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PREPROTOTYPE VAPOR COMPRESSION DISTILLATION SUBSYSTEM

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FINAL REPORT

by

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by

Life Systems, Inc.
Cleveland, OH 44122

for

LYNDON B. JOHNSON SPACE CENTER
National Aeronautics and Space Administration

FOREWORD

The development work described herein was conducted by Life Systems, Inc. during the period April, 1977, to May, 1979. The Program Manager was Franz H. Schubert. Technical Support was provided by the following:

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LIST OF ACRONYMS

A/D	Analog/Digital
C/M I	Control/Monitor Instrumentation
CPU	Central Processing Unit
CRT	Cathode-Ray Tube
DARS	Data Acquisition and Reduction System
FMECA	Failure Mode, Effects and Criticality Analysis
OCRS	Oxidizable Contaminant Removal Subsystem
RLSE	Regenerative Life Support Evaluation
RO	Reverse Osmosis
RTE	Real-Time Executive
TSA	Test Support Accessories
VCD	Vapor Compression Distillation
VCDS	Vapor Compression Distillation Subsystem

SUMMARY

A program to design, develop, fabricate, assemble and test a three-person capacity (minimum) preprototype Vapor Compression Distillation Subsystem for the recovery of potable water from wastewater aboard future spacecraft was completed under Contract NAS9-15267.

The Vapor Compression Distillation Subsystem was developed by Life Systems, Inc. to be a completely self-contained subsystem for the processing of the wastewater from a three-person crew. The mechanical hardware dry weight is 143 kg (316 lb), it occupies 0.467 m^3 (16.5 ft^3) and requires 171 W of electrical power.

A computer-based Control/Monitor Instrumentation was included in the Vapor Compression Distillation Subsystem to carry out operating mode change sequences, to monitor and display subsystem parameters, to maintain intramode controls and to store and display fault detection information.

During testing the subsystem recovered potable water at a rate of 1.59 kg/h (3.5 lb/h) which is equivalent to a duty cycle of approximately 30% for a crew of three (including startup and drydown). Conversely, at a 100% duty cycle the subsystem has a 10-person capacity.

The product water was found to have a conductivity of 20 µmhos/cm and no foul taste or odor.

Major components that were designed, fabricated, assembled and tested for the Vapor Compression Distillation Subsystem were a distillation unit which included a compressor, centrifuge, central shaft and outer shell; a purge pump; a liquids pump; a post-treat cartridge and a recycle/filter tank.

Sensors that were designed, fabricated, assembled and tested specifically for the Vapor Compression Distillation Subsystem include the evaporator high liquid level sensor and the product water conductivity monitor.

Vapor Compression Distillation was shown to be an effective process for reclaiming water from wastewater. Continued development of the Vapor Compression Distillation Subsystem is recommended for reclaiming water for human consumption as well as for flash evaporator heat rejection, urinal flushing, washing and other on-board water requirements.

PROGRAM ACCOMPLISHMENTS

The following significant accomplishments were realized at the conclusion of the Vapor Compression Distillation Subsystem development program.

- Successfully developed a completely integrated Vapor Compression Distillation Subsystem

- Surpassed design water production rate goal - 1.59 kg/h (3.5 lb/h) versus 1.36 kg/h (3.0 lb/h)

- Demonstrated a low friction distillation unit (5.66 in-oz, equivalent to 13 W for the distillation unit at 3,200 rpm)
- Demonstrated a durable timing gear design through eight days of uninterrupted operation
- Demonstration of automated process control and monitoring
- Demonstration of leak-free dynamic seal which permits direct drive to the compressor
- Development of a low power consuming fluids pump - 24 W
- Development of extended peristaltic pump tubing life - 6×10^7 cycles demonstrated
- Demonstration of a durable liquid level sensor which yielded reliable evaporator liquid level data
- Demonstration of a radial flow demister which eliminates the need for a dynamic seal between the central shaft and the demister
- Development of a Math Model computer simulation program

INTRODUCTION

For relatively short duration space missions, on-board water requirements can be met with fuel cell byproduct and/or stored water. As mission length increases and other power sources (i.e., solar) are used, it will become necessary to reclaim water from on-board generated wastewater. Vapor Compression Distillation (VCD) has been shown to be a low specific energy consumption technique for accomplishing water recovery from waste, specifically urine and wash water brine.

The objective of this program was to develop a three-person capacity (minimum) preprototype Vapor Compression Distillation Subsystem (VCDS) for the recovery of potable water from wastewater aboard future spacecraft. The VCDS is located between the various spacecraft wastewater sources and the spacecraft potable water stores. Its function is to recover water (1) as part of the Regenerative Life Support Evaluation (RLSE) and (2) to evolve water recovery technology for future long-duration multi-crew missions. The subsystem hardware, resulting from the effort described herein, will be combined with other regenerative life support elements to comprise an integrated preprototype subsystem. This integrated system is scheduled for testing by National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) prior to the procurement of prototype hardware, which is scheduled for evaluation in a manned 30-day test potentially followed by a Spacelab flight in 1983. The objective of such a flight evaluation will be to demonstrate the operational readiness of the VCDS concept while operating as part of an integrated Regenerative Life Support System.

Background

NASA has developed the VCD technique to the point where the ability to produce potable water from urine and waste rinse water with a very low expenditure of energy has been demonstrated. Under Contract NAS9-1680, the Marquardt Corporation developed and characterized the major components of the distillation unit, i.e., the boiler, condenser and compressor of the still. Under Contracts NAS9-13714 and NAS9-14234, Chemtric, Inc. developed a subsystem which produced water at 0.73 kg/h (1.6 lb/h) with an energy expenditure of 220 w-h/kg (100 w-h/lb).

Recent efforts with Lockheed Missiles & Space Co., Inc. under Contract NAS9-15136 and Life Systems, Inc. (LSI) under Contract NAS9-15267, have been directed towards automating the process and evolving a low power, maintainable system suitable for long-term operation aboard a spacecraft. Additional development work was required on auxiliary components such as the purge pump and fluids pump, waste fluid pretreatment, the Control/Monitor Instrumentation (C/M I) and, to a lesser extent, the waste storage tank.

Life Systems advanced the development accomplishments of contract NAS9-14234 by designing, fabricating, assembling and testing a self-contained, preprototype VCDS shown in block diagram form in Figure 1. The LSI VCDS is capable of recovering water from urine as well as Reverse Osmosis (RO) brine at 1.6 kg/h (3.5 lb/h) with an energy expenditure of 107 W-h/kg (49 W-h/lb). The subsystem is capable of accepting both pretreated urine and urinal flush water as well as RO brine, although the present test program did not have provisions for experimentation with the latter.

Program Objective

The objective of this program was to develop a three-person (minimum) preprototype VCDS. The VCDS would interface between the various spacecraft wastewater sources and the spacecraft potable water stores.

This development included solving the following problems identified at the start of the activities:

1. Process control and monitoring
2. Fluids pump endurance
3. Gas leakage into the still
4. Still and transducer corrosion

Program Organization

An eight-task program was undertaken to achieve the program objective. These eight tasks were:

1. Design, develop, fabricate and assemble a fully operational preprototype VCDS. The VCDS was designed to be compatible with the RLSE and was sized to meet operational life time for individual components and the overall preprototype life of six months while operating at the design conditions. It is anticipated that this operating life will be achieved within two years of hardware delivery to JSC.

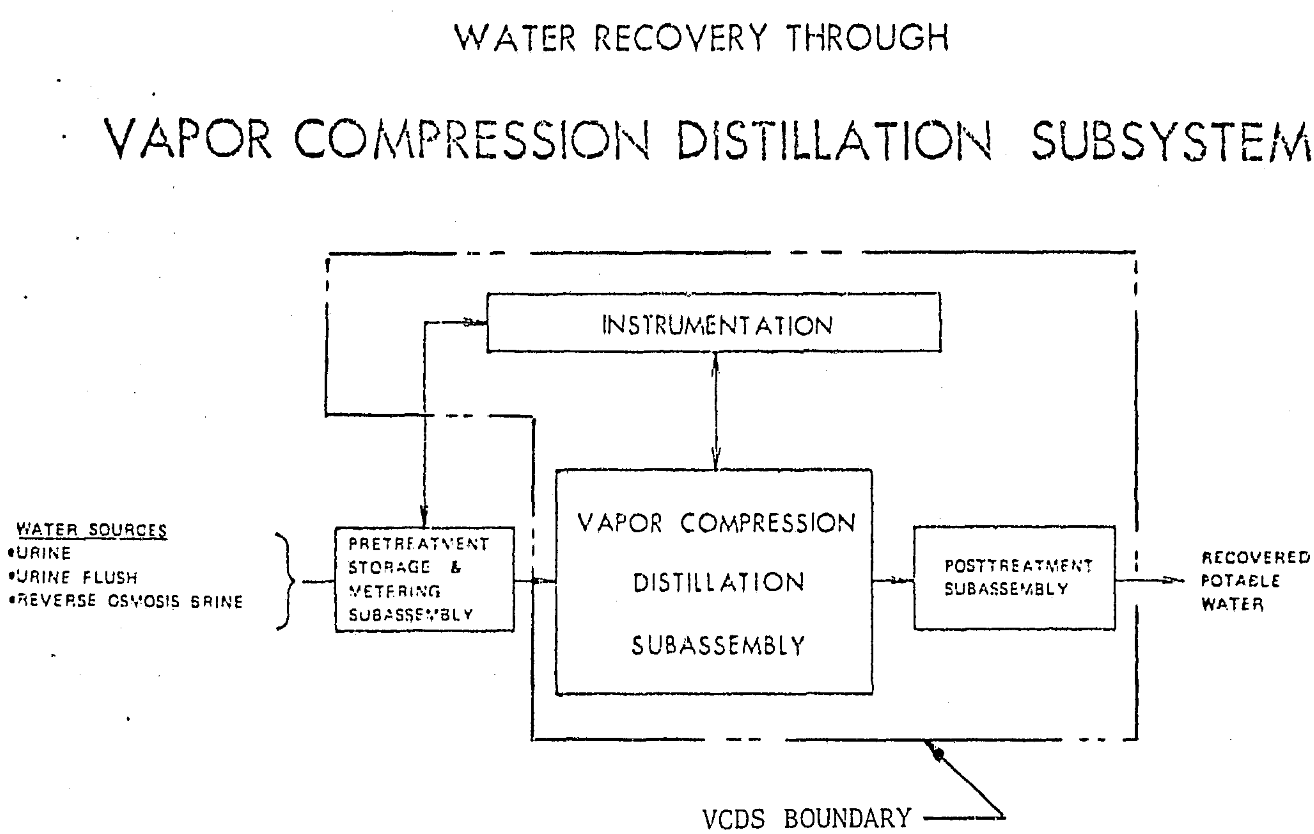


FIGURE 1 VCDS WATER RECOVERY PROCESS BLOCK DIAGRAM

2. Design, develop, fabricate, assemble, functionally checkout and calibrate, as appropriate, Test Support Accessories (TSA) to be compatible with the test objectives of the supporting research and development testing, preprototype component bench tests and preprototype tests. These activities included the following:

   a. Test stands for the supporting Research and Development (R&D) effort.
   b. Preprototype component and subassembly test stands.
   c. Preprototype VCDS test stand.

3. Establish, implement and maintain a mini-Product Assurance Program throughout all phases of contractual performance, including design, fabrication, testing and delivery.

4. Perform preprototype/subassembly bench testing of the instrumentation subassembly, purge pump and fluids pump. This task also provided for checkout, shakedown, parametric (verification and baseline), operating modes and endurance testing of the preprototype VCDS to demonstrate hardware maturity and characterize its performance.

5. Provide the supporting R&D to determine the extent to which components must be redesigned, which designed components are compatible with performance objectives, status of designs and programs and technology level. A product of these activities was the definition of the operating conditions and performance levels expected of the VCDS.

6. Prepare and submit the program's documentation and data requirements.

7. Incorporate program management needed to successfully meet the program's cost, schedule and technical performance objectives and requirements to result in NASA satisfaction.

8. Incorporate additional advanced instrumentation capabilities.

VAPOR COMPRESSION DISTILLATION SUBSYSTEM

Concept Description

The basic premise of operation with this, as with any vapor compression distillation concept, is reclaiming the latent heat of condensation. This reclamation is accomplished by compressing the evaporate to raise its saturation temperature, and then condensing it on a surface which is in thermal contact with the evaporator. The result is a heat flux from the condenser to the evaporator which is sufficient to evaporate an equal mass of liquid. Thus, the required energy addition is that necessary to do the compression and overcome the system inefficiencies. The resultant system is characterized by low specific energy consumption for the water recovered from liquid wastes.

An important feature of this concept is that the boiling surface is protected from residue deposition by circulating the waste liquid through the evaporator and an external filter tank. This feature is important because of the use of a large surface area and a small temperature difference.

Design Specification

The design specification for the VCDS was governed by the needs of a three-person crew and the spacelab-type rack mounting. Emphasis, but to a lesser degree, was placed on meeting the projected size requirements for a Shuttle Orbiter VCDS.

Table 1 lists the contractual design specification for the VCDS. Additional design requirements selected by LSI for the VCDS are summarized in Table 2.

Packaging Considerations

The projected location of the RLSE subsystem within the Spacelab and the RLSE envelope for the prototype VCDS is shown in Figure 2. The VCDS is located in the right-hand cross-section. The specific packaging envelope provided for the VCDS consists of the bottom third of a double Spacelab-mounted rack. Although not required, the preprototype mechanical VCDS was designed to fit within this packaging envelope.

Maintenance Considerations

All VCDS components were designed to be Line Replaceable Units (LRU). As a goal, the VCDS package was designed to allow LRU maintainability from the front and rear sides of the subsystem only. This goal was met.

Interface Specifications

The fluid, power and heat rejection interfaces for the VCDS are listed in Table 3. The power required by the VCDS is 115/200 VAC, 400 Hz, 3Ø and 115 VAC, 60 Hz, 1Ø.

Subsystem Operation

The VCDS has five steady-state modes. The five modes are Normal, Reprocessing, Partial Drydown, Shutdown and Unpowered. Figure 3 shows the five modes including allowable intermode transitions.

Normal Mode

Pretreated wastewater enters the subsystem interface for temporary storage in the waste storage tank (WT1).[a] When the waste storage tank quantity sensor (Q1) indicates that the liquid in tank WT1 reaches a preset level, subsystem operation is initiated automatically. The distillation unit (VS1) is evacuated and the centrifuge is rotated, the liquids pump (M3) is activated and valve V1 is opened. The process liquid is recirculated between the still (VS1) and the recycle filter tank (WT2) as the product water is removed by pump M3 and pumped out through the post-treatment cartridge (PT1) through the product water interface. Recycle flow rate is preadjusted by valve MV4. Wastewater is continuously fed from WT1 to keep the recycle loop full. Noncondensables which collect in the condenser, are purged from the still (VS1) and are directed by valve V3 to either space vacuum or to the Oxidizable Contaminant

(a) Schematic reference identification per Figure 4.

TABLE 1 VCDS DESIGN SPECIFICATION

Crew Size	3
Processing Rate, kg/d (lb/d)	
Urine - Nominal	6.0 (13.2)
- Range	1.7 to 12.0 (3.7 to 26.4)
Flush - Nominal	1.7 (3.8)
- Range	1.7 to 3.4 (3.8 to 7.5)
Brine, Hyperfiltration	
- Nominal	1.4 (3.0)
- Range	0.9 to 1.8 (2.0 to 4.0)
Water Quality Monitor Recycle	0.9 (2.0)
Total, Nominal	10.2 (22.4)
Total, Maximum	18.1 (39.9)
Duty Cycle	Intermittent
Cabin Pressure, kPa (psia)	101 (14.7)
Cabin Temperature, K (F)	291 to 300 (65 to 80)
Electrical Power, VAC	115/200, 400 Hz, 3Ø 115, 60 Hz, 1Ø
Gravity, g	0 to 1
Mission Duration, d	30

TABLE 2 LSI SELECTED VCDS DESIGN REQUIREMENTS

- Independent operation as a subsystem, requiring only electrical energy and the liquid to be processed
- Compatible with zero- and one-g testing
- Capable of being rack mounted as required for Spacelab
- Separate Control/Monitoring Instrumentation
- Computer-based instrumentation
- CRT type display on front panel
- Demonstrate flight replaceable component concept employed for maintenance at the component level
- Incorporate RLSE design specification
- Shelf life $\geq$1 Year
- Optimized design for major components
- Compatible with JSC test facility
- All materials flight qualifiable (or flagged if not)

