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VOLUME 1

PRELIMINARY DESIGN AND DEVELOPMENT OF THE INTERMEDIATE WATER RECOVERY SYSTEM

Report No. 70-7018, Rev. 1
March 12, 1971

Combined Final Reports on Contracts
NAS 9-8460
NAS 9-9981

CASE FILE COPY

Prepared for

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas

AIRESEARCH MANUFACTURING COMPANY
Los Angeles, California

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Los Angeles, California

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FOREWORD

This report was prepared by the AiResearch Manufacturing Company of Los Angeles to summarize the results of two programs sponsored by the Manned Spacecraft Center of the National Aeronautics and Space Administration under Contracts NAS 9-8460 (Task B) and NAS 9-9981. These two programs were conducted simultaneously and were concerned with (1) the preliminary design for an Intermediate Water Recovery System (NAS 9-8460) and (2) the design of an Intermediary Water Recovery System (NAS 9-9981). The first contract involved system analyses, which culminated in the preparation of a system specification; the second was concerned with the development of a breadboard unit to provide data for system design. The interactions between the programs were such that a single report was deemed more informative and more logical than two separate reports, each covering the activities of a single contract.

Contract NAS 9-8460, Task A, was initiated in September, 1968, and was concluded with the submittal of the Task A final report (AiResearch Report No. 69-5470) in August, 1969. The overall period of performance of the two contracts covering the activities reported here was from September 1969 to December 1970.

Initially, Mr. Dean Thompson of NASA MSC was the program technical monitor; Mr. Don Hughes was appointed to this post in February 1970. At AiResearch, the program manager was Mr. A. H. Bauer. AiResearch personnel who contributed substantially to these programs include: O. Morton, C. Albright, K. Ikeda, W. Hendrickson, and J. Rousseau.

The report is divided in two volumes. Volume I contains the results of the investigations conducted, Volume 2 contains the appendices. This is Volume I.

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SECTION I

INTRODUCTION AND SUMMARY

GENERAL

The Intermediate Water Recovery System (IWRS) comprises a number of functions concerned with the collection, processing, and storage of urine, wash water and humidity condensate produced by a 3-man crew on board an Earth orbital spacecraft. Mission duration is one year with a 90-day resupply period. Figure I-1 is a block diagram illustrating the overall arrangement of the system. The two processing units are identical and are designed to process water at the same nominal rate of 1 lb/hr. The product potable water can be stored within the IWRS or transferred to the spacecraft water supply. Interconnecting lines permit water transfer from one unit to the other and also provide backup capability in emergency. All waste products from the processing units are stored in the form of a concentrated brine for return to earth at the 90-day resupply period.

BACKGROUND

Feasibility Investigations

Design and development of the IWRS was initiated in 1967. The first phase of the program was conducted under a company sponsored R & D program and resulted in

(a) development of guidelines for system design

(b) selection of processes

(c) feasibility demonstration through the development of a pilot plant system.

The water recovery process selected uses low temperature distillation with vapor pyrolysis as the post-treatment. Vapor compression provides the means for balancing the thermal requirements of the evaporation-condensation processes. Figure I-2 is a schematic of the system.

The system uses a highly concentrated brine solution as the heat transport medium. The brine solution is circulated through a heat exchanger where its temperature is increased. The brine pressure is then reduced below its saturation value in a flash valve. The vapor thus formed is separated from the liquid which is returned to the heat exchanger. As water is extracted from the brine loop, waste water is added to maintain the liquid level in the separator. The solid content of the brine increases until a predetermined concentration is reached; then a portion of the brine is dumped from the liquid loop.

The vapor separated from the brine is compressed, mixed with a minute quantity of oxygen, heated and passed through a reactor; thus trace contaminants which may be present in the vapor are oxidized. Also, any bacteria entrained with the vapor are killed in the high temperature reactor.

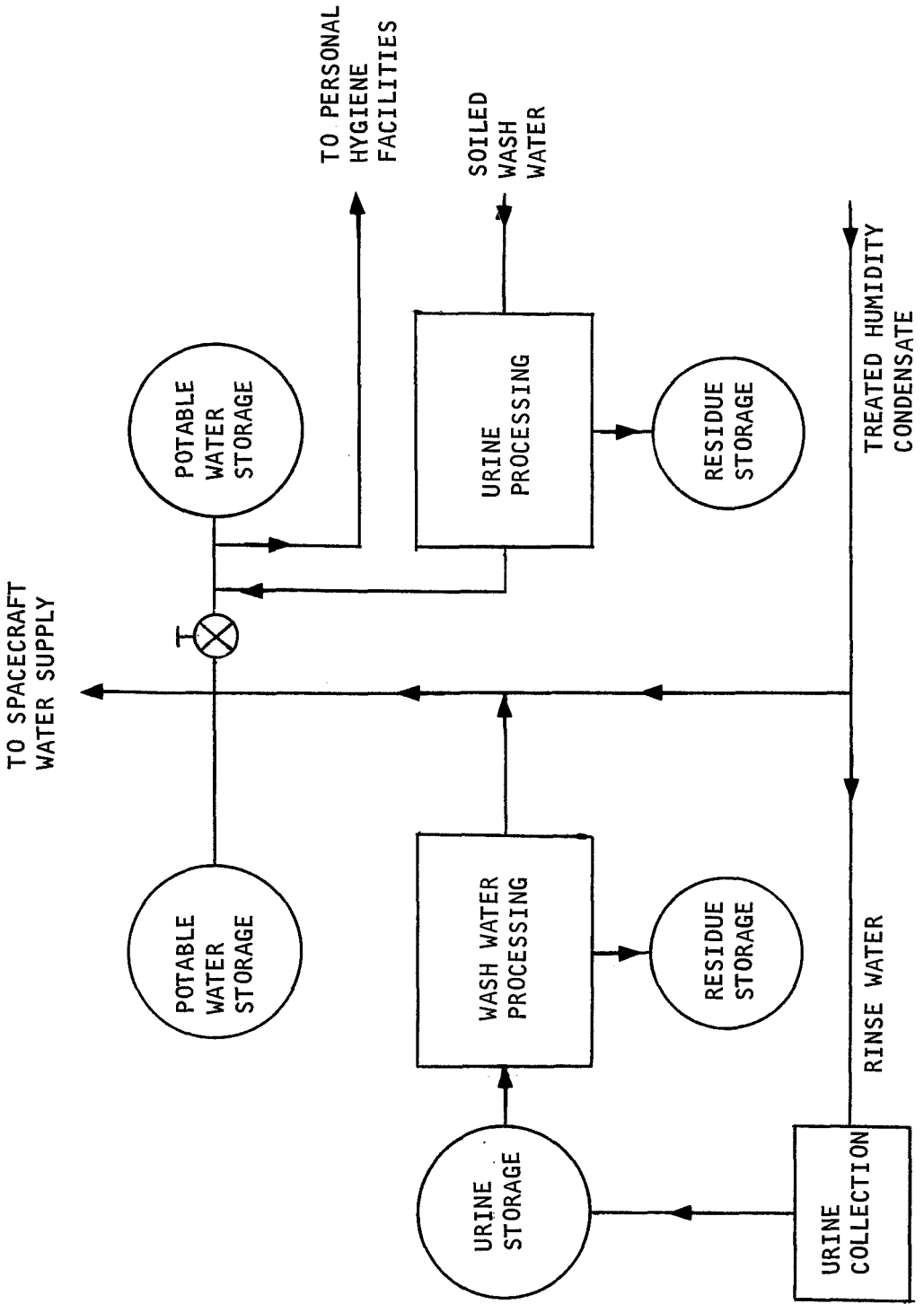


Figure 1-1. Overall IWRS Arrangement

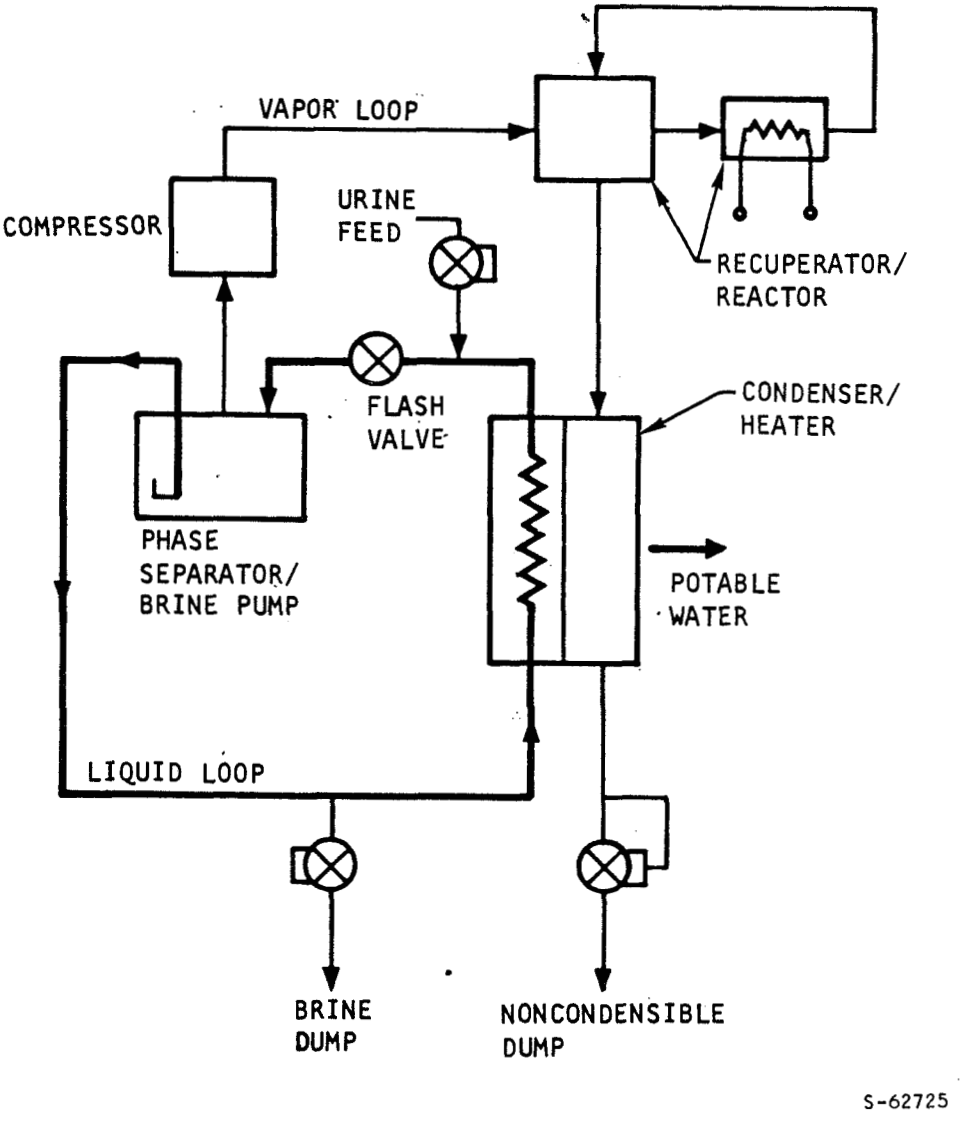


Figure I-2. Water Processing System Schematic

The sterile vapor is then cooled and condensed. The heat of condensation provides the source of energy for the evaporation process in the liquid loop. Liquid water is drawn from the condenser. Noncondensible gases formed in the phase separator or by the oxidation reaction are dumped overboard.

Testing of the pilot plant demonstrated the capability of the process to produce water of a very high quality, free of bacteria. Also the pilot plant unit showed that recovery efficiencies higher than 95% could be achieved.

Early Development

The second phase of the program was conducted under NASA sponsorship (NAS 9-8460, Task A) and was concerned with

(a) Development of hardware approaches for the major system components

(b) Upgrading of the pilot plant to include this new hardware

(c) System level tests to demonstrate system and component performance.

This program was very successful as an initial step toward the development of flight equipment. Major achievements included

(a) Development of a rotary drum phase separator incorporating a pitot pump for liquid circulation

(b) Development of a heater-condenser

(c) Selection of a system control technique based on the use of nucleonic sensors for liquid inventory control.

In addition major problems were identified which required further attention in the following phase of the program. One area of concern was the development of a very low specific speed vapor compressor which could be developed into a long life unit. Another problem involved system thermal balance which indicated the need for detailed system/component analyses.

SCOPE OF CURRENT PROGRAMS

The third phase of the program, which is the subject of this report, was also sponsored by NASA and constituted a continuation and an expansion of previous activities. These two programs were concerned primarily with

(a) The preliminary design of the complete IWRS as defined in Figure 1-1 (NAS 9-8460, Task B)

(b) The continuation of component/system development in support of the preliminary design effort. This developmental work was conducted under Contract NAS 9-9981.

The efforts under these two contracts were very much interrelated, so that both contracts were conducted as a single program. The scope of the work can best be realized through a review of the major program achievements. The

major portion of the effort was concerned with the water processing portion of the IWRS; the collection and storage subsystems were only subjected to the analysis necessary for the development of the specifications.

PROGRAM ACHIEVEMENTS

Design and Analysis

Under the preliminary design activities extensive analyses were conducted at the system and at the component level. Much of this effort was expended in the detailed analysis of test data. As a result analytical tools were developed which permit accurate system performance prediction through a complete understanding of the complex relationships between the parameters relating the various system components. Under this program preliminary reliability analyses were conducted in support of the development of the flight system schematic. An electrical schematic was evolved and package drawings were prepared. In addition microbiological studies were aimed at the selection of approaches for the control of bacteria throughout the IWRS. Major accomplishments identified as the direct result of the preliminary design efforts are listed below.

(a) Development of a performance prediction computer program--This program was demonstrated accurate by comparison with system test data

(b) Optimization of the system operating parameters using the computer program--Considerable insight was gained in the complex interactions between the components

(c) Development of a flight system schematic and preliminary system specification

(d) Preparation of component performance specifications

(e) Development of preliminary package drawings

(f) Preparation of sketches and drawings adequate for the fabrication of major components.

Component Development

Development testing under Contract NA9-9981 was mainly concerned with system level testing. The only components tested separately were

(a) Compressor--A two stage vortex compressor was designed and tested successfully before installation in the breadboard system.

(b) Phase separator--The rotary drum unit designed and fabricated in the previous phase of the program was subjected to development testing. Liquid entrainment was reduced from 0.2 to 0.015 weight percent by incorporation of a baffle upstream of the demistor.

(c) Catalytic reactor--A catalyst screening program was conducted as a result of which rhodium plated on stainless steel screens was selected for the design of a breadboard reactor bed.

(d) Fluid Inventory Control--The scheme for fluid inventory control in the brine loop was changed. Previously separator level was maintained constant and brine concentration oscillated between 48 and 52 percent. In order to reduce power requirement and yet maintain high recovery effectiveness a semi-batch process was devised whereby the level in the separator is maintained constant by urine addition when the brine concentration is between 17 and 25 percent. When this concentration is reached, urine feed to the liquid loop is interrupted and the distillation process continues until the brine concentration reaches 50 percent. At that point a portion of the brine is dumped. Then the separator is refilled to capacity and operation starts again. This control scheme requires that the level and concentration controller be integrated through electronic circuitry which programs the cycle. This control was designed and tested in this phase of the program.

The system tests provided much data which were used in evaluating the performance of major recovery system components. The performance of the heater-condenser and of the semi-batch control were demonstrated satisfactorily during the system test program.

System Development

System level testing was conducted in two steps. The upgraded pilot plant used in the previous program was modified to include more comprehensive instrumentation and to incorporate new components, namely a diaphragm compressor and a plexiglass phase separator. Testing of this unit revealed that major test setup modifications were necessary to reduce thermal losses and line pressure drops. Further, the test system required major rework for installation of new components: catalytic reactor and vortex compressor. The decision was made to rebuild the test system. Testing of the upgraded breadboard constituted the major developmental effort under Contract NAS 9-9981.

The upgraded breadboard was subjected to 185 hours of testing and culminated in the successful completion of a continuous five-day test during which water was recovered from urine. These tests demonstrated (1) the capability of the system to produce water of very high purity and free of bacteria (water purity under normal operation exceeded the requirements of the specification), (2) the soundness of the basic hardware approaches, and (3) the adequacy of the overall system arrangement.

The system level tests were very valuable in providing a clear understanding of the system operational peculiarities and in identifying further component design requirements.

RESULTS

System Characteristics

Reference is made to Section 2 for a detailed description of the flight system; a schematic diagram is presented as Figure 1-3. Overall characteristics of the flight IWRS including two water processing units (see Figure 1-1) are listed below.

Water production rate:	2.50 lb/hr (per shipset)
Minimum recovery efficiency:	95 percent
System weight:	258 lb (per shipset)
Expendable weight:	14.6 lb/90 days
Power requirement (Total):	440 watts per shipset continuous; 60 watts intermittent
Heat leaks:	1320 Btu/hr (per shipset)
Number of components:	216 (per shipset)
Number of component designs:	63 (per shipset)

Figure 1-4 shows the thermodynamic performance of the system at design point.

Component Designs

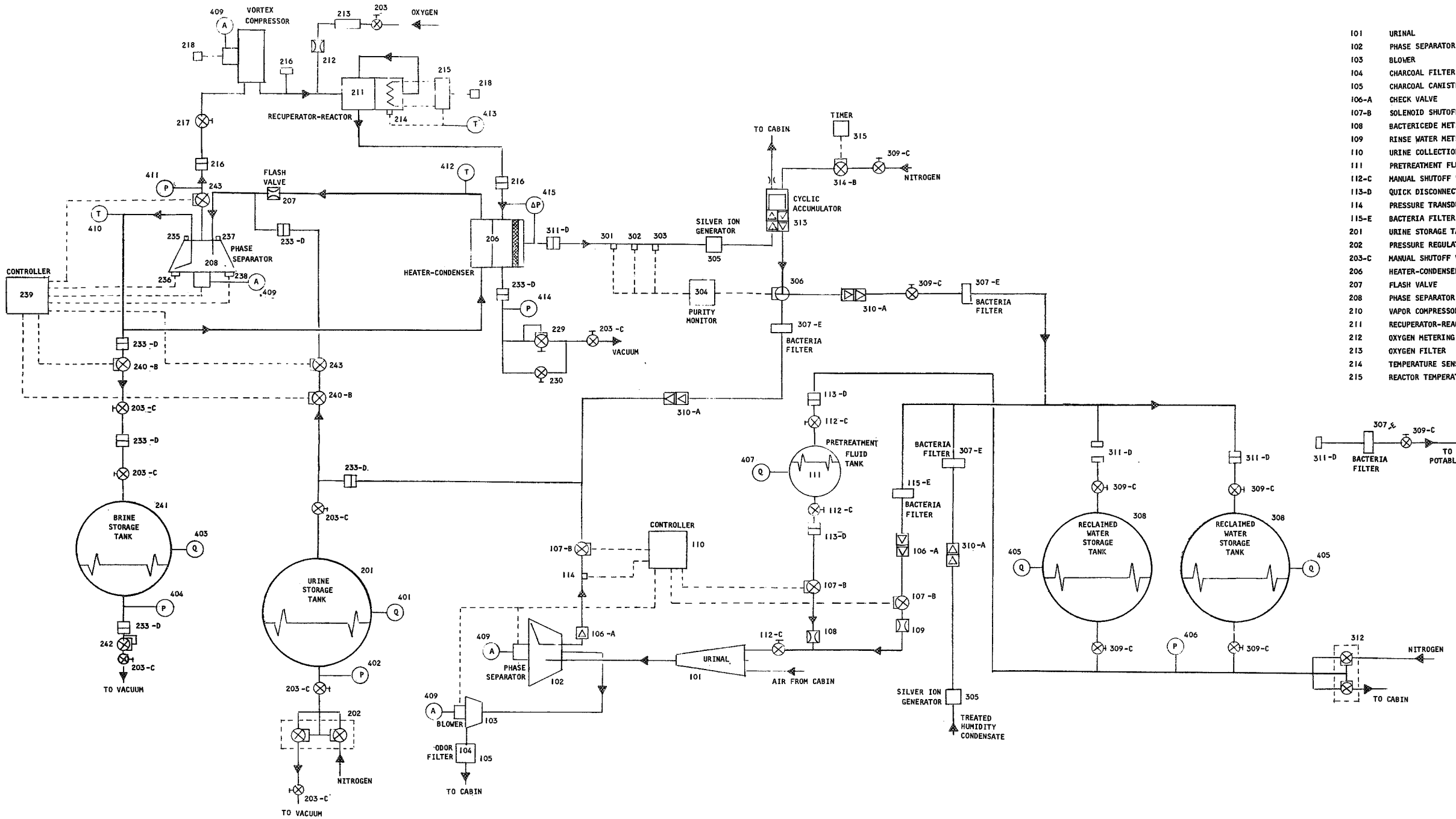
Major components are reviewed below in terms of the program findings.

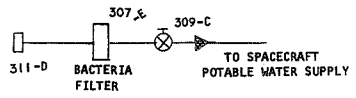
1. Compressor

The compressor performed satisfactorily although improvements are indicated to improve flow - ΔP characteristics and power consumption. Motor problems encountered during system tests are not a compressor problem per se since the motor used was an existing unit operated well above its design operating requirements.

2. Phase Separator

Major problems encountered during the test program can be traced to the phase separator. In its present configuration the phase separator incorporates a face seal between the vapor loop and ambient. Deterioration of this seal during the breadboard tests resulted in high air leakage into the brine loop. In turn, the air leakage deteriorated compressor performance and resulted in a four-fold reduction in heater-condenser heat transfer capacity. The overall result was high specific power requirement and a drop in water production rate. The separator face seal is incorporated to permit direct drive of the rotating bowl by the motor; a flight separator would be statically sealed and bowl rotation would be effected through a magnetic coupling.





101	URINAL
102	PHASE SEPARATOR
103	BLOWER
104	CHARCOAL FILTER
105	CHARCOAL CANISTER
106-A	CHECK VALVE
107-B	SOLENOID SHUTOFF VALVE
108	BACTERICEDE METERING ORIFICE
109	RINSE WATER METERING ORIFICE
110	URINE COLLECTION PACKAGE CONTROLLER
111	PRETREATMENT FLUID TANK
112-C	MANUAL SHUTOFF VALVE
113-D	QUICK DISCONNECTS
114	PRESSURE TRANSDUCER
115-E	BACTERIA FILTER
201	URINE STORAGE TANK
202	PRESSURE REGULATOR-RELIEF
203-C	MANUAL SHUTOFF VALVE
206	HEATER-CONDENSER
207	FLASH VALVE
208	PHASE SEPARATOR
210	VAPOR COMPRESSOR
211	RECUPERATOR-REACTOR
212	OXYGEN METERING ORIFICE
213	OXYGEN FILTER
214	TEMPERATURE SENSOR
215	REACTOR TEMPERATURE CONTROLLER

216	QUICK-DISCONNECT
217	MANUAL SHUTOFF VALVE
218	SWITCH
229	CONDENSER PRESSURE REGULATOR
230	BLEED VALVE
233-D	QUICK-DISCONNECT
235	DENSITY CONTROL SOURCE
236	DENSITY CONTROL DETECTOR
237	LEVEL CONTROL SOURCE
238	LEVEL CONTROL DETECTOR
239	BRINE LOOP CONTROLLER
240-B	SOLENOID SHUTOFF VALVE
241	BRINE STORAGE TANK
242	BRINE PRESSURE REGULATOR
243	SOLENOID SHUTOFF VALVE
301	pH SENSOR AND DISPLAY
302	CONDUCTIVITY SENSOR
303	ORGANICS MONITOR
304	PURITY CONTROLLER
305	SILVER ION GENERATOR
306	SELECTOR VALVE
307-E	BACTERIA FILTER
308	RECLAIMED WATER TANK
309-C	MANUAL SHUTOFF VALVE
310-A	CHECK VALVE
311-D	QUICK DISCONNECT
312	PRESSURE REGULATOR - RELIEF
313	CYCLIC ACCUMULATOR
314-B	SOLENOID VALVE
315	CYCLIC ACCUMULATOR TIMER
401	URINE STORAGE QUANTITY METER
402	URINE STORAGE PRESSURE METER
403	BRINE STORAGE QUANTITY METER
404	BRINE STORAGE PRESSURE METER
405	RECLAIMED WATER STORAGE QUANTITY METER
406	RECLAIMED WATER STORAGE PRESSURE METER
407	PRETREATMENT TANK QUANTITY METER
409	AMMETER
410	BRINE TEMPERATURE - SEPARATOR OUTLET
411	SEPARATOR PRESSURE METER
412	BRINE TEMPERATURE - CONDENSER OUTLET
413	CATALYTIC REACTOR TEMPERATURE
414	CONDENSER PRESSURE TRANSDUCER
415	DIFFERENTIAL PRESSURE TRANSDUCER

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Figure 1-3. System Schematic

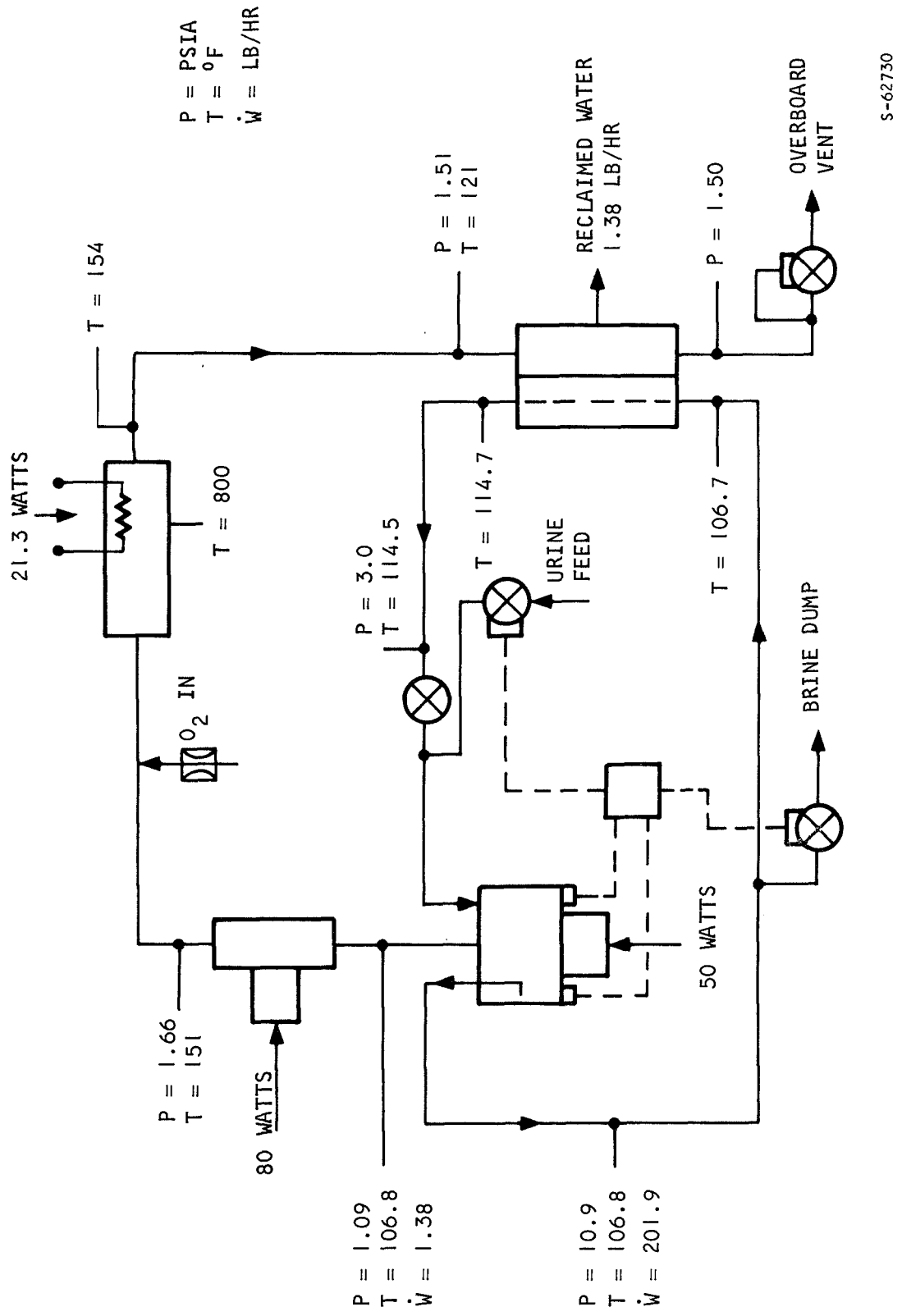


Figure 1-4. Baseline System Performance

3. Heater-Condenser

Analysis shows that this unit is adequate to handle the design water production rate of the IWRS. The configuration of the unit should be modified to reduce heat losses.

4. Catalytic Reactor

The rhodium catalyst proved very efficient in oxidizing trace contaminants produced during urine distillation. Evidence of corrosion of the substrate used (stainless steel screens), in the conditions of operation of the breadboard system was observed. A new substrate appears necessary to safeguard against this problem which would most probably not exist on a flight unit.

5. Level and Concentration Controller

The level controller performed extremely well throughout the test program. The circuitry developed to provide semi-batch operation was demonstrated. The density sensor was found to be limiting primarily because of the effect of separator brine level on brine density sensing. This problem can be overcome by redesign of the separator bowl and careful detail design of the sensor.

System Considerations

Long-term testing with urine permitted identification of system peculiarities which are discussed below.

(a) The pyrolysis reactor was very effective in maintaining sterility of the reclaimed water.

(b) Brine entrainment into the vapor loop was experienced during the test program due to rapid depressurization of the vapor cavity within the separator. This resulted in overloading of the catalytic reactor and in the presence of odors in the product water. The problem can easily be resolved by addition of equipment to prevent sudden depressurization of the liquid loop and also brine entrainment in the event of equipment malfunction.

(c) System thermal balance was identified as a major system design problem during the pilot plant run and also during testing of the upgraded breadboard. Overall imbalance at the condenser resulted in water vapor venting to vacuum. This is partly due to heater-condenser performance limitations resulting from phase separator air leakage. Careful thermal analyses were conducted of the flight system equipment and package. The result of these analyses were incorporated in the system computer model developed.

(d) Water purity monitoring was performed by sampling and extensive testing to determine sterility and chemical composition. More work remains in this area to identify all the parameters which need monitoring and to select on-line instrumentation which could be evaluated experimentally as a secondary objective of a complete long-term breadboard test.

(e) System sterilization and flushing did not present a problem during system test because of the availability of large quantities of water and steam at the temperature desired. However, the techniques used do not appear suitable for spacecraft application. Further investigations are necessary in this area.

RECOMMENDATIONS

As a result of the analyses and tests conducted, a number of problems have been identified at the component and system levels. The following recommendations are designed to eliminate these problems and improve the efficiency of the water recovery system. In general, these recommendations represent a continuation of the current program and involve analyses and testing at the component and system level. The component level design activities and test programs are aimed at the development of better quality hardware so that system level testing could be conducted for long duration with confidence.

Listed below are AiReseaach recommendations pertaining to component improvements.

(a) Compressor--Design and developmental efforts are required for (1) performance improvement through redesign of the impeller buckets for higher aerodynamic and volumetric efficiencies and (2) performance assessment of a flight weight unit with a motor specifically designed to drive the compressor impeller.

(b) Phase Separator--Redesign of the unit and testing on the existing rig for(1) reduction of entrainment by a factor of 10, (2) elimination of the rotating seal by use of a magnetic coupling, and (3) accommodation of the nucleonic density sensor.

(c) Heater-Condenser--Redesign the unit to flight configuration to reduce heat losses. No component level tests appear necessary; the unit should be tested in the system.

(d) Catalytic Reactor--Investigate alternate substrates suitable for rhodium plating and generate performance data on the rhodium catalyst for design optimization. Design and fabricate a flight unit recuperator-reactor for incorporation in the breadboard unit.

(e) Level and Concentration Control--Refine design and packaging of the electronic circuitry. Calibrate the density sensor as part of the separator test program.

Much work remains at the system level. Here activities involve continuation of the work performed to upgrade the system configuration and specification. Also, operational procedures should be refined, including maintenance actions. Major areas of investigations recommended for system level activities are listed below:

(a) Long term continuous testing of the system with a new generation of components to ascertain performance stability and equipment life. A 180-day test with flight prototype hardware is recommended to fully establish the capability of the system.

(b) Updating of the performance prediction computer program as a result of system and component development.

(c) Maintainability investigations resulting in the definition of maintenance level and in the development of maintenance procedures.

(d) Reliability analyses including component level FMEA's.

(e) Human factors testing to evaluate operational characteristics of the unit. This would involve the performance of typical maintenance tasks.

(f) Development testing of on-line purity monitoring equipment (chemical and bacteriological). This could be performed concurrently with the 180-day system test.

(g) Development of sterilization and flushing techniques.

(h) System and component specification updating

To date system tests have been conducted with good quality engineering development hardware. The basic process for water recovery and the component design approaches have been demonstrated adequately. At this time, it is recommended that better quality hardware be developed to fully realize the advantages of the flash evaporation - vapor compression - vapor pyrolysis process.

REPORT ORGANIZATION

The remainder of this report gives the details of the analyses and testing performed. Section 2 gives the system specification including a detailed description of the system and its overall characteristics. Component design and development activities are summarized in Section 3. Section 4 is concerned with efforts at the system level.

Two appendices are included: (1) Appendix A presents the component preliminary design specifications for the entire IWRS, (2) Appendix B documents the computer program developed as part of NAS 9-8460.

SECTION 2

SYSTEM DESCRIPTION

INTRODUCTION

This section contains a description of the system evolved as a result of the preliminary design studies and supporting development activities conducted under Contracts NAS 9-8640 and NAS 9-9981. All analyses at the component and system levels were aimed at the definition of the system described here. As such, the description and the performance data presented constitute the preliminary specification for the IWRS. Preliminary component specifications including description, performance, and design data are given in Appendix A.

REQUIREMENTS AND GUIDELINES

The Intermediate Water Recovery System (IWRS) provides for collection, storage, and processing of the urine and wash water produced by three men in earth orbit. Design mission duration is one year with a 90-day resupply interval. Functional, performance, and interface requirements are summarized in Table 2-I. Basically, the water recovery system described in this section performs five separate functions:

(a) Urine collection and storage

(b) Water reclamation from urine

(c) Wash water storage

(d) Wash water reclamation

(e) Potable water storage

OVERALL SYSTEM ARRANGEMENT

The schematic in Figure 2-I illustrates the overall arrangement of the flight system and identifies major interfaces. The system comprises two identical water reclamation units. Normally, the two units operate independently; one is used for urine and urinal rinse processing, the other is used for recovery of the wash water. Interconnecting lines provide backup capabilities in the event of malfunction in one of the systems. In normal operation, these lines also are used to maintain overall vehicle water balance.

Humidity condensate, pretreated to make it potable, is fed to the system where it is sterilized and integrated with the potable water supply.

Sterile conditions are maintained throughout by incorporation of sterilization equipment at the water collection points and at the outlets of the reclamation units. Residue from the reclamation units is stored for periodic disposal at the scheduled 90-day resupply time.

