERILIZATION	READ DETAILED MAINTENANCE PROCEDURES
RESET AFTER FAILURE	ENTER '102 DISPLAY'

FOR OPERATION DIAGRAM' ENTER 'RETURN'

INPUT_100J

SS 15305-4

FIGURE 32
MODE SELECTION TABLE

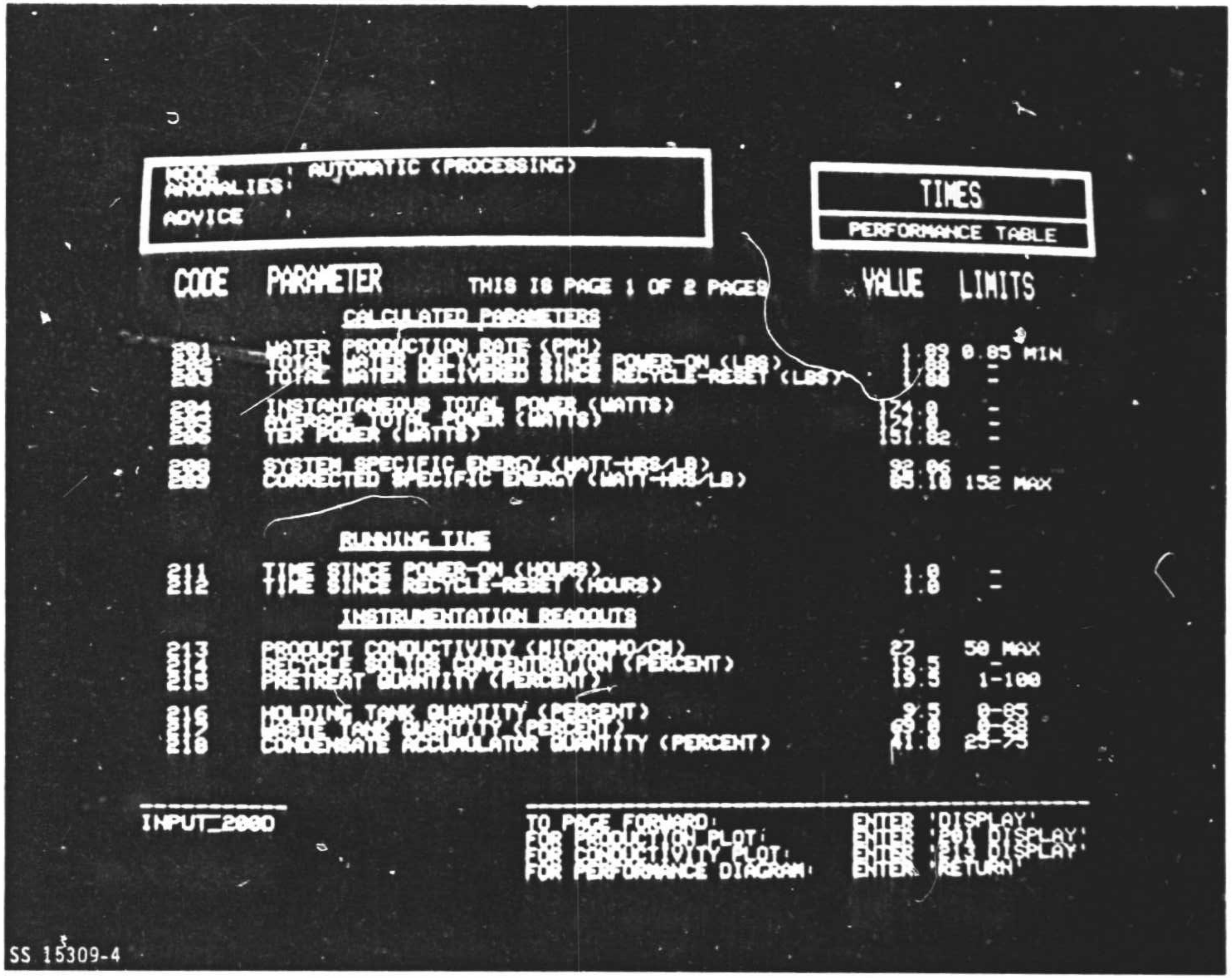


MODE: AUTOMATIC (PROCESSING)
ANOMALIES:
ADVICE:

FOR PERFORMANCE TABLE: ENTER "[illegible] DISPLAY"
FOR MAINTENANCE DIAGRAM: ENTER "DISPLAY"
FOR OPERATION DIAGRAM: ENTER "RETURN"

INPUT_R

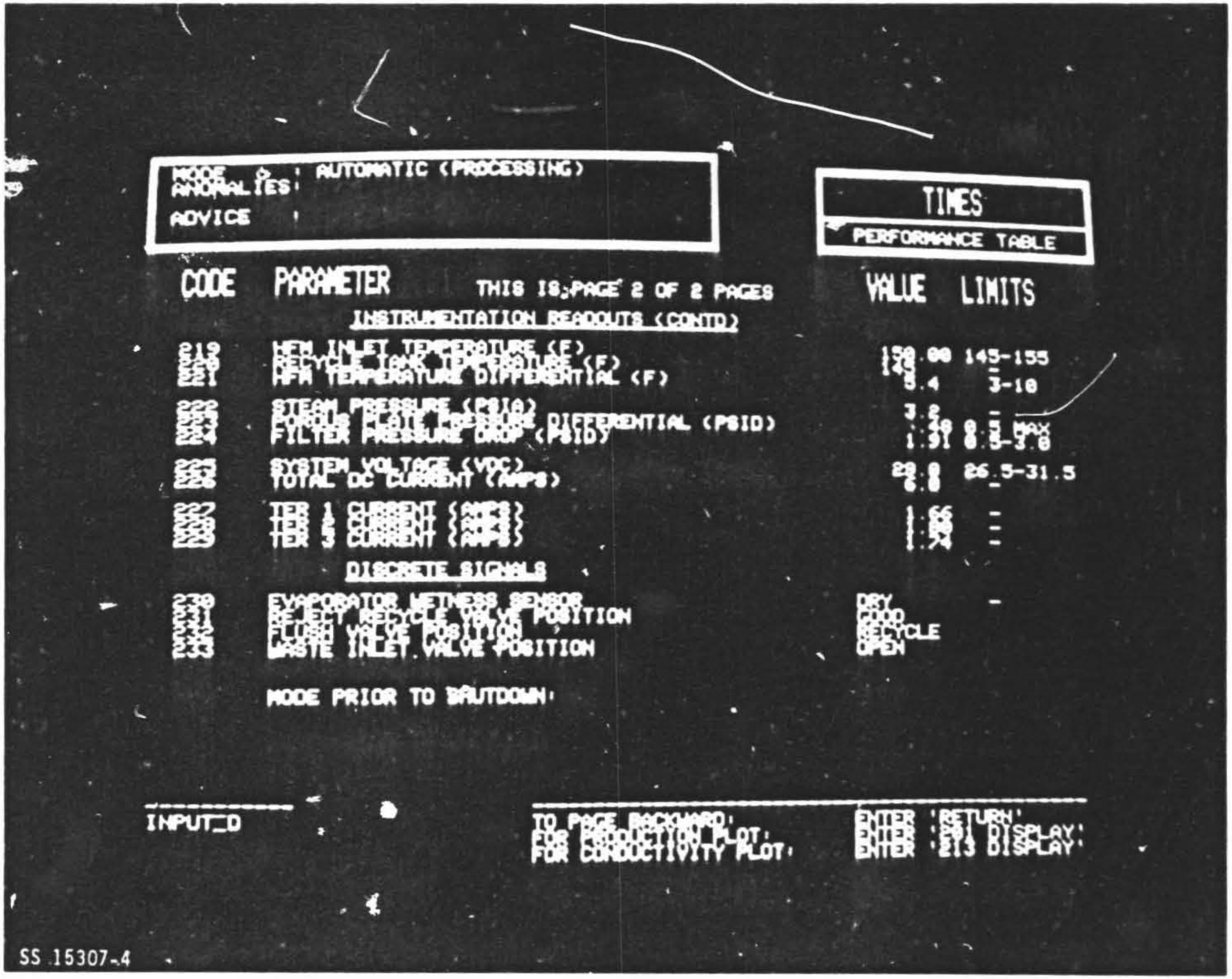
FIGURE 33
PERFORMANCE DIAGRAM



```
MODE      : AUTOMATIC (PROCESSING)                    TIMES
ANOMALIES :
ADVICE    :                                     PERFORMANCE TABLE

CODE  PARAMETER        THIS IS PAGE 1 OF 2 PAGES       VALUE  LIMITS
              CALCULATED PARAMETERS
201   WATER PRODUCTION RATE (PPH)                       1.89  0.85 MIN
202   TOTAL WATER DELIVERED SINCE POWER-ON (LBS)        1.88   -
203   TOTAL WATER DELIVERED SINCE RECYCLE-RESET (LBS)   1.88   -
204   INSTANTANEOUS TOTAL POWER (WATTS)               124.8    -
205   AVERAGE TOTAL POWER (WATTS)                     124.8    -
206   TER POWER (WATTS)                               151.82   -
208   SYSTEM SPECIFIC ENERGY (WATT-HRS/LB)             92.06   -
209   CORRECTED SPECIFIC ENERGY (WATT-HRS/LB)          85.18  152 MAX

              RUNNING TIME
211   TIME SINCE POWER-ON (HOURS)                       1.8    -
212   TIME SINCE RECYCLE-RESET (HOURS)                  1.8    -
              INSTRUMENTATION READOUTS
213   PRODUCT CONDUCTIVITY (MICROMHO/CM)               27     50 MAX
214   RECYCLE SOLIDS CONCENTRATION (PERCENT)           19.5    -
215   PRETREAT QUANTITY (PERCENT)                      19.5   1-100
216   HOLDING TANK QUANTITY (PERCENT)                   9.5   0-85
217   WASTE TANK QUANTITY (PERCENT)                    69.8   0-[illegible]
218   CONDENSATE ACCUMULATOR QUANTITY (PERCENT)        41.8   25-75

INPUT_2000            TO PAGE FORWARD:            ENTER 'DISPLAY'
                      FOR PRODUCTION PLOT:        ENTER '201 DISPLAY'
                      FOR CONDUCTIVITY PLOT:      ENTER '213 DISPLAY'
                      FOR PERFORMANCE DIAGRAM:    ENTER 'RETURN'
```

SS 15309-4

FIGURE 34
PERFORMANCE TABLE PAGE 1

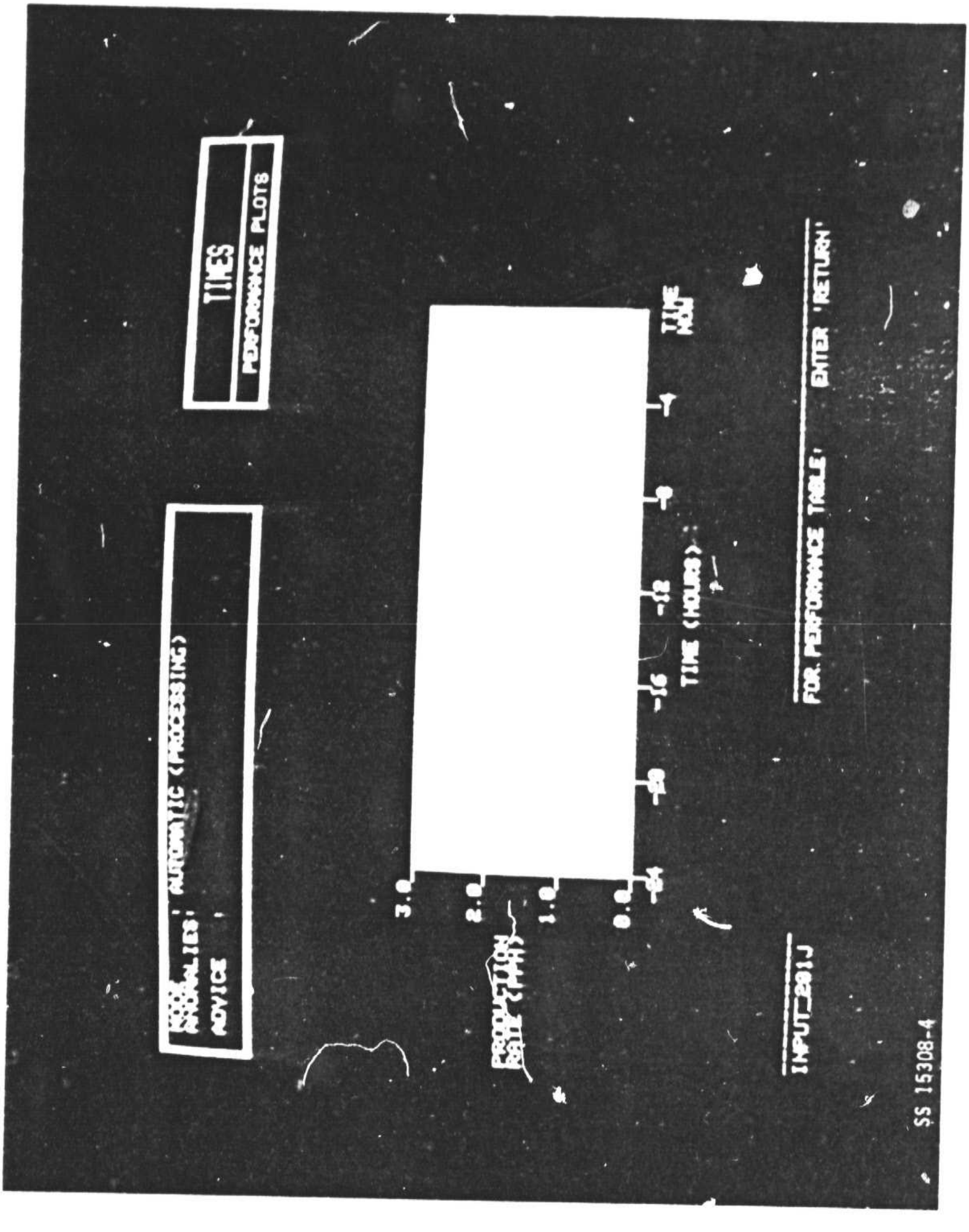


```
MODE &         : AUTOMATIC (PROCESSING)                    TIMES
ANOMALIES                                              PERFORMANCE TABLE
ADVICE         :

CODE  PARAMETER         THIS IS PAGE 2 OF 2 PAGES       VALUE   LIMITS
           INSTRUMENTATION READOUTS (CONTD)
219   HFM INLET TEMPERATURE (F)                        150.00  145-155
220   RECYCLE TANK TEMPERATURE (F)                     145      -
221   HFM TEMPERATURE DIFFERENTIAL (F)                   5.4    3-10
222   STEAM PRESSURE (PSIA)                              3.2     -
223   POROUS PLATE PRESSURE DIFFERENTIAL (PSID)           .38   0.5 MAX
224   FILTER PRESSURE DROP (PSID)                        1.91   0.5-3.0
225   SYSTEM VOLTAGE (VDC)                              28.8   26.5-31.5
226   TOTAL DC CURRENT (AMPS)                            6.8     -
227   TER 1 CURRENT (AMPS)                               1.66    -
228   TER 2 CURRENT (AMPS)                              [illegible]  -
229   TER 3 CURRENT (AMPS)                              [illegible]  -
           DISCRETE SIGNALS
230   EVAPORATOR WETNESS SENSOR                         DRY      -
231   REJECT RECYCLE VALVE POSITION                     GOOD
232   FLUSH VALVE POSITION                              RECYCLE
233   WASTE INLET VALVE POSITION                        OPEN

      MODE PRIOR TO SHUTDOWN:

INPUT_D                TO PAGE BACKWARD:           ENTER :RETURN:
                       FOR PRODUCTION PLOT:        ENTER :201 DISPLAY:
                       FOR CONDUCTIVITY PLOT:      ENTER :213 DISPLAY:
```

SS 15307-4

FIGURE 35

PERFORMANCE TABLE PAGE 2



TIMES
PERFORMANCE PLOTS

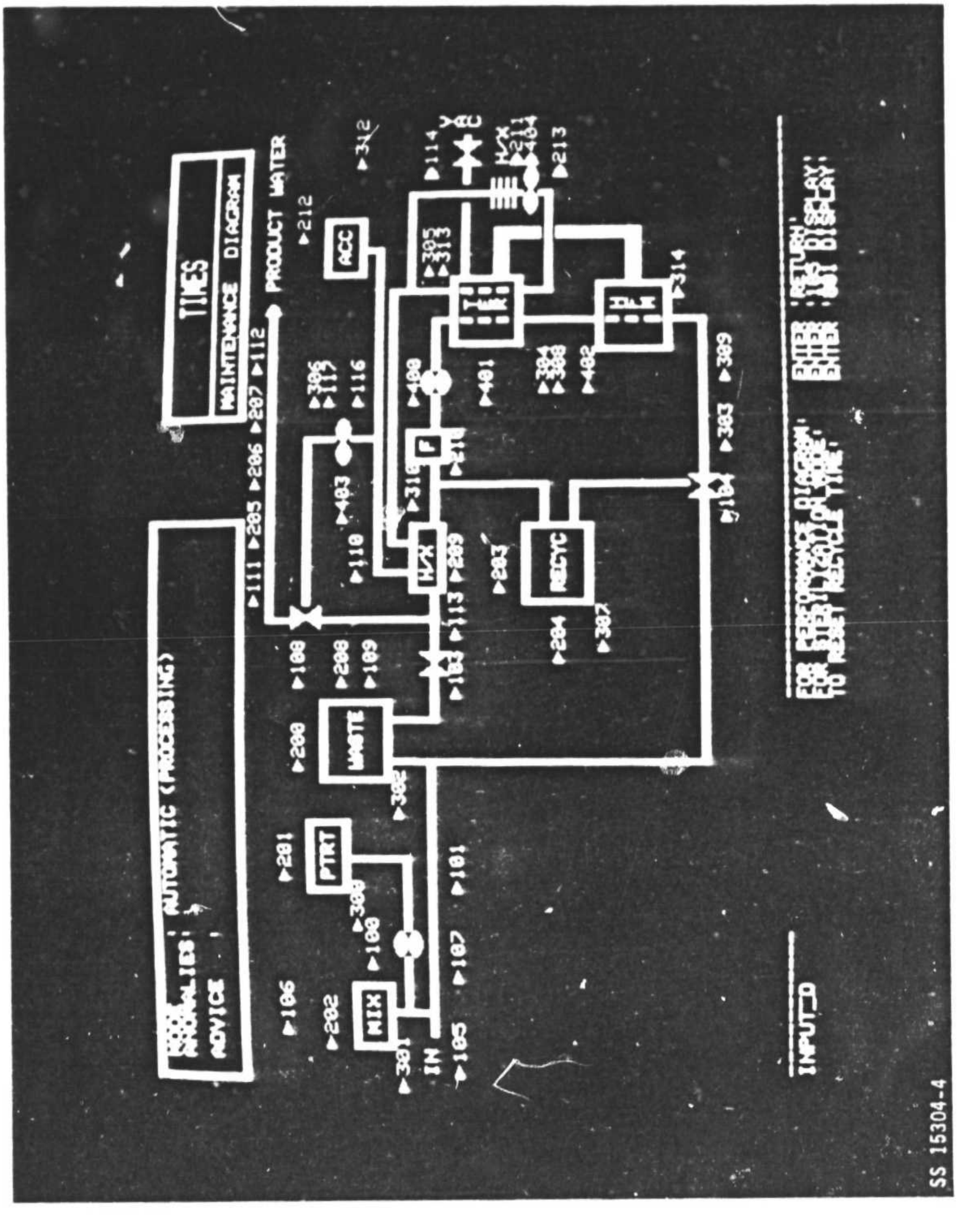
ANOMALIES : AUTOMATIC (PROCESSING)
ADVICE :

FOR PERFORMANCE TABLE, ENTER 'RETURN'

INPUT_201J

FIGURE 36

PERFORMANCE PLOT
WATER PRODUCTION RATE



MODE : AUTOMATIC (PROCESSING)
ANOMALIES :
ADVICE :

TIMES
MAINTENANCE DIAGRAM

FOR PERFORMANCE DIAGRAM' ENTER 'RETURN'
FOR STERILIZATION MODE' ENTER '[illegible] DISPLAY'
TO RESET RECYCLE TIME' ENTER '[illegible] DISPLAY'

INPUT_D

FIGURE 37
MAINTENANCE DIAGRAM

The display provides maximum essential information at a glance and requires minimum interpretation and training for monitoring or subsystem control. The microprocessor controller provides automatic sequencing, dynamic control, failure detection and isolation, processes instrumentation signals, calculates and plots product water production rate, and plots product water conductivity.

Control of the subsystem is straight forward and requires minimal instruction for operator usage as control is accomplished by inputting commands designated on the CRT display using the keyboard shown in Figure 29.

Four operating modes, normal shutdown, start, automatic, and standby are provided. The logic summary for these modes is shown in Table 6. Also shown is the failure shutdown mode and the conditions that initiate failure shutdown. Logic programmed into the controller automatically initiates a 10 minute hollow fiber membrane evaporator transient flush with unconcentrated urine from the waste storage tank before the subsystem can be shutdown; this flush eliminates the possibility of solids precipitation in the membranes during shutdown by removing the potentially high solids concentration recycle loop fluid from the membranes. When the subsystem is in the automatic mode accumulating wastewater, the controller will initiate wastewater processing when the waste storage tank reaches a predetermined full level, process until a predetermined low level is reached, transient flush, and place the subsystem back in the accumulating sub-mode.

Subsystem cumulative on-time is record by an elapsed time meter mounted on the driver box. On-time for the current run is displayed on the CRT on page 1 of the performance tables.

Component Description

The hollow fiber membrane evaporator, the thermoelectric regenerator, and the control and display modules are state-of-the-art components incorporated into the TIMES subsystem and will be described in detail in the following paragraphs. Other TIMES components are either modified off-the-shelf items or designs based on existing components.

Hollow Fiber Membrane Evaporator

The hollow fiber membrane evaporator, item 402, as shown in Figure 38 consists of two major parts, the cartridge assembly and the liquid trap and sensor assembly. Eighteen hollow fiber membrane cartridges, each containing 92 Nafion membrane tubes retained at each end by round elastomeric headers, are mounted in a cylinderical polysulfone and titanium hollow fiber membrane assembly. The total active membrane area is 1.95 m^2 (3024 in^2). Titanium end caps at ach end of the assembly provide inlet and outlet headers for the wastewater mixture circulating through the inner diameters of the tubular hollow fiber membranes. A central standpipe in the assembly vents the outer diameters of the membranes through the center of the wastewater inlet header to the upstream portion of the liquid trap and sensor assembly. A hydrophobic teflon screen with liquid sensor electrodes at its apex is contained in the assembly. The screen allows steam to flow through it while trapping and sensing any liquid breakthrough that might exist from a failed membrane condition. After the steam passes through the liquid trap and sensor assembly it is routed to the thermoelectric regenerator steam inlet tubes.

Table 6
TIMES OPERATING LOGIC SUMMARY

MANUALLY SELECTED MODE	NORMAL SHUTDOWN	START		AUTOMATIC			STANDBY	---
CONTROLLER SELECTED SUB-MODE	---	WARMING-UP	READY	PROCESSING	TRANSIENT FLUSH	ACCUM-ULATING	---	FAILURE SHUTDOWN
SUB-MODE SELECTION PARAMETER			HFM TEMPERATURE	WASTE QUANTITY	WASTE QUANTITY	END OF FLUSH		MALFUNCTION
FUNCTIONS								
. TER	OFF	ON	ON	ON	ON	OFF	OFF	OFF
. RECYCLE PUMP	OFF	ON	ON	ON	ON	OFF	OFF	OFF
. HEATER CONTROL	OFF	ON	OFF	OFF	OFF	ON	ON	OFF
. COOLING TEMPERATURE CONTROL	OFF	OFF	ON	ON	ON	OFF	OFF	OFF
. STEAM PRESSURE CONTROL	OFF	ON	ON	ON	ON	OFF	OFF	OFF
. CONDENSATE PUMP CONTROL	OFF	ON	ON	ON	OFF	OFF	OFF	OFF
. TANK TRANSFER CONTROL	OFF	ON	ON	ON	ON	ON	ON	OFF
. VALVE POSITION								
.WASTE . FLUSH . REJECT	SHUTOFF FLUSH REJECT	OPEN RECYCLE REJECT	OPEN RECYCLE REJECT	OPEN RECYCLE f(CONDUCTIVITY)	OPEN FLUSH REJECT	SHUTOFF FLUSH REJECT	SHUTOFF FLUSH REJECT	SHUTOFF RECYCLE REJECT
MALFUNCTION SHUTDOWNS								
. HFM BREAKTHROUGH	YES	YES	YES	YES	YES	YES	YES	---
. NO RECYCLE FLOW	NO	YES	YES	YES	YES	NO	NO	---
. HFM INLET OVERTEMPERATURE	NO	YES	YES	YES	YES	YES	YES	---
. ACCUMULATOR LEVEL HIGH	NO	YES	YES	YES	NO	NO	NO	---
. RECYCLE TANK OVERTEMPERATURE	YES	YES	YES	YES	YES	YES	YES	---
. HFM TEMP. SENSOR FAILURE	YES	YES	YES	YES	YES	YES	YES	---

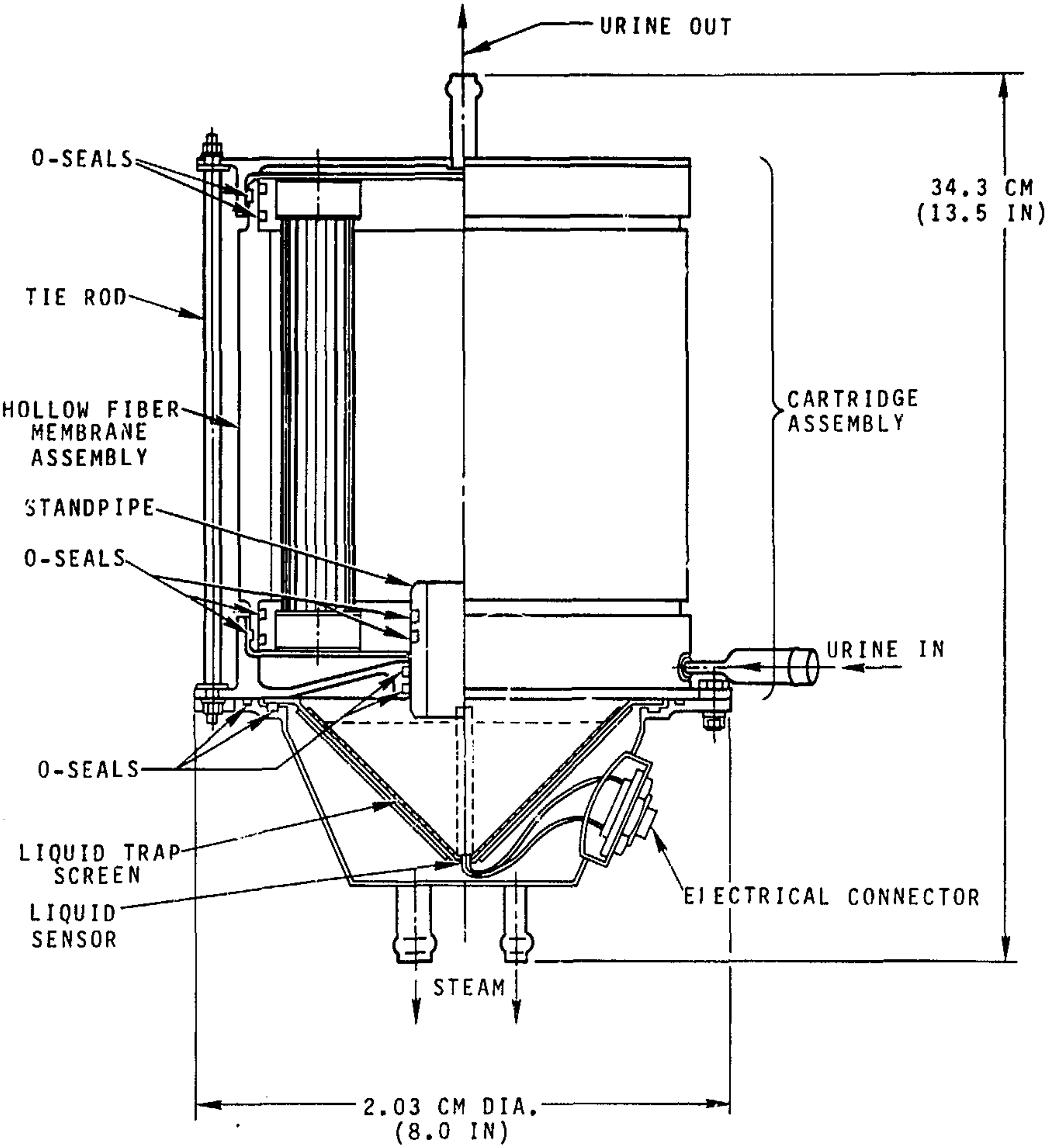


FIGURE 38

HOLLOW FIBER MEMBRANE EVAPORATOR

The cartridge assembly is readily removable from the subsystem for maintenance by isolating the hollow fiber membrane evaporator urine inlet and outlet lines using maintenance valves, and unbolting the cartridge assembly from the liquid trap and sensor assembly.

Thermoelectric Regenerator

The thermoelectric regenerator, item 401, as illustrated in Figure 39, contains three identical wastewater heat exchanger/thermoelectric heat pump/steam condensing modules packaged in parallel. For packaging convenience the inner module shares steam headers with the inner side of the outer modules.

Figure 40 shows a cross section of an individual module which contains a single urine heat exchanger with an identical hardware buildup on each side. Steam from the HFM evaporator enters the passages in the steam header and condenses on the porous plate. Heat flow from the condensing steam to the cold side of the thermoelectric elements is by conduction across the thickness of the pin fin collector plate located between the porous plate and the thermoelectric elements. The pin fin side of the collector plate is held against the porous plate allowing the condensate to be withdrawn from the porous plate and collected within the cavities between the pin fins. The condensate is either removed from these cavities as product water or recirculated through the external condensate cooling heat exchanger and returned to the cavity for temperature control purposes.

Heat removed from the porous plate is pumped by the thermoelectric elements to the pin fin wastewater heat exchanger where it reheats the wastewater mixture prior to return to the HFM evaporator.

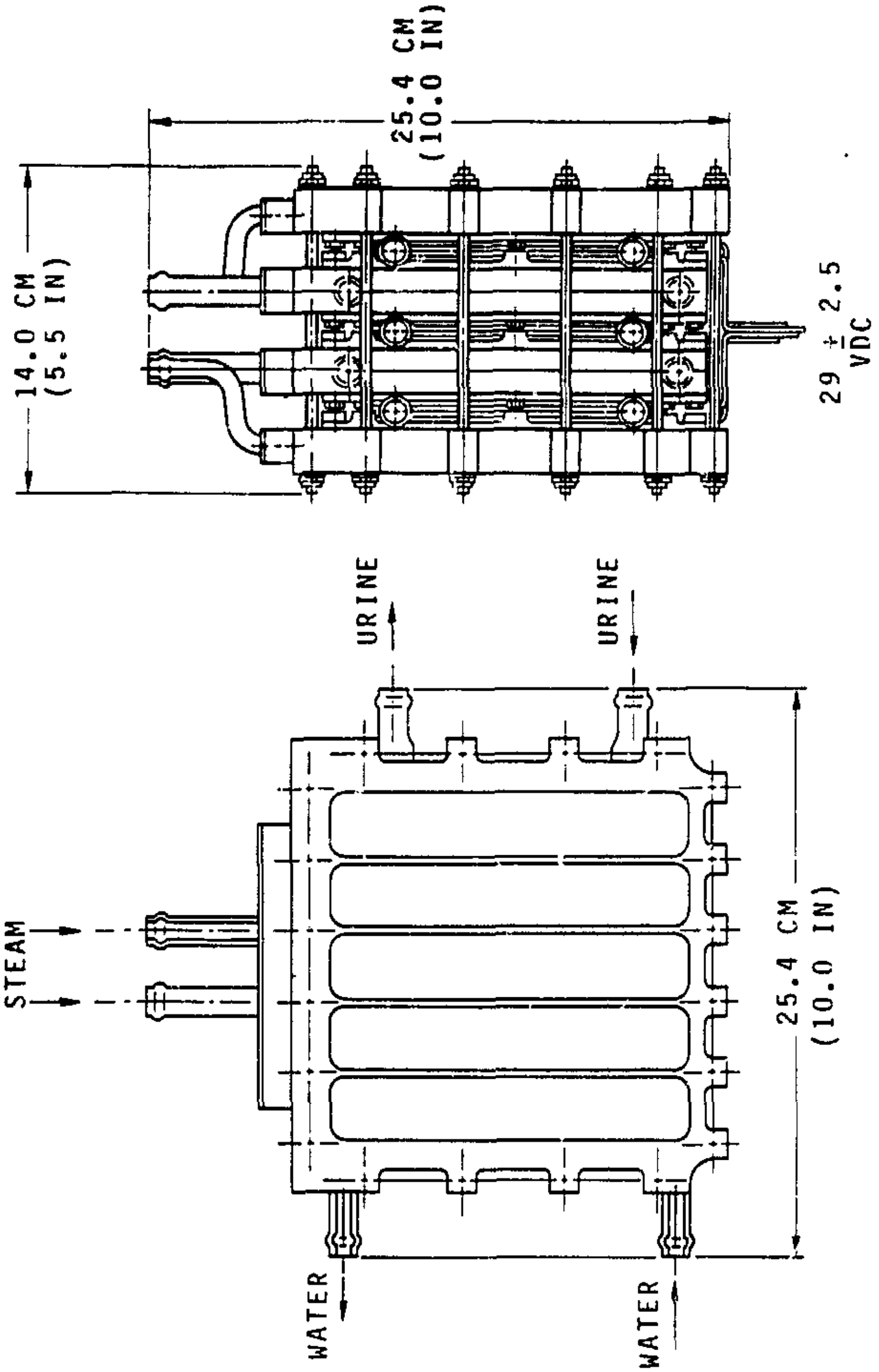


FIGURE 39
THERMOELECTRIC REGENERATOR

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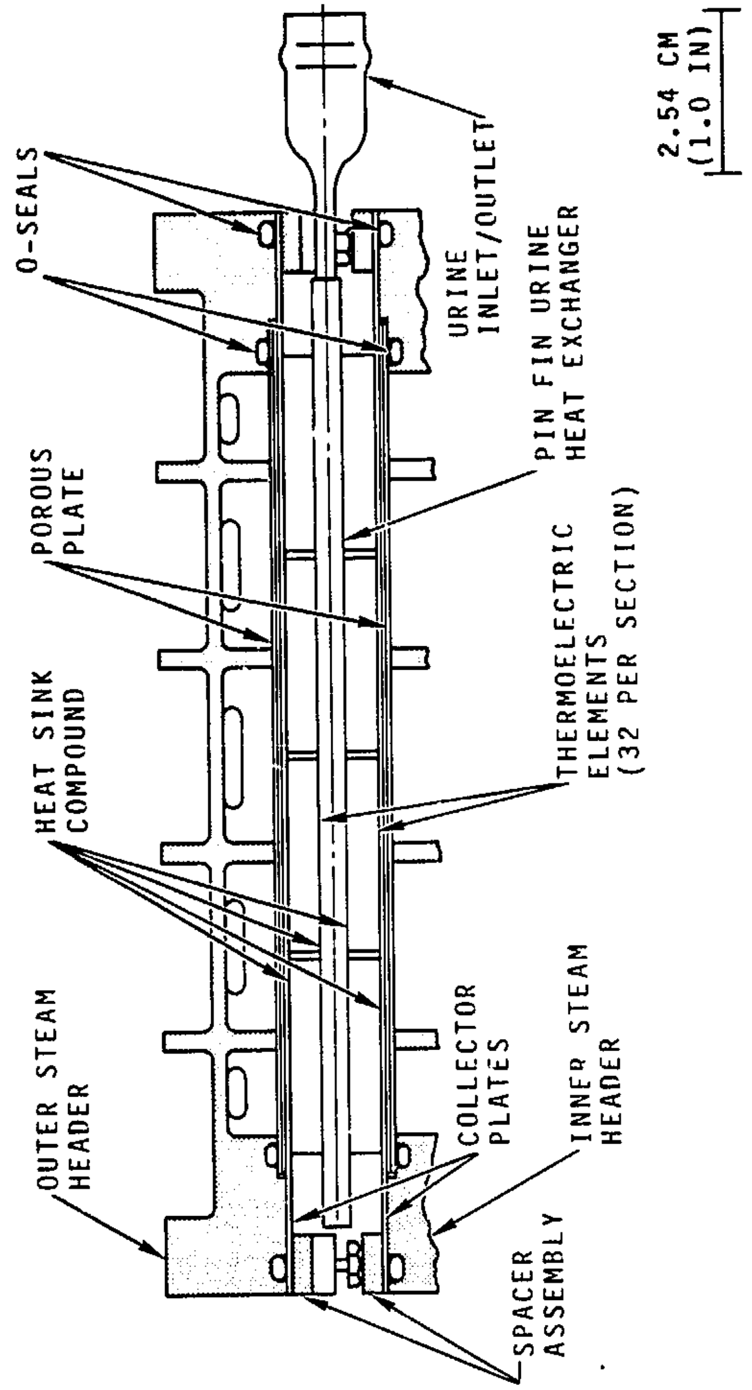

FIGURE 40
THERMOELECTRIC REGENERATOR CROSS SECTION

MAINTENANCE

The TIMES has been designed to operate for a minimum of 6 months without requiring maintenance of any kind except for the changeout of the item 203 recycle tank and item 210 filter that is required when the solids concentration in the wastewater recycle loop reaches 39%. Probe type maintenance quick disconnect valves items 133 and 134, respectively, have been incorporated into the recycle tank and the filter designs to allow rapid spill-free changeout of these two items.