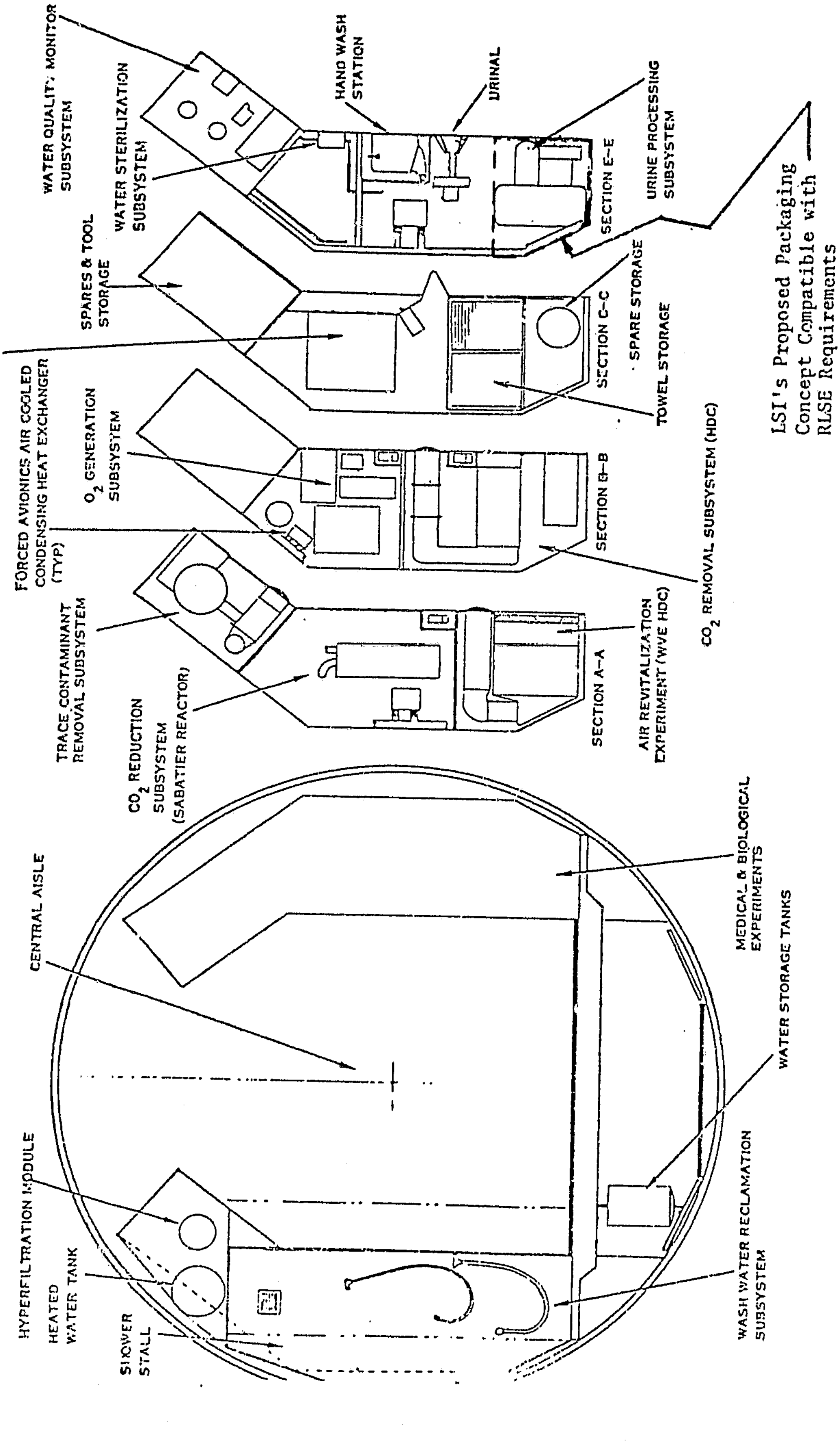
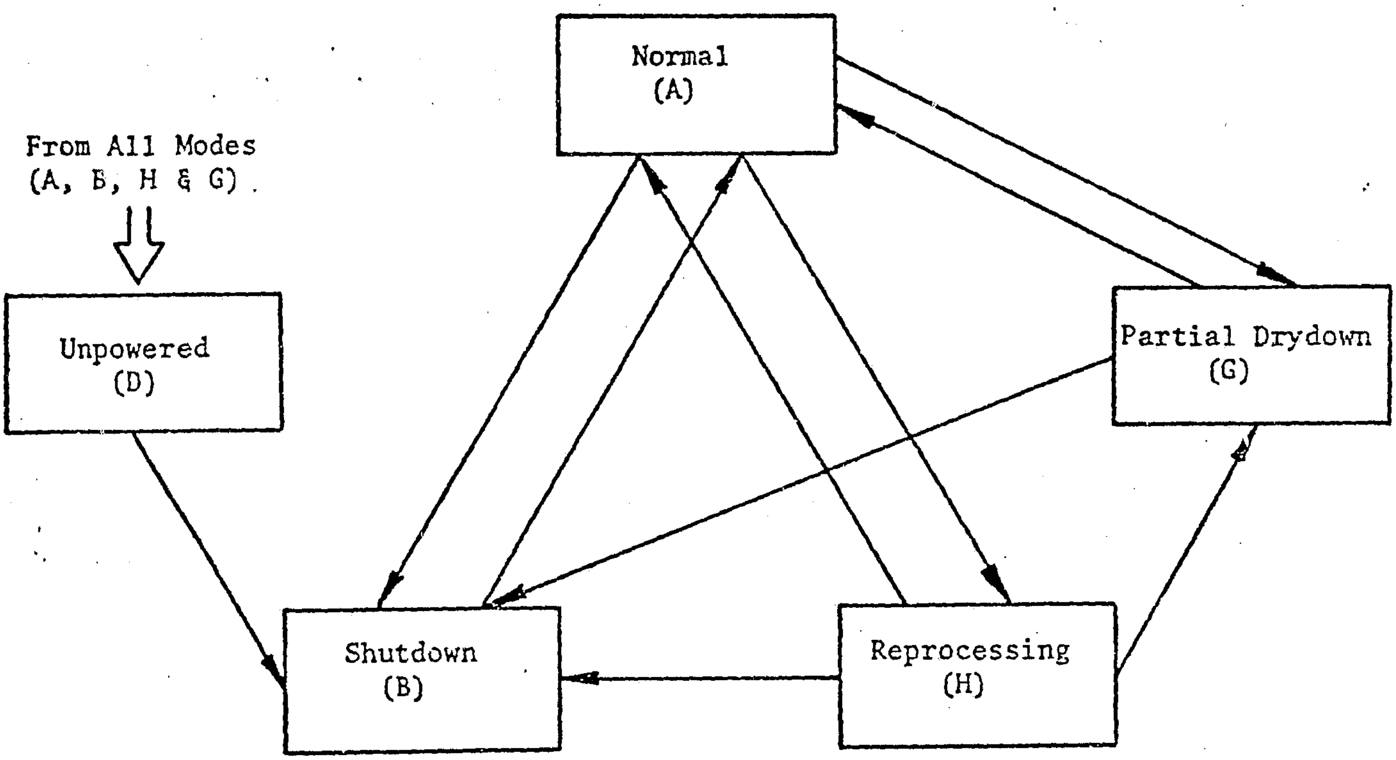


FIGURE 2 RLSE PACKAGING CONFIGURATIONS

TABLE 3 VCDS INTERFACES

Pretreated Waste, kg/d (lb/d)	10.2 (22.4)
Product Water, kg/h (lb/h)[(a)]	0.62 to 1.57 (1.37 to 3.45)
Purge to Cabin/Vacuum, dm^3/s (ft^3/min)	5.9 (0.21)
Waste Storage Tank Vent to Cabin	N/A
Electrical Power, Type	115/200 VAC, 400 Hz, 3Ø 115 VAC, 60 Hz, 1Ø
Electrical Power, W[(b)]	171
Heat Load, W[(b)]	171

(a) Intermittent as required.
(b) Mechanical portion of VCDS only.



- 5 Modes
- 4 Operating Modes
- 14 Mode Transitions
- 10 Programmable, Allowed Mode Transitions

FIGURE 3 VCDS MODES AND ALLOWABLE MODE TRANSITIONS

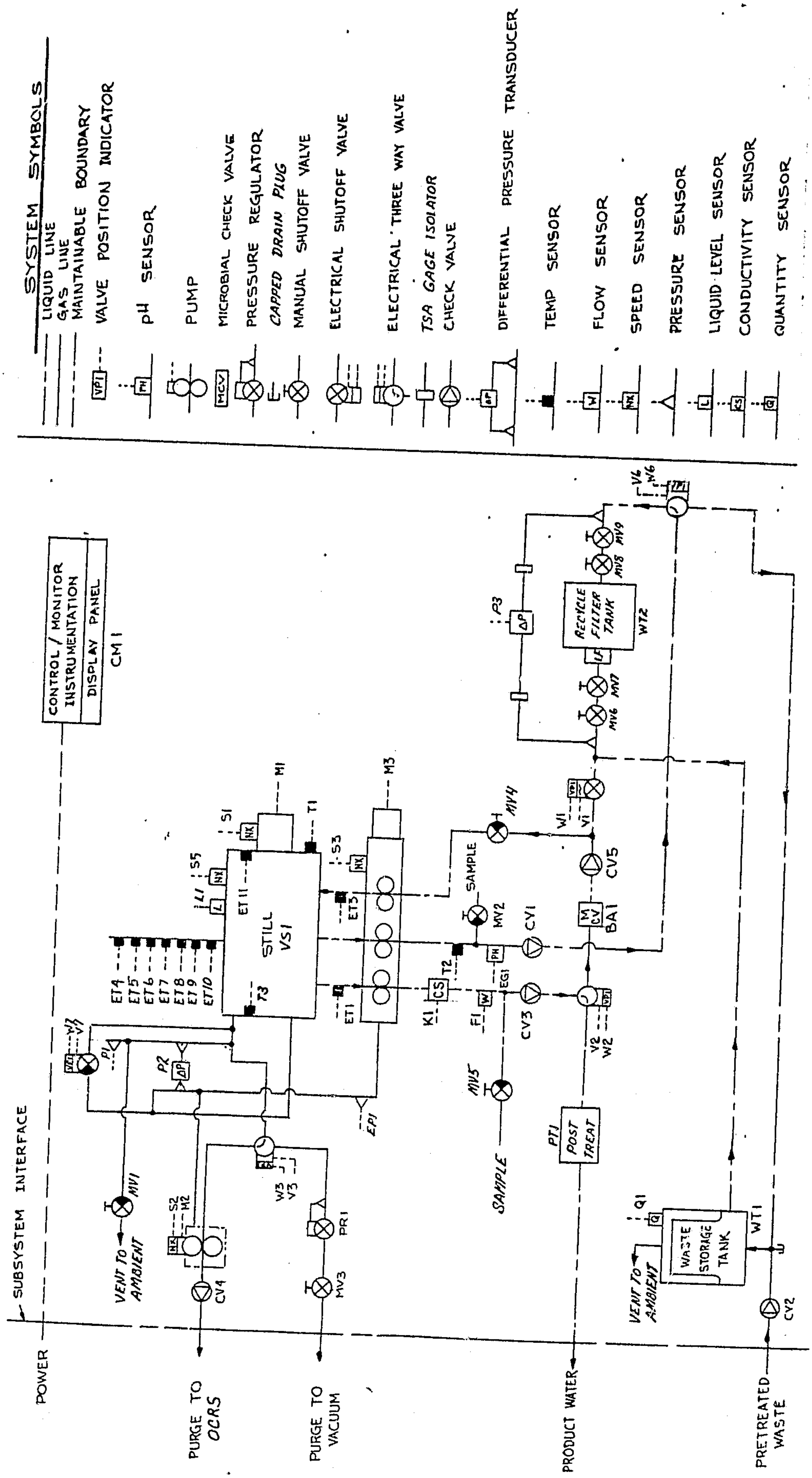


FIGURE 4 VCDS SCHEMATIC WITH TEST SENSORS

Removable Subsystem (OCRS). The purge pump (M2) is used to direct the noncondensables to the OCRS through check valve CV4. Overboard venting is accomplished through regulator PR1 which maintains still pressure above space vacuum. Manual valve MV3 can be used to isolate the VCDS from space vacuum.

The VCDS distillation unit is designed as part of a circulating loop and all of the available water is not extracted in one pass. In order to keep the still (VS1) from collecting a nonevaporated residue, the wastewater is continuously cycled between the recycle filter tank (WT2) and the evaporator surface.

Although wastes may be added continuously to the waste storage tank (WT1) during still operation, the system is a batch system. That is, the signals that automatically initiate and terminate operation are, respectively, high liquid level (Q1) and low liquid level (Q1) in the waste storage tank (WT1).

An alternate recycle path is used when the dissolved solids concentration in the recycle filter tank (WT2) is above 20%. The wastewater processed after 20% dissolved solids concentration is reached is recycled through the waste storage tank (WT1) instead of the recycle filter tank (WT2). This is accomplished by energizing valve V6. As this recycle loop approaches 20% dissolved solids, V6 is switched back to its original position for the remainder of the batch. This alternate path is used to reduce energy requirements since water production rate is inversely proportional to solids concentration. Care is taken to prevent WT1 from reaching higher than 20% dissolved solids because it is at this point that the solids may begin to precipitate and no filter is located within the alternate path.

The low pressure required in the still to permit low temperature boiling must be actively maintained because of the constant liberation of noncondensable gases which would increase the condenser pressure. Noncondensables are purged from the distillation unit based on a change in compressor pressure differential as measured by pressure transducer P2. Since this differential also changes with solids concentration, an automatically increasing differential pressure value is used by the C/M I to initiate purging when the VCDS is configured to purge to the OCRS.

Reprocessing Mode

The quality of the product water is checked continuously by the conductivity sensor (K1). If found unacceptable (>50 μmohs/cm), the product water is recycled back into the distillation unit through a microbial check valve (BA1) by the actuation of valve V2. The microbial check valve protects the product water loop of the subsystem from contamination by upstream diffusion of the recycle liquid.

Partial Drydown Mode

If the liquid level (L1) in the distillation unit (VS1) exceeds a preset level, the partial drydown mode is initiated.

During this mode the flow of liquid into the still is halted by closing V1. The liquid level in the still is reduced as the liquids pump (M3) continues to operate and returns the liquid to the waste storage tank. Partial drydown is completed and operation is automatically returned to the Normal Mode when the liquid level (L1) in the evaporator has indicated continuously less than the upper allowable liquid level for 10 min.

Shutdown Mode

In the shutdown mode the VCDS is not performing the function of converting pretreated waste into water. All the VCDS rotating equipment (still, liquids pump and purge pump) is turned off. The C/M I remains powered and continues to monitor VCDS parameters during the shutdown mode.

Unpowered Mode

In the unpowered mode no power is provided to the subsystem and no water is recovered.

Mechanical Hardware Description

Figures 5 and 6 show front and back views of the mechanical hardware, respectively. Table 4 contains the VCDS Mechanical System characteristics while Table 5 displays a system breakdown, by component, of weight, power and heat rejection.

Major Mechanical Components

The subsystem's major components include the distillation unit, purge pump, liquids pump, post-treatment canister, recycle filter tank and waste storage tank.

Distillation Unit (VS1). The LSI-developed VCDS distillation unit concept is depicted in the schematic cross-section shown in Figure 7. The latent heat of condensation is conserved by compressing the evaporate and condensing it on a surface in thermal contact with the evaporator. This process is carried out at low temperature by maintaining a nominal condenser pressure of 4.8 kPa (0.70 psia). Due to the zero gravity design requirement, the evaporator, condenser and condensate collector are rotated to provide the desired phase separation and liquid level control.

Since this distillation unit's operating objective is one of low specific energy consumption and because the heat flux is being driven by a very low temperature differential, the flows of heat and mass must be carefully controlled. Figure 8 is a schematic depicting the heat and mass flows in the LSI VCDS distillation unit.

The distillation unit is the heart of the system. Figure 9 is a photograph of its components. Design features of the distillation unit are as follows:

1. The centrifuge is a welded structure from bearing to bearing. As a result, the still can be completely serviced without disturbing the balance of this major dynamic component. Internal access is provided through the spoked end.

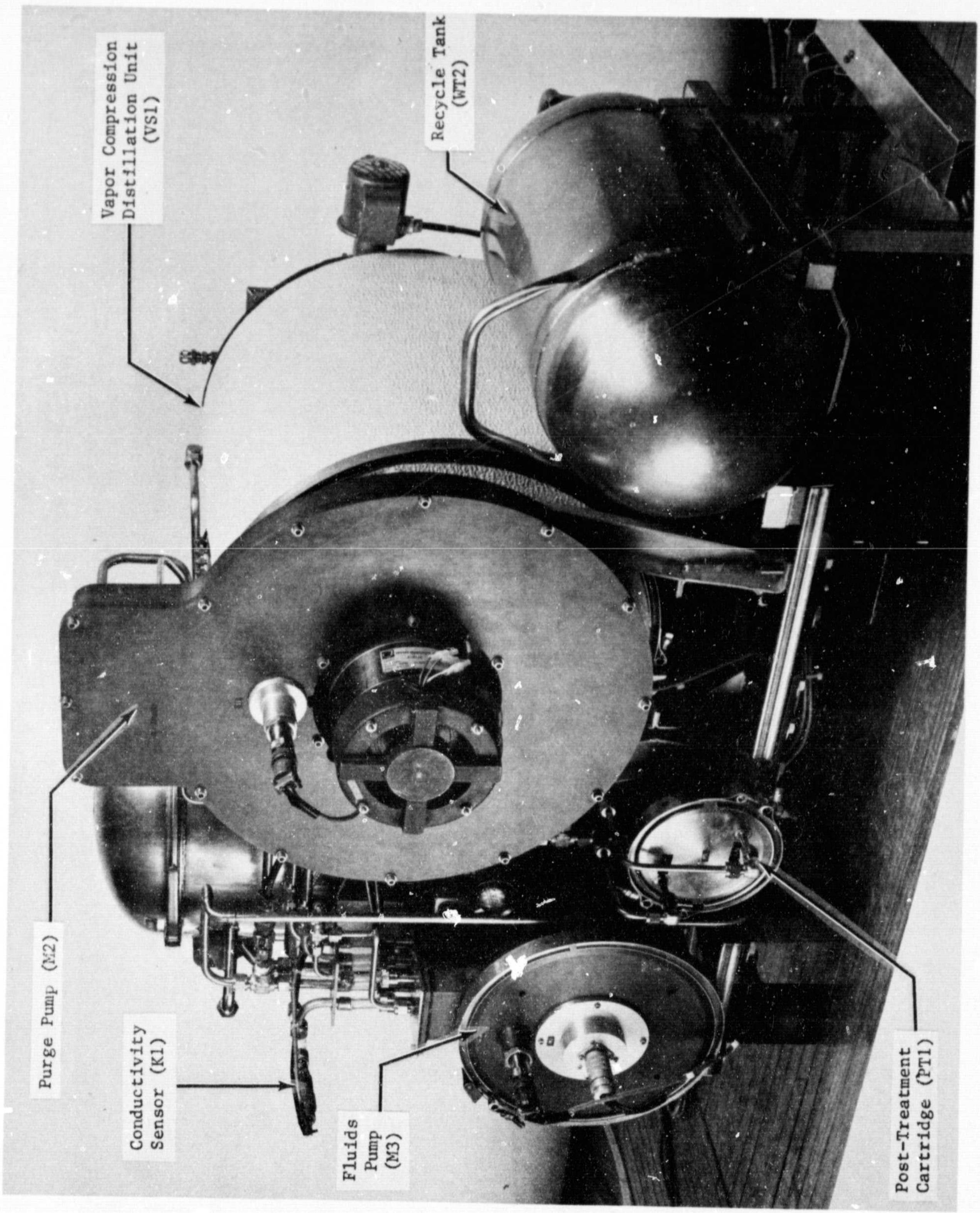


FIGURE 5 VCDS MECHANICAL HARDWARE (FRONT VIEW)

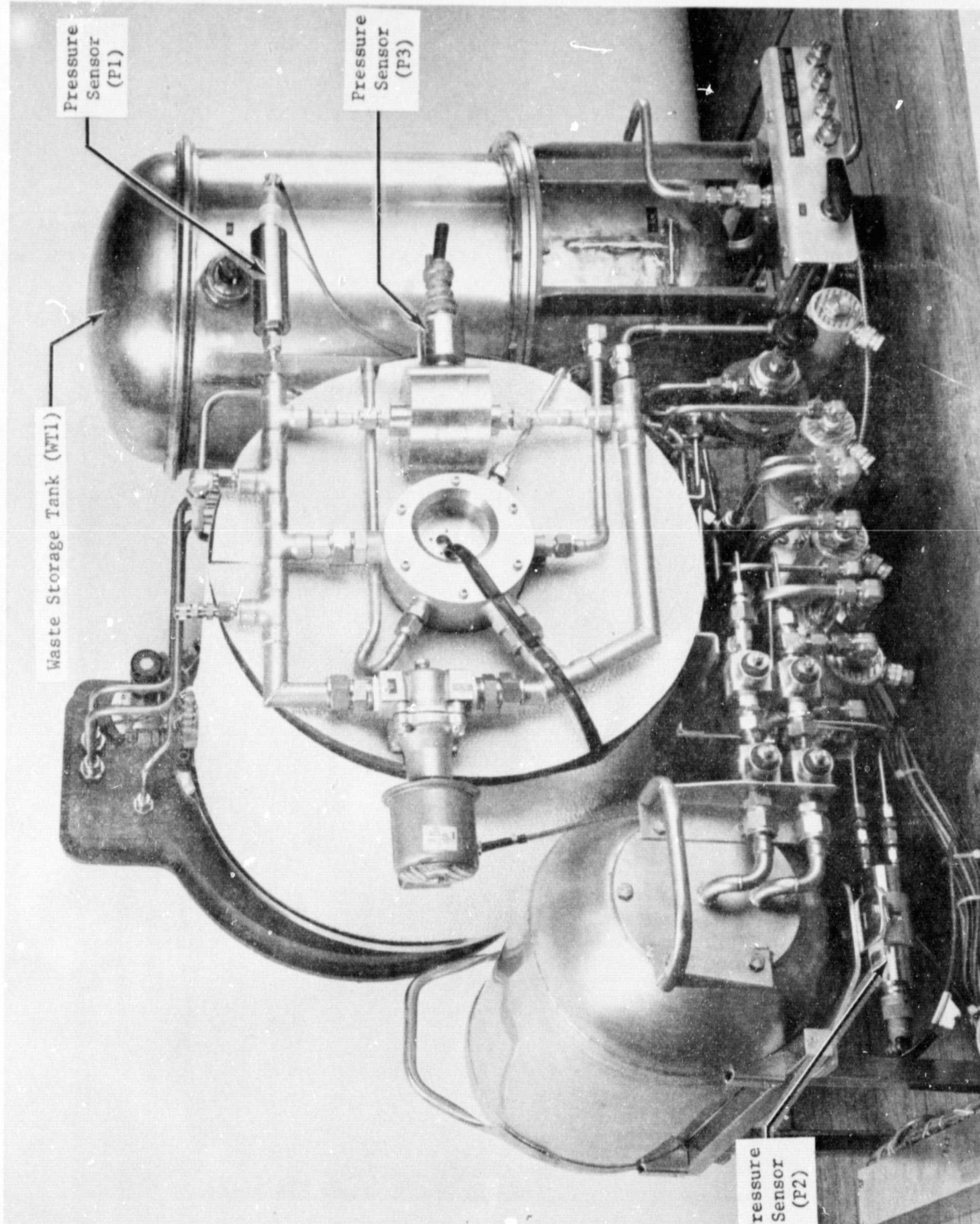


FIGURE 6 VCDS MECHANICAL HARDWARE (REAR VIEW)