TABLE 2-I

IWRS DESIGN REQUIREMENTS

FUNCTIONAL REQUIREMENTS

- Separate collection, transport and storage of urine and wash water
- Biological inactivation of all fluids and equipment
- Processing of urine and wash water in separate but identical units
- Storage of sterile potable water in water recovery system tanks with provision for transfer to spacecraft water management system
- Scheduled maintenance and servicing performed at the 90-day resupply period
- Continuous monitoring of recovered water physical and chemical characteristics
- Automatic operation with adequate instrumentation for monitoring by the crew - instrumentation readouts provided on the subsystem packages; provisions for remote display incorporated

INTERFACE REQUIREMENTS

- Minimum interfaces with spacecraft and other subsystems
- Independence from thermal control loop(s)
- No contamination of spacecraft atmosphere
- Overboard vacuum vent available
- Power availability: 28 v dc and 115 v ac - 400 cps - 3Ø
- Power penalty: (a) 28 vdc: 669 lb/kw
  (b) 115 vac: 982 lb/kw
- Penalty for heat rejection to cabin air: 0.0885 lb/Btu/hr
- Spacecraft cabin
  (a) Total pressure: 5 - 7 psia normal
  0 - 3.5 psia emergency
  (b) O_2 partial pressure: 3.5 psia
  (c) N_2 diluent
  (d) Temperature: 70 ±5°F selectable

PERFORMANCE REQUIREMENTS

- Crew size: 3 men
- Mission duration: 1 year
- Resupply interval: 90 days
- Processing rate: 16.35 lb/day urine and rinse water
  and 16.35 lb/day wash water nominal
  rate: 1 lb/hr
- Water balance data:
  - Drinking, food preparation water: 18.39 lb/day
  - Water of oxidation: 1.98 lb/day
  - Urine water: 10.35 lb/day
  - Urinal rinse water: 6.00 lb/day
  - Fecal water: 0.75 lb/day
  - Wash water: 16.35 lb/day
  - Perspiration and respiration: 9.27 lb/day
  - Reclaimed water purity in accordance with MSC-SPEC-C35 (January 15, 1968)
  - Storage of residues from the processing units for periodic removal at the 90-day resupply period

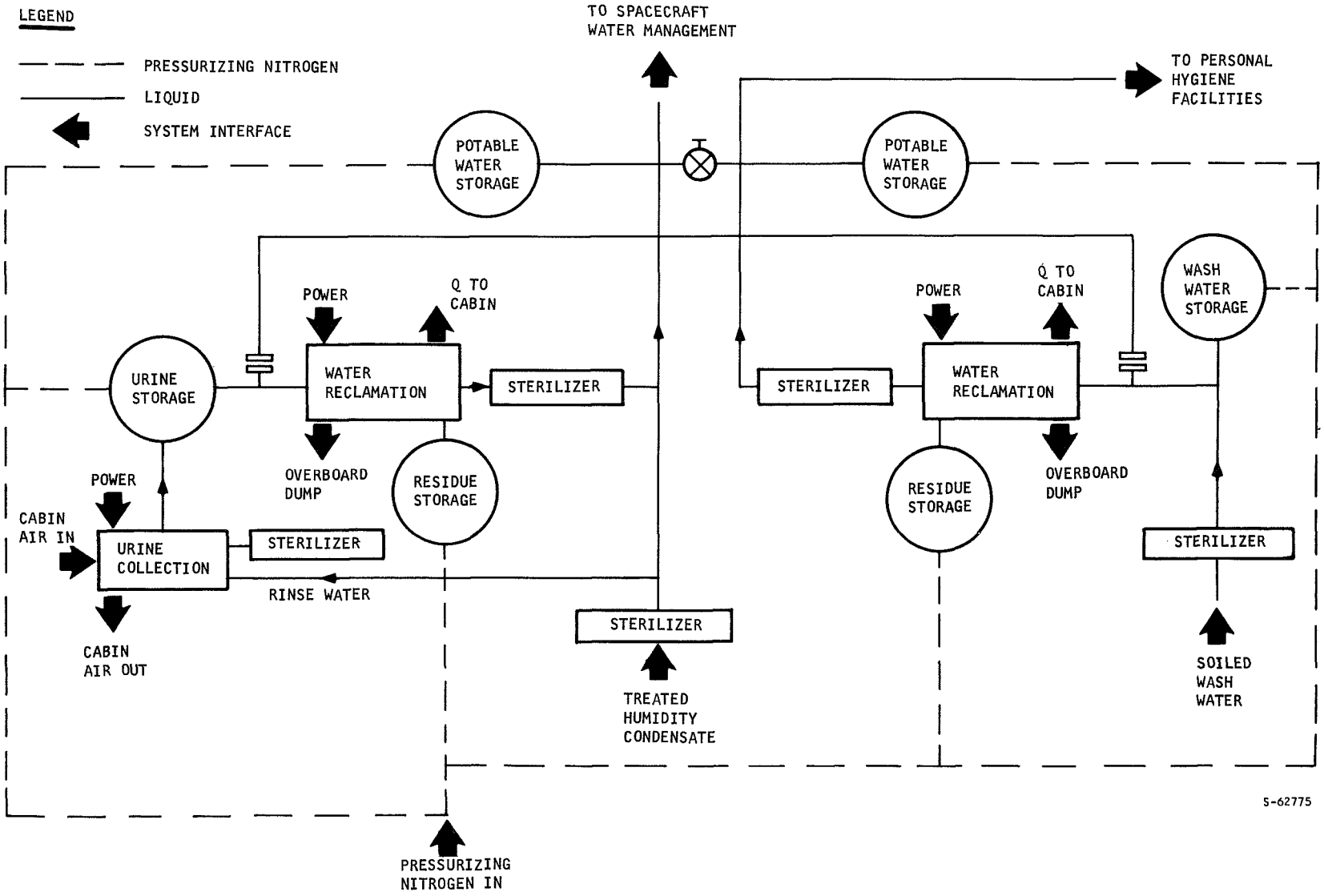


Figure 2-1. Overall Arrangement and Interfaces

The capacity of the system waste water storage tanks is sufficient to hold the waste water production of 2 days. Normally the waste tanks will contain a 1-day charge of waste water; in this manner failure of equipment on one side of the tank will not require shutdown of the equipment on the other side for a period of one day. For example, a malfunction of the urine collection unit will not necessitate shutdown of the urine processing unit; similarly, failure of the urine processing unit will not hamper urine collection for the same period. This arrangement provides ample time for maintenance action.

The reclaimed water tanks are sized to hold the water produced in one day. Two tanks are used with each reclamation unit. Operation is as follows: When a reclaimed water tank is filled, it is isolated from the system and a sample is taken from that tank for bacteriological analysis. It is estimated that about 18 hours will be required to complete this analysis. If the water is found to be potable it is transferred to the spacecraft water supply system; if not, the water will be recycled and the tank will be sterilized. While one reclaimed water tank is on hold, the second is being filled with the effluent of the water processing unit.

Since the system tanks are sized on operational considerations based on daily water rates, the wash water and urine loop tanks are identical. The requirements for the urine residue storage are one order of magnitude larger than for the wash water residue; however both residue tanks are identical in keeping with the redundant nature of the wash water loop.

Humidity condensate, pretreated to make it chemically potable, is fed to the system, sterilized, and stored together with the water reclaimed from urine. A silver ion generator is used for this sterilization. The detailed system description presented below is concerned only with the urine recovery portion of the IWRS. The equipment required for waste water recovery is identical to that described, with the exception of the urine collection unit.

SYSTEM DESCRIPTION

Figure 2-2, presented at the end of this section for ease of reference, is a schematic of the urine recovery portion of the IWRS. The subsystem is divided in four separate portions identified as follows:

100--Urine collection and transfer

200--Urine storage and processing

300--Reclaimed water collection and transfer

400--Instrumentation

All components are identified by a three-digit number; the first digit of this number refers to a subsystem as defined above. A letter following the component number identifies an item which is used in more than one subsystem.

The description below is concerned only with system-level considerations. Details on components can be found in the component specifications presented in Appendix A.

Urine Collection and Transfer--100

Urine is collected in an open funnel type urinal (101) and propelled pneumatically to a phase separator (102) by cabin air. The air is drawn into the system at the periphery of the conical urinal by a centrifugal blower (103) located downstream of the phase separator. The air is returned to the cabin through an odor filter (105). The filter contains an expendable charge of activated charcoal (104) impregnated with phosphoric acid. The charcoal bed is designed for replacement at 90-day intervals.

The phase separator is a rotating drum device with a stationary pitot tube which serves as a liquid pump. Air exits the separator at the center of the unit and liquid is pumped to the urine storage tank (201) through a solenoid shutoff valve (107) and a check valve (106) which prevents reverse flow of urine when the separator is inactive. The disconnect (113) at pretreatment tank outlet can be used to flush the entire urine collection subsystem if necessary.

Following micturation, a metered mixture of fresh water and pretreatment fluid is introduced into the urinal and flushed through the phase separator to the urine collection tank in the same manner as the urine. This mixture will prevent decomposition of urine in storage and also will check bacteria growth in the tank. The rinse water and pretreatment fluid flows are automatically controlled by orifices (108 and 109) downstream of solenoid shutoff valves (107) which are opened for a predetermined time period upon a signal from the urinal controller (110).

The rinse water is drawn from the reclaimed water tank (308). The pretreatment fluid is stored in an expendable tank (111) which is replaced at the 90-day resupply period. The pretreatment tank is pneumatically pressurized with nitrogen from the reclaimed water storage unit. Shutoff valves (112) and quick disconnects (113) permit easy replacement of the tank.

After the rinse mixture is pumped out of the separator, the air flow is maintained through the unit to dry the urinal and the phase separator.

The rinse, dry, and shutdown cycle is controlled automatically by the urinal controller (110). The sequence of operation is as follows: Prior to micturation a selector switch on the controller is used to signal the controller to activate the phase separator and the blower. All urine is stored in the separator. After micturation the selector switch is positioned to initiate automatic operation of the controller:

(a) The solenoid valve (107) downstream of the phase separator is opened and remains opened until the pressure at outlet of the separator-pump drops to 0.5 psig. A pressure transducer (114) is provided for this purpose. The solenoid valve (107) is then closed.

(b) The rinse water and pretreatment fluid are then metered into the urinal by the solenoid valves (107) upstream of the orifices (108 and 109) opening for a predetermined period of time.

(c) The phase separator is drained by opening the solenoid valve (107) again until the liquid outlet pressure drops to 0.5 psig. This valve is then closed again.

(d) Air flow is maintained until the separator is dried.

(e) The blower and separator are shut down and the selector switch returned to the "off" position automatically.

A bacteria filter (115) in the rinse water line prevents bacteria migration from the urine collection package to the reclaimed water portion of the system. Ammeters (409) monitor motor current to alert the crew in the event of impending malfunction.

A quick-disconnect (233) at the interface with the urine storage tank permits disconnecting of the urine collection effluent and routing to the wash water reclamation unit in emergency.

Urine Storage and Processing--200

This package is subdivided into three separate functional groups:

(a) Urine storage

(b) Water reclamation

(c) Process control

The following paragraphs describe these functional groups.

1. Urine Storage

Urine and rinse water is pumped to the waste storage tank (201) from the phase separator (102). The waste storage tank incorporates a bladder which is pressurized by nitrogen at a nominal pressure of 4 psia. A pressure regulator-relief valve (202) is used for this purpose. The regulator is set at 4.0 ±0.5 psia and the relief valve at 7 ±0.5 psia. The tank is sized to hold a two-day production of urine. In normal operation the tank will be maintained at 4.0 psia and will contain about 16 lb or urine and rinse water. The relief valve setting is such that more than 2000 cc of liquid could be pumped into the tank from the urine collection loop without reaching the relief pressure. Such a volume of liquid corresponds to four maximum volume micturation and rinses. In normal operation the relief valve will remain closed and nitrogen relief to vacuum will be avoided.

Shutoff valves (203) are provided to permit tank and regulator-relief isolation. These valves will only be used in the event of malfunction.

2. Water Reclamation

The basic water reclamation process is vacuum distillation followed by vapor pyrolysis as a secondary cleanup process. Vapor compression is employed to balance the thermal requirement of the vaporization-condensation processes.

The system consists of two loops: (1) a concentrated waste water (or brine) loop and (2) a vapor loop. The brine loop, where the distillation process takes place, consists of three major components: a heater-condenser (206), a flash valve (207), and a phase separator (208). The brine from the phase separator is circulated in a single tube heater-condenser where it is heated. Water vapor condensing on the other side of the tube provides the thermal energy for brine heating. The warm brine (about 115°F) is then expanded across the flash valve to a pressure (1.1 psia) below its saturation pressure. As a result, a portion of the liquid brine is vaporized and the bulk of the liquid is cooled. In the process, the salt concentration of the brine is increased. The mixture of liquid brine and water vapor enters the phase separator, where a rotating drum within the separator provides the centrifugal action necessary to effect phase separation. Vapor is withdrawn from this unit along the axis of rotation of the drum while the liquid is collected at its periphery. A stationary pitot tube near the surface of the drum collects the liquid and converts the kinetic energy of the liquid into a pressure head sufficient to overcome the pressure drop of the liquid loop (about 9 psi). From the separator, the brine is returned to the heater-condenser. Liquid loop control will be described later.

The phase separator rotating drum is driven by a brushless dc motor through a magnetic coupling. In this manner, the use of rotating seals is obviated and air leakage into the low pressure liquid loop is prevented.

The water vapor formed in the liquid loop is compressed in a two-stage vortex compressor (210). This machine is also statically sealed and driven by a brushless dc motor through a magnetic coupling. A manual shutoff valve (217) permits isolation of the brine and vapor loops. A solenoid shutoff valve (243) in the vapor line from the separator will automatically isolate the vapor loop from the brine circuit should a separator failure occur.

The vapor then flows to a recuperator-reactor (211) where trace quantities of contaminants vaporized in the brine loop are oxidized at high temperature. A minute flow of oxygen is metered into the vapor line upstream of the catalytic reactor for this purpose. Oxygen flow control is maintained constant by an orifice (212) in the oxygen feed line; a filter (213) in that line prevents fouling of the orifice. Quick-disconnects (216) can be used for flushing or sterilizing the vapor loop if necessary.

The recuperator consists of a shell-and-tube heat exchanger of very low pressure drop and high effectiveness. Vapor from the condenser is heated in the recuperator to a temperature of about 765°F. The vapor then flows through the catalytic bed, which is maintained at 800°F by an electrical heater. A

temperature sensor (214) and a controller (215) are provided for heater power control. redundant heaters, controllers, and sensors are used to enhance system reliability. The catalyst consists of circular sections of rhodium plated stainless steel screens stacked to form a cylinder. The contaminants entrained with the vapor from the phase separator are oxidized over the catalyst surface. The vapor then returns through the shell side of the reactor where it is cooled to about 155°F. The recuperator-reactor also acts as a sterilizer.

Water vapor from the recuperator enters the heater-condenser (206) where it is cooled and condensed on the external surface of the brine tube. Condensation occurs at a pressure higher than the phase separator pressure so that the saturation temperature of the vapor is higher than the brine temperature from the separator. In this manner, the heat of condensation of the water vapor is dumped into the brine loop. The condensing pressure is maintained constant at 1.5 psia; separator pressure is 1.09 psia.

Refrasil wicks within the condenser are used to collect the condensate formed on the surface of the tube and transport it to a hydrophylic sintered metal plate which serves as the phase separator. A cyclic accumulator (313) provides the pressure differential necessary to pump the water through the plate and out of the condenser. A differential pressure transducer (415) monitors cyclic accumulator performance.

Non-condensibles formed into the separator and the reactor, and unreacted oxygen bled into the vapor loop upstream of the recuperator, are exhausted to vacuum through a pressure regulator (229). The regulator maintains a constant pressure in the heater-condenser vapor cavity. A shutoff valve (203) downstream of the regulator permits system isolation in the event of failure. A needle shutoff valve (230) installed in parallel with the regulator is used upon system startup to reduce the system pressure from ambient to its normal operating level (1 to 1.5 psia). This valve slowly bleeds the air from the system to vacuum, thus preventing foaming in the phase separator.

3. Reclamation Process Control

Control of the water reclamation process is fairly simple; it is accomplished mainly through monitoring and control of (1) the phase separator liquid level and (2) the brine concentration. As mentioned previously, the condensing pressure of the water vapor is maintained constant. The pressure regulator (229) dumps to vacuum the non-condensible gases entrained with the vapor in the condenser vapor cavity. This pressure is normally controlled at a nominal value of 1.5 psia; however, it is manually selectable and can be used to control the water production rate of the system. Water production rates can be adjusted from 1.0 to 1.73 lb/hr by varying condensing pressure from 1.0 to 2.0 psia (at the nominal brine concentration of 20 percent).

The brine level and concentration are measured at the separator (208) by similar nucleonic devices. A radioactive source (235) mounted on the separator casing emits radiation, which is directed toward a detector (236) (Geiger Mueller tubes) mounted on the other side of the casing. The radiation generated passes through the separator casing, the rotating drum,

and the fluid contained in the drum before it reaches the detector. The amount of radiation sensed by the detector is a function of the quantity which has been absorbed between the constant source and the sensing device. Since the quantity absorbed by the fluid is dependent on its density, the signal received is a function of density. Similarly, the quantity of radiation detected will be dependent on the presence of liquid in the radiation beam path.

Two sources (235 and 237) are used in conjunction with two detectors (236 and 238). Signals from these instruments are used by a controller (239) to control the inventory of fluid in the liquid loop. Operation is as follows:

Initially, the system is filled with urine at about 4 percent solids concentration. As water vapor is formed and extracted from the phase separator the solids content of the liquid will increase and the liquid level in the separator will drop. The controller will then admit more urine into the liquid loop by opening the solenoid valve (240) in the line from the urine storage tank (201). (The second valve (243) in that line is normally opened and is only shut in the event of open failure of the first valve (240); this is done automatically by the controller and prevents separator flooding.) In this manner, the liquid level in the separator is maintained approximately constant, at about 750 cc. As the brine concentration increases, the water production rate will slowly drop and the system operating parameters will also change. When the brine concentration reaches 25 percent as sensed by the density controller, addition of urine into the loop is interrupted. As a result the liquid level will drop and the concentration of the liquid will increase rapidly. When the concentration reaches 50 percent, the urine level in the separator is about 375 cc. At this point the controller opens a solenoid valve (240) in the separator delivery line and brine is dumped into a storage tank (241) maintained at low pressure. This valve is shut when separator level reaches 150 cc. The liquid loop is then replenished with fresh urine until the level reaches 750 cc again. At this point the brine concentration is about 17 percent due to dilution with the fresh urine. Operation starts again, with the level being maintained constant until the 25 percent density mark is reached. In this manner, a 95 percent recovery efficiency is achieved (assuming 5 percent solids in urine) since the brine is dumped at 50 percent concentration.

The brine tank is a bladder-type tank which is vented to vacuum through a pressure regulator (242). The tank is sized for periodic replacement at the 90-day resupply interval. Quick disconnects (233) and shutoff valves (203) on each side of the tank permit easy replacement.

Water Collection and Transfer-300

The cyclic accumulator (313) provides the pressure necessary to pump the recovered water into the reclaimed water tank (308). High pressure (100 psia) nitrogen gas provides the pneumatic power for water expulsion from the cyclic

accumulator. During the fill cycle, a spring within the accumulator provides the suction pressure. Nitrogen is introduced into the accumulator at regular intervals for a predetermined time period. Nitrogen control is effected by a timer (315) which opens and closes a solenoid valve (314) according to a preset time sequence.

At the condenser outlet, reclaimed water purity is monitored on-line to determine acceptability. A pH sensor (301), a conductivity meter (302), and a sensor to monitor dissolved organic contents (303) are provided for this purpose. Signals from these instruments are compared to preset maximum limits in the purity controller (304). If any of the measered parameters exceeds the maximum, the controller will switch selector valve (306) and thus will divert the cyclic accumulator discharge to the urine storage tank (201) for recycle. An alarm will also be activated to alert the crew of the abnormal condition. Check valves (310) in the return line to the urine tank prevents reversal of flow in that line. A bacteria filter (307) downstream of the selector valve provides a barrier against bacteria migration from the urine tank to the reclaimed water portion of the system.

A silver ion generator (305) upstream of the cyclic accumulator introduces a minute quantity of silver ions into the reclaimed water stream. The bactericidal quality of the silver maintains sterile conditions throughout the reclaimed water system and prevents bacteria growth on the filters should bacteria reach these filters.

Reclaimed water which has been checked for purity is pumped into one of two reclaimed water tanks (308). Check valves (310) in the delivery line prevent reverse flow. A shutoff valve (309) can be used for isolation of the reclamation system from the storage tank. A bacteria filter (307) protects the reclamation system from bacteria which potentially could enter the water loop at a location in the storage area.

Two water tanks are used; while one is on stream and being filled, the other is isolated from the system by unmating a quick disconnect (311). The isolated tank is on hold and is being checked for bacteria contents. If the water contained in the tank on hold is found to be acceptable, the tank is emptied into the spacecraft potable water system. A disconnect on the spacecraft water line is provided for this purpose. The disconnects are maintained sterile by the use of covers which house a sponge soaked with bactericide. The bactericide is added to the sponge manually at periodic intervals. If the tank is found to contain bacteria, it is recycled to the urine storage tank. In such an event, sterilization of the entire reclamation system (including the tank) would be necessary. Each water reclamation tank is sized to hold the water production of one day to permit microbiological analysis of the water. The disconnect (311) downstream of the condenser can be used for flushing the reclaimed water loop.

The reclaimed water tanks are pressurized with nitrogen from the spacecraft supply. A pressure regulator-relief valve (312) controls the nitrogen pressure at 30 psig.

Humidity condensate, pretreated to make it potably pure, is furnished to the system from the spacecraft humidity control system. As specified by NASA, this liquid stream is circulated through a silver ion generator (305) and

mixed with the effluent from the water reclamation unit. Check valves (310) and a bacteria filter (307) in the humidity condensate feed line prevent return flow and bacterial contamination of the remainder of the IWRS.

Instrumentation-400

A number of instruments are installed on the system for performance monitoring and for fault isolation in the event of failure. In general, all tanks are instrumented for content and pressure. Fluid inventory can thus be established and system processing rate can be adjusted to achieve material balance.

Ammeters (409) are used to monitor compressor and separator motor performance.

Reclamation circuit thermodynamic performance is monitored by pressure and temperature sensors installed at selected locations:

(a) Brine temperature at separator outlet (410)

(b) Separator pressure (411)

(c) Brine temperature at condenser outlet (412)

(d) Catalytic Reactor Temperature (413)

(e) Condenser pressure (414)

The temperature transducers are mounted externally on the brine tube and are not in contact with the liquid.

In addition to the above, the level and concentration of the brine in the liquid loop will be monitored. Purity sensor readings will also be displayed.

ELECTRICAL SCHEMATIC

The electrical schematic of the system is presented in Drawing SK 38192, which can be found at the end of this section. The schematic represents the system flight configuration as defined in the previous discussion. All wiring and cables will be silver plated and insulated with Teflon. The equipment is designed for normal operation from a dc bus as specified below:

(a) Input voltage, 25 to 30 v

(b) Bus under voltage, 22 v for 1 sec

(c) Bus over voltage, 33 v for 1 sec

(d) Bus ripple, ±0.5 v peak from 20 to 22 kHz

(e) Bus interruption, 30 msec max

(f) Transients, ±80 v with respect to steady-state bus voltage for 10 μsec at 10 pps

The input 400-Hz power is used to provide a time base for the timer controlled circuits. As such, neither the current nor the voltage requirements of this power are important; however, frequency stability is important for the accuracy of the timing circuits.

Only a visual alarm is shown. Pending further maintainability investigation, which will identify the system parameters which will require continuous monitoring for system failure detection, automatic instrumentation monitoring has not been shown. Further work will most probably identify the need for an automatic (audio and visual) alarm system to be incorporated on the spacecraft subsystem central control panel. This will require the addition of switching devices, comparator circuits, and relays to read the sensor outputs sequentially, compare this output to preset tolerance bands, and relay the information to the spacecraft control console.

SYSTEM PACKAGE

Inherent to the concept of maintenance on a spacecraft system is the packaging of the system to allow simple maintenance tasks by flight crews without the need for highly specialized tools. This requires 1) accessibility to all elements of the system, 2) mountings and connections to allow easy removal of the failed items, and 3) system provisions to facilitate either shutdown and startup operations or switchover to alternate modes of operation.

Package drawings were developed early in the program to define preliminary equipment groupings and to develop maintainability approaches for the IWRS. The schematic used as a basis for the preparation of these drawings differs somewhat from the final schematic of Figure 2-2. The differences involve minor equipment (valves, disconnects, and instrumentation); the major components are essentially the same. In addition maintainability investigations conducted at a later date resulted in slightly different approaches to maintainability. For these reasons the package drawings are only typical of the final design. However, they serve to illustrate the general equipment groups and their location in the overall package.

Description

A package layout for the urine recovery portion of the IWRS is shown on Drawing L-145719, sheets 1 through 4, which can be found at the end of this Section. Sheet 4 of this layout is an isometric of the package design, showing the placement of the major components. Walkways are provided on all sides of the package. As indicated, the package is arranged in three levels as follows:

(a) Top level for system controls and instrumentation.

(b) Mid level for major operating elements of the system

(c) Bottom level for storage tanks

The upper level, shown on sheet 1 of L-145719, is arranged to provide all of the normal crew interfaces. Included at this level are system controls, system monitoring instrumentation, and some of the interfaces needed for certain maintenance actions. All of the electronic elements of the system are packaged on a side panel near the top.

Most of the operational elements of the system are packaged in the mid level shown on sheet 2 of L-145719. These include the following components:

(a) Vapor compressor

(b) Process loop phase separator

(c) Heater-condenser

(d) Water quality sensors

(e) Urinal phase separator

(f) Urinal blower and filter

Mounting the components in this manner allows a minimum of interconnecting lines and minimizes process loop heat balance problems. It also allows for grouping the components into replaceable assemblies according to maintenance level determinations.

The lower level of the package, shown on sheet 3 of L-145719, contains the urine, brine, and reclaimed water storage tanks and tank instrumentation.

Discussion of Packaging Considerations

Component groupings into assemblies in the package design described above will facilitate maintenance operations. Examples of component assemblies are the brine, urine, and water storage tanks. These assemblies include tank, gauging system, pressure control valve assembly, and disconnects. Replacement would be accomplished by merely disconnecting the fluid lines and the electrical line and removing the tank assembly. The tank mounting consists of a saddle bracket and a strap clamp. Most liquid line connections will be made with no-spill quick-disconnects.

Components of the brine loop will be difficult to replace due to contamination and cleanup problems with this material. For this reason, it is recommended at this time that replacement of any element of this unit be done by replacement of the entire brine loop assembly. This loop will consist of the separator, the heater-condenser, and the flash valve. The placement and mounting these units in the package could allow this level of maintenance to be accommodated; quick-disconnects are provided for this purpose (see schematic). The package shown does not incorporate this capability .

Provisions for shutdown and startup are incorporated to permit isolation of various sections of the system. Disconnects at various points in the system allow flushing of the system sections requiring maintenance, and sterilization following maintenance action. Flexible lines with disconnects are provided for this purpose. Water used for sterilization and flushing can be directed to the urine storage tank to be processed in the unit. Interfaces (quick disconnects and shutoff valves) are provided in easily accessible areas at the top and side of the package to facilitate such maintenance tasks.

Commonality in components can greatly reduce the required number and type of spares provided. For the IWRS, it is proposed that many of the valves, as well as virtually all of the display meters and signal conditioners be the same. It is probable that most of the temperature sensors could be of two or three different designs. The same applies to the pressure transducers. It is also proposed that careful consideration be given to the use of identical storage tanks for the three primary functions of feed, brine dump, and reclaimed water storage. The brine tank is presently approximately twice the size of the water tanks. Perhaps two brine tanks the same size as the water tanks would be preferable for provisioning requirements.

A primary requirement for removal and installation of components or assemblies in space is ease in accomplishing the mechanical connections. As indicated earlier, the storage tanks are mounted in a saddle mount with a strap clamp. Other components will be mounted utilizing similar techniques. By the use of magnetic coupling drives for all rotating machinery, replacement is greatly facilitated. This will also aid in fault isolation since new motors can be readily installed on suspect components to verify a failure diagnosis. Similarily, placement of temperature sensors external to the line wherever possible will allow removal and replacement without interruption in system operation.

SYSTEM CHARACTERISTICS

Overall System

1. Component Summary

A complete list of the components shown in the schematic of Figure 2-2 is given in Table 2-2. Component weights and power requirements are also listed in the table. The system shown comprises 119 components (excluding wash water reclamation) as follows:

100--Urine Collection and Transfer	22
200--Urine Storage and Processing	46
300--Reclained Water Collection and Transfer	34
400--Instrumentation	17
Total	119

TABLE 2-2

COMPONENT SUMMARY

Item Number	Description	Number Required	Item Weight, lb	Power, Watts	Remarks
100--URINE COLLECTION AND TRANSFER					
101	Urinal	1	1	-	Incorporates air and water manifolds
102	Phase separator	1	10	20	Brushless dc motor drive; statically sealed unit
103	Blower	1	4	10	Brushless dc motor drive; ΔP = 3.5 in. H_2O
104	Charcoal filter	1	1.5	-	Expendable; charcoal impregnated with phosphoric acid
105	Charcoal canister	1	2.5	-	Rechargable every 90 days
106-A	Check valve	3	0.1	-	
107-B	Solenoid shutoff valve	3	0.3	See remarks	Spring loaded closed - 6 watts to activate by Item 110
108	Bactericide metering orifice	1	0.1	-	
109	Rinse water metering orifice	1	0.1	-	
110	Urine collection package controller	1	3.0	60	Power includes power to valves and motors
111	Pretreatment fluid tank	1	11 (full)	-	Contains 7 lb of pretreatment fluid; replaced at 90-day intervals
112-C	Manual shutoff valve	3	0.3	-	
113-D	Quick disconnects	2	0.8	-	
114	Pressure transducer	1	1.0	-	40 ma at 28 vdc
115-E	Bacteria filter	1	0.2	-	
200--URINE STORAGE AND PROCESSING					
201	Urine storage tank	1	8 (dry)	-	Capacity: 37.6 H_2O; operating pressure: 4 to 7 psia
202	Pressure regulator-relief	1	1	-	Regulates at 4 psia, relieves at 7 psia
203-C	Manual shutoff valve	8	0.3	-	
206	Heater-condenser	1	5	-	1440 Btu/hr capacity at design point (20 percent brine concentration)
207	Flash valve	1	0.1	-	
208	Phase separator	1	10	60	Brushless dc motor; magnetic coupling; brine ΔP: 10 psi
210	Vapor compressor	1	8	80	Brushless dc motor; magnetic coupling; pressure ratio: 1.59 at design point
211	Recuperator-reactor	1	5	25	Contains rhodium catalyst; operating temperature: 800°F
212	Oxygen metering orifice	1	0.1	-	O_2 flow controlled at 0.0005 lb/hr
213	Oxygen filter	1	0.2	-	
214	Temperature sensor	2	0.1	-	
215	Reactor temperature controller	2	0.6	40	Power includes reactor power input
216	Quick-disconnect	3	1.0	-	
217	Manual shutoff valve	1	0.7	-	Similar to -C valve
218	Switch	2	0.1	-	
229	Condenser pressure regulator	1	1.0	-	Adjustable aneroid to permit regulation between 0.5 and 2.5 psia
230	Bleed valve	1	0.2	-	Limit depressurization of vapor drop at rate of 0.5 psi/min
233-D	Quick-disconnect	6	0.8	-	
235	Density control source	1	0.6	-	Nucleonic source (americium 241)
236	Density control detector	1		-	Geiger-muller tubes
237	Level control source	1	0.6	-	Americium 241 source
238	Level control detector	1		-	Gieger mueller tubes
239	Brine loop controller	1	3	85	Manage fluid inventory in brine loop; power includes powerr for valve and separator operation
240-B	Solenoid shutoff valve	2	0.3	See remarks	Spring loaded closed; 6 watts to open
241	Brine storage tank	1	12 (dry)	-	Capacity: 94 lb of 50 percent solids brine; pressure 4 to 6 psia
242	Brine pressure regulator	1	1.0	-	
243	Solenoid shutoff valve	2	0.3	-	Normally opened; 6 watts to open

TABLE 2-2 (Continued)

Item Number	Description	Number Required	Item Weight, lb	Power, watts	Remarks
300--RECLAIMED WATER COLLECTION AND TRANSFER					
301	pH sensor and display	1	0.2	-	
302	Conductivity sensor	1	0.2	-	
303	Inorganics monitor	1	1.0	-	
304	Purity controller	1	2.5	25	32 watts maximum when selector valve actuated; display meters on unit
305	Silver ion generator	2	0.7	-	Self-contained electronic unit
306	Selector valve	1	0.8	-	6 watts required for actuation; valve actuated when water unacceptable
307-E	Bacteria filter	4	0.2		
308	Reclaimed water tank	2	6 (dry)	-	Capacity: 20 lb of water
309-C	Manual shutoff valve	7	0.3	-	
310-A	Check valve	6	0.1	-	
311-D	Quick disconnect	4	0.8	-	
312	Pressure regulator-relief	1	1.0	-	Maintains reclaimed water tank at 30 psig
313	Cyclic accumulator	1	2.0	-	Powered by nitrogen from spacecraft supply
314-B	Solenoid valve	1	0.3	-	Powered by timer (315)
315	Cyclic accumulator timer	1	0.5	5	Also 7 watts for activation of valve 314-B
400--INSTRUMENTATION					
401	Urine storage quantity meter	1	0.7	40	Range: 0 to 40 lb
402	Urine storage pressure meter	1	0.8	30	Range: 0 to 8 psia
403	Brine storage quantity meter	1	0.7	40	Range: 0 to 110 lb
404	Brine storage pressure meter	1	0.8	30	Range: 0 to 8 psia
405	Reclaimed water storage quantity meter	1	0.7	40	Range: 0 to 20 lb
406	Reclaimed water storage pressure meter	1	0.8	30	Range: 0 to 40 psig
407	Pretreatment tank quantity meter	1	0.7	40	
409	Ammeter	4	0.5	1 to 4	Range: 0 to 5 amps
410	Brine temperature-separator outlet	1	0.7	40	Range: 80 to 130°F
411	Separator pressure meter	1	0.8	40	Range: 0.2 to 3.0 psia
412	Brine temperature-condenser outlet	1	0.7	40	Range: 80 to 130°F
413	Catalytic reactor temperature	1	0.7	40	Range: 600 to 1000°F
414	Condenser pressure transducer	1	0.8	40	Range: 0.2 to 3 psia
415	Differential pressure transducer	1	0.8	40	Range: 0 to 0.5 psia

Five components in the listing of Table 2-2 are found to be common to the four subsystems listed above. The number of these components in each subsystem is listed in Table 2-3.

TABLE 2-3

COMMON COMPONENT SUMMARY

(excluding instrumentation)

Item Dash No.	Description	Subsystem			
		100	200	300	Total
-A	Check valve	3	-	6	9
-B	Solenoid shutoff valve	3	2	1	6
-C	Manual shutoff valve	3	8	7	18
-D	Quick disconnect	2	6	4	12
-E	Bacteria filter	1	-	4	5

The extent of commonality can only be realized by comparing the total number of components (119) to the total number of designs (63). Examination of the system schematic and parts list shows that commonality was stressed in component selection; and that the wide use of identical shutoff valves and quick disconnects in diversified fluid streams represents a design goal. Only through detail design activities can the final extent of commonality be defined accurately.

2. System Weight

The weight of the system depicted on the schematic of Figure 2-2 is estimated at 148 lb including a 90-day charge of expendables. On startup the urine storage tank is full of water, all other system tanks are empty with the exception of the pretreatment fluid tank. The system weight breakdown by subsystem is as follows:

1.00--Urine collection and transfer	38 lb (including bactericide)
2.00--Urine storage and processing	69 lb
3.00--Water collection and transfer	29 lb
4.00--Instrumentation	12 lb

System expendables include:

Brine dump: 1.1 lb/day

Oxygen for catalytic reactor operation: 0.012 lb/day

Pretreatment tank assembly: 13.1 lb/90 days,

Activated charcoal bed (104): 1.5 lb/90 days

Nitrogen used to provide the pneumatic power for cyclic accumulator operation and tank pressurization is discharged to the cabin and therefore is not charged to the system as an expendable.

3. Power Requirements

The water recovery system continuous power requirement is estimated at 195 watts excluding instrumentation and controls. Intermittent power consumption in the urine collection subsystem is estimated at 60 watts.

A rough estimate of the power necessary to operate the controls and the instrumentation transducers indicates that 25 watts will be necessary for this purpose.

4. Heat Leaks

Conceptually a vapor compression system is thermally balanced since the heat of condensation provides the thermal energy necessary for vaporization of the water. In practice, heat is generally added to the working fluid in the power consuming components. However, since the entire system is operated at a temperature higher than ambient, heat will be transferred from the system components to the environment. A total of about 660 Btu/hr is dumped from the system under normal operating conditions. This heat loss is balanced by the system power use.

5. Material Balance

Overall system material balance over the cycle is presented in Figure 2-3. The data are given for a urine solids content of 5 percent and a wash water solids content of 0.185 percent. Water processing rate is 16.35 lb in each reclamation unit. A water recovery efficiency of 95 percent is assumed for the urinal loop, as specified by NASA; a 98 percent recovery efficiency is estimated for the wash water loop.