Although no maintenance within the 6 month period is anticipated for the item 402 hollow fiber membrane evaporator, series shutoff valves and couplings have been incorporated in the recycle loop inlet and outlet lines of this component to allow spill-free removal for the inspection of the membranes if desired. The actual life of the membrane cartridge is yet to be determined, but is expected to exceed 5 years.

The charcoal and ion exchange resin in the item 206 postfiltration module has been sized for 6 months of operation, at which time schedued maintenance is required. Removal of this component requires the disconnection of Swagelok type fittings in the product water line.

Complete details of all maintenance operations for the TIMES are contained in the Operations and Maintenance Manual SVHSER 7237.

SUBSYSTEM FABRICATION

Table 7 identifies the principal items in the preprototype TIMES and shows whether they are make, buy, or GFE items. The TIMES subsystem package assembly is assembled using 0.635 cm (1/4 inch) and 0.953 cm (3/8 inch) stainless steel tubing, as appropriate, and Swagelok or equivalent stainless steel fittings. Components are located to facilitate maintenance, to allow manual positioning and visual monitoring of valves, to minimize line lengths and crossover points, and to locate all interface connectors on the back side of the package.

Table 7
TIMES PRINCIPLE ITEMS DESCRIPTION

Item No.	Part No.	Part Name	Remarks
100	SVSK97814	Pretreat Metering Unit	Modified Buy
200	SVSK96683	Waste Storage Tank	Make
201	SVSK96682	Pretreat Chemical Tank	Make
202	SVSK96681	Pretreat Mixing Tank	Make
203	SVSK96710	Recycle Tank	Make
205, 207, 208	SVSK96720	Bacteria Trap, Liquid	Make
206	SVSK96720	Multifilter	Make
209	SVSK97505	Preheater	Make
210	SVSK96795	Filter	Make
211	SVSK96791	Condensate Cooling H/X	Make
212	SVSK96713	Condensate Accumulator	Make
213	SVSK96718	Bacteria Trap, Air	Make
303	---	Concentration Sensor	Buy
304, 308, 309	SVSK85443	Temperature Sensor	Buy
305, 310, 313	---	Pressure Transducer	Buy
306	SVSK97533	Conductivity Sensor	Buy
311	SVSK97811	Controller	Make
315	SVSK97812	Driver box	Make
316	SVSK101112	Differential Temperature Box	Make
400	SVSK102747	Urine Recycle Pump	Buy
401	SVSK95545	Thermoelectric Regenerator	Make
402	SVSK95638	HFM Evaporator	Make
403	SVSK102747	Condensate Delivery Pump	Buy
404	SVSK102788	Condensate Recycle Pump	Buy

Table 7 (Continued)
TIMES PRINCIPLE ITEMS DESCRIPTION

Item No.	Part No.	Part Name	Remarks
---	SVSK97562	Collection Package	Make
---	SVSK96789	Process Package	Make
---	SVSK103179	CRT Display	Buy
---	SVSK103178	Keyboard	Modified Buy
---	SVSK103177	Floppy Disk Drive	Buy
---	---	Frame, CRT	GFE

SUBSYSTEM ACCEPTANCE TESTING

URINE VERIFICATION TESTING

Objective

Post-assembly verification testing is conducted on the completed water recovery subsystem to verify subsystem functionality and to demonstrate that all the contractual design, subsystem performance, and fabrication specifications are met. Subsystem specific energy requirements, weight, volume, processing rate, water loss to vacuum, consumption of expendables, operation, endurance and product water quality are demonstrated to verify acceptability. As a minimum, the cumulative time at test conditions during this task is to be equivalent to 30 eight-hour days (240 hours).

Summary

The TIMES was operated for a total of 30 eight-hour days (240 hours), employing a feed of pretreated urine having dissolved solids concentrations averaging 4.0%. The recycle tank was changed out once during the 240 hours, when the dissolved solids concentration reached 37.0% in the recycle loop, which is equivalent to 93% water recovery from the pretreated urine feed.

Performance data were collected at 26.5 and 29.0 volts DC while processing unconcentrated and concentrated urine. The specific energy at 26.5 VDC for unconcentrated urine was 157.3 W-h/kg (71.5 W-h/lb), and the processing rate after 30 eight-hour days was 0.88 kg/h (1.95 lb/h) at 29.0 VDC and with urine concentrated to 27% solids content. Water loss from vacuum purging averaged 0.0059 kg/h (0.013 lb/h) over the test period, and expendables amounted to 0.88 kg/100 kg (0.88 lb/100 lb) pretreated urine. These results are compared to the test requirements in Table 8.

With the exception of pH, water quality met or exceeded the standards recommended by the National Academy of Science - National Research Council, Committee on Toxicology in their Report of the Panel on Potable Water Quality in Manned Spacecraft, August, 1972 (contained in Appendix A of this report) for those onstituents actually analyzed. Table 9 compares test results with the requirements of the standard.

Test Description

The subsystem test setup is schematically illustrated in Figure 41. Appendix D, Acceptance Testing Test Data, contains the test log sheets. The subsystem was initially charged with distilled water and put in the 'START' mode at 29.0 VDC. The two startup sub-modes occurred in accordance with the TIMES logic summary, Table 6. The subsystem was then put into the 'AUTOMATIC' mode, and performance was maintained with readings taken every 15 minutes. The steady state condensate production rate was verified as being greater than 0.77 kg/h (1.7 lb/h) and all submode operation was confirmed. The subsystem was then placed in the 'STANDBY' mode.

Table 8
URINE VERIFICATION TEST RESULTS SUMMARY

Parameter/Condition	Requirement	Results/Condition
Total test time	240 h	240 h
Specific energy/26.5 VDC Unconcentrated Urine	334.4 W-h/kg (152 W-h/lb)	157.3 W-h/kg (71.5 W-h/lb)
Processing rate/29.0 VDC Unconcentrated Urine--240 h	0.77 kg/h (1.70 lb/h)	0.88 kg/h @ 27% solids (1.95 lb/h)
Vacuum purge water loss	0.014 kg/h (0.030 lb/h)	0.0059 kg/h (0.013 lb/h)
Expendables	0.65 kg/100 kg (0.65 lb/100 lb)	0.88 kg/100 kg (0.88 lb/100 lb)
Water Recovery	95%	93%

Table 9
URINE VERIFICATION TEST WATER ANALYSIS

DETERMINATION	SPECIFICATION	SAMPLES							
		NON-POSTTREATED							POST-TREATED
Urine Solids %		4.4	30.0	37.0	12.7	26.5	20	4-8	4-8
pH	7.0-8.0	3.7	7.3	6.9	3.5	3.7	6.9	3.9	5.7
Resistivity (Megohm-cm at 25°C)		.012	.003	.003	.006	.009	.007	.016	.042
Total Solids, ppm	500	5.5	3.7	3.0	2.4	3.0	2.4	3.6	246.4
Organic Carbon, ppm	100	55	76	75	68	80	72	68	402
Inorganic Carbon, ppm		1	20	21	2	2	10	5	6
Cadmium as Cd, ppb	10	45	<10	<10	80	<10	<10	<10	<10
Chromium as Cr^{+6}, ppb	100	<10	<10	<10	<10	<10	<10	<10	<10
Copper as Cu, ppb	1000	<10	<10	<10	<10	<10	<10	<10	<10
Iron as Fe, ppb	1000	45	<10	<10	15	<10	<10	<10	<10
Lead as Pb, ppb									
Magnesium as Mg, ppb		60	<10	10	80	15	<10	<10	<10
Manganese as Mn, ppb	100	<10	<10	<10	<10	15	20	<10	<10
Mercury as Hg, ppb									
Nickel as Ni, ppb	100	<10	<10	<10	<10	980	<10	<10	<10
Potassium as K, ppb									
Silver as Ag, ppb									
Sodium as Na, ppb		<10	<10	<10	<10	<10	<10	<10	100
Zinc as Zn, ppb									
Ammonia as N, ppm	5.0	0.27	41.3	47.3	0.52	5.75	21.8	0.31	2.64
Fluoride as F^-, ppb	2000	105	15	22	80	55	<10	30	<10
Nitrate as N, ppb									
Sulfate as SO_4^{-2}, ppb									
Chloride as Cl^-, ppb	250000	115	85	260	50	<50	325	<50	3840
Conductivity µmho/cm		80.07	334.65	352.18	169.78	115.4	137.19	63.75	23.64

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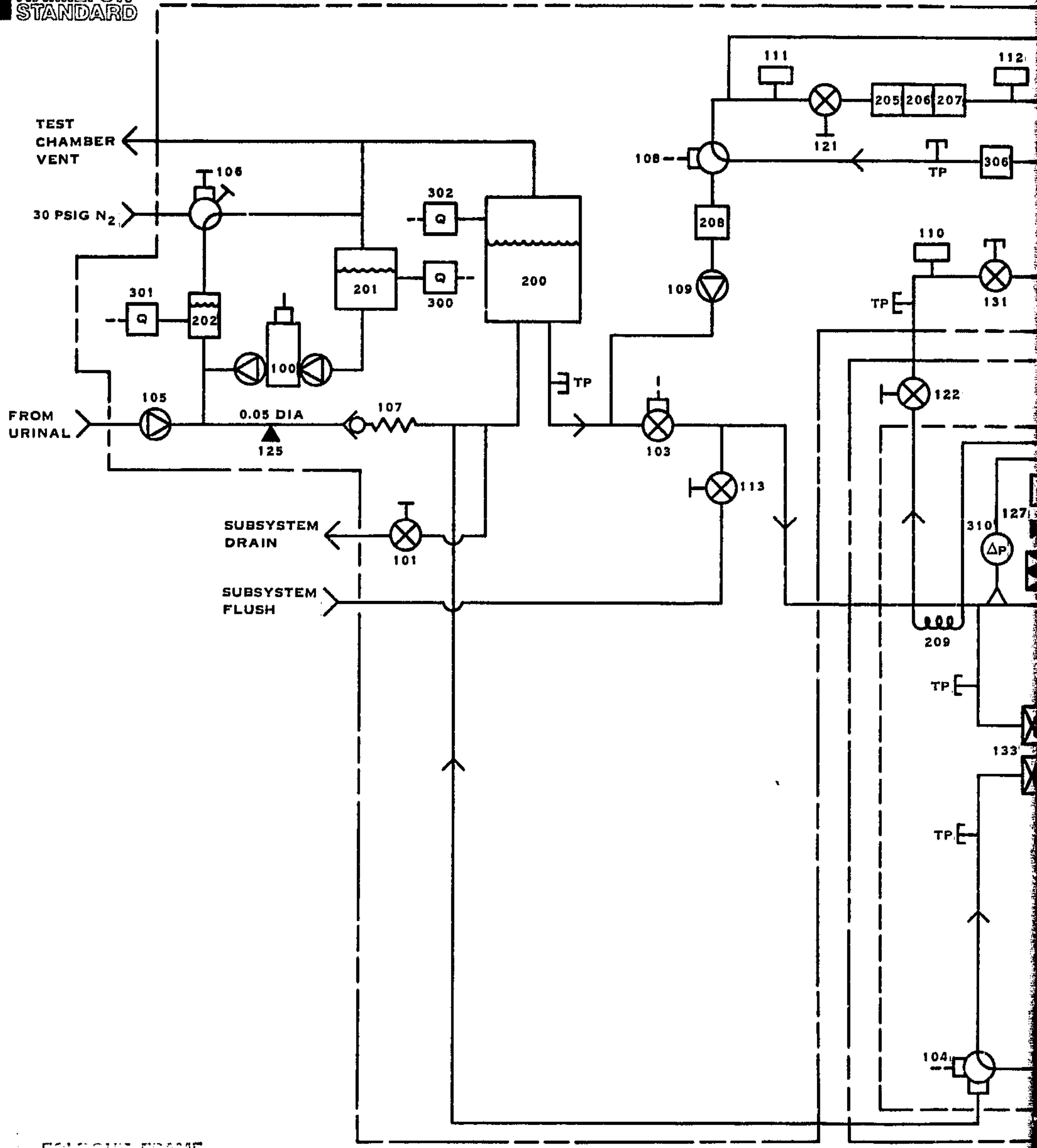

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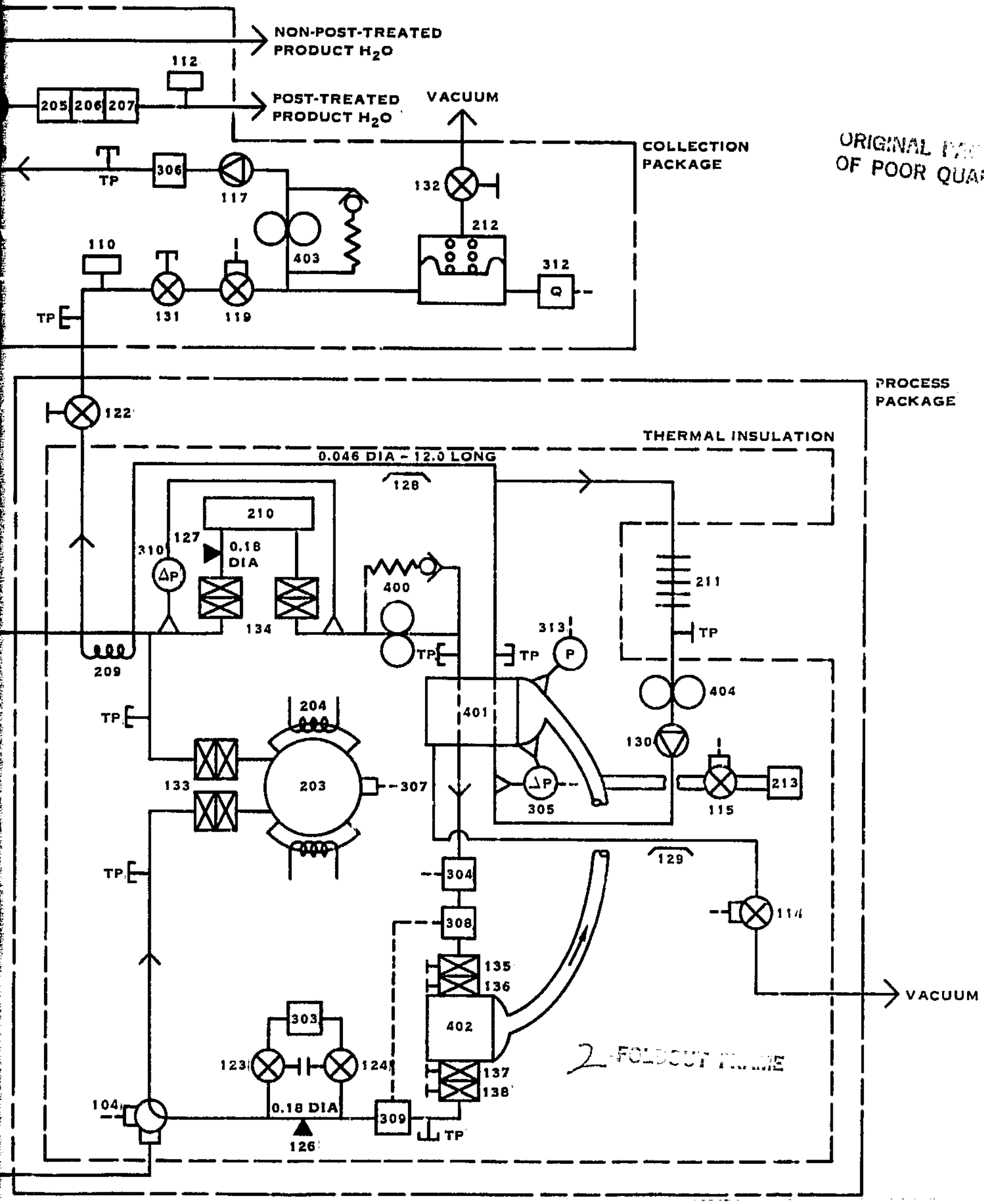

FIGURE 41
TIMES SCHEMATIC

The subsystem was recharged and tank level readings were taken to calculate a mass balance, and then restarted. Warning, failure, and shutdown sensor operation was then verified as indicated in Table 10. The performance was again checked to ensure that the production rate was at least 0.77 kg/h (1.7 lb/h) and that the specific energy was less than 334.4 W-h/kg (152 W-h/lb) at 26.5 VDC.

The distilled water was then drained from the holding, waste storage and recycle tanks. Fresh urine, pretreated with 4 ml/liter of chromic/sulfuric acid mix, was added to the recycle and waste storage tanks. By mutual agreement with NASA, raw urine was substituted for the urine/urinal rinse water mix called out in the contract. This was done to permit comparisons with other urine processing subsystems. The subsystem was placed in the 'START' mode and allowed to reach the submode 'READY'. This determined the warm-up time with the recycle heaters. Subsystem heat-up without the heater was delayed until the baseline test. Both warm-up time checks will be discussed in the Baseline Test section.

The test continued automatically until the calculated solids content reached 37.0% in the recycle loop. The subsystem was then shut down, the recycle loop filter changed, and the recycle tank removed, emptied and recharged with fresh pretreated urine. The test resumed, and continued until the 240 hour point (30 eight-hour days) was reached.

All data was recorded hourly for the first eight hours of operation and at least twice daily thereafter. A mass balance between input and output was maintained, and water samples were taken upstream and downstream of the post-filtration module at seven different dissolved solids concentrations during the 240 hour test. Samples of the recycle liquid were taken every 24 hours to calculate the dissolved solids concentration and check pH. A list of readings that were recorded is presented in Table 11.

Discussion of Results

Performance

The performance data are presented in Figure 42. The data represent readings taken at 24-hour intervals throughout the test, as well as several more points near scheduled subsystem operational mode changes (such as recycle tank change-out).

The processing rate decreases as recycle solids increase due to the solution vapor pressure lowering effect, as well as the decrease in water permeability through the Nafion membranes caused by the increased concentration of dissolved species. The data matched predicted performance as seen in Figure 43 where the curve represents the normal operating characteristic of the subsystem.

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Table 10
SENSOR CHECKOUT

ITEM	LOW LEVEL TRIP	HIGH LEVEL TRIP	WARNINGS/SHUTDOWN
1) Mixing Tank	9.5%	86.5% (Actuates Blowdown)	96.0% Yellow
2) Waste Tank	5.0% (Initiates Flush)	67.5% (Recycle Pump On)	72.5% White 91.5% Yellow
3) Pretreat Tank	---	---	<1.0% Yellow 4.5% White
4) Recycle Tank Heater Control	62.2°C (144°F) (On)	65.6% (150°F) (Off)	68.9°C (156°F) (Failure Shutdown)
5) Recycle Tank/HFM Inlet Delta Temp. Sensor Failure	---	---	21.7°C (71°F) (Failure Shutdown)
6) HFM Inlet Temp.	---	---	71.7°C (161°F) For 5 Min. (Failure Shutdown)
7) Liquid Breakthrough	---	---	Wet (Failure Shutdown)
8) Recycle Filter ΔP	---	---	0.0 kPa (0.0 psid) (Failure Shutdown) 26.20 kPa (3.80 psid) White 27.24 kPa (3.95 psid) Yellow
9) Accumulator	25% (Pump Off)	75% (Pump On)	100% For 10 Min. (Failure Shutdown)
10) Conductivity	---	450 µmho/cm (Recycle Valve To Recycle)	---
11) Processing Rate	---	---	<0.5 kg/h (1.1 lb/h) White
12) Shutdown Mode	---	---	White

Table 11
DATA READINGS

Readings	Comment
TIME	Actual Daily Time
T_{HFM}	Feed Inlet Temperature At The Hollow Fiber Membranes
$T_{RECYCLE}$	Recycle Tank Temperature
ΔT_{HFM}	Feed Temperature Differential Across The Evaporator
P_{STEAM}	Steam Pressure At Evaporator
ΔP_{PP}	Porous Plate Differential Pressure
ΔP_{F}	Recycle Loop Filter Differential Pressure
V	Subsystem Input DC Voltage
A	Subsystem Total Current
PROD RATE	Water Production Rate
AVG PWR	Average Subsystem Power
TER PWR	Thermoelectric Regenerator Power
SPEC ENGY	Specific Energy At Operating Voltage
CORR SP ENGY	Specific Energy Corrected to 26.5 VDC
PROD COND	Product Water Conductivity
SOL CONC	Feed Solids Concentration
WASTE TANK	Waste Tank Level
ACCUM	Accumulator Vacuum
PROD pH	Product Water pH
BURP VOL	Water Loss To Vacuum Purge
ACTUAL H_2O DEL	Measured Quantity Of Product Water
WATER DEL	Subsystem Calculated Quantity Of Product Water
URINE ADDITION	Quantity Of Feed Added To Subsystem

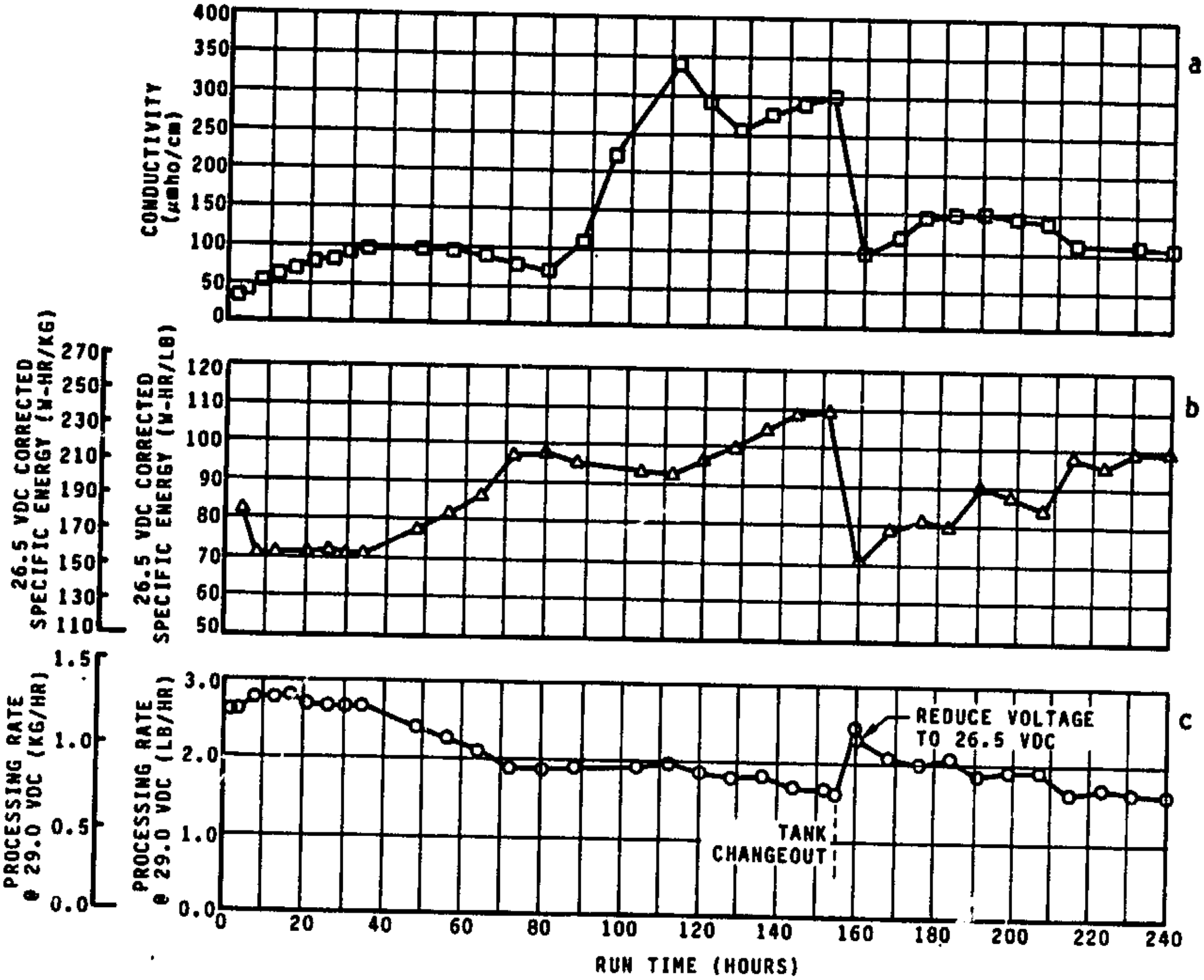


FIGURE 42

URINE VERIFICATION TEST PERFORMANCE

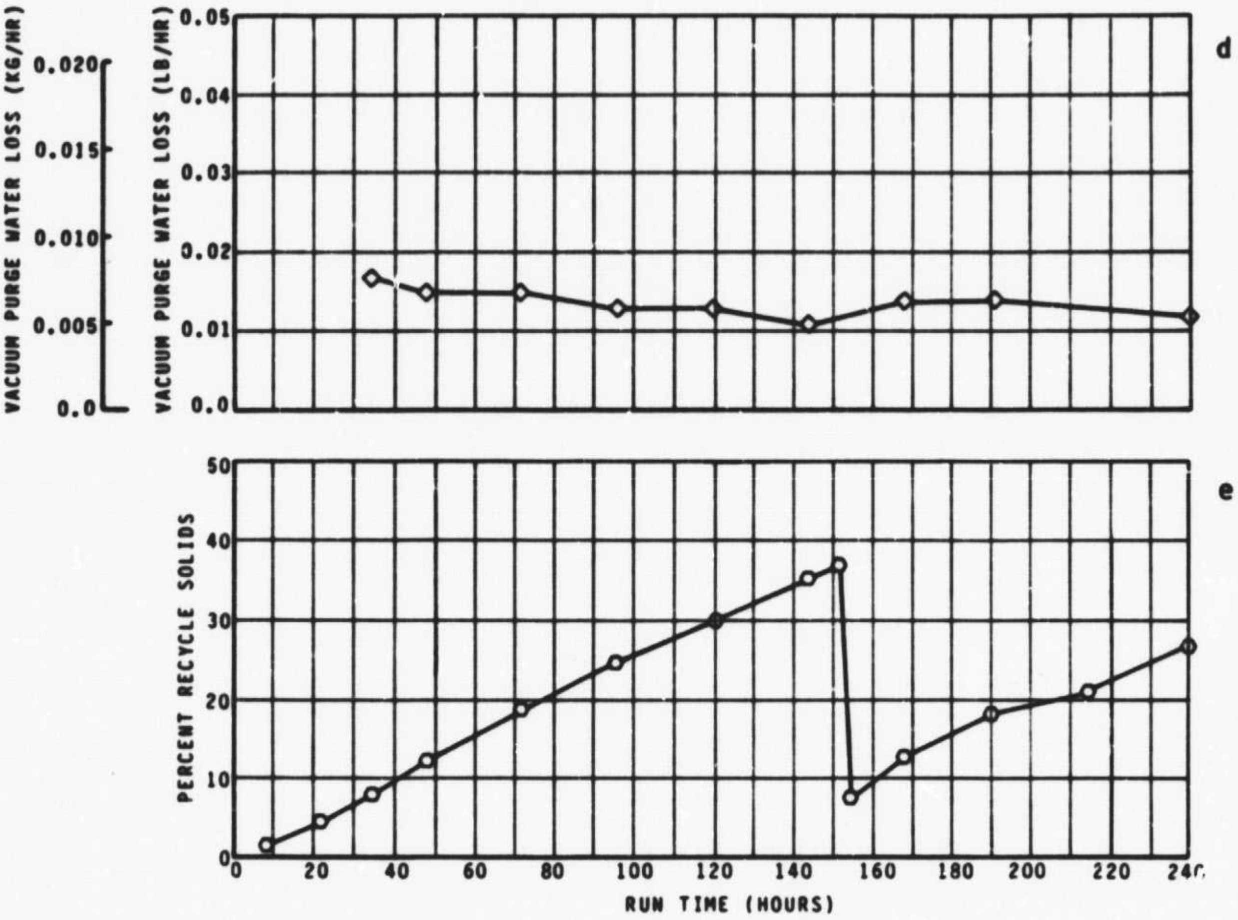


FIGURE 42
URINE VERIFICATION TEST PERFORMANCE

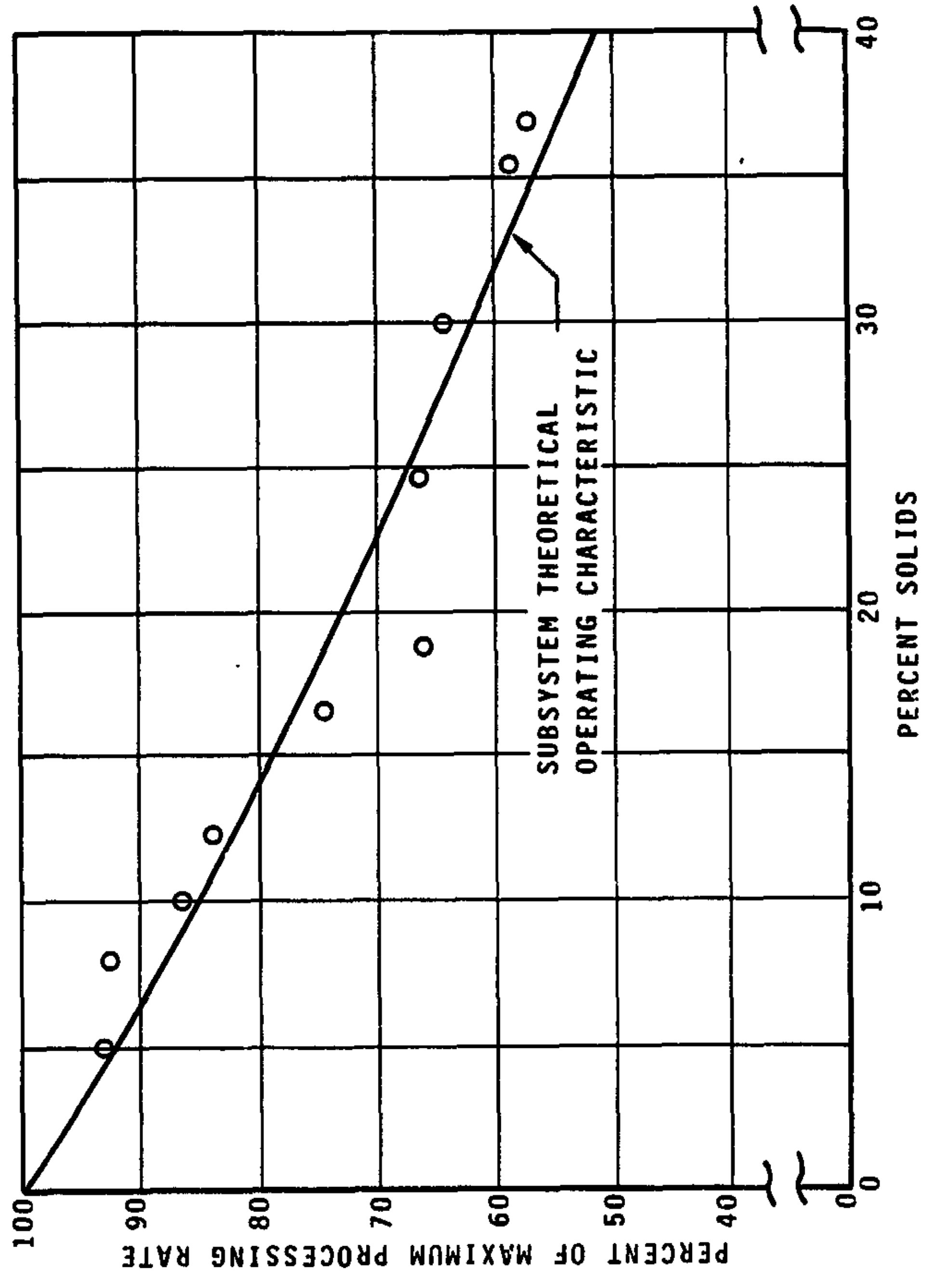


FIGURE 43

URINE VERIFICATION TEST
RELATIVE PROCESSING RATE

The recycle tank was changed-out at 37.0% dissolved solids accumulation. The target concentration for 95% water recovery was 39% for the design concentration of 3.1% dissolved solids in urine/urinal rinse water. Due to the effect of withdrawing recycle loop samples, and the time involved boiling the sample to determine the actual solids concentration, the 39% solids tank change-out point was incorrectly projected and the actual solids concentration was therefore lower. There was no observed undissolved solids residue on any of the tank surfaces or in the concentrated recycle fluid; the elevated temperature in the recycle loop provides high solids solubility. This is an important feature of the TIMES, since considerable solids concentrations can thus be tolerated without causing any solids deposition problems. After recharging with fresh pretreated urine, the processing rate returned to 1.11 kg/h (2.45 lb/h) at 29.0 VDC or 92% of the value at the start of the urine testing. This represents a nearly complete processing rate recovery if the controller's processing rate calculation band of ±6% is considered. This band is generated because calculated rates are the average of the previous four readings, updated every 15 minutes. This effect can be observed in Figure 44, which is a photograph of the actual TIMES controller plot of processing rate vs. time.

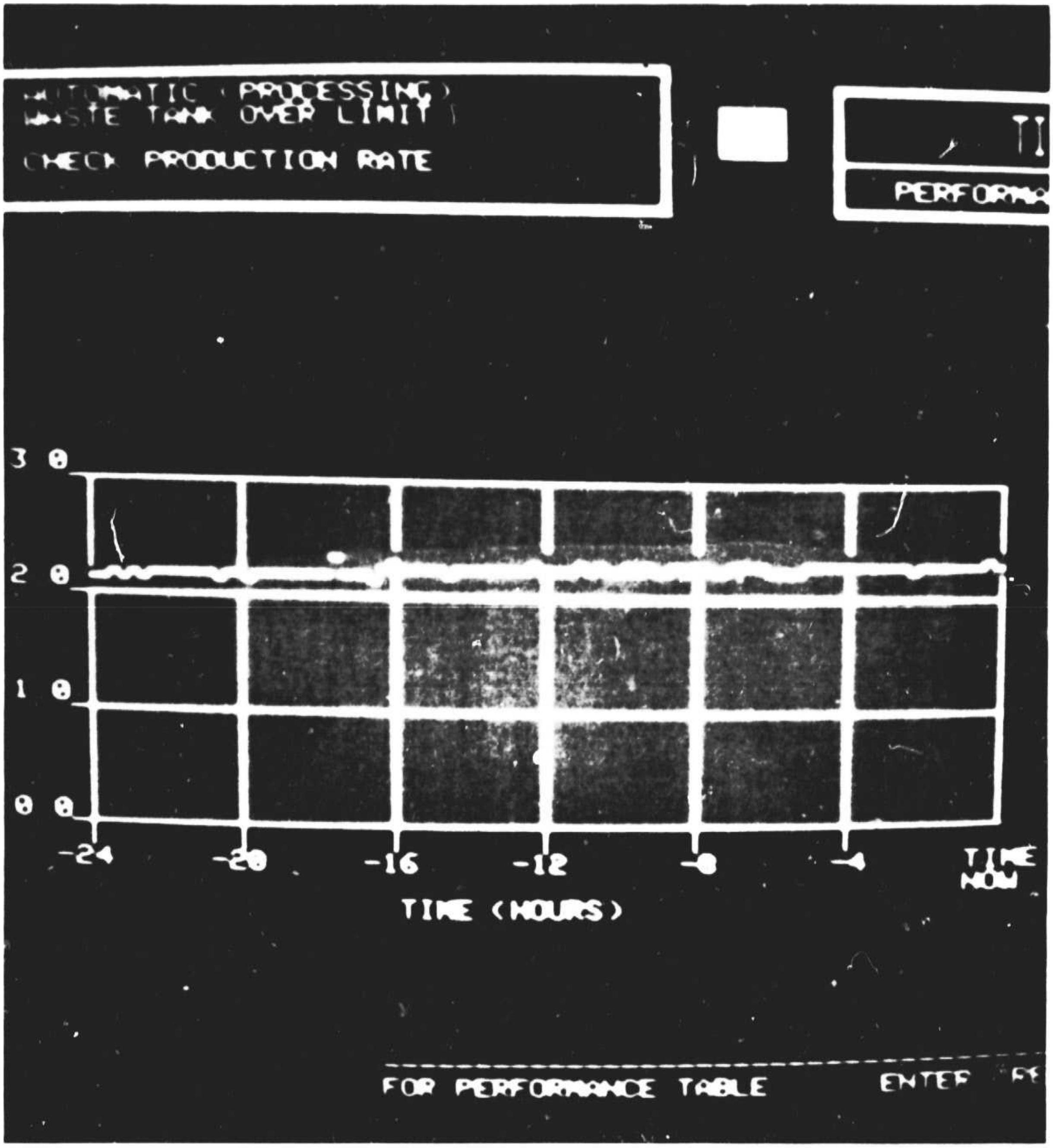
The specific energy at 26.5 VDC for unconcentrated urine was 157.3 W-h/kg (71.5 W-h/lb) and the maximum value was 240.9 W-h/kg (109.5 W-h/lb) at 37% solids. Projected to 40%, this value would have been 249.0 W-h/kg (113.2 W-h/lb). This is significantly below the specification of 334.4 W-h/kg (152 W-h/lb) for unconcentrated urine, and reflects the result of the relatively high processing rates attained by the subsystem.