TABLE 4 VCDS MECHANICAL SYSTEM CHARACTERISTICS

Capacity, Crew Size	8[a]
Fixed Dry Hardware Weight, kg (lb)	143 (316)[b]
Overall Dimensions, cm (in)	67.3 x 73.7 x 94.0 (26.5 x 29.0 x 37.0)
Volume, m^3 (ft^3)	0.47 (16.5)
Power Required, W[c]	
Basic Process	161
Total Subsystem	171
Heat Load, W	171
Water Recovery Rate, kg/d (lb/d)	
Instantaneous (Range)[a]	16.9 - 26.2 (37.0 - 57.6)
Average (For 3 people)	9.3 (20.4)

(a) At 80% duty cycle, 30% duty cycle for 3 persons
(b) Dry weight
(c) Excluding instrumentation

TABLE 5 VCDS MECHANICAL COMPONENTS WEIGHT, POWER AND HEAT REJECTION

Item No.	Component	Schematic Symbol	No. Req'd	Total Wt, kg (lb)	AC Power, W	DC Power, W	Heat Power, W
1	Still	VS1	1	42.2 (93.0)	--	--	--
2	Motor, Still Drive	M1	1	4.1 (9.0)	62[a]	--	62[a]
3	Pump, Purge	M2	1	11.4 (25.0)	71[b]	--	71[b]
4	Pump, Liquids	M3	1	15.9 (24.0)	28	--	28
5	Tank, Waste Storage	WT1	1	16.8 (37.0)	--	--	--
6	Tank, Recycle	WT2	1	7.3 (16.0)	--	--	--
7	Cartridge, Post-Treatment	PT1	1	5.9 (13.0)	--	--	--
8	Regulator, Backpressure	PR1	1	1.0 (2.3)	--	--	--
9	Valve, 2-Way Solenoid, Liquid	V1	1	0.7 (1.5)	10	--	10
10	Valve, 2-Way Solenoid, Gas	V7	1	0.9 (2.0)	(c)	--	(c)
11	Valve, 3-Way Solenoid	V2,V3,V6	3	2.0 (4.5)	(d)	--	(d)
12	Valve, Manual	MV1,MV3,MV4 MV6-MV9	7	3.2 (7.0)	--	--	--
13	Filter, Bacteria	BA1	1	0.6 (1.3)	--	--	--
14	Valve, Check	CV1-CV5	5	0.5 (1.0)	--	--	--
15	Sensor, Pressure, Absolute	P1	1	1.8 (4.0)	--	(e)	(e)
16	Sensor, Pressure, Differential, Gas	P2	1	4.8 (10.5)	--	(e)	(e)
17	Sensor, Pressure Differential, Liquid	P3	1	0.2 (0.5)	--	(e)	(e)
18	Sensor, Temperature	T1-T3	3	0.3 (0.6)	--	(e)	(e)
19	Sensor, Conductivity	K1	1	0.5 (1.0)	--	(e)	(e)
20	Sensor, Liquid Level	L1	1	0.1 (0.2)	--	(e)	(e)
21	Sensor, Flow	F1	1	0.9 (2.0)	--	(e)	(e)
	Components Subtotal			116.0 (255.4)	171	0	171
	Packaging			27.5 (60.6)			
	Hardware Total			143.5 (316.0)			

(a) Calculated from Torque
(b) Not required when vent mode selected (projected power, not demonstrated)
(c) Draws 22.5 W, but not energized during normal operation
(d) Each valve draws 10 W, but not actuated during normal operating
(e) Sensor power included in C/M I

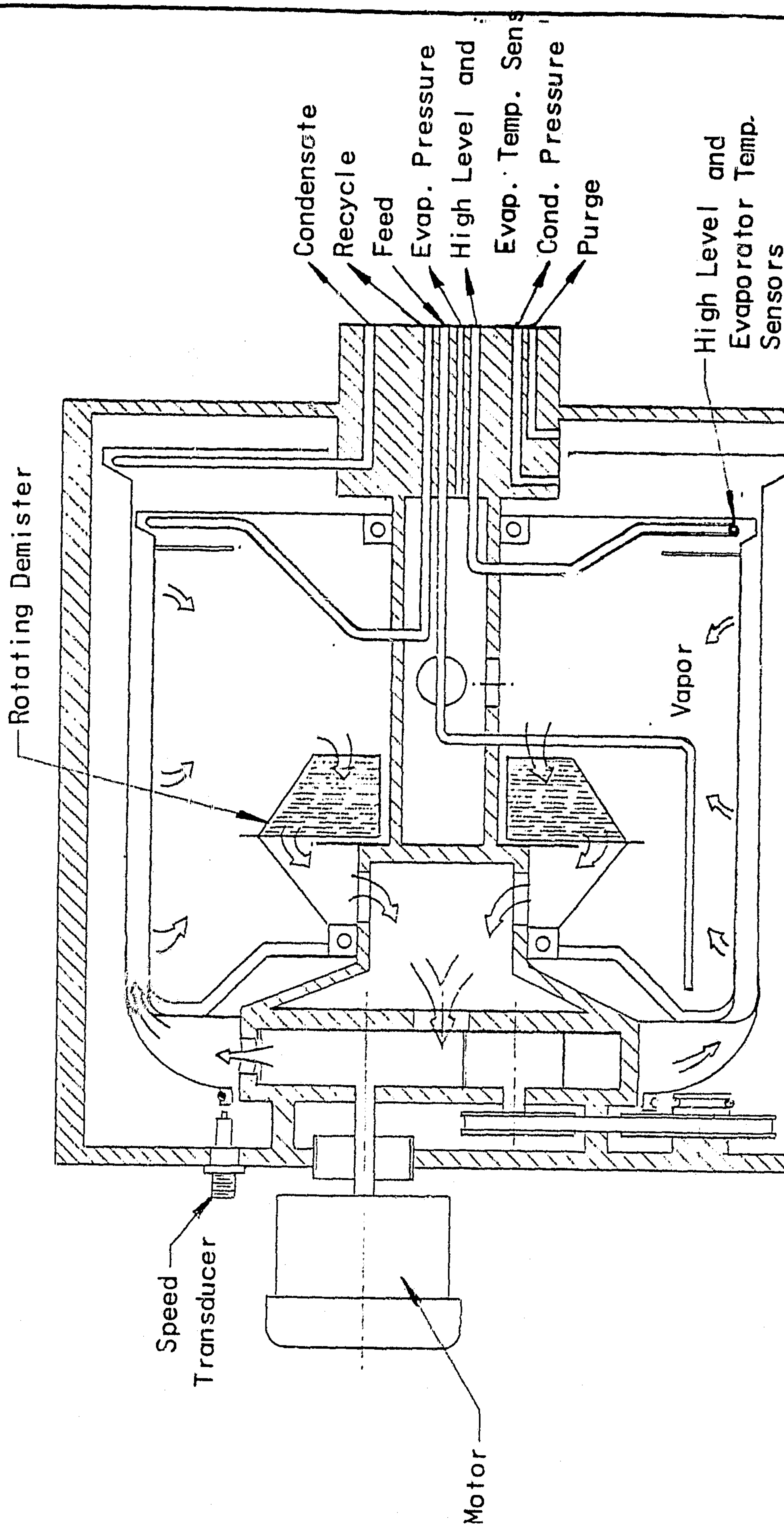


FIGURE 7 DISTILLATION UNIT, FUNCTIONAL SCHEMATIC

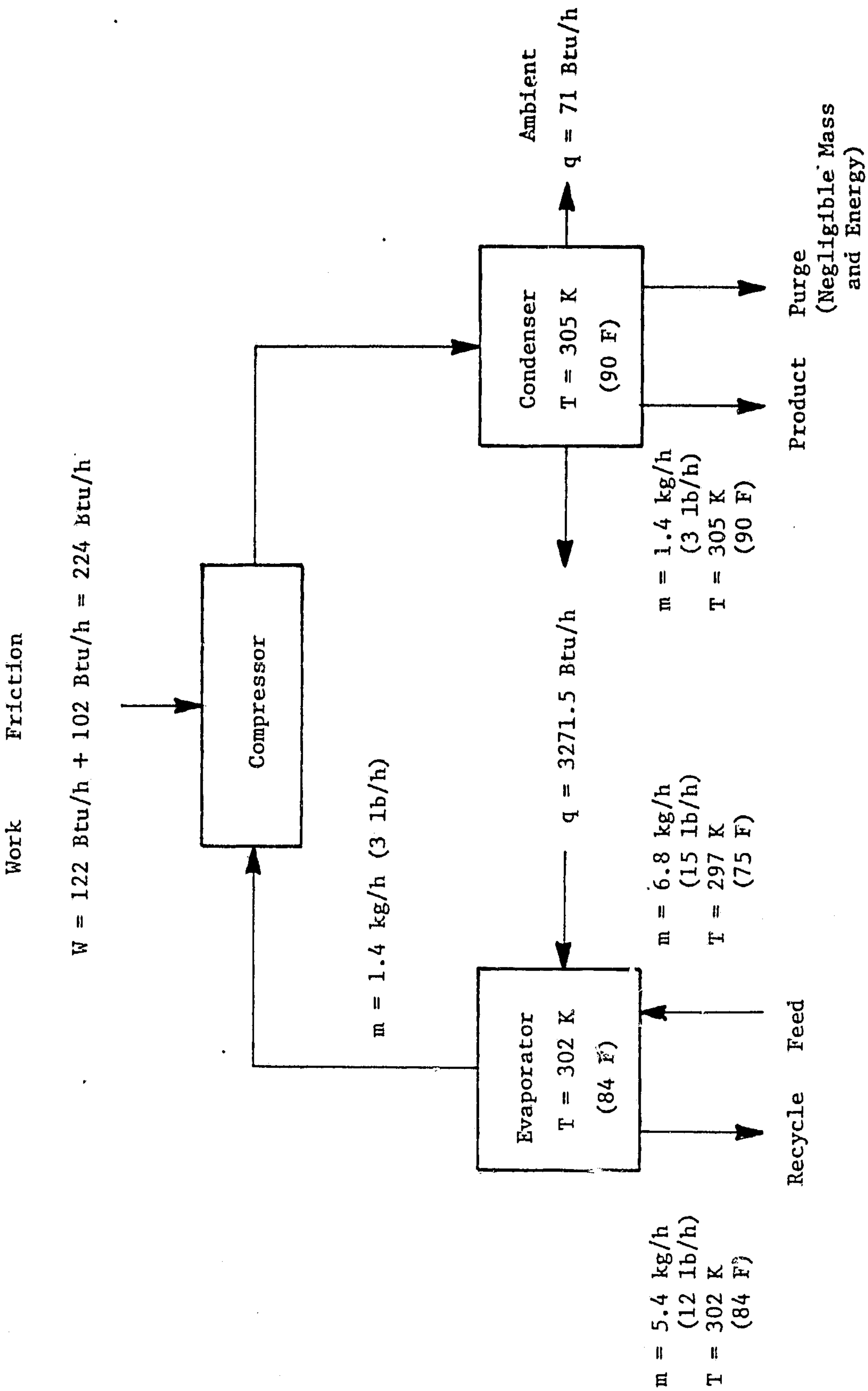


FIGURE 8 HEAT AND MASS FLOWS

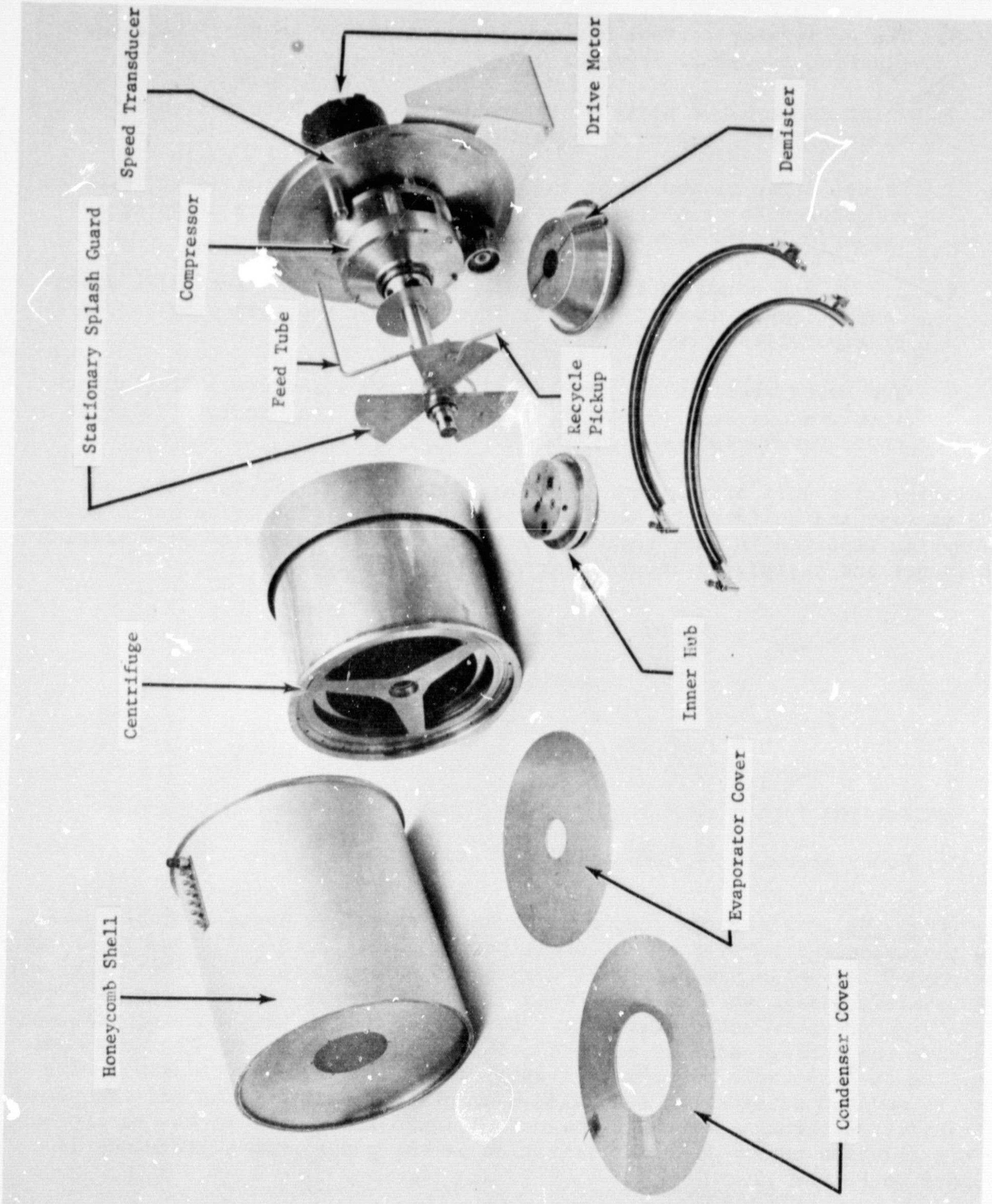


FIGURE 9 STILL COMPONENTS

2. A radial path demister has been employed to avoid the need for axial seals, with their inherent wear and friction.

3. The evaporator surface has a 0.10 degree taper to facilitate self-cleaning and rapid drydown.

4. Inlet and exhaust ports of the compressor have been designed to minimize the pressure drop in the steam path.

5. Direct drive of the compressor by the external motor is achieved by incorporation of a dynamic seal made by magnetically trapping a magnetic liquid between the shaft and housing.

6. All welded components of the still were fabricated from 316L stainless steel to prevent the loss of corrosion resistance by carbide precipitation in welded areas.

7. The outer shell is a double wall honeycomb structure. This structure reduces heat rejection, noise transmission, resists collapse under vacuum and is lightweight.

The distillation unit drive motor used during testing at LSI was selected based on cost and delivery rather than optimum sizing. The drive motor power consumption reported in this report is derived from the measured distillation unit torque and calculated work of compression as follows:

$$\text{Power}_I = \frac{\text{Torque} \times N \times 2\,\Pi}{8498\ \frac{\text{in-oz}}{\text{watt-min}}}$$

$$\text{Torque} = 5.66 \text{ in-oz}$$

$$N = 3100 \text{ RPM}$$

$$\text{Power}_I = 13 \text{ W}$$

$$\text{Compression Work} = 30 \text{ W}$$

$$\text{Power Actual} = \frac{13 + 30}{0.7} = 62 \text{ W}$$

Purge Pump (M2). The purge pump's function is to remove noncondensable gases from the condenser portion of the distillation unit. Figures 10 and 11 are photographs of the purge pump internal components and assembled unit, respectively. A peristaltic design was chosen because of its low energy consumption in spite of the high pressure ratio across it. Evacuation of the pump housing was used to assure the tubing shape is restored after each compression. The purge pump is driven at 3.56 rad/s (34 rpm) and displaces 0.98 l/min (60 in^3/min). The motor is mounted outside the evacuated housing to permit cooling and the power is transmitted through a rotating magnetic liquid seal, similar to the one on the distillation unit. A characterization of the purge pump performance is included in Figure 12.