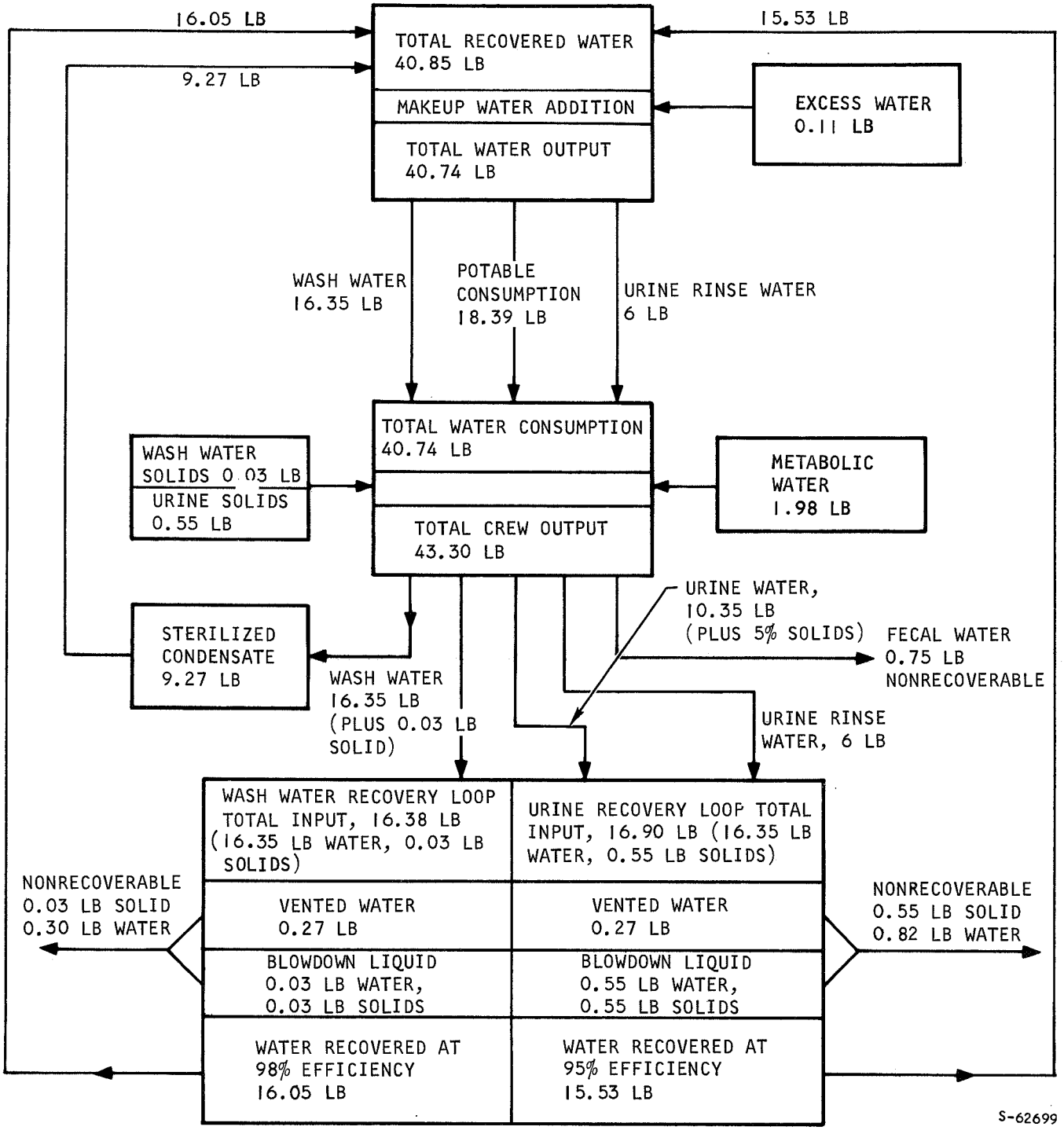


Figure 2-3. System Water Balance on a Daily Basis

System Performance

1. Urine Collection and Transfer

The weight of this subsystem is estimated as 38 lb including the expendable bactericide tank (111) and the charcoal charge (104) used for odor control. The weight of these expendable items sufficient for 90 days of usage is estimated as 13.1 lb and 1.5 lb respectively.

Pertinent performance characteristics are listed below:

(a) Maximum micturation rate, 50 cc/sec

(b) Maximum micturation volume, 500 cc

(c) Rinse water flow rate, 30 cc/sec

(d) Rinse water volume, 175 cc/micturation

(e) Bactericide use rate, 0.0027 lb/micturation

(f) Phase separator discharge pressure, 5 to 7 psig

(g) Phase separator power, 20 watts

(h) Blower power, 10 watts

(i) Controller power, 60 watts max (including blower and phase separator)

(j) Total cycle time, 6 to 7 minutes including drying

The power used by the urine collection subsystem is intermittent. The entire cycle is controlled automatically.

2. Urine Collection and Processing

As mentioned previously a semi-batch mode of operation is employed whereby the separator level is maintained constant by urine feed to the liquid loop as the brine concentration increases from 17 to 25 percent. When the concentration reaches 25 percent urine feed is stopped and the concentration is allowed to increase to 50 percent as more water is extracted from the brine. At 50 percent, a portion of the brine is dumped and the separator is refilled with urine. This cycle is illustrated in Figure 2-4 for system operation at a condenser pressure of 1.5 psia and a urine solids content of 4 percent.

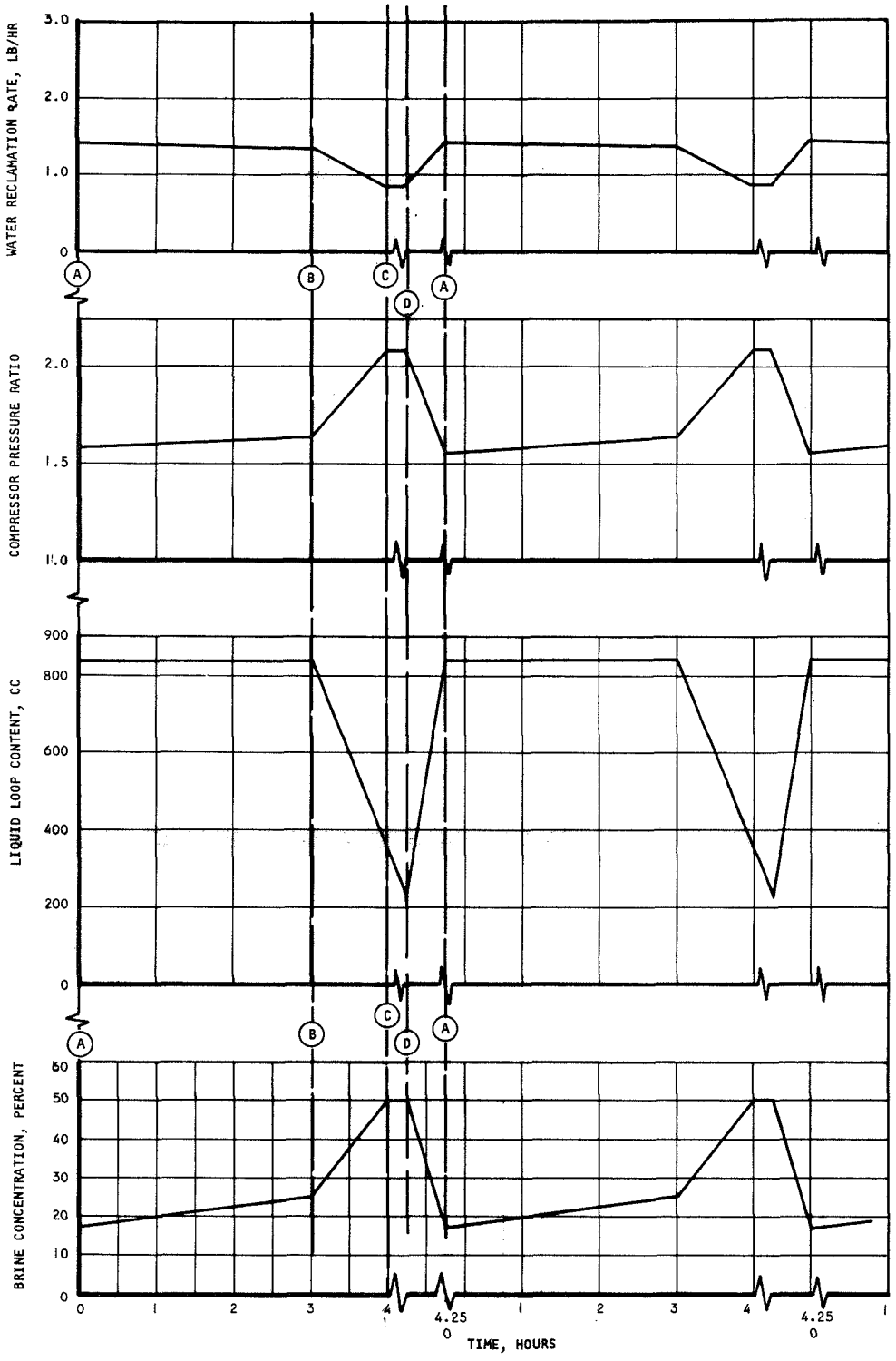


Figure 2-4. Semi-Batch Operational Sequence

The total cycle time for the above conditions is estimated at 4.25 hours. Brine dump and separator fill is 15 minutes. The average processing rate over the cycle is calculated to be 1.25 lb/hr, which exceeds the design specification rate of 1.0 lb/hr. Processing rate can easily be adjusted by control of the condenser pressure as discussed previously. Calculations show that the processing rate will vary from 1.0 to 1.73 lb/hr when condenser pressure is increased from 1.0 to 2.0 psia.

About 75 percent of the water is recovered during the constant level operation represented by the time interval A-B in the plot of Figure 2-4. For the purpose of component design a brine concentration of 20 percent was selected. Component data presented in Appendix A were prepared for this value of the brine solids content.

Figure 2-5 gives system thermodynamic data for design point operation. Additional data corresponding to other operating points are presented in Section 4.

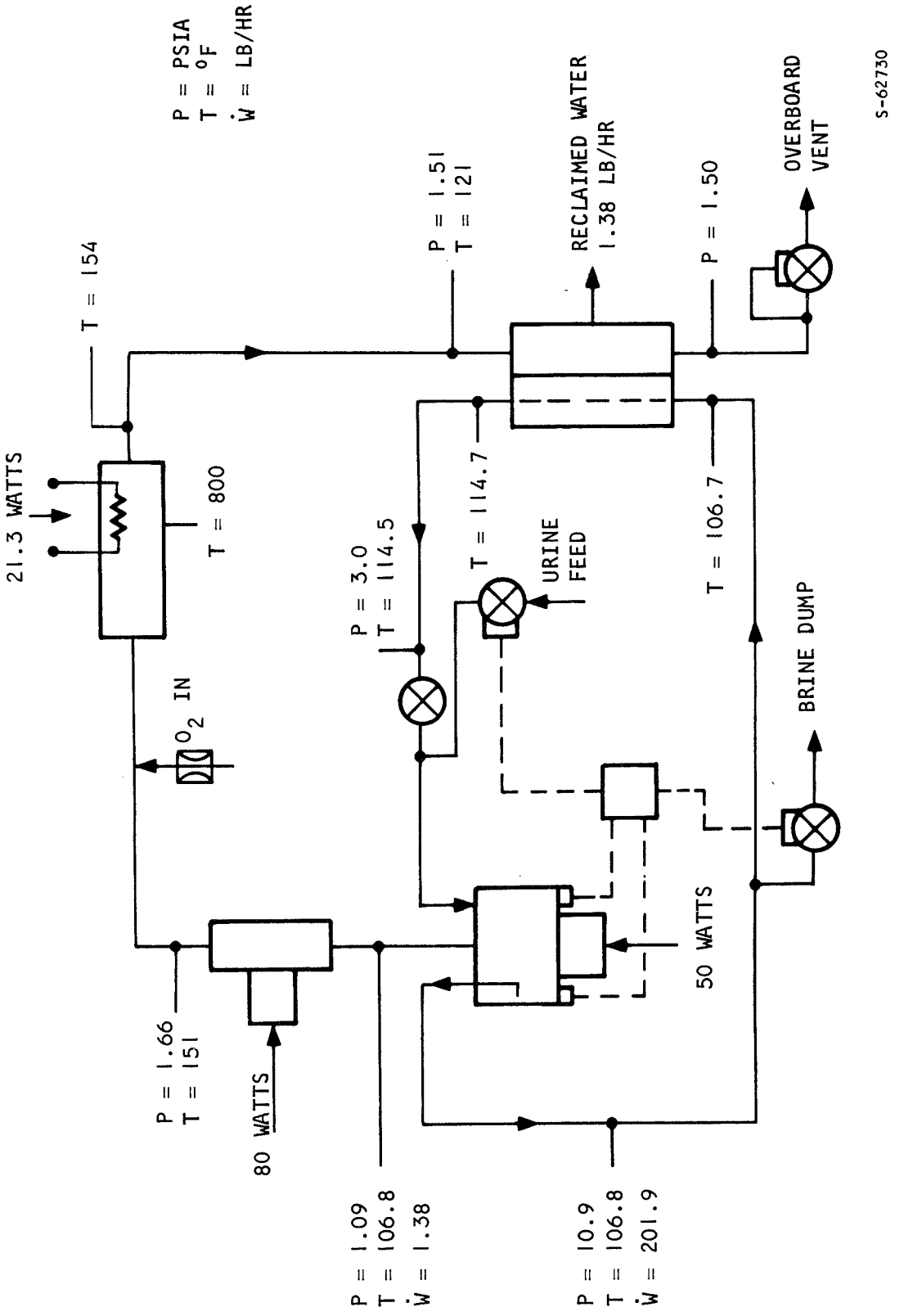
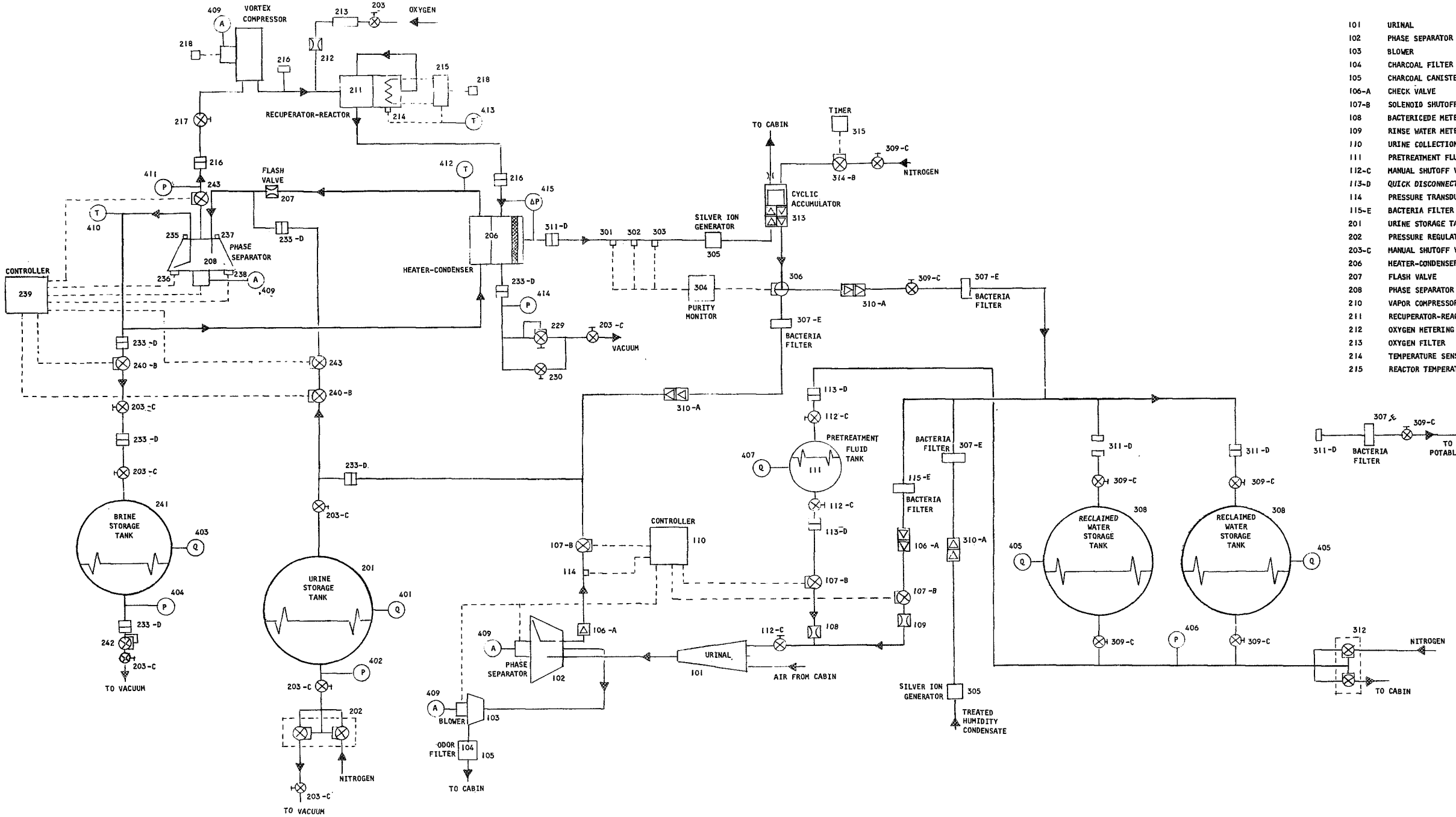


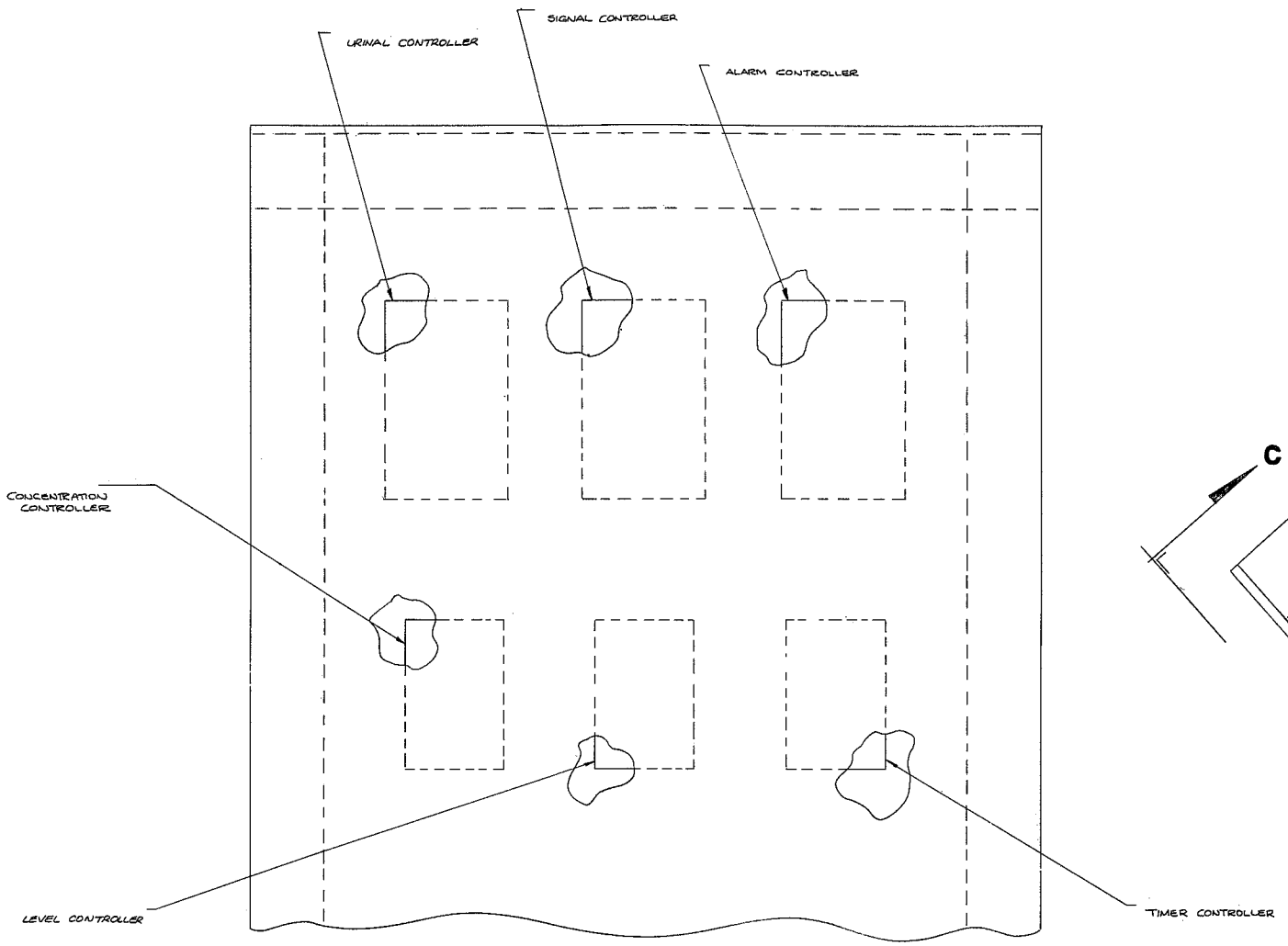
Figure 2-5. Processing Unit Design Point Performance



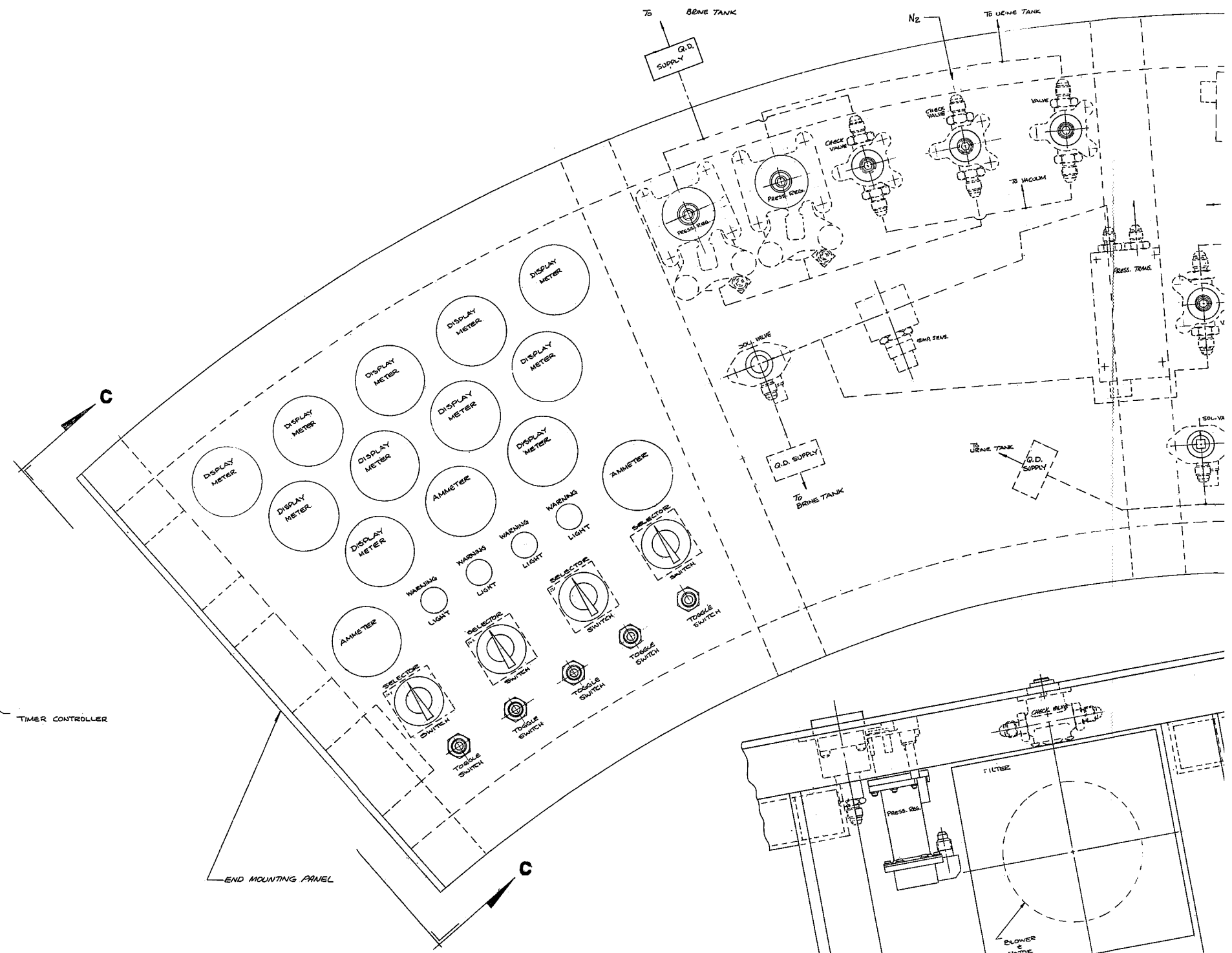
101	URINAL
102	PHASE SEPARATOR
103	BLOWER
104	CHARCOAL FILTER
105	CHARCOAL CANISTER
106-A	CHECK VALVE
107-B	SOLENOID SHUTOFF VALVE
108	BACTERICIDE METERING ORIFICE
109	RINSE WATER METERING ORIFICE
110	URINE COLLECTION PACKAGE CONTROLLER
111	PRETREATMENT FLUID TANK
112-C	MANUAL SHUTOFF VALVE
113-D	QUICK DISCONNECTS
114	PRESSURE TRANSDUCER
115-E	BACTERIA FILTER
201	URINE STORAGE TANK
202	PRESSURE REGULATOR-RELIEF
203-C	MANUAL SHUTOFF VALVE
206	HEATER-CONDENSER
207	FLASH VALVE
208	PHASE SEPARATOR
210	VAPOR COMPRESSOR
211	RECUPERATOR-REACTOR
212	OXYGEN METERING ORIFICE
213	OXYGEN FILTER
214	TEMPERATURE SENSOR
215	REACTOR TEMPERATURE CONTROLLER
216	QUICK-DISCONNECT
217	MANUAL SHUTOFF VALVE
218	SWITCH
229	CONDENSER PRESSURE REGULATOR
230	BLEED VALVE
233-D	QUICK-DISCONNECT
235	DENSITY CONTROL SOURCE
236	DENSITY CONTROL DETECTOR
237	LEVEL CONTROL SOURCE
238	LEVEL CONTROL DETECTOR
239	BRINE LOOP CONTROLLER
240-B	SOLENOID SHUTOFF VALVE
241	BRINE STORAGE TANK
242	BRINE PRESSURE REGULATOR
243	SOLENOID SHUTOFF VALVE
301	pH SENSOR AND DISPLAY
302	CONDUCTIVITY SENSOR
303	ORGANICS MONITOR
304	PURITY CONTROLLER
305	SILVER ION GENERATOR
306	SELECTOR VALVE
307-E	BACTERIA FILTER
308	RECLAIMED WATER TANK
309-C	MANUAL SHUTOFF VALVE
310-A	CHECK VALVE
311-D	QUICK DISCONNECT
312	PRESSURE REGULATOR - RELIEF
313	CYCLIC ACCUMULATOR
314-B	SOLENOID VALVE
315	CYCLIC ACCUMULATOR TIMER
401	URINE STORAGE QUANTITY METER
402	URINE STORAGE PRESSURE METER
403	BRINE STORAGE QUANTITY METER
404	BRINE STORAGE PRESSURE METER
405	RECLAIMED WATER STORAGE QUANTITY METER
406	RECLAIMED WATER STORAGE PRESSURE METER
407	PRETREATMENT TANK QUANTITY METER
409	AMMETER
410	BRINE TEMPERATURE - SEPARATOR OUTLET
411	SEPARATOR PRESSURE METER
412	BRINE TEMPERATURE - CONDENSER OUTLET
413	CATALYTIC REACTOR TEMPERATURE
414	CONDENSER PRESSURE TRANSDUCER
415	DIFFERENTIAL PRESSURE TRANSDUCER

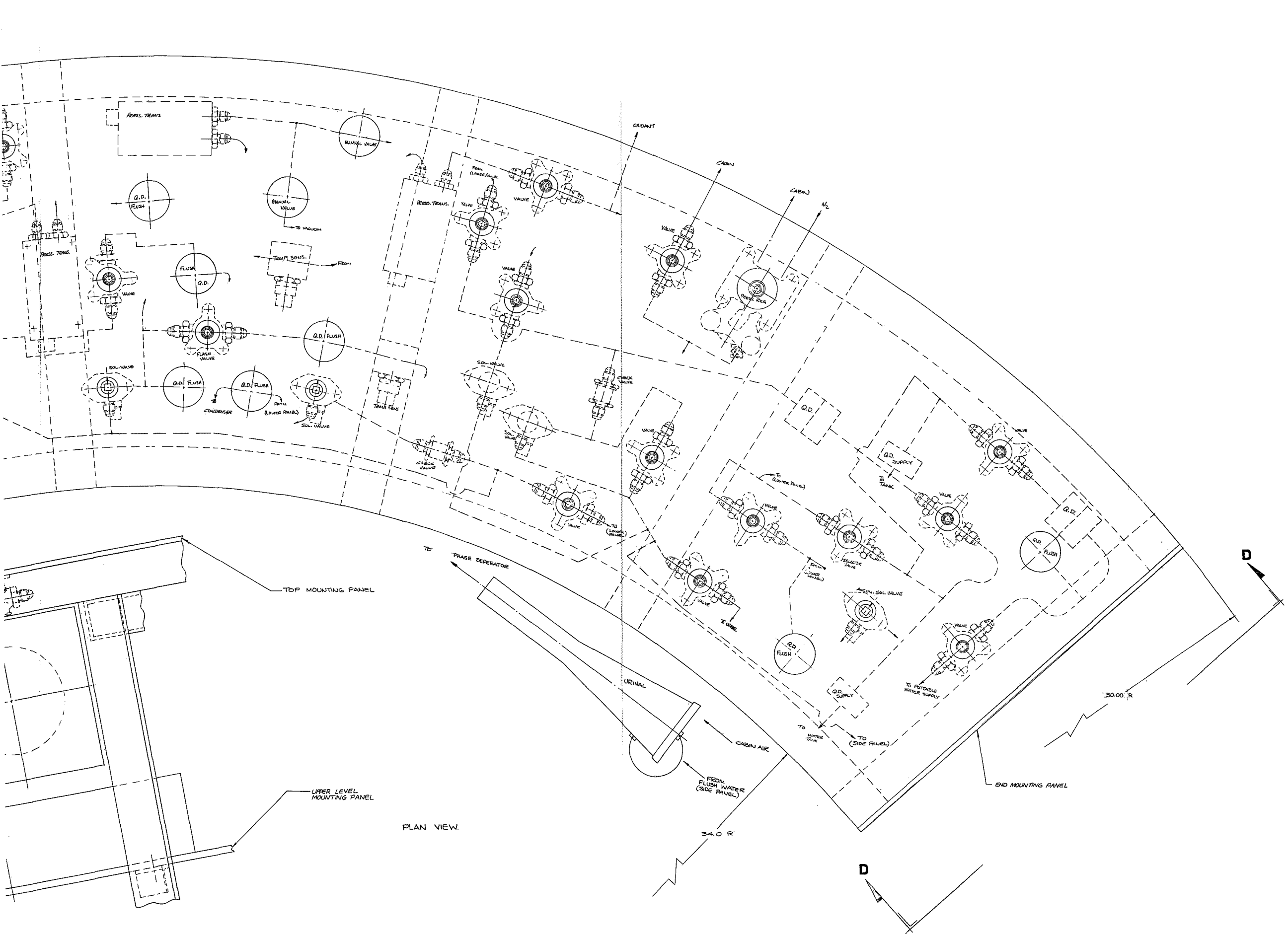
L-63871

Figure 2-2. System Schematic


URINAL CONTROLLER
SIGNAL CONTROLLER
ALARM CONTROLLER
CONCENTRATION CONTROLLER
LEVEL CONTROLLER
TIMER CONTROLLER

VIEW **C C**

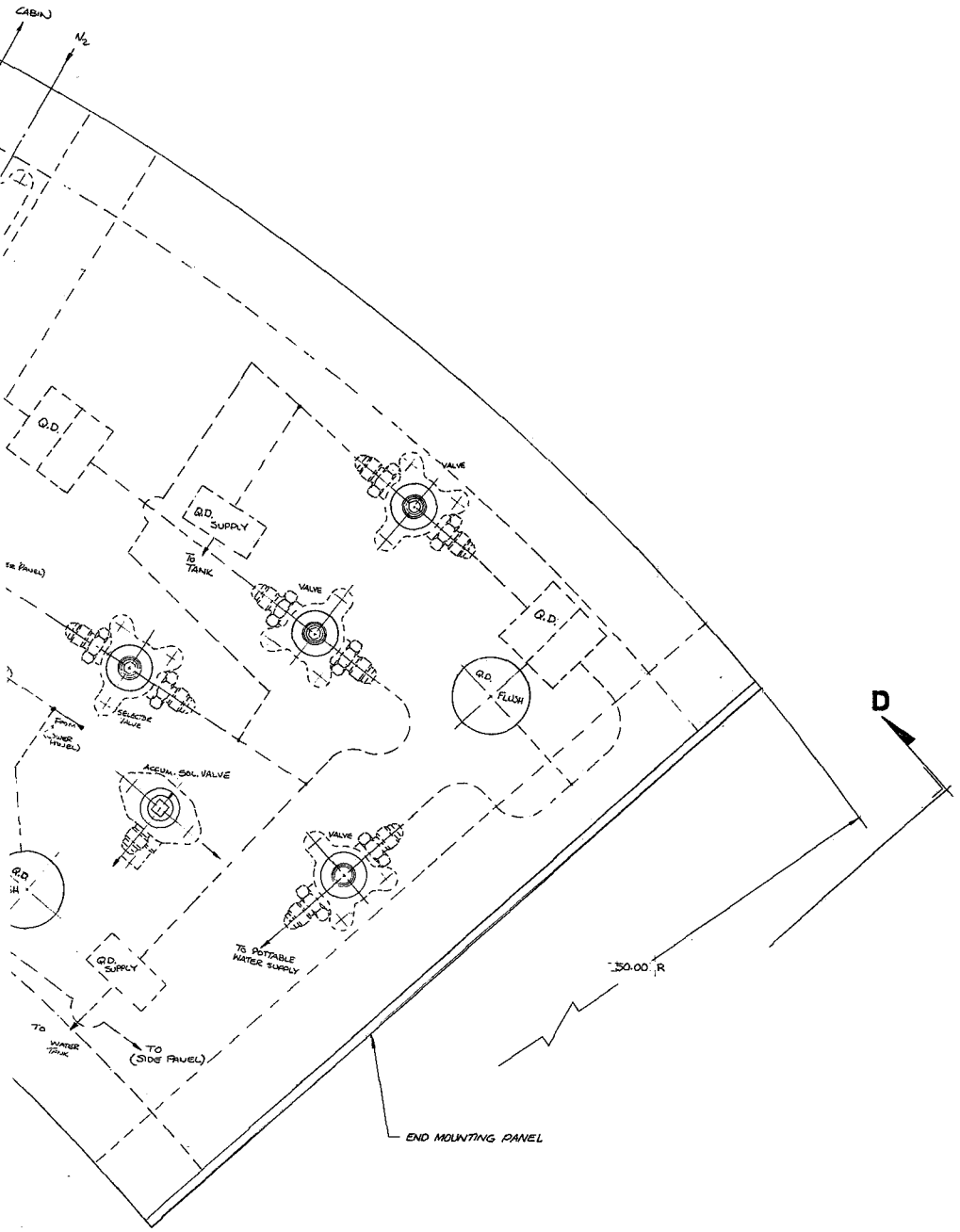

C
DISPLAY METER
AMMETER
WARNING LIGHT
SELECTOR SWITCH
TOGGLE SWITCH
END MOUNTING PANEL
C
To BRINE TANK
Q.D. SUPPLY
N_2
To URINE TANK
CHECK VALVE
VALVE
To VACUUM
PRESS. REG.
PRESS. TRANS.
SOL. VALVE
SOL. VALVE
To BRINE TANK
To URINE TANK
Q.D. SUPPLY
FILTER
PRESS. REG.
BLOWER & MOTOR
HEATER/CONDENSER

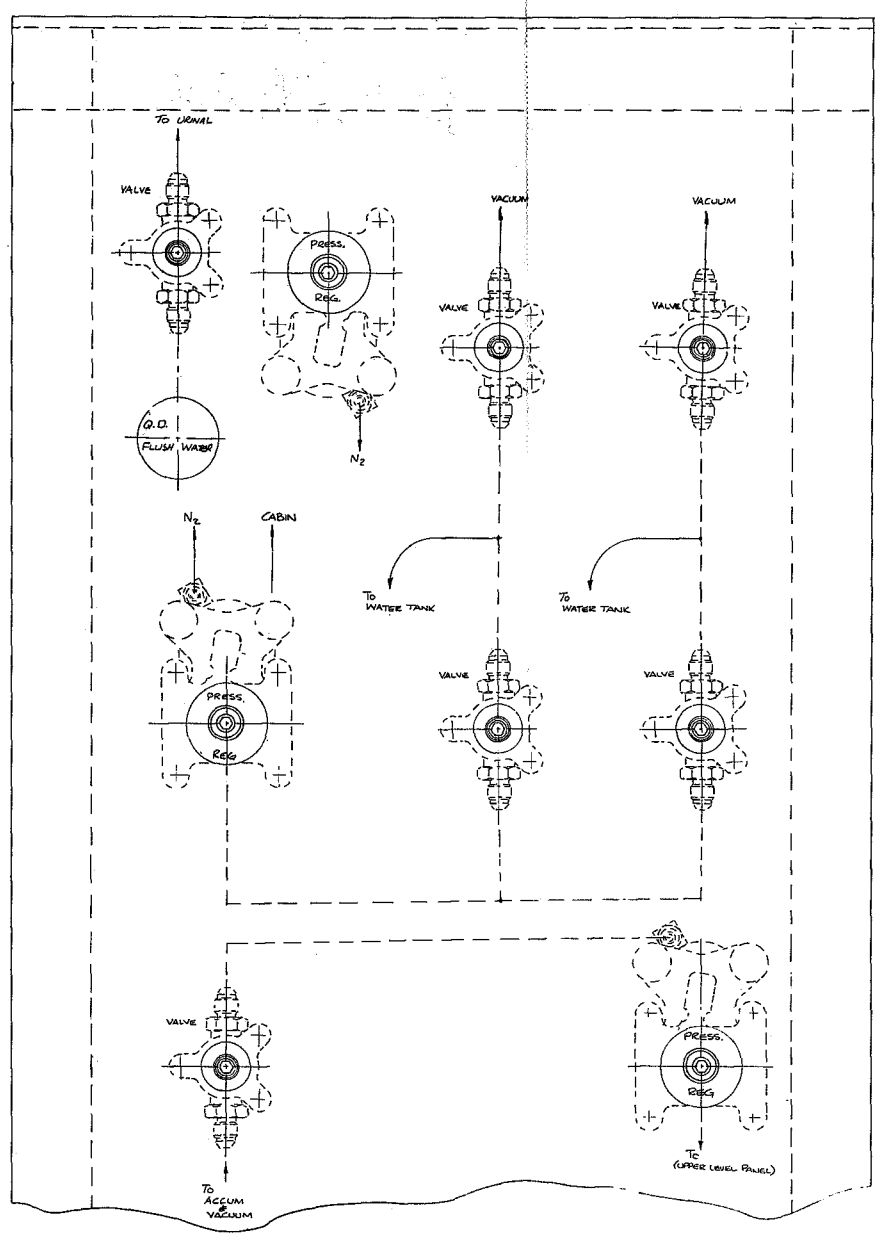

PRESS. TRANS
MANUAL VALVE
Q.D. FLUSH
MANUAL VALVE
TO VACUUM
PRESS. TRANS.
TEMP. SENS.
FROM
FLUSH Q.D.
VALVE
FLUSH VALVE
Q.D. FLUSH
SOL. VALVE
Q.D. FLUSH
Q.D. FLUSH
TO CONDENSER
PATH (LOWER PANEL)
SOL. VALVE
TEMP. SENS
CHECK VALVE
FROM (LOWER PANEL)
VALVE
VALVE
PRESS. TRANS.
VALVE
OXIDANT
CABIN
CABIN
N_2
VALVE
PRESS REG
VALVE
SOL. VALVE
CHECK VALVE
Q.D.
Q.D. SUPPLY
TO TANK
VALVE
VALVE
VALVE
VALVE
TO (LOWER PANEL)
VALVE
SOLENOID VALVE
Q.D. FLUSH
Q.D.
Q.D. FLUSH
ACCUM. SOL VALVE
VALVE
Q.D. SUPPLY
TO POTABLE WATER SUPPLY
TO WATER TANK
TO (SIDE PANEL)
TO PHASE SEPERATOR
URINAL
CABIN AIR
FROM FLUSH WATER (SIDE PANEL)
34.0 R
50.00 R
END MOUNTING PANEL
D
D
TOP MOUNTING PANEL
UPPER LEVEL MOUNTING PANEL

PLAN VIEW.