For the remaining 80 hours of the test, the system voltage was reduced from 29.0 to 26.5 VDC and at the 240 hour point, the processing rate with 27% recycle solids was 0.74 kg/h (1.63 lb/h), which is equivalent to 0.88 kg/h (1.95 pph) at 29 VDC. Using the subsystem operating characteristic, this would project to 1.26 kg/h (2.78 lb/h) at 29 VDC for unconcentrated urine.

Water Quality

The water analysis shows that the posttreated product water was of excellent quality throughout the test. The high ammonia levels found in the raw product water collected at higher dissolved solids concentrations did not affect the posttreated product water quality.

A sharp conductivity rise that occurred at 25% solids concentration was brought under control by increasing the quantity of pretreat added to the urine in the waste storage tank. This served to bring the recycle loop pH down, thereby inhibiting increased ammonia evolution which was primarily responsible for the conductivity rise. The slightly low pH level in the posttreated product water is attributed to residual dissolved carbon dioxide and trace carryover of hydrogen chloride. It is recommended that pH levels be more closely monitored so that the quantity of pretreat added can be adjusted in order to control recycle loop pH, and simultaneously optimize expendables usage.



AUTOMATIC (PROCESSING)
WASTE TANK OVER LIMIT)

CHECK PRODUCTION RATE

FIGURE 44
ACTUAL TIMES WATER PRODUCTION PLOT

URINE BASELINE TESTING

Objective

The purpose of the baseline test is to establish the exact operating characteristics in earth gravity conditions. The testing establishes subsystem endurance, component maintenance or replacement requirements, and determines subsystem suitability for inclusion in future flight systems.

The cumulative test time at test conditions is to be equivalent to 30 eight-hour days (240 hours), and the subsystem is to process urine produced by three crew men in 30 days with system maintenance allowed, except for the processing module.

Summary

The TIMES, after completing the 240 hour verification test, was operated for a total of 30 eight-hour days (240 hours), employing pretreated urine feed having dissolved solids concentrations averaging 3.8%. The recycle tank was changed out once during the 240 hours, when the dissolved solids concentration reached 37.7% in the recycle loop, which is equivalent to 93.5% water recovery from the pretreated urine.

Performance data were collected at 26.5, 29.0, and 31.5 VDC while processing unconcentrated and concentrated urine. The specific energy at 26.5 VDC for unconcentrated urine was 158.4 W-h/kg (72.0 W-h/lb). The processing rate after the first 4 hours of steady state operation was 1.20 kg/h (2.65 lb/h) at 29.0 VDC for unconcentrated urine, and 0.86 kg/h (1.90 lb/h) at 29.0 VDC after 240 test hours with urine having 11.5% dissolved solids. Water loss from vacuum purging averaged 0.035 kg/h (0.077 lb/h), and expendables amounted to 1.15 kg/100 kg (1.15 lb/100 lb) pretreated urine. These results are compared to the test requirements in Table 12.

With the exception of pH, water quality met or exceeded the standards recommended by the National Academy of Science - National Research Council, Committee on Toxicology in their Report of the Panel on Potable Water Quality in Manned Spacecraft, August, 1972 (contained in Appendix A of this report) for those constituents actually analyzed. Table 13 compares test results with the requirements of the standard.

Disassembly of the subsystem after completion of testing did not reveal any degradation in functional capability or condition that would prevent 180 days of operation.

Test Description

The test setup was identical to that used for the verification test and is schematically illustrated in Figure 41. The holding, waste storage and recycle tanks were drained of any concentrated urine residue from the verification test. The holding and waste storage tanks were charged with fresh, pretreated urine, and the subsystem was placed in the 'START' mode. Upon attaining 'READY'

Table 12
URINE BASELINE TEST RESULTS SUMMARY

Parameter/Condition	Requirements	Results/Condition
Total Test Time	240 h	240 h
Specific Energy/ 26.5 VDC--Unconcentrated Urine	334.4 W-h/kg (152 W-h/lb)	158.4 W-h/kg (72.0 W-h/lb)
Processing Rate/ 29.0 VDC--Unconcentrated Urine--240 h	0.77 kg/h (1.70 lb/h)	0.86 kg/h @ 11.5% Solids (1.90 lb/h)
Vacuum Purge Water Loss	0.014 kg/h (0.030 lb/h)	0.035 kg/h (0.077 lb/h)
Expendables	0.65 kg/00 kg (0.65 lb/100 lb)	1.15 kg/100 kg (1.15 lb/100 lb)
Water Recovery	95%	93.5%

Table 13
URINE BASELINE TEST WATER ANALYSIS

DETERMINATION	SPECIFICATION	SAMPLES NON-POSTTREATED				SAMPLES POSTTREATED			
Urine Solids %		7.5	21.0	28.0	34.0	7.5	21.0	28.0	34.0
pH	7.0-8.0	3.6	3.5	3.6	5.8	5.8	4.3	3.9	4.0
Resistivity (Megohm-cm at 25°C)		.007	.005	.006	.006	.083	.007	.007	.005
Total Solids, ppm	500	1.3	4.0	4.1	2.0	1.1	54.3	29.1	
Organic Carbon, ppm	100	37	56	53	24	6	20	24	40
Inorganic Carbon, ppm		8	22	22	31	2	17	18	23
Cadmium as Cd, ppb	10								
Chromium as Cr^{+6}, ppb	100	<10	<10	<10	<10	<10	<10	<10	<10
Copper as Cu, ppb	1000								
Iron as Fe, ppb	1000								
Lead as Pb, ppb									
Magnesium as Mg, ppb									
Manganese as Mn, ppb	100	10	20	10	15	20	<10	20	10
Mercury as Hg, ppb									
Nickel as Ni, ppb	100	<10	<10	<10	<10	<10	<10	<10	<10
Potassium as K, ppb									
Silver as Ag, ppb									
Sodium as Na, ppb									
Zinc as Zn, ppb									
Ammonia as N, ppb	5000	160	770	4500	15000	430	1125	1400	9000
Fluoride as F^-, ppb	2000	70	125	80	13	80	105	85	23
Nitrate as N, ppb									
Sulfate as SO_4^{-2}, ppb									
Chloride as Cl^-, ppb	250000	110	275	150	260	850	1000	700	750
Conductivity µmho/cm		134.7	197.6	173.6	175.7	12.0	146.5	145.3	184.1

status, the subsystem was placed in the 'AUTOMATIC' mode with the voltage set to 29.0 VDC.

The water production rate was monitored after the first four hours of steady state operation to ensure that the value was a minimum of 0.77 kg/h (1.7 lb/h). The subsystem was operated until 37.7% solids accumulated in the recycle loop, and then the recycle loop filter and the recycle tank were changed-out and charged with fresh pretreated urine. The subsystem was brought back to a steady state condition and the test continued until a total of 240 hours were accumulated.

Readings were taken at least once per hour during the first eight hours, and at least twice daily during the remainder of the test. Water samples were taken at four different solids concentrations during the testing, for both raw and posttreated product water.

A number of startup and shutdown conditions were manually selected at the end of the test to complete the determination of heatup times for the 'START' mode with and without the recycle tank heater.

Discussion of Results

Performance

The data presented in Figure 45 represent steady state performance at 29.0 VDC, except for two points at the high (31.5 VDC) and low (26.5 VDC) voltage levels of TIMES operation. For the first 24 hours, the subsystem was manually cycled between startup and shutdown four times, so no readings are presented for this period. It is seen that the initial steady state baseline processing rate is approximately equal to the initial value established at the beginning of the verification test and therefore represents full throughput recovery for the membranes after a return to unconcentrated urine input. However, the rate of decrease of the processing rate after 100 hours is greater than that seen in the verification testing. This step change in the processing rate is the first indication of marginal porous plate operation, which became an acute problem after a high temperature shutdown that occurred during the subsequent wash water testing (the porous plates are further discussed in the Wash Water Testing section of this report). The presumption that the porous plate effectiveness was decreasing is supported by the observed increased vacuum purge water loss occurring simultaneously. For the entire test, this loss averaged 0.035 kg/h (0.077 lb/h), but for the first 100 hours, it averaged only 0.012 kg/h (0.027 lb/h).

The reason for the decreased porous plate effectiveness is attributed to a small amount of raw feed carryover observed in the purge water at this point in the test. Examination of the hardware failed to uncover a leak in the urine/steam interface. Subsequent testing with wash water indicated a problem where the silicone rubber tube headers were allowing raw feed to leak into the steam chamber under certain operational conditions in the testing; the leakage problem may have been occurring at this point in the baseline testing and would have been the source of the contamination. The header problem is discussed further in the Wash Water Demonstration Testing section.

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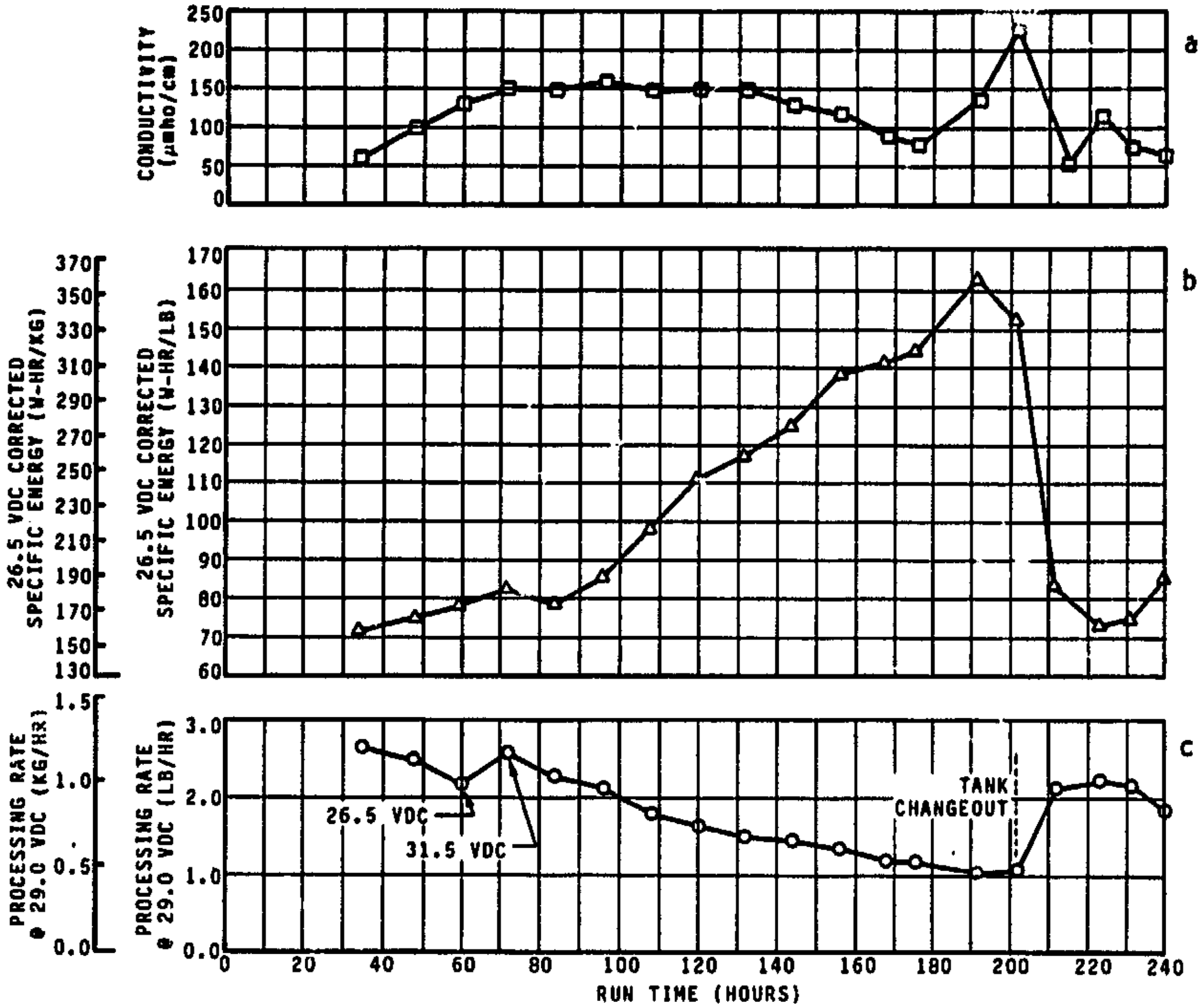

FIGURE 45

URINE BASELINE TEST PERFORMANCE

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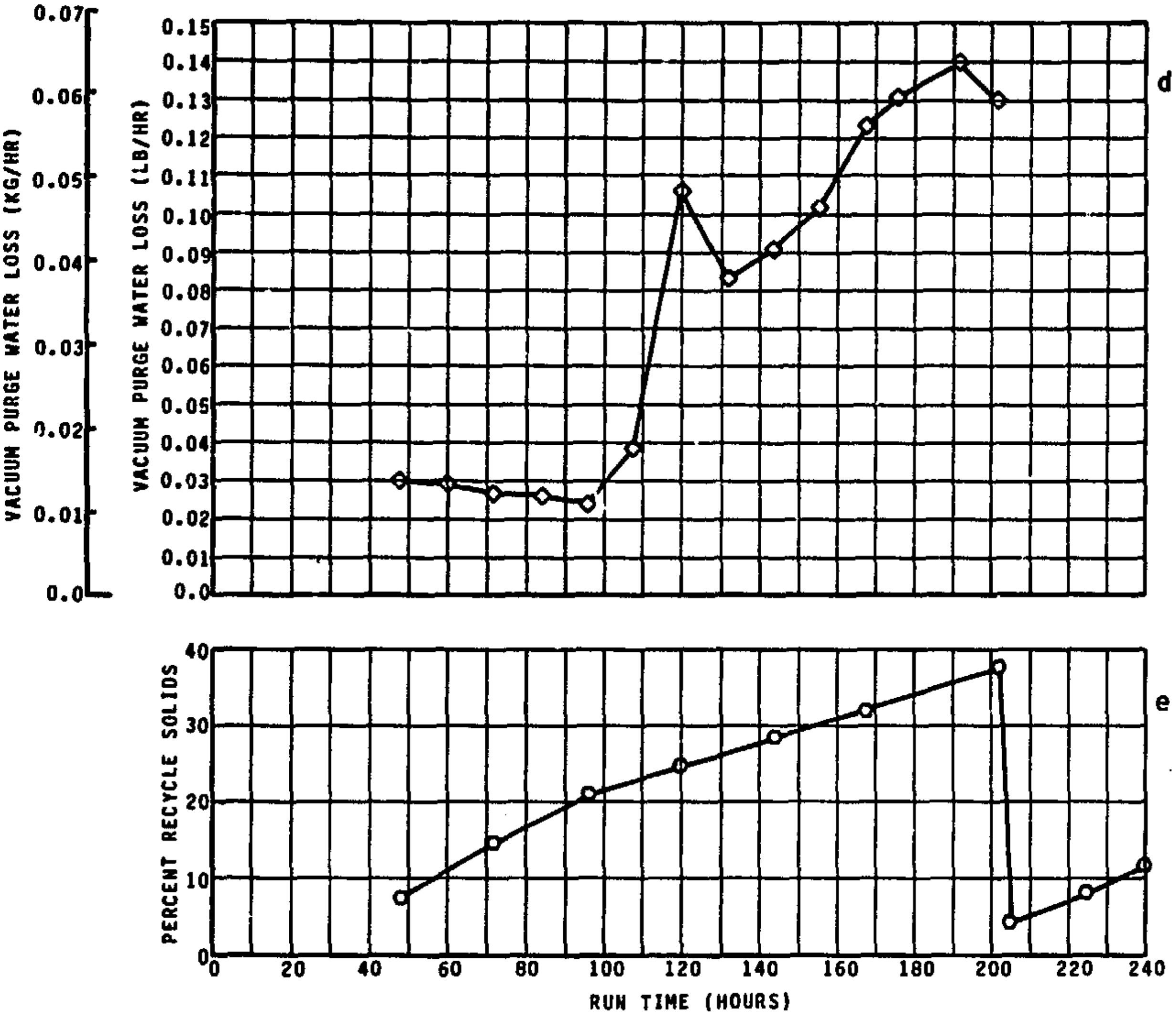

FIGURE 45
URINE BASELINE TEST PERFORMANCE

The recycle tank was changed-out at 37.7% solids, which was slightly earlier than anticipated because the subsystem had to be shutdown to inspect for leaks as mentioned in the previous paragraph, and therefore, did not reflect an inability to concentrate the solids to a greater degree. After the recycle tank changeout a significant processing rate recovery was observed, but the rate for unconcentrated urine at this point was 17% lower than at the start of steady state baseline testing, reflecting the degraded porous plate condition. At the end of the 240 hours, there were approximately 12% dissolved solids in the recycle loop and the processing rate was 0.86 kg/h (1.90 lb/h) at 29.0 VDC. This projects to 0.97 kg/h (2.14 lb/h) for unconcentrated urine using the subsystem operating characteristic.

As expected, specific energy corrected to 26.5 VDC shows a steady increase as the solids concentrate in the recycle loop. The levels are elevated over those obtained in the verification test primarily because of the decreased average processing rates during the baseline testing. But again, a large decrease in the specific energy is evident after the recycle tank was changed-out, and averaged 176.7 W-h/kg (80.3 W-h/lb) at 26.5 VDC during the last 40 hours of the test, with solids concentrating to 12%.

Water Quality

Conductivity levels shown in Figure 45a remained fairly constant at 150 μmho/cm after the initial rise. After the recycle tank change-out, the average value was 82.5 mho/cm.

Water quality was excellent except for the ammonia levels which, due to the acidic pH conditions, were not being controlled by the ion exchange bed in the postfiltration module. This condition will be corrected by the use of a different ion exchange resin as discussed later in the Water Quality Improvement section.

Subsystem Operation

The results of the heatup times required during the 'START' mode with and without a recycle tank heater are presented in Table 14. As can be seen, the time required to reach a 'READY' submode without a heater is twice that necessary with the recycle tank heater.

Disassembly of the evaporator at the end of the test did not indicate any obvious degradation of the components and materials. There was a thin deposit of residue on the tube header faces and titanium plenum section, but it was easily removed with a gentle water spray. Although difficult to see, some trace residue was observed on the tube internal walls but was not considered significant. There was no absolute way to assess the condition of the porous plates, and with sufficient flushing using distilled water to remove the suspected contamination, the plates appeared to recover their capacity.

Table 14
HEATUP TIMES

TEST CONDITION		T_{HFM} INLET °C (°F)	$T_{RECYCLE TANK}$ °C (°F)	TIME TO 'READY' SUBMODE (MINUTES)
No Recycle Tank Heater	Initial	37.8 (100)	62.8 (145)	
	Final	64.4 (148)	61.7 (143)	100
Heater On At Start	Initial	36.1 (97)	62.8 (145)	
	Final	64.4 (148)	62.8 (145)	49
Heater Off At Start	Initial	37.2 (99)	65.0 (149)	
	Final	64.4 (148)	62.8 (145)	47

WASH WATER DEMONSTRATION TESTING

Objective

The objective of this test is to determine the feasibility of and performance for shower wash water processing by the TIMES subsystem. The equivalent of 30 days of shower wash water from 3 crewmen (30 days x 3 men x 8 pounds per man-day = 720 pounds) are to be processed.

Summary

The TIMES subsystem after completing the urine verification and baseline testing was operated for a total of 371 hours using two different synthetic wash water mixtures, and was able to process water at an average rate of 0.97 kg/h (2.13 lb/h) at 29 VDC, with an average specific energy of 163.7 W-h/kg (74.4 W-h/lb) at 26.5 VDC. A total of 328.9 kg (725 lb) of water was processed. Over the course of the testing, manual and automatic start-ups and shutdowns were executed and several cooling schemes were investigated. Vacuum purge water loss averaged 0.015 kg/h (0.033 lb/h).

With the exception of pH, water quality met or exceeded the standards recommended by the National Academy of Science - National Research Council, Committee on Toxicology in the Report of the Panel on Potable/Water Quality in Manned Spacecraft, August, 1972 (contained in Appendix A of this report) for those constituents actually analyzed. Table 15 compares test results with the requirements of the standard.

Test Description

The subsystem was configured in the same manner as for urine testing. Refer to Figure 41. A baseline water test was run first to establish the post-urine performance levels and thereby assess the condition of the membranes.

A synthetic wash water mix with 0.1% dissolved solids was made based on a formulation provided by NASA and shown in Table 16. Chromic/sulfuric acid pretreat was added to 5 gallon tanks of the mix in the proportion 4 ml/l or 80 ml/5 gal, the same dosing employed during urine testing. The test data included all of the customary information as well as readouts from thermocouples strapped externally to the Thermoelectric Regenerator (TER) heat exchanger inlet and outlet tubes, to the condensate line upstream of the capillary tube, and downstream of the cooling loop heat exchanger pump. Data points were taken about every 4 hours.

After 240 cumulative hours and 194.1 kg (428 lb) of water were collected, a high temperature malfunction occurred. As a result, the TER was disassembled, and new porous plates having a higher throughput were substituted for the original plates to determine the impact on performance. Simultaneously, three thermocouples were installed on one cold side pin-fin plate at different locations, and one thermocouple was attached to the adjacent steam passage wall. This instrumentation provided more accurate temperature data, so the external thermocouples were eliminated. In order to evaluate another NASA approved cleansing agent candidate, a second wash water mix was introduced, which used a soap rather than a detergent.

Table 15
WASH WATER TEST WATER ANALYSIS

Determination	Specification	Samples	
		Posttreated	Non-posttreated
pH	7.0-8.0	4.1	3.8
Resistivity (Megohm-cm at 25°C)		.024	.017
Total Solids, ppm	500		
Organic Carbon, ppm	100	27	60
Inorganic Carbon, ppm		13	1
Cadmium as Cd, ppb	10	<10	<10
Chromium as Cr^{+6}, ppb	100	<10	60
Copper as Cu, ppb	1000	<10	<10
Iron as Fe, ppb	1000	<10	65
Lead as Pb, ppb		<10	<10
Magnesium as Mg, ppb		<10	10
Manganese as Mn, ppb	100	<10	<10
Mercury as Hg, ppb		<10	<10
Nickel as Ni, ppb	100	<10	<10
Potassium as K, ppb		<10	<10
Silver as Ag, ppb		<10	<10
Sodium as Na, ppb		50	<10
Zinc as Zn, ppb		<10	<10
Ammonia as N, ppm	5000	<10	<10
Fluoride as F^-, ppb	2000		
Nitrate as N, ppb		<50	<50
Sulfate as SO_4^{-2}, ppb		4000	4500
Chloride as Cl^-, ppb	250000	2740	550
Conductivity µmho/cm		42.35	58.30
Urea, ppm		1.5	1.5

Table 16
FOMULATION FOR SYNTHETIC WASH WATER

Reagent	Reagent State	Amount Added Per 50 Gals
Ammonium Hydroxide	29% Aq. Solution	17.60 cc
Dextrose	Anhydrous Powder	2.514 g
Lactic Acid	85% Aq. Solution	28.766 g
Potassium Hydroxide	Pellets (Contain 10-15% Water)	8.895 g
Sodium Chloride	Crystal	34.633 g
Sodium Lauryl Sulfate or (M-11 Emollient Soap)	Powder (Liquid)	69.644 g (69.644 g)
Urea	Crystal	12.112 g

At the 256 hour and 208.2 kg (459 lb) mark, subsystem operation was evaluated with air-cooling instead of liquid cooling to determine if this mode of operation was possible and as efficient. Fans were installed in the top cover of the processing package and run continuously, drawing ambient air in through the lower rear of the package and blowing it out at the top. This served to cool the box and recycle tank and thereby effect temperature control. After two days, fan control logic was installed, along with a box partition to effectively isolate the cooling effect at the recycle tank. Air-cooling was used until the final six hours of the test, when liquid cooling was again employed.

Water samples were taken during the second wash water portion of the test, and posttreated samples were passed through a test bed of strong acid ion exchange resin in order to determine its effectiveness for ammonium ion removal.

Discussion Of Results

Performance

Performance data is presented in Figure 46. The water baseline production rate averaged 1.04 kg/h (2.30 lb/hr) at 29.0 VDC and represents a 5% increase in rate compared to the previous data point for the subsystem operating with unconcentrated urine. The decrease and subsequent recovery of the production rate observed during the first 60 hours of the wash water test with the detergent is due to the evaporator tube membrane characteristics. As the wash water mix was introduced, the production rate decreased due to the establishment of an equilibrium state between the membrane and constituents in the mix, which are known to reduce water transport through the membrane. However, the detergent action of the mix cleaned the trace solids deposits left over from the urine tests from the tube internal walls, causing an increase in water throughput. Once the tube walls were clean, the production rate stabilized at a constant level of 1.02 kg/h (2.25 lb/h) as predicted. This same effect would have been noted with the soap mixture.

The test proceeded automatically until 68.0 kg (150 lb) of water were collected. At this point an abnormal high temperature shutdown occurred that was a result of an undetected recycle pump failure because the flow sensor normally used for pump failure detection had been removed for repair. The external thermocouples on the urine exit lines indicated almost 99°C (210°F), whereas the subsystem would have normally shutdown at an evaporator inlet temperature of 71°C (160°F). It is entirely likely that TER temperatures were considerably higher than 99°C (210°F), since with no pump or condensate flows, heat transfer was by conduction alone from the powered-up TER to the evaporator inlet temperature probe. Subsequent testing showed degraded performance which was directly attributable to the high TER temperatures or 'bakeout'.

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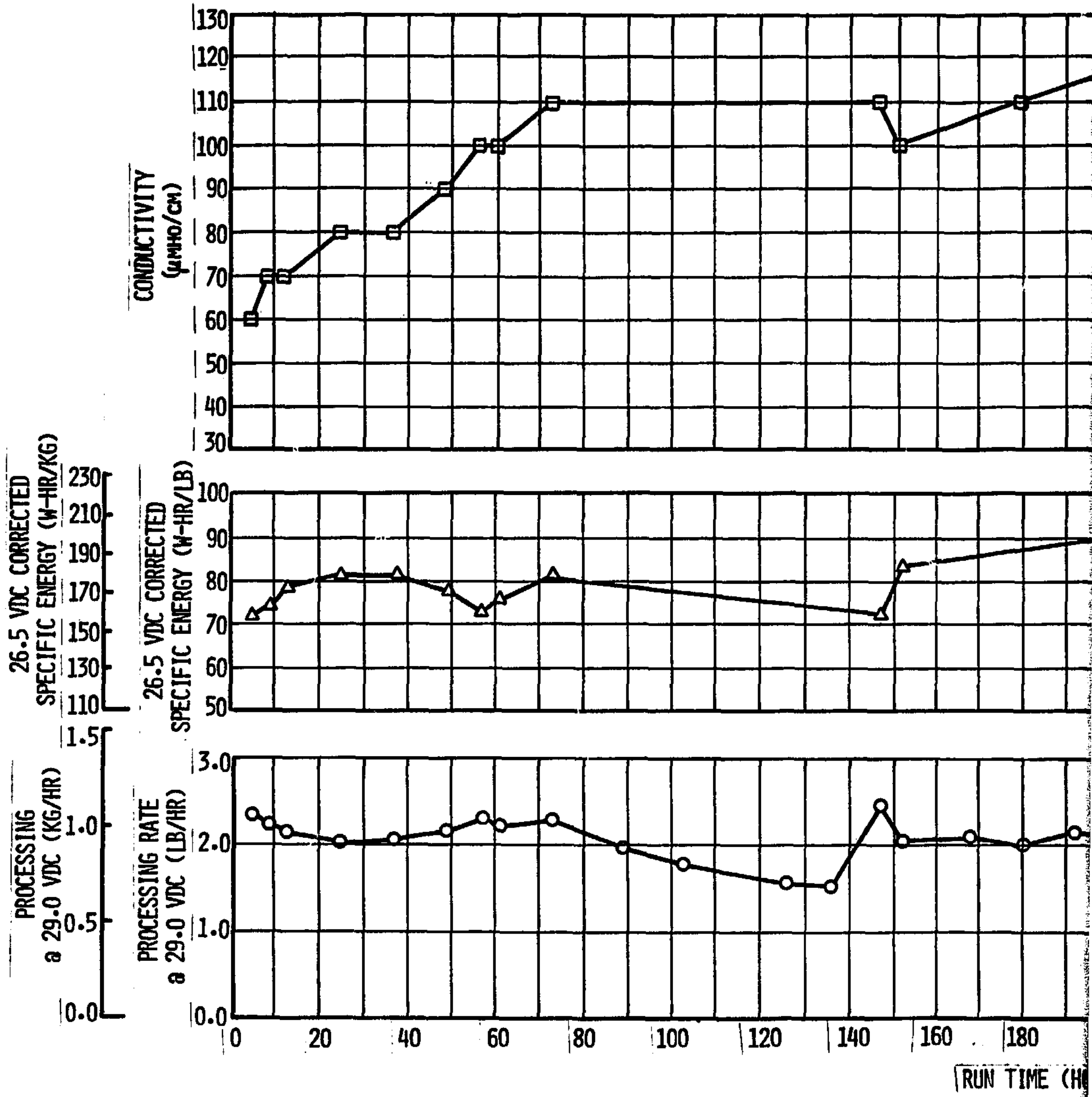


FOLDOUT FRAME

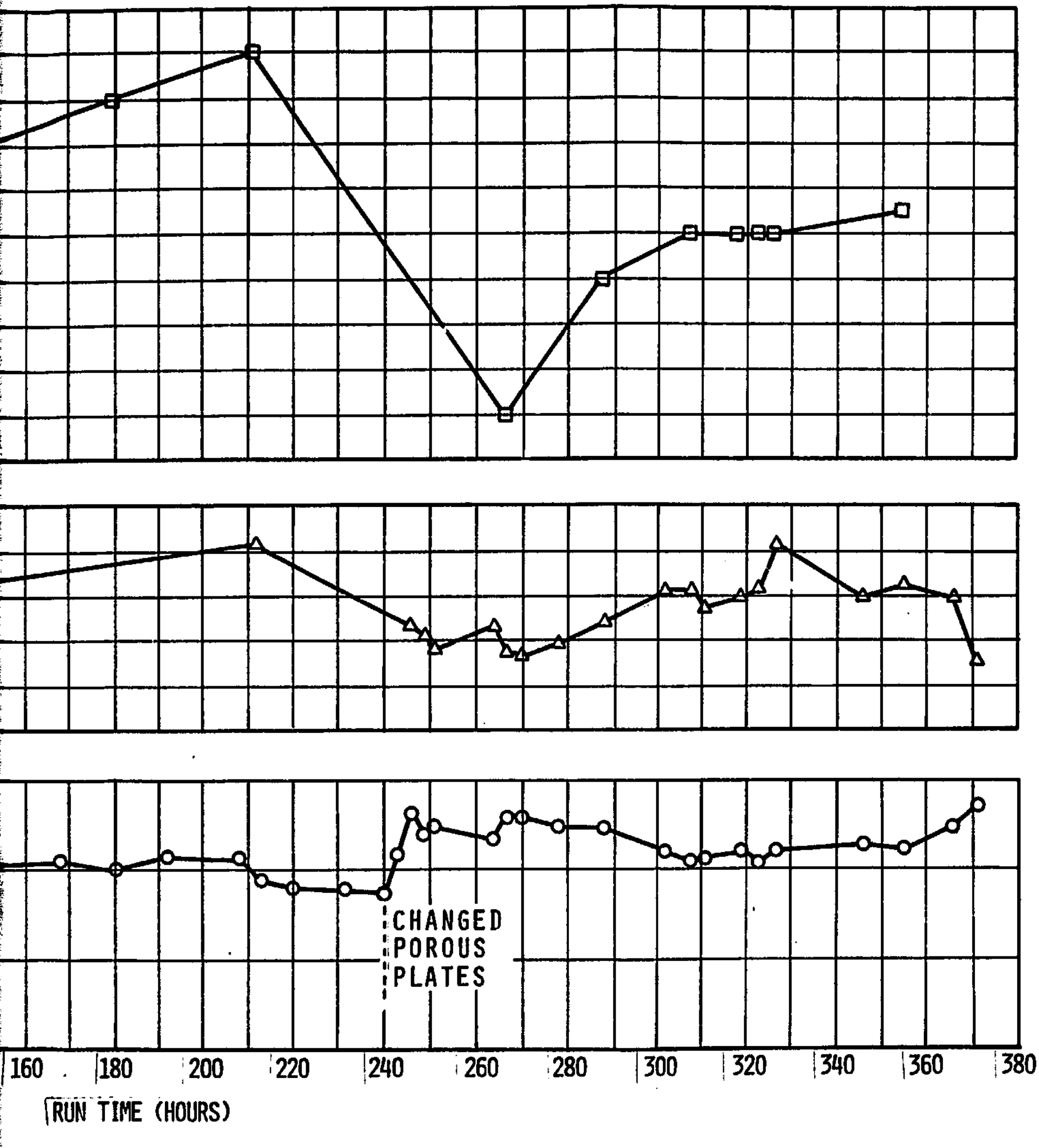
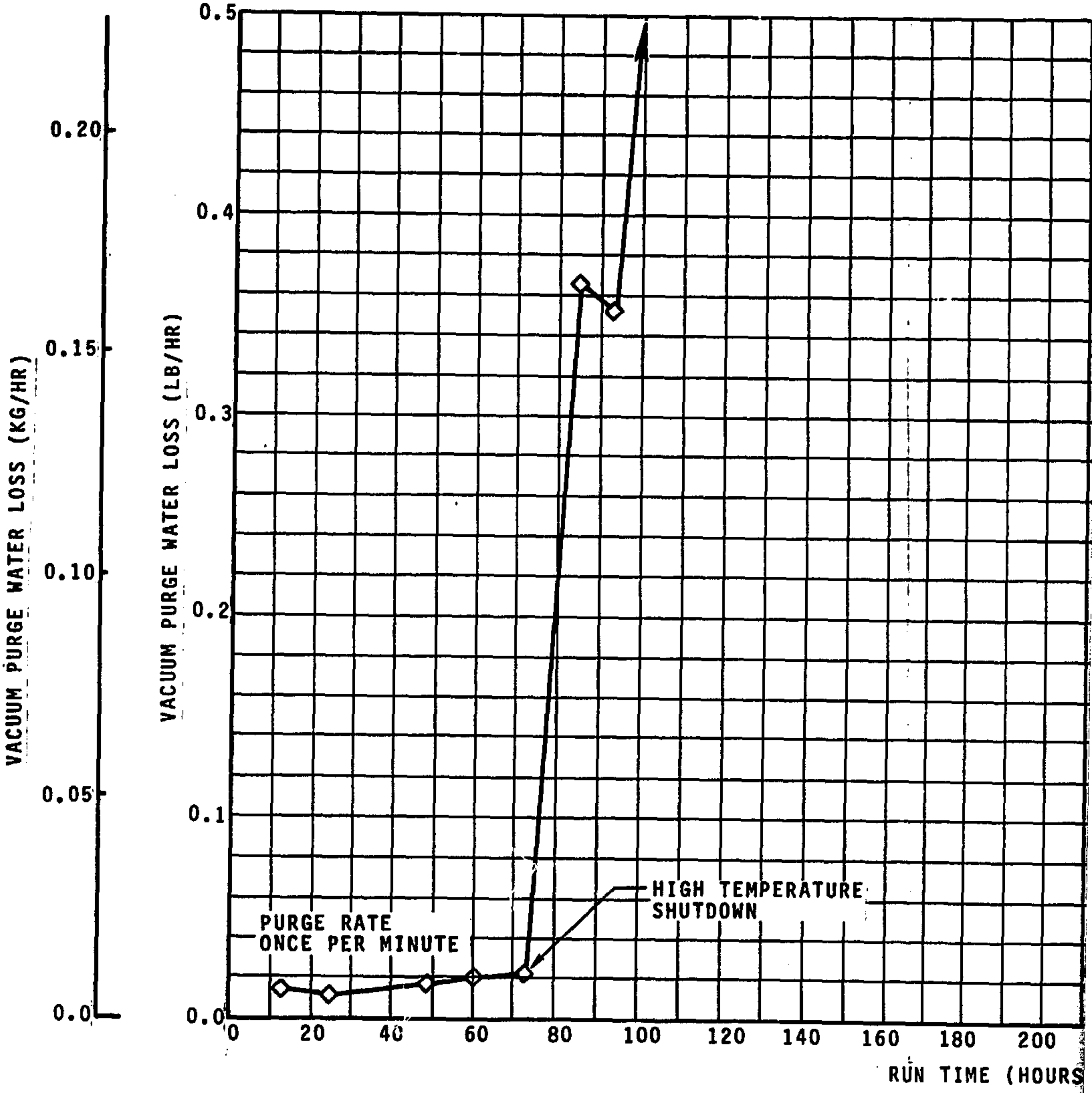


FIGURE 46
WASH WATER TEST PERFORMANCE


VACUUM PURGE WATER LOSS (KG/HR)
0.0
0.05
0.10
0.15
0.20
VACUUM PURGE WATER LOSS (LB/HR)
0.0
0.1
0.2
0.3
0.4
0.5
PURGE RATE
ONCE PER MINUTE
HIGH TEMPERATURE
SHUTDOWN
0
20
40
60
80
100
120
140
160
180
200
RUN TIME (HOURS

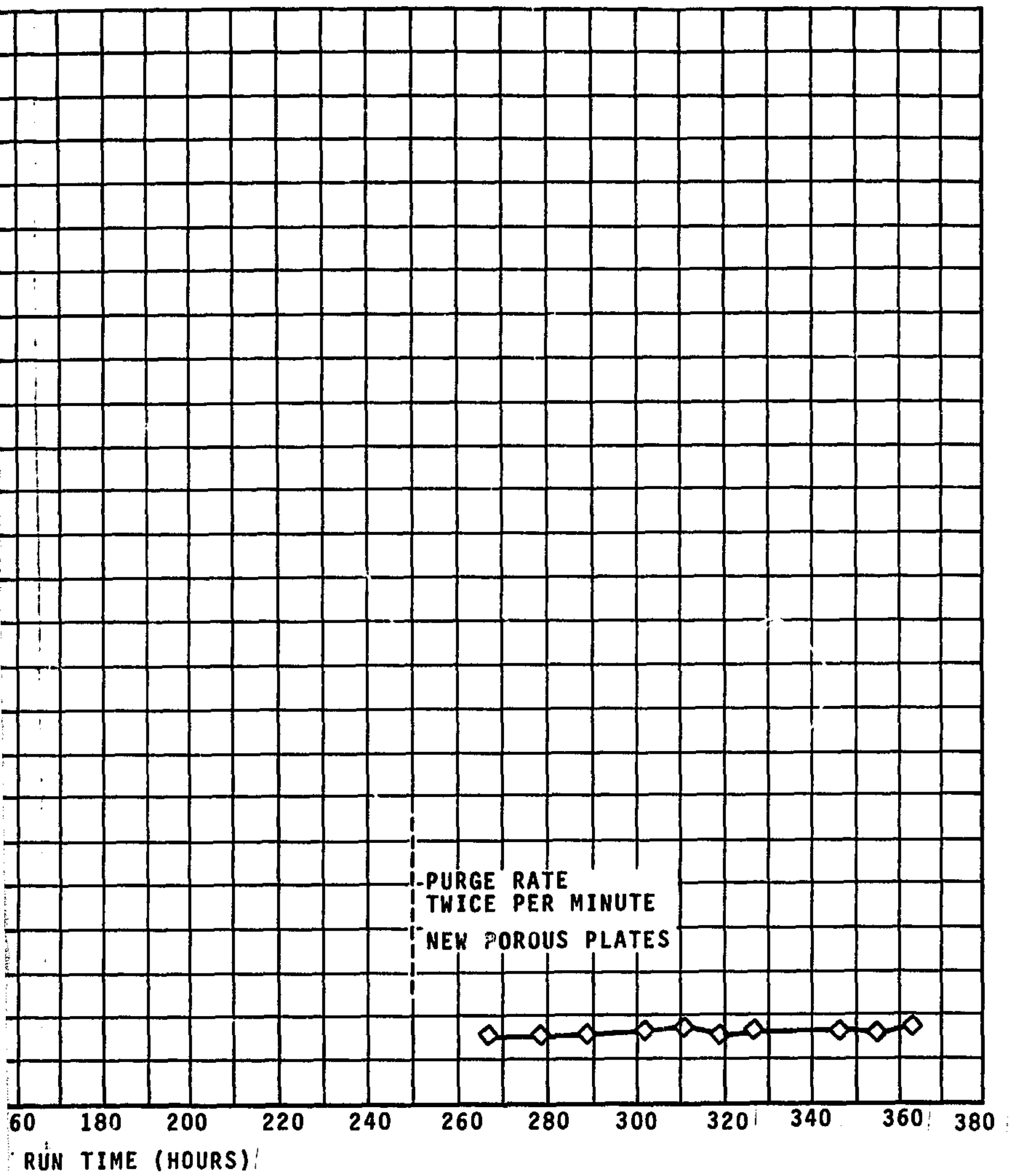


FIGURE 46d
WASH WATER TEST PERFORMANCE

Before the TER was actually removed and disassembled, a temporary improvement in performance was observed after in-place cleaning with isopropyl alcohol. It was thought that the lauryl sulfate in the synthetic mix was being converted to lauryl alcohol by the acidic pretreat solution, and in one way or another was contaminating the plates. The isopropyl alcohol was used to dissolve any lauryl alcohol that might be contaminating the plates and thereby making them non-wetting, as well as flow restrictive. Since the improvement was only temporary, it was clear other contaminants were present.