Liquids Pump (M3). The liquids pump consists of three separate peristaltic sections driven by one eccentric rotor and motor and is packaged in one housing. One pump section feeds the recycle liquid to the still, the second pump section removes recycle liquid from the distillation unit and the third pump

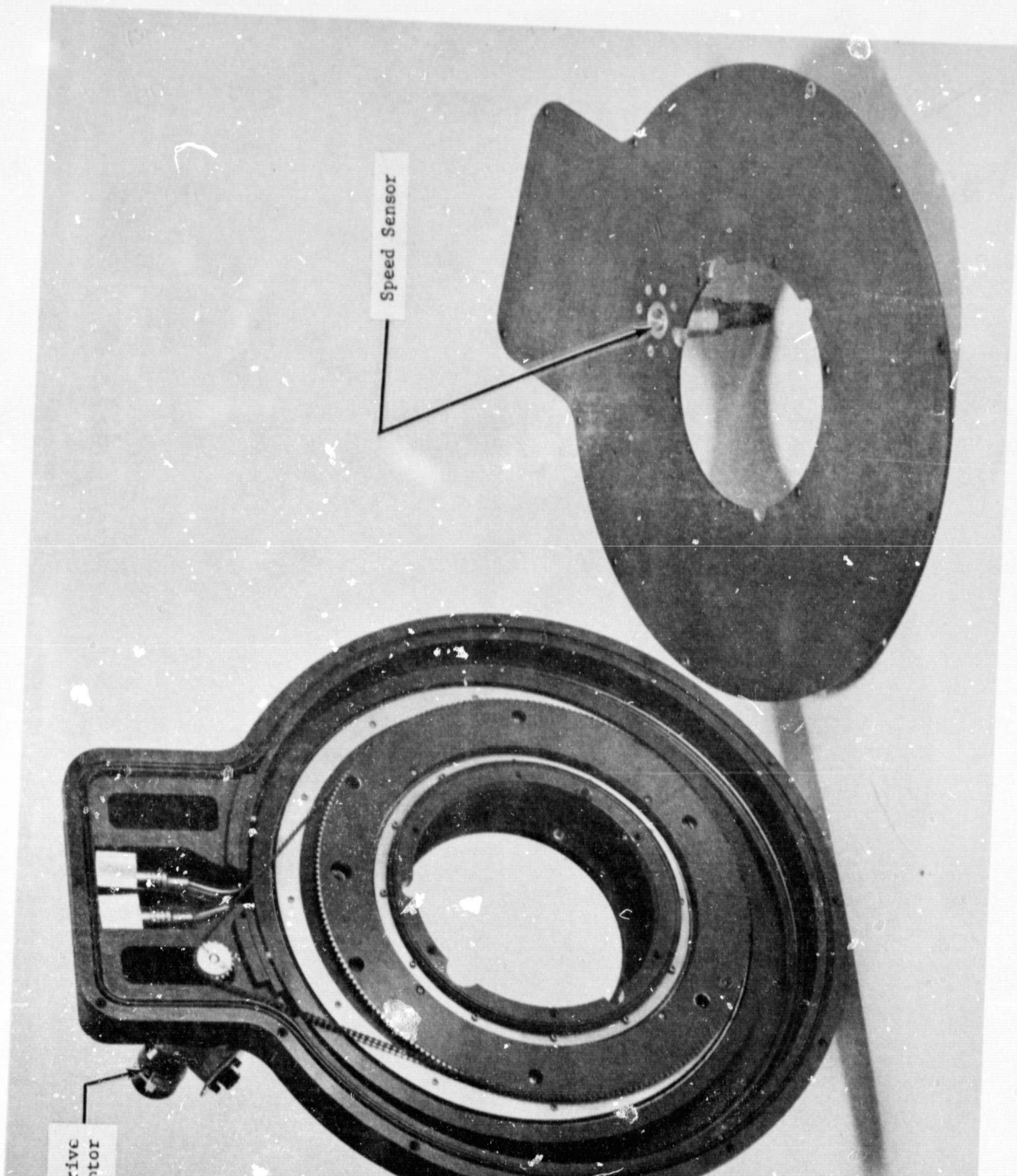


FIGURE 10 PURGE PUMP, INTERNAL VIEW

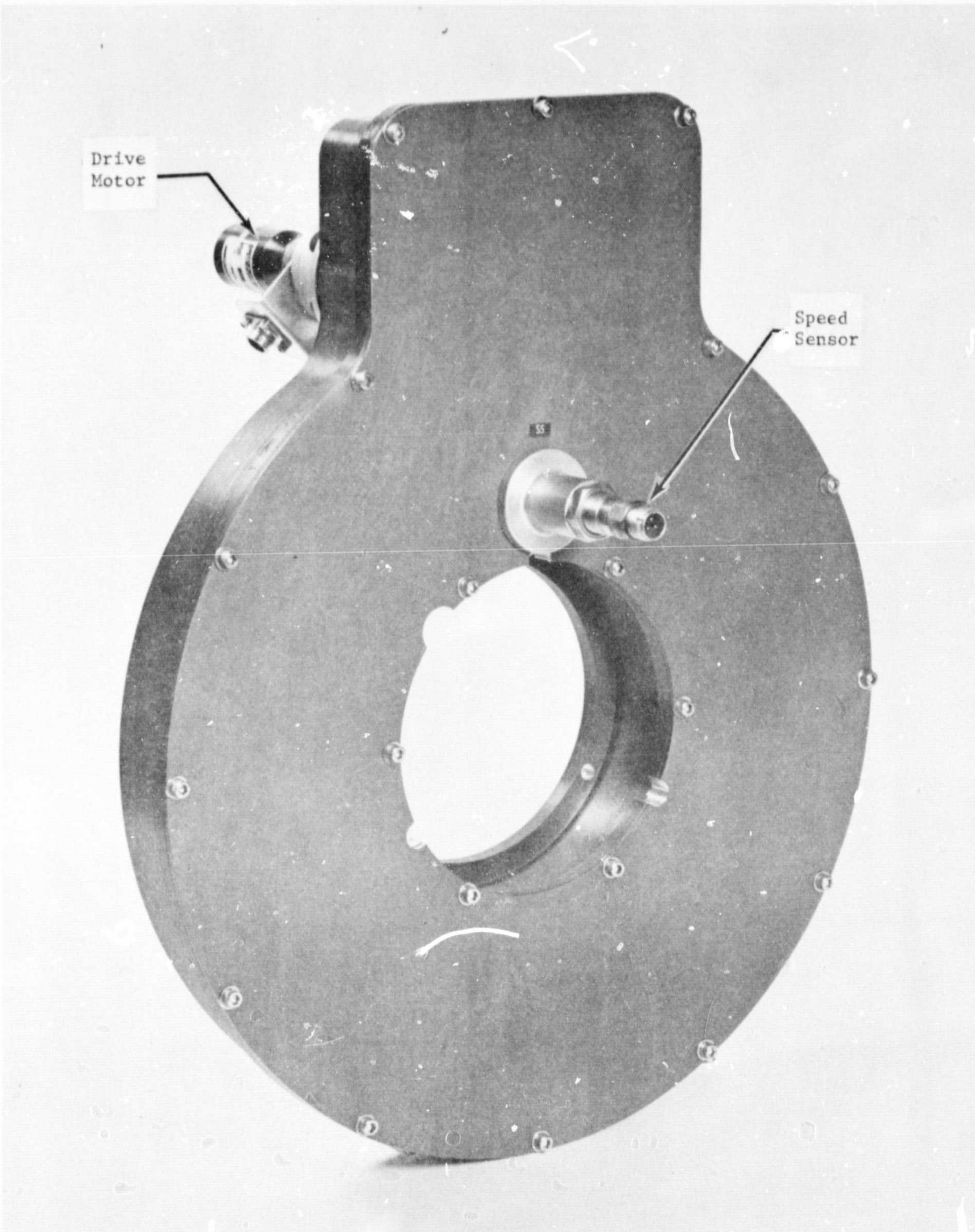


FIGURE 11 PURGE PUMP

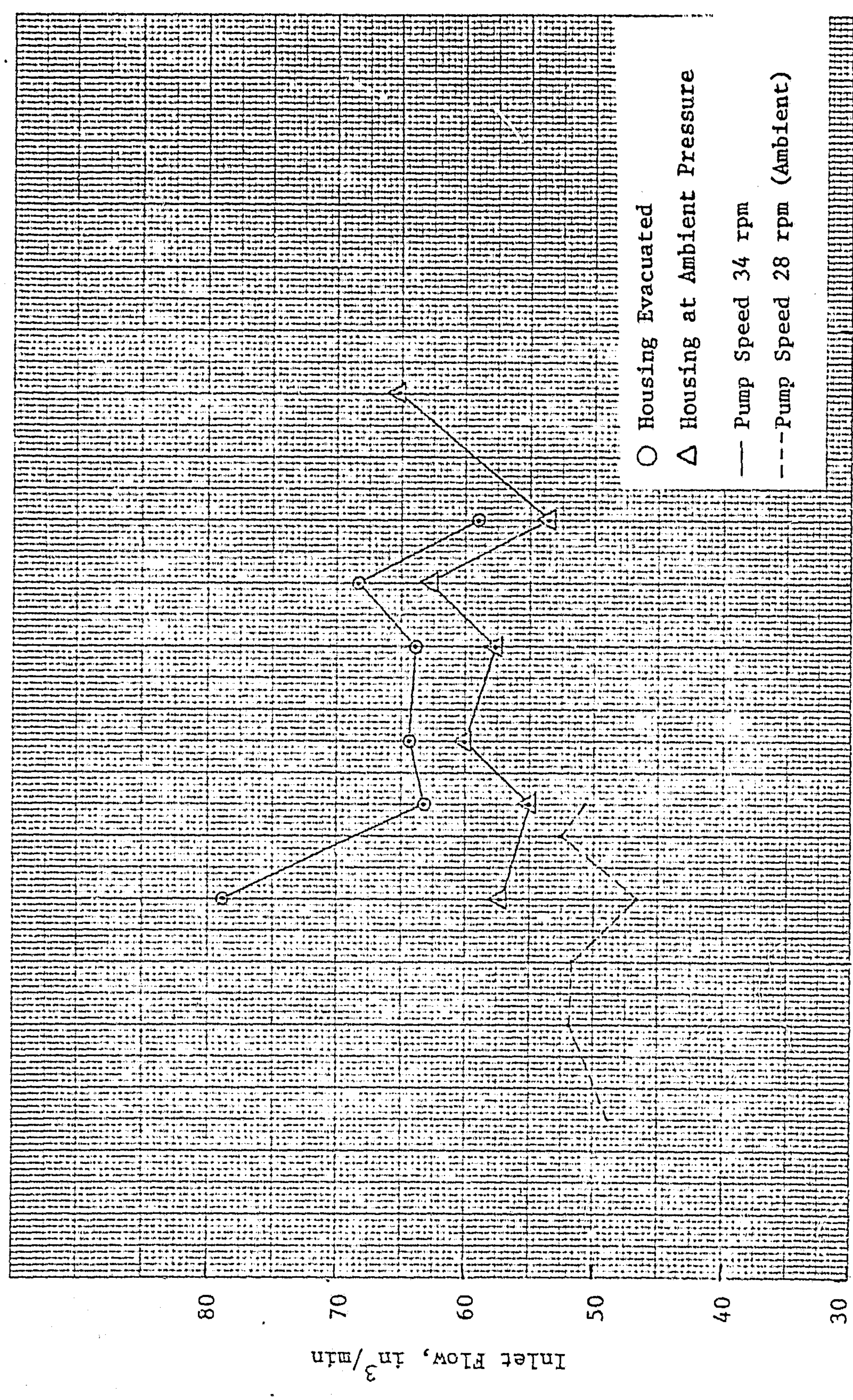


FIGURE 12 PURGE PUMP PERFORMANCE

section removes the product water from the condenser side of the still. Evacuation of the pump housing is again used to assure maximum restoration of the tubing shape after each compression. The motor is mounted within the evacuated housing for compactness, but the motor winding is thermally connected to the external surface for heat dissipation. This pump is operated at 2.20 rad/s (21 rpm) and yields a maximum flow rate of 330 cm^3/min (20 in^3/min) per channel.

Post-Treatment Canister (PT1). The Post-Treatment Canister provides taste and odor control of the product water. A filter and biocide have been incorporated into the unit to prevent the passage and growth of organisms. The Post-Treatment Canister (PT1) is shown in Figure 13. A compact design was achieved by using two concentric flow sections which permit the proper volume and path length of carbon bed in series with the biocide and filter. Flow is directed through the center path and then the outside area, thus reducing the canister length to one half the required flow length.

Recycle/Filter Tank (WT2). The Recycle/Filter Tank is a reservoir where the wastes remaining from the distillation process are concentrated. The tank, shown in Figures 14 and 15, is almost identical to the Space Station Prototype (SSP) 20 liter capacity unit. Provisions have been made in its mounting technique to permit replacement, with access required only from the rear of the unit.

Waste Storage Tank (WT1). The Waste Storage Tank provides a reservoir for incoming waste and for distillation unit evaporator liquid upon drydown. The Waste Storage Tank used was Government-Furnished Equipment (GFE). It has a rolling diaphragm similar to the SSP design. An extra fluid passage port was added to the tank to permit recycling through the tank while bypassing the Recycle/Filter Tank.

WT1 has a capacity of 17 liters (4.49 gal) and has been mounted so that only rear access is required for maintenance.

Subsystem Sensors

Both LSI-designed and off-the-shelf sensors were used to monitor the VCDS process.

Condenser Pressure (P1). The condenser absolute pressure sensor (P1) performs two functions in the VCDS. First, its signal is used by the C/M I to select the purge mode during the transition from shutdown to normal. If the condenser pressure is greater than 66.7 kPa (9.7 psia), purging to space vacuum is selected. Otherwise, the purge pump is used. Secondly, P1 is monitored continuously to indicate either a too high or too low pressure condition in the condenser. The transducer used to measure the condenser pressure was chosen primarily because the wetted surfaces are all either 347 stainless steel or Carpenter 20. The unit is a strain gage type transducer with a full scale range of 0 to 68.9 kPa (0 to 10 psia) and an overpressure capability of 2,068 kPa (300 psia). Therefore, it provides the precision required and the ruggedness to prevent accidental damage.