2

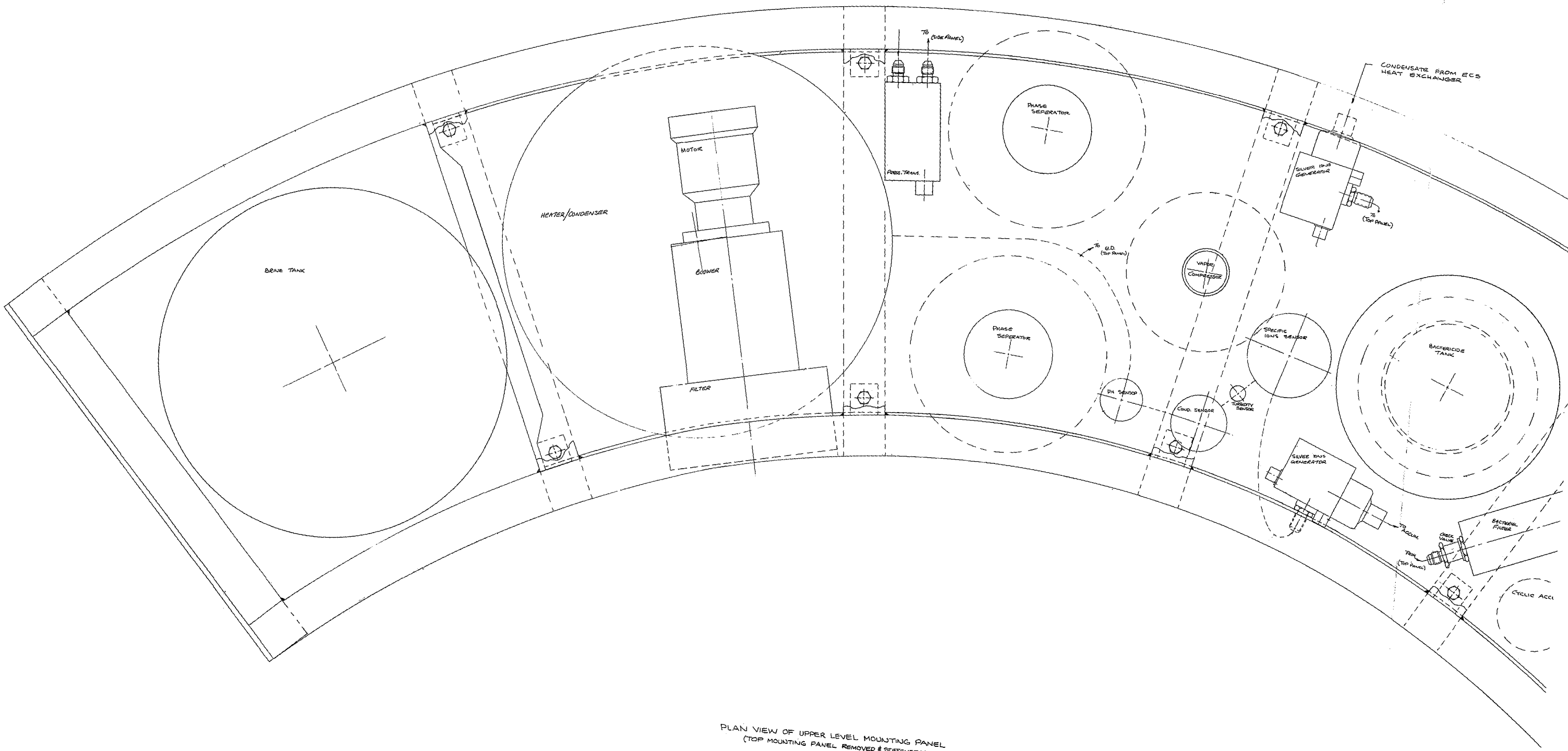
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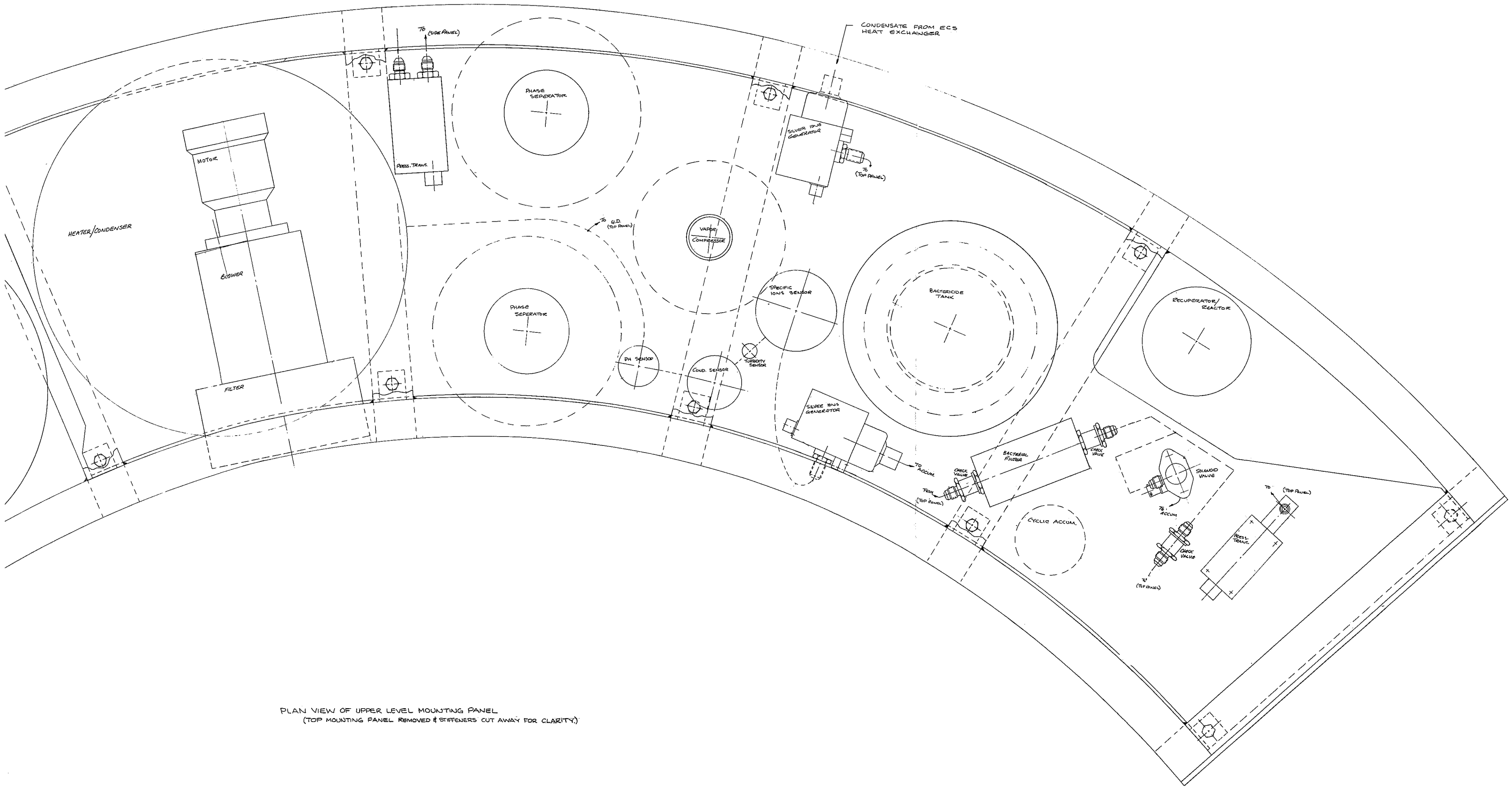


PARTIAL VIEW **D-D**

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SIGNATURES / DATES / DATE STARTED / WITNESSED BY	WATER RECOVERY SYSTEM (TYPICAL)
DES R. MILLER 9-28-70	
DRAFTING 1-14-70	
STRESS	
WEIGHT	
APPD DATE COMPLETED 4-6-70	
APPD	
APPD DRAWING NO. 3502-150143-20-0300	
FEATURES	SIZE J 70210 CODE IDENT NO. DWG NO. L 145719
	SCALE 1/1 WT SHEET 1 OF 4



PLAN VIEW OF UPPER LEVEL MOUNTING PANEL
(TOP MOUNTING PANEL REMOVED & STIFFENERS CUT AWAY FOR CLARITY)



PLAN VIEW OF UPPER LEVEL MOUNTING PANEL
(TOP MOUNTING PANEL REMOVED & STIFFENERS CUT AWAY FOR CLARITY.)

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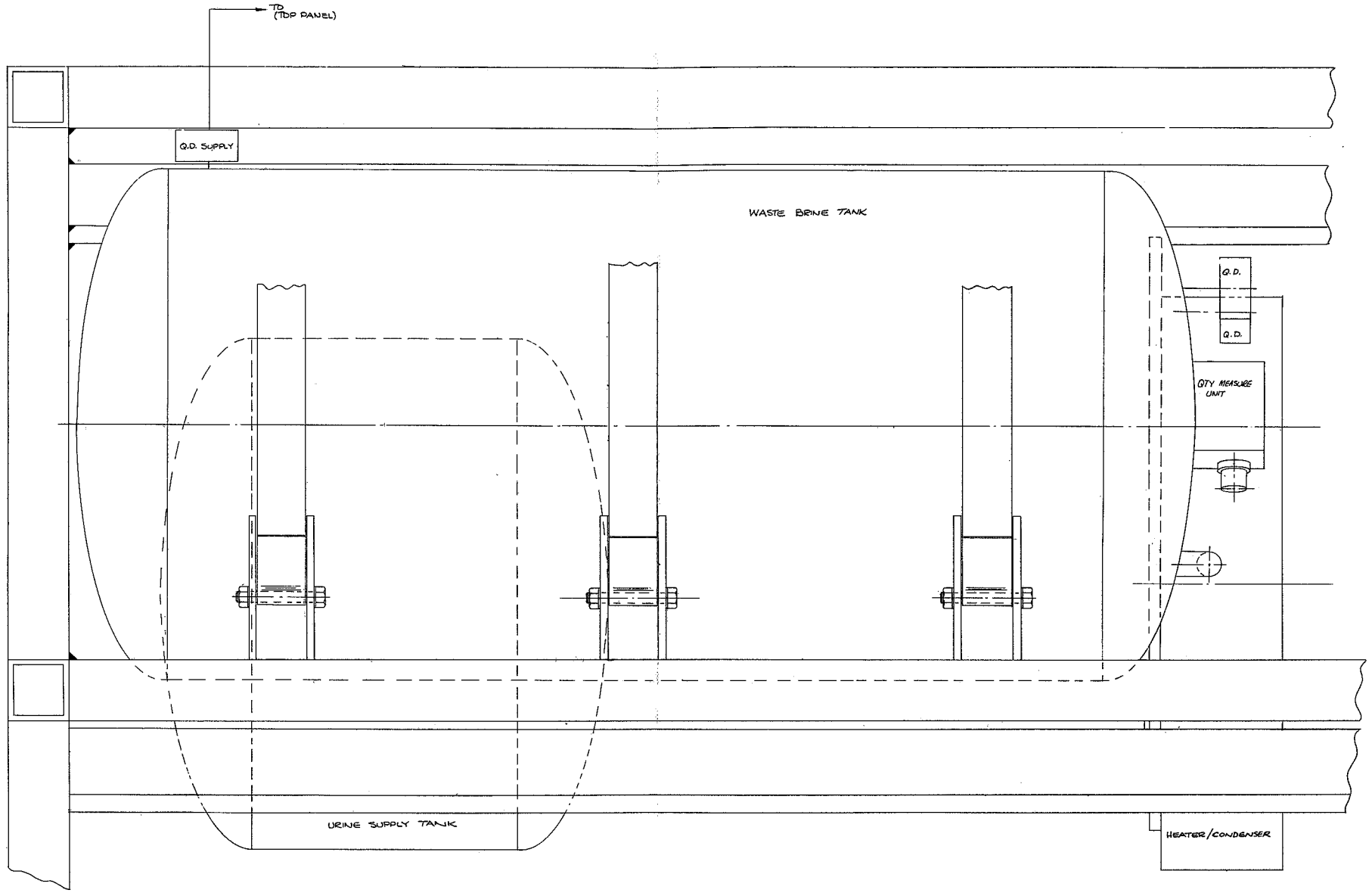
LAYOUT

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MATL		7-26-70	
STRESS		DATE COMPLETED	WITNESSED BY
WEIGHT			
APPD		7-30-70	
APPD		CODE IDENT NO.	
APPD		3502-50143-20-0300	
FEATURES			

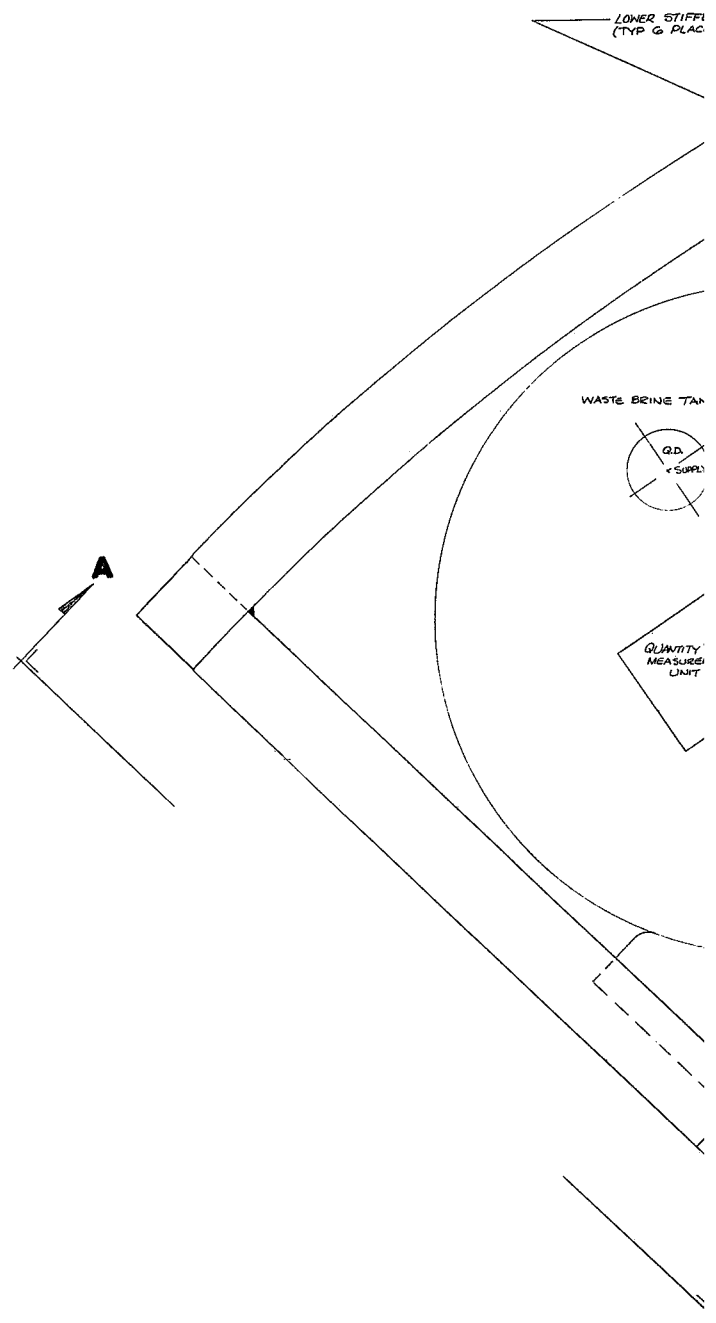
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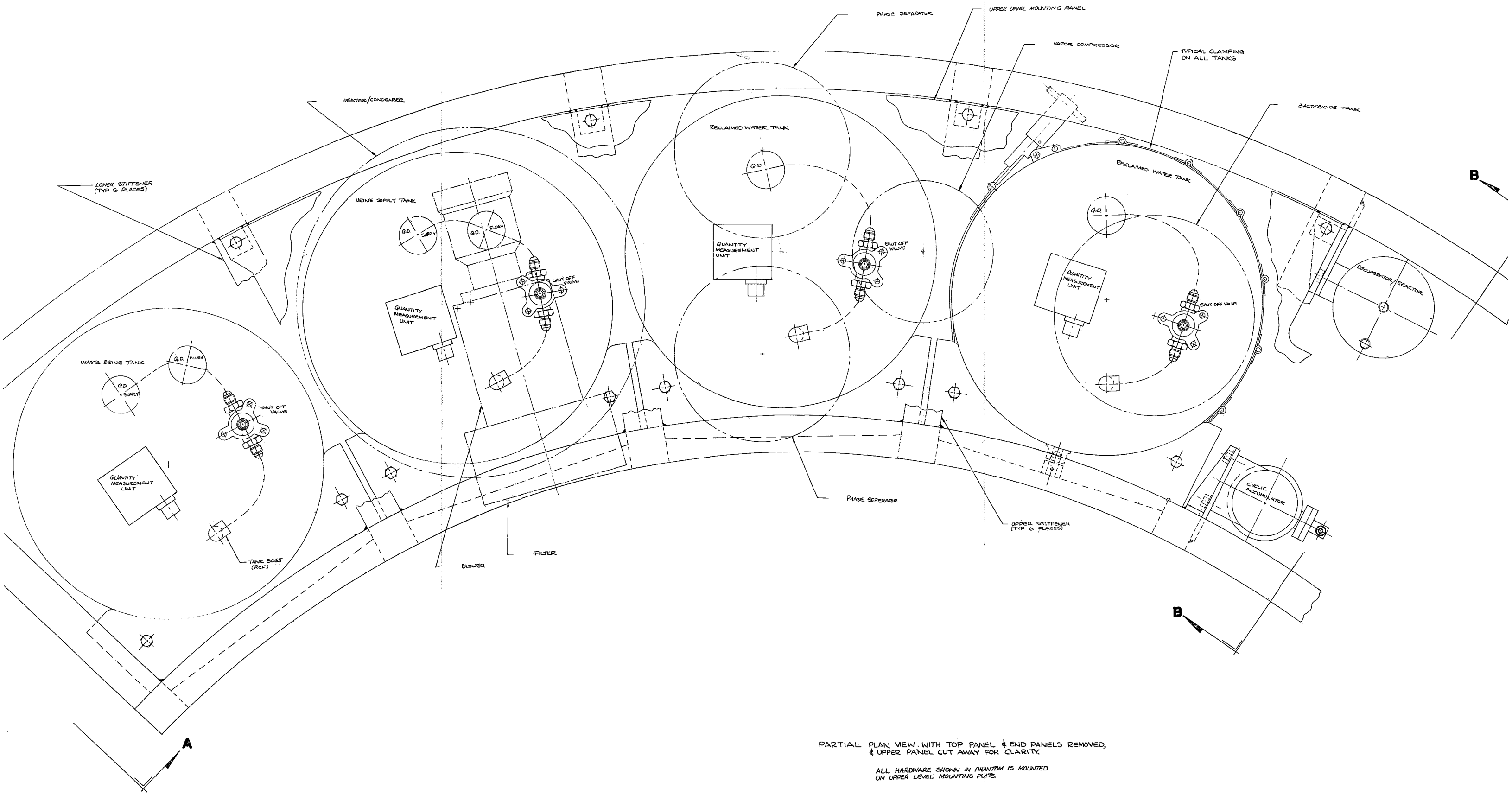
SIZE	CODE IDENT NO.	DWG NO.
J	70210	L 145719
SCALE 1/1	WT	SHEET 2 OF 4

2


TO
(TOP PANEL)
Q.D. SUPPLY
WASTE BRINE TANK
Q.D.
Q.D.
QTY MEASURE
UNIT
URINE SUPPLY TANK
HEATER/CONDENSER

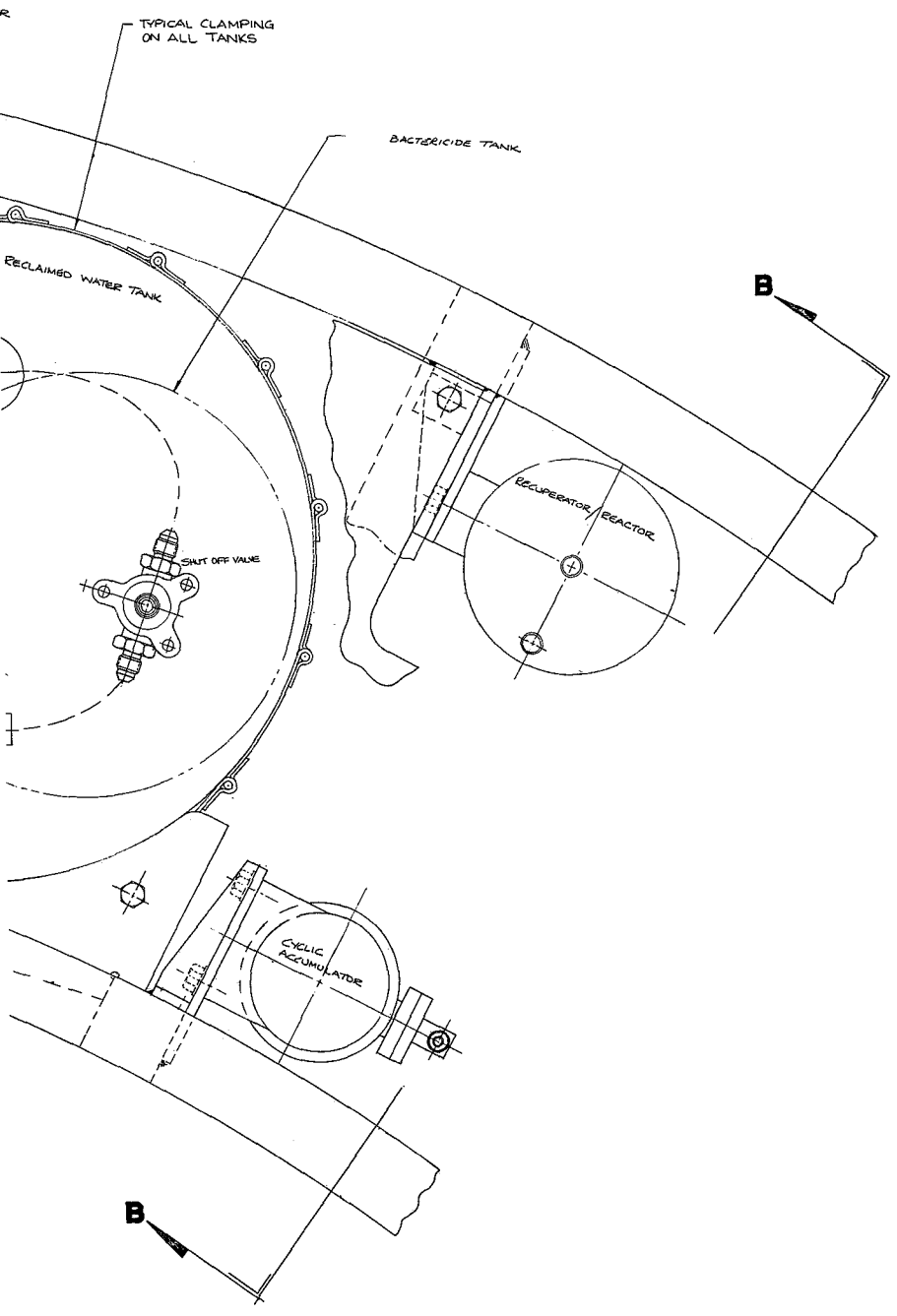
VIEW **A-A**

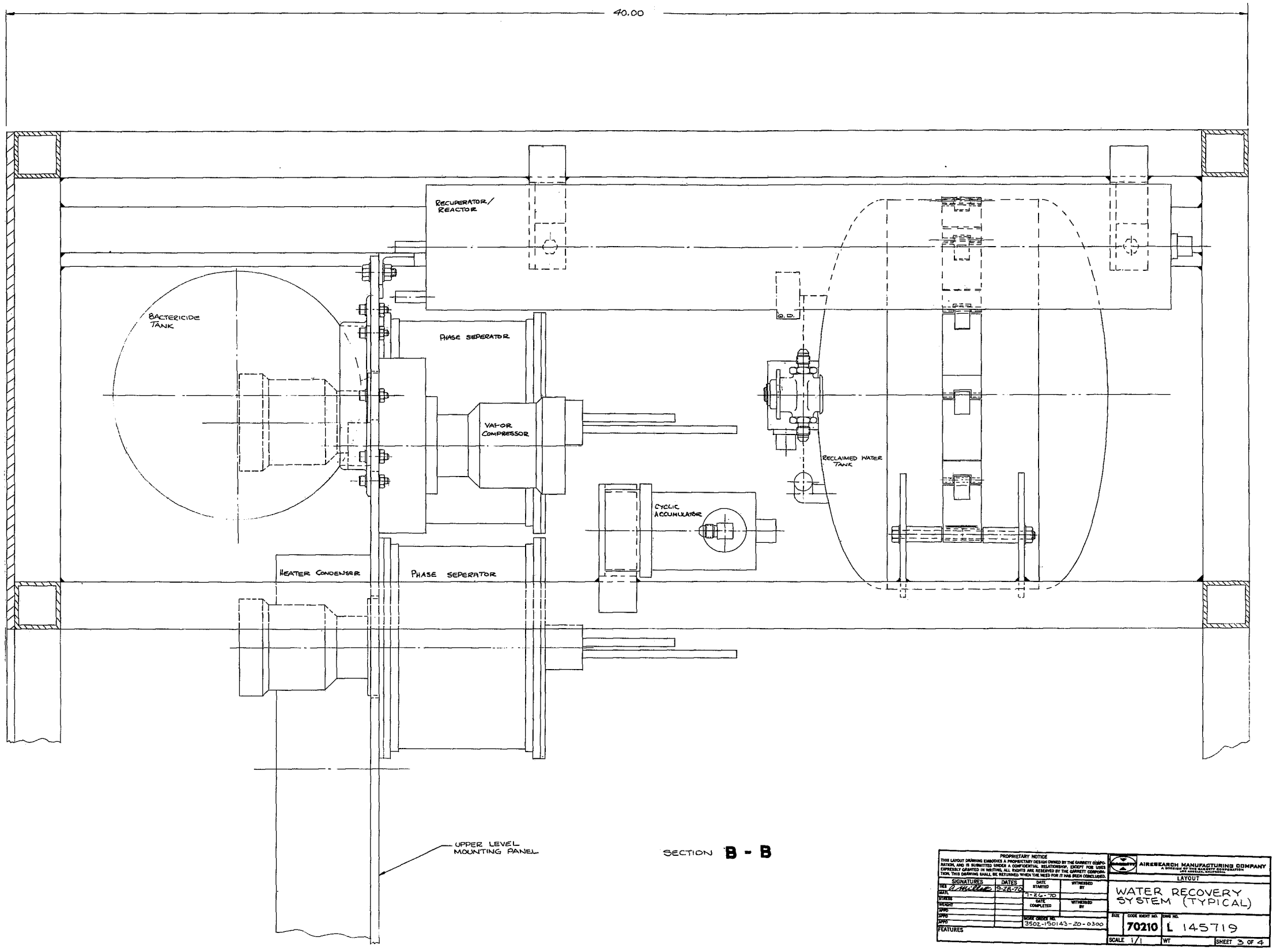

LOWER STIFFE
(TYP 6 PLAC
WASTE BRINE TAN
Q.D.
SUPPL
A
QUANTITY
MEASURED
UNIT



PARTIAL PLAN VIEW. WITH TOP PANEL & END PANELS REMOVED, & UPPER PANEL CUT AWAY FOR CLARITY.

ALL HARDWARE SHOWN IN PHANTOM IS MOUNTED ON UPPER LEVEL MOUNTING PLATE.