Upon disassembly and checkout, it was observed that the porous plates were indeed contaminated not with lauryl alcohol, but with non-volatiles that could only have migrated to the plates at the high temperature, causing condensate throughput flow capacity to be substantially reduced. In order to provide a greater flow capacity while still maintaining the wetting characteristics (as defined by bubble point tests) necessary for successful porous plate operation, new plates were manufactured and installed into the TER. The final characteristics represented a 20 fold increase in flow capacity, at a reduction in bubble point of approximately 2 to 1. Figure 47 illustrates these operating characteristics in detail.

After the replacement plates were installed, an emollient soap was substituted for the lauryl sulfate in the wash water formulation to determine the effect on subsystem performance using a soap rather than a detergent.

System performance improved upon resumption of the test and production rates averaged 1.11 kg/h (2.44 lb/h) at 29.0 VDC compared to an initial rate of 1.04 kg/h (2.30 lb/h) at the very beginning of the wash water test. This increase is attributable to the increased throughput of the porous plates.

In order to evaluate an alternative cooling mode, the controller cooling logic was modified slightly and fans were installed in place of the liquid phase heat exchanger. The processing rate decreased to an average value of 1.03 kg/h (2.26 lb/h) at 29.0 VDC with this cooling mode. Simultaneously, temperatures recorded on the cold plate were 0.5-1.0°C (1-2°F) higher than for liquid cooling. If we consider that the permeability coefficient for the membranes is a function of the partial pressure difference of water vapor across the walls, then a decrease in ΔP created by a higher cold plate temperature (hot side temperature is constant) accounts for the lower processing rate. Reflecting this change in rate, the specific energy at 26.5 VDC was noticeably different for the two cooling modes and averaged 173.8 W-h/kg (79.0 W-h/lb) and 151.8 W-h/kg (69.0 W-h/lb) for air and liquid cooling respectively. The fans employed were test items, and an actual unit would be much more efficient having a power draw of 1 watt on the average, so the specific energy reported uses this value and not actual power draw. As expected, the 0.5-1.0°C (1-2°F) ΔT across the TER produced a negligible change in TER power, since the semiconductor temperature characteristics represent second and third order effects. The subject of air cooling versus liquid cooling is discussed in detail in the Improved Temperature Control section of this report.

Water loss to vacuum purging averaged 0.014 kg/h (0.03 lb/h) over the latter phase of the test, because the purge timer cycle had been doubled to twice a minute. Before the high temperature problem, the loss had averaged 0.0077 kg/h (0.017 lb/h) at a purge rate of once every minute.

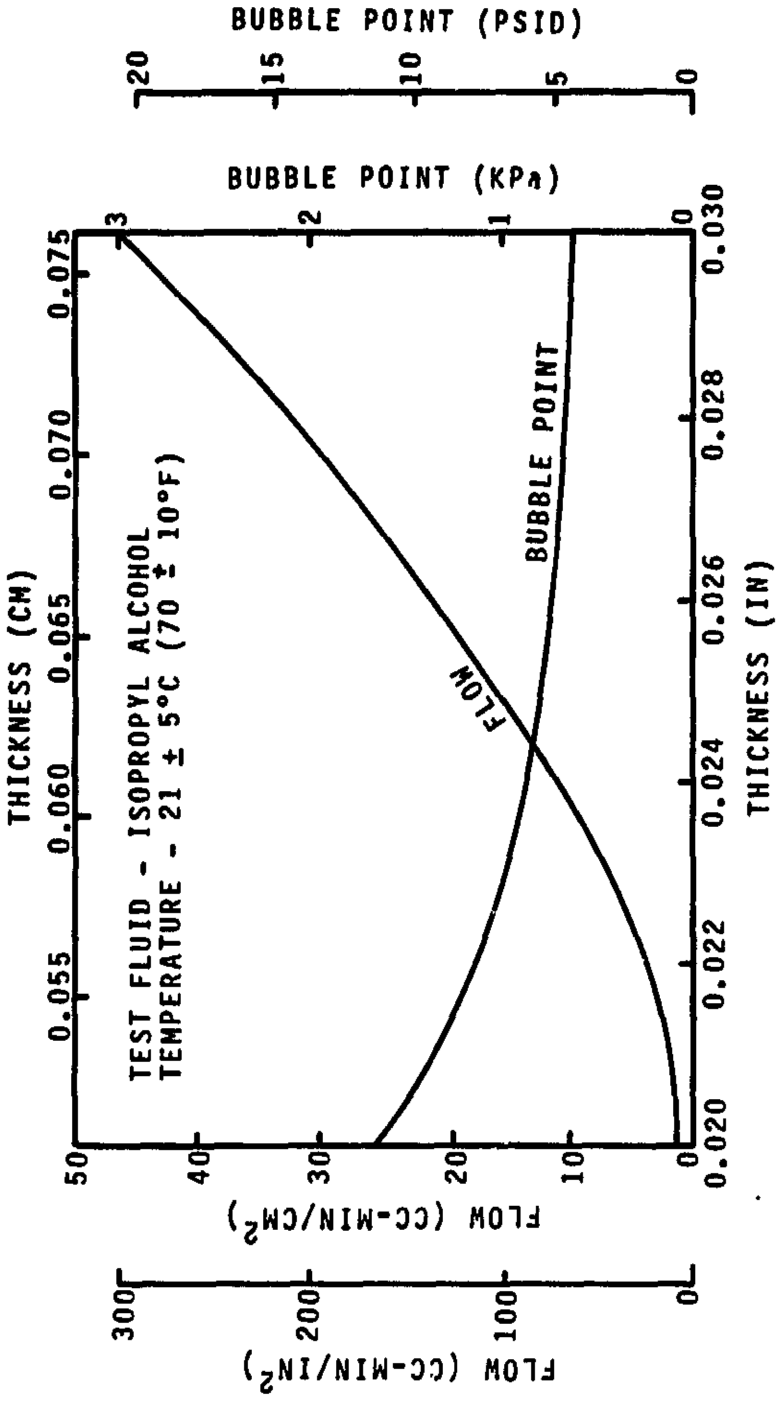


FIGURE 47

POROUS PLATE CHARACTERISTICS

Water Quality

The results of the water analysis are presented in Table 15. Throughout the test, product water conductivity remained at 120 μmho/cm or less, and the pH averaged 3.5 to 4.0. An initial rise to 100 μmho/cm can be attributed to the equilibrium of the dissolved solids with the membrane. As the membrane equilibrium concentration of chemical species from the mix is reached, trace quantities of volatile hydrogen chloride (HCl) as well as the urea decomposition products NH_3 and CO_2 are carried along with the steam and redissolve in the condensed product. Because trace HCl carryover is dependent on feed water pH, the acidic wash water mix (pH = 1.5) resulted in recovered water having low pH values; however, the wash water mix initially had only 0.1% dissolved solids (of which urea represented 7%), so the total carryover was minimal, and a stabilized value for the conductivity and pH was reached during this testing where dissolved solids concentrations never reached 1.5%. Since the TIMES posttreatment filters are sized for recycle loop feeds with up to 50% dissolved solids, no additional hardware is necessary to provide high purity product water while operating with wash water.

The trace total chromium observed during the analysis probably resulted from leakage caused by the silicone tube headers that degraded near the end of the test.

Subsystem Operation

After the test was completed, the evaporator was removed and disassembled for inspection. The silicone rubber plugs used to header the Nafion hollow tube membranes were obviously degraded on the exposed front face. Removal and dissection of the plugs indicated that the internal ribs serving as sealing and retention grommets for the tubes were also deteriorated. The materials compatibility testing had shown no deterioration of an unstressed silicone rubber coupon during 72 day exposure to pretreated urine. Reevaluation of the initial materials compatibility testing methods compared with the actual test conditions, indicate that during subsystem testing the total exposure time to the pretreat liquid was greater, the subsystem test plugs were stressed, and in the case of wash water testing, the pH of the pretreated liquid was considerably more acidic than that of the materials compatibility test liquid (pH = 1.5 vs. pH = 4.0 respectively). During a normal mission profile the TIMES subsystem would see a relatively consistent mix of urine and wash water and would not encounter the strong acid condition that occurred during wash water testing. Due to the extent of the deterioration, it appeared desirable to incorporate a more acid compatible header material to extend the assembly life. Two materials, Viton-GF, and Hypalon, are much more acid resistant and appeared to have acceptable physical properties including stress life and reasonable softness. An evaluation program for these two materials concluded that Viton-GF would best ensure long term stability and was therefore chosen as the proper headering material for the membranes. This change has been incorporated into the subsystem.

All Viton-A parts such as o-rings in the evaporator which are exposed to the feed water were not degraded.

The tube membranes themselves were in excellent condition and showed only a slight degree of set in the portion headered by the plugs. They retained their original tensile strength, flexibility, and other dimensional properties after 850 total run hours and approximately 6 months of exposure to urine and wash water feeds. The tubes appeared transluscent since there were no internal areas where permanent fouling had occurred and the tube membranes will be used in subsequent testing.

CONCLUSIONS AND RECOMMENDATIONS

Urine Testing

Operating with the pretreated urine mix, the subsystem's processing rate of 0.97 kg/h (2.14 lb/h) after 480 hours of operation exceeds the contract requirement of 0.77 kg/h (1.7 lb/h) at 29.0 VDC for unconcentrated urine. The average rate for unconcentrated urine over the course of testing was 1.13 kg/h (2.49 lb/h). The specific energy at 26.5 VDC for unconcentrated urine averaged 161.7 W-h/kg (73.5 W-h/lb) over the verification and baseline testing period. Water recovery averaged 93% due to premature recycle tank change-outs, and would have surpassed 95% without any problem arising from the high dissolved solids concentration, since no precipitates were found during the change-outs.

Figure 48 shows the change in processing rate for unconcentrated urine at 29.0 VDC over the 480 hour test period. The 20% decrease of the processing rate is attributable to the loss of throughput capacity for the porous plate and not to any permanent fouling of the membranes. Figure 49 illustrates the change in the processing rate as dissolved solids concentrate in the recycle loop. Also shown for comparison is the theoretical curve based on the effect of solids concentration vapor pressure depression and Nafion permeability. The theoretical curve represents the subsystem operating characteristic and the plot clearly shows how actual data followed that characteristic. Figure 50 shows the recycle loop solids concentration profile for first urine concentration cycle during verification testing. This is a typical concentrating profile for the subsystem operating on urine, since it includes several manual shutdowns and subsequent system flushes. For totally steady state operation, the recycle tank change-out frequency would be equivalent to 14 mission days at the design three crewman liquid waste input rate of 8.91 kg/day (19.65 lb/day).

More expendables (pretreat solution) were required than originally specified due to the use of raw, undiluted urine in place of a mix of raw urine and rinse water. The raw urine feed averaged 3.6% dissolved solids in contrast to 3.1% in the original model, and this higher level required more pretreat to maintain a sufficiently low pH in the water storage tank and thereby effect pH control in the recycle loop. The rather crude volumetric method of introducing pretreat solution could be modified, resulting in less pretreat consumption, by employing continuous pH monitoring of the recycle loop and waste storage tank, and using this signal to feed the optimum amount of pretreat into the raw urine charge.

There was no observable corrosion of any materials at the end of the urine testing. The hollow fiber membrane evaporator assembly, including Nafion membrane tubes, silicone rubber tube headers, and the titanium/polysulfone structural components were in excellent condition. There was no gross precipitate buildup evident in the recycle loop plumbing, filter housing, recycle tank, or other urine handling components. Some trace residue could be seen on the membrane internal walls and headers, but it was easily removed with clean water, and therefore not considered a problem.

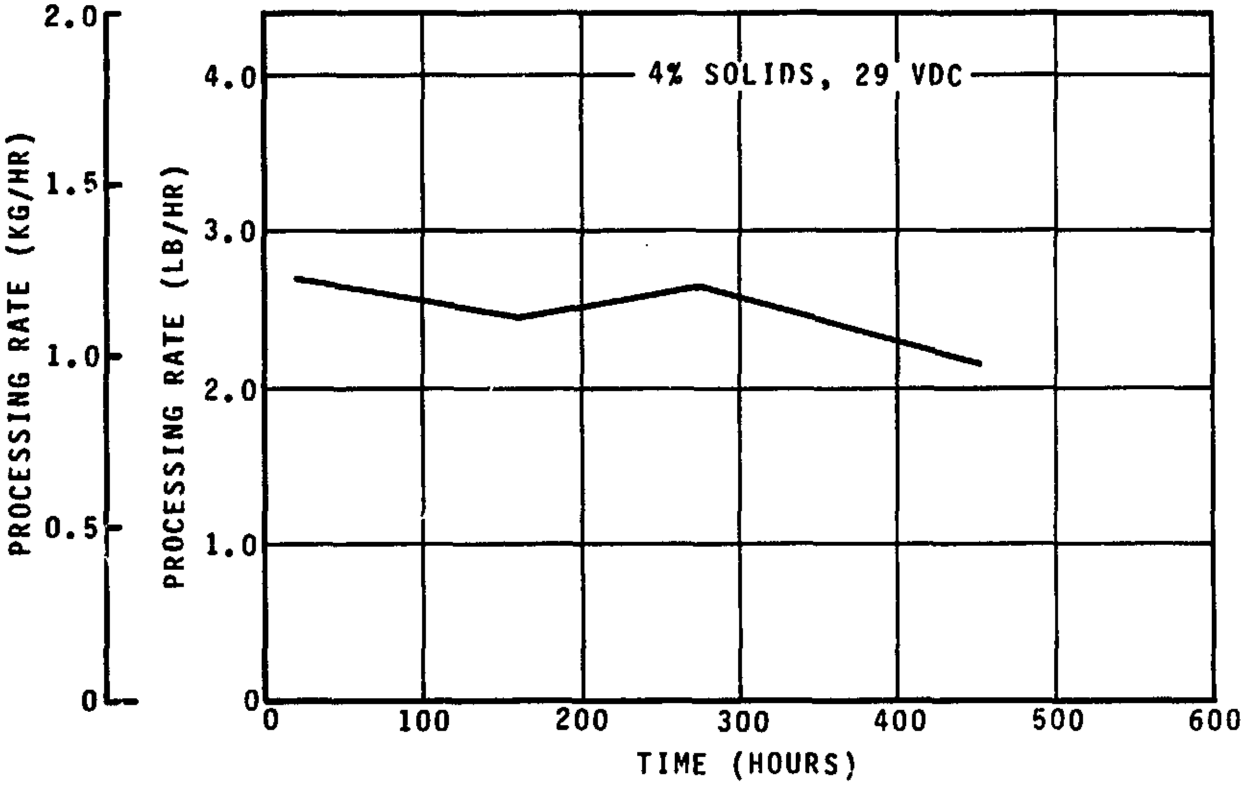


FIGURE 48

SUBSYSTEM PERFORMANCE FOR
UNCONCENTRATED URINE

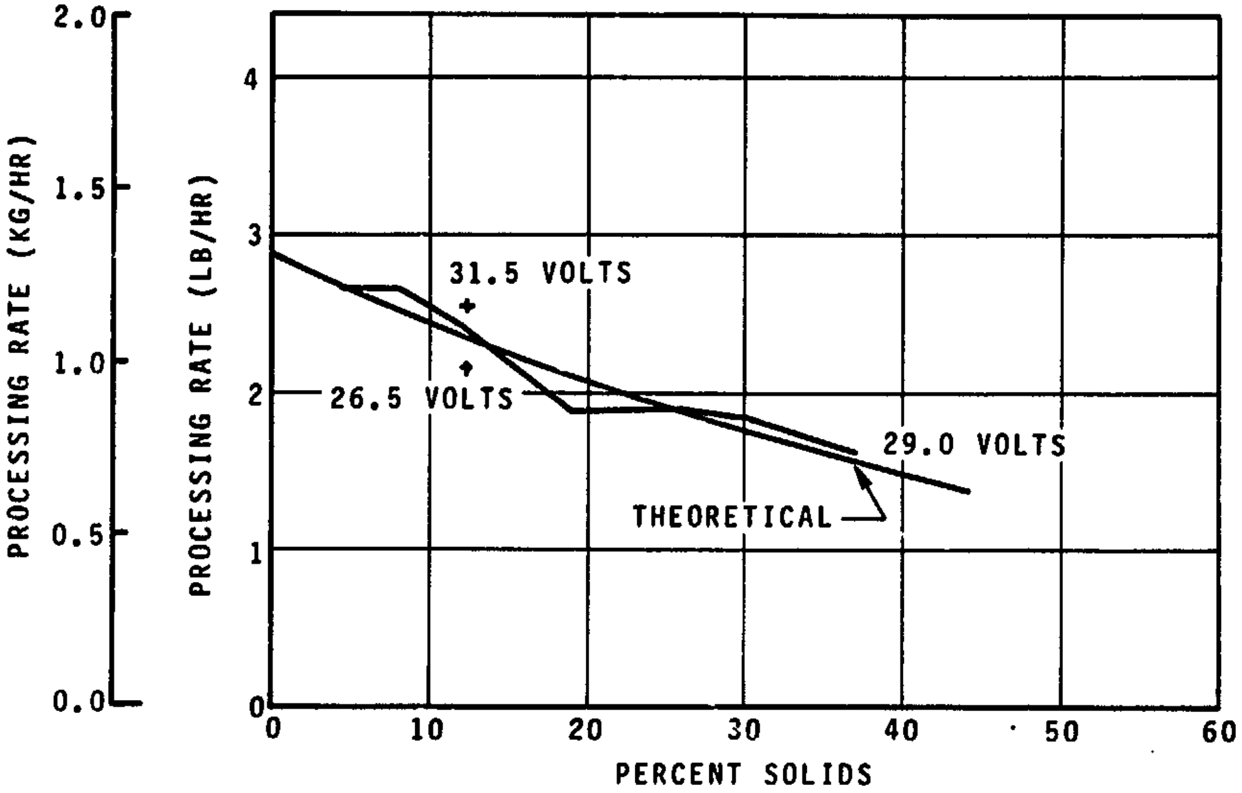


FIGURE 49
SUBSYSTEM PERFORMANCE
vs
SOLIDS CONCENTRATION

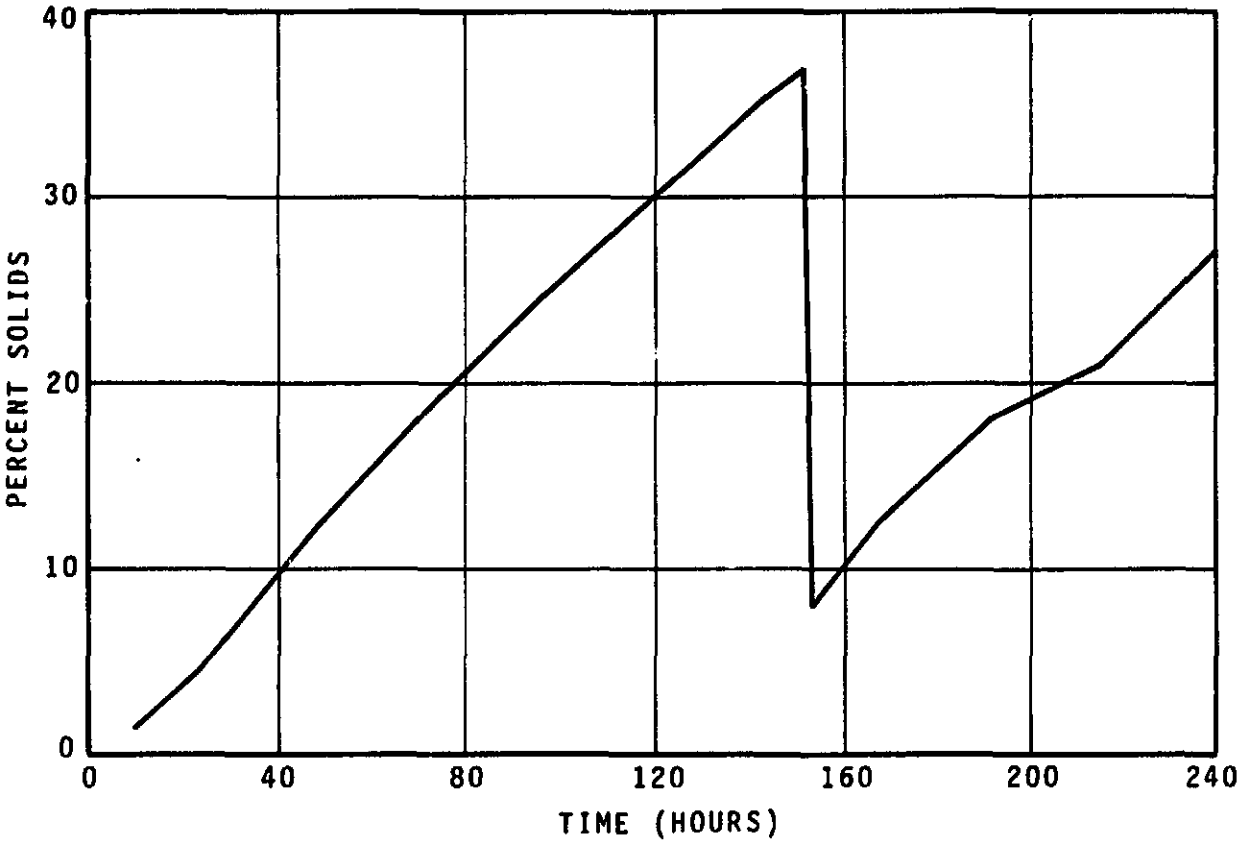


FIGURE 50
URINE SOLIDS CONCENTRATION CYCLE

Wash Water Testing

A total of 370 hours was accumulated on the subsystem during this testing, hours. Figure 51a shows the relative processing rate based on initial membrane/subsystem throughput over the course of the urine and wash water testing. There are six cycles evident, including four concentrating phases for urine, and two steady state runs on low solids concentration wash water. With the present subsystem configuration, operating on wash water, a processing rate of at least 1.02 kg/h (2.25 lb/h) at 29.0 VDC seems maintainable over long periods of time due to the slow increase in concentration of wash water dissolved solids.

First a detergent and an then emollient soap were used in the wash water mix during different portions of the testing, and there appears to be no reason why the subsystem would not satisfactorily operate with either cleansing agent. The premise originally made with respect to performance was that urine and wash water would present two extremes of water reclamation operating conditions expected for TIMES.

This premise was verified by the production rate data obtained during the subsystem operation on wash water. The data matched the expected values based on urine testing performance, if the urine results were extrapolated to cover 0.1% solids. Thus, it is clear that both pretreated wash water and urine interact identically with the membrane material, resulting in performance being dependent on dissolved solids concentration only, and not on the chemical nature of the wastewater feed.

The silicone rubber headers retaining the membrane tubes showed signs of degradation near the end of the test; it was decided that a Viton rubber substitute should be employed as a header material since Viton has been extensively tested during the design support testing portion of this program and has exhibited excellent compatability to acidic solutions. A Viton-GF formulation has been selected and is now incorporated into the subsystem design.

Midway through the test new porous plates were installed in the Thermoelectric Regenerator. An order of magnitude increase in thoughput flow capacity has been realized with these new plates, while still retaining the necessary wetting characteristics.

Water Quality For Urine And Wash Water Testing

Posttreated product water was of excellent quality, but anomolous ammonia results were obtained. Five major components are plotted in Figures 52 and 53 for non-posttreated and posttreated samples taken during urine testing, and it is seen that some ammonia levels were higher in the posttreated water.

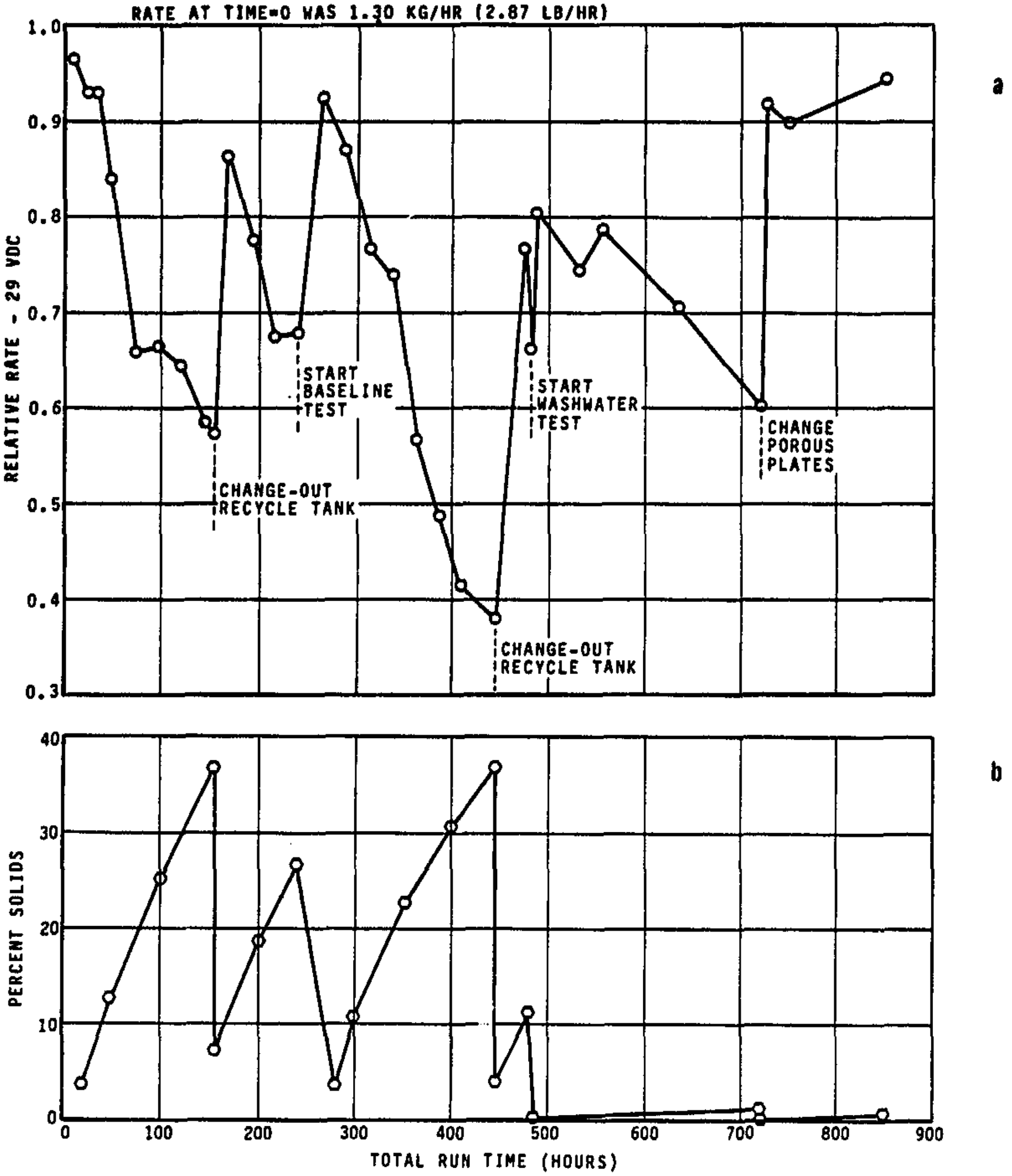


FIGURE 51

SUBSYSTEM RELATIVE PROCESSING RATE AND SOLIDS CONCENTRATION

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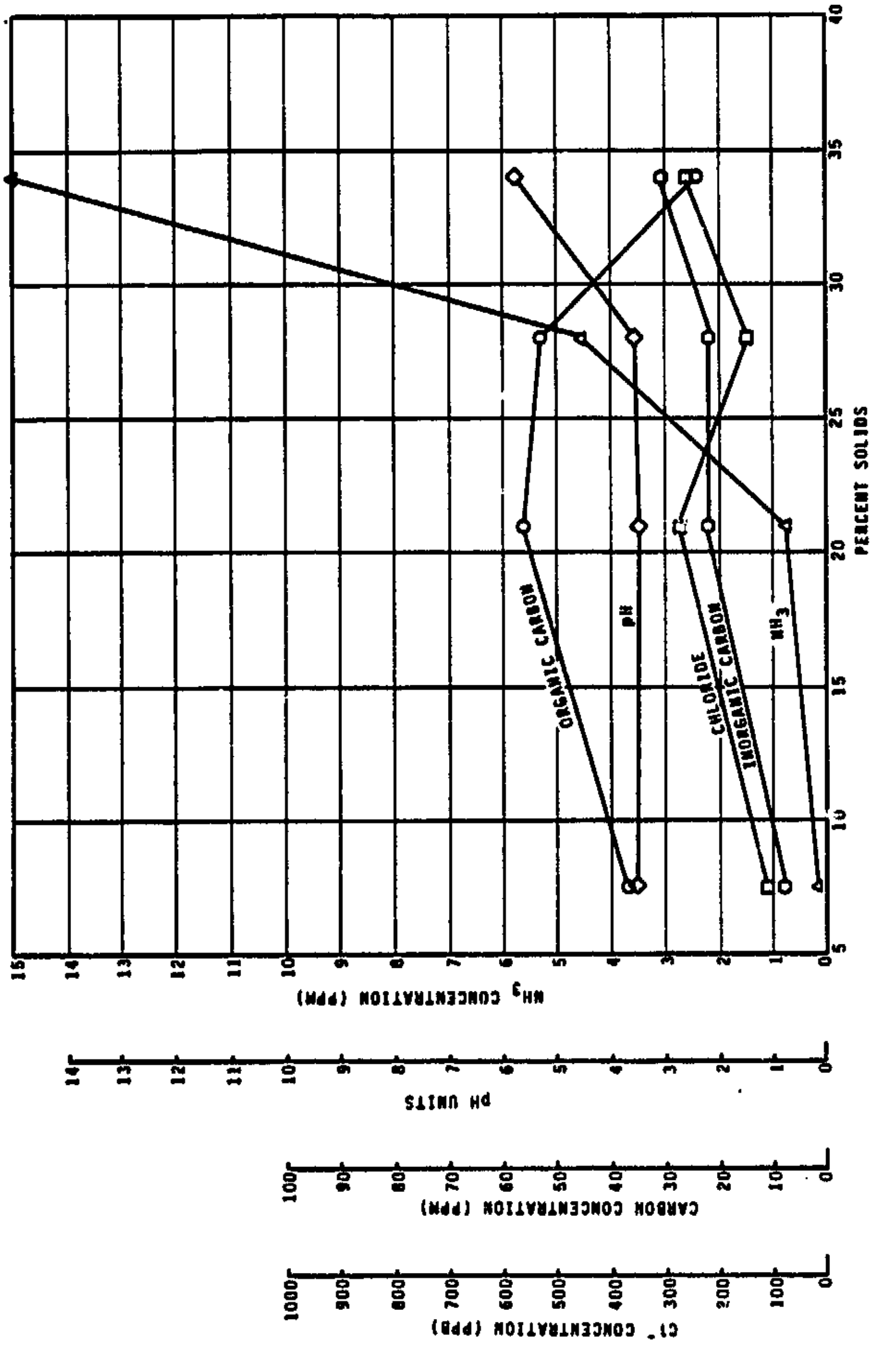

FIGURE 52

NON-POSTTREATED PRODUCT WATER

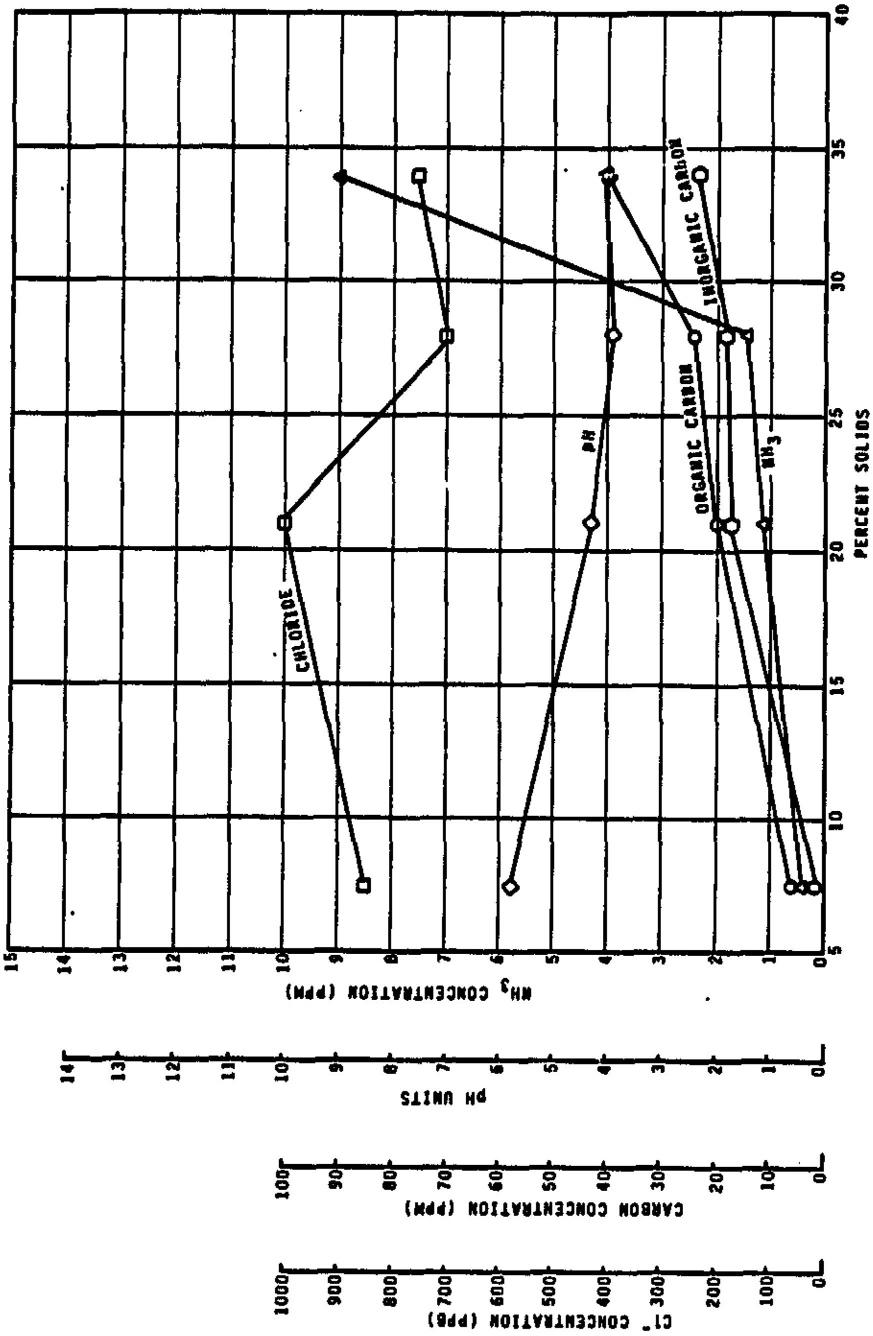

FIGURE 53
POSTTREATED PRODUCT WATER

These curious results are explained fully in the Water Quality Improvement section of this report, but basically result from the pH limitations of the Ionac CC ion exchange resin used in the posttreatment multifilter. As the product water pH decreased, more exchange sites in the bed were deactivated, resulting in replacement of the absorbed ammonium ions by hydrogen ions, hence higher ammonia levels were generated. As recommended in the Water Quality Improvement section of this report, a change to a strong acid ion exchange resin will drastically lower posttreated product water ammonia levels.