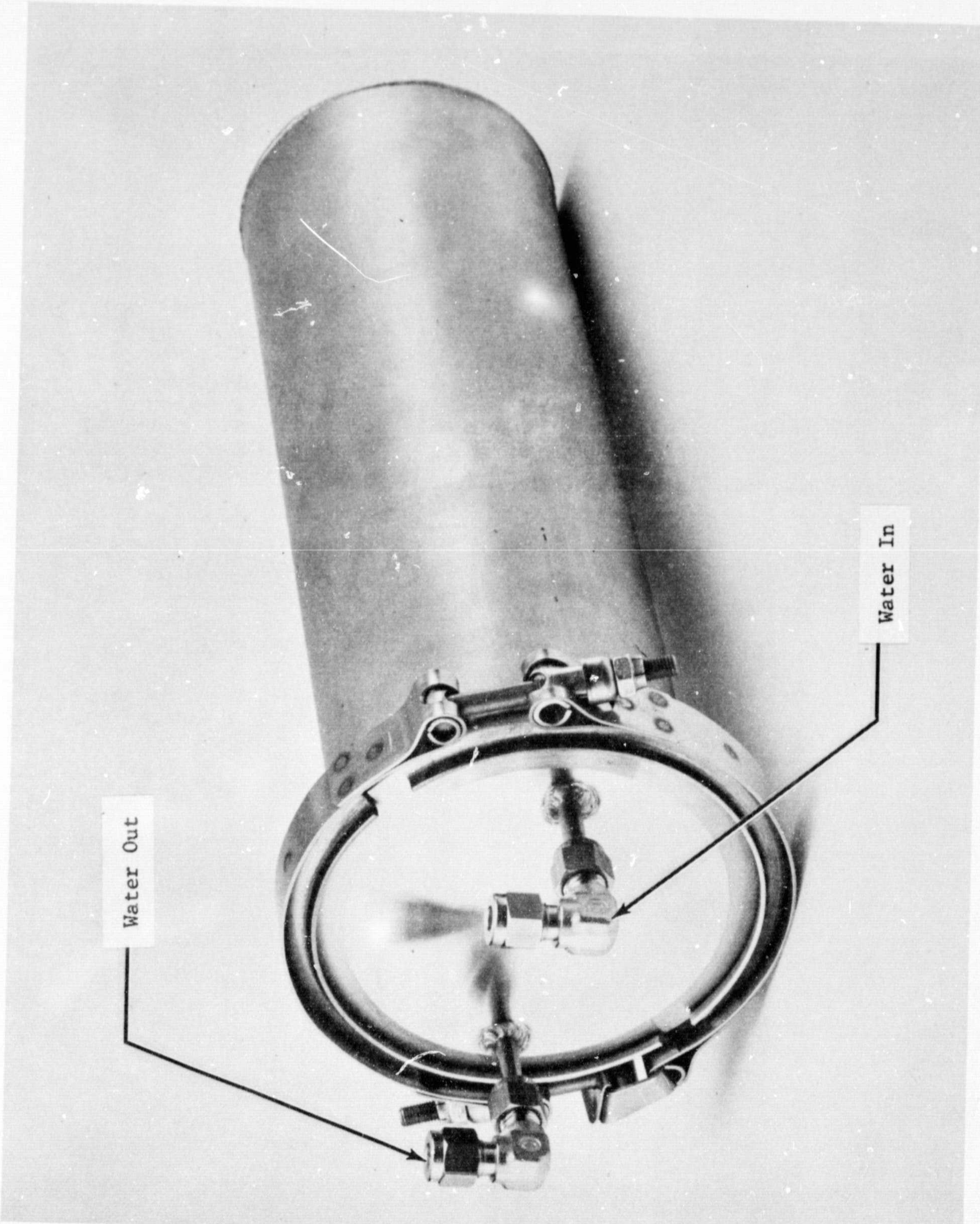


FIGURE 13 POST-TREATMENT CANISTER

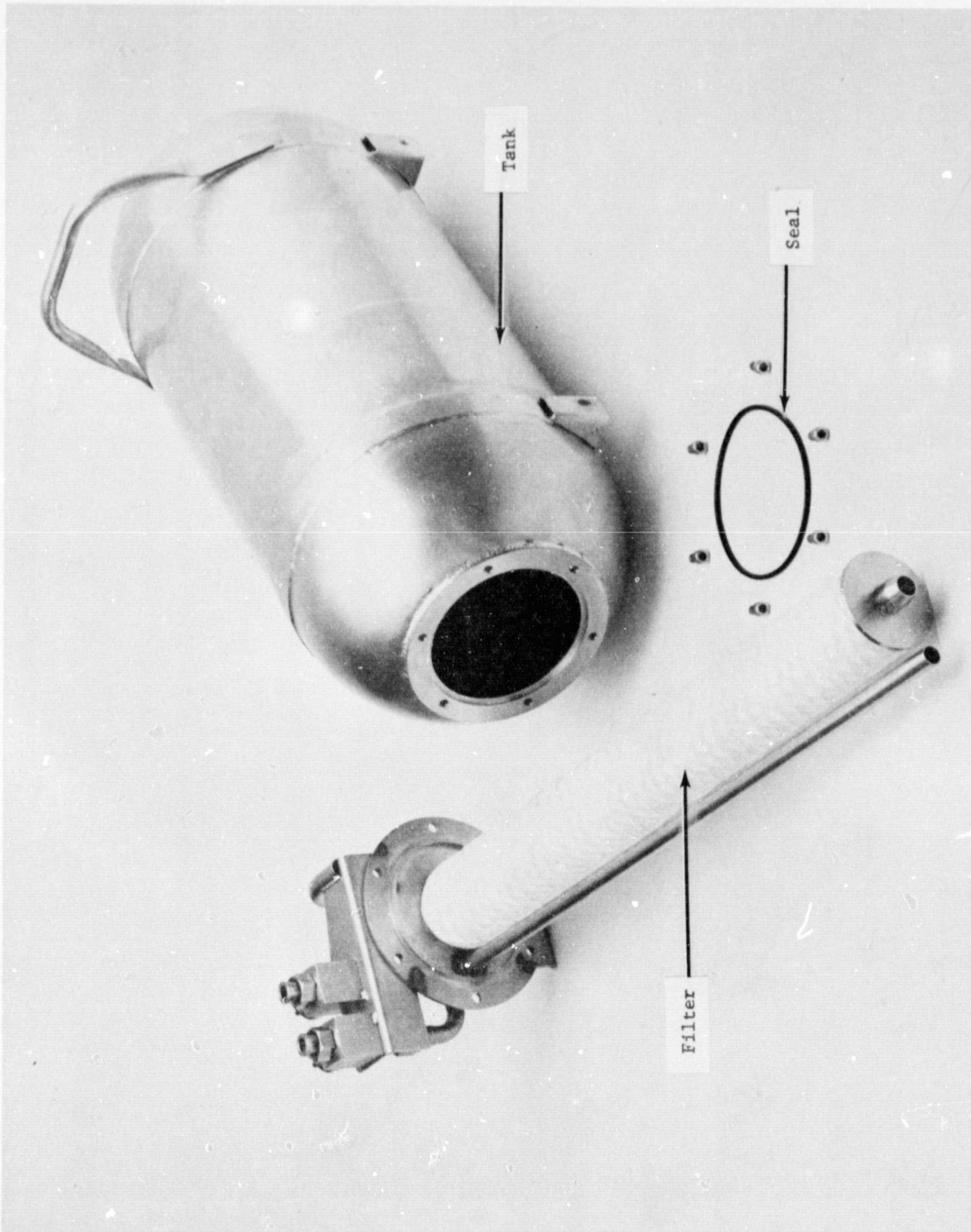


FIGURE 14 RECYCLE FILTER TANK COMPONENTS

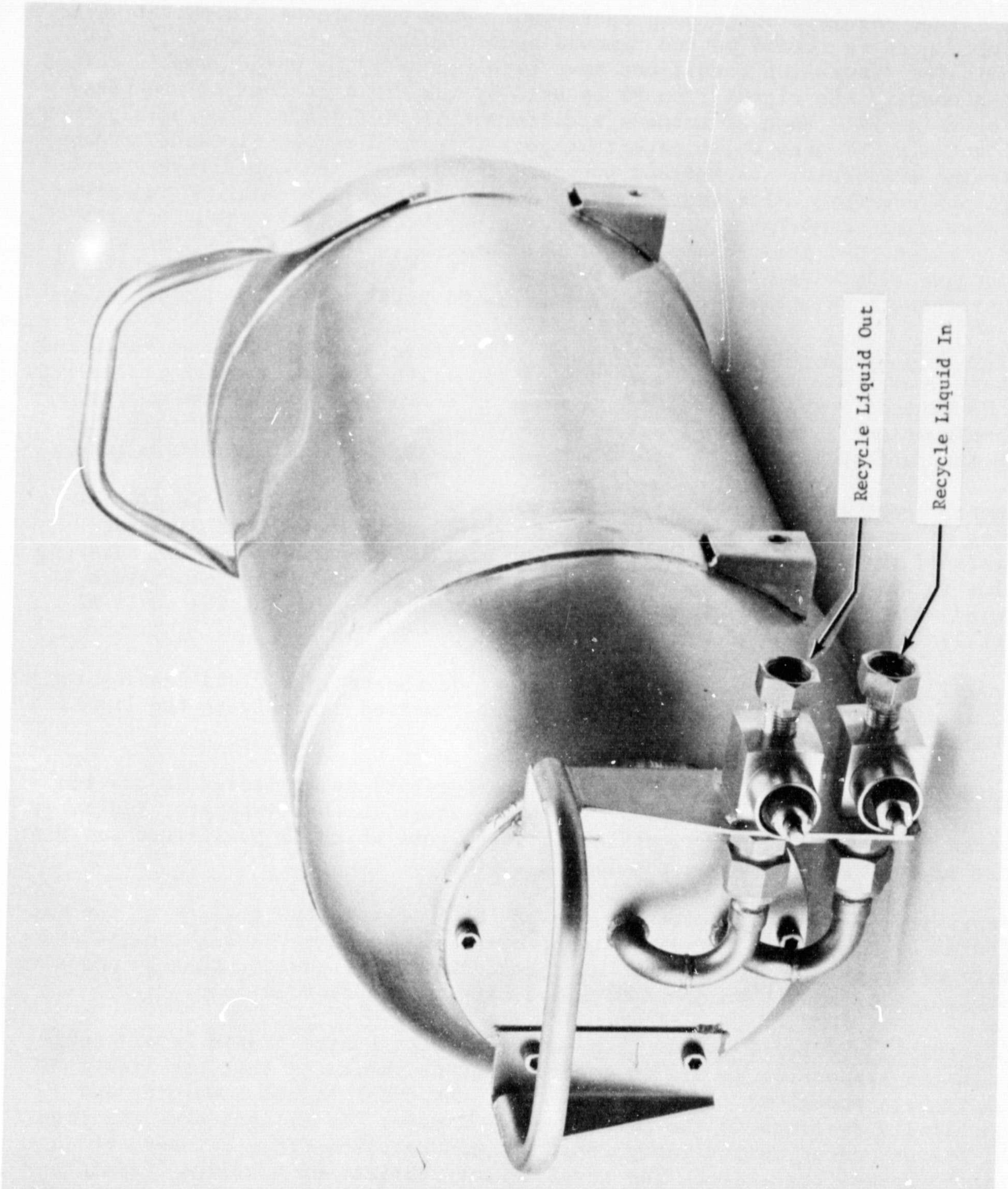


FIGURE 15 RECYCLE FILTER TANK

Compressor Differential Pressure (P2). The compressor differential pressure sensor (P2) performs two functions in the VCDS. First, its signal is used by the C/M I to regulate purge pump operation. When P2 exceeds its preset value, the purge pump is turned on and removes noncondensables from the still. When P2 indicates saturation conditions have been reached, the purge pump is turned off. Secondly, the signal from P2 is used by the C/M I to control the position of valve V7. When P2 exceeds a differential of 2.3 kPa (0.33 psid), the C/M I actuates V7 open which permits vapors to pass directly from the condenser to the evaporator and thereby prevents stoppage of the centrifuge due to compressor overload. The transducer chosen to measure the differential pressure across the compressor was chosen primarily because the wetted surfaces are all either 347 stainless steel or Carpenter 20. This unit is also a strain gage type with a full scale range of 0 to 12.4 kPa (0 to 1.8 psid) and an overpressure capability of 17,237 kPa (2,500 psid).

Recycle Tank Differential Pressure (P3). The recycle filter tank differential pressure sensor monitors the condition of the filter in the recycle filter tank. When P3 exceeds a differential pressure of 2.76 kPa (0.4 psid), the subsystem will automatically shutdown and a message will be displayed to indicate that the pressure drop across the recycle filter has reached the high alarm level.

Condenser Temperatures (T1). Condenser temperature is monitored to provide warning of an out-of-tolerance condition in the still as well as data for analysis of the process. In lieu of measuring the temperature in the rotating annulus in which the condensing actually occurs, the condenser temperature is measured with a sheathed thermistor projecting through the outside shell of the still to a point near the centrifuge.

Recycle Fluid Temperature (T2). Temperature of the recycle fluid leaving the still is measured with a sheathed thermistor inserted directly in the liquid stream.

Evaporator Temperature (T3). Evaporator temperature is monitored to provide data for analysis of the process. The temperature in the evaporator region is measured by a thermistor in a stainless steel tube which is positioned approximately 19 mm (0.75 in) above the liquid surface.

Conductivity (K1). A conductivity sensor (K1) monitors the quality of the water recovered by the VCDS. It was designed by LSI to be compact, lightweight and easy to maintain. In the event that a conductivity of greater than 50 μmhos/cm is sensed, the product water is diverted back to the recycle loop.

Evaporator Liquid Level (L1). This sensor detects a high liquid level condition in the evaporator should it occur. When L1 indicates that the liquid level is high enough to contact the sensor, the C/M I issues a warning and automatically switches to the partial drydown mode. If L1 indicates the liquid level has decreased sufficiently after ten minutes, the C/M I returns the subsystem to normal operation. The level sensor consists of a heated thermistor and operates by detecting a dramatic increase in thermal conductance and specific heat of its environment. At acceptable liquid levels the thermistor will dissipate very little energy to the rarified atmosphere in the evaporator and its temperature will be maintained above its surroundings by a small constant current. Should the liquid rise to contact the thermistor, the liquid's increased thermal conductance and specific heat will quickly cool the thermistor and keep it cool until the liquid level is lowered. This sensor has been made of 316L stainless steel, glass and epoxy, all corrosion resistant materials.

Product Water Flow (F1). Flowmeter F1 provides a constant indication of the rate at which water is being delivered by the VCDS. This signal is also integrated so that the percent dissolved solids present in the recycle loop can be calculated. Product water flow measurement is made by a turbine type flowmeter. Its rotor is supported on an hydrodynamic layer of the measured liquid rather than a bearing. Rotor rotation is detected optically and an electrical pulse generating circuit is stimulated by the optical pulses.

Even though the manufacturer's specification indicated that the sensor would function in the VCDS operating range, it was found not to be repeatable. As a result, a timer was installed to replace the dependency on a zero reading from F1 in the transitions to shutdown. Also, the calculated value of recycle percent dissolved solids based on the flowmeter reading was considered unreliable and was determined by actual measured values of liquid extracted from the recycle loop.

Valve Position Indicators (VPI). The VPIs indicate the position of each of the subsystem valves and are used for fault isolation. Each of the solenoid valves is equipped with a relay for valve position indication. When a valve is activated, the VPI relay is energized and the C/M I receives a signal that the valve has been energized.

Waste Storage Tank Quantity (Q1). Q1 indicates the amount of pretreated waste present in the waste storage tank (WT1) and is used to indicate subsystem startup and shutdown. The quantity of liquid in the Waste Storage Tank is sensed by a rotating potentiometer attached through a cable to the moving piston in the tank.

Speed (S). The subsystem speed sensors indicate the rotational speeds of the following actuators: still motor (S1), purge pump (S2), liquids pump (S3) and centrifuge (S5). All of the speed sensors in the VCDS are of the magnetic pickup type. Speed sensors that are mounted internal to subsystem components (centrifuge S5, liquids pump S2, purge pump S3) have been sheathed in 316L stainless steel for corrosion protection.

Control/Monitor Instrumentation Description

Instrumentation Design

The VCDS C/M I provides automatic process control, mode transition control, automatic shutdown for self-protection, monitoring of subsystem parameters and interfacing with Test Support Accessories (TSA) including a Data Acquisition and Reduction System (DARS). In addition, the C/M I contains an operator/subsystem interface with Cathode-Ray Tube (CRT) display for evaluating and analyzing the monitored parameters of an experiment.

As was shown in Figure 3, four operating modes and the unpowered mode exist with fourteen mode transitions, of which ten are programmable, allowed mode transitions.

Table 6 lists the VCDS steady-state actuator conditions which are the energized or unenergized state of the solenoid valves, motors and pumps during the four operating modes and the unpowered mode.

Table 7 presents the VCDS control functions for each of the four operating modes. The subsystem actuators and sensors are listed, as well as the control setpoints and their ranges.

The VCDS sensors as well as their symbols are listed in Table 8. All sensors in the VCDS have a redundancy level of one - meaning no redundant sensor elements are used.

Table 9 lists the VCDS C/M I design characteristics including detailed instrumentation computer characteristics. The C/M I design is of a developmental nature stressing flexibility, versatility and expandability. No attempt was made to reduce size.

Hardware Description

The C/M I hardware, excluding interface cabling, is contained in a 53.3 cm (21 in) wide x 53.3 cm (21 in) deep x 72.6 cm (28.6 in) high enclosure. Included within the enclosure are signal conditioning, power supplies, computer, analog/digital (A/D) interface circuitry, CRT display and display controller as shown in Figure 16, the VCDS C/M I hardware block diagram.

Power is supplied to the C/M I in the form of both 60 Hz and 400 Hz power. Internal power supplies convert this power to +24 VDC, ±15 VDC, ±12 VDC and +5 VDC power. The +24 VDC power supply is used for actuator control. The ±15 VDC power supplies are used in the signal conditioning circuits. The +5 and ±12 VDC power supplies are used in the computer and control logic circuits.

The signal conditioning circuits consist of ten printed circuit cards which accept sensor signals and condition them to 0 to 5 VDC. A signal conditioning circuit is required for each sensor except the pressure sensors which contain built-in signal conditioning. The signal conditioning outputs are applied to the A/D interface board which digitizes the sensor signals for scanning by the computer.

The VCDS C/M I is a minicomputer-based automatic instrumentation. The minicomputer consists of a 16-bit Central Processing Unit (CPU), 16K core of memory, a Real-Time Clock, Power-Fail control circuits, a communication link to an external DARS and a communication link to a line printer. The CPU executes the control/monitor programs stored in the 16K core memory. The Real-Time Clock allows the programs to be executed on a real-time basis. The Power-Fail control circuits allow the computer to detect and differentiate between a short-term power interruption and a long-term power failure. The communication link to the DARS allows the sensor data to be recorded on the DARS. The line printer communication link allows the operator/subsystem messages displayed on the CRT to be printed on the line printer.

TABLE 6 VCDS STEADY-STATE ACTUATOR CONDITIONS

Operating Mode	Actuator Conditions							
	Solenoid Operated Valves					Still Motor	Pumps	
	V1	V2	V3	V6	V7	M1	M2	M3
Shutdown (B)	U[a]	U	U	U	U	Off	Off	Off
Normal (A)	E	U	U[b]	U[c]	U	On	On[d]	On
Reprocessing (H)	E	E	U[b]	U[c]	U	On	On[d]	On
Partial Dry-Down (G)	U	E	U[b]	U[c]	U	On	On[d]	On
Unpowered (D)	U	U	U	U	U	Off	Off	Off

(a) U = Unenergized, E = Energized
(b) Shown for purge through purge pump. V3 is E for purge to vacuum.
(c) Shown for circulation through Recycle Tank. V6 is E for circulation through the Waste Storage Tank depending on amount of fluid processed.
(d) Intermittent, as required.

TABLE 7 VCDS CONTROLS DEFINITION

NORMAL MODE

Control	Control Parameter	Description	Actuator(s)	Sensor(s)	Setpoint	Setpoint Range
Pressure	Compressor ΔP	Maintain ΔP within the range between the variable[b] setpoint and 0.27 kPa (0.04 psid) above its value. Used in all modes and transitions except B and B to A.	M2 or V3[a]	P2	Variable	0.07 kPa (0.01 psia)
		Energize Bypass valve. Display "Compressor ΔP too high" and go to shutdown	V7	P2	2.27 kPa (0.33 psid)	0.13 kPa (0.02 psid)
Recycle Mode	Waste Tank Quantity	Accumulate amount that has been fed into the WS1 during current run. Check Q1 once per minute and accumulate all positive deviations as Qt. $Qm = 0.1 \times Qt$ De-energize V6 when $Q1 \leq Qm$. Used in all modes and transitions except B and B to A.	V6	Q1	Qm	±0.2 ℓ (0.4 lb)
Waste Quantity	Waste Tank Level	Call transition to shutdown.	A11	Q1	1.5 ℓ (3.3 lb)	±0.2 ℓ (0.4 lb)
Water Quality	Conductivity	Call transition to Reprocessing sequence.	V2	K1	50 μmho/cm	±1μmho/cm

(a) M2 unless front panel selection of "To Overboard Vent" is made, or if the purge pump (M2) is unable to maintain P2 within the control bank.

(b) Variable setpoint is reset each time compressor ΔP reaches previous variable setpoint + 0.27 kPa (0.04 psid). The variable setpoint is reset by purging the still until compressor ΔP is observed to not decrease over a 120 second (2 minute) interval.

-continued-

Table 7 - continued

REPROCESSING MODE

Control	Control Parameter	Description	Actuator(s)	Sensor(s)	Setpoint	Setpoint Range
Water Quality	Conductivity	If in this mode for $\geq$15 minutes, call transition to Shutdown.	All	K1	50 μmho/cm	±1μmho/cm
		When conductivity is <50 μmho/cm for 2 minutes, return to Normal mode.	V2	K1	50 μmho/cm	±1 μmho/cm

continued-

Table 7 - continued

PARTIAL DRYDOWN MODE

Control	Control Parameter	Description	Actuator(s)	Sensor(s)	Setpoint	Setpoint Range
Liquid Level	Evaporator Liquid	De-energize V1 to stop inputting liquid while continuing to remove liquid.[a] Continue in this mode for 25 minutes after L1 no longer indicates high liquid level,[b] then return to Normal mode. Use during Partial Drydown Mode only.	V1	L1	N/A	N/A

(a) If this call for Partial Drydown has come with 900 seconds (15 minutes) of the completion of the previous call for this mode, call for transition to Shutdown.
(b) If after 600 seconds (10 minutes) Q1 still indicates high level in the evaporator, call for transition to Shutdown.

continued-

Table 7 - continued

SHUTDOWN MODE

Control	Control Parameter	Description	Actuator(s)	Sensor(s)	Setpoint	Setpoint Range
Waste Quantity	Waste Tank Level	Call transition to Normal sequence.	All	Q1	15.6 ℓ (34.3 lb)	±0.2 ℓ (0.4 lb)
		Requests for startup must not be honored if Q1 is below the minimum allowed.		Q1	1.5 ℓ (4.4 lb)	±0.2 ℓ (0.4 lb)

TABLE 8 VCDS SENSOR LIST

Description	Quantity	Redundancy Level	Systems Symbol
Condenser Pressure	1	1	P1
Compressor ΔP	1	1	P2
Recycle Filter Tank ΔP	1	1	P3
Condenser Temperature	1	1	T1
Recycle Fluid Temperature	1	1	T2
Evaporator Temperature	1	1	T3
Product Water Conductivity	1	1	K1
Evaporator Liquid Level	1	1	L1
Product Water Flow	1	1	F1
Valve Position Indicators	5	1	W1,W2,W3, W6,W7
Waste Storage Tank Liquid Quantity	1	1	Q1
Still Motor Speed	1	1	S1
Centrifuge Speed	1	1	S5
Purge Pump Speed	1	1	S2
Fulids Pump Speed	1	1	S3
Total	19		

TABLE 9 VCDS CONTROL/MONITOR INSTRUMENTATION CHARACTERISTICS

Dimensions (Depth x Width x Height), cm (in)	53.3 x 53.3 x 72.6 (21 x 21 x 28.6)
Weight, kg (lb)	100 (221)
Power Consumption, W	696
Line Voltage, V	115/200, 3Ø; 115, 1Ø
Line Frequency, Hz	400, 60
Input Sensor Signal Range, VDC	0 to 5
Output Actuator Signal Range, VDC	0 to 5
Processor	
Type of Computer	CAI LSI-2/20 Minicomputer
Word Size, Bits	16
Memory Size, Words	16K Core
Memory Speed, ns	1200
Instruction Cycle Time, ns	150
I/O Transfer Rate, Megawords/s	1.67
Other Important Features	• Real Time Clock • Hardware Multiply/Divide • Stack Processing • Automatic and Blocked Input/Output • Power Fail Restart
Input/Output	
Number of Analog Inputs	9
Number of Analog Outputs	2
Number of Digital Inputs	11
Number of Digital Outputs	6
Transfer Rate, Megawords/s	1.67
Front Panel	
Command Inputs	Pushbutton Switches
Message Display	(a) Color-Coded Indicators and (b) 9 in CRT Display
Display CRT Capacity, characters	1,920 (80 x 24)
Number of Manual Overrides	11
Operating Modes	
Number of Operating Modes	5
Number of Allowable Mode Transitions	10

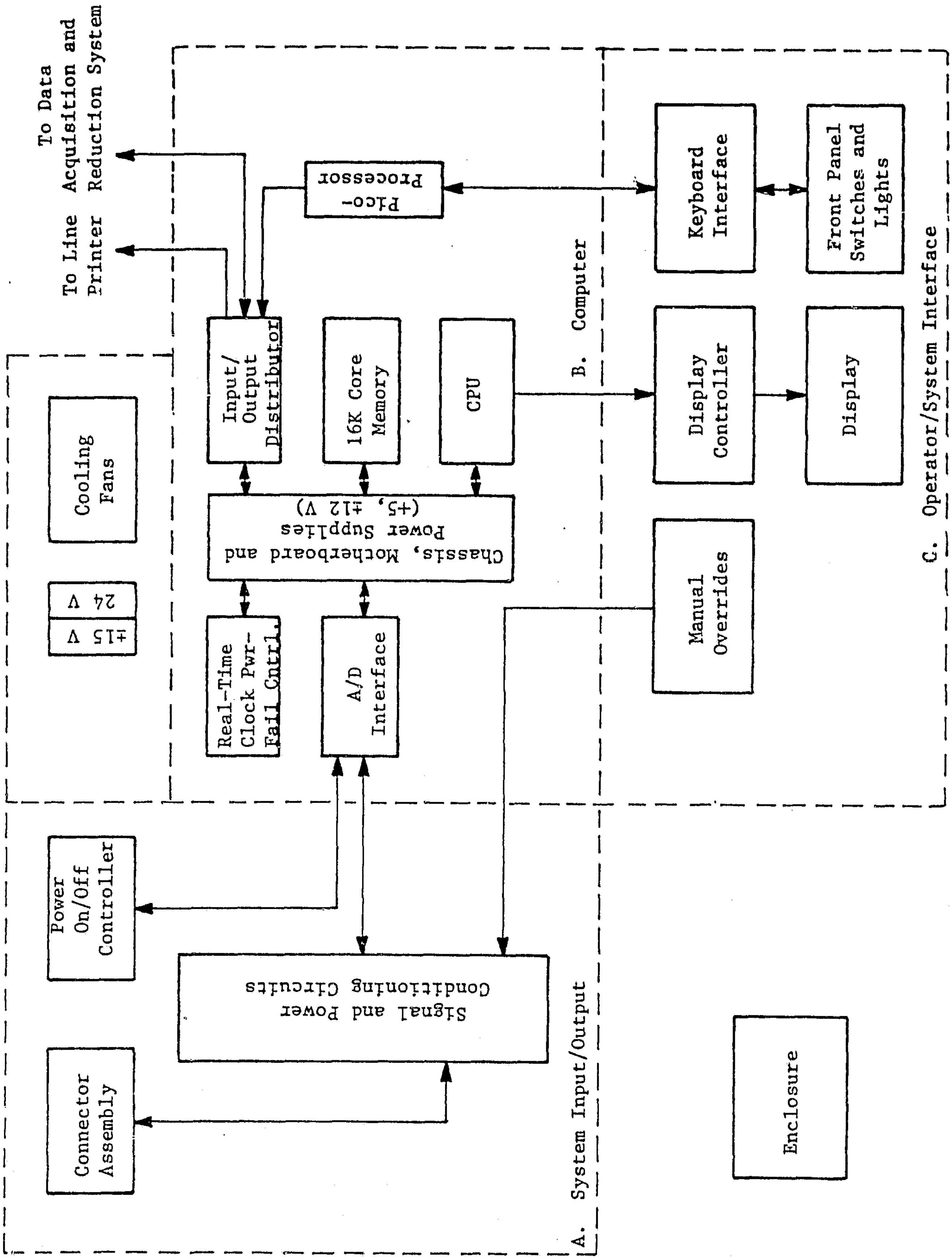


FIGURE 16 C/M I HARDWARE BLOCK DIAGRAM

The C/M I hardware and software are designed to provide real-time process control and communication between the operator and the subsystem. On the operator/subsystem interface side, the C/M I provides the operator with a front panel with keyboard designed to accept operator commands and display subsystem messages. On the process side an A/D interface board is used for communication of the minicomputer with the sensors and the actuators on the mechanical portion of the subsystem.