SECTION **B - B**

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SIGNATURES	DATES	
DES R. Miller	9-28-70	DATE STARTED: 1-REL-70
ENGR		WITHDRAWN BY
STRESS		DATE COMPLETED
SPEC/QUAL		WITHDRAWN BY
APPD		
APPD		WORK ORDER NO. 3502-150143-20-0300
APPD		
FEATURES		

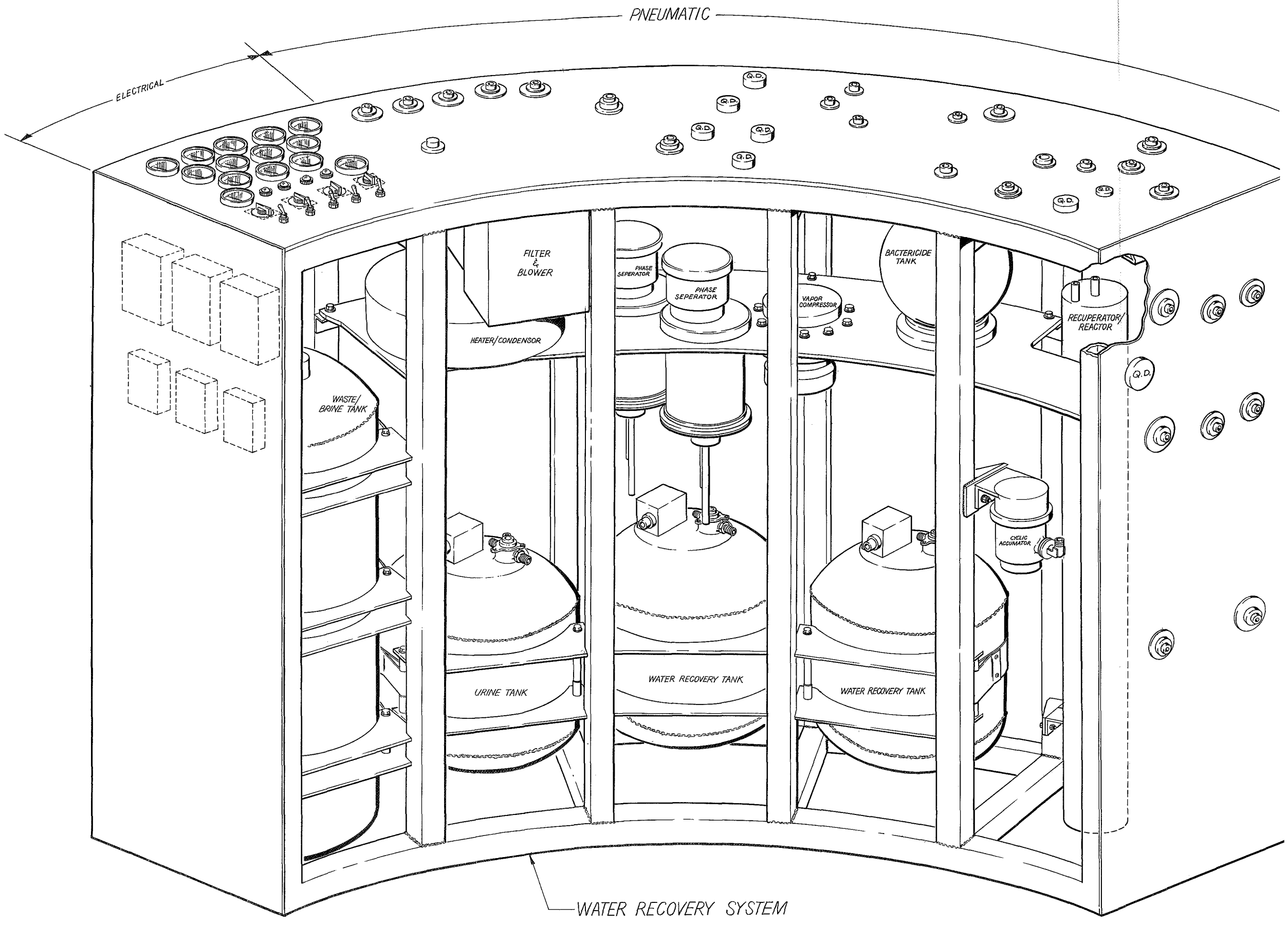
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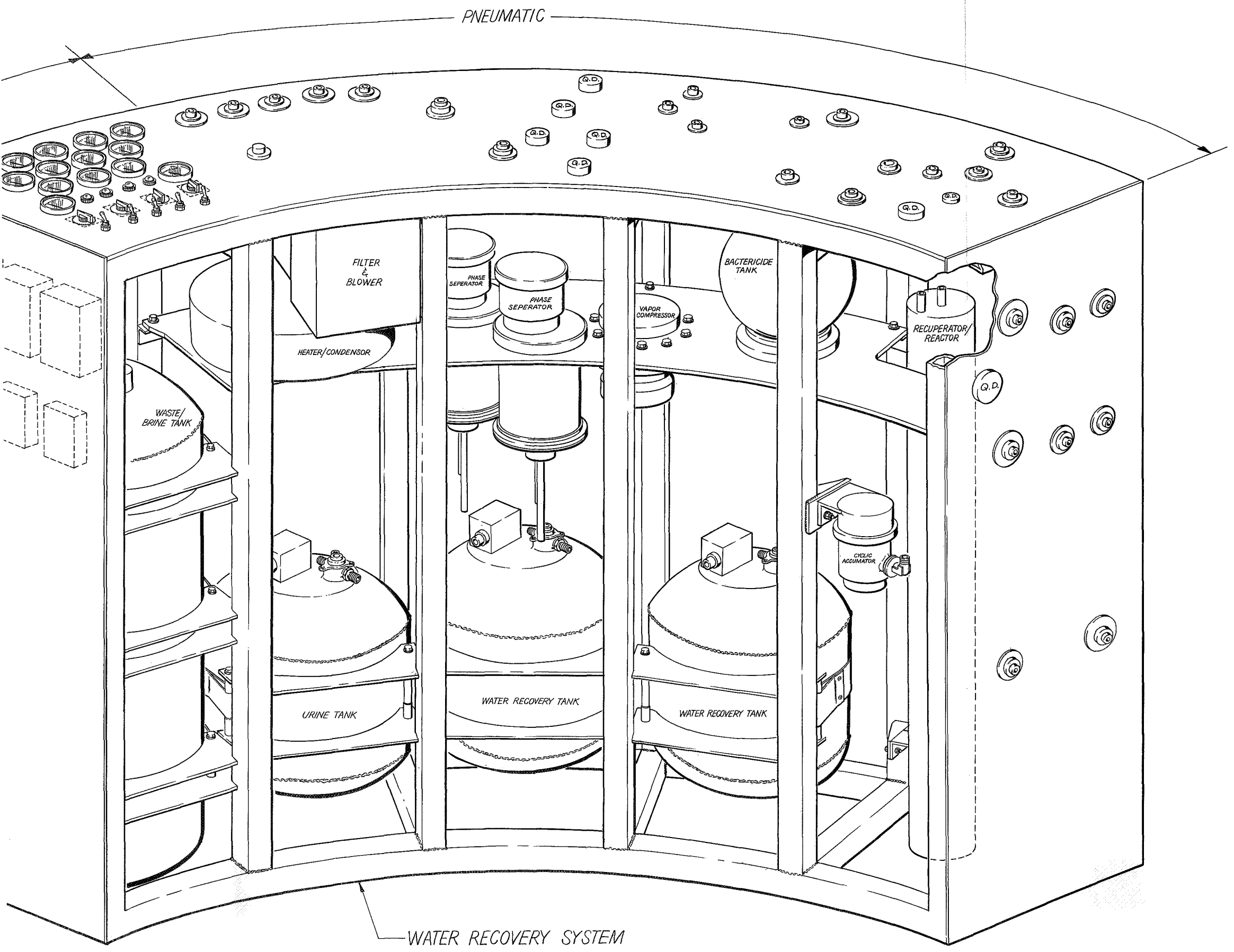
LAYOUT

WATER RECOVERY SYSTEM (TYPICAL)

SIZE	CODE IDENT NO.	DWG NO.
	70210	L 145719

SCALE 1/1 | WT | SHEET 3 OF 4


PNEUMATIC
ELECTRICAL
FILTER & BLOWER
PHASE SEPERATOR
PHASE SEPERATOR
VAPOR COMPRESSOR
BACTERICIDE TANK
RECUPERATOR/ REACTOR
Q.D.
HEATER/CONDENSOR
WASTE/ BRINE TANK
CYCLIC ACCUMATOR
URINE TANK
WATER RECOVERY TANK
WATER RECOVERY TANK
WATER RECOVERY SYSTEM



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AIRESEARCH MANUFACTURING COMPANY
A DIVISION OF THE GARRETT CORPORATION
LOS ANGELES, CALIFORNIA

LAYOUT

WATER RECOVERY SYSTEM (TYPICAL)

SIGNATURES	DATES	
DES	5-28-70	DATE STARTED 7-26-70
MATL		WITNESSED BY
STRESS		DATE COMPLETED 8-13-70
WEIGHT		WITNESSED BY
APPD		WORK ORDER NO. 3502-150143-20-0300
APPD		
APPD		
FEATURES		

SIZE: — CODE IDENT NO.: 70210 — DWG NO.: L 145719
SCALE 1/2 — WT — SHEET 4 OF 4

400 CYCLE POWER
400 CYCLE RETURN
+28 VDC
DC RETURN
CHASSIS
P
+28V
28V RETURN
WATER QUALITY WARNING LAMP
DIVERTER VALVE ITEM 306
SELECTOR SWITCH
AMMETER ITEM 409
URINAL CYCLE CONTROLLER ITEM 110
BLOWER ITEM 103
PHASE SEPARATOR ITEM 102 (BRUSHLESS D.C. MOTOR)
PRESSURE SWITCH ITEM 114
PHASE SEPARATOR OUTLET SOL VALVE ITEM 107-B
RINSE WATER SOL VALVE ITEM 107-B
BACTERIOCIDE SOL VALVE ITEM 107-B
CONDUCTIVITY METER
ORGANOMET
A
B
C
D

METER
M 409

AMMETER
ITEM 409

PRESSURE
SWITCH
ITEM 114

PHASE
SEPARATOR
OUTLET
SOL VALVE
ITEM 107-B

RINSE
WATER
SOL VALVE
ITEM 107-B

BACTERIOCIDE
SOL VALVE
ITEM 107-B

CONDUC-
TIVITY
METER

ORGANIC
MONITOR
METER

pH METER

P

Q

SELECTOR SWITCH
AUTO
OFF
DIV

WATER QUALITY
WARNING LAMP

DIVERTER
VALVE
ITEM 306

ALARM — PURITY MONITOR
ITEM 304

pH SENSOR
ITEM 301

ORGANICS
MONITOR
ITEM 303

CONDUC-
TIVITY
SENSOR
ITEM
302

REACTOR
POWER
SWITCH
ITEM 218

DISPLAY
METER
ITEM 413

TEMP
CONTROLLER
ITEM 215

TEMP SENSOR
ITEM 214

HEATER

SWITCH
AUTO
OFF
VALVE

SOL VALVE
ITEM 314-B

TIMER
ITEM 315

SOL VALVE
ITEM 243

VALVE
OFF
AUTO
SWITCH

CONCENTRATION
SENSOR
ITEM 236

LEVEL SENSOR
ITEM 238

SOL VALVE
ITEM 240-B

OFF
SWITCH

VALVE
OFF
AUTO
SWITCH

AMMETER
ITEM 409
A

PHASE
SEPARATOR
ITEM 208

CONCENTRATION
AND LEVEL
CONTROL
ASSY
MODULE
ITEM 239

OFF
SWITCH
ITEM 218

SOL VALVE
ITEM 240-B

AMMETER
ITEM 409
A

VAPOR
COMPRESSOR
ITEM 210

VALVE
OFF
AUTO
SWITCH

+28V
28V RETURN

+28V
28V RETURN

+28V
28V RETURN

SK 38192

SK 38192

2

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REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED

T/M OUTPUTS

DISPLAY METER ITEM 410

DISPLAY METER ITEM 412

COMBINED TEMP. SIGNAL CONDITIONER ITEMS 410 412

TEMP SENSOR ITEM 410

TEMP SENSOR ITEM 412

DISPLAY METER ITEM 402

PRESSURE TRANSDUCER ITEM 402

DISPLAY METER ITEM 411

PRESSURE TRANSDUCER ITEM 411

DISPLAY METER ITEM 404

PRESSURE TRANSDUCER ITEM 404

DISPLAY METER ITEM 414

PRESSURE TRANSDUCER ITEM 414

DISPLAY METER ITEM 127-B

PRESSURE TRANSDUCER ITEM 127-A

DISPLAY METER ITEM 406

PRESSURE TRANSDUCER ITEM 406

QUANTITY SENSOR ITEM 403

SIGNAL CONDITIONER

DISPLAY METER

QTY SENSOR ITEM 403

SIGNAL CONDITIONER

DISPLAY METER

QUANTITY SENSOR ITEM 407

SIGNAL CONDITIONER

QUANTITY SENSOR ITEM 401

SIGNAL CONDITIONER

DISPLAY METER

QUANTITY SENSOR ITEM 405

SIGNAL CONDITIONER

+28 V

28V RETURN

INSTR. POWER

1 ELECTRICAL & ELECTONIC GRAPHIC SYMBOLS PER USA-Y-32.2-1967

NOTES: UNLESS OTHERWISE SPECIFIED

QTY REQD	ITEM NO.	CODE IDENT NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	SYM	ZONE
	← ASSY			PARTS LIST		

UNLESS OTHERWISE SPECIFIED: BURR CONTROL PER SC003
IDENTIFICATION MARKING PER MC05
STD INTERPRETATIONS PER P/B5
HEAT TREATMENT HARDNESS AND SPEC
PROCESS NAME AND SPEC

CONTRACT NO.
DR J. L. Curtis 4-23-70
CHK
ENGR
MATL
STAGE
SPEC
DATE
ASSEMBLED NAME
DESIGN ACTIVITY APPD

AIRESEARCH MANUFACTURING COMPANY
A DIVISION OF THE GARRETT CORPORATION
LOS ANGELES, CALIFORNIA

ELECTRICAL SCHEMATIC, WATER RECOVERY SYSTEM

SIZE	CODE IDENT NO.	DWG NO.
J	70210	SK 38192

SCALE — SHEET 1 OF 1

REQD | NEXT ASSY | USED ON
APPLICATION

SK 38192

SECTION 3

COMPONENT DESIGN AND DEVELOPMENT

INTRODUCTION

Completion of Task A of Contract NAS 9-8460 marked a major milestone in the overall development of the Intermediate Water Recovery System (IWRS). Hardware approaches were selected for the major system components; first generation breadboard equipment was fabricated for integration and test in an upgraded pilot plant developed under a previous research program. Limited component testing was performed with emphasis placed on compressor development. With the exception of the compressor, where major problems were encountered, the basic component approaches developed proved satisfactory although further development and analysis were found to be necessary in order to achieve the desired performance levels.

A complete summary of the Task A achievements under NAS 9-8460 can be found in AiResearch Report No. 69-5470, published at the conclusion of that phase of the program. The report also contains a list of recommendations for future work.

In general, the recommendations for component development and preliminary design listed in report 69-5470 were incorporated in the phase of the program reported here and conducted under NAS 9-8460, Task B, and NAS 9-9981. These component-level activities were centered primarily on the following equipment:

(a) Compressor

(b) Phase separator

(c) Heater-condenser

(d) Catalytic reactor

(e) Level and concentration control

(f) Purity monitoring equipment, including bacteria control

The compressor, the phase separator, and the catalytic reactor were subjected to limited component-level tests under this phase of the program. The heater-condenser and the level and concentration control system were tested only at the integrated system level. No testing, except for a pH sensor and a conductivity meter, was performed on the purity monitoring system.

All equipment was subjected to analysis and preliminary design studies. The analytical tasks were very closely related to the development test program in order to provide support and guide the modification of the breadboard components. In addition, analytical investigations of all processes and components were conducted, using test data where available, in the preparation of preliminary component specifications. These specifications are presented in Appendix A of this report.

Table 3-I summarizes the recommendations of report 69-5470, the accomplishments of the current programs, and the recommendations ensuing from the work performed. No problems other than those normally encountered in development are foreseen at this time. Briefly, the progress on the components of the IWRS is as follows:

- Compressor design and development, which was identified as the critical problem on Task A of NAS 9-8460, was successfully resolved. The two-stage vortex compressor developed was eminently successful.
- Phase separator liquid entrainment was reduced by a factor of 10.
- Heater-condenser limitations were diagnosed and design criticality was obviated by the changes in the system control system.
- A catalyst for the vapor pyrolysis unit was selected and run successfully.
- A new system control method using the nucleonic sensor technique was evolved, thus relieving the heater-condenser problem and increasing the system water production rate.
- Purity monitoring and bacteria control and process requirements and equipment availability were investigated and approaches were recommended.
- Preliminary design specifications were prepared for all components of the system.

At this stage of component development, little breadboard work at the component level remains, as shown in Table 3-I. It is recommended that, as a minimum, flight configured hardware be developed as a first step toward the design of the flight prototype system.

The remainder of this section of the report summarizes the preliminary design and development activities of this phase of the program. All components listed previously are considered. Component discussions include a brief review of previous work, where applicable, to identify the starting point of Contract NAS 9-8460, Task B, and Contract NAS 9-9981. The scope of the work performed is delineated and the activities of the current programs are described. Conclusions and recommendations for future work are also given for each component.

In general, the data presented were not revised as a result of the system-level tests and system analyses performed following the breadboard system tests conducted at the end of the program. Consequently, minor discrepancies exist between some of the detailed data presented here and those given in other sections. These discrepancies do not affect the conclusions reached as a result of the component-level tests and analyses.

TABLE 3-I

COMPONENT DESIGN AND DEVELOPMENT

Component	Conclusions/Recommendations at End of NAS 9-8460, Task A	Achievements of NAS 9-8460, Task B, and NAS 9-9981	Recommendations for Future Work
Compressor	• Compressor constitutes most critical problem area. • Abandon vane separator development. • Pursue diaphragm compressor development. • Investigate other types of machine.	• Proceeded with development of diaphragm unit. • Two-stage vortex machine designed and developed successfully. • Vortex machine selected for flight prototype.	• Development test to improve efficiency. • Life test a lightweight flight prototype unit.
Phase Separator	• Continue development of rotating drum unit to reduce entrainment.	• Developed separator test rig. • Developed baffle; entrainment reduced from 0.2 to 0.015 percent lb liquid/lb vapor.	• Redesign drum separator to represent flight configurations: (1) eliminate rotating seals through use of magnetic coupling; (2) reduce entrainment to 0.0015 percent by redesign.
Heater-Condenser	• Investigate causes for low performance and modify.	• Tested at system level to provide data. • Performed analyses of test results and diagnosed causes of poor performance. • Performed minor modification of breadboard unit. • Performed preliminary design of flight prototype.	• Detail design, fabricate, and test a flight prototype.
Catalytic Reactor	NA	• Performed catalyst screening test. • Performed limited development and life test of rhodium plated on stainless steel screens.	• Investigate alternate substrates for rhodium catalyst. • Perform basic data acquisition to permit size and operating temperature optimization.
Level and Concentration Control	• Demonstrated feasibility of nucleonic technique. • Developed constant level--constant concentration control. • Develop electronic circuitry.	• Designed new semi-batch control scheme of high recovery efficiency and high system operating effectiveness using nucleonic controls. • Developed circuitry for semi-batch control scheme.	• Refine design and packaging of electronics.
Purity Monitoring	• Conductivity meter recommended.	• Developed scheme for bacteria control and monitoring. • Identified instrumentation for chemical and physical analysis including pH, conductivity, and organic content.	• Perform development testing of equipment selected for flight prototype including (1) on-line bacteria monitor, (2) pH sensor, (3) conductivity probe, and (4) organic content monitor. • Perform experimental evaluation of sterilization techniques. • Perform experimental evaluation of bacteria control method using silver ion generator and bacteria filters.
Miscellaneous	NA	• Performed preliminary sizing. • Prepared component specifications.	• Update specifications.

VAPOR COMPRESSOR

Introduction

1. Background

The vapor compressor performs two functions in the IWRS: (1) it provides the head necessary to overcome the pressure drop of the vapor loop and (2) it maintains a condenser pressure adequate to assure heater-condenser thermal performance. Early in the program this component was identified as critical because of the very low specific speed requirement of such a machine. Candidate compressor types identified for development under the IWRS program included diaphragm, rotary-vane, rotary-lobe, and vortex compressors.

Activities under Task A of Contract NAS 9-8460 were concentrated on the rotary-vane and diaphragm compressors. Early work concerned the development of a nonlubricated rotary vane machine. Serious problems involving vane-housing materials and seal leakage indicated that the development of a long-life nonlubricated vane compressor should be abandoned in favor of other types of machines (see AiResearch Report 69-5470). A diaphragm compressor was designed and tested as an alternate approach. These two compressor types were selected because of their high potential effectiveness at the low flow considered for the IWRS.

Development of the rotary vane machine involved matching the vane and housing materials to obtain high performance and low wear without lubrication. Table 3-2 presents a summary of the materials tested. The best combination found was carbon vanes with a Tuftride finished housing. This gave relatively low vane wear; however, carbon powder accumulation on the surface of the vanes and the housing interfered with free blade motion in the vane guides and also resulted in high vane friction on the housing. Thus the potential high efficiency of a rotary vane machine was not realized. Overall efficiencies on the order of 12 percent were obtained at design point. Probably more significant long life could not be achieved.

TABLE 3-2

VAPOR COMPRESSOR MATERIALS INVESTIGATION

Vane Material	Housing Material	Remarks
Carbon	Cast Iron	Vane wear noted; housing corrosion
Carbon	Copper plate	Copper plate excessive wear
Fluoraloy	0.002 in. soft chrome plating	Housing corrosion marginal; high vane friction
Carbon	0.001-in. electroless nickel	Extremely high vane wear
Carbon	Cast iron/Tuftride treated	Satisfactory corrosion resistance; improved vane wear but carbon accumulation on housing
Vespel	Cast iron/Tuftride treated	Vane friction extremely high

The diaphragm compressor development effort of Task A (NAS 9-8460) identified many mechanical design problems. These problems included bearing failures, vibration, noise, diaphragm failures, and low performance due to poor valve design and low volumetric efficiency.

At the conclusion of Task A (NAS 9-8460), compressor development was identified as a major problem. Further development of the rotary vane compressor was not recommended. Rather it was suggested that a fresh approach be considered with other types of compressors reconsidered as candidates.

2. Scope of Present Program

Following the recommendations of the previous program, development of the rotary vane compressor was abandoned. Early in the program, effort was expended in modifying the diaphragm compressor. Also, a lobe compressor supplied by NASA-MSC was tested as a candidate unit type. Concurrently, an off-the-shelf, single-stage, vortex compressor was tested to assess its applicability to the IWRS. As a result of these tests a two-stage unit was designed and fabricated for installation on the breadboard system.

The vortex compressor work proved to be very fruitful and this type of compressor is recommended for the flight prototype system.

Work associated with compressor development is summarized in the following paragraphs.

Diaphragm Compressor Development

A sketch of the compressor unit is shown in Figure 3-1. Two diaphragms are driven by an eccentric drive. The two compression chambers are connected in parallel. The chamber diameter is 5 in. and the stroke of the diaphragm is 0.38 in. This unit was designed to produce a 2:1 pressure ratio at the following operating conditions:

Inlet water vapor flow: 4.53 cfm

Inlet pressure: 1.25 psia saturated

Rotational speed: 700 rpm

Figure 3-2 shows the test data on the latest Teflon diaphragm compressor using air as the process gas. The flow rate changes by only a small amount over a wide range of pressure ratio at a given speed. With air as the working fluid, an inlet air pressure of 1 psia, and a temperature of 70^{0}F, an estimated air flow of 5.57 cfm (1.7 lb/hr) is necessary at a 2:1 pressure ratio in order to meet the above performance requirements with vapor. Referring to the 1000 rpm condition in Figure 3-2, the flow obtained was 5.58 cfm. The corresponding input shaft power was 34.7 watts and the overall compressor efficiency was 40.2 percent. Of the input shaft power, 17.0 watts are attributed to bearing and diaphragm losses. Assuming that a brushless dc motor is used, a motor efficiency of approximately 65 percent would be obtained so that the total input power to

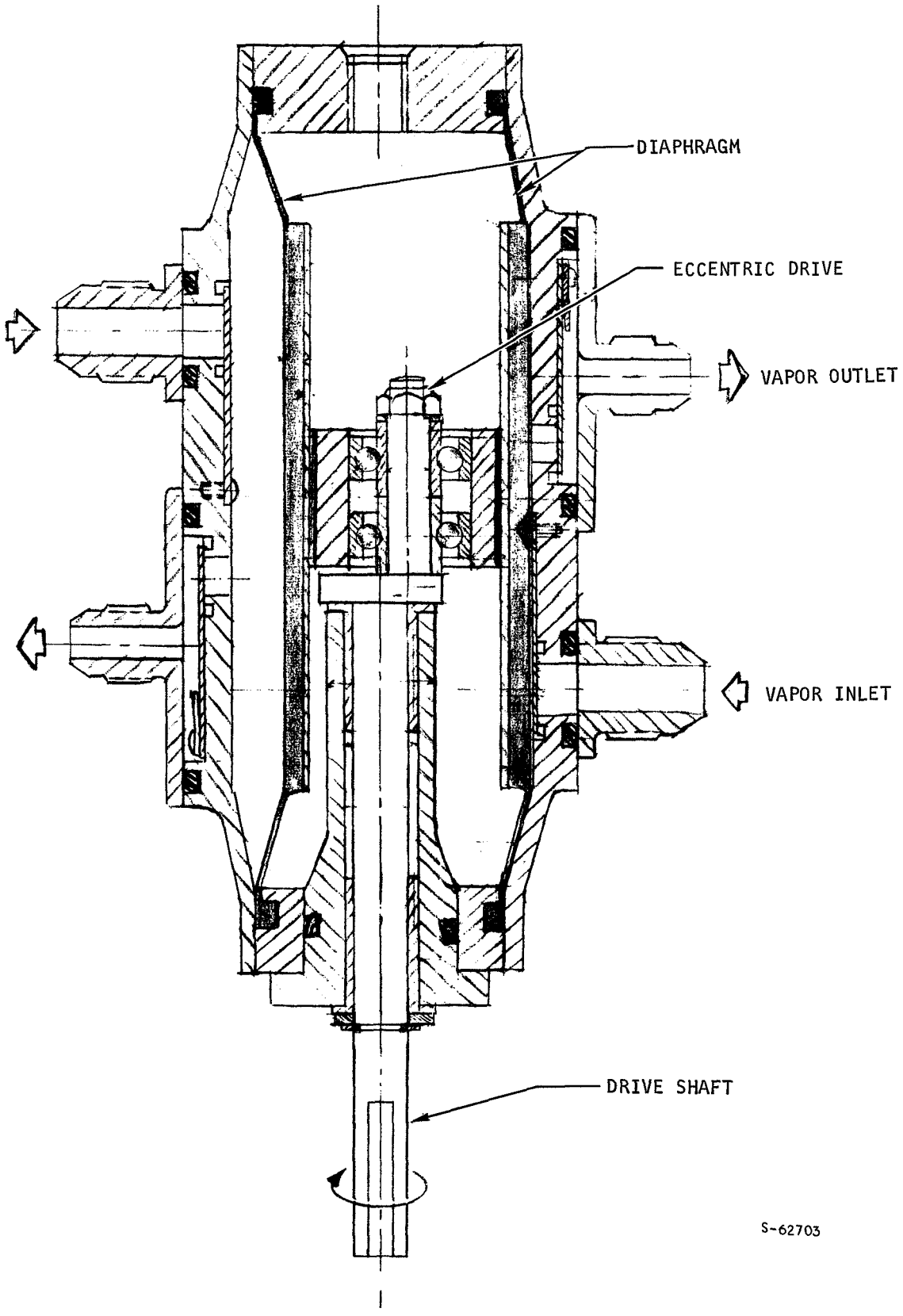


Figure 3-1. Diaphragm Compressor

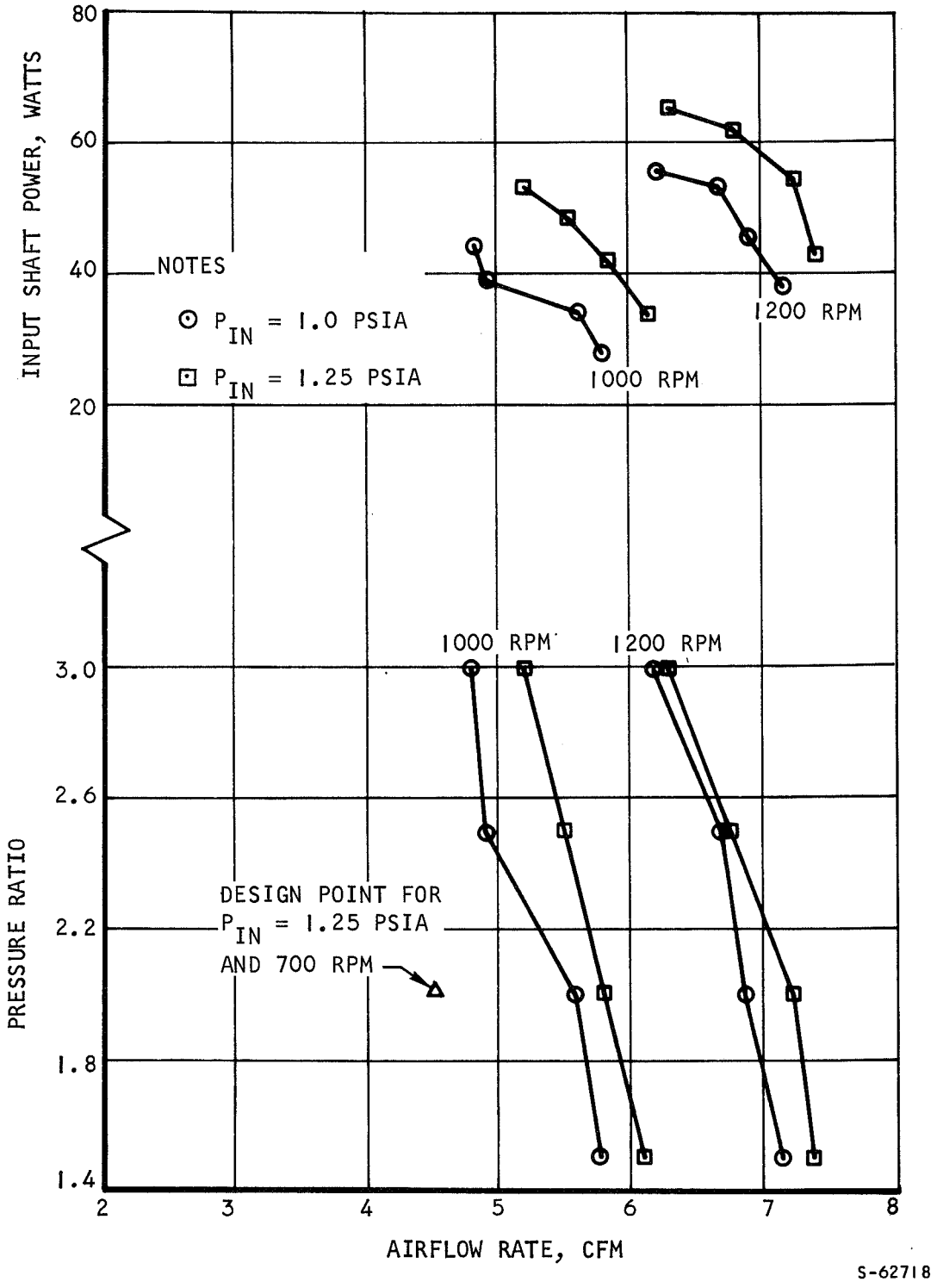


Figure 3-2. Performance of Diaphragm Compressor

the motor is estimated at 53.4 watts. This represents an overall efficiency of 26.1 percent for the entire unit. Relating total power to the gas flow rate, the unit has a power-to-flow-rate ratio of 31.2 watts/lb-per-hr of gas.

Three diaphragm materials were testing during development: Mylar, Teflon, and rubber. The Mylar diaphragm tested tore after one hour of operation. Two Teflon diaphragm configurations were tested, but diaphragm life was found to be completely inadequate for IWRS application. A rubber diaphragm was fabricated and tested for over 100 hours.

Development of the diaphragm compressor was abandoned in view of the success obtained with the vortex machine.

Rotary Lobe Compressor

A rotary lobe compressor was furnished to AiResearch by NASA-MSC for evaluation as a potential condidate for the IWRS. This unit was tested and found to have about twice the capacity required by the system.

Operated at 1725 rpm, the rotary lobe compressor produced an air flow of 12.1 cfm (3.7 lb/hr) at an inlet pressure of 1 psia and a pressure ratio of 2. Figure 3-3 shows the performance of this unit. Adiabatic power required for the compression process was 30.2 watts. It is estimated that approximately 300 watts of input power to the motor was necessary to drive the compressor, thus giving an overall efficiency of about 10 percent. The power-to-gas-flow ratio for this unit is 81.1 watts/lb per hr of gas. The estimated weight of a flight designed compressor of this type is 10 lb.

Vortex Compressor Development

Vortex compressors are high-speed rotating machines. They accomplish compression by imparting a velocity head to the gas and converting that velocity head into a pressure head. In this respect, vortex compressors are similar to centrifugal compressors.

Figure 3-4 shows the major elements of a typical vortex machine. The gas passing through a vortex compressor travels around the periphery of the impeller within a horseshoe-shaped stator channel. Within this channel, the gas travels along helical streamlines, the centerline of the helix coinciding with the center of the curved channel. This flow pattern, shown in Figure 3-5, causes the gas to pass through the impeller buckets many times while it is traveling through the compressor. As a result, vortex compressors can produce discharge heads up to 15 times those produced by centrifugal compressors operating at equal tip speeds.

The high-speed, low-flow performance characteristics of vortex compressors are well suited to a number of applications where reciprocating compressors, rotary displacement compressors, and low specific-speed centrifugal compressors are used. The vortex compressor has a number of advantages which lead to its selection as a candidate approach worthy of development under the present program. These advantages include:

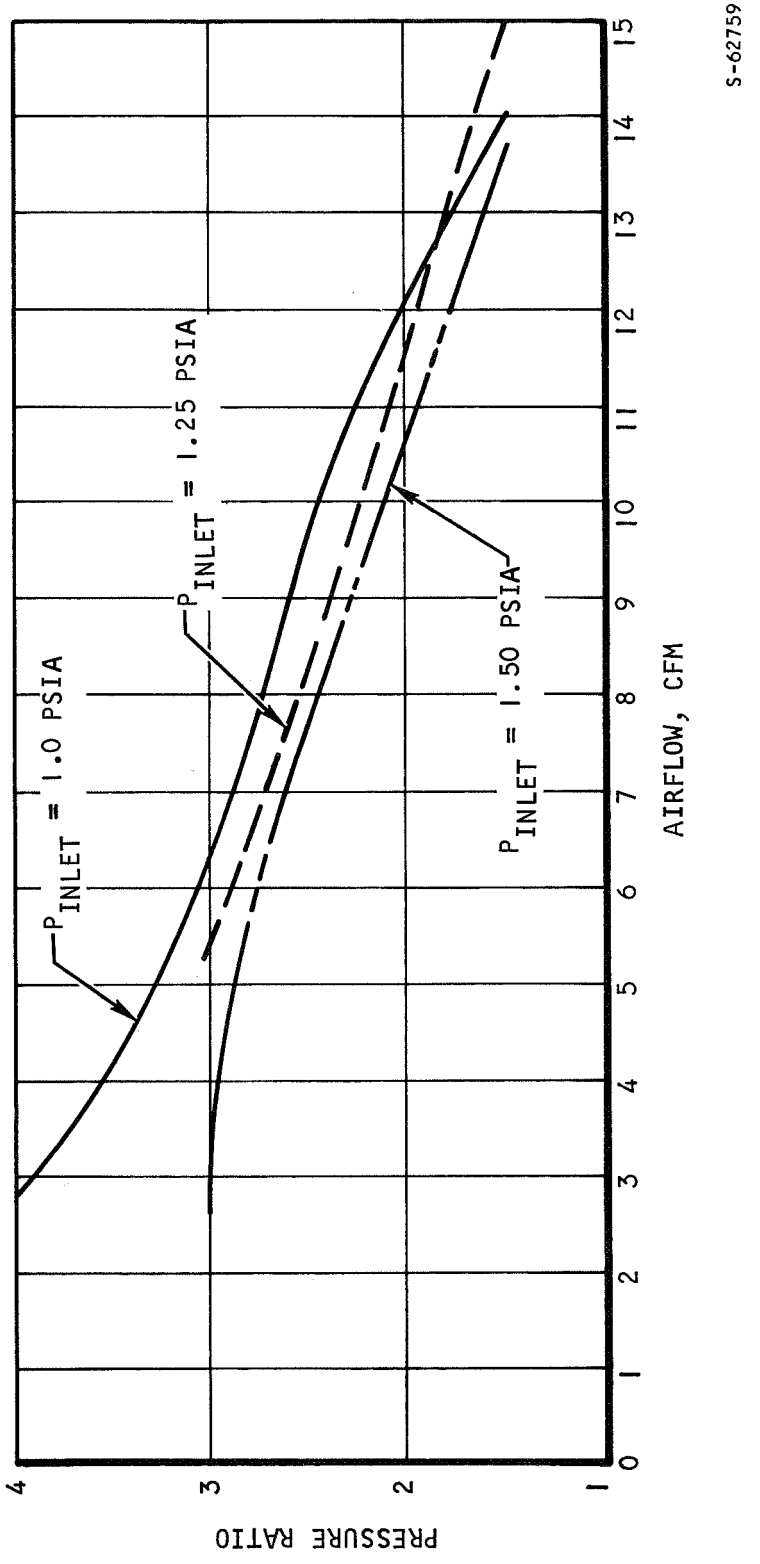


Figure 3-3. Performance of Rotary Lobe Compressor

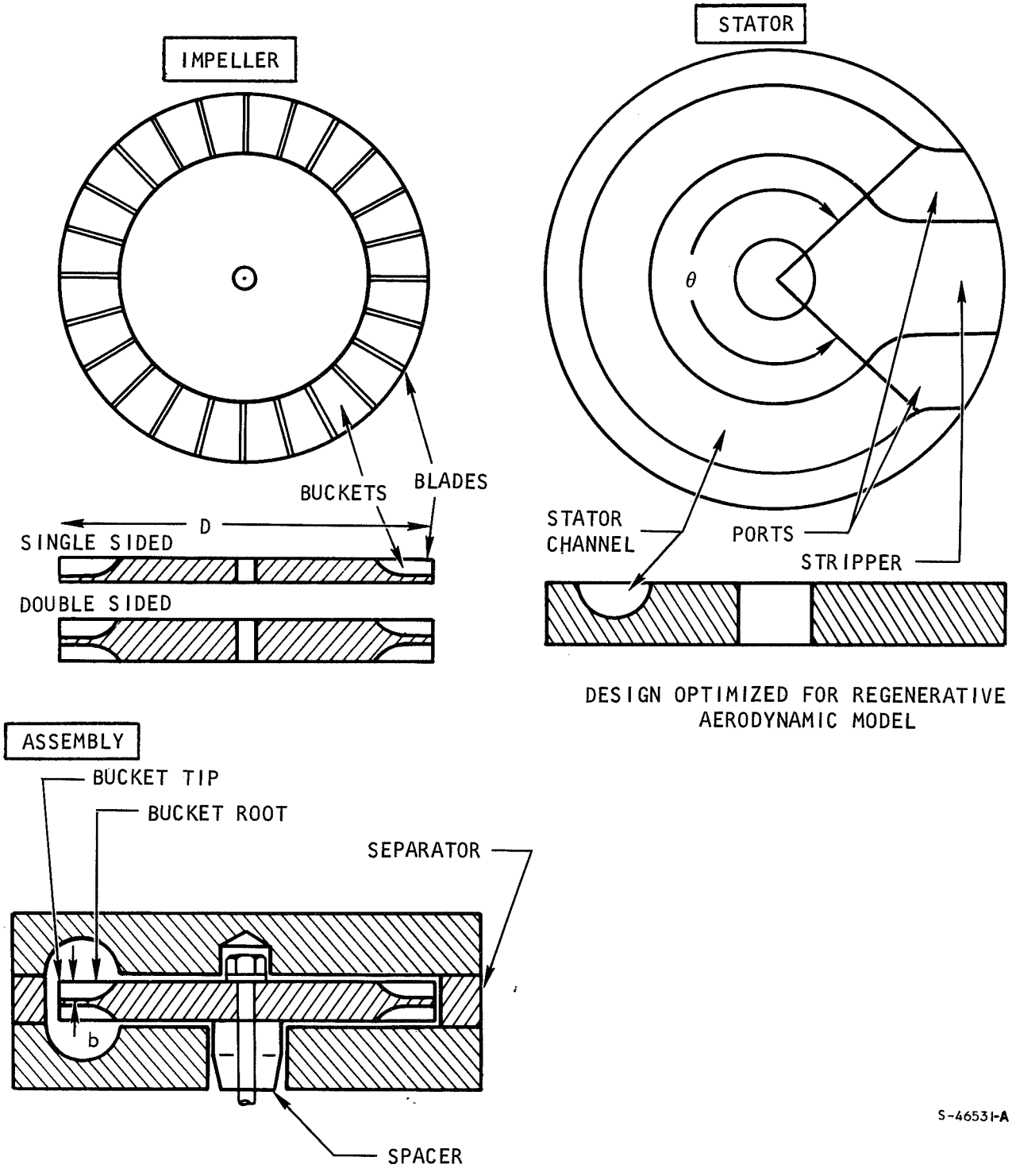


Figure 3-4. Typical Radial Bladed Vortex Compressor

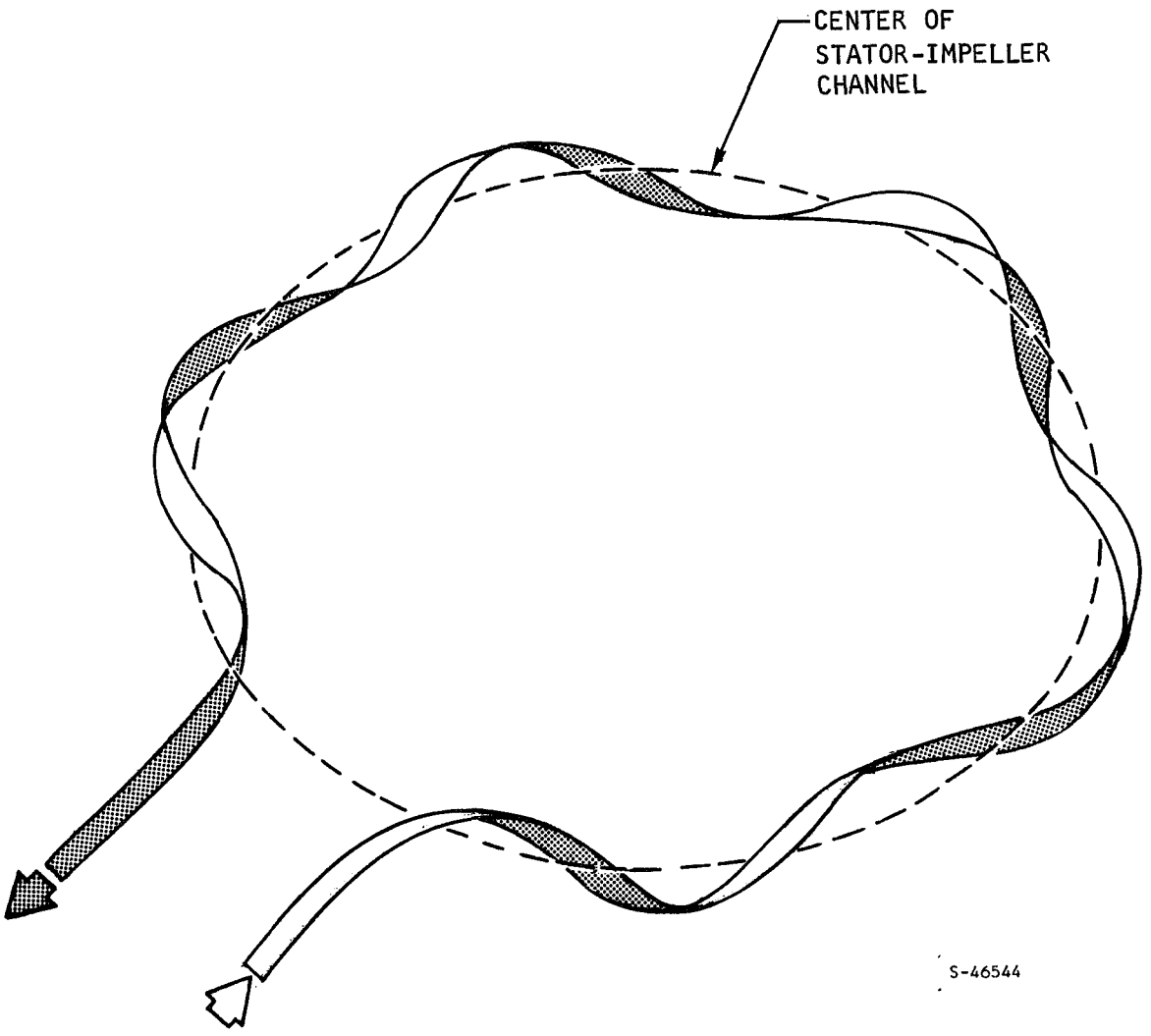


Figure 3-5. Helical Flow Pattern

(a) Simple, reliable design (only one rotating assembly)

(b) Stable, surge-free operation from full-flow to no-flow conditions

(c) Long life (e.g., 20,000 hr as limited by bearing life)

(d) Freedom from wear product and oil contamination (no rubbing or lubricated surfaces are used)

(e) High operating efficiencies compared to very low specific speed centrifugal compressors

A major disadvantage of such a machine is its relatively low adiabatic efficiency; however, for an application such as the IWRS, equipment life is more important than efficiency. Furthermore, in a small compressor (of the size necessary for IWRS operation), the mechanical losses incurred can easily offset the losses due to thermodynamic inefficiencies. In this respect, the vortex machine has a minimum of moving parts and is relatively free of losses of mechanical origin.

An existing single-stage vortex compressor with flow capabilities in the range of interest was tested with air to provide design data. Figure 3-6 shows the performance of this single-stage machine. As shown, the pressure ratio is not adequate at the design flow rate even when rotational speed is increased to well above design value (23,400 rpm). The data obtained confirmed the accuracy of the design methods available at AiResearch for the design of vortex compressors.

The two-stage machine designed and fabricated for installation on the breadboard water recovery unit is shown in Figure 3-7. The diameter of the impeller housing is 5.46 in.; its thickness is 1.5 in., excluding the motor and the bearing support. This unit was fabricated using steel and Inconel for the casing and the rotor wheels. An existing ac motor (the Apollo suit compressor motor) was selected to drive the compressor. The wheels are installed on each side of the casing into which the stator channels are machined. The passage from the first to the second stage is machined in the steel casing. The entire unit is statically sealed and the rotor is driven through a magnetic coupling.

Figure 3-8 is a plot of the performance of the unit tested with air as the working fluid. Predicted performance is shown for comparison. The data given are for a nominal speed of 21,800 rpm; design compressor speed was 23,500 rpm. Experience with single-stage machinery has shown that predicted performance is generally in good agreement with actual test data. In this case, the lower actual performance is attributed to high inlet and outlet losses and mismatch between the two stages. These problems could be resolved by minor redesign of the inlet and outlet ports and by changing the shape and size of the impeller buckets. The bucket blades of the machine are radial--it is felt that considerable improvement in efficiency could be realized by reshaping the blades to allow smoother flow transition between the wheel and the stator channel. This change would reduce aerodynamic losses within the

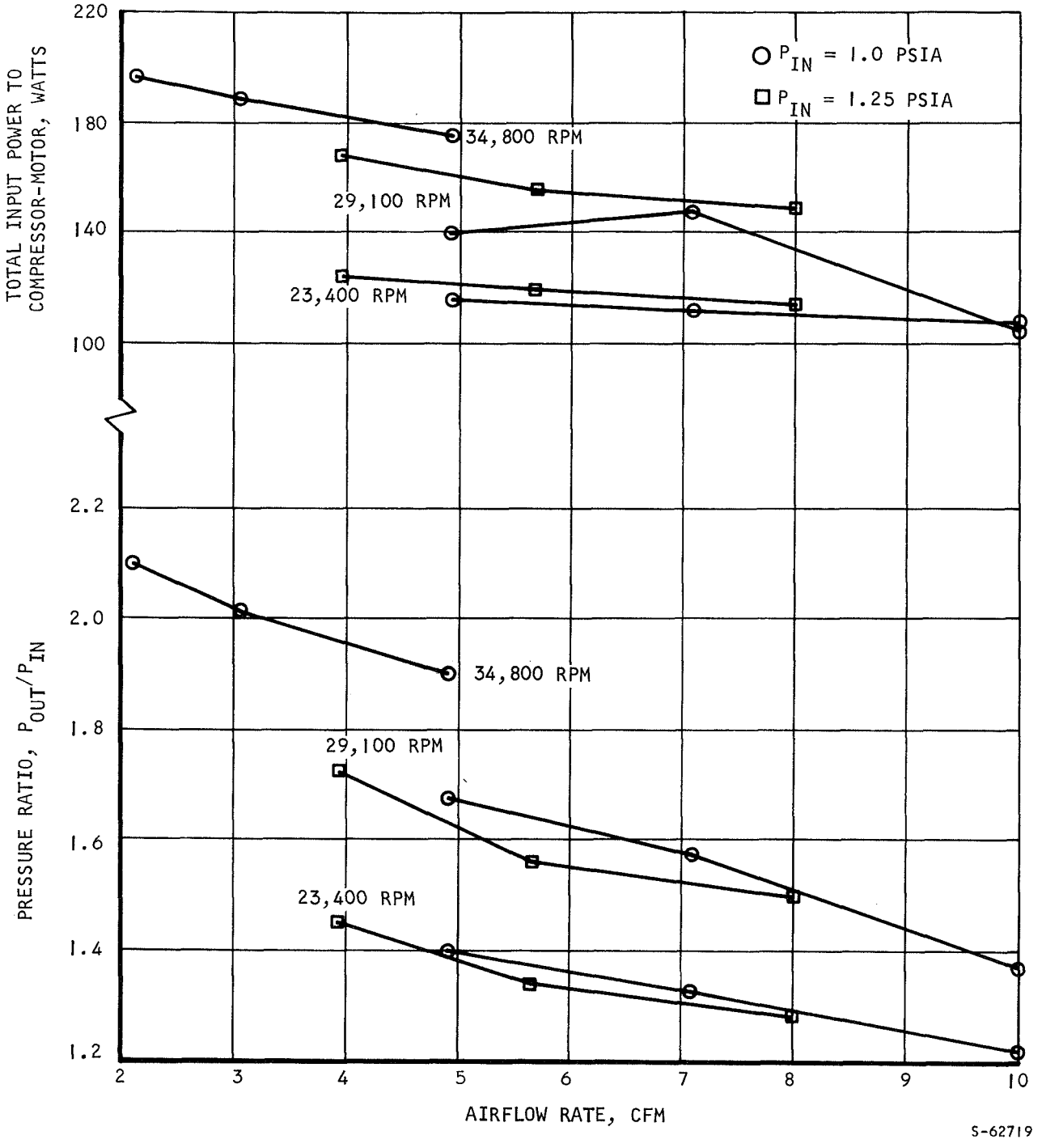
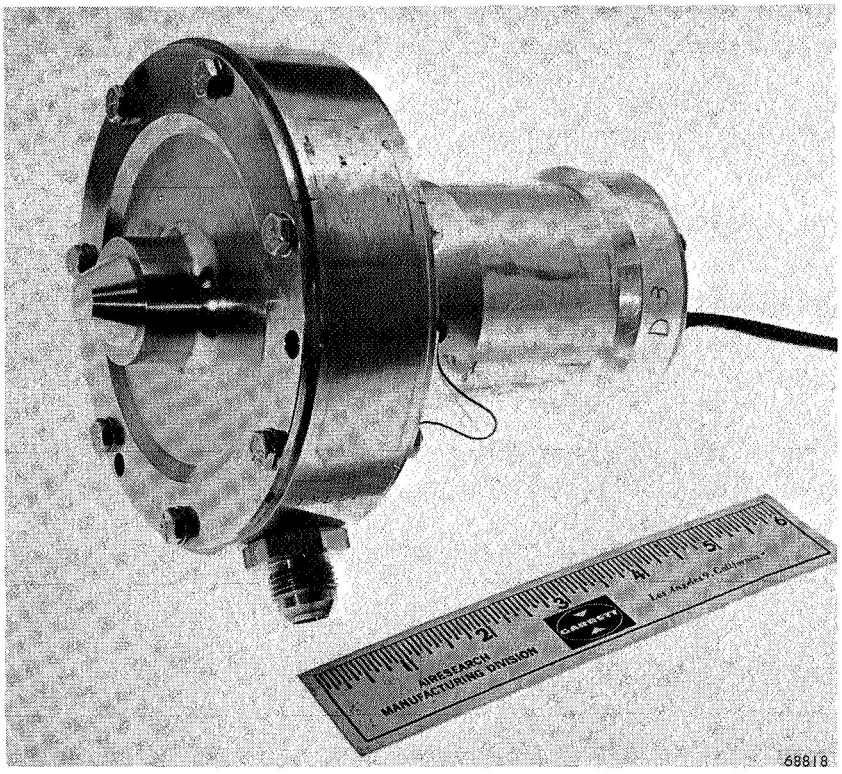
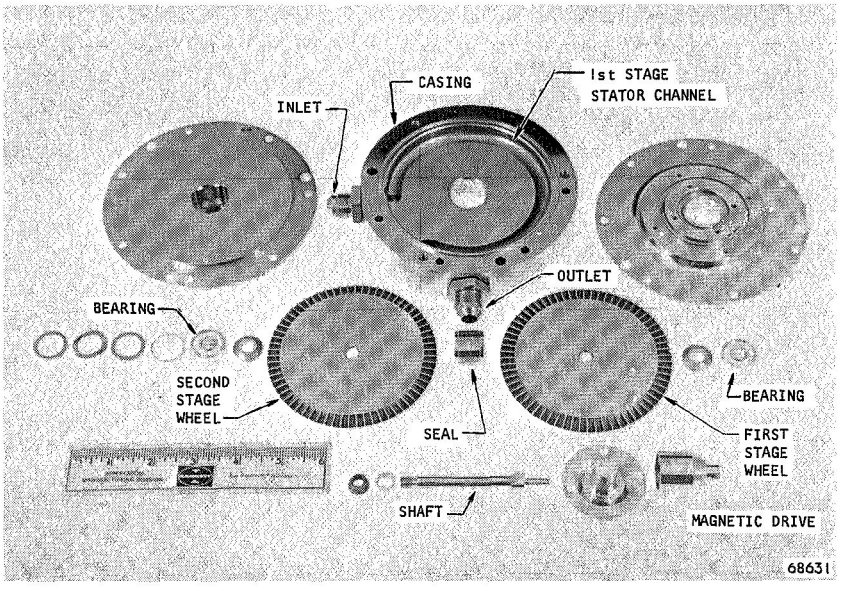


Figure 3-6. Single-Stage Vortex Compressor Performance





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Figure 3-7. Two-Stage Breadboard Vortex Compressor

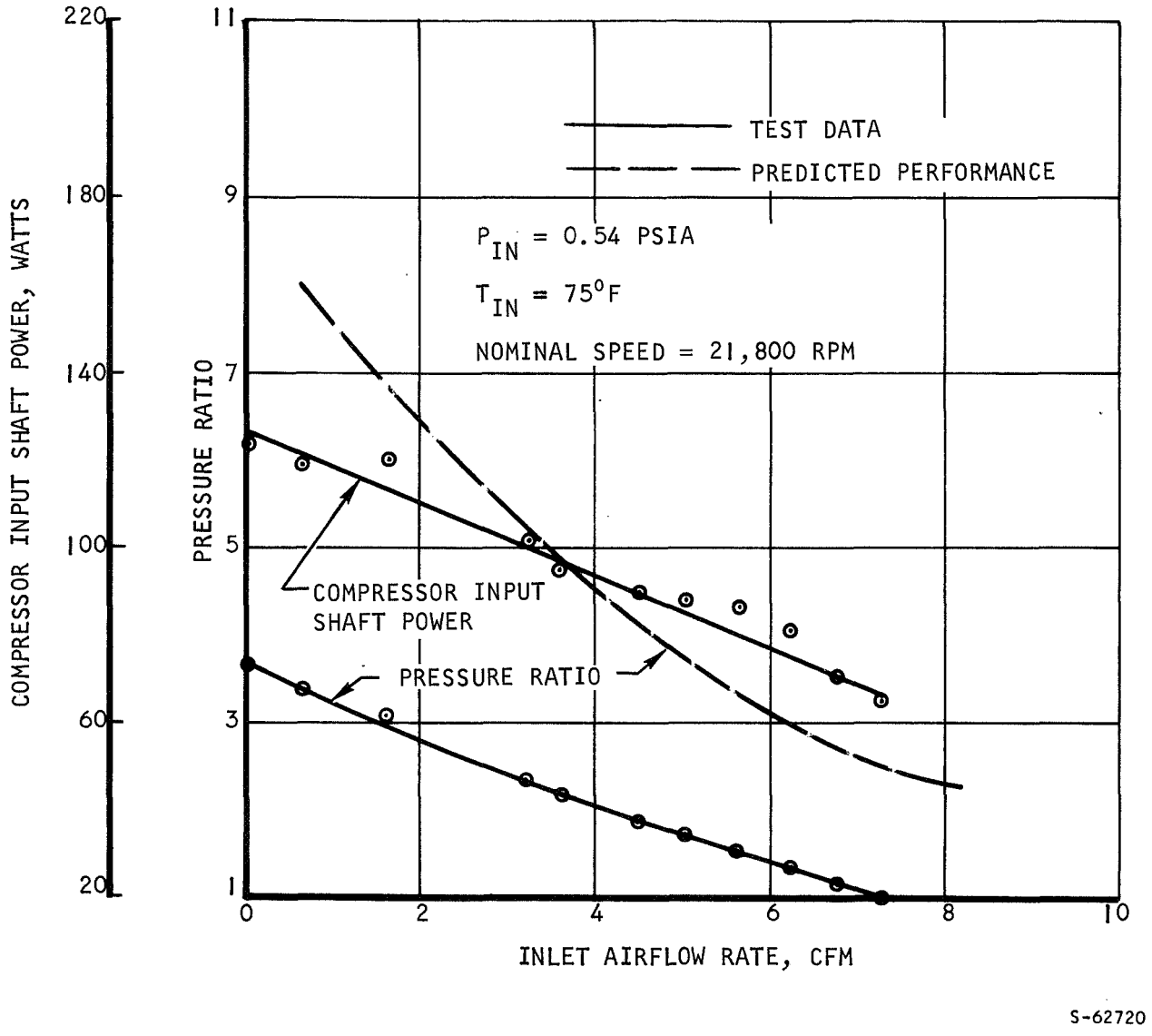


Figure 3-8. Two-Stage Vortex Compressor Performance With Air (Predicted and Experimental)

the compressor considerably because of the increased number of times the working fluid is circulated through the impeller buckets (see Figure 3-5). Additional efficiency improvements could be achieved by reducing the free volume of the buckets. The volumetric efficiency of the machine would be increased by reducing the quantity of compressed gas entrained within the buckets from the high pressure outlet port to the low pressure inlet through the stripper area (see Figure 3-4).

Following component-level testing with air, the two-stage vortex compressor was installed in the breadboard system. Design performance was not achieved; this was anticipated following analysis of the component level performance tests with air. Preliminary system calibration tests conducted with water showed that the design water production rate of 1 lb/hr could not be obtained. System analyses revealed that this was due to

(a) Low heater-condenser performance (see heater-condenser development discussions presented later).

(b) Inadequate compressor pressure ratio which further degraded heater-condenser overall heat transfer capability

To accommodate the test system operational requirements and achieve thermal balance at the heater-condenser (with minimum overboard water losses through the system pressure regulator), the compressor design point inlet pressure had to be about 0.75 psia. (As will be seen later the flight system is designed for a compressor inlet pressure of 1.05 psia.) The predicted performance of the vortex compressor at that inlet pressure is plotted in Figure 3-9. The data are shown for a compressor speed of 23,500 rpm and a design point water vapor flow rate of 8 cfm (1 lb/hr).

In the system, at the design speed of 23,500 rpm, the predicted and experimental performance of the compressor with water vapor as the working fluid were as shown in the following listing:

	Predicted Performance	Apparent Performance
Water vapor flow, lb/hr	1.0	0.48
Inlet vapor pressure, psia	0.75	0.88
Outlet vapor pressure, psia	1.2	1.42
Pressure ratio	1.6	1.6
Shaft power, watts	30.0	69.5

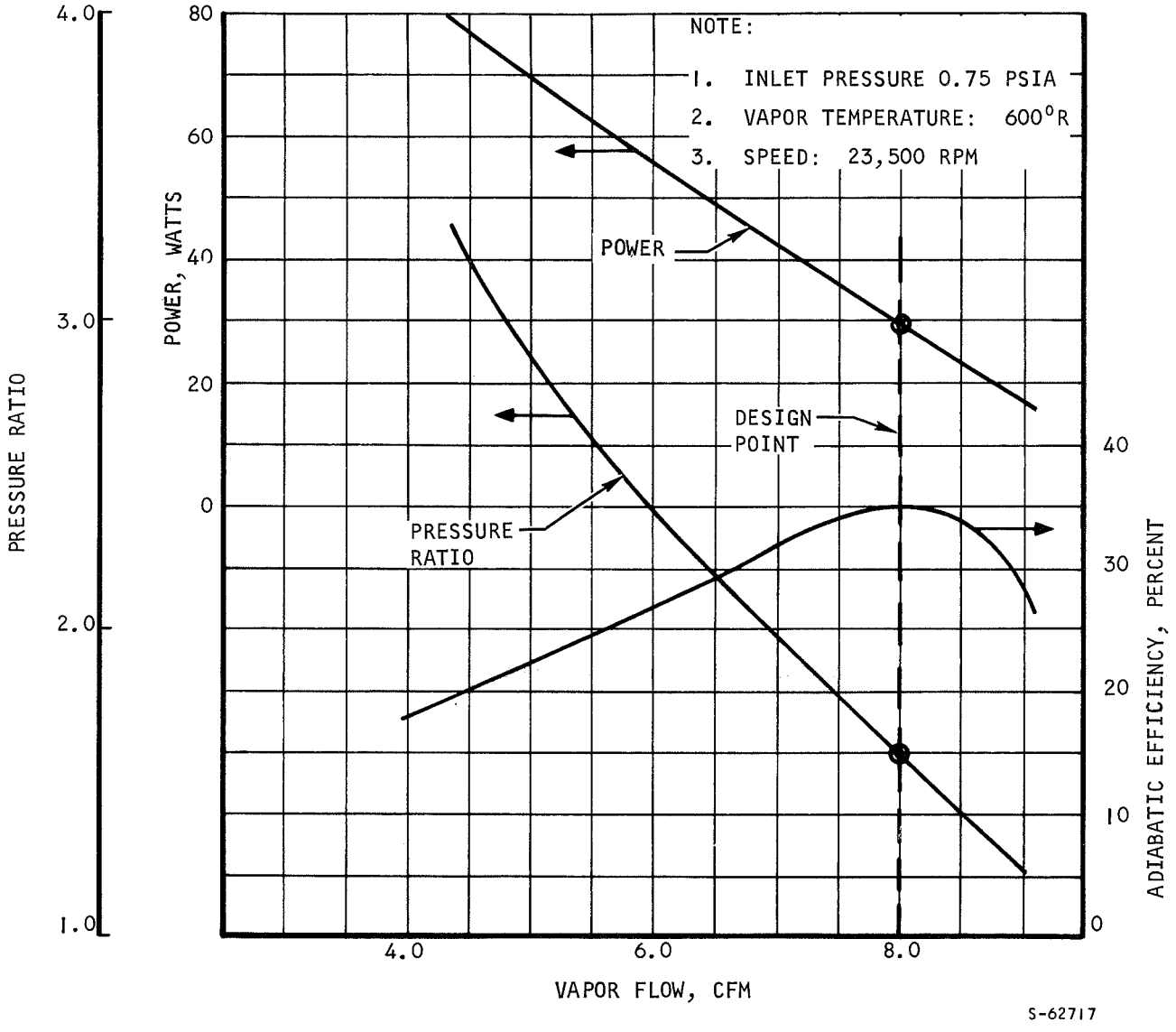


Figure 3-9. Performance of Prototype Vortex Compressor with Water Vapor

The low performance (estimated from system test data) was attributed to the following factors:

(a) The data of Figure 3-9 was generated for a casing temperature of 140°F estimated roughly from the compressor losses. In operation, the compressor casing temperature was measured at about 200°F. At this higher temperature, the flow capacity of the unit in lb/hr is reduced by about 10 percent.

(b) The system instrumentation was not designed to provide accurate component data. With the compressor installed in the system vapor flows were not measured directly; rather the condensate output from the condenser was measured so that only an average value of the flow could be obtained. Furthermore, the pressure at the phase separator outlet was assumed to be the same as that at compressor inlet.

(c) The most significant error made in estimating compressor performance from system test data is that the air leakage into the system at the separator is completely ignored. Rough estimates based on system pressure build-up revealed that the air leakage into the system at the phase separator was as high as 20 percent of the vapor flow. This alone is sufficient to explain the low flow rate obtained during the system tests.

For these reasons the actual performance data listed above is not representative of the true compressor performance.

The decision was made to increase the speed of the compressor by increasing the frequency and voltage of the ac power input to the driving motor. The speed selected for system operation was 26,400 rpm, at which the following apparent performance was obtained:

Water vapor flow, lb/hr	0.768
Inlet vapor pressure, psia	0.71
Outlet vapor pressure, psia	1.50
Pressure ratio	2.11
Shaft power, watts	84.0

Although the design water production rate of 1 lb/hr could not be attained, higher compressor speeds were not attempted because of motor limitations.

Motor bearing problems were encountered during the program. The Apollo compressor motor used to drive the unit was used at much higher load and temperature than designed for. The data below shows pertinent motor data in normal Apollo use and in IWRS use.

	Apollo Use	IWRS Use
Motor speed, rpm	23,500	26,400
Input power, watts	85	145
Operating temperature, ^{0}F	120	190

Also, in Apollo usage considerable air flow is assured around the motor for cooling purposes. On the IWRS, some flow was forced through the motor casing; however, it is doubtful that this air flow provided any significant bearing cooling as evidenced by the temperature listed above.

Conclusions and Recommendations

The vortex compressor designed and tested as part of the present program was found to be satisfactory although not optimum. Further analysis of the test data obtained and, possibly, single-stage testing should yield the reasons for the deviation between predicted and actual performance. Adiabatic efficiencies as high as 30 percent are within the state-of-the-art for this type of compressor and should be achieved with a minimum development program. Higher efficiencies could be obtained by suitable design of the fluid flow passages within the rotating wheels. The estimated power input to the flight system vortex compressor motor is estimated at 80 watts at design point. The flight system design point is defined as follows in terms of the pertinent system and compressor operating parameters:

Brine concentration: 20 percent

Compressor inlet pressure: 1.05 psia

Compressor pressure ratio: 1.59

Compressor flow: 7.4 cfm

The average water production rate over the entire semi-batch cycle is estimated at 1.29 lb/hr. On this basis specific compressor power is calculated at 62 watt-hr/lb.

The vortex compressor offers the prime advantage of long life potential. Rotating machines such as the Apollo ECS cabin fans and glycol pumps have demonstrated lives on the order of 20,000 hours, AiResearch feels confident that a vortex machine can be developed with a life expectancy at least that long.

In view of the potential offered by this type of machine, it is strongly recommended that development of the unit be pursued in the next phase of the program. The component-level development program should include:

(a) Further testing of the existing unit to identify the major losses

(b) Design and testing of curved impeller passages of reduced volume to improve efficiency and flow-pressure ratio characteristics

As mentioned previously, the unit fabricated under the present program was built of stainless steel and Inconel; it is far from weight optimized in terms of a flight prototype design. It is suggested that a lightweight unit be designed, fabricated, and life tested at the system level in the next phase of the program. It is important to note here that, although the steel unit is adequate to demonstrate performance, a near-flight configuration is necessary to develop meaningful life data.

PHASE SEPARATOR

Introduction

1. Background

Investigations performed in previous phases of the IWRS development were concerned with two types of integral liquid pump-phase separator designs: the rotary vane (or paddle separator) unit and the rotating drum-pitot pump unit. In both designs, the pumping function for the brine loop is accomplished in the separator itself to minimize a number of system components such as pump, motor, and controls. Early analysis indicated that the brine loop pressure drop will be 7 to 11 psi, which is within the pumping range of the separator operated at higher rotational speeds than required for the normal vapor-liquid separation function.

Models of the two units were built and tested. The test data confirmed analytical predictions and the rotary drum-pitot pump unit was selected. This model required about 30 watts of shaft power to effect separation and produce an 8.7 psi rise in the liquid loop at design point flow rate. By comparison, the rotary paddle separator consumed about 100 watts. Other advantages of the rotary drum separator include:

(a) Higher basic separation effectiveness

(b) Higher storage capacity at lower power

(c) Potential as a controllable liquid accumulator

The breadboard rotary drum separator developed in the previous phase of the program is illustrated in Figure 3-10. Overall diameter is 7.12 in. and casing height is 5.03 in. Figure 3-11 shows a photograph of the unit dismantled to display all components. The unit consists of a motor driven drum within an outer housing. A shaft seal and a spring loaded carbon face seal are used to prevent internal leakage of air. The main purpose of the outer housing is to support the rotating drum. Initially a secondary function of the housing was to present a second sealing barrier for the drum interior from external ambient; however, due to numerous modifications and cutouts on this housing, this sealing provision could not prevent leakage of ambient air into the housing through the shaft so that only the rotating carbon face seals were effective in controlling ambient air leakage into the unit.

The water-vapor and urine-brine mixture enters the separator through a delivery tube passing through the center of the drum. The mixture is directed towards the liquid surface in the drum. Centrifugal force created by the rotating drum holds the brine against the peripheral surface of the drum. A pitot tube placed near the drum periphery removes the highest velocity liquid from the separator and converts the velocity head of the liquid into a pressure head. Because of the low pressure drop in the pitot tube, the pressure head is nearly constant with flow rate.

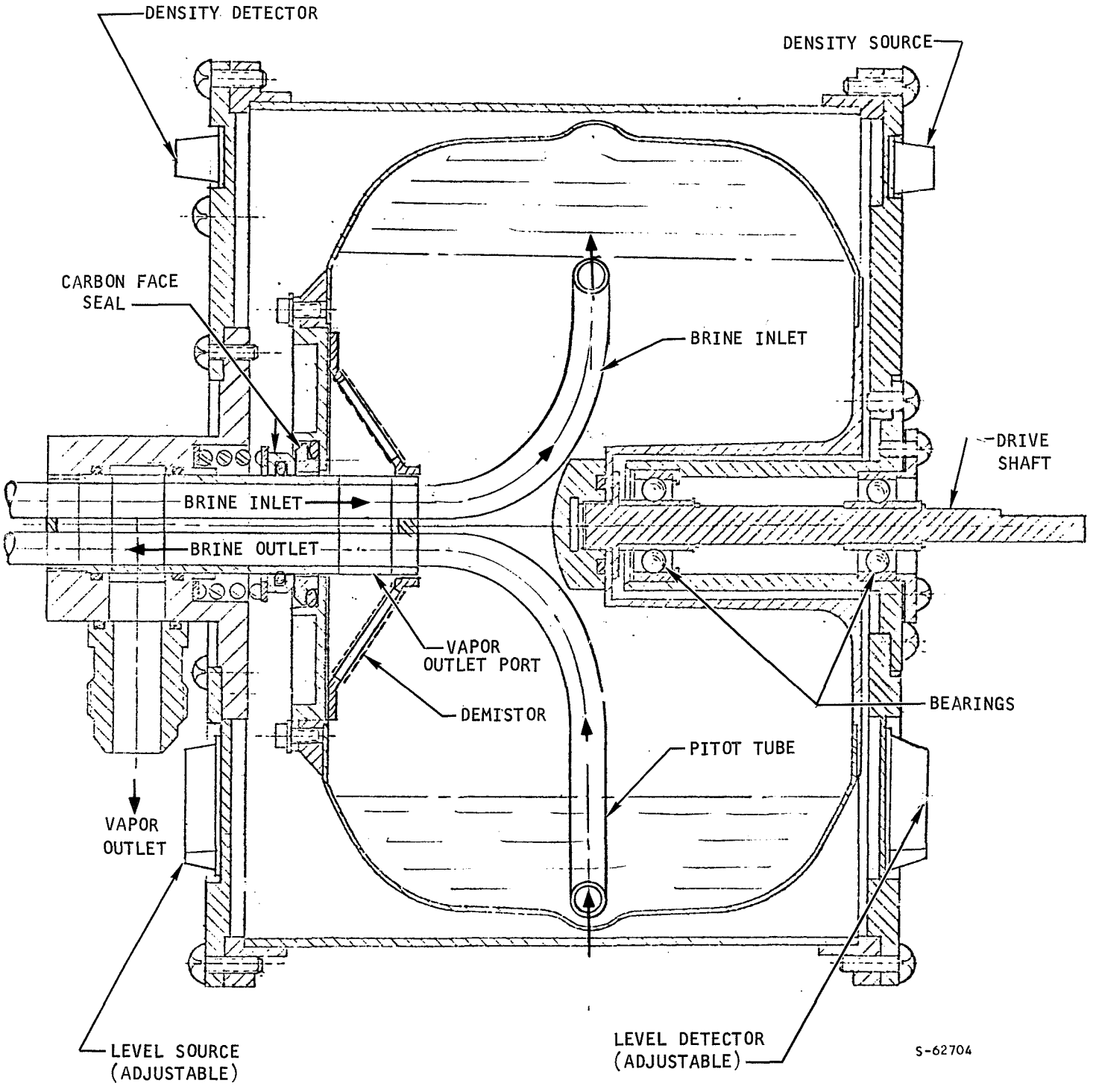


Figure 3-10. Rotary Drum Phase Separator Configuration

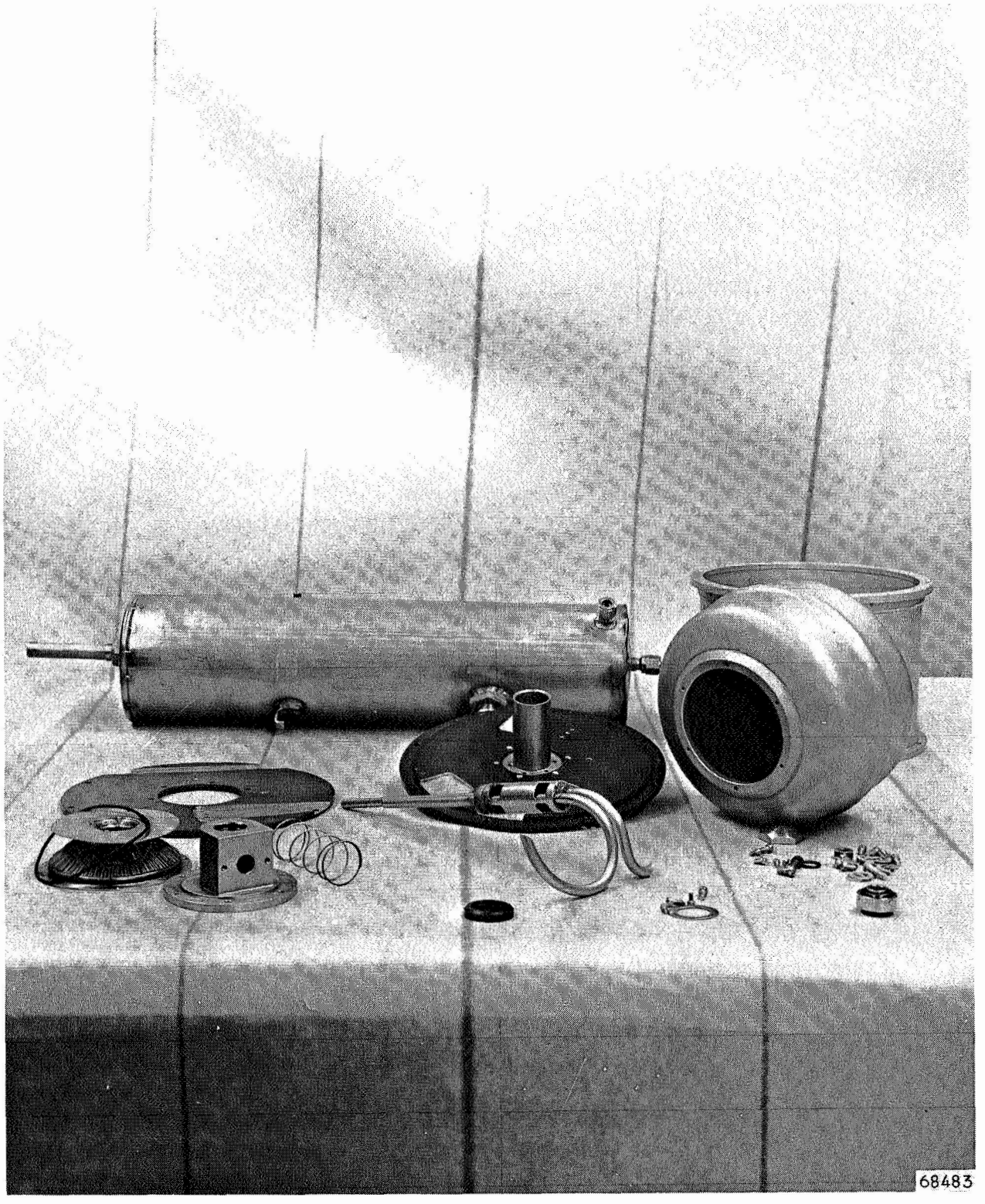


Figure 3-11. Phase Separator Components

The water vapor swirling in the center section of the drum flows out of the unit through the tube housing, the pitot tube and brine delivery tube. A demistor consisting of wire spokes arranged in a cone around the vapor outlet ports prevents liquid carryover. (Figure 3-11 shows a circular baffle with the demistor. The breadboard developed in Task A of NAS 9-8460 did not incorporate this baffle. The development of this baffle as part of the present program is discussed later.) Following system test, however, evidence of entrainment was observed. The salt deposit on the demistor could be attributed to two sources. (1) entrainment during normal operation--this contributed only a small portion of the total deposit, and (2) accidental carryover due to foaming which occurred when the urine loop was depressurized too rapidly at several occasions during the test program. Accumulation of solids in the drum was found to be negligible.