Thoughout the testing, pH of the recovered water was low, undoubtably the result of the highly acidic waste feed. As previously explained, more volatile hydrogen chloride carries over with this condition, resulting in low pH levels in the recovered water. Better pH control of the waste feed should resolve this problem.

ANALYTICAL MODEL CORRELATION

A mathematical computer model was written to simulate the operation of the TIMES water reclamation subsystem. It assumes the use of an integral controller so that only steady state responses from the subsystem are obtained. The model is flexible enough to incorporate changes in major design parameters as well as environmental conditions with little difficulty.

The input data set allows a choice of sixteen parameters, of which ten were chosen and fixed throughout the runs, while six were adjusted to simulate a number of different operational conditions which occur with TIMES. By manipulating the values of certain selected parameters, the effects caused by altering the cooling mode, for example, could be investigated, even though no direct provision is incorporated into the main program to allow this change.

A typical run for concentrated urine presents a data summary as illustrated in Figure 54. Additional information concerning the nodal analysis of the Thermoelectric Regenerator (TER) and Hollow Fiber Membrane (HFM) evaporator are not included.

The actual TIMES urine and wash water operational data are correlated with computer predicted values in Table 17. Several parameters merit some comment:

UA- this represents the subsystem heat transfer coefficient, but can be adjusted to simulate 100% liquid cooling, partial liquid and partial air cooling, or 100% air cooling.

PA- this represents the membrane mass (water) transfer coefficient, and was selected on the basis of bench test evaluation. It can be adjusted to accommodate the coefficient's dependence on solids concentration by keeping membrane area fixed and varying the permeability constant.

It can be seen from Table 17 that the computer model simulates subsystem operation quite well. Runs #1 and #2 represent wash water feeds and the correlation is very good. The 29.0 VDC (#1) data point correlates better than the 31.5 VDC point (#2) with respect to processing rate, but still the difference for run #2 is less than 10%. Run #3 represents a urine data point and again correlation is excellent; the parameter PA has been reduced by 50% to simulate the Nafion water transport characteristic.

These three runs use a simulated liquid cooling mode, which in the computer model is a variable flow coolant loop affecting the TER cold side temperature. Run #4 approximates an air cooling mode utilizing heat transfer from the TER hot side (primarily the recycle tank) to the environment; UA has been increased to match the total expected heat load. Run #4 shows that the program predicts a reduction in the processing rate which is indeed observed in actual TIMES data collected during the wash water testing.

```
        - SYSTEM DESCRIPTION -

    NUMBER OF TER MODULES IS 3
    TANK HEAT TRANSFER COEFFICIENT, UA =   3.50
    VOLTAGE INPUT TO TER IS   29.0
    AMBIENT TEMPERATURE IS   70.0
    FRACTION SOLIDS IN TANK IS  0.400
    TEMPERATURE OF FEED URINE IS  110.0
    FRACTION SOLIDS OF FEED URINE IS  0.040
    MEMBRANE AREA IS  21.000
    PERMEABILITY CONSTANT IS   0.119
    AM MULTIPLIER IS   1.000
    KM MULTIPLIER IS   1.000
    RM MULTIPLIER IS   1.000
    CONVERGING HFM TEMP IS   150.0
    EFFECTIVENESS OF COOLER IS   0.5000
    COOLER AMBIENT TEMP IS    70.0
    MAX NUMBER OF ITERATIONS IS 10


      ***** RUN HAS BEEN COMPLETED *****

          ENGLISH UNITS ARE USED

    PROPERTIES OF URINE LEAVING HFM
         TEMPERATURE =   145.32
         FRACTION SOLIDS =  0.40017
         MASS FLOW URINE =   485.86

    PROPERTIES OF URINE LEAVING RECIRCULATING TANK
         TEMPERATURE =   144.56
         FRACTION SOLIDS =  0.40000
         MASS FLOW URINE =   485.83

    PROPERTIES OF URINE ENTERING PUMP
         TEMPERATURE =   144.45
         FRACTION SOLIDS =  0.39880
         MASS FLOW URINE =   487.49

    PROPERTIES OF URINE ENTERING TER
         TEMPERATURE =   144.72
         FRACTION SOLIDS =  0.39880
         MASS FLOW URINE =   487.53

    TEMPERATURES OF URINE AND STEAM FLOWS BETWEEN TER AND HFM
         URINE TEMP =   150.07
         STEAM TEMP =   130.28

    COOLANT OR CONDENSATE FLOWS THROUGH TER
       MASS FLOW OF COOLANT IN =   10.328   TEMPERATURE =   100.77
       MASS FLOW OF COOLANT OUT =   11.992   TEMPERATURE =   129.89

    ELECTRICAL POWER TO TER =   154.0 WATTS

    HEAT LEAK FROM THE UNIT =    261.0 BTU/HR

    NET HEAT INTO SYSTEM =   21

    CURRENT INTO TEDS =  1.7702 AMPS


             ***** WATER RECLAIMED FROM URINE IS  1.665 LBS PER HOUR *****

    POWER / PRODUCT WATER RATE =    92.51
```

FIGURE 54

TYPICAL COMPUTER MODEL RUN

Table 17
DATA CORRELATION

PARAMETER	#1 COMPUTER RUN	ACTUAL DATA	% DIFFER-ERENCE	#2 COMPUTER RUN	ACTUAL DATA	% DIFFER-ERENCE	#3 COMPUTER RUN	ACTUAL DATA	% DIFFER-ERENCE	#4 COMPUTER RUN	ACTUAL DATA	% DIFFER-ERENCE
VOLTS	29.0	29.0	---	31.5	31.5	---	29.0	29.0	---	31.5	31.5	---
UA--HEAT TRANSFER COEF. (BTU/H-°F)	(3.5)	---	---	(3.5)	---	---	(3.5)	---	---	(8.5)	---	---
W/°C	1.85	---	---	1.85	---	---	1.85	---	---	4.50	---	---
TANK SOLIDS %	1.0	1.0	---	1.0	1.0	---	40.0	37.0	---	1.0	1.0	---
FEED SOLIDS %	1.0	1.0	---	1.0	1.0	---	4.0	4.0	---	1.0	1.0	---
PA--MASS TRANSFER COEF. (LB/H-PSID)	(5.0)	---	---	(5.0)	---	---	(2.5)	---	---	(5.0)	---	---
KG/H-KPA	0.33	---	---	0.33	---	---	0.17	---	---	0.33	---	---
HFM INLET TEMPERATURE (°F)	(150.2)	(150)	.13	(150.1)	(150)	.07	(150.1)	(150)	.07	(150.1)	(150)	.07
°C	65.7	65.6	---	65.6	65.6	---	65.6	65.6	---	65.6	65.6	---
HFM EXIT TEMPERATURE (°F)	(144.5)	(144.7)	.14	(143.9)	(143.6)	.21	(145.3)	(145.2)	.07	(144.6)	(144.1)	.34
°C	62.5	62.6	---	62.6	62.0	---	62.9	63.9	---	62.6	62.3	---
HFM TEMPERATURE (°F)	(5.7)	(5.3)	7.0	(6.2)	(6.4)	3.1	(4.7)	(4.8)	2.1	(5.5)	(5.9)	6.8
°C	3.2	2.9	---	3.4	3.6	---	2.6	2.7	---	3.1	3.3	---
STEAM TEMPERATURE (°F)	(141.6)	---	---	(140.6)	(141.2)	.42	(130.3)	---	---	(141.7)	(143.5)	1.3
°C	60.9	---	---	60.3	60.7	---	54.6	---	---	60.9	61.9	---
STEAM PRESSURE (PSIA)	(3.03)	---	---	(2.96)	---	---	(2.26)	---	---	(3.04)	---	---
KPA	20.89	---	---	20.40	---	---	15.58	---	---	20.96	---	---
TER COLD SIDE TEMPERATURE (°F)	(141.0)	---	---	(140.0)	(139.4)	.43	(129.9)	---	---	(141.0)	(141.6)	.42
°C	60.6	---	---	60.0	59.7	---	54.4	---	---	60.6	60.9	---
PRODUCTION RATE (LB/H)	(2.29)	(2.26)	1.3	(2.53)	(2.77)	8.7	(1.67)	(1.69)	1.2	(2.24)	(2.37)	5.5
KG/H	1.04	1.03	---	1.15	1.26	---	0.76	0.77	---	1.02	1.08	---
TER POWER (W)	166.5	163.3	1.9	196.5	200.6	2.0	154.0	155.0	.65	199.0	200.6	1.3
TER SPECIFIC ENERGY (W-H/LB)	(72.65)	(72.26)	.54	(77.80)	(72.42)	6.9	(92.65)	(91.72)	1.0	(89.30)	(84.64)	4.1
W-H/KG	159.8	159.0	---	171.2	159.3	---	203.8	201.8	---	191.3	186.2	---

DESIGN AND PERFORMANCE IMPROVEMENTS

WATER QUALITY IMPROVEMENT

Objective

The high temperature operation of the urine water recovery subsystem causes some ammonia to carryover into the product water in the preprototype subsystem, and even though the relative quantity of ammonia is low, it is desirable to reduce or eliminate it altogether.

The objective of this study task is to investigate and evaluate techniques that would result in the reduction of the ammonia concentration level in the water recovered from the TIMES urine processing unit.

Approach

The task of reducing ammonia concentration levels in recovered water was evaluated for several general techniques that attacked the problem from different directions. Basically, ammonia levels can be decreased either by treating the urine input in the collection or recycle loop, or by posttreating the product water itself. From a systems analysis standpoint, each technique has its advantages and disadvantages and these are addressed in the study. A number of system options were investigated with consideration given to 1) the ease of integration of each into the existing TIMES, 2) electrical power penalties, and 3) use of consumables and/or hazardous chemicals.

Candidate Descriptions

There were five basic candidate techniques investigated from which a preferred method was selected. They are listed below:

1. Urea decomposition - from bulk urine
    a) thermal decomposition
    b) enzyme hydrolysis
    c) chemical reaction

2. Urea complexation/filtration

3. Ammonia catalytic removal - from urea decomposition
    a) urine loop vapor liquid/gas separator or membrane
    b) product vapor steam

4. Ammonia removal via strong acid ion exchange resin

5. Ammonia decomposition by ozone/ultraviolet radiation

A detailed description for each candidate is now presented.

1. Urea Decomposition - From Bulk Urine

One way to reduce ammonia levels in the product water is to eliminate urea as the source, or at least diminish its contribution. Because nearly 98% of all the ammonia in urine/water systems is generated by urea decomposition, the objective of this technique is to accelerate the urea breakdown process in the urine recycle loop, or the collection loop, and withdraw the decomposition products before they permeate through the membrane evaporator. The advantages are twofold; namely, the ammonia carryover rate can be maintained at a constant low level as total dissolved solids are concentrated in the recycle loop, and consequently, the recycle tank change-out frequency can be lengthened, resulting in increased overall water recovery. The advantages are realized for the recycle loop because as the solids concentration increases (including urea), a point is reached where the rate of urine/urea introduction into the recycle loop equals rate of urea decomposition. From then on, the urea concentration remains constant, while other dissolved solids still accumulate. Alternatively, if urea is allowed to decompose in the urine collection loop instead of the recycle loop, less urea is available to enter the recycle loop, which again ultimately leads to lower ammonia carryover and decreased tank change-out intervals.

Urea decomposition can be accelerated in several ways: thermally, by elevating the system operation temperature; catalytically, through the use of the enzyme urease; or chemically, by reaction with strong oxidizing agents.

Thermal Decomposition

Urea is present in concentrations of up to 50% of the total dissolved solids in human urine, and it decomposes to ammonia and carbon dioxide through the action of bacteria, or by high temperatures. Most urine processing systems employ a pretreat solution consisting of bactericidal and acidic components which inhibit urea breakdown as well as fix any dissolved free ammonia in the ammonium ion form. In addition, if elevated operating temperatures are required, a maximum of 66°C (150°F) is generally established in order to prevent the thermal decomposition mechanism from occurring to any significant degree. If the goal is to eliminate or reduce the urea concentration in the urine, then the above mentioned decomposition pathways can be exploited.

Work done by Shaw and Bordeaux[1] for urea decomposition in aqueous media resulted in the determination that the reaction is 1st order with respect to urea. In acidic solution the reactions are as follows:

$$NH_2CONH_2 \text{ (Urea)} \xrightarrow{k_t} NH_4^+CNO^- \qquad (1)$$

$$CNO^- + 2H^+ + 2H_2O \xrightarrow{\text{RAPID}} NH_4^+ + H_2CO_3 \qquad (2)$$

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[1] W. Shaw, J. Bordeaux, "The Decomposition Of Urea In Aqueous Media," J. Amer. Chem. Soc., 77 (1955), 4729-4733

Reaction (2) is complete at room temperature in sufficiently concentrated acid solution. A plot of acid concentration versus NH_4^+ production is shown in Figure 55.

The rate equation for the first order decomposition is:

$$-\frac{dU}{dt} = k_t U \tag{3}$$

where U is in the urea concentration in moles/liter, $\frac{dU}{dt}$ is the change of urea concentration with time, and k_t the temperature dependent rate constant in units of h^{-1}. The ammonia generated is simply related by the relation:

$$\frac{dNH_3}{dt} = 2\,\frac{dU}{dt} \tag{4}$$

As stated, under acidic conditions the ammonia produced is converted immediately to the ammonium ion, NH_4^+.

An Arrhenius plot of rate constant versus temperature (K) is shown in Figure 56 and the data is arranged more conveniently in Table 18.

The rate constants presented are sufficiently accurate for urine-urea/water systems because it was shown that varying ionic strength did not affect the rate constant at 90°C to any observable degree. So in effect, we have the overall conversion in acid solution:

$$NH_2CONH_2 + 2H_3O^+ \longrightarrow 2NH_4^+ + H_2CO_3$$

The NH_3 and CO_2 distribution curves are shown in Figures 57 and 58, respectively and give the relative proportions of each species present in the solution as a function of pH. Thus at pH = 5, we expect to see only a small fraction of the dissolved ammonia as undissociated NH_3, whereas carbon dioxide will exist primarily in the undissociated form, or H_2CO_3.

With this information, a TIMES application can be envisioned that creates a situation where the urea decomposition rate is made equal to the urea introduction rate into the recycle loop. At low temperatures there appears to be no way to breakdown the urea at a practical rate. Since the recycle loop necessarily is heated in order to establish the design water evaporation rate, it is this loop where urea decomposition could profitably be accelerated.

For TIMES, using a processing rate average of 0.90 kg/h (2 lb/h) would yield a urea input of 0.30 moles/h (0.0113 lb/h), 0.0051 kg/h assuming a urea concentration in urine of 2%.

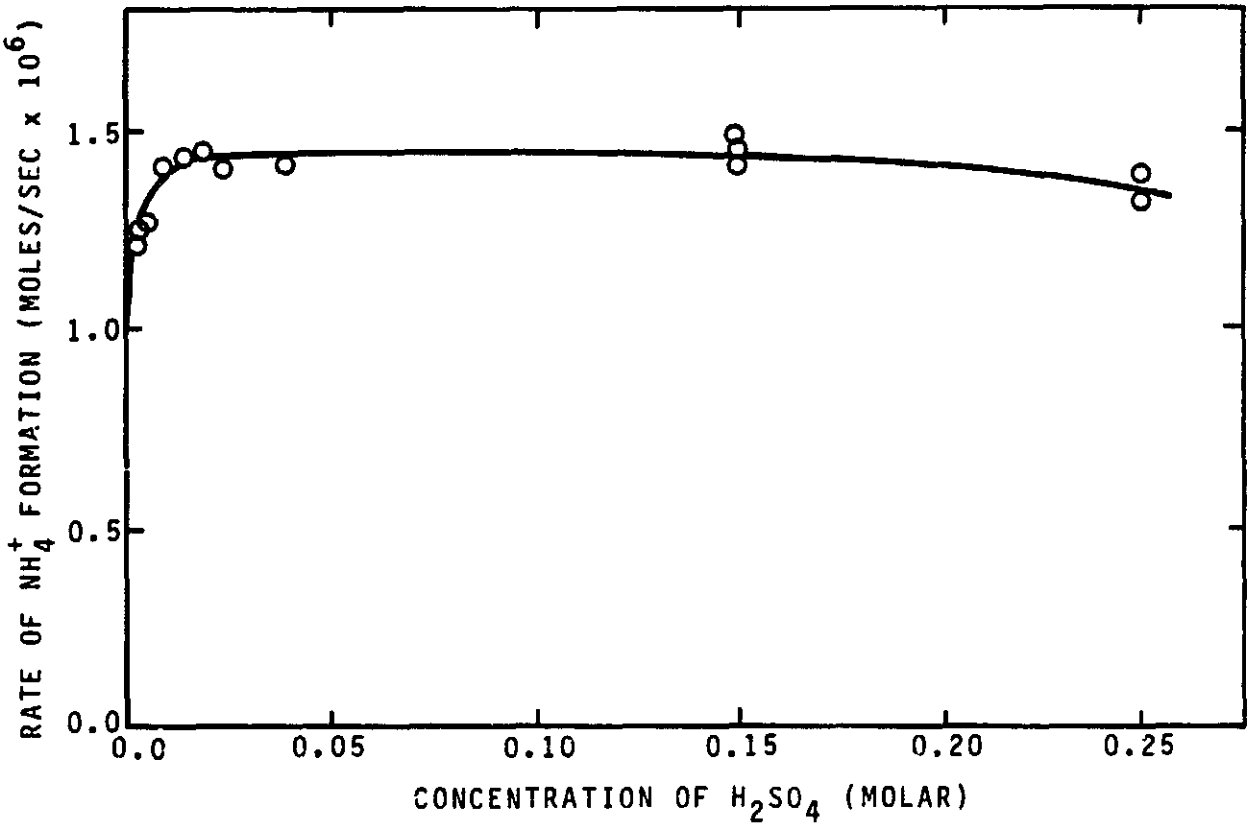

FIGURE 55
AMMONIUM ION FORMATION

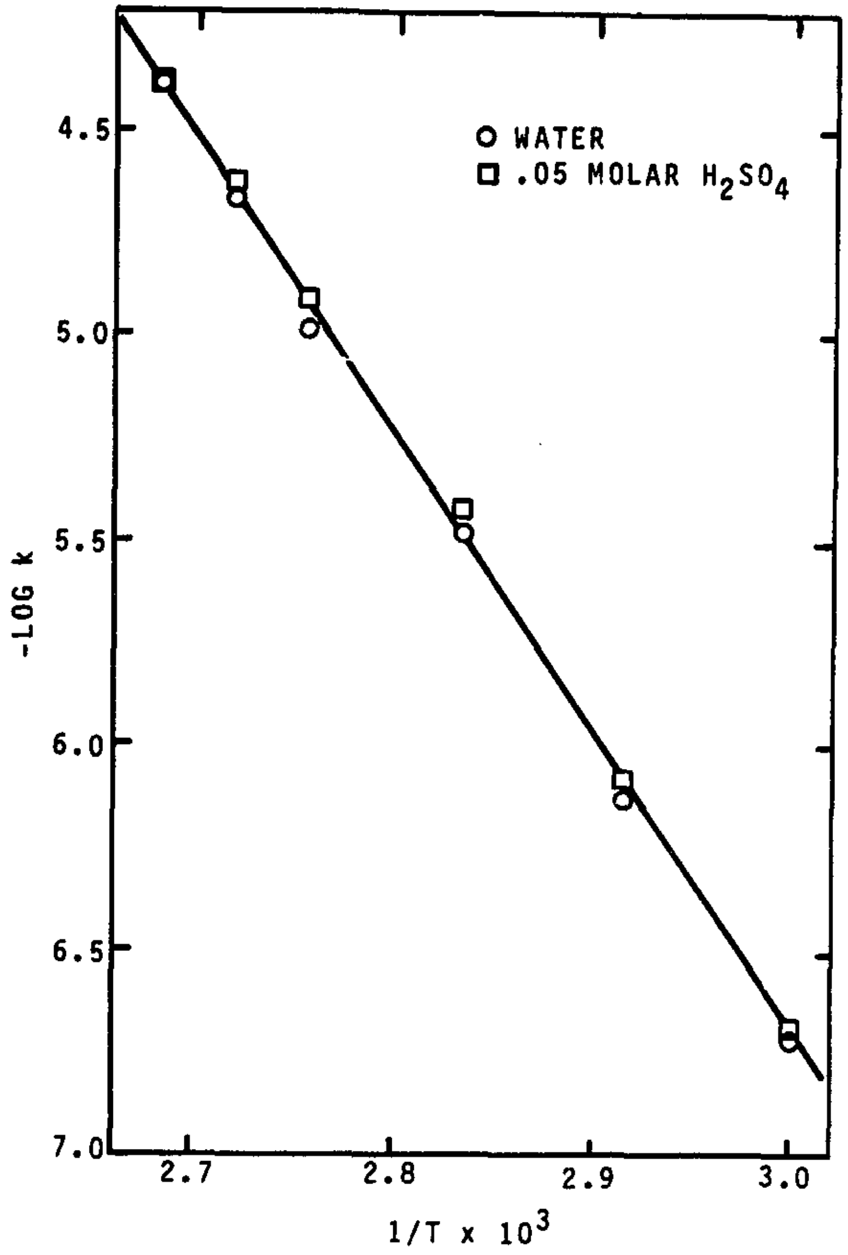

FIGURE 56
UREA DECOMPOSITION RATE CONSTANT

Table 18
UREA DECOMPOSITION RATE CONSTANT

°C	(°F)	k (h^{-1})
60	(140)	7.56×10^{-4}
70	(158)	2.99×10^{-3}
80	(176)	1.39×10^{-2}
90	(194)	4.32×10^{-2}

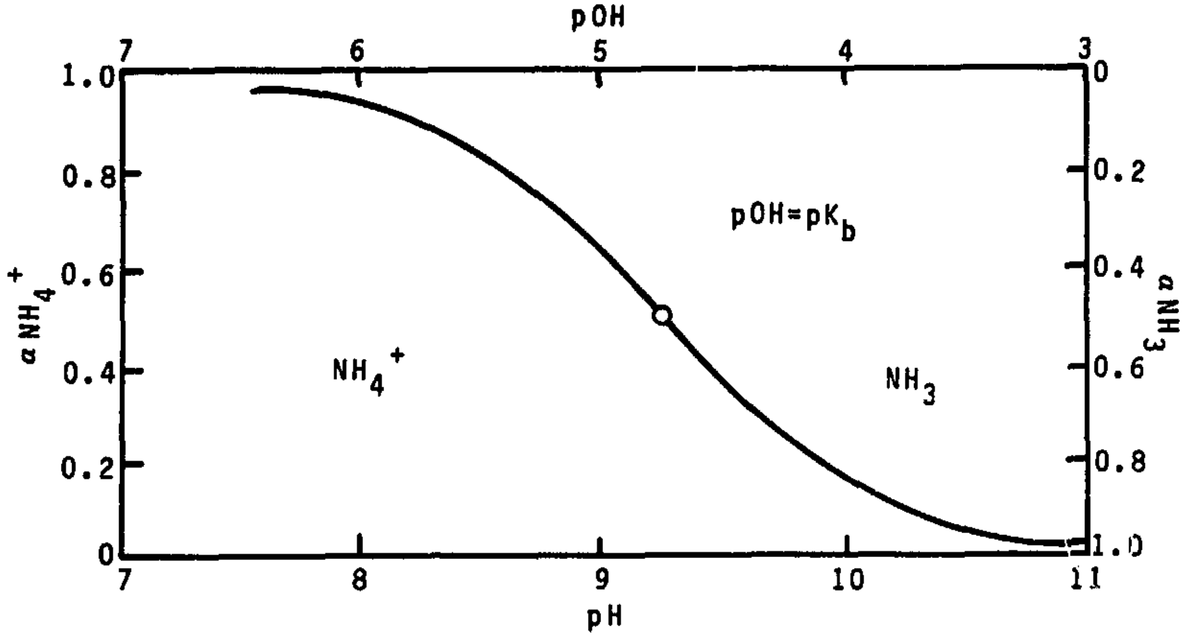

FIGURE 57
DISTRIBUTION DIAGRAM FOR AMMONIA

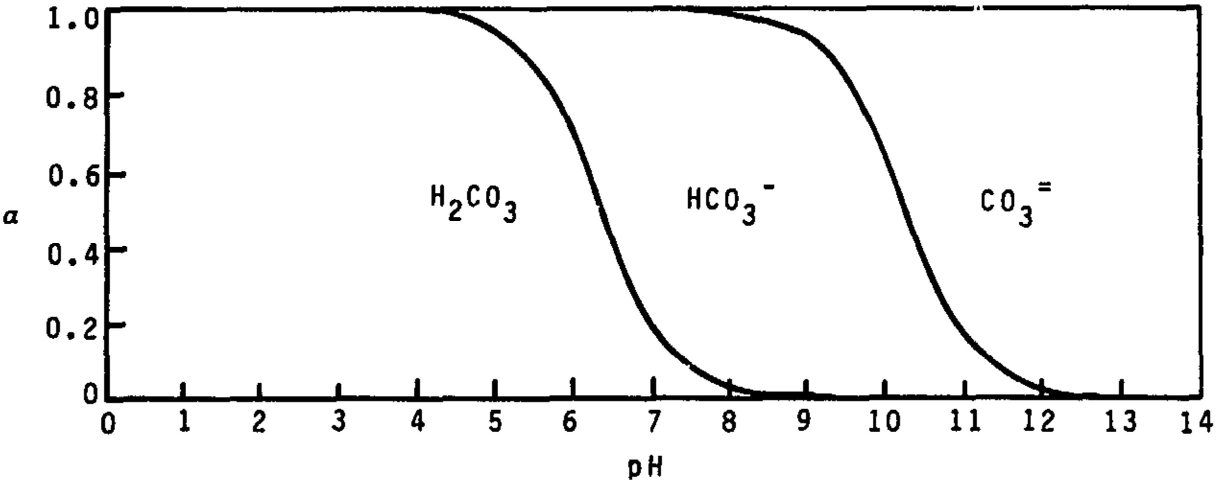

FIGURE 58
DISTRIBUTION DIAGRAM FOR CARBON DIOXIDE

Since the urea mass balance can be expressed as a function of urea concentration and recycle loop volume as:

$$Uin = A \times U_e(\%) \times V(l)$$

where U_e is the equilibrium urea concentration, Uin is the urea input rate in moles/h, and A is a proportionality constant, it is clear that the volume can be increased (most easily by changing the recycle tank volume) in order to reduce the urea concentration necessary for dynamic equilibrium. In addition, if one considers that TIMES can, and probably would, be operated on other than a 100% duty cycle, a number of design options are obtained and presented in Figure 59.

The graph shows that at the present operating temperature of 150°F, 100% duty cycle, and recycle loop volume of 12 liters (0.424 cubic feet), the urea concentration would never reach an equilibrium point over a normal operating cycle where 42% total solids accumulate (21% urea) before the recycle tank is changed out (this corresponds to 95% water recovery). A practical operating point could be achieved by running TIMES at 71°C (160°F), and 33% duty cycle, keeping the present volume, because then the urea concentration would stabilize at 19%. A significant improvement would be obtained by operating at 77°C (170°F) and 33% duty cycle, which gives an equilibrium point at 8% urea. Considering the undesirable increase in weight and envelope of a recycle tank twice the size, it would not seem practical to decrease the urea equilibrium value by this means.

The effect of duty cycle on the process is easily explained. At a given equilibrium concentration of urea, there is an exponential decay in the decomposition rate during the off-duty cycle since breakdown is proceeding while no urea is entering the loop. For a 33.3% duty cycle, the urea decomposed during the 16 hour off-time equals the amount decomposed during the 8 hour on-time, and thus the effective decomposition rate for a 24 hour period is twice the on-time rate. This would allow the system volume to be decreased by 1/2 in order to achieve the same equilibrium urea concentration as the 100% duty cycle.

Furthermore, as the other dissolved solids concentrate in the recycle loop, the water production rate decreases, accompanied by a like decrease in urine input, this in turn lowering the urea input rate. Since at a given temperature the decomposition rate constant is fixed, the equilibrium concentration of urea would necessarily shift to a lower value than the initial point established by the given temperature, volume, and duty-cycle.

The most practical operational point would be where the equilibrium urea concentration is minimized, since that results in a longer time period between recycle tank change-outs. If it takes longer for the other dissolved solids to concentrate to 40%, e.g., the overall water recovery is improved since fewer tank changes mean the remaining 60% water is dumped less often. Another advantage is improved water quality, since the ammonia generated is directly proportional to urea concentration. At the equilibrium point, the urea concentration remains constant, and

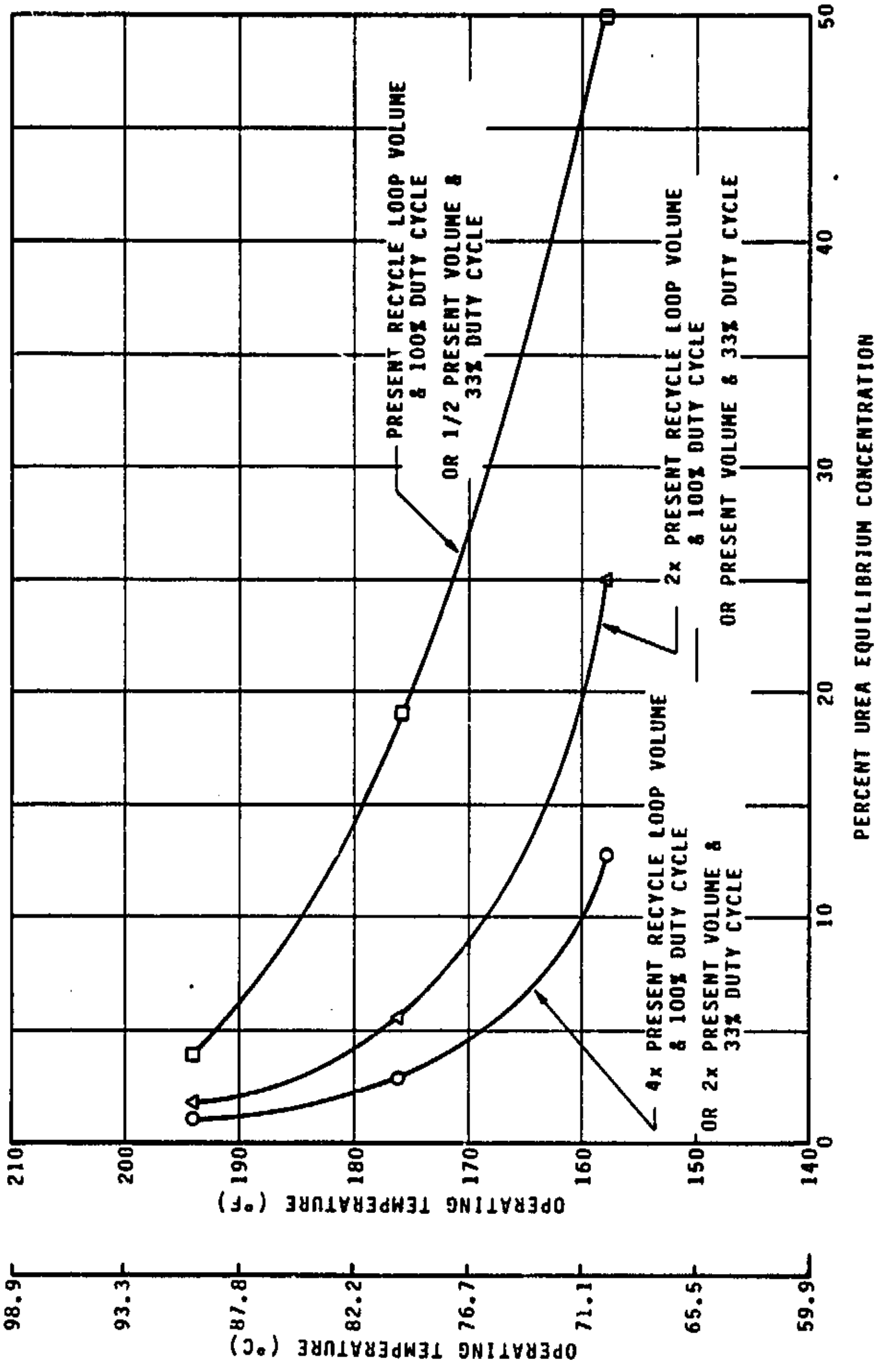

FIGURE 59

UREA EQUILIBRIUM CONCENTRATION

therefore the NH_3 carryover would be fixed as well. With time, the equilibrium value decreases as stated before, allowing water quality to actually improve with respect to NH_3 contamination.

Once the operational parameters are selected for practical urea breakdown, other system conditions must be adjusted to remove the ammonia generated. At the equilibrium point, the resulting dissolved ammonia would cause a $pH > 10.5$ to arise. Allowing this much NH_3 to accumulate would result in unacceptable carryover. So, a means must be provided to remove any NH_3 as soon as it is formed. Because of the relatively small quantities of NH_3 being generated, no bubbles would form, and therefore normal liquid/gas separation is not possible. Thus, permeable membrane separation would seem to be the only feasible method. According to Cole[2], for aquo-ammonia systems the best membrane is one in which NH_3 is very soluble while water vapor is not. Nylon 6 and Zytel were shown to be favorably permselective to NH_3, but lacked sufficient throughput. Celluose acetate was suggested as another candidate. However, selectivity could be sacrificed for increased throughput, allowing the use of a material which has excellent gas transport properties. Table 19 gives the gas permeability for the various major constituents of concern for several membrane materials. Since we are talking about aqueous systems, the permeation rate for dissolved, undissociated NH_3 would be a fraction of its gas phase permeability, but relative comparisons can still be made among membrane materials. Material selection and design of this zero-gravity separator would involve another study at the very minimum, and probably laboratory testing as well. The separator would have to be located upstream of the evaporator, and must be able to quantitatively remove ammonia in a single pass. Physical dimensions of the package would have to be minimized since space in the present system configuration is limited, and this means a very efficient membrane is needed with respect to throughput/active area.