Figure 17 shows the advanced operator/subsystem front panel of the VCDS C/M I. All commands, control and status information of the VCDS are communicated through this panel.

The operator/subsystem front panel is subdivided into three distinct sections.

1. The subsystem status display section which includes subsystem status indicators (normal, caution, warning and alarm) and a CRT display for operator/subsystem messages such as monitor commands, control setpoints and maintenance instructions.

2. The subsystem control panel section which contains operating mode/commands switches, control status indicators, automatic protection switches, actuator override switches and actuator controls.

3. An operator commands section which includes a keyboard for entering operator commands.

Figure 18 illustrates the rear panel of the VCDS C/M I. It shows the panel mounted connectors for the sensors, TSA, valves, pumps and motors, and power input. It also shows the access to the CRT display controller subassembly (middle section) and the rear of the minicomputer.

Software Description

The software of the instrumentation can be divided into two portions: (1) control and monitor modules and (2) communication modules for operator/subsystem interface and data acquisition functions. The software structure is shown in Figure 19. The control and monitor modules are run under the direction of a Real-Time Executive (RTE) software routine. The software RTE handles the automatic scheduling of the input/output modules, operating mode control and mode transition modules, parameter control modules, and fault detection, isolation and trend analysis modules.

The communication modules for operator/subsystem interface data acquisition functions include the front panel command handler and the DARS handler. The front panel command handler accepts the operator commands, displays operator/subsystem messages, controls front panel lights and interprets the commands entered. As a part of the display routine, a software module permits the CRT display messages to be printed on a line printer connected to the C/M I through the interface panel. The front panel command handler has built-in command validity checking functions to avoid operator mistakes and to prevent unauthorized use of the front panel. The DARS handler transmits the digitized process parameters to the DARS for test data recording.

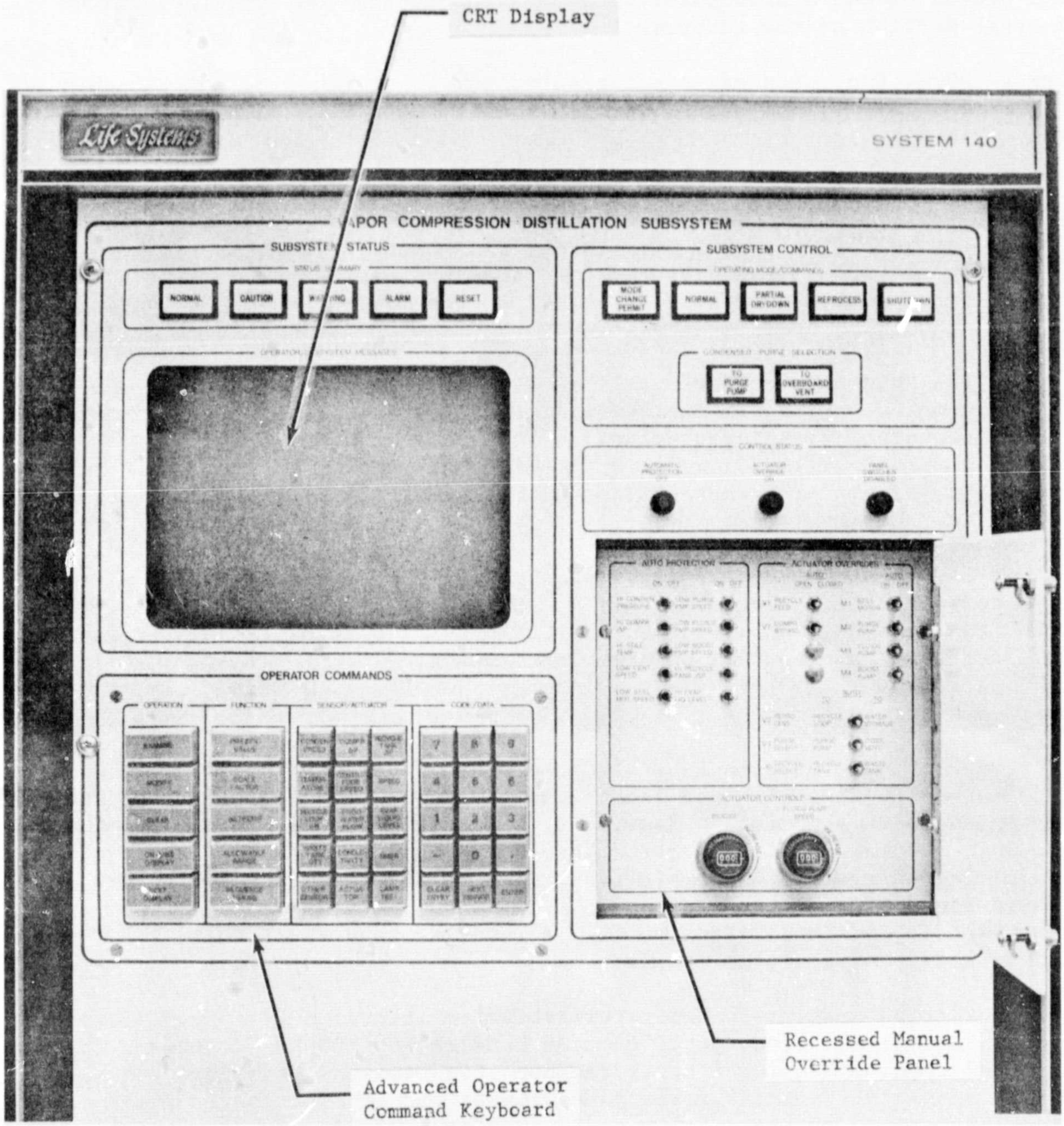


FIGURE 17 C/M I OPERATOR/SUBSYSTEM FRONT PANEL

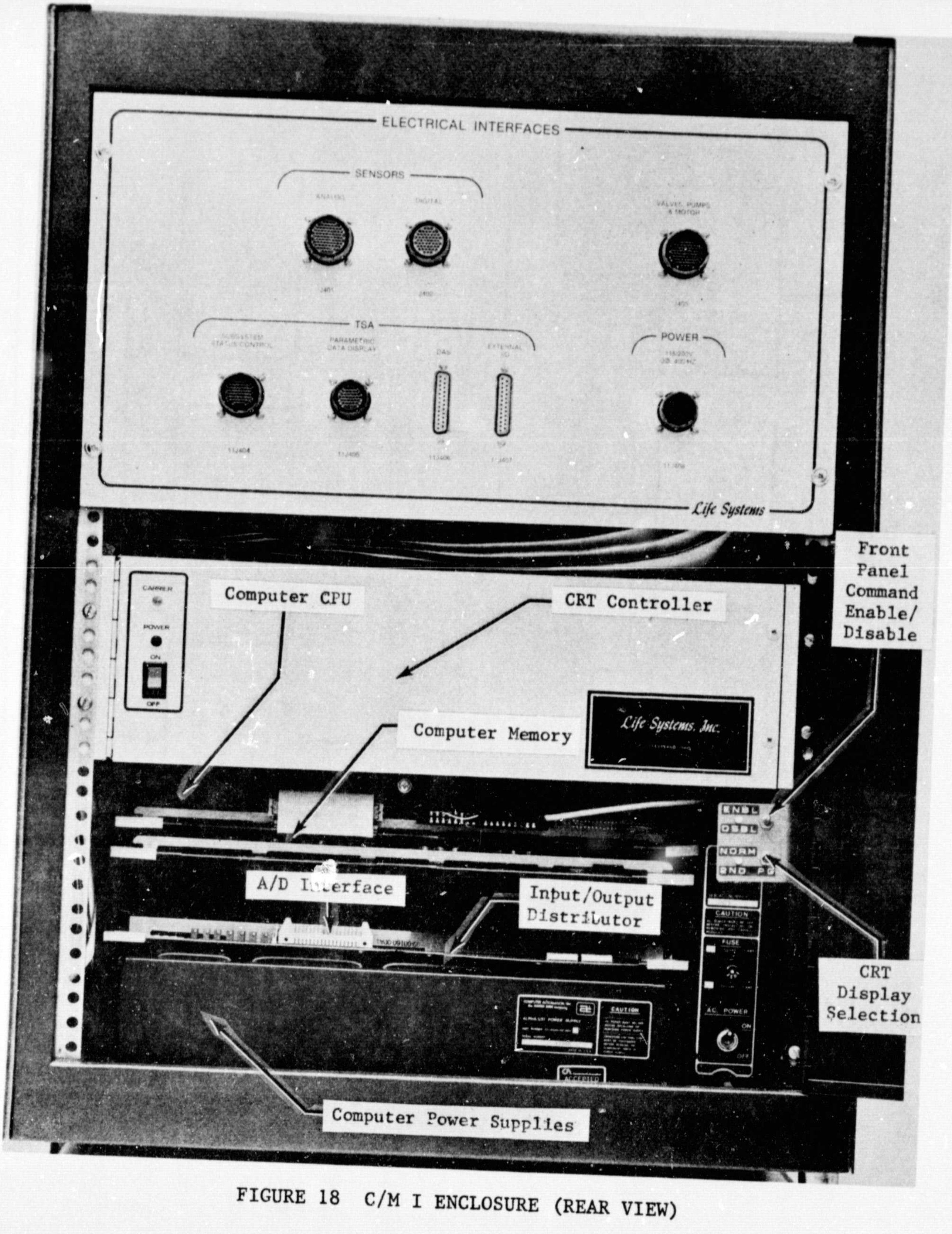


FIGURE 18 C/M I ENCLOSURE (REAR VIEW)

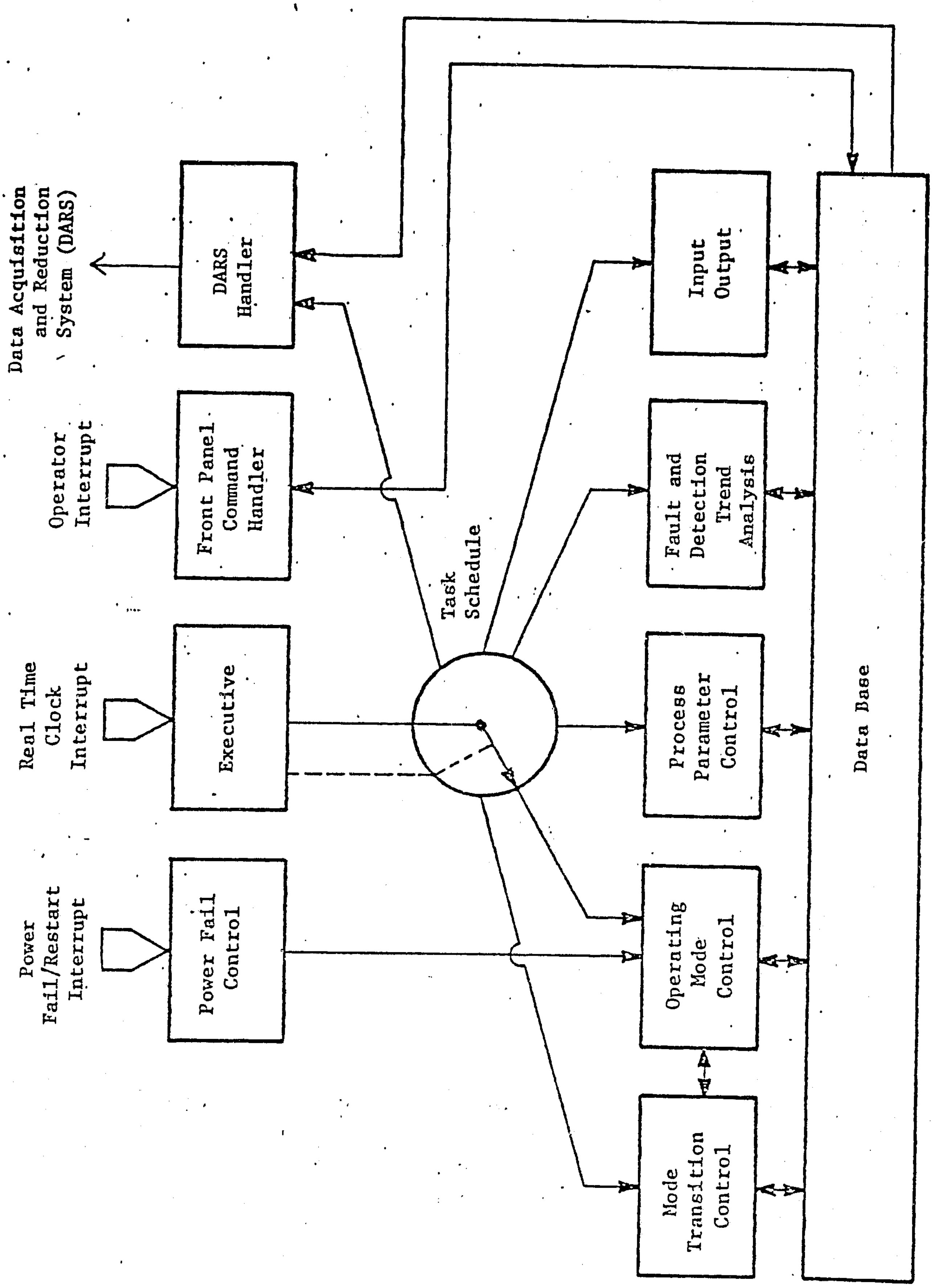


FIGURE 19 C/M I SOFTWARE BLOCK DIAGRAM

Control

The process parameters controlled by the automatic C/M I include compressor differential pressure, conductivity, waste tank liquid level and evaporator liquid level.

The process parameters monitored for system performance trend analysis include the above parameters plus condenser absolute pressure, recycle tank differential pressure, centrifuge speed, product water flow, purge pump speed, fluids pump speed, condenser temperature, recycle fluid temperature and evaporator temperature. The performance trend analysis compares a parameter reading with setpoints indicating Caution, Warning and Alarm thresholds. Visual displays indicating whether a parameter is in Normal, Caution, Warning or Alarm range are provided on the front panel.

The process operating mode control is a relatively complex operation. It includes selection of valve positions, sequencing of actuators and checking parametric conditions as transitions proceed. This procedure for control is fully automated by the C/M I so that the operator is only required to press the mode change request buttons to initiate a mode transition sequence.

PRODUCT ASSURANCE PROGRAM

The Product Assurance Program encompasses the activities associated with Quality Assurance, Reliability, Safety, Materials Control and Maintainability.

Quality Assurance

The Quality Assurance activities for the VCDS consisted of the following:

1. Participation in the design phase of the program to search out quality weaknesses and recommend appropriate corrective measures.

2. Participation in design activities to ensure that the Quality Assurance inputs were included in design studies, trade-off analyses, engineering assessments and interface requirements.

3. Performance and documentation of receiving, in-process and final inspection of all VCDS components.

4. Ensuring configuration control as required by monitoring the drawing and change control procedures.

5. Monitoring subsystem checkout, shakedown and design verification tests.

6. Controlling Life Systems failure/problem reporting for the testing phase of the VCDS program.

Reliability

The reliability tasks accomplished consisted of performing a Failure Mode, Effects and Criticality Analysis (FMECA) and identifying single point failures.[a] The FMECA presents all hypothesized equipment failure modes and describes the effects of each failure mode on individual components. The analysis also describes the failure detection method and crew action required to correct the component failure mode. The FMECA identifies safety hazards and single point failures and was used to verify subsystem instrumentation requirements. An example of an FMECA is presented in Figure 20.

The results of the FMECA performed on the VCDS revealed that there are no critical subsystem failures which result in single point failures.

Safety

The safety program carried out in conjunction with the design and development of the VCDS consisted of:

1. Monitoring subsystem and component design for compliance to Life Systems' safety design criteria.
2. Identification of dangerous subsystem characteristics and failure modes. This was done in conjunction with the FMECA performed on the subsystem.
3. Review both the nonmetallic and metallic materials included in the design to assure that personnel and subsystem safety were not impaired by use of unacceptable materials.
4. Review of designs and design changes for potential safety problems.
5. Review of NASA Alerts for safety information.
6. Review of test plans and procedures to ensure that safety precautions were included.
7. Review of failure/problem reports to assure that corrective action taken did not have safety impact on the design.
8. Review of the instrumentation design to assure that a failure detection mechanism and warnings were provided for all failures which could have a safety impact on crew or the subsystem.

Materials Control

The materials control activities consisted of reviewing the VCDS LRU designs to ensure that the materials selected were compatible with the highly corrosive

(a) A single point failure is a single failure that could cause loss of personnel, cause return of one or more crew members to earth or could make it possible for the next associated failure to cause loss of personnel.

Life Systems, Inc. CLEVELAND, OHIO 44122	FAILURE MODE, EFFECTS & CRITICALITY ANALYSIS	PAGE 1 OF 1	REVISION LTR.
			DATE 10/31/77

TITLE VALVE, TWO-WAY, SOLENOID ACTUATED

☐ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
	V1	Two-Way Solenoid Actuated Valve	Valve is used to stop recycle liquid flow during partial drydown mode and is used to shut off the flow of waste to the fluids pump during shutdown mode.

FAILURE MODE AND CAUSE:

(a) Fails open.
(b) Fails closed.
(c) External leakage.

CRITICALITY

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:

(a) Valve remains open at all times.
(b) Valve remains closed at all times.
(c) Valve permits recycle liquid to leak from it.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:

(a) If the valve fails open, it is impossible to switch the subsystem to the partial drydown mode as recycle liquid flow to the still cannot be stopped. Eventually a second high evaporator liquid level shutdown occurs. In addition, if the valve fails open when going to the shutdown mode, total drydown is not possible and waste fluid may remain in still.
(b) If the valve fails closed, it will not be possible to process waste from the waste storage tank as the flow to the still would be shut off. Eventually the waste storage tank would fill and urinals would backup.
(c) If the valve leaks recycle liquid will contaminate the cabin atmosphere. Materials contacted by the recycle liquid may be subject to corrosion.