The test data of Figure 3-12 is typical of the rotary drum separator with water and brine containing 44 percent solids. The combined bearings and seal power loss was measured as 13.3 watts at a speed of 1800 rpm. Total shaft power was measured at 31.2 watts. Note that a drum speed of about 200 rpm is adequate for phase separation; the higher speed is necessary only to provide the liquid pressure rise desired.

2. Scope of Present Program

Separator development under contract NAS 9-9981 included the following tasks:

(a) Design, fabrication, and testing of a Plexiglass unit

(b) Demistor-baffle development to assess the liquid carryover problem during normal operation and to develop adequate startup procedures

These activities are discussed in the following paragraphs.

Plexiglass Separator Development

A Plexiglass separator was fabricated and installed on the breadboard system for test, as shown in Figure 3-13. The purpose of the test was to provide visual observation of the spray patterns within the unit. These tests demonstrated that the conical wire demistor by itself was not adequate to prevent liquid carryover; consequently, the separator design was modified to incorporate a baffle to shield the demistor from the liquid plume generated by the pitot pump tube. Two baffle designs were generated for experimental evaluation on this breadboard unit. Testing of the Plexiglass unit was abandoned because of excessive air leakage within the unit. This leakage was of such a magnitude as to affect the flow pattern within the separator.

Demistor-Baffle Development

A special test rig was built to permit accurate evaluation of demistor-baffle designs. The test unit is shown schematically and photographically in Figures 3-14 and 3-15, respectively.

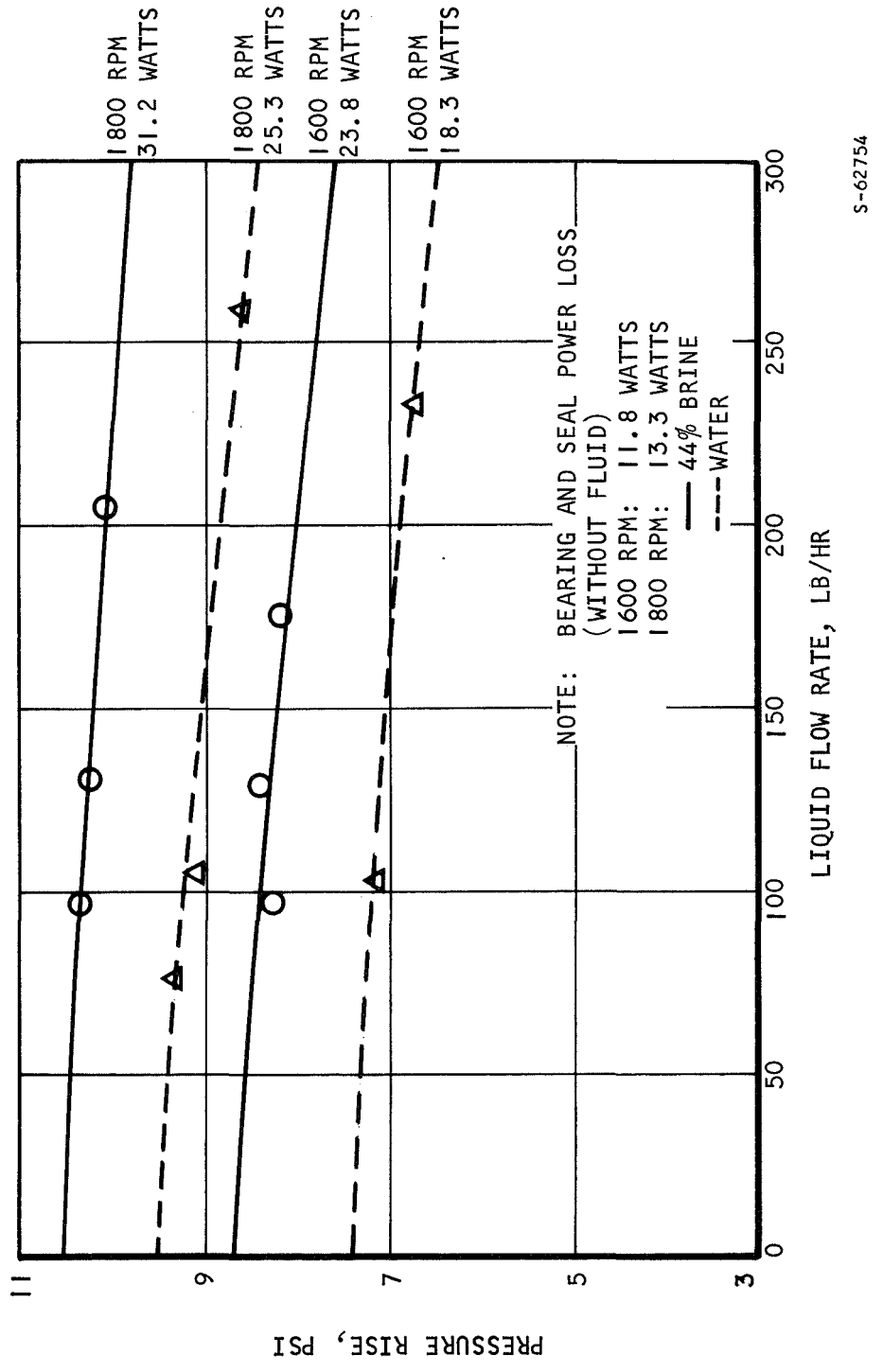


Figure 3-12. Rotary Drum Separator Characteristics

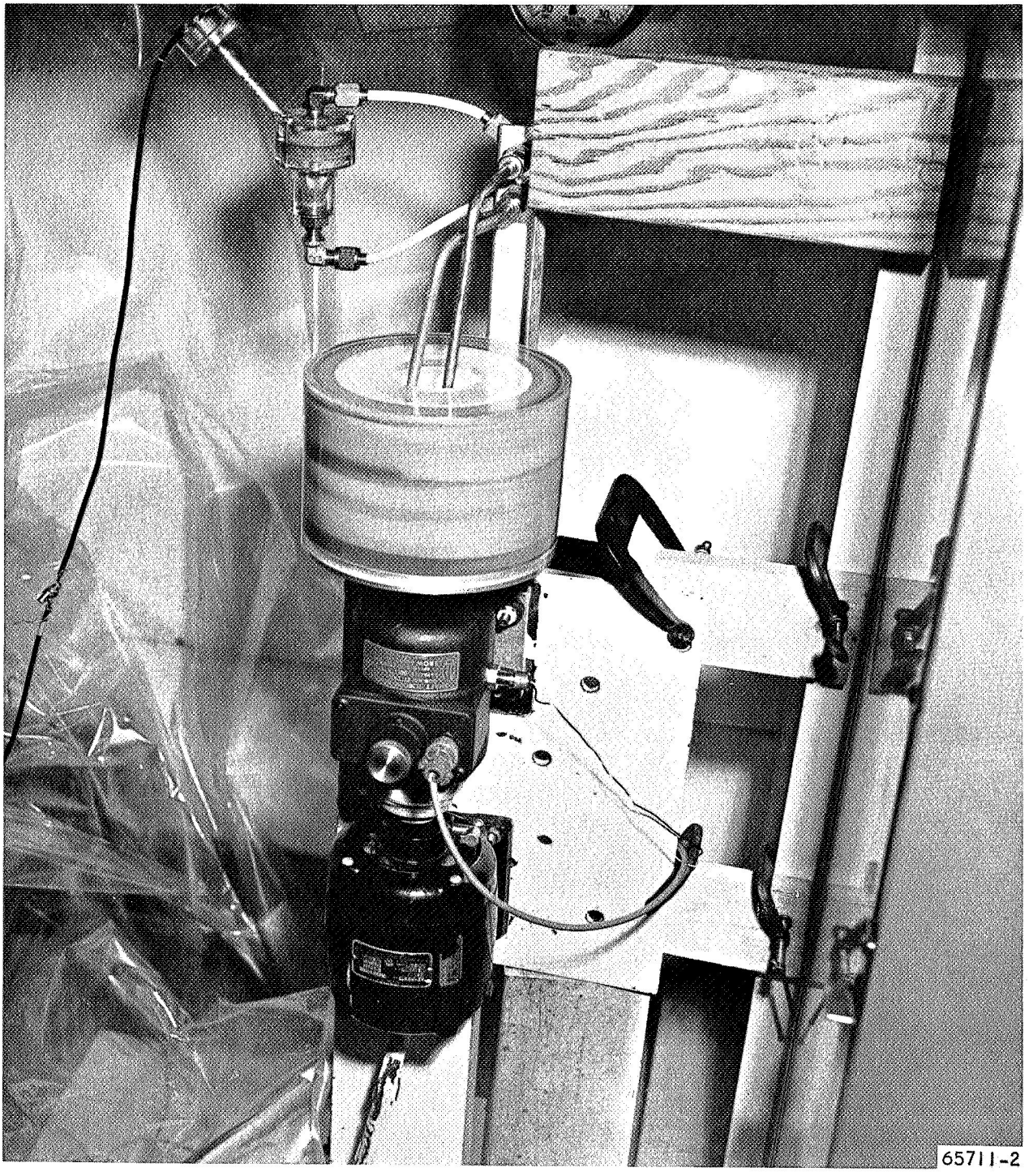


Figure 3-13. Plexiglass Phase Separator

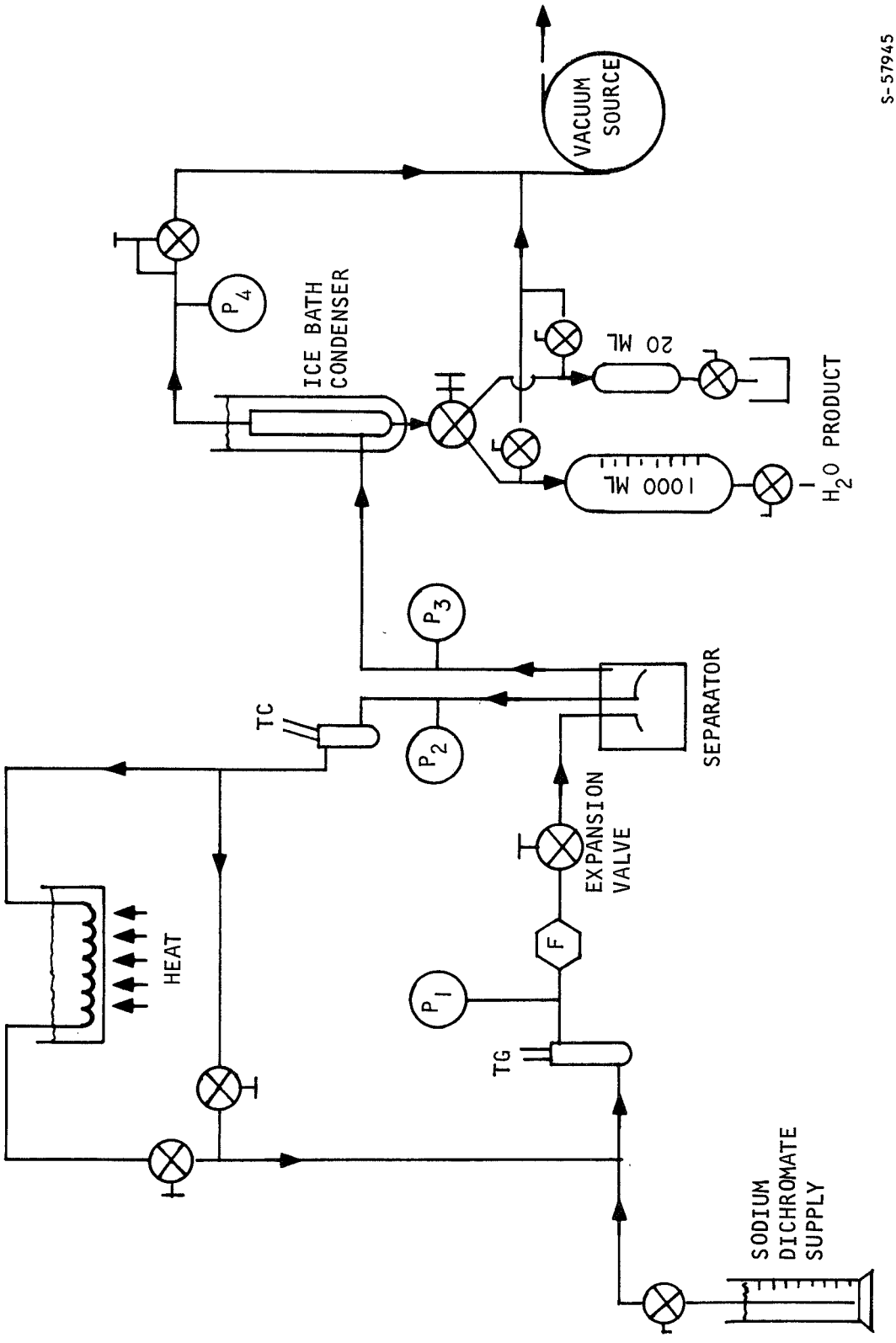


Figure 3-14. Phase Separator Test Rig Schematic

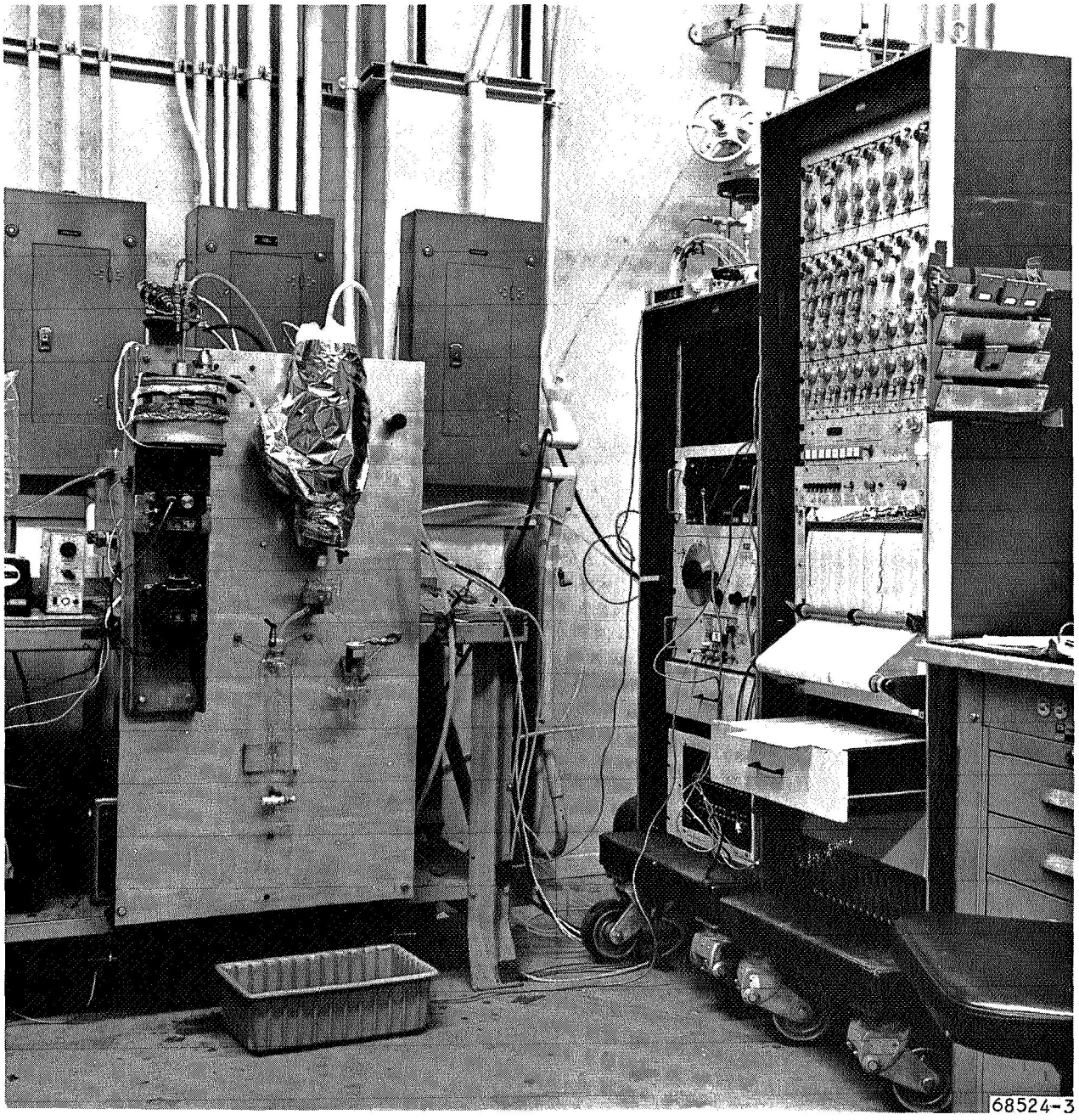


Figure 3-15. Phase Separator Test Setup

A solution of sodium chromate of known concentration is circulated in a closed loop by the separator being tested. Heat is added to the solution in a constant temperature bath. The liquid is then flashed across a valve and the mixture of water and vapor thus formed is dumped in the test separator. Vapor and fine liquid water particles entrained with the vapor are routed to an ice bath where the water is condensed. The rate of water evaporation is controlled by adjusting the bypass around the constant temperature bath. Since only a small quantity of sodium chromate solution is entrained with the vapor, the salt concentration in the liquid loop is maintained very nearly constant by addition of pure water.

At the concentration maintained in the liquid loop (700 mg $Na_2Cr_2O_7$ in 2 liters of water), the salt solution is deep red in color. At lower concentrations, the color shifts to yellow. Visual estimate at the concentration is possible down to about 500 ppm sodium chromate. Chemical analysis of the condensate was conducted on a Beckman Spectral Photometer Model DB-2. This instrument is capable of measuring $Na_2Cr_2O_7$ at concentrations down to the ppm level.

Two baffle configurations were tested as shown in Figure 3-16. All tests were run at the following conditions:

Separator pressure, 1.0 psia

Separator speed, 1800 rpm

Liquid flow, 160 lb/hr

Vapor flow, 1.0 lb/hr

Separator liquid content, 410 cc

The conical baffle and the circular baffle displayed similar performance. Carryover rates of 0.015 percent were achieved, compared to 0.2 percent with the demistor alone and no baffle. The flat circular baffle was selected because it provides a larger vapor-flow area from the bowl to the vapor outlet ports. In case of heavy foaming, the vapor velocity immediately upstream of the demistor will be reduced considerably with this configuration, thus minimizing the possibility of liquid entrainment. This was observed during the tests of the two baffle designs, which showed the conical baffle unit to be more sensitive to initial carryover upon startup. This problem is discussed below.

A photograph of the demistor-baffle selected for system test is shown in Figure 3-17, which also shows the vapor inlet and outlet ports and the carbon face seal.

Testing the unit in an inverted position with the vapor port downward resulted in increased carryover in excess of 0.2 percent (limit of experimental measurement), as expected. This occurred at rotational speeds up to a maximum drum speed of 2200 rpm. The high level of entrainment was due to gravitational force aiding the drag force on the liquid droplets, thus causing the removal of a higher percentage of entrained liquid from the separator.

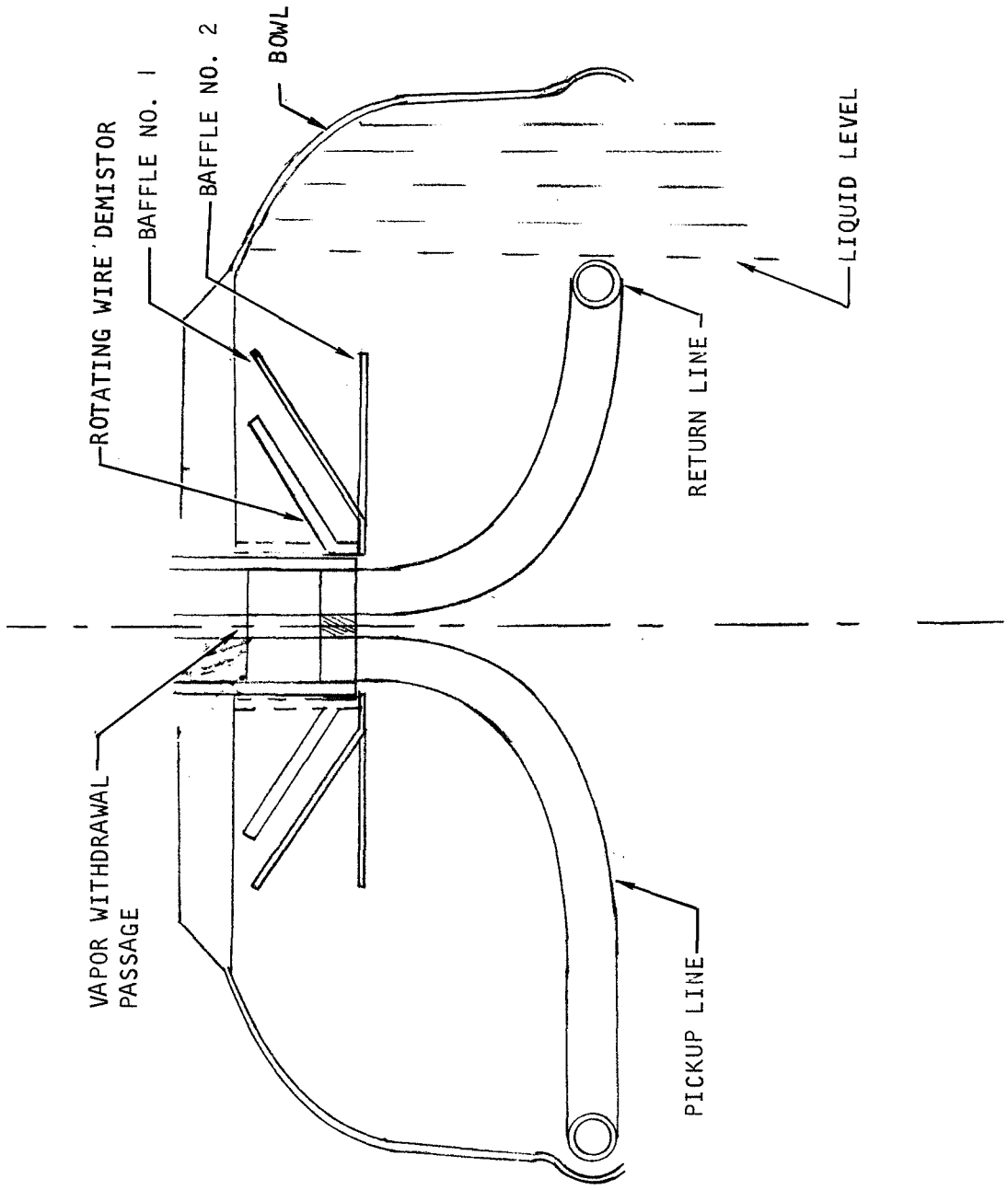


Figure 3-16. Separator Baffle Configurations

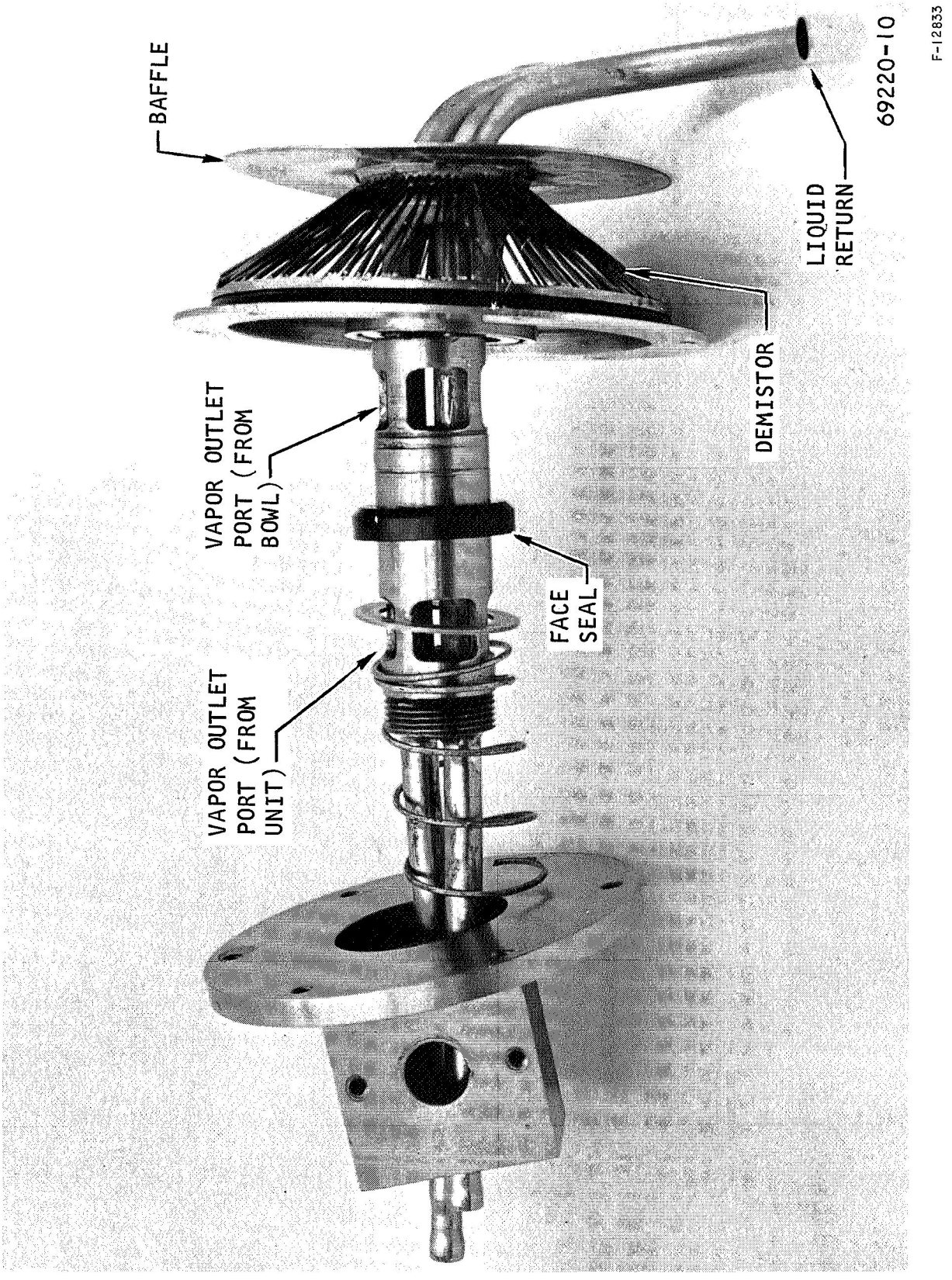


Figure 3-17. Selected Baffle-Demistor Arrangement

Generally, entrainment should be reduced at higher drum rotational speeds due to the greater influence of the centrifugal force field acting on the liquid droplet; however, test observations revealed an increase in entrainment when the drum speed was increased. This is attributed to an apparent increase in the energy imparted to the spray produced by the submerged pitot tube at higher speeds. On this basis, it may be desirable to operate at lower rotational speeds instead of higher speeds as originally theorized.

In normal operation, the brine and water vapor enter the separator as a two-phase mixture. No vapor is formed from the mass of the liquid in the rotating drum. Conditions are very different on startup when the liquid is saturated with air at ambient pressure. Then brine (or water) deaeration in the liquid loop must proceed at a low rate to prevent excessive foaming, resulting in liquid entrainment. This problem was encountered in the previous development program and was investigated experimentally on the separator test rig. The following observations were made:

- Foaming does not appear to be a problem during steady state operation at low separator pressure
- Foaming is more of a problem when the liquid loop is operated at sea level
- Liquid carryover could be minimized by keeping the rate of brine temperature increase below $1^{0}F$ per minute
- Similarly liquid carryover is minimized by limiting the rate at which pressure is reduced in the separator
- In the semi batch system operation periodic filling of the brine loop with fresh urine (following brine dump) will occur over a 10-minute period, furthermore, the urine is introduced in the loop downstream of the flash valve . No evidence of entrainment during feed was detected during system test.

These tests resulted in the development of the following separator and liquid loop tentative startup procedure.

1. Start separator rotation
2. Fill liquid loop at ambient pressure
3. Reduce pressure over separator at maximum rate of 1 psi/min to the 5 psia level, then at the rate of 0.1 psi/min to 1 psia.
4. Following step 3, increase brine temperature at a maximum rate of $1^{0}F$/min to $100^{0}F$ then at the rate of $0.5^{0}F$/min to $110^{0}F$.

Separator Capacity

As mentioned previously, the separator constitutes the liquid loop accumulator. In order to provide data upon which to base the development of the liquid loop feed and dump controls, separator maximum- and minimum-level tests were performed. The following data were obtained:

(a) The minimum separator liquid content to prevent gas entrainment in the liquid loop is 95 cc

(b) As an accumulator, the separator operated satisfactorily with a liquid content of 750 cc.

These data are a direct function of the bowl and pitot tube geometry. Flushing of the liquid loop and separator by means of the pitot pump (with vapor entrainment) would leave about 50 cc of liquid in the rotating bowl.

Conclusions and Recommendations

The breadboard separator tests have demonstrated the soundness of the rotating drum-pitot pump approach. Liquid carryover was reduced by one order of magnitude by the addition of a simple baffle and by controlling the rate of liquid deaeration upon startup.

On the basis of the data obtained the following recommendations are made with respect to future development of the separator.

(a) Entrainment from the bowl could be reduced by one order of magnitude through redesign of the bowl/demistor/baffle--the distance between the baffle/demistor and the tubes carrying the liquid would be increased and the baffle diameter could be increased slightly. Changes in delivery tube and pitot tube configuration should significantly reduce the entrainment by reducing production level of spray from the pitot tube or by improving the deflection of liquid droplets away from the vapor outlet.

(b) As mentioned in the discussions of the level and concentration control for the IWRS, reshaping of the bowl is desirable to improve the accuracy of the density controller. Attention will be given to this aspect of separator design in redesigning the unit.

(c) The rotating seal can be eliminated by driving the bowl through a magnetic coupling. The casing will then be sealed and the vapor from the rotating bowl could be exhausted through the cavity between the casing and the bowl. Insulation will be required to maintain the casing at a temperature above the system distillation temperature so that condensation does not occur on the surface of the casing. Calculations indicate that the heat losses from the motor driving the separator will be adequate to make up the heat losses from the casing with 0.5 in. of insulation.

(d) The casing cavity should be utilized to assure zero-entrainment from the separator unit--vapor from the bowl would be heated on the warmer outer casing and any liquid entrained with the vapor would be vaporized on the surface of the casing. Note that with an entrainment rate from the bowl of 0.0016 percent, only a minute amount of salt will be deposited on the surface of the casing. It is estimated that a negligible quantity of salt, about 0.05 lb per year, will accumulate in the bowl.

(e) Elimination of the face seal through the use of the magnetic coupling will reduce power usage by about 20 percent.

Elimination of the face seal will reduce air leakage into the system to a minimum. This problem has been very troublesome and has resulted in poor compressor and heater-condenser performance. In addition to eliminating the leakage problem, the use of the magnetic coupling will facilitate an improvement in the bearing installation which should result in lower frictional losses. At present, the combined bearing and seal loss accounts for approximately 40 to 50 percent of the total input shaft power. Design changes should reduce this loss to about 20 percent of the total shaft power.

In conclusion, it is recommended that in subsequent programs for the separator the basic design be retained and efforts be concentrated on reducing entrainment, eliminating sealing problems, and reducing mechanical and frictional power loss.

HEATER-CONDENSER

Introduction

1. Background

The heater-condenser is used to transfer heat from the condensing water vapor to the liquid brine solution. The heat absorbed by the brine consists of (1) the latent heat of vaporization of steam at the saturation pressure existing in the phase separator and (2) the heat of solution of the concentrated brine. The heat removed from the vapor essentially includes (1) the heat of condensation which is slightly less than the latent heat of vaporization because of the higher condensing pressure and (2) the heat added to the vapor by the compressor and the catalytic reactor.

The heater-condenser designed and fabricated under Task A of NAS 9-8460 is shown in Figures 3-18 and 3-19. This unit consists of a single spiral tube through which the brine is circulated. The tube is sandwiched between two layers of Refrasil wicks which collect the condensate as it forms on the outer surface of the tube. Screens between the tube and the wicks prevent blockage of the vapor passage by the wicks. A sintered metal plate adjacent to one of the wicks acts as the gas barrier. Water is pumped through the porous metal plate by a cyclic accumulator which maintains a 0.8 psi differential across the plate. Condensate is transferred from the wick not in contact with the plate to the wick which is in contact with the plate by means of a refrasil strip at the periphery of the unit.

In operation, the vapor flows in a counterflow pattern through the spiral passage formed by the tube. Some cross flow will take place because of the presence of the screens. Noncondensible gases carried with the vapor to the heater-condenser are exhausted through a discharge tube in the center section of the unit.