One concern with the membrane separator would be the loss of water vapor along with NH_3 if the permeants are dumped overboard. Therefore, the separator sizing would have to trade-off maximum ammonia throughput capacity with the need to minimize water loss, keeping in mind this water loss can also be offset by savings accruing to less frequent recycle tank change-out intervals.

To summarize, thermal decomposition would only be practical for the urea in the recycle urine loop. If the present subsystem configuration is retained, the operating temperature would have to be increased from 66 (150) to 77°C (170°F) in order to create a condition where the urea concentration stabilizes at 8%. To date, TIMES operation at 77°C (170°F) has not been demonstrated. A membrane separator would be necessary to remove the generated ammonia at some point in the recycle loop downstream of the urine feed inlet, and before the evaporator. The membrane material would have to be chosen and evaluated for ammonia/water vapor selec-

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[2] C. Cole, E. Genetelli, "Pervaporation of Volatile Pollutants From Water Using Selective Hollow Fibers," J. Water Poll. Cont. Fed., 42, (1970),R290-R298

Table 19
GAS PERMEABILITIES

	Nylon 66	Silicone Rubber	Mylar	Celluose Acetate
NH_3		4396	22	2067
O_2		450	.02	.6
CO_2		1500		5
CO_2	2453	28500	98	5500

All @ 25°C $P = \frac{CC\ (STP) - CM}{CM\text{-}SEC\text{-}BAR\ (\Delta P)}$

tivity and ammonia throughput, as well as compatibility in the corrosive environment existing in the urine loop. No obvious membrane candidates are known so a materials study would be necessary.

Enzyme Hydrolysis

The enzyme urease catalyses the hydrolysis of urea to ammonia and carbon dioxide according to the general enzyme reaction scheme:

a) enzyme + substrate = enzyme-substrate (ES)
b) ES + H_2O = enzyme + product A + product B

The rate of reaction during the initial phase depends on the amount of enzyme present as long as the amount of substrate remains in excess and conditions are constant. If the amount of enzyme is held constant, the rate is influenced by the substrate concentration, product concentration, temperature and pH. This is seen in Figures 60, 61, and 62, respectively.

Characteristically for enzyme reactions, there is an optimum temperature pH where the rate is maximized. Within a few pH units of the optimum, the loss of rate is reversible, but pH's beyond those points leads to permanent deactivation. At the minimum temperature, the reaction proceeds very slowly, but the enzymes are not at all damaged. At the other extreme of maximum temperature, the rate goes to zero and the enzymes can be destroyed as well. Within these limits, the rule of thumb is a doubling of reaction rate for every 10°C (18°F) change in temperature up to the optimum as long as the enzymes are not damaged. For urease, the optimum pH is 8.0 and a temperature of 20°C (68°F) is generally recommended.

As a means of maintaining a constant enzyme concentration, the enzymes can be trapped in a suitable matrix, and are then characterized as being immobilized. Work done at Martin Marietta Corporation investigated the immobilization of urease using nylon netting impregnated with an acrylamide gel solution. It was found that with time enzyme activity decreased, primarily because of loss of bound enzyme from the structure with varying storage conditions. Other entrapment schemes include porous hollow fibers, spun fibers, covalent bonding, and microencapsulation.

In order to avoid the disadvantage of having another consumable for TIMES, immobilized urease would be preferred over any other means by which the enzyme is continuously added to the urine. This necessitates designing a suitable apparatus which would retrofit on the present subsystem, and the most practical design would be another holding tank or canister. In addition, the temperature and pH criteria for urease suggest that the urine should contact the immobilized urease in the urine collection loop before any pretreat is added. As the hydrolysis proceeds, the ammonia and carbon dioxide formed would have to be removed at some point in the canister (or tank) before the urine enters the mixing tank. Since the reaction rate at room temperature is approximately two orders of magnitude less than the thermal decomposition rate at 66°C (150°F), fairly large amounts of immobilized urease would be

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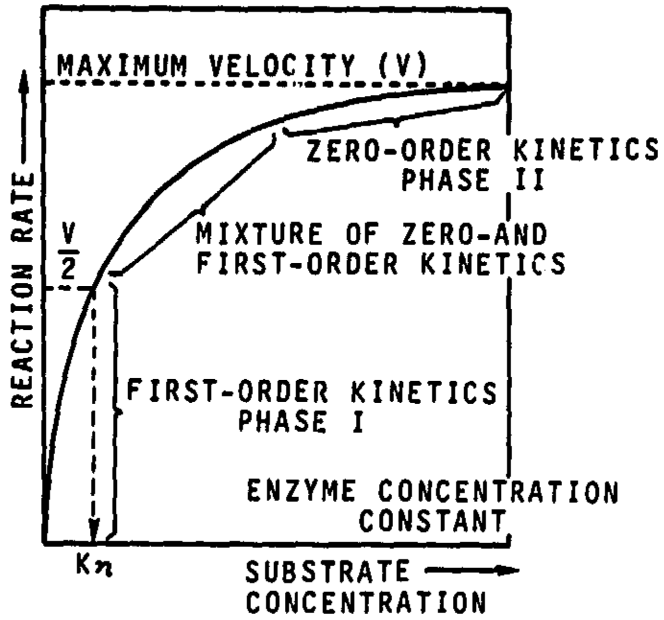

FIGURE 60

SUBSTRATE CONCENTRATION vs REACTION RATE

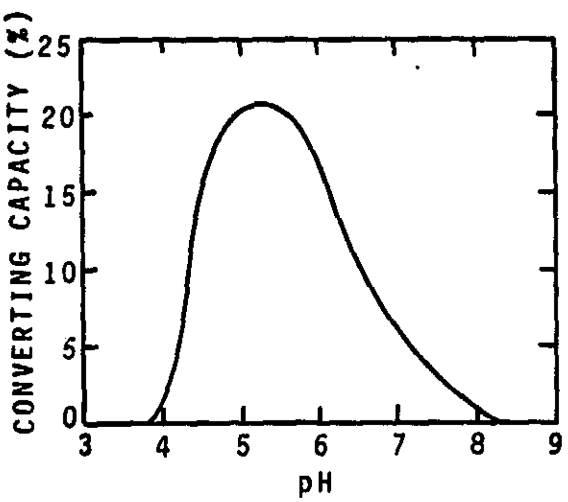

FIGURE 61

pH vs ACTIVITY

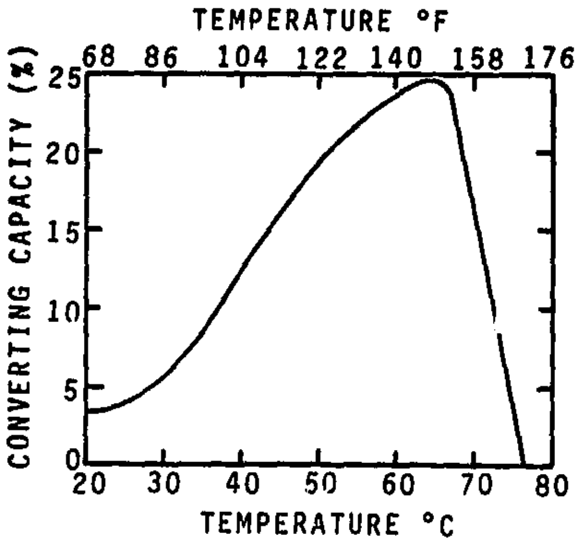

FIGURE 62

TEMPERATURE vs ACTIVITY

needed for complete urea decomposition to occur in the required time frame. Furthermore, the actual amount must be sufficient to offset loss of bound enzymes and resultant loss of activity as mentioned above.

Thus, the drawbacks associated with immobilized enzymes are: the low reaction rate, which necessitates an additional holding tank, vented to relieve decomposition gas pressure buildup; the potential loss of activity with time. The latter process would have to be further investigated in order to establish the optimum means of entrapment and stabilization for the TIMES configuration and operational parameters.

Chemical Reaction

Urea can be decomposed to N_2 and CO_2 by reaction with certain strong oxidizing agents such as hypochlorites. Sodium hypochlorite (NaOCl) usually is obtainable in liquid form but presents a fire hazard and is generally unstable. Far more suitable from a stability and handling standpoint is calcium hypochlorite ($Ca(OCl)_2$) which is used in powdered form. However, adding water (or urine) to dry, soluble, hypochlorite almost certainly would generate chlorine gas, so an insoluble powder would be more desirable. An insoluble, chlorinated compound that could perform the same oxidation function is trichloroisocyanuric acid. It is fairly inexpensive since it is used as bleaching agent in detergents, and in a dry bed form, could be employed in the urine inlet line to react with the urine/urea. The large quantity of gases that are generated would have to be vented.

From a design viewpoint, the insoluble acid would have to be loaded into a canister through which incoming urine would have to pass. A means of assuring that the gases generated are vented and do not backflow into the urinal would have to be determined, and at frequent intervals the canister would have to be replaced because of the depletion of the acid. The most significant disadvantage would be the weight of material needed, which is over 90.7 kg (200 lb) for a 180 day, 3 man design point.

2. Urea Complexation/Filtration

An efficient way of dealing with urea would be to completely remove it from the urine, without generating decomposition by-products, prior to introduction of the urine into the recycle loop. A practical means might be to bind it up chemically, so that it can be removed via a filtration apparatus.

This binding up, or complexation, could be accomplished by attaching a soluble polymeric molecule to the urea, thereby significantly increasing its effective size and molecular weight, and then filtering the urine through a microporous membrane, that would not otherwise restrict the flow of any species in the urine, including uncomplexed urea.

Use of this technique for Cu^{+2} and Fe^{+2} ions, I_2, and phenol, where each of these species was complexed with a suitable polyacidic macromolcule, was shown to give at least an 80% rejection, except for phenol which had a 25% rejection[3].

Rejection was defined according to the reaction:

$$R = 1 - \frac{M^{n+}}{M_{Total}}$$

where M^{n+} is the free cation concentration, and M_{Total} is the total concentration of cation available. After combining the polyacid and the cation in solution, the following equilibria are established:

$$LH \rightleftharpoons L^- + H^+$$
$$L^- + M_n^+ \rightleftharpoons LM^{(n-1)+}$$

where LH represents a ligand group on the polymer chain.

Considering urea, a suitable polyacid would have to be chosen that ensures complete complexation would occur over the pH range of pretreated to raw urine, and an ultrafiltration membrane would have to be selected which would allow sufficient urine throughput, while rejecting the urea complex. The disadvantages therefore are 1) another consumable would have to be added to the system, and 2) a filtration apparatus would have to be selected, designed and retrofitted.

3. Ammonia Catalytic Removal

The objective of this method is to completely remove the available free NH_3 with a single or dual reactor system and oxidize it to N_2 and H_2O. This approach is applicable to the present TIMES configuration, or to a modified design where urea decomposition is accelerated. There are a number of options, depending on where and in what form the NH_3 is removed.

A - Treats Entire Product Vapor Stream Catalytically

The schematics are shown in Figures 63 and 64. This urine loop would operate as presently, with pretreat added to the urine as it is collected. Steam is generated in the evaporator at 0.90 kg/h (2 lb/h) along with trace amounts of NH_3, but instead of going directly to the condensing plates in the Thermoelectric Regenerator (TER), the evaporant is mixed with 5% O_2, either from air or some other source. This mix is then heated from 66 to 249°C (150 to 480°F) and passed into an oxidizing catalyst bed consisting of 0.5% Pt on alumina pellets. From the bed, the products including N_2O are partially cooled by a regenerative heat exchanger, and then air cooled to 63°C (145°F). The products enter the TER, where the steam is condensed as usual on the cold plates, while the non-condensible gases are treated in either of two ways: 1) The products,

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[3] O. Nguyen, P. Aptel, J. Neel, "Application Of Ultrafiltration To The Concentration And Separation Of Solutes Of Low Molecular Weight," J. Membrane Sci., 6, (1980), 71-82

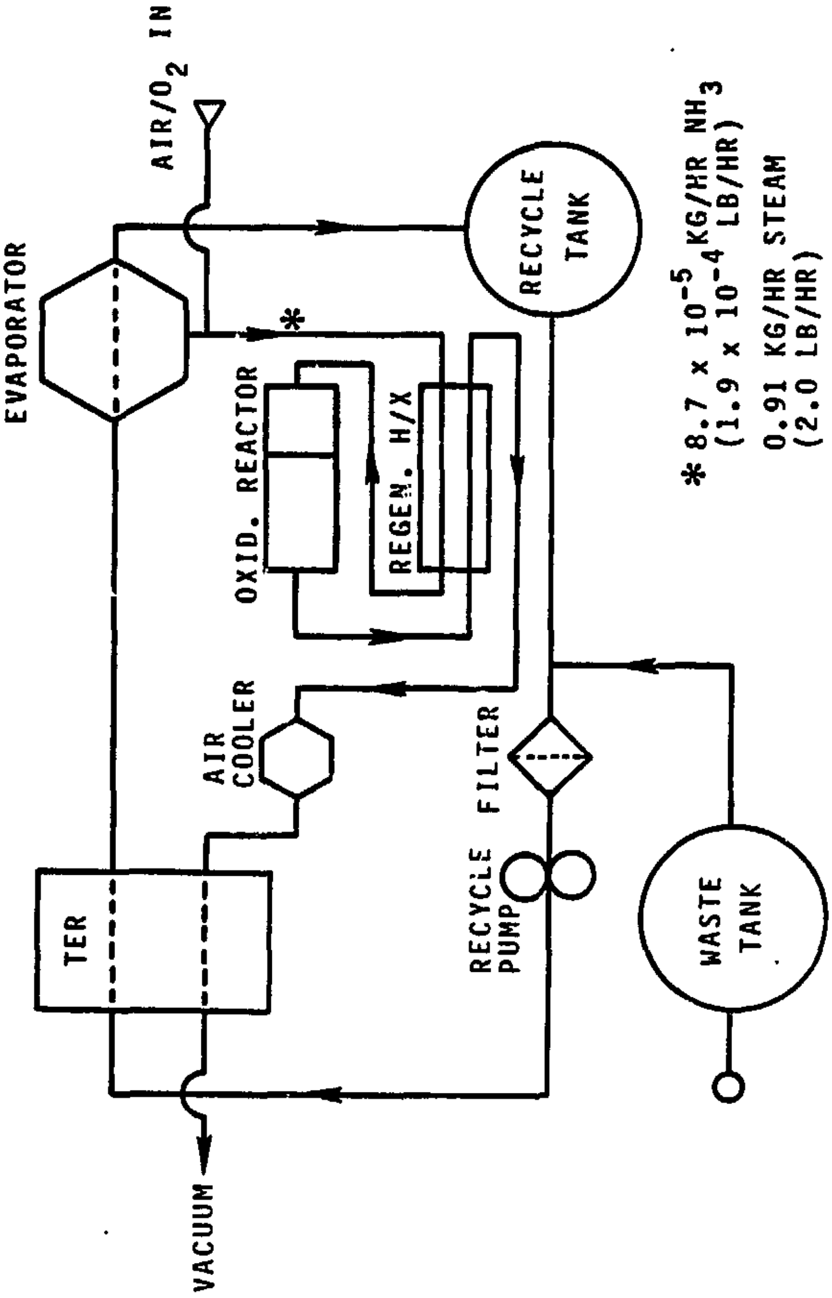

FIGURE 63
AMMONIA OXIDATION - PRODUCT WATER STREAM

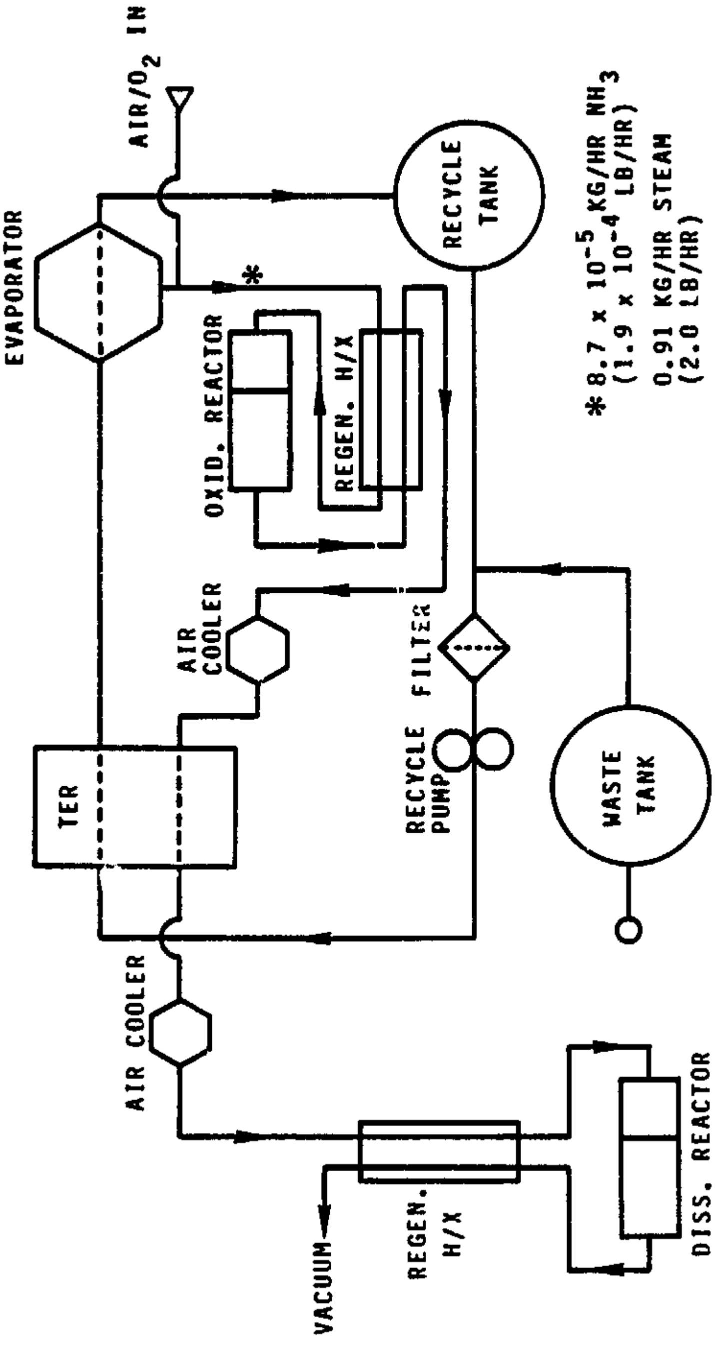

FIGURE 64

AMMONIA OXIDATION AND DISSOCIATION - PRODUCT VAPOR STREAM

N_2, N_2O, as well as some H_2O vapor, O_2, and CO_2 are dumped overboard by the TIMES burper as non-condensibles; 2) The non-condensibles exiting the TER burper would be further cooled to 18°C (65°F) (to condense additional H_2O vapor) by passage through an air cooled heat exchanger. From there, the mix would enter a regenerative heat exchanger followed by a second reactor containing a dissociation catalyst (0.5% Ru on alumina) heated to 449°C (840°F). Here, N_2O breaks down to N_2 and O_2. Besides the reactor, the major disadvantage here is the additional hardware necessary for preheating and postcooling the product vapor and gases.

The source of O_2 for the oxidation reaction can be either cabin air or O_2 generated from some other source. If cabin air is utilized, venting the non-condensibles to vacuum via the burper results in total consumption, whereas employing tne dissociation reactor provides a means to reclaim some of the air. Water electrolysis as a means of O_2 generation was investigated but the hardware is complicated, water is consumed, and the specific energy penalty is excessive at all but the minimum NH_3 production rates.

A tabulation of the mass and heat balances for both approaches is presented in Table 23 using a back calculated NH_3 production rate based on actual H_2O analysis data from TIMES operation on urine. The maximum NH_3 level found in the H_2O was 50 ppm, but 100 ppm was used in the construction of Table 20 in order to have some margin.

It can be seen that because of the large H_2O/NH_3 ratio, almost all of the energy lost is in the partial heat recovery after the oxidation reactor. Even if the regenerative heat exchanger effectiveness is 0.50, the net increase in specific energy is still 44 W-h/kg (20 W-h/lb) at this point. Whether the dissociation reactor is used or not makes very little difference in terms of specific energy for NH_3 levels of 100 ppm or less.

B - Treats Urine Recycle Loop Vapor Catalytically

This approach involves stripping dissolved NH_3 and CO_2 directly from the recycle loop. The two gases are urea decomposition products, and their production rate can be accelerated by raising the recycle loop temperature 20°C(35°F). Once formed, the dissolved gases would have to be removed using a membrane separator, which as previously discussed, has to be microporous so that sufficient degassing capability is obtainable, and sized so that water vapor loss is minimized. Use of a microporous material allows the differential pressure across the device to be less than the system generated P across the homogeneous Nafion membrane used in the evaporator, while still ensuring quantitive removal of NH_3 and CO_2 (microporous material permeability is generally much greater than homogeneous material for the same P and given permeant).

Since the goal is to maximize NH_3 removal, pH should be as high as possible in order to establish a favorable NH_3/NH_4^+ ratio. This could be accomplished by reducing the amount of pretreat in the waste tank or by eliminating it altogether. The latter presents bacteria growth problems, however. Figures 65, 66, and 67 illustrate the urine vapor treatment approach.

Table 20
AMMONIA REMOVAL PRODUCT VAPOR STEAM

Location/Process	Specific Energy		Option Subtotal		Reference
	W-h/kg	(W-h/lb)	W-h/kg	(W-h/lb)	
Preheat	+88.00	(+40.00)			
Ox-Reaction	- 0.44	(- .20)			
Post-Cool* 1	-44.00	(-20.00)	+43.60	(+19.80)	Figure 63
Post-Cool* 2	- 0.03	(- 0.01)			
Preheat	+ 0.18	(+ 0.08)			
Diss-Reaction	- 0.022	(- 0.01)			
Post-Cool* 3	- 0.088	(- 0.04)	+ 0.05	(+ 0.02)	Figure 64
Total			+44.10	(+20.00)	
With Electrolysis	+ 1.87	(+ 0.85)			
Total			+46.00	(+20.85)	

*Assumes Heat Exchanger Effectiveness = 0.5

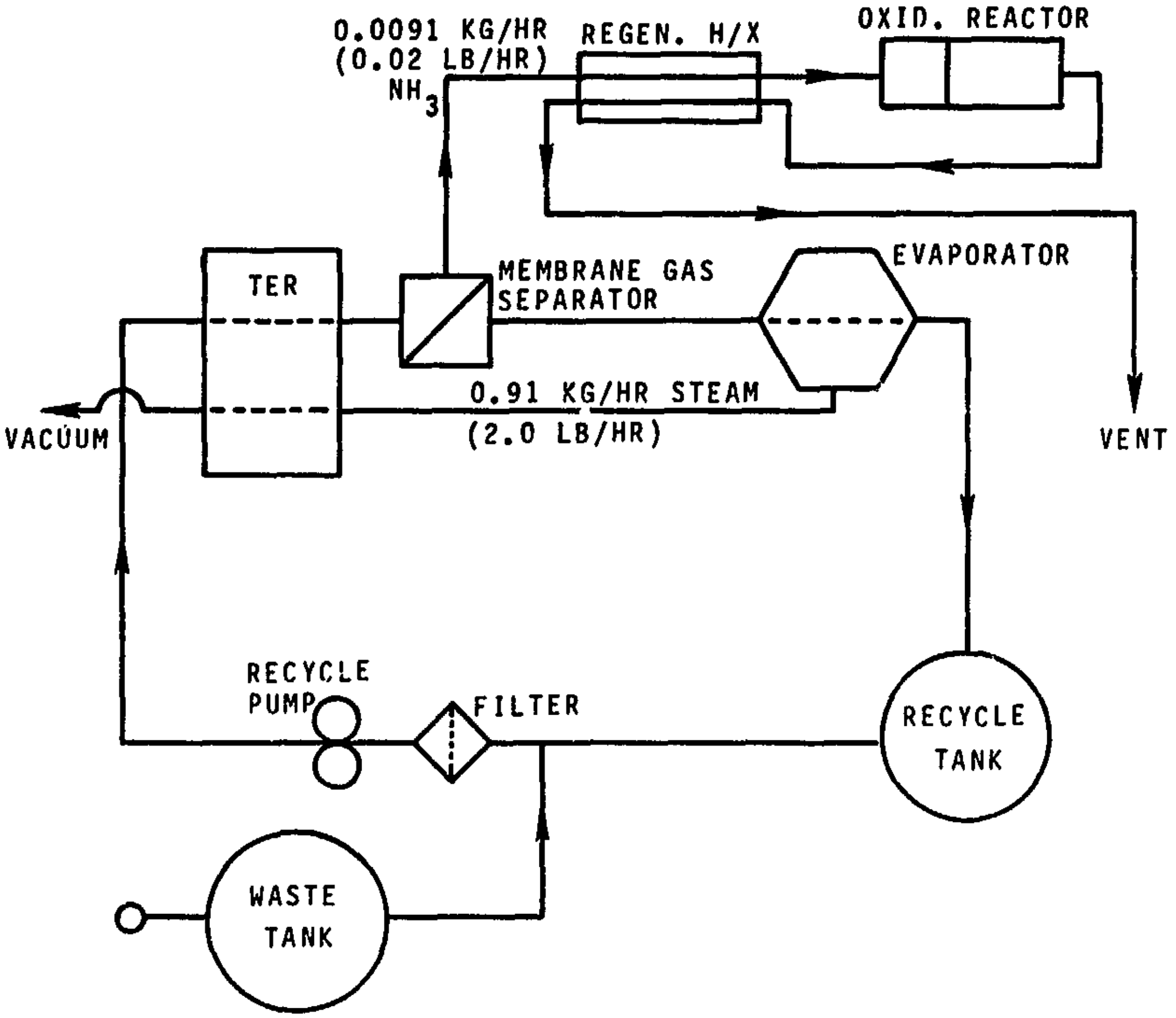

FIGURE 65
AMMONIA OXIDATION - URINE VAPOR

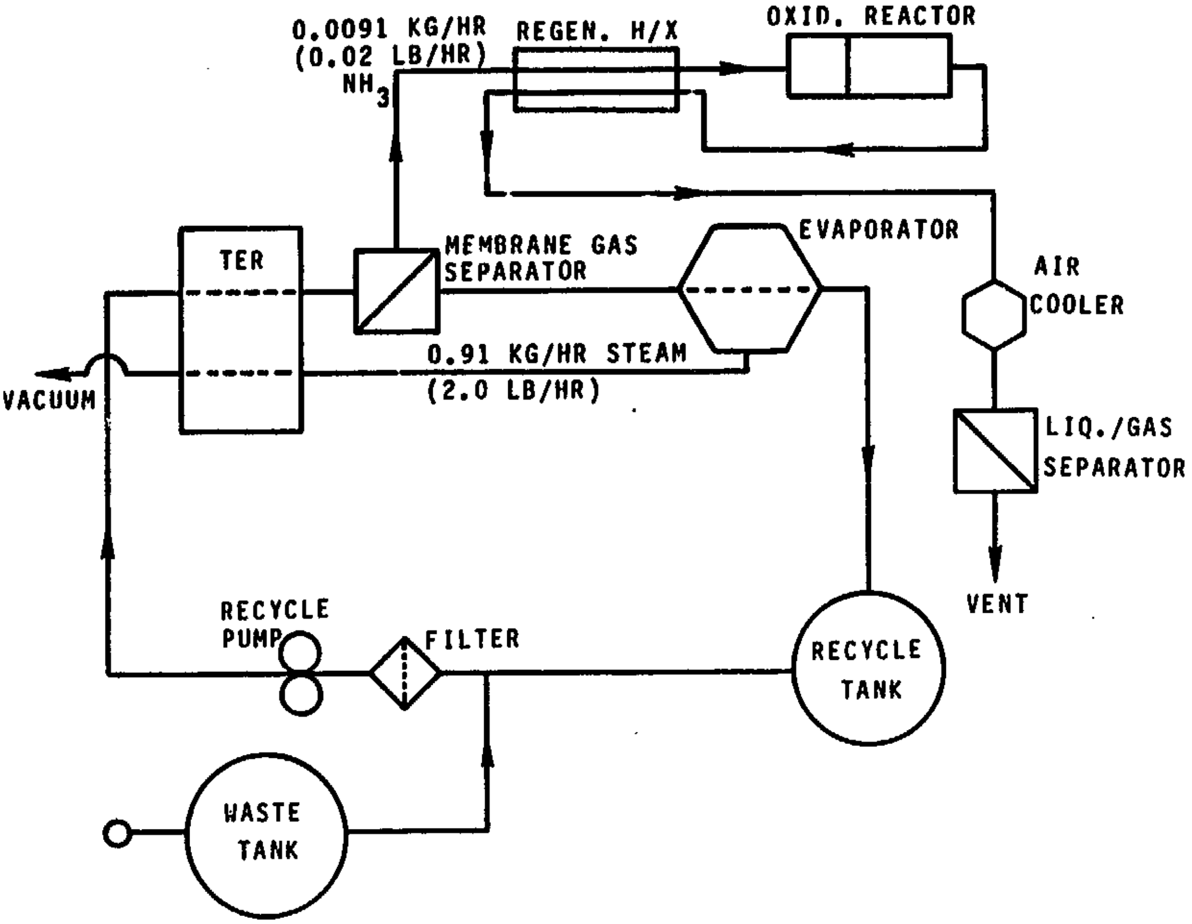

FIGURE 66

AMMONIA OXIDATION -
URINE VAPOR WITH WATER RECLAIM

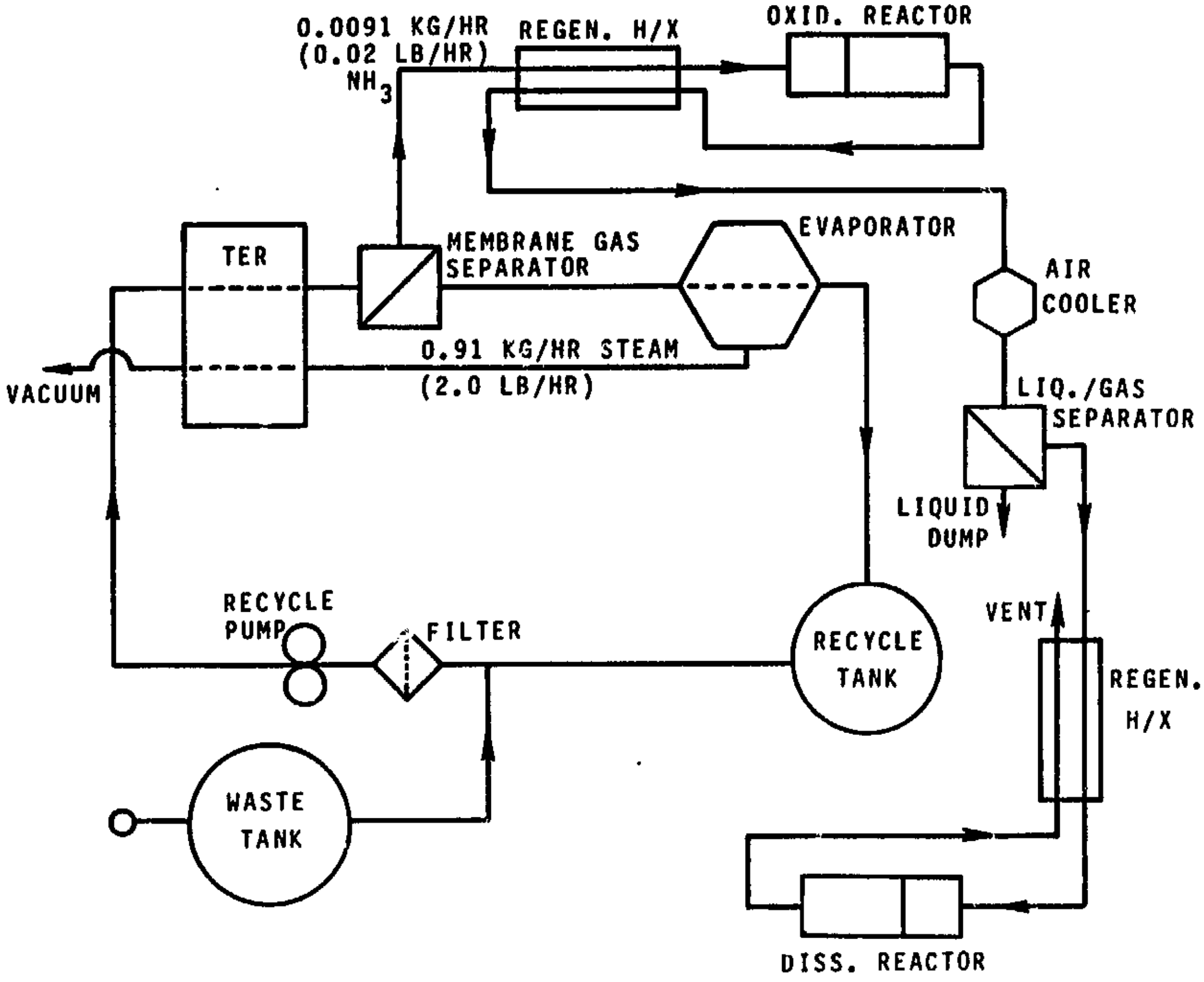

FIGURE 67

AMMONIA OXIDATION AND DISSOCIATION - URINE VAPOR

Once the NH_3 and CO_2 by-products are stripped from the urine loop, the NH_3 is catalytically removed via the oxidation method described previously. The major difference here is that much less water vapor is involved. The oxidation reaction products are subsequently vented overboard along with any residual water vapor, which is a disadvantage from a water reclamation efficiency standpoint.

This water loss can be mitigated if, instead of venting all the products overboard, the water vapor is condensed via an additional heat exchanger and added to the main production stream after collection in a liquid/gas separator. Thus, two additional pieces of hardware are necessary in order to reclaim otherwise lost water.

If venting the oxidation reaction products is not desirable after exiting the oxidation reactor, the products can be post-cooled and introduced into the dissociation reactor after passing through an air cooler and regenerative heat exchanger as previously described.

The mass and heat balances for the urine vapor treatment approach are presented in Table 21 using the maximum expected NH_3 production rate based on urine/urea levels. This is used since it is assumed the process can be driven by temperature to breakdown all the incoming urea, and that the membrane separator can be sized to remove all the NH_3 formed, thus driving the urine loop equilibrium as expressed by the relation:

$$H^+ + NH_3 \rightleftharpoons NH_4^+$$

In the direction of NH_4^+ conversion to NH_3. In order to compare the two catalytic ammonia removal approaches Table 22 combines the data from Tables 20 and 21. Processing NH_3 in the recycle loop appears to be more favorable than from the steam side. As is seen, the exothermic reaction during the oxidation process can make this approach very efficient depending on reactor design. Figure 68 is a sketch of an integrated, dual reactor geometry that would make good use of available energy while considering the various temperature differentials of the processes. The reactor could be designed so that the 1st preheat cycle requires a heater all the time; with exothermic reaction, heat is transferred to the cooled product stream before it enters the preheat section of the dissociation reactor. A second heater would be required to boost the temperature up further.

4. Ammonia Removal With Ion Exchange

Use of the present TIMES ion exchange resin for posttreatment of product water was dictated by the large total absorption capacity as stated in the manufacturer's performance data. The Ionac CC resin consists of carboxylic functional groups in the hydrogen form, and therefore is classified as a weak acid resin. It is only recommended for use where pH > 5. At pH levels lower than 5, the acid group is mostly undissociated leaving only a small percentage of active sites available for exchange.