FAILURE DETECTION METHOD:

(a) Valve position indicator W1, liquid level sensor in the still, L1.
(b) Valve position indicator W1, flow sensor F1 and quantity sensor Q1.
(c) Visual observation of leak.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
(a,b) Replace the faulty valve. (c) Repair if leak is at fittings, otherwise replace the valve.		

FIGURE 20 FAILURE MODE, EFFECTS & CRITICALITY ANALYSIS

environment of the VCDS. In addition, fabrication processes were reviewed to ensure that the metallurgical structure of corrosion resistant materials would not be changed as a result of fabrication. For example, 316L stainless steel was specified for all weldments in order to prevent carbide precipitation which occurs when welding 316 stainless steel. This carbide precipitation depletes the Cr content of the stainless steel, thereby, making it susceptible to corrosion. Table 10 lists, by component, the materials wetted by recycle liquid.

Maintainability

The maintainability activities performed in conjunction with the design of the VCDS were:

1. Participation in the design and mock-up reviews to ensure that the maintenance and packaging considerations listed in the design report were adhered to.

2. Preparation of a Familiarization/Operation and Maintenance/Repair Manual for the VCDS.

TEST SUPPORT ACCESSORIES

Various items of support equipment are required to simulate the actual spacecraft interfaces of the VCDS. These TSA, shown in Figure 21, are needed to compensate for the absence of spacecraft cabin resources (power, wastewater and vacuum). Four distinct TSA functions were provided: (1) fluid interface simulator, (2) electrical interface simulator, (3) parametric data display and (4) analytical apparatus.

Fluid Interface Simulator

The fluid interface simulator is designed to feed the following liquids to the pretreatment port of the VCDS through a progressive cavity pump: (1) urinal flush, (2) urinal flush with pretreat, or (3) urine with pretreat. The fluid interface simulator also simulates space vacuum. This is done through the use of a vacuum pump and a dry ice cooled liquid trap. A third function of the fluid interface simulator is to accept the water recovered from the product water port of the VCDS. This is done by a graduated cylinder, either directly from the VCDS or through a boost pump, to increase the delivery pressure.

Electrical Interface Simulation

The electrical interface simulator supplies the C/M I with 115/200 VAC, 400 Hz, 3Ø and 115 VAC, 60 Hz, 1Ø power.

Parametric Data Display

The parametric data display provides for the analog and digital readout of parameters necessary to monitor the performance of the subsystem during the program test phase. Since the VCDS does not require parametric data display instrumentation to perform its intended function, the parametric data display

TABLE 10 WETTED MATERIAL

Wetted Components	Materials
Centrifuge:	
Drums	316L
Seals	Teflon, CRES
Bearings	CRES, Brass
Pulley	Lexan
Drive, O-Ring	Viton-A
Drive, Belt	Neoprene
Toothed Pulley	Delrin
Pumps:	
Tubing	PVC (Norton R-3603)
Water Storage Tank:	
Tank	316L
Diaphragm	Buna-N
Piston	Polypropylene
Recycle/Filter Tank:	
Tank	316L
Filter	Polypropylene
Seal	Viton-A
Solenoid Valves:	
Body	430 F
Seat	Viton
Manual Valves:	
Body	316
Stem	316
Packing	TFE
Check Valves:	
Body	316
Seat	Buna-N
Spring	301
Pressure Sensors:	
P1, P2, P3	347, Carpenter 20 NI-Span C
Thermistors:	
Sheathed	316L
Liquid Level Sensor:	
Thermistor	Glass
Potting	Epoxy
Plumbing:	
Tubing	316L
Compression Fittings	316
Weld Fittings	316L

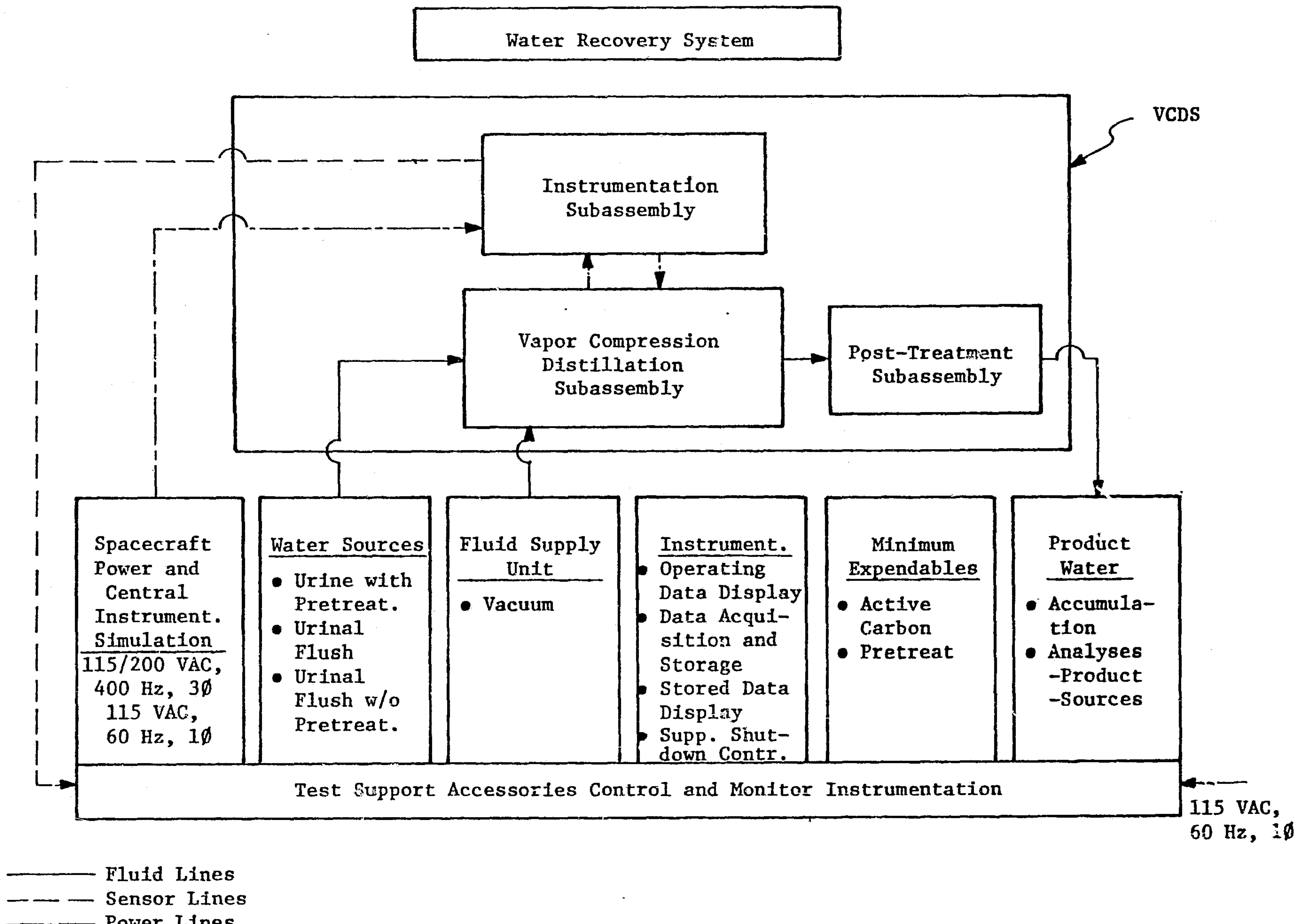


FIGURE 21 VCDS/TSA INTERFACES

has been designed only to read out important parametric test data. The front panel of the parametric data display is shown in Figure 22. For temperature monitoring, a digital display is provided for the readout of the various thermocouples in the subsystem, and an analog readout for a thermistor is used to monitor ambient temperature. Product water flow readout is provided on an analog meter. Recycle loop liquid pH readout is provided by an analog meter, and a control shutdown point may be set on the accompanying potentiometer. Provision for high pH shutdown is included because a high pH in the recycle liquid may cause precipitation, clogging and poor water quality. Power consumption of the various motors in the VCDS is monitored on an analog meter. A rotary switch selects either the still motor or one of the pump motors. The toggle switch selects which pump motor will be displayed. The chart recorder which accompanies the power monitoring section continuously measures the still motor power. Also, the chart records the power of the pump which is currently selected by the toggle switch. The VCDS condensate is delivered either through a boost pump or directly to the final collection vessel. On the parametric data display, the pressures before and after the boost pump are displayed on gauges. A regulator for adjusting the VCDS output head pressure and a metering valve for adjusting the boost pressure head are provided.

Analytical Apparatus

Standard laboratory analytical equipment was used to test VCDS product water quality. Specific tests made were for taste, odor, pH and conductivity.

Pretreatment Formula

The pretreat solution in the VCDS serves four functions: (1) to inhibit microbial growth in the water storage tank and still (in an actual system this would include urine collection hardware), (2) to minimize noncondensable volatiles (ammonia and organics, consisting mainly of siloxanes), (3) to control foaming and (4) to prevent precipitation in the still and recycle loop. During an evaluation of possible pretreat solutions, a LSI-unique solution was derived based on discussions with vendors, consultations with NASA-JSC, and the prior results of the SSP program. The problems associated with the SSP pretreat solution were: (1) the iodophor decomposes forming dioxane, (2) the iodophor foams excessively and (3) the antifoam agents decompose in the acidic pretreat solution forming volatile siloxanes.

The LSI pretreat solution used for the VCDS consists of the following components: iodophor (Biopal VRO-20), antifoam (SWS-211), acid (sulfuric acid) and water. The quantity of each component per micturation is 0.61 g (0.02 oz) Biopal VRO-20, 0.13 g (0.005 oz) antifoam, 0.61 g (0.021 oz) sulfuric acid, and 1.17 g (0.04 oz) water or a total of 2.52 g (0.09 oz).

TEST PROGRAM

The VCDS test program as outlined in the Master Test Plan was designed to demonstrate system maturity and characterize its baseline operation. The program was parametric in nature and determined the effect of variations in operating parameters that will be encountered during flight. These parameters are ambient temperature, feed water composition and operating time.

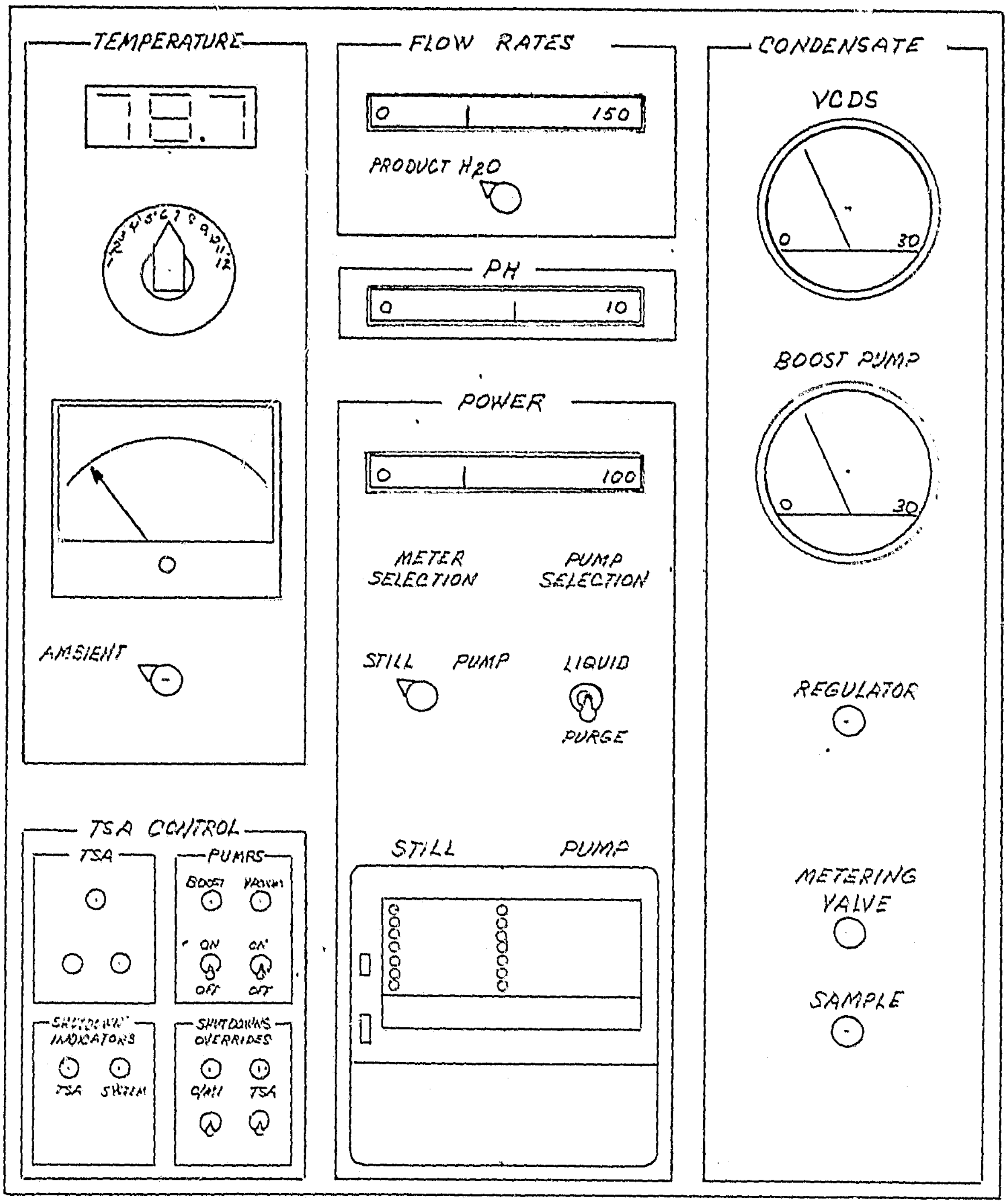


FIGURE 22 VCDS PARAMETRIC DISPLAY

Checkout/Calibration Test

In addition to functionally checking each component and calibrating the subsystem sensors, a vacuum leak test was performed on the VCDS distillation unit. As can be seen in Figure 23, the still was found to leak at the low rate of 0.089 mm Hg/h. This greatly exceeded the design goal which is also indicated in Figure 23 for comparison.

During the 31.4 hours of checkout testing, water production was 0.8 kg/h (1.8 lb/h) when both deionized water and deionized water with pretreat were processed.

At the completion of this phase of the test program, a modification to the steam path between the compressor and the condenser was implemented. (See Supporting Technology Studies.)

Shakedown Test

Shakedown testing demonstrated the function of the integrated subsystem and TSA, while operating for four days. Included was 24 hours of continuous operation to demonstrate subsystem stability. Deionized water, deionized water with pretreatment solution, and pretreated urine were processed at 1.36 kg/h (3.0 lb/h) during shakedown testing, as shown in Figure 24.

The overall heat transfer coefficient, from the condenser to the evaporator, was calculated from data collected while processing water during shakedown testing. This data was selected, over urine processing data, because the enthalpy change of the water is known precisely. The overall heat transfered is represented by:

$$q = UA\Delta T$$

where:

q = Energy transfered in BTU/h
U = Overall Heat Transfer Coefficient BTU/h cm^2 K (BTU/h ft^2 F)
A = Evaporator Surface Area = 2,694 cm^2 (2.9 ft^2)
ΔT = Temp. Cond. - Temp. Evap. = 302.5 K (85.2 F) - 298.8 K (78.5 F)

The energy received by the evaporator may also be expressed as:

$$q = \dot{m}\Delta h$$

where:

$\dot{m}$ = Steam Generation Rate = 1.25 kg/h (2.75 lb/h)
Δh = Phase Change Enthalpy = 2,306 BTU/kg (1048 BTU/lb)

Thus, U may be calculated as:

$$U = \frac{\dot{m}\,\Delta h}{A\,\Delta T} = \frac{1.25\text{ kg/h} \times 2306\text{ BTU/kg}}{2694\text{ cm}^2 \times 3.7\text{ K}} = 0.289\ \frac{\text{BTU}}{\text{h-cm}^2\text{-K}}\ (148\text{ BTU/h ft}^2\text{ F})$$