Table 21
AMMONIA REMOVAL PRODUCT URINE LOOP VAPOR

Location/Process	Specific Energy		Option Subtotal		Reference
	W-h/kg	(W-h/lb)	W-h/kg	(W-h/lb)	
Preheat	+10.6	(+ 4.8)			
Ox-Reaction	-56.5	(-25.7)			
Post-Cool*	- 5.7	(- 2.6)	-51.6	(-23.5)	Figure 65
Condensing	-12.8	(- 5.8)	0.0	(0.0)	Figure 66
Preheat	+18.0	(+ 8.2)			
Diss-Reaction	- 2.9	(- 1.3)			
Post-Cool*	- 9.2	(- 4.2)	+ 5.9	(+ 2.7)	Figure 67
Total			-45.7	(-20.8)	

*Assume Heat Exchanger Effectiveness, = 0.5

Table 22
AMMONIA CATALYST COMPARISON TABLE

Process	Temp. Range °C	(°F)	Specific Energy W-h/kg (W-h/lb) Steam		Specific Energy W-h/kg (W-h/lb) Urine Vapor		Hardware Steam	Hardware Urine Vapor
1st Preheat	63-249	(145-480)	+88.00	(+40.00)	+10.6	(+ 4.8)		Separator 1
Oxidation*	249	(480)	- 0.40	(- 0.20)	-56.5	(-25.7)	Reactor 1	Reactor 1
1st Post-Cool*	249-Ti	(480-Ti)	-44.00	(-20.00)	- 5.7	(- 2.6)	Reg. H/X 1	Reg. H/X 1
2nd Post-Cool*	18.3-Ti	(65-Ti)	- 0.02	(- 0.01)	0.0	(0.0)	Air Cooler 1&2	Air Cooler
2nd Preheat	18.3-449	(65-840)	+ 0.18	(+ 0.08)	+12.8	(+ 8.2)		Separator 2
Dissociation*	449-RT	(840)	- 0.09	(- 0.04)	- 9.2	(- 4.2)	Reg. H/X 2	Reg. H/X 2
Total			+44.00	(+20.00)	-45.8	(-20.8)		

* - Reclaimable Assuming Heat Exchanger Effectiveness = .5
Ti - Intermediate Temperature

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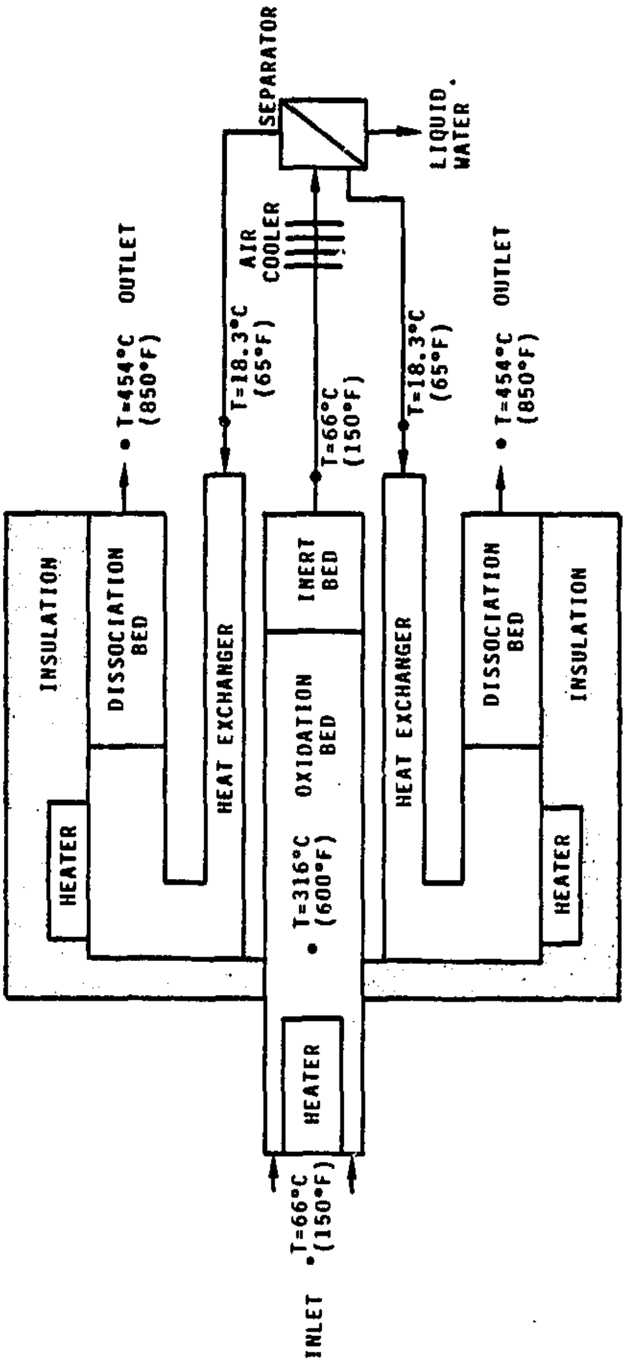

FIGURE 68
CONCENTRIC INTEGRATED DUAL REACTOR
DESIGN CROSS SECTION

Looking at some actual TIMES data in Table 23 for before and after posttreatment, we see trends that can be explained in terms of the weak acid resin characteristics. Samples #1 and 2 show pH and NH_4^+ increasing as the conductivity decreases. This is saying that at a pH = 3.5, the resin wants to be predominantly undissociated and therefore tends to remove H^+ from the water at the expense of releasing NH_4^+ previously bound. This causes the conductivity to decrease since the equivalent conductance of H^+ compared to NH_4^+ differs by 5 to 1. For sample #4, a pH = 5.8 causes the resin to remove NH_4^+ from solution and release H^+, causing the pH to decrease, NH_4^+ to decrease, and the conductivity to rise. Sample #3 is probably a transition point and shows both trends.

A bench test was performed with an ammonium salt in the concentration and pH range found in actual TIMES water analysis data. One batch each of 2.5 and 50 mg/l NH_4^+ (from $(NH_4)_2\ SO_4$) and pH = 4.5 was percolated through equal dry volumes of Ionac CC and Rohm & Haas IR-118H resins. The latter is a strong acid resin that can be used over the full range of pH, but which has less total capacity than the weak acid resin. Analyses were performed on the resin effluent and the results are shown in Table 24. It can be seen that the strong acid resin is > 94% effective in removing NH_4^+ ions at that low a pH, while the weak acid resin shows minimal activity, being <40% effective at high NH_4^+ levels and <8% at low NH_4^+ levels.

Sizing

The Rohm & Haas IR-118H strong acid action exchange resin has a dry total capacity of 5 meq/g. If we use 3 ppm NH_4^+ as the average TIMES raw product water level, and assume a margin of 3 ppm for additional total cations, then for 180 days of operation 1604 kg (3537 lb) wastewater, 0.110 kg of dry resin are required. Under the quasi-static flow conditions on TIMES, resin swelling is 100% from the dry state.

5. Ammonia Oxidation By Ozone/Ultraviolet Radiation

Ozone (O_3) pretreatment alone oxidizes a substantial amount of dissolved organics in water. Low intensity ultraviolet (UV) radiation, when coupled with ozone injection, excites ozone and intermediate organic radicals which improve the oxidizing power of ozone to the extent that essentially complete conversion to CO_2, H_2O, and NO_3^- is attainable. With respect to ammonia, the overall reaction would be:

$$NH_3 + O_3 \xrightarrow{UV} NO_3^- + 3H^+.$$

The oxidation is usually accomplished in a stirred tank with ozone sparged in, and the water is irradiated by a UV source located in the tank. On a weight basis, 0.91 kg (2 lb) of ozone are required for every 0.46 kg (1 lb) of oxidizable species. UV radiation in the wavelength range of 180 to 400 NM, with intensities of 1-5 W/m^3 (28-142 W/ft^3) has been shown to be effective experimentally. Unfortunately, ozone operation is very

Table 23
TIMES WATER ANALYSIS

	pH	Ammonia As Nitrogen (ppm)	Conductivity (μmho/cm)	Sample
Non-Posttreated	3.6	0.16	135	1
	3.5	0.17	198	2
	3.6	4.50	174	3
	5.8	15.00	176	4
Posttreated	5.8	0.43	12	1
	4.3	1.12	147	2
	3.9	1.40	145	3
	4.0	9.00	184	4

Table 24
ION EXCHANGE RESIN COMPARISON TEST RESULTS

Sample	Ammonia As Nitrogen (ppb)	pH	Conductivity (μmho/cm)	Percent Reduction
Feed #1	55000	4.6	308	---
Ionac CC	33750	4.9	295	38.6
IR-118H	765	2.6	696	98.6
Feed #2	2230	4.5	34	---
Ionac CC	2070	5.8	25	7.2
IR-118H	125	3.7	71	94.4

inefficient (<10%) with respect to power, and requires pure oxygen or air at a dew point of <-51°C (-60°F). Approximately 5% of the O_2 is converted to O_3 and this for an average ammonia level of 3 ppm in the product water, and a 0.91 kg/h (2 lb/h) processing rate, 0.0027 kg (0.006 lb) of oxygen per day is required. If air is used as the oxygen source, 0.014 kg (0.03 lb) (air) per day is required, and must be vigorously dried prior to use with a canister of desiccant, for example. The biggest disadvantage here is that the amount of ozone required is small but no excess is desired, especially since ozone is stable in an acidic environment. At low ammonia levels, this would be difficult to achieve. UV lamps are usually mercury-filled and this is a potential problem on spacecraft. On the positive side, since the expected levels of ammonia are low, a unit could be constructed compactly and therefore would present no retrofitting problems.

Conclusions And Recommendations

A summary of the operational criteria for the five candidates is given in Table 25. Of all the approaches, the simplest and most effective for the present TIMES design configuration is the substitution of a strong acid resin for the weak acid type in an additional posttreatment canister. The ion exchange bed is a passive device, requiring no electrical power. For a 180 day mission, only 0.11 kg (0.25 lb) of material is needed to reduce the expected ammonium ion concentration in the TIMES raw product water to levels much below the potable water standard for spacecraft (5 ppm). The only disadvantage to this is the finite capacity of the bed and its ability to absorb all cations, not just ammonium ion. Being potentially regenerable, it is not considered an expendable. A relatively small 394 cm^3 (24 in^3) bed can be sized to easily handle the total load of positively charged ionic contaminants expected for a typical mission.

While urea decomposition and ammonia removal schemes offer other advantages such as a real decrease in dissolved solids, the overall complexity, additional hardware, and power penalties associated with these approaches render them unsuitable when compared to the ion exchange technique. If the present subsystem configuration was changed for reasons such as temperature control improvement, it is possible that urea thermal decomposition with venting of the product gases might then be justifiable. From the practical standpoint, if ammonia removal by catalytic oxidation and decomposition is to be considered, it would be more useful on the steam side than urine side of the evaporator. However desirable an add-on reactor used to remove any ammonia carrying over in the product vapor seems, the data in Table 25 have shown it to be impractical.

Enzyme hydrolysis and chemical decomposition do not offer any significant advantages other than zero power consumption, since it is the additional expendables needed, the complications of gas generation, and the bacteria growth that demand the most consideration from an engineering viewpoint.

Urea complexation, while preventing decomposition, is another solids accumulation problem of a different sort, and the necessary separation steps and hardware introduce additional complexities when retrofitted to the present subsystem configuration.

Table 25
CANDIDATE COMPARISON TABLE

Candidate	Expendables	Accumulables	Gaseous Byproducts	Hardware	Additional Electrical Power Reqmts.	Hazardous Material
●Urea Decomposition						
. Thermal			NH_3, CO_2	Membrane Gas Separator		
. Enzyme Hydrolysis	Enzyme (Urease)		NH_3, CO_2	Immobilization Medium, Canister		
. Chemical	Oxidant		N_2, CO_2	Canister		Oxy-Chlorinated Compounds
●Urea Complexation/ Filtration	Polyacids	Sludge		Feed Tank Filter, Canister		
●Ammonia Catalysis						
. Steam Phase	Air/O_2		N_2O, N_2, O_2, CO_2	Oxidation Reactor Dissociation Reactor Membrane Gas Separator	Reactor Heaters	
. Urine Vapor	Air/O_2		N_2O, N_2, O_2, CO_2	Liq./Gas Separator Air Coolers Regen. H/Xs		
●Ion Exchange				Canister		
●Ultraviolet/Ozone	Air/O_2		N_2, CO_2	Ozone Generator	Ozone Generator	Mercury Vapor
●Catalysis				Contacter (Tank) UV Lamp	UV Lamp	

Ammonia decomposition in the product water by ozone/ultraviolet light treatment involves an apparatus with an ozone generator and ultraviolet lamp. Both are characterized by high power consumption, and include hazardous materials in their operation, namely ozone itself, and mercury vapor from the UV lamp.

LIQUID TRAP IMPROVEMENT

Objective

The original liquid carryover trap downstream of the hollow fiber membrane evaporator is sensitive to small amounts of condensation that could falsely indicate liquid carryover.

The objective of this task is to evaluate and implement means of improving the liquid trap and the carryover indicator to eliminate unwarranted failure shutdowns.

Discussion

The liquid trap configuration as originally designed consists of a teflon screen cone with its apex positioned down in a gravity field, located in the steam passage between the hollow fiber membrane evaporator and the thermoelectric regenerator. Refer to Figure 69. Any liquid that might be present in the vapor leaving the evaporator tends to collect at the apex of the cone, due to gravity in a gravity field or vapor flow in a zero-gravity field, and is sensed by the electrical probes of the liquid carryover indicator located in the apex. A problem occasionally occurs with this design where small droplets can form from condensation of vapor on the membrane tubes during the shutdown mode when the membrane tubes are flushed with room temperature unconcentrated urine. Experimental evidence obtained during subsystem acceptance testing shows that these droplets of liquid in the evaporator shell caused during shutdown are sufficiently volatile during subsystem start-up decompression, and perhaps even during normal operation, to be drawn out of the shell and onto the teflon screen cone liquid carryover indicator where they indicate a subsystem failure condition which initiates a subsystem failure shutdown. During normal operation the droplets revaporize and free liquid is present in the shell only during a failure condition, such as a leak in a membrane tube or a membrane header; a subsystem failure shutdown is then required. During shutdown the liquid supply to the membrane tubes is shut off and the hollow fiber membrane evaporator shell is repressurized thereby preventing significant quantities of liquid from leaving the evaporator and overloading the teflon screen liquid trap. A liquid trap and carryover indicator design that permits the accumulation of a small quantity of condensed liquid in the evaporator shell during shutdown and startup, but protects the thermoelectric regenerator condensing plates from carryover of the potentially contaminated liquid in the case of a failure condition is required.

The liquid trap and carryover indicator design has been revised to provide protection in both one-gravity and zero-gravity situations. Refer to Figure 70. The inlet tube has been capped and extended into the evaporator shell, and vertical windows have been milled near the top of the tube. The windows are covered with a hydrophobic teflon screen that is held in place with bands of hydrophobic teflon shrink tubing. During one-gravity or zero-gravity operation the vertical teflon screen covering the windows keeps the volatile droplets from accumulating at the windows, thereby preventing liquid carryover to the carryover indicator and causing a failure shutdown signal. During an

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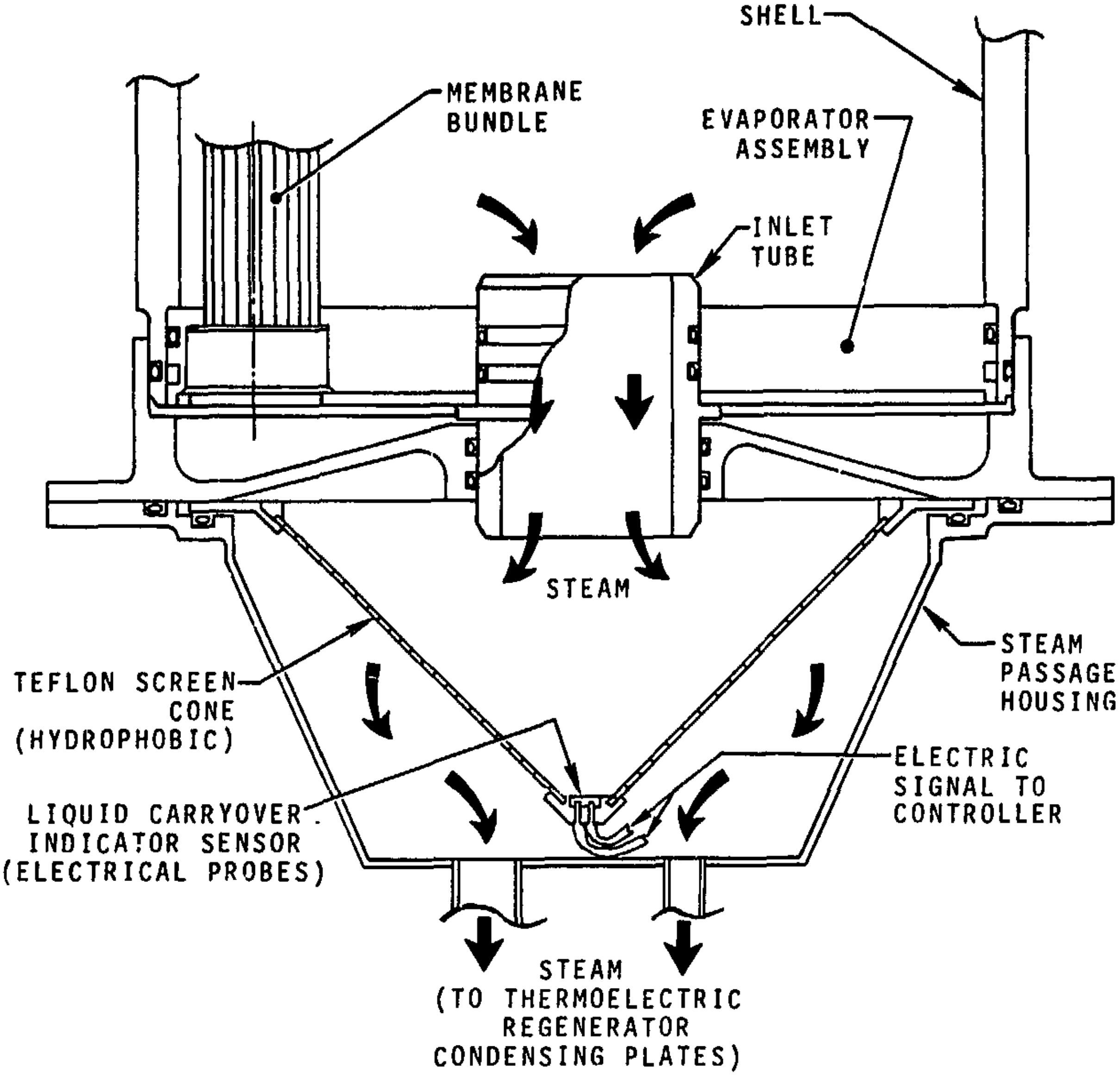

FIGURE 69
ORIGINAL LIQUID TRAP CONFIGURATION

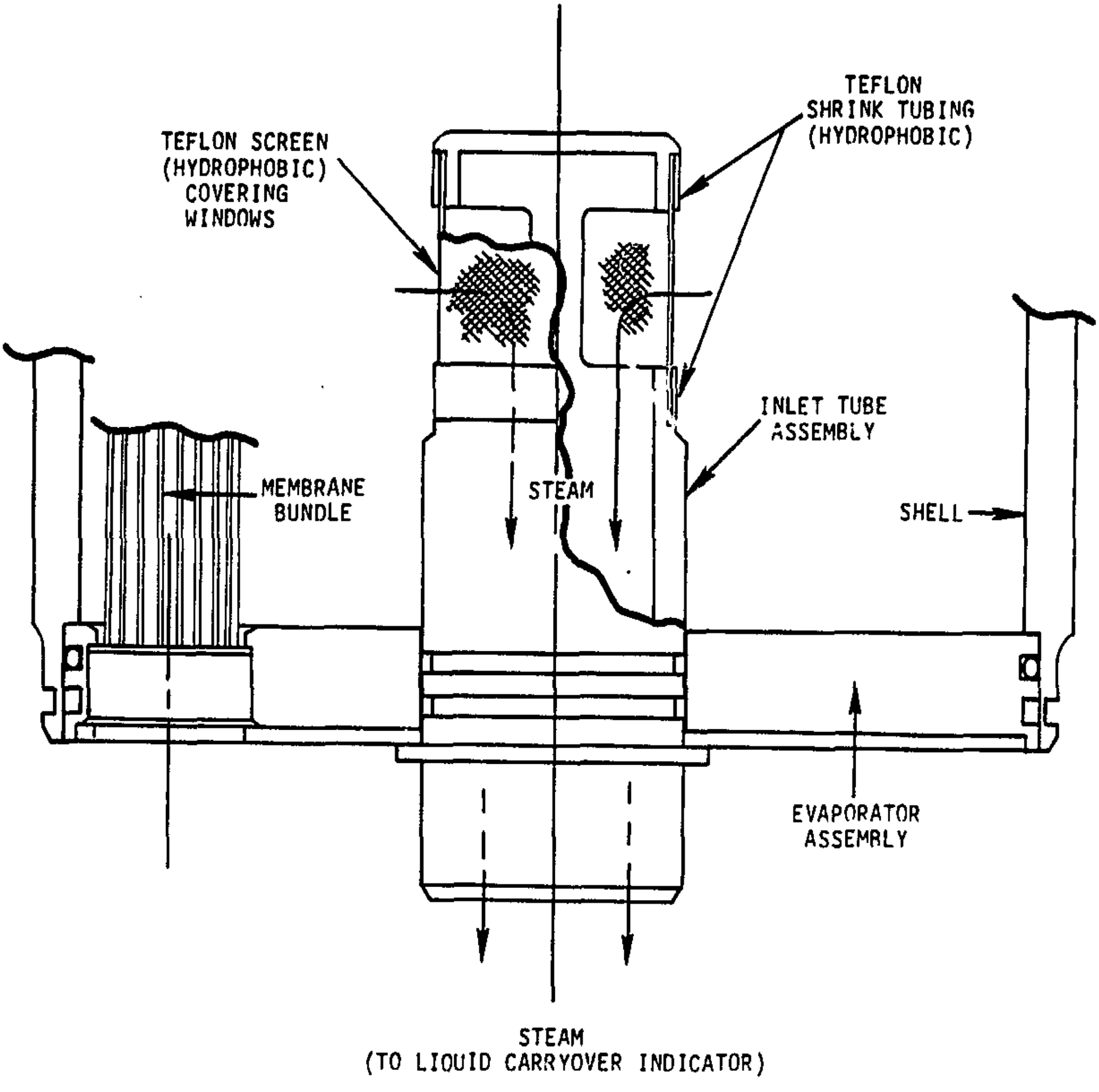

FIGURE 70
IMPROVED LIQUID TRAP CONFIGURATION

actual malfunction when excessive liquid is present in the evaporator shell, small quantities of liquid will be drawn through the teflon window screen when the liquid level is high enough in one-gravity or sufficiently blocks off the screen in zero-gravity to overcome the hydrophobicity of the screen, and will trip the liquid carryover indicator in the teflon screen cone, causing a fail safe failure shutdown. The hydrophobic teflon shrink tubing bands protect the teflon window screen from zero-gravity migration of the liquid to the area of the window screen thereby preventing an unwarranted failure indication. This improved design has been implemented into the TIMES subsystem.

A further desirable feature whose implementation is beyond the scope of this task would be the addition of sensing elements inside the evaporator shell at the base of the inlet tube to sense the presence of a small quantity of liquid in the shell and report its presence. This signal would cause a "white flag" indication, print out a message "liquid in evaporator shell", and print out advice "no corrective action required". When the liquid disappeared as it would during normal operation, the white flag and messages would disappear. If the liquid did not disappear within 30 minutes of start-up, the white flag would change to a yellow flag and the advice message would change to "check for liquid leak". At that point the operator could opt to shut down the subsystem if the liquid quantity in the evaporator shell kept increasing, and replace the maintainable evaporator assembly.

IMPROVED TEMPERATURE CONTROL

Objective

The original TIMES subsystem utilizes a large passively air-cooled heat exchanger to remove the excess heat generated by the process. The objective of this task is to determine and evaluate means to reduce the size or eliminate the need for this heat exchanger.

Background

In the TIMES process, the heat required to vaporize the urine in the evaporator is drawn from the urine flow in the recycle loop. This heat is then recovered and pumped back to the recycle loop as the purified steam condenses on the porous plates in the TER. In addition to the process heat which is conserved, there is heat addition due to the power required by the heat pump and by the fluid pumps. In addition, there is heat leak from the hot recycle loop. Since the heat leak and the valve and fluid pump powers balance, there must be heat rejection from the subsystem equivalent to the power consumed by the thermoelectrics. This varies from approximately 132 W (450 Btu/h) at 26.5 VDC to 205 W (700 Btu/h) at 31 VDC. In the baseline TIMES, heat rejection is accomplished by recirculating condensate through an external air-cooled heat exchanger and back to the condenser section. This cooling circulation flow is varied to maintain a 65.6°C (150°F) inlet temperature to the HFM. The external heat exchanger is cooled by either cabin circulation or natural convection, since the air velocities associated with either are approximately 0.13 to 0.20 m/s (25 to 40 ft/min). However, these low velocities result in poor heat transfer coefficients requiring approximately 3.25 m^2 (35 ft^2) of heat transfer area to reject the 205 W (700 Btu/h) through 28°C (50°F) temperature difference. The large natural convection cooled heat exchanger is unwieldy from a packaging point of view, contains a large liquid hold-up volume, and has inherent long time constants. To simplify the operating and packaging considerations associated with the cooling scheme, it is desirable to determine and evaluate attractive alternates. It is the object of this study to do that evaluation.

Results

As part of the trade study, eight different temperature control options were evaluated. These are described and evaluated briefly in Table 26. The evaluation was based on the predicted specific energy required for each concept and on general operating considerations. Tables 27 and 28 define the parameters in the specific energy calculations at 26.5 and 29.0 VDC respectively. As a result of this study, there are several system options that require further activity. The primary candidate for temperature control is using a fan and reduced size heat exchanger combination in place of the present natural convection unit. This results in a much smaller unit with only a very small increase in specific energy. A second candidate offers the potential of greatly simplifying the subsystem. In this technique, defined as Option 8 (Fixed Steam Pressure), the temperature and pressure controls are eliminated and the temperature is allowed to float. A third candidate defined as Option 7 (Modulated Suction Pressure)

Table 26
TEMPERATURE CONTROL OPTIONS

Option No.	Title	Description	Specific Energy (W-h/lb) W-h/kg 26.5 VDC	Specific Energy (W-h/lb) W-h/kg 29.0 VDC	Comments	Decision
1	Baseline-Convector	. Liquid Cooling Pump . Large Natural Convection HX	(70.7) 155.5	(76.2) 167.6	. Large HX unwieldy. . Not truly 0-G configuration unless Fan is added.	EVALUATE ALTERNATES
2	Cold Side Recirculation Fan Assist	. Liquid Cooling Pump (variable speed) . Air/Liquid HX . Fan	(72.8) 160.2	(78.5) 172.7	. Small HX/Fan assembly insensitive to g or cabin circulation. . High Confidence . Special HX Design	PRIMARY CANDIDATE - Low Specific Energy - Minimum Vapor Lock Potential - High Confidence
3	Hot Side Fan Cooled	. Eliminate Liquid cooling loop. . Baffle hot side and install fan (variable speed).	(79.3) 174.5	(86.7) 190.7	. Simple	UNDESIRABLE AS PRIMARY CANDIDATE - High Specific Energy
4	Ducted TER	. Eliminate liquid cooling loop. . Duct air through TER . Variable Speed Fan	(86.4) 190.1	(93.8) 206.4	. High Air Pressure Drop	REJECT - High Specific Energy
5	Finned TER	. Eliminate liquid cooling loop. . Add two air-cooled condensing passages to TER . Variable Speed Fan	(71.1) 156.4	(76.6) 168.5	. Difficult Thermal Design of TER (adjacent hot and ambient temperature passages)	GOOD POTENTIAL FOR SECOND GENERATION HARDWARE New Hardware Required
6	Vented Steam Cavity	. Eliminate liquid cooling loop. . Burper valve in line from steam cavity to accumulator. . Fan/HX in burp line.	(72.0) 158.4	(77.3) 170.1	. Accumulator and pump must accept non-condensable gas. . Reduces flow through porous plate. . Eliminates filtration due to porous plate.	REJECT - Porous Plate Phase Separation Desirable

Table 26 (Continued)
TEMPERATURE CONTROL OPTIONS

Option No.	Title	Description	Specific Energy (W-h/lb) W-h/kg 26.5 VDC	Specific Energy (W-h/lb) W-h/kg 29.0 VDC	Comments	Decision
7	Flashing Condenser	. Eliminate liquid cooling loop. . Pulser valve in parallel with capillary. . Fan/HX in condensate line.	(72.0) 158.4	(77.3) 170.1		TEST AND EVALUATE - Low Specific Energy
8	Fixed Condensate Package Pressure	. Eliminate liquid cooling loop. . Eliminate capillary . Eliminate active temperature control. . Fan/HX in condensate line.	(73.7) 162.1	(80.3) 176.7	. System temperature floats. . Requires development . Extremely simple . Low production rate	TEST AND EVALUATE - Low Specific Energy

Table 27
SPECIFIC ENERGY AT 26.5 VDC

Option	1	2	3	4	5	6	7	8
Power (watts)								
TFR	140	140	140	140	140	140	140	140
Recirculation Pump	20	20	20	20	20	20	20	20
Cooling Pump	4	4	---	---	---	---	---	---
Fan	---	5	5	30	5	5	5	5
Valves	---	---	---	---	---	2	2	---
Total Power	164.00	169.00	165.00	190.00	165.00	167.00	167.00	165.00
Production kg/h Production (pph)	1.05 (2.32)	1.05 (2.32)	0.94 (2.08)	1.00 (2.20)	1.05 (2.32)	1.05 (2.32)	1.05 (2.32)	1.02 (2.24)
Specific Energy W-h/kg Specific Energy (W-h/lb)	155.50 (70.70)	160.20 (72.80)	174.50 (79.30)	190.10 (86.40)	156.40 (71.10)	158.40 (72.00)	158.40 (72.00)	162.10 (73.70)

Table 28
SPECIFIC ENERGY AT 29.0 VDC

Option	1	2	3	4	5	6	7	8
Power (watts)								
TER	165	165	165	165	165	165	165	165
Recirculation Pump	25	25	25	25	25	25	25	25
Cooling Pump	5	5	---	---	---	---	---	---
Fan	---	6	6	35	6	6	6	6
Valves	---	---	---	---	---	2	2	---
Total Power	195.00	201.00	196.00	225.00	196.00	198.00	198.00	196.00
Production kg/h	1.16	1.16	1.03	1.09	1.16	1.16	1.16	1.11
Production (pph)	(2.56)	(2.56)	(2.25)	(2.40)	(2.56)	(2.56)	(2.56)	(2.44)
Specific Energy W-h/kg	167.60	172.70	190.70	206.40	168.50	170.10	170.10	176.70
Specific Energy (W-h/lb)	(76.20)	(78.50)	(86.70)	(93.80)	(76.60)	(77.30)	(77.30)	(80.30)

also eliminates the liquid cooling loop but does provide thermal control. The condensate removal suction pressure is controlled as a function of HFM inlet temperature using a variable rate pulsating valve in the condensate removal line, thereby regulating the quantity of product water removed directly as steam. A fourth candidate defined as Option 5 (Finned TER) also eliminates the cooling loop. Temperature control is obtained by adding condensing sections to the TER. These condensing sections are cooled by forced airflow rather than by thermoelectric cold junctions. The forced airflow is modulated as a function of HFM inlet temperature. The hardware modifications required for this option regulate it to a second generation hardware category.

Except for the primary candidate, these candidates all require test evaluation before they can be considered viable.

Discussion

In general, the potential cooling schemes for the TIMES can be grouped into three classifications:

1. Cooling of the hot side urine recycle loop
2. Cooling of the cold side condenser loop
3. Removing the heat as steam in the product water and condensing it externally.

Each of the three basic schemes were used as baseline for defining eight operating options. Each of these options was evaluated based on both specific energy consumption and on operating considerations. A performance computer program was utilized to evaluate the throughput for each and thereby calculate the specific energy. In general, specific energy considerations will favor the second and third scheme defined above. Both of these remove heat either on the cold side of the TER or in an external condenser. Specific energy will be higher for any concept which utilizes heat rejection on the hot side of the TER. For hot side heat rejection the excess heat must be pumped by the thermoelectrics up to the higher temperature recycle loop. A power penalty must be paid for pumping this excess heat.

A detailed discussion of each of the eight options follows. Table 26 summarizes the options and Tables 27 and 28 define the specific energy at 26.5 and 29.0 VDC for each one of the options. In general, at 29 VDC the production rate is higher than at 26.5 VDC, but the power penalties increase at a faster rate.

Option 1 - Baseline-Convector-Figure 71

In the baseline TIMES thermal control configuration, the condensed product liquid is recirculated through an external heat exchanger to achieve the required heat rejection. The recirculation flow is modulated to maintain the required temperature control. Modulation is achieved by pulsing the recirculation pump. The external heat exchanger is cooled by either natural convection in the earth gravity environment or by forced air cabin circulation in the spacecraft. For either one of these design points, the air velocity is in the order of 0.13 to 0.20 m/s (25 to 40 ft/min). The low heat transfer coefficients result in a large heat exchanger with a face area 45.7 cm (18 in) by 76.2 cm (30 in) and a fin depth of 5.1 cm (2 in). These fins are welded to a backing

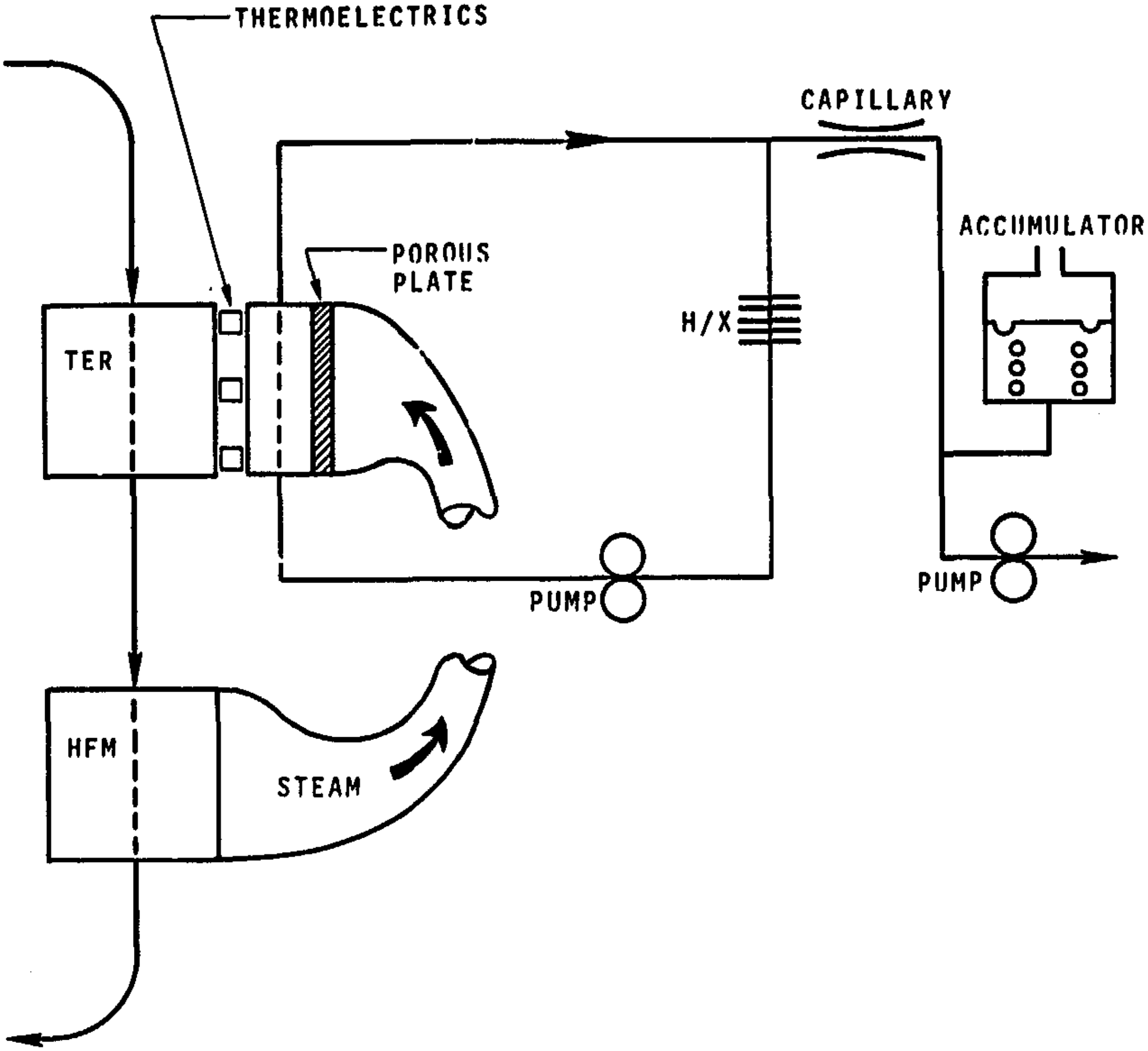

FIGURE 71

OPTION 1
BASELINE CONVECTOR

plate upon which a serpentine tube carries the recirculation flow. The large heat exchanger and the low condensate flow rate result in long fluid transport times through it. With the pulsed fluid pump approach, the flow advances through the tubing approximately 10 percent with each pulse. This results in control system operating difficulties and the potential of vapor lock in the heat exchanger. This concept works but an alternate is desirable. One alternate considered initially was to use the existing package surfaces and/or the water tank surfaces for heat rejection. However, this would still require high surface temrpatures approximately 48.9°C (120°F), and large surface areas, approximately 3.25 m^2 (35 ft^2). The recirculating cooling flow does, however, contain an advantage in that it tends to sweep out non-condensable gas from passages that would otherwise have to be drawn out with the condensate. As summarized in Table 26, this option exhibits the lower specific energy of any of the alternates, but the packaging and operating characteristics make it wise to seek alternates.