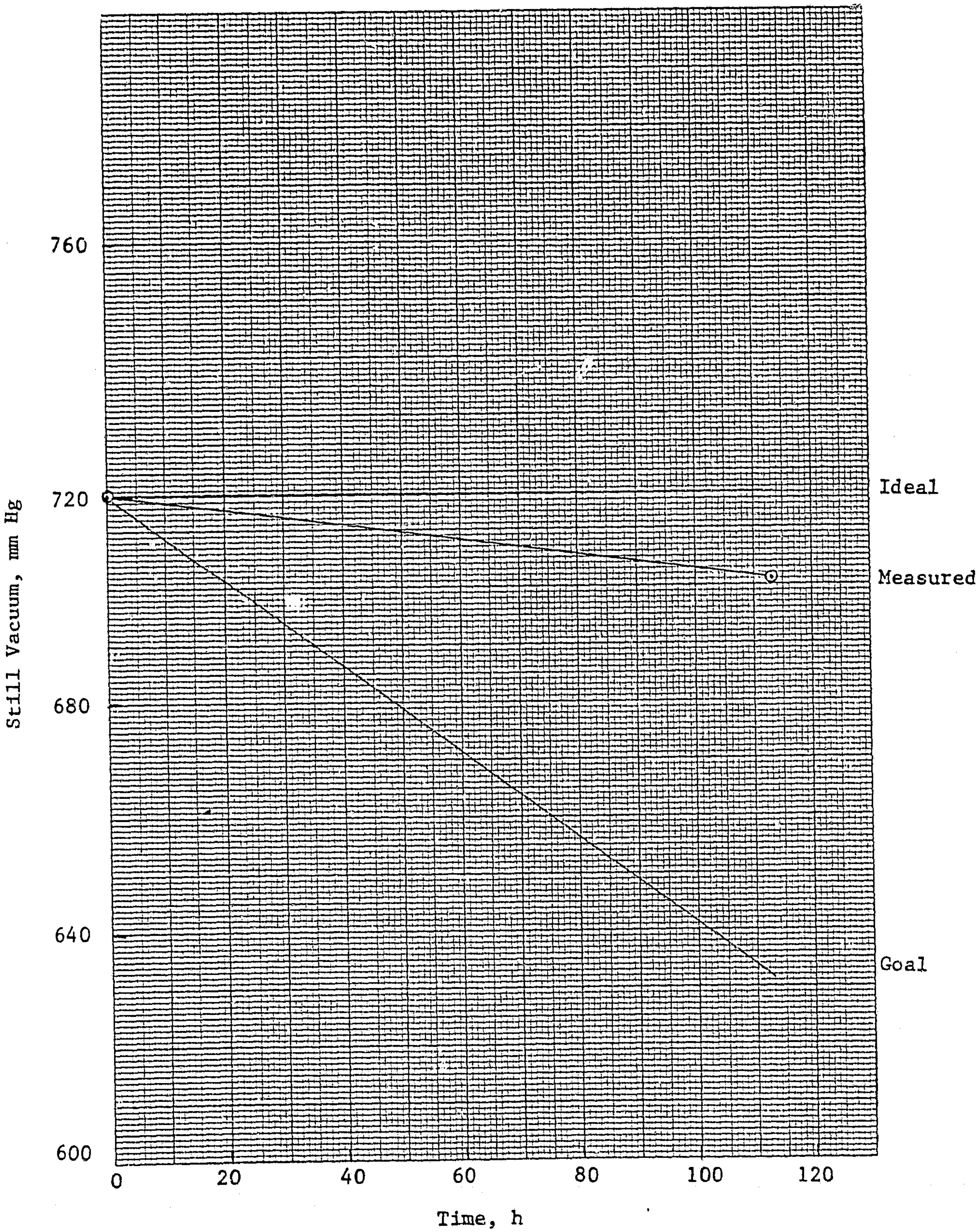


FIGURE 23 STILL VACUUM LEAK TEST

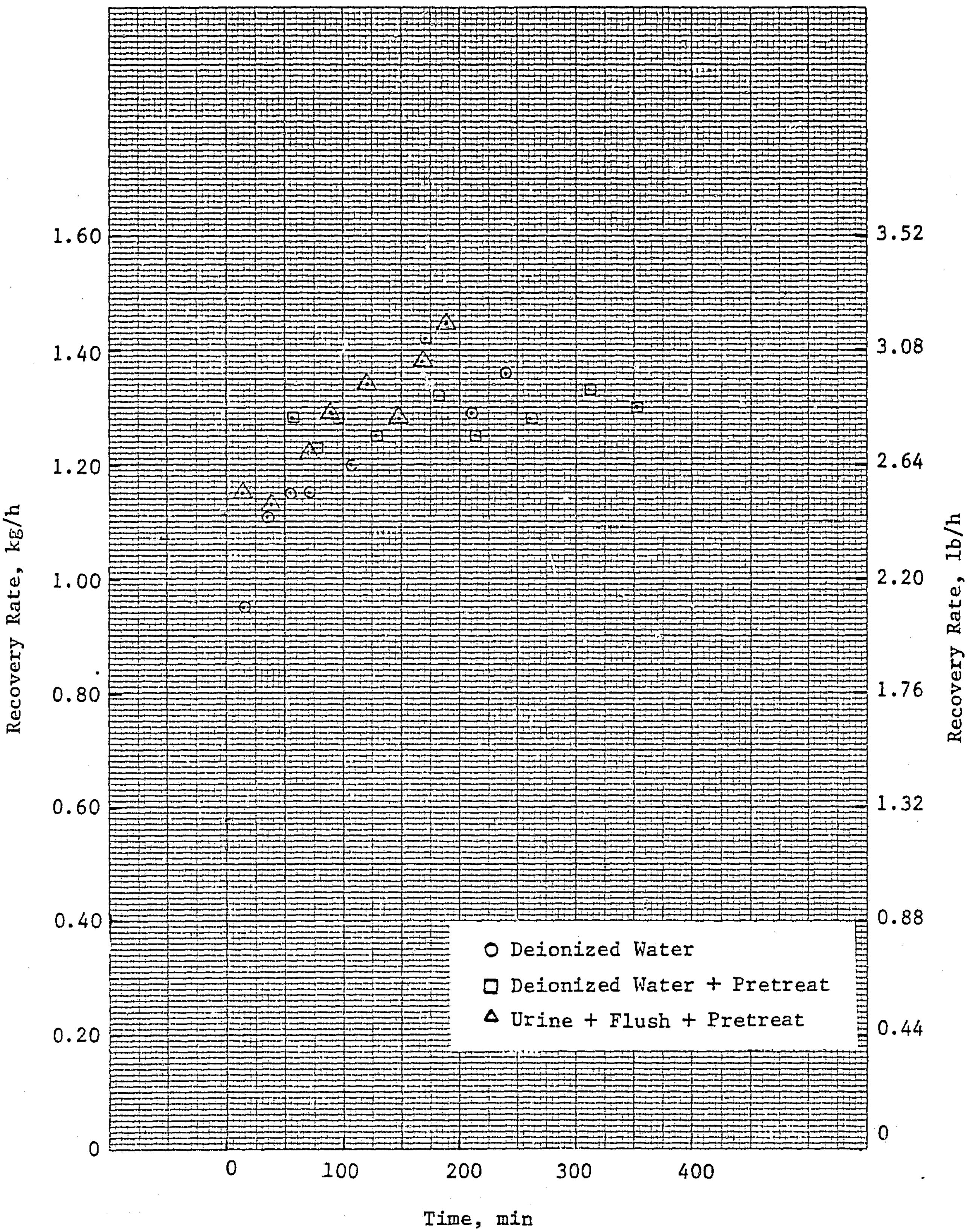


FIGURE 24 SHAKEDOWN TEST

Parametric Testing

Parametric testing included both verification testing to demonstrate the achievement of design performance levels and baseline testing to establish operating conditions and subsystem operability as a function of time. Parametric data was gathered throughout the 12 days of operation.

Subsystem performance, as affected by condenser temperature and percent dissolved solids in the recycle loop, is shown in Figure 25. The condenser temperature was found to reach a level of about 8.3 K (15 F) above ambient and the VCDS environment varied from 289 K (60 F) to 298 K (77 F) periodically throughout the test program.

Water lost through continuous purging was found to be approximately 1% of the water recovered. This met the design goal of $\leq$1% water lost.

Supporting Technology Studies

As part of the contractual effort, several studies directed toward the advancement of the VCDS technology were completed. The studies were grouped into seven different areas. A short description and major results of the studies are listed in Table 11 and further described below. These studies provided valuable information which led to improved VCDS hardware and performance and subsystem operation as well as the establishment of further technology goals.

Steam Path Modification

A deflection was introduced to direct the steam from the compressor outlet to the condenser along the shortest path.

Gear Lubrication Investigation

A lubrication approach for the compressor timing gears was demonstrated. The VCDS was operated with this lubrication approach in the Normal mode for 236 h, of which 186 h was uninterrupted, before it was shutdown for shipment. There was no indication of gear degradation throughout this demonstration.

Pump Tubing Tests

Tests of three different types of tubing were conducted to assess their resistance to failure under the flexure loading experienced in a peristaltic pump. The results, shown in Figure 26, indicate the Norton R-3603 compound, used by LSI, was the most durable at 6 x 10^7 flexures.

High Temperature Operation

A study was done to characterize a VCDS operating with the evaporator temperature greater than 373 K (212 F). Condenser pressure would be above 101 kPa (14.7 psia) and therefore a purge pump would not be required since noncondensable gases could be vented from the higher pressure still to ambient or overboard. A reduction in subsystem hardware size and energy consumption would result. Additional studies are recommended to further quantify potential energy savings.

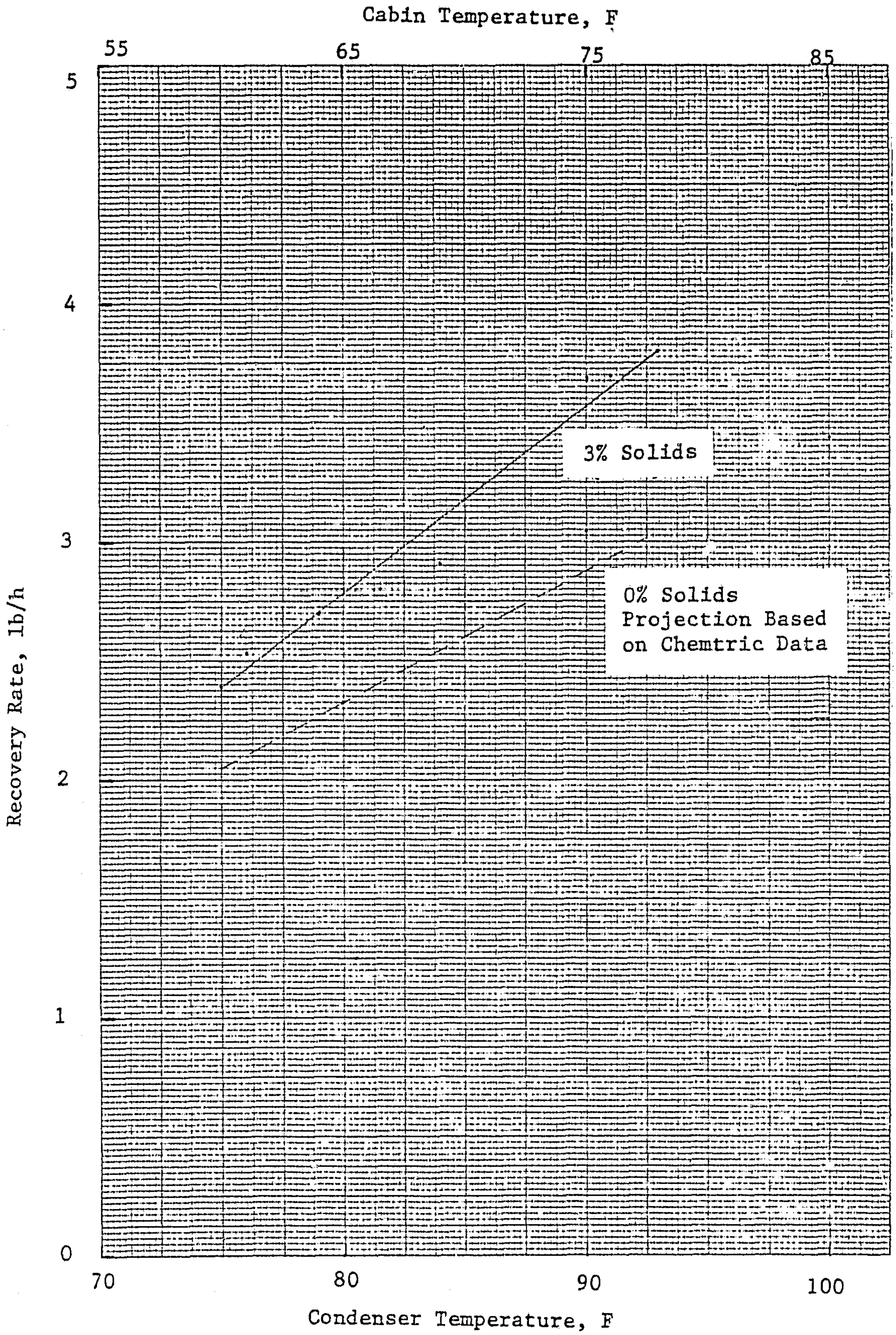


FIGURE 25 SUBSYSTEM PERFORMANCE, RECOVERY RATE VERSUS CONDENSER TEMPERATURE

TABLE 11 SUPPORTING TECHNOLOGY STUDIES SUMMARY

Title	Description	Result
Steam Path Modification	Determine effect on performance of routing steam directly to condenser versus indirectly for superheat removal	Direct steam routing increased the water recovery rate from 0.8 to 1.4 kg/h (1.8 to 3.0 lb/h).
Gear Lubrication Investigation	Demonstrate effect on compressor timing gear life of continuous lubrication versus unlubricated operation.	Light oil lubrication permitted 236 hours of operation with no sign of degradation compared to a maximum previous gear life of 120 hours.
Pump Tubing Tests	Subject various types of tubing to flexural stresses in a commercial peristaltic pump	Norton R-3603 proved the most durable, lasting 6×10^7 flexures.
High Temperature Operation	Determine feasibility of operating a VCDS at above ambient pressure.	Potential for reduction of both subsystem weight and power consumption.
Purge Pump Tests	Test peristaltic purge pump with two different torque and speed motors, and with two different size tubings.	Pump was found capable of reaching 711 mm Hg (28 in Hg) vacuum but was limited to a flow rate of 0.98 l/min (60 in^3/min).
Computer Math Model	Steady-State Simulation of VCDS.	Predicts actual values within tolerances of measurement hardware.
Pretreatment Solution for RO Brine	Compare the pretreatment requirements of RO brine and those of urine.	A single formulation for treatment of RO brine and urine is not suitable.

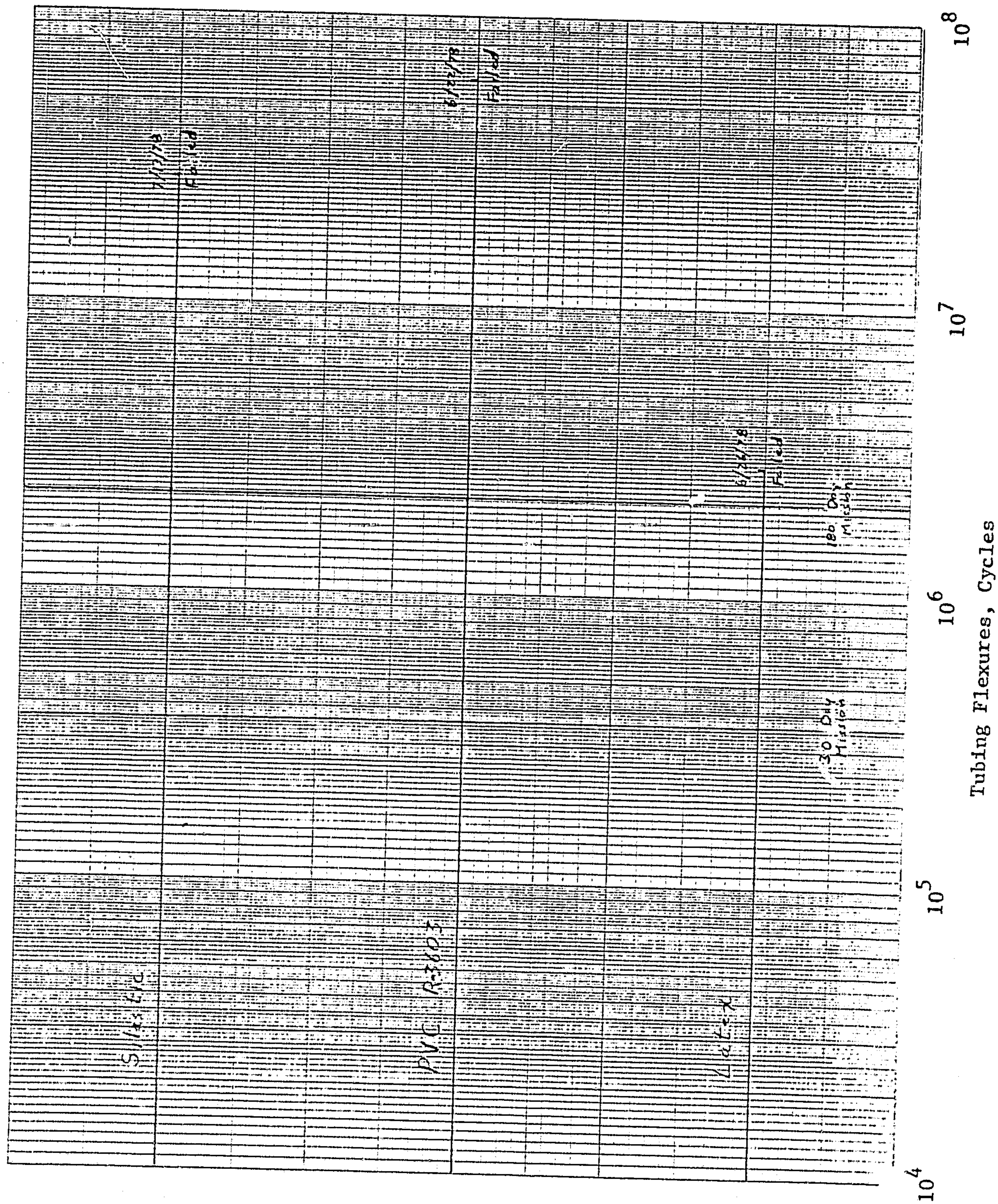


FIGURE 26 PUMP TUBING TESTS

Purge Pump Tests

Life Systems, after careful evaluation and with the concurrence of NASA-JSC, selected to complete the peristaltic purge pump development based on the preliminary design work provided by NASA-JSC. The pump was fabricated and tested. The following was observed during testing:

1. The squeeze required to simultaneously close the inlet and outlet tubing sections of the pump was excessive.

2. The drive belt tensile strength and configuration was not adequate to carry the higher loading imposed by the excessive tube squeeze required by the design.

3. The drive motor did not develop sufficient torque to overcome the higher loading.

Life Systems derived and implemented a technique to minimize tubing over-squeeze. As part of this activity a new drive belt was selected and the gear sprockets were remachined to match the new belt configuration. This modified purge pump was assembled and used to further evaluate the overall purge design. The following results were obtained:

1. The pump could deliver 3.7 l/min (228 in^3/min) using the initial tube and motor design (2.54 cm (1.0 in) O.D. and 28 W, respectively). This rate could not be achieved below a source pressure of 95.2 mm Hg (8 in of Hg), vacuum. The design values for pumping rate and source pressure are 6.6 l/min (400 in^3/min) and 711 mm Hg (28 in Hg) vacuum, respectively.

2. With a slower speed motor (23 rpm versus design level of 32 rpm) and the baseline 2.54 cm (1 in) O.D. tubing, the pump achieved a flow rate of 4.9 l/min (296 in^3/min), but only to a source pressure of 483 mm Hg (19 in Hg) vacuum.

3. With a lower diameter tubing (1.1 cm (0.44 in) O.D. versus 2.54 cm (1.0 in) O.D.) and the initially selected 28 W motor, the purge pump could operate to its designed level of 711 mm Hg (28 in Hg) vacuum source pressure, but only at a flow rate of 0.98 l/min (60 in^3/min).

Computer Math Model

A steady-state computer simulation model[a] has been developed to study the operation of the VCDS subsystem. The model predictions agree closely with experimental data and may be used for predicting performance under conditions not achieveable in the laboratory, such as a zero gravity environment.

Pretreatment Solution for RO Brine

A study was performed to determine the pretreatment solution requirements for use with the RO brine derived from wash water. It was concluded that a single

(a) LSI ER-312-22, Computer Model User's Manual pretreatment formulation would not be suitable for use with both urine and RO brine. A recommended approach that should be examined in a more extensive study would be the separate addition of the acid and antifoam constituants so that their proportions may be varied in accordance with the waste liquid being processed.

CONCLUSIONS

The following conclusions were reached, based on the development program.

1. The low pressure VCD technique is a viable solution for water recovery from wastewater aboard manned spacecraft.

2. The ability to automatically control and monitor the VCDS process was demonstrated over 35 days of testing while processing liquid with 0% to 6% dissolved solids.

3. Peristaltic pumps can be made to operate on low power and are durable enough for extended missions, as was demonstrated by the 28 W liquids pump.

4. Low friction dynamic seals capable of providing an effective seal between cabin pressure and vacuum can be achieved by the magnetic containment of a magnetic fluid, as was demonstrated on the still and the purge pump.

5. A heated corrosion-resistant thermistor is a viable approach for detecting a high liquid level condition in the evaporator.

6. A radial flow demister can be incorporated in the still and thereby circumvent the friction and sealing problems of an axial flow design.

7. A centrifuge which is structurally continuous from bearing to bearing can be produced with good maintenance characteristics. The centrifuge design provides for precise reassembly with regard to dynamic balance and pickup tube alignment.

8. The product water conductivity monitor demonstrates an approach to maintainability which permits insertion into and removal from a fluid line without process flow interruption.

RECOMMENDATIONS

The following recommendations are made as a result of the work completed under this program.

1. Although the LSI-developed VCDS has been parametrically tested, it has not undergone extensive endurance testing. This should be done to facilitate judicious design of the prototype unit.

2. Determine, by experimentation, the effect of centrifuge speed on still performance.

3. Determine, by a combination of analytical investigation and empirical testing, the optimum recycle flow rate to the still.

4. The VCDS test data indicates that increasing process temperature increases the production rate for a given still. Testing of the VCDS at slightly higher than above ambient pressure operation should be conducted to document this potentially very attractive region of operation.

5. The VCDS has demonstrated itself as a viable approach to water recovery from on-board wastewater. In order to take technology to the next step, a subsystem which optimizes weight, volume and power should be designed, fabricated, assembled and tested.

6. The recycle filter tank used in all VCD systems to-date has been one that is launched full of water. Both launch weight and total energy consumed could be reduced by a "start empty" recycle filter tank. This concept should be incorporated into the next VCDS design.

7. The bladder-type tank used for waste storage is too large for the volume it holds and is susceptible to bladder failure. A Waste Storage Tank of reduced volume and weight, as well as increased reliability, should be designed, fabricated, assembled and tested.

8. In order to better understand the incorporation of the VCDS into future spacecraft, the composition of the purge gas, under various operating conditions, should be determined.