Option 2 - Cold Side Recirculation - Fan Assist - Figure 72

This option is quite similar to the Option 1 baseline except that forced air cooling is utilized in the external heat exchanger. A small low power 1 m^3/min (35 ft^3/min) fan is close coupled to the heat exchanger to provide the convection. By utilizing forced air, there is a heat exchanger size reduction of greater than 10:1 from a face area of 45.7 cm (18 in) by 76.2 cm (30 in) to a face area 17.8 cm (7 in) by 17.8 cm (7 in). This size reduction should eliminate some of the development problems encountered in the baseline system. However, it maintains the advantages of liquid recirculation in the condensate passages. Furthermore, since the package contains its own cooling fan, it is not dependent on cabin circulation or placement. Temperature control can be achieved by the recirculation pump flow. Since this concept is identical to the configuration tested except for the means of removing heat from the air side, there is a very high confidence in this concept's success. Furthermore, with a low cooling airflow, 1 m^3/min (35 ft^3/min) and a low pressure rise 0.5 cm (0.2 in) of water, the low power consumption (5 watts) results in a low specific energy. The only disadvantage to this concept is that due to the low condensate cooling flow rate, a non-standard heat exchanger will be required. This heat exchanger would be a typical spacecraft design but would be relatively expensive for a development program. In summary, since this concept exhibits low specific energy and minimum technical risk, it is the primary candidate for thermal control of the TIMES.

Option 3 - Hot Side Fan - Cooled - Figure 73

In this approach cooling is accomplished by forcing ambient air circulation over the hot surface of the recycle loop. A 1 m^3/min (35 ft^3/min) fan is included to provide the airflow, and baffles are provided to direct the flow over the hot surfaces of the recycle tank. The 65.6°C (150°F) temperature control is achieved by varying the fan flow inresponse to the temperature sensor at the HFM inlet. Flow variation can be achieved utilizing either a variable speed fan or by pulsing a single speed fan. This concept exhibits high specific energy because the TER must pump the excess heat as well as the process heat. With the elimination of the cooling recirculation loop, there is no flow to clear potential non-condensable gas pockets from the pin fin area behind the condenser porous plate. Although it is a simple concept, the high specific energy renders this concept undesirable as a primary candidate.

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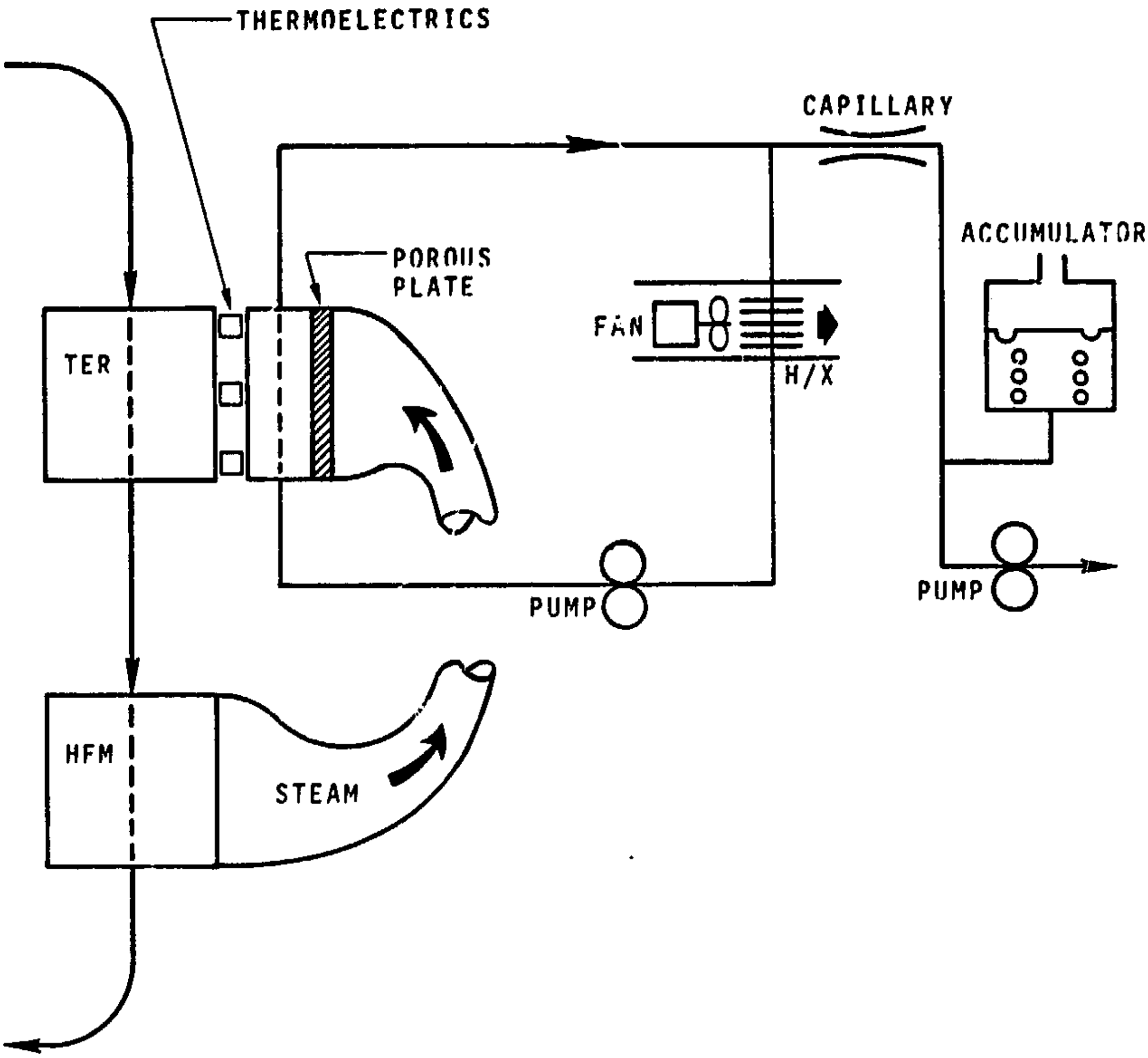

FIGURE 72

OPTION 2
COLD SIDE RECIRCULATION--FAN ASSIST

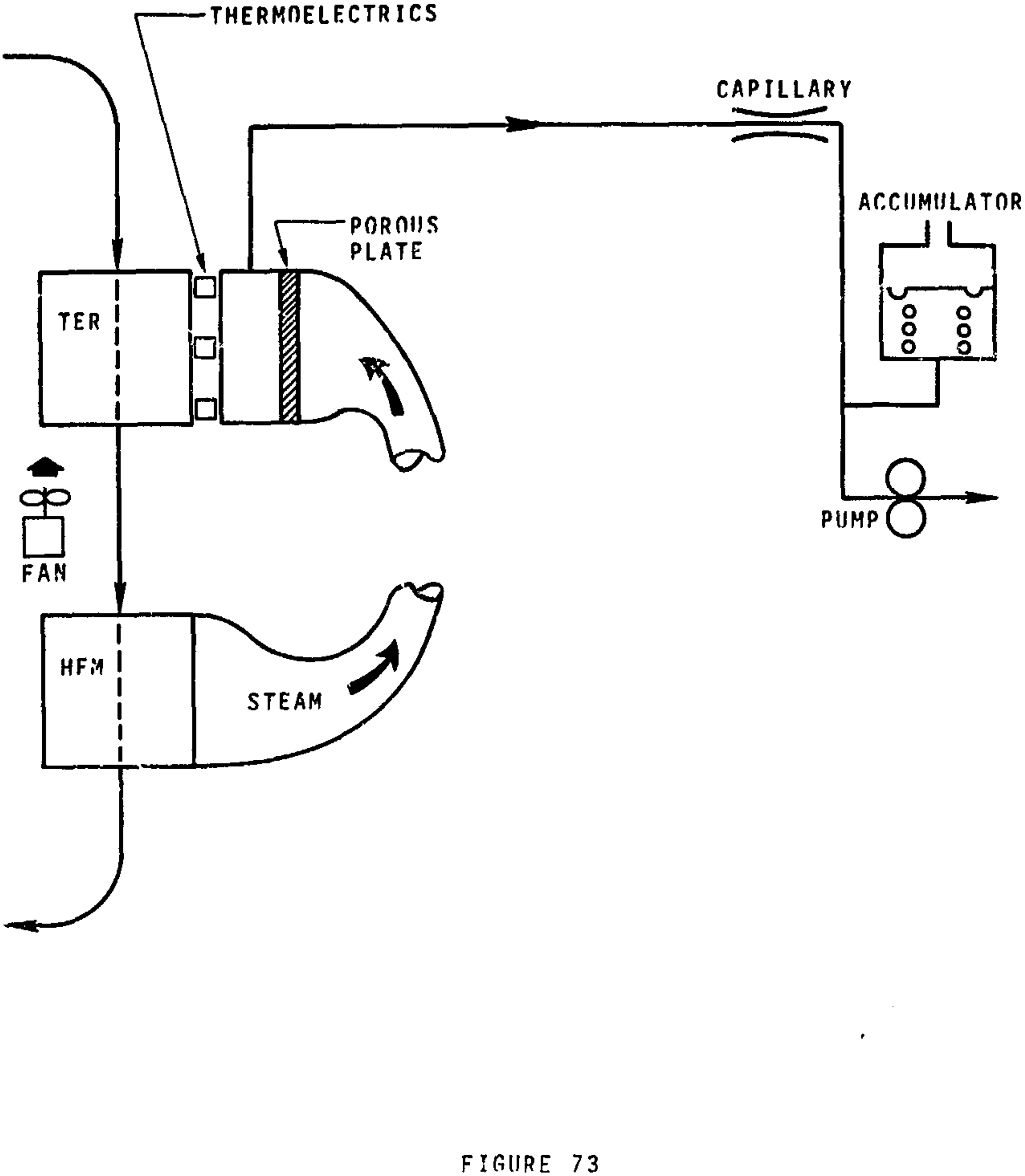

FIGURE 73

OPTION 3
HOT SIDE FAN COOLED

Option 4 - Ducted TER - Figure 74

This approach is very similar to Option 3 in that it uses forced air to cool the process package elements. HFM inlet temperature is controlled by varying the cooling airflow. In this concept the fan blows the ambient air through the exposed TER surfaces in an effort to achieve some cold side cooling. A duct from outside the insulated package enters the package and encases the TER before exiting back to ambient. Thus the air flows between the individual thermoelectric elements providing direct cooling at the energy source. A high heat transfer efficiency is achieved because the thermoelectric elements expose a large surface area to the air stream. However, this configuration also yields the biggest negative feature, namely, a high pressure drop. Utilizing the lowest possible flow, 0.43 m^3/min (15 ft^3/min) pressure drop, 12.7 cm (5 in) of water results in a fan power consumption of 30 watts. This yields a quite high specific energy, and for this reason the concept is rejected.

Option 5 - Finned TER - Figure 75

In this concept two additional condensing sections would be added to the TER. Instead of being mated to thermoelectric elements, these condensing sections would have external fins which extend through the package insulation for air cooling. An external variable speed fan would provide variable flow rate over these fins to achieve modulated temperature control. Although this approach exhibits a very low specific energy, it is a relatively complicated thermal design and would require substantial modification to existing hardware. The complication results from the steam cavity thermodynamics with two different sink temperatures in the same vapor cavity. Since steam will preferentially condense on the coldest surface, there is a very strong tendency for an imbalance in the steam flow to each of the sections. This concept exhibits low specific energy but further evaluation is required to develop an acceptable confidence level.

Option 6 - Vented Steam Cavity - Figure 76

As opposed to the previous approaches, which provide direct cooling of either the hot or cold side of the TER, this and the following approaches utilize a different technique. They remove energy from the TER/HFM assembly in the form of live steam which is condensed in the product water delivery line external to the central processing package. The flow rate of steam which is condensed externally is modulated to balance the excess heat generated by the heat pump. In these concepts a mixture of live steam at the steam cavity saturation conditions is drawn from the TER in parallel and mixed with liquid product water. This mixture then flows through an air-cooled heat exchanger and condenses before continuing on to the product water accumulator. For each one of these concepts, a 1 m^3/min (35 ft^3/min) fan provides the forced air convection through the external heat exchanger. In this particular approach (Option 6), live steam is vented directly from a steam cavity upstream of the porous plate to the product water line downstream of the capillary tube. The combined flow then enters the condensing heat exchanger. Pressure control in the condensate passages is achieved by the self-regulating capillary tube approach. A pulsed burper valve in the steam line modules the steam flow withdrawal rate to maintain HFM inlet temperature control. This is a simple approach with a lower specific energy. By bypassing flow from the steam passages around the porous plate, non-condensable

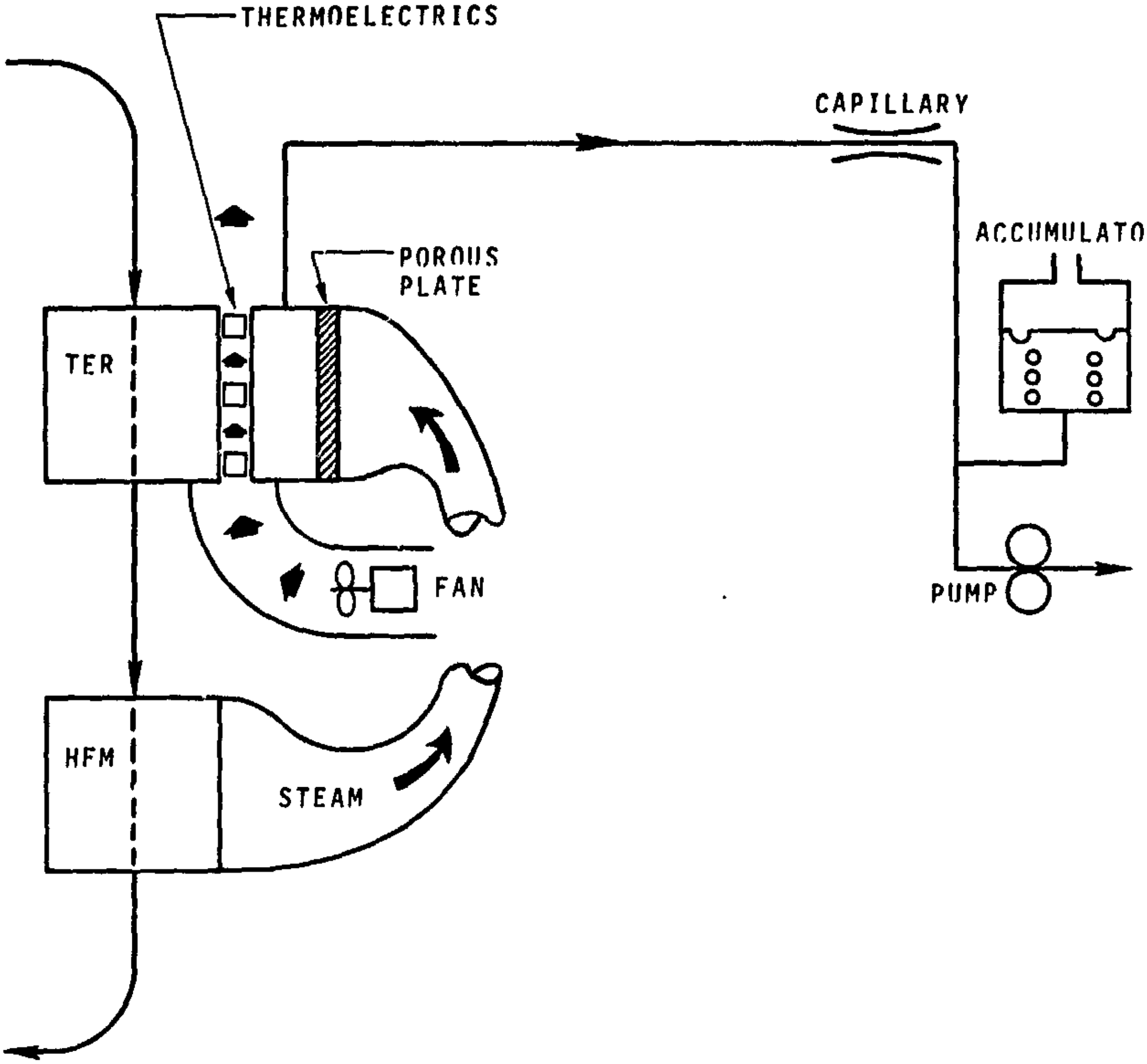

FIGURE 74
OPTION 4
DUCTED TER

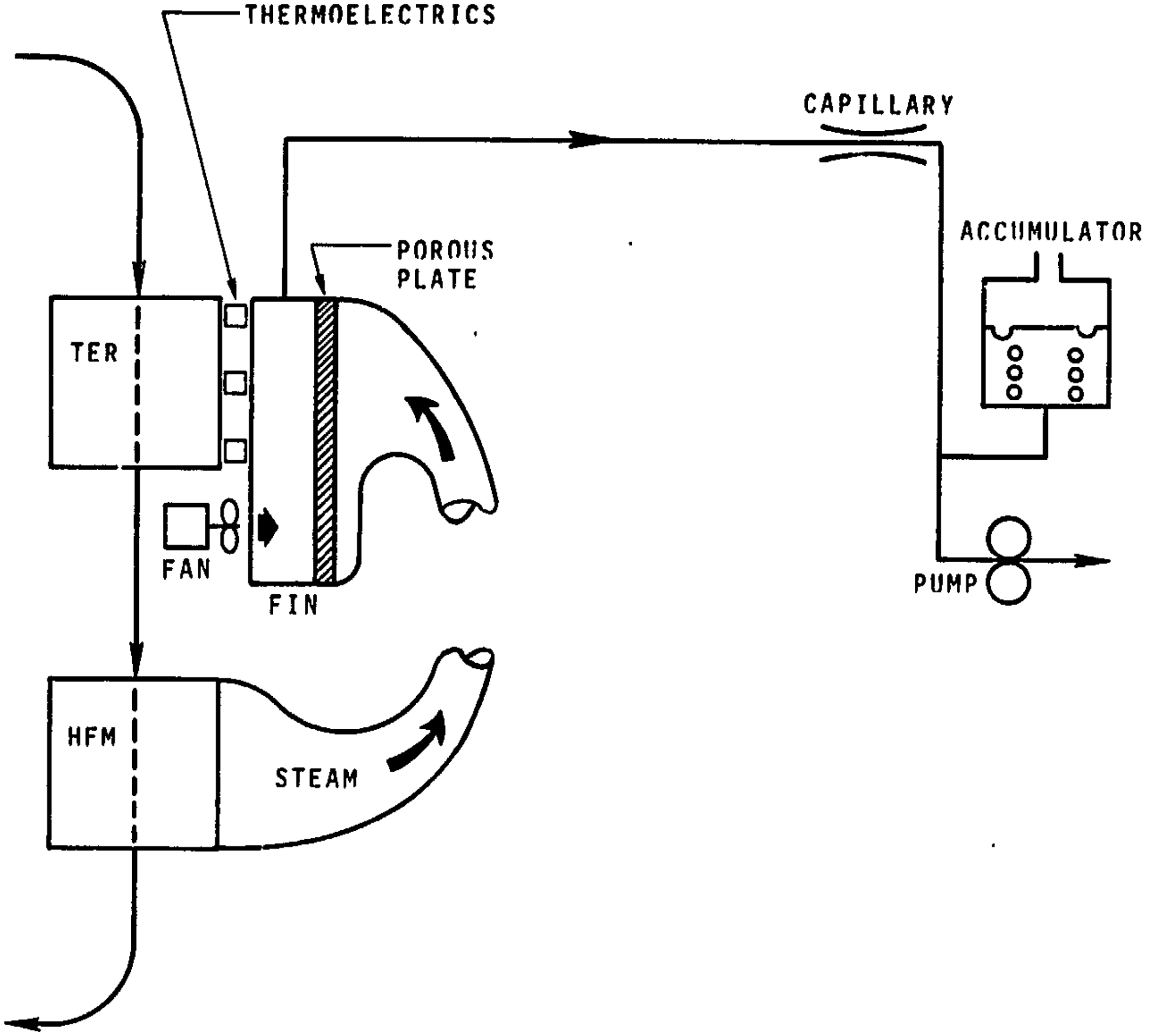

FIGURE 75

OPTION 5
FINNED TER

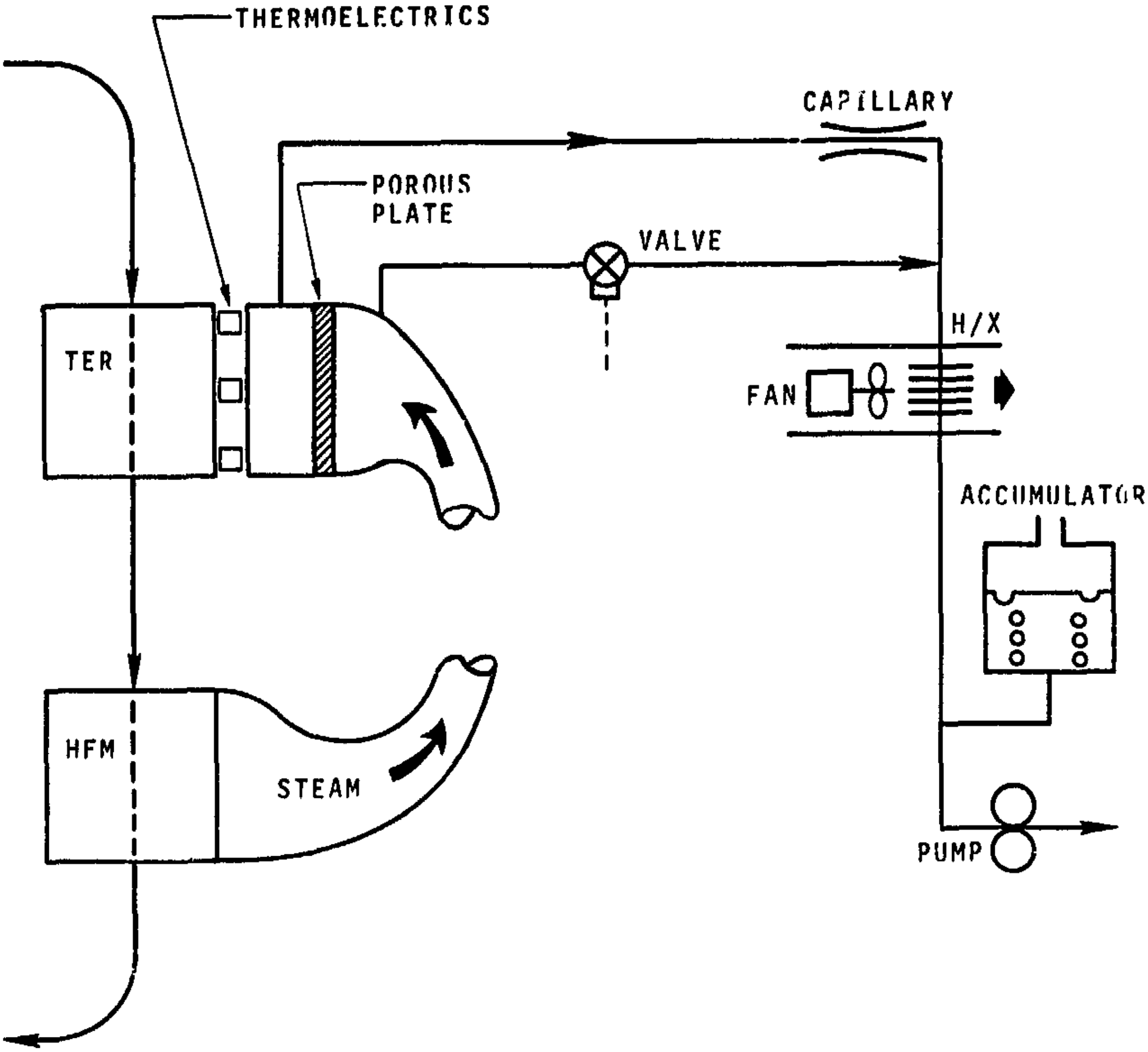

FIGURE 76

OPTION 6
VENTED STEAM CAVITY

gases that would otherwise be "burped" overboard are passed through to the condensate line eliminating the positive phase separation at the porous plate. Thus the accumulator and the pump must be designed to accommodate non-condensables. This is undesirable and would cause error in the current quantity measuring approach. For these reasons and in particular for the desire that the porous plate be utilized to achieve phase separation, this concept is rejected.

Option 7 - Flashing Condenser - Figure 77

This approach is quite similar to Option 6 except that the pusling valve is located downstream of the porous plate in parallel with the capillary tube. When the steam valve pulses open, it momentarily reduces water pressure under the porous plate causing a portion of the condensate in the condenser to flash. It thus causes evaporative cooling of the condenser. The steam valve pulsing frequency would be modulated to maintain HFM inlet temperature control. Although the steam cavity pressure would momentarily drop during the valve pulsing the capillary tube would provide pressure control during the period when the control valve is closed. Since the percentage of valve open time is quite small, effective pressure control during the period when the control valve is closed. Since the percentage of valve open time is quite small, effective pressure control would be achieved by the capillary tube. The low specific energy and simplicity of this concept makes it desirable. Further testing is required to fully evaluate this temperature control scheme.

Option 8 - Fixed Condensate Passage Pressure - Figure 78

Similar to Option 7, this approach achieves cooling by venting energy in the form of steam from behind the porous plate in the condenser. However, it is markedly different in that it eliminates the capillary pressure control and the precise HFM inlet temperature control. With the capillary tube eliminated, the pressure in the condenser and in the steam cavity will equal the accumulator pressure of 13.1 to 15.8 kPa (1.9 to 2.3 psia). This will then set the TER temperature at 51.1 to 55°C (124 to 131°F). The hot side urine temperatures will then be allowed to float in response to variations in voltage and solids concentration. At the minimum accumulator pressure condition of 13.1 kPa (1.9 psia) and with a 26.5 VDC voltage input and fresh urine in the recycle loop, the HFM inlet temperature will settle out at 57.2°C (135°F). Under the worst combination of voltage, 31.5 VDC, and solids concentration 40%, the maximum HFM inlet temperature would be 68.3°C (155°F). As can be seen in Tables 27 and 28, the low temperature 57.2°C (135°F), is not so low as to seriously impair specific energy. Conversely, since the maximum temperature is less than the 71.1°C (160°F) limit established previously, this is acceptable. This approach is attractive because it greatly simplifies the operating system by eliminating the capillary tube pressure control and the active HFM inlet temperature control. The change in accumulator pressure during the fill cycle will result in saturation temperature changes in the condenser and transient temperature response unknowns in the recycle loop. These unknowns must be fully evaluated by a test program.

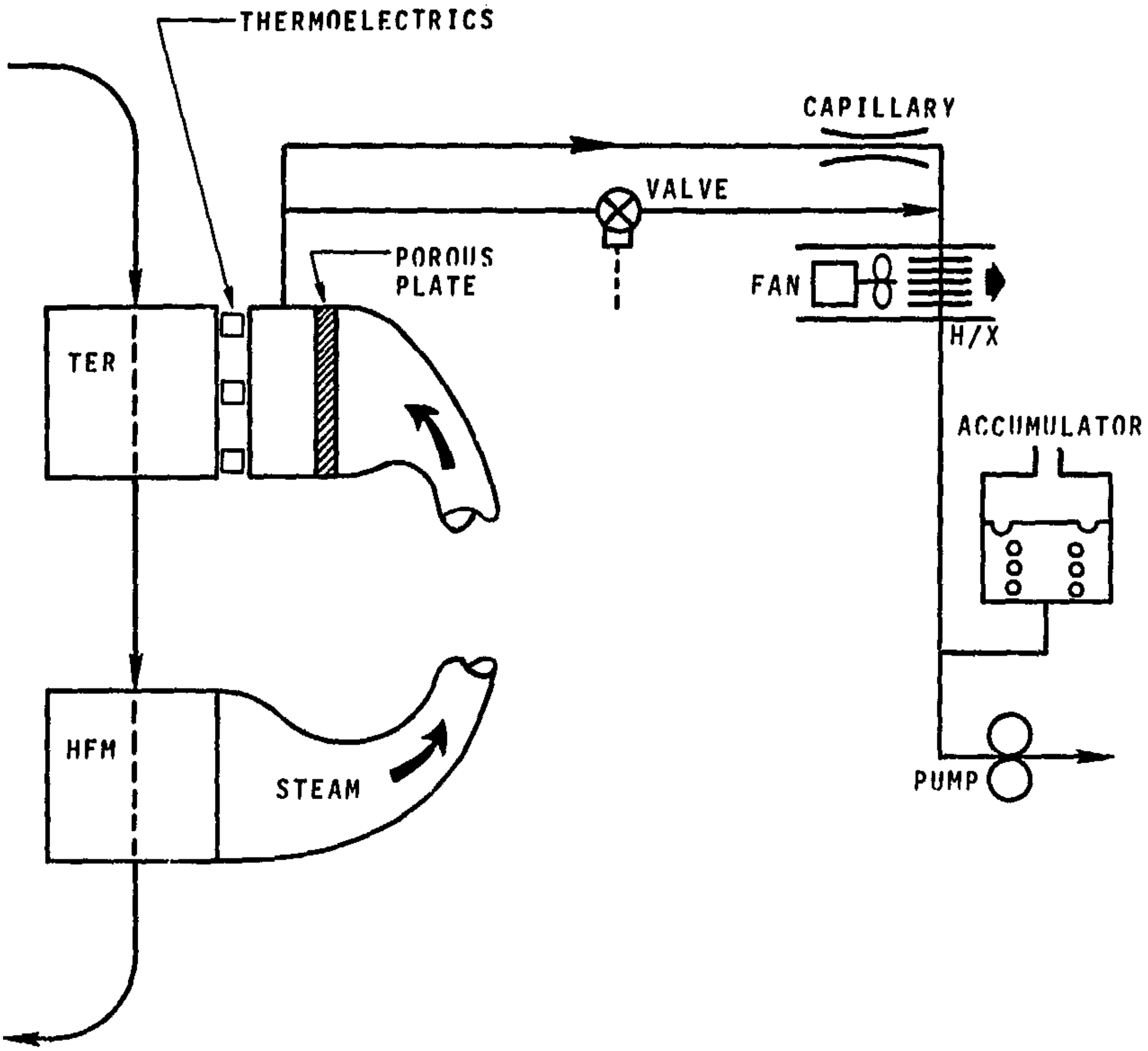

FIGURE 77

OPTION 7
FLASHING CONDENSER

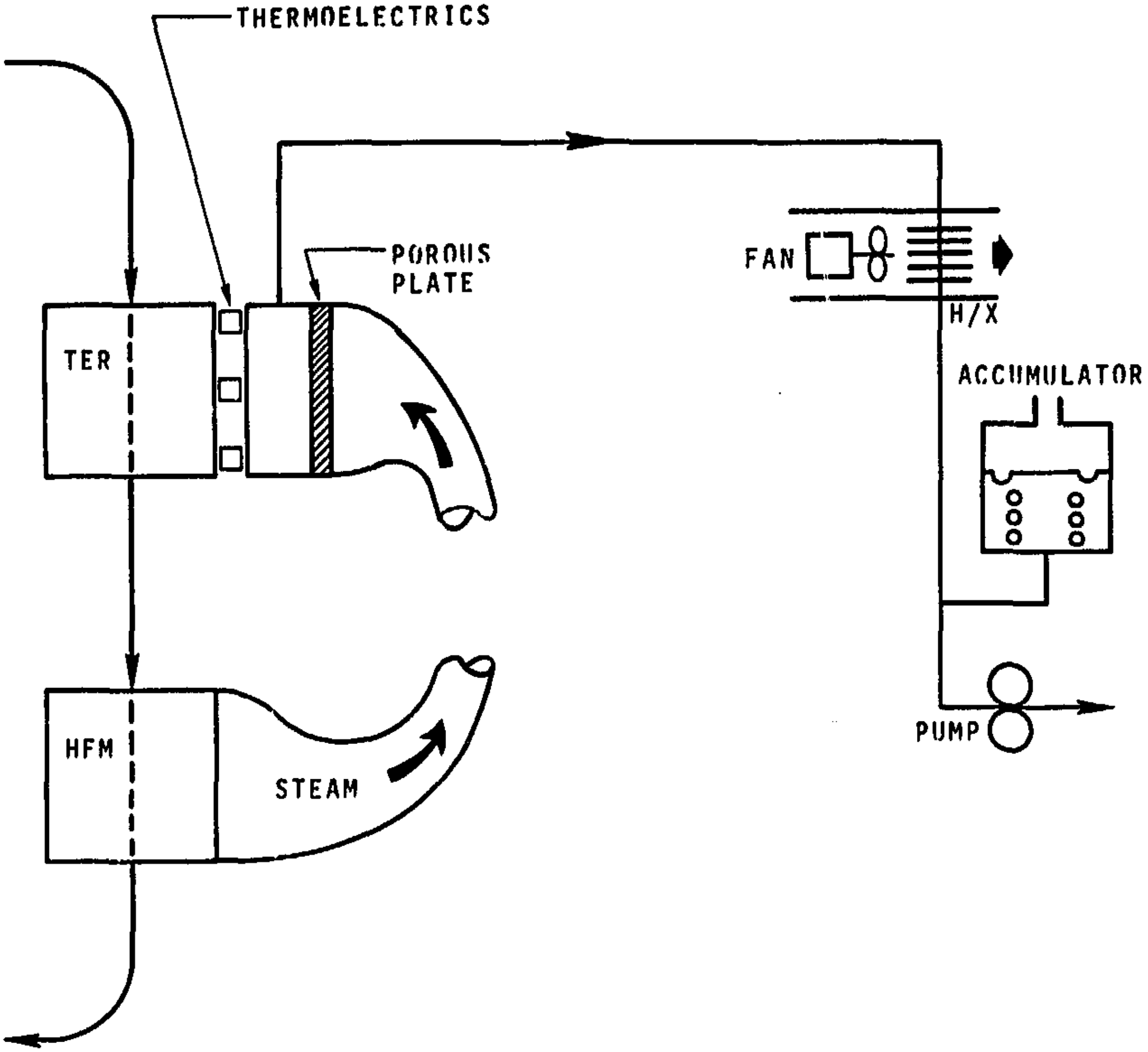

FIGURE 78

OPTION 8
FIX CONDENSATE PASSAGES PRESSURE

SUBSYSTEM DELIVERY

The following hardware was shipped under this contract to NASA/JSC.

TIMES Collection Package Assembly	SVSK 97562
TIMES Process Package Assembly	SVSK 96789
TIMES Controller	SVSK 97811
TIMES Driver Box	SVSK 97812
TIMES Console (GFE Frame)	
CRT	SVSK 103179
Keyboard	SVSK 103178
Floppy Disk Drive	SVSK 103177
Electrical Harness	SVSK 97814

DOCUMENTATION

The following list defines the contract documentation required and the documents submitted in response to the data requirements for this program test by Hamilton Standard.

DRL Item No.	Name	Document
1	Report, Monthly Progress	Submitted Monthly
2	Plan, Program	TIMES-03 dated February 17, 1978
3	Plan, Master Test	TIMES-12 dated August 21, 1978 Supplemented September 9, 1979
4	Report, Final	SVHSER 7236 dated January 1, 1982
5	Technical Information Release	No Reports
6	Report, Financial Management	Not Required
7	Drawings, Engineering and Associated Lists	January, 1982
8	Manual, Familiarization and Operation	SVHSER 7237 dated January, 1982
9	Analysis, Failure Mode And Effect	TIMES-EM-08 dated October 30, 1978
10	Manual, Maintenance and Repair	Combined with DRL Item No. 8
11	Lists, Nonmetallic Materials	TIMES-EM-07 dated October 27, 1978

QUALITY ASSURANCE

The objective of the Quality Assurance Program was to search out quality weakness and provide appropriate corrective actions. Quality assurance considerations were included during the TIMES Water Recovery Subsystem Design, engineering evaluations, procurement and fabrication activities. All vendor-supplied items were checked out and inspected per engineering instructions prior to assembly into the subsystem. Prior to delivery of the hardware, a First Article System Inspection (FASI) was held. The review committee consisted of senior engineering, reliability and quality personnel.

RELIABILITY

The TIMES Water Recovery Subsystem, as concepted, has a high inherent reliability. The TIMES membrane evaporator and thermoelectric regenerator are passive devices.

The urine recycle pump has been extensively tested and will perform as required for a minimum of 90 days continuous operation.

The water quantity measurement and delivery equipment consists of a pump and a calibrated accumulator. The cyclic operation of the accumulator is estimated at 3600 cycles per month. This results in a pump on-time of only 30 hours per month. At this low usage rate, this equipment would not be considered limited life items.

The condensate cooling pump is identical in design to the condensate delivery pump, and the on-time is less than 30 hours per month, so it too is not considered a limited life item.

The Failure Mode and Effects Analysis (FMEA) was completed as a part of this program and submitted to the NASA/JSC.

SAFETY

Safety was a consideration in design of the TIMES Water Recovery Subsystem because of the presence of corrosive liquid waste in the subsystem. During the design of the subsystem, safety was enhanced through simplification, and automatic failure detection and shutdown. The following safety features in the hardware and/or subsystem were incorporated:

1. Two dedicated overtemperature sensors and one pressure sensor to initiate automatic subsystem shutdown.
2. A single failure in one component will not cause successive failures in other components.
3. The controller provides automatic hands-off operation and automatically flushes the subsystem during any shutdown with unconcentrated feed from the waste storage tank.
4. A visual warning is provided during any abonormal condition.
5. All interfaces and connectors are clearly labeled.
6. Circuit breakers are incorporated to protect electrical equipment.
7. In all connectors the hot connector is a female socket.