The unit is fabricated of stainless steel; its dimensions are 1.625 in. in thickness by 13.75 in. in diameter. The tube is 13.5 ft long with an O.D. of 0.219 in. and an I.D. of 0.187 in. The pitch of the tube along the spiral varies to account for the drop in vapor flow rate as the condensate forms on the unit.

This heater-condenser was not tested at the component level, but was installed in the original breadboard unit for system level testing. Initial tests conducted as part of Task A of NAS 9-8460 demonstrated that:

(a) The wick-porous plate design is satisfactory

(b) The unit heat transfer capability is limited by the brine side heat transfer coefficient. Calculations based on system data indicated that laminar flow exists within the tube at high brine concentration;

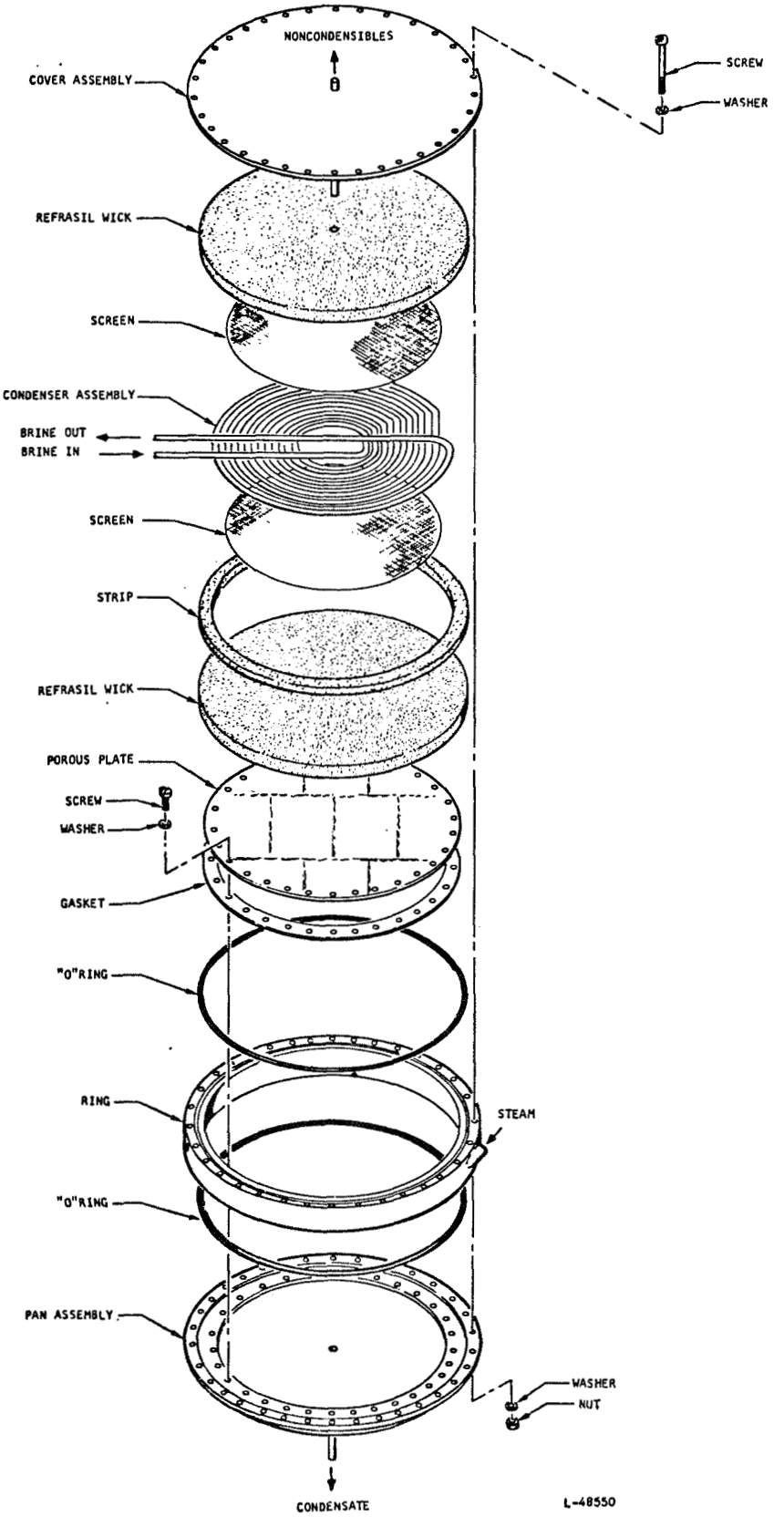


Figure 3-18. Heater-Condenser Arrangement

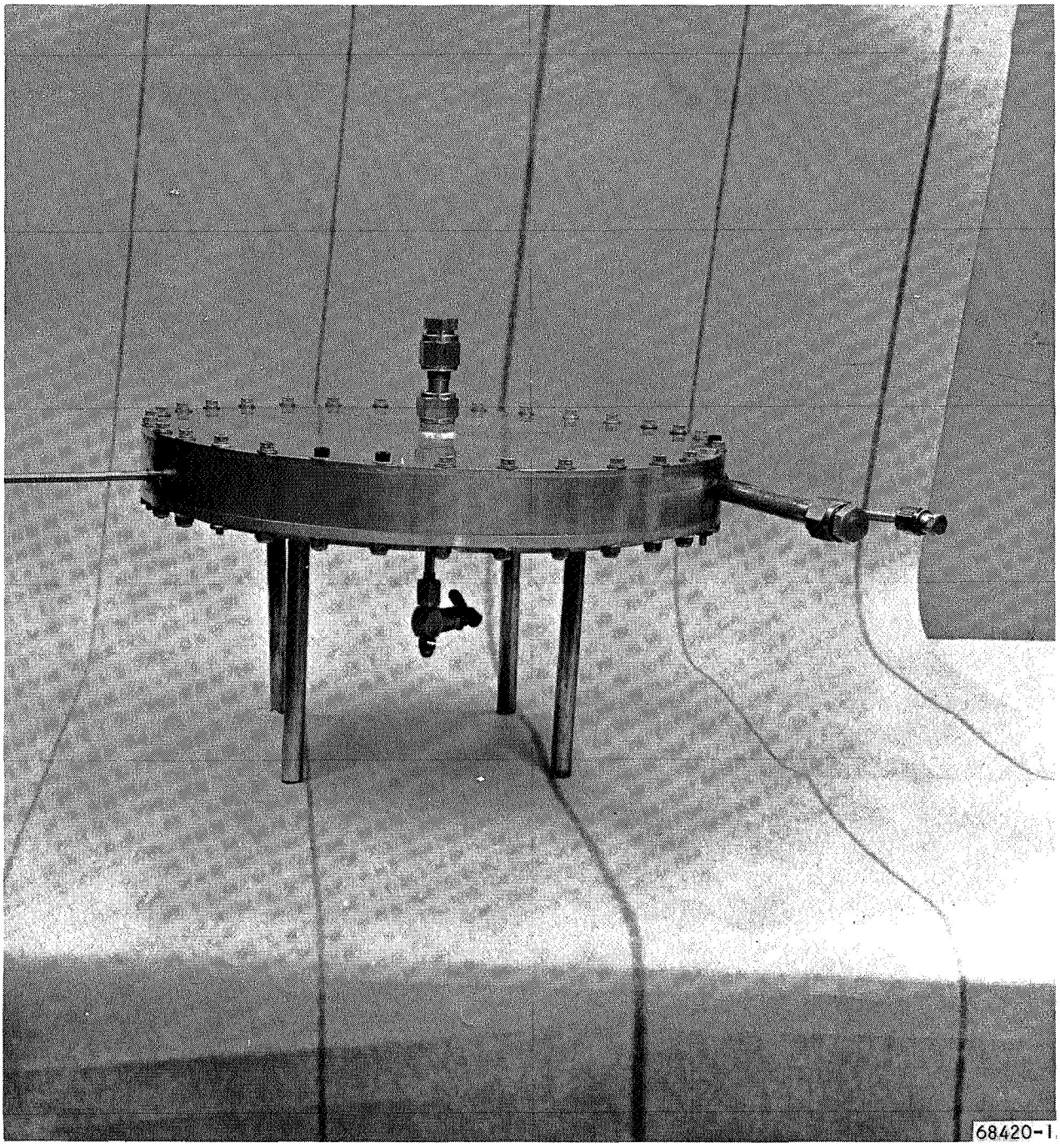


Figure 3-19. Heater-Condenser

as a result, the rate of heat transfer was about 1/3 of the design value. This was offset on system test by operating the compressor at a higher pressure ratio than design value.

(c) The brine tube is susceptible to plugging. This was attributed to operation at low velocity in the laminar flow regime.

2. Scope of Present Programs

As a result of these findings, the following tasks were planned in an effort to develop a satisfactory unit:

(a) Analysis of the test data obtained in the previous program and in the system level tests of NAS 9-9981 (no component level testing was planned)

(b) Incorporation of modifications before installation in the breadboard unit

(c) Development of a preliminary design for the flight prototype unit

The results of these tasks are discussed in the following paragraphs.

Thermal Performance

All testing of the heater-condenser was conducted at the system level. These tests provided data from which the thermal performance of the unit could be analyzed. The analytical efforts were concerned with (1) the effect of the brine concentration on the heat transfer characteristics of the unit and (2) the effect of noncondensibles on vapor-side performance.

The heater-condenser was subjected to three series of system level tests. These tests were performed in July 1969 (under Task A of NAS 9-8460), in December 1969, and in October 1970. Data obtained from these tests are summarized in Table 3-3. The December 1969 tests were run with distilled water to permit more accurate liquid-side heat transfer prediction and, thus, to provide a better basis for estimation of the vapor-side heat transfer coefficient.

1. July 1969 Test Results

Analyses of the July 1969 test data revealed that the heater-condenser overall UA was about 1/3 that necessary for system operation at the design pressure ratio. The heater-condenser was originally designed to meet the following steady-state operation requirements:

TABLE 3-3

HEATER-CONDENSER TEST PERFORMANCE

	Test Date				
	7/31/69	12/15/69	12/16/69	10/5/70	10/6/70
Brine Side					
Brine concentration, percent	43	0	0	20	20
Flow rate, lb/hr	200	144	147	133	155
Inlet temperature, ^{0}F	105	107	110	100	103.5
Outlet temperature, ^{0}F	109	114	119	106.4	108.3
Heat transfer coefficient, h, But/hr ^{0}F ft^2	304	1048	1175	660	862
Vapor Side					
Condensation rate, lb/hr	0.7	0.963	0.983	0.75	0.67
Inlet vapor temperature, ^{0}F	116	123	159	188	205
Condensing pressure (average), psia	1.4	1.57	1.76	1.22	1.37
Heat transfer coefficient, h, Btu/hr ^{0}F ft^2	377	289	317	398	196
Overall conductance, UA, Btu/hr ^{0}F	118	163	179	154.5	103.6

(a) Brine side

Flow, 157 lb/hr

Concentration, 50 percent solids

Inlet temperature, 120°F

Minimum velocity, 2 ft/sec

(b) Water vapor side

Flow, 1 lb/hr nominal

Inlet temperature, 445°F

Noncondensible vent pressure, 2.5 psia

At the design condition, the overall heat transfer UA was calculated to be 310 Btu/hr °F based on a vapor-side heat transfer coefficient of 700 Btu/hr °F ft^2 and a brine-side heat transfer coefficient of 718 Btu/hr °F ft^2. The vapor-side surface area of 0.775 ft^2 was used for the heat transfer area. The vapor-side coefficient was considered to be very conservative with sufficient allowances included for the presence of noncondensibles and film buildup within the vapor side passage. Note that at design point an overall UA of only 146 Btu/hr °F is necessary for adequate heat transfer performance; this is about half the estimated UA of the unit, which includes a 50 percent margin based on the available tube heat transfer area.

Further analysis of the unit revealed the brine flow to be in the transition region rather than the turbulent region as originally considered (at that time, the brine concentration in the liquid loop was controlled at a value around 50 percent). As a result, the brine-side heat transfer coefficient varies drastically with the concentration of the brine. Figures 3-20 and 3-21 show this effect for brine temperatures of 125° and 100°F, respectively. As shown in Figure 3-21, the brine-side heat transfer coefficient is about 304 Btu/hr °F ft^2 for the conditions of the July 1969 test (see Table 3-3). This This corresponds to a vapor-side coefficient of about 377 Btu/hr °F ft^2 for that test condition. This is much lower than the design estimate of 700 Btu/hr °F ft^2; this very low vapor side performance is indicative of large quantities of noncondensible gases entrained into the condenser with the vapor.

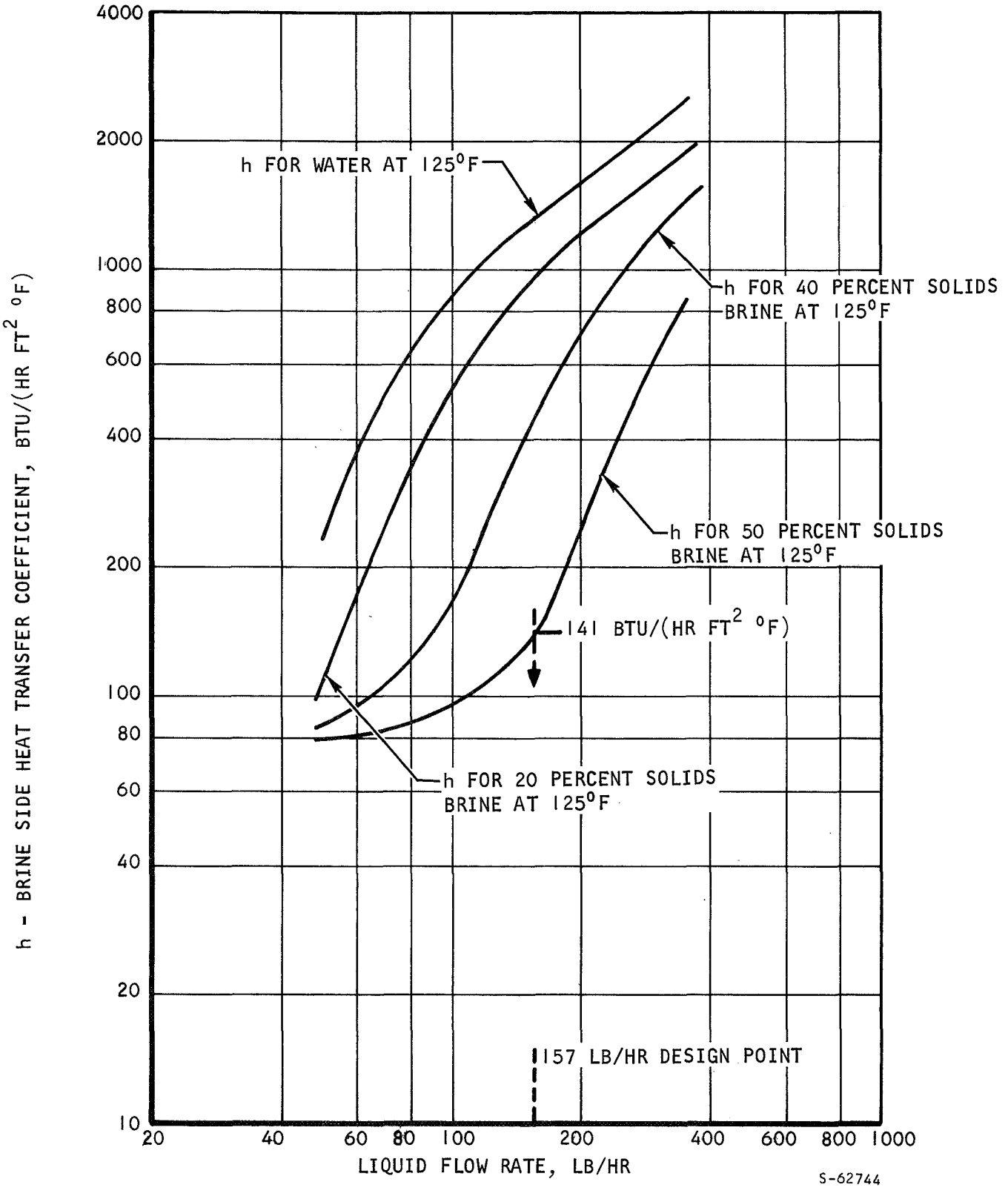


Figure 3-20. Brine Side Heat Transfer Coefficient for Heater-Condenser (125°F)

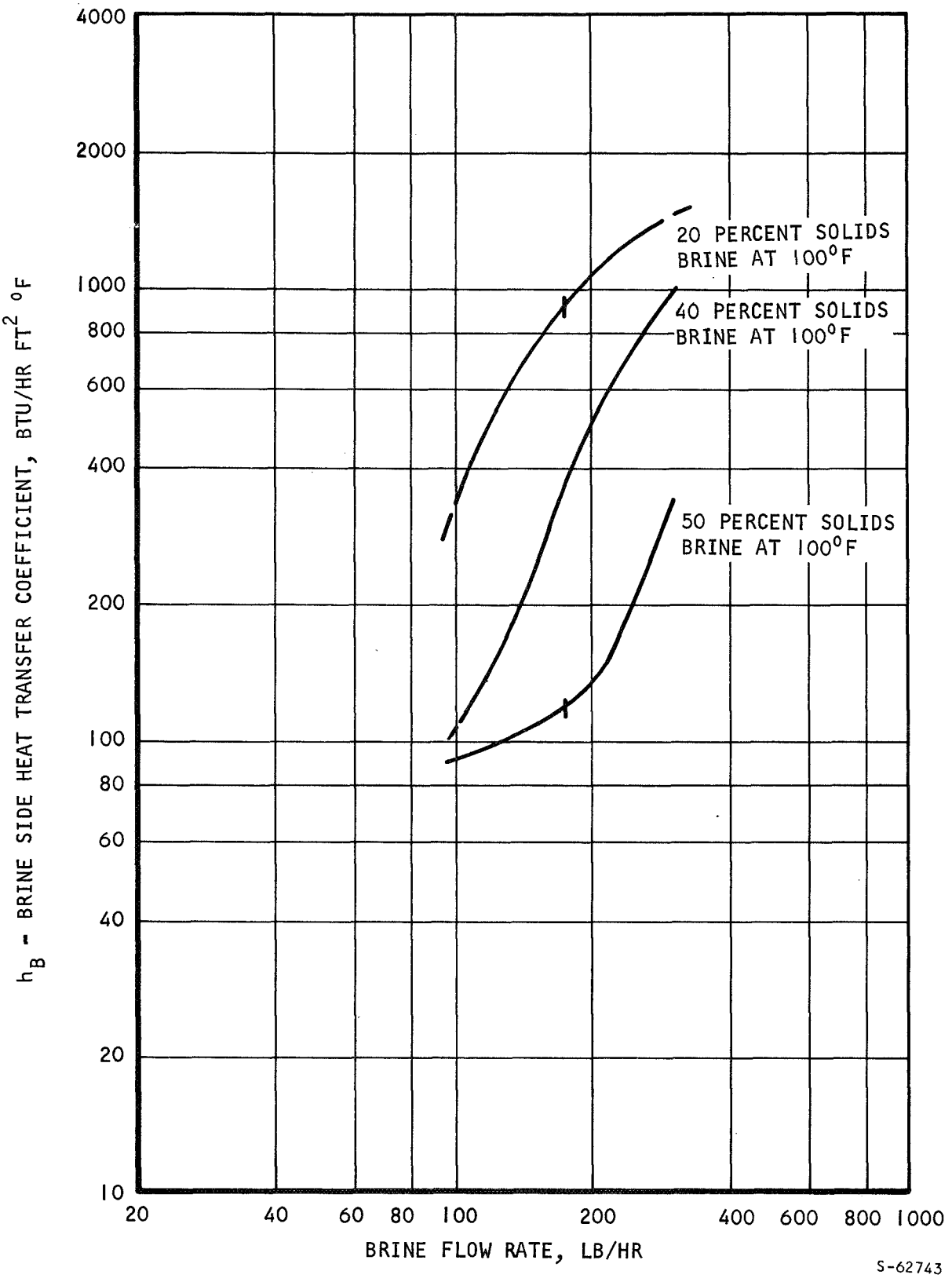


Figure 3-21. Brine Side Heat Transfer Coefficient for Heater Condenser (100°F)

2. December 1969 Test Results

In order to gain insight into the effect of noncondensibles on vapor-side heat transfer performance, the December 1969 tests were run with distilled water in the liquid loop. As expected, the overall UA of the unit was higher primarily because of higher liquid side performance; however, the performance improvement did not meet expectations. Referring to Table 3-3, the calculated liquid side coefficient, h, is higher than 1000 Btu/hr ^{0}F ft^{2}; however, the vapor-side coefficient is on the order of 300 Btu/hr ^{0}F ft^{2}. Here again the low performance of the unit can be attributed only to a large noncondensible flow rate on the vapor side of the tube.

Following the December tests, the unit was disassembled for refurbishment. Considerable quantities of carbon-like granules were found in the vapor passages. Although chemical analysis of these deposits was not conducted, they appear to have originated from the carbon vane compressor used earlier in the program. It is not felt that these deposits contributed significantly to the vapor side performance deterioration.

Data are not available to estimate the leakage rate of ambient air into the system; therefore, the deleterious effect of the air on the vapor-side heat transfer performance cannot be determined accurately. Figure 3-22 shows the reduction in h of condensing water vapor as a function of the concentration of noncondensible in the steam; the plot was prepared using data published by Rohsenow. The plot shows that although the condenser was designed very conservatively (with a 64 percent reduction in steam side coefficient due to the presence of 2 percent noncondensible), a further reduction of 50 percent could easily occur in the breadboard system if noncondensible concentration were to increase to about 5 percent. Experimental evidence of air leakage higher than 15 percent of the vapor flow through the separator face seal was found during the October 1970 tests.

It is believed that the design value of the vapor-side heat transfer coefficient of 700 Btu/hr ^{0}F ft^{2} is indeed conservative if air leakage into the system is adequately checked. A leak-tight system is an essential requirement for any flight system; elimination of the separator face seal should reduce the leakage to negligible values.

The following conclusions can thus be reached from analysis of the July 1969 and December 1969 test data:

(a) As mentioned previously, the wick plate type separator appears satisfactory.

(b) Air leakage into the breadboard system deteriorates the vapor side performance of the heat exchanger by a factor of 2. However, in a flight prototype, leakage of noncondensibles into the system will be controlled to the amount of oxygen necessary to assure complete oxidation of the trace contaminants in the pyrolysis reactor. Thus it is felt that the predicted steam side performance of the unit is conservative and adequate.

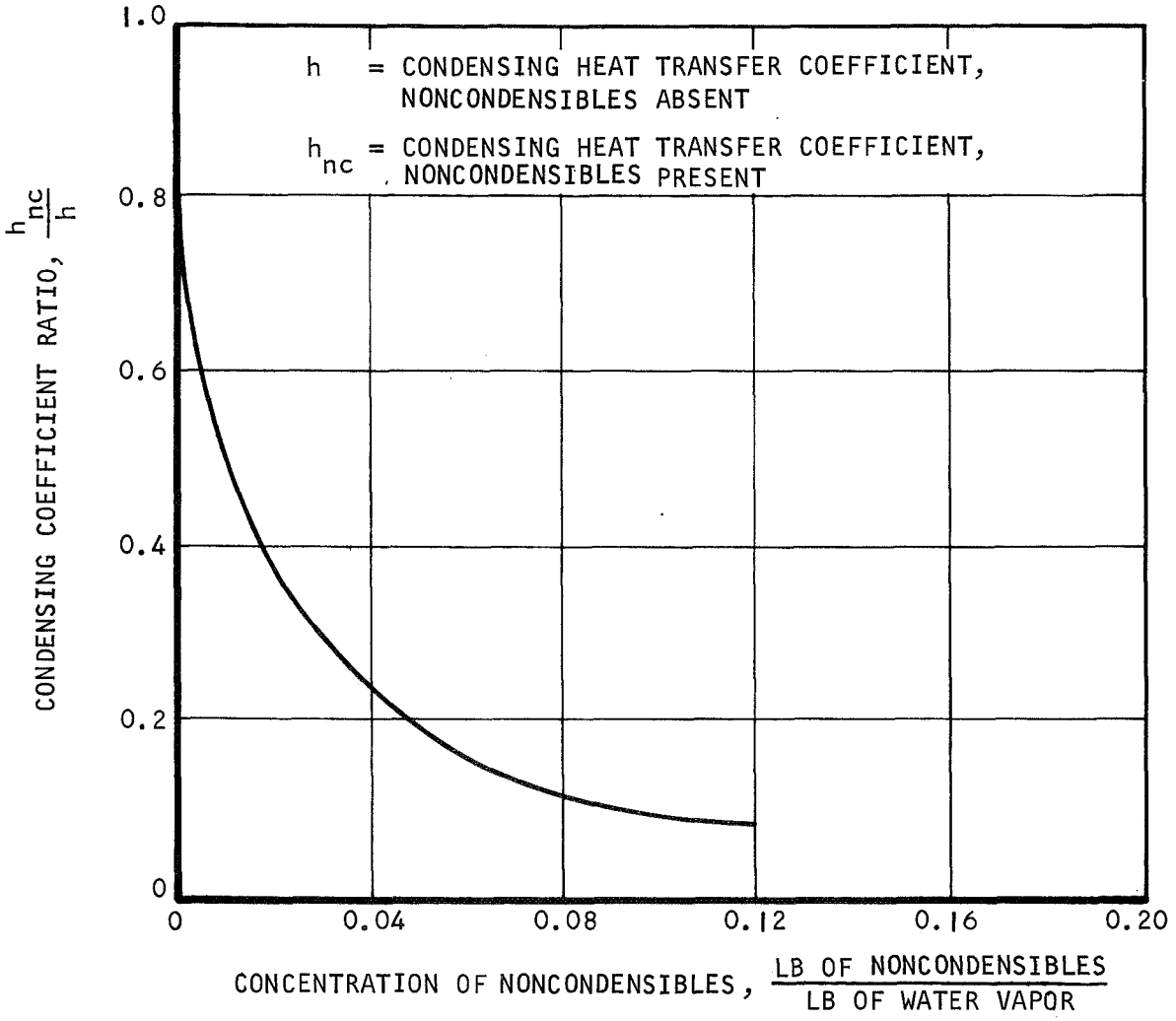


Figure 3-22. Effect of Noncondensibles on Condensing Heat Transfer Coefficient

(c) Thermal performance improvement is necessary on the brine side of the unit if design performance is to be met at the design compressor pressure ratio. Assuming that the vapor side coefficient of 700 can be achieved without modification of the unit, the brine side hA necessary to achieve the performance requirement, listed previously, is 200 Btu/hr ^{0}F; overall UA requirements was initially estimated at 146 Btu/hr ^{0}F (see page 3-39).

Modifications of the heater-condenser design were considered, involving tube length and tube diameter only so as not to affect the design point performance of other system components (namely, the separator-pump and the vapor compressor). The results of these analyses are tabulated below. The data are given for a brine temperature of 125^{0}F and a solids concentration of 50 percent.

	Baseline Unit	Modified Unit--Shorter Tube	Modified Unit--Larger Diameter Tube
Tube ID, in.	0.187	0.187	0.264
Tube length, ft	13.5	10.1	13.5
Brine flow, lb/hr	157	170	245
Heat transfer area, ft^2	0.77	0.58	1.04
Brine side conductance, hA, Btu/hr ^{0}F	93	84	123

Reducing the tube length results in an increase in brine flow and heat transfer coefficient through the system. However, since the flow is limited by the separator-pump pressure rise capability, the overall effect is a net reduction in the brine-side heat transfer conductance, hA. Obviously this change is unacceptable.

Increasing the tube diameter to permit higher brine flow rate results in an increase in brine-side heat transfer conductance. However, the hA improvement is not sufficient to assure adequate performance at 50 percent brine concentration and design point operation. In addition, doubling the flow area, as shown in the tabulation, results in a drop in brine velocity from 2.9 to 2.3 ft/sec. This represents an undesirable change, as will be discussed later.

Other changes considered involved particularly the separator-pump, the vapor compressor, and the liquid loop control system. Some of these changes are listed below:

- Flow rate increase through the present unit from 151 lb/hr to 230 lb/hr. This would require a circuit ΔP of 13 psia (from 8.3) so that separator speed would need to be increased from 1800 rpm to 2600 rpm; power usage rises from 44 to 87 watts.

- Increase length of the tube of the present unit from 13.5 to 29 ft to provide larger heat transfer area at the same brine flow rate. This will result in a loop pressure drop of 17.8 psi (from 8.3 psi). Here again, separator speed must be increased from 1800 rpm to 2800 rpm with a power expenditure of 100 watts (from 44 watts).

- Increase compressor pressure ratio to obtain higher temperature difference between the brine and the condensing vapor and thus to reduce the heater-condenser UA requirement. This approach is very costly in terms of power and was rejected at the time of the December 1969 test. At that time compressor development was a serious problem. Later in the program a vortex compressor was selected for the system. This type of compressor is essentially a low pressure-ratio machine, and increasing pressure ratio to alleviate heater-condenser problems did not appear a very promising solution especially in view of the fact that the heater problem could be resolved by changing the system control system as explained below.

- Control system change. Up to this time the brine concentration was controlled in the liquid loop at about 50 percent, with essentially constant-level control in the separator. Operation in this manner unnecessarily penalizes the system because of the boiling point elevation of the brine and also because of performance deterioration of the heater-condenser at high brine concentration (see Figures 3-20 and 3-21). A semi batch process was devised whereby the brine is dumped at 50 percent (thus maintaining high recovery effectiveness) while system operation during the major portion of the semi batch cycle is at low brine concentration (thus at high average processing rate). This system is described in detail later. Generally operation is as follows:

  (a) The brine contained in the separator is dumped when the concentration is 50 percent. The liquid loop is then refilled (from 225 cc to 830 cc), thus diluting the brine remaining in the loop to a concentration of about 17 percent.

  (b) The liquid level in the separator is maintained around 830 cc by the addition of waste water to replace the water vaporized from the loop. In this manner the brine concentration will increase.

  (c) When the brine concentration reaches 25 percent, replenishment of the liquid loop is stopped until the concentration reaches 50 percent, at which time the dump valve opens and the operation is repeated.

  It is estimated that about 4 lb of water will be evaporated at brine concentrations between 17 and 25 percent, while only one lb will be processed between 25 and 50 percent. The average processing rate will be well above the 1 lb/hr design value at low concentration (between 17 and 25 percent); however, due to a decrease in flow rate

and in water-condenser performance, the processing rate will drop below average value at 50 percent concentration. Tabulated below are preliminary data based on fixed evaporator and condenser pressure which show the effect of concentration on processing rate.

	Brine Concentration at 20 percent	Brine Concentration at 50 percent
Brine side flow, lb/hr	225	157
Brine side, h, (at 125°F) Btu/hr °F ft^2	1300	141
Water processing rate, lb/hr	1.4	0.8

As a result of these investigations, the decision was made to change the system control scheme to the semi batch process described above. Not only does this control method reduce the heater-condenser design requirements because of lower average brine concentration, it also results in other important systems savings by allowing operation at a lower compressor pressure ratio.

3. October 1970 Test Results

The semi batch mode of operation was employed in the October 1970 tests. Following the December 1969 tests, the condenser was refurbished and a new tube was installed in the unit. This new tube was similar to the original, but was shorter in length and had smoother inlet and outlet configurations to reduce the possibility of plugging. The new tube was 12 ft long in comparison to 13.5 ft for the original unit, corresponding to a reduction in surface area from 0.77 ft^2 to 0.69 ft^2.

The results of the October 1970 breadboard tests are given in Table 3-3. The October 1970 breadboard incorporated the vortex compressor. Generally the condenser pressure was lower than in the previous tests. This, together with the effects of noncondensibles on the vapor-side heat transfer coefficient, contributed to relatively low water production rates.

The brine-side heat transfer coefficient is not controlling in the cases listed. Estimates of air leakage into the system were obtained from pressure rise data at system shutdown. These data indicate that about 0.112 lb/hr of air leaked into the liquid loop and was entrained with the vapor to be exhausted through the condenser. Air leakage through the system upstream of the catalytic reactor bed was more than ample for oxidation of the water vapor contaminants so that no additional oxygen was introduced in the test rig for this purpose. This large quantity of air easily explains the relatively low steam-side heat transfer coefficients obtained in the test (see Figure 3-22). Examination of the phase separator after completion of the system tests revealed that the separator face seal was badly damaged; the high air leakage rates (0.0252 scfm) could have occurred through that seal.

Tube Fouling

Blocking of the heater brine tube occurred once during the October tests, following a system shutdown for the purpose of repairing a failed compressor motor bearing. At the time of the failure, the brine concentration in the liquid loop was about 40 percent. While the compressor motor was being replaced, the phase separator maintained flow through the liquid loop. After compressor repair, when the system returned to normal operating conditions, the brine temperature in the liquid loop was found to have dropped to 88.5°F where it remained for several hours. Although brine flow rate was not measured during the test, pressure drop calculations indicate that the viscosity increase of the brine at that temperature could result in a reduction in brine velocity to a value of about 1.6 ft/sec. The corresponding Reynolds number is estimated at 1610--well into the laminar region.

Solids were apparently deposited on the tube walls during that low temperature period which persisted for approximately 4 hours. As the solids accumulate in the tube, the brine velocity will drop further because of the flat pressure-rise characteristic of the separator-pump (see Figure 3-12). Thus the solids accumulated until complete blockage occurred. The solids were disloged by inserting a flexible wire into the heater-condenser tube.

Previous studies have indicated that the liquid velocity should be maintained above 2 ft/sec to prevent solids deposition on the tube walls. In the worst case condition, with 50 percent concentration and a flow of 160 lb/hr, the velocity will normally be 3 ft/sec. This appears to be adequate as long as the temperature of the brine remains higher than about 100°F.

Means are available to prevent such a situation from occurring. In actual operation at low brine concentration the Reynolds number will be much higher, even at temperatures on the order of 85°F, so that adequate flow will be maintained in the tube to obviate fouling. At high brine concentration, the normal liquid temperature will be on the order to 105°F, thus assuring velocities well above 2 ft/sec in the circuit. In the event of a failure in the vapor loop, circulation through the brine loop could be maintained. This will result in a slow increase in brine temperature to a level at which the power expended in the phase separator balances the heat leak from the liquid loop components. (This increase in temperature was measured on test when compressor failure occurred.) Following repair of the vapor loop, the isolation valve in the vapor line between the phase separator and the compressor should be opened slowly so as to obviate rapid transients in the liquid loop causing a rapid temperature drop in the brine. This was not done during system tests; as a result, the brine temperature dropped by about 15°F immediately after opening the isolation valve. It should be mentioned here that slow depressurization of the liquid loop is the standard system start-up procedure to prevent liquid carryover due to foaming in the separator, and that no additional requirements are imposed upon the system automatic control.

Conclusions and Recommendations

Previous discussions have indicated that the design of the separator is adequate when the system is operated in a semi batch cycle whereby most of the

water is processed at relatively low brine concentration. The low performance obtained during system test is due primarily to large quantities of air leaking into the system, resulting in low heat transfer coefficient on the vapor side of the unit. In a flight prototype heater-condenser incorporating a statically sealed phase separator, such a problem will not exist.

The tube fouling problem experienced during the 5-day test run was traced to low temperature (88^{0}F) operation of the brine loop at high concentration following a failure in the vapor loop. Analysis of the sequence of events which preceded tube fouling reveals that such a problem can easily be obviated by suitable system startup after interruption of normal operation. An alternate solution would be to dump the brine loop to the waste tank should a failure occur in the vapor loop. Refilling with fresh waste would assure against tube fouling.

On the basis of the tests reported above and of the analyses conducted, the preliminary design of a flight prototype unit was performed. Figure 3-23 is a sketch of the unit. A cylindrical configuration was developed mainly to reduce heat leaks and to facilitate packaging. From a thermal standpoint the unit is very similar to the breadboard unit. The brine tube is coiled in two concentric spirals. Tube length is 13.5 ft; tube diameter is 0.21 OD. Overall size is 3-1/2 in. in diameter by 5-1/2 in. in height. The unit height is limited by the water transport capacity of the wicks (this is the reason for using the two concentric coils configuration).

Phase separation is effected by means of a sintered metal porous plate. A sponge is used to transport the condensate from the collection wicks to the separator plate.

No further work on this component is recommended other than fabrication of the flight prototype unit for system-level testing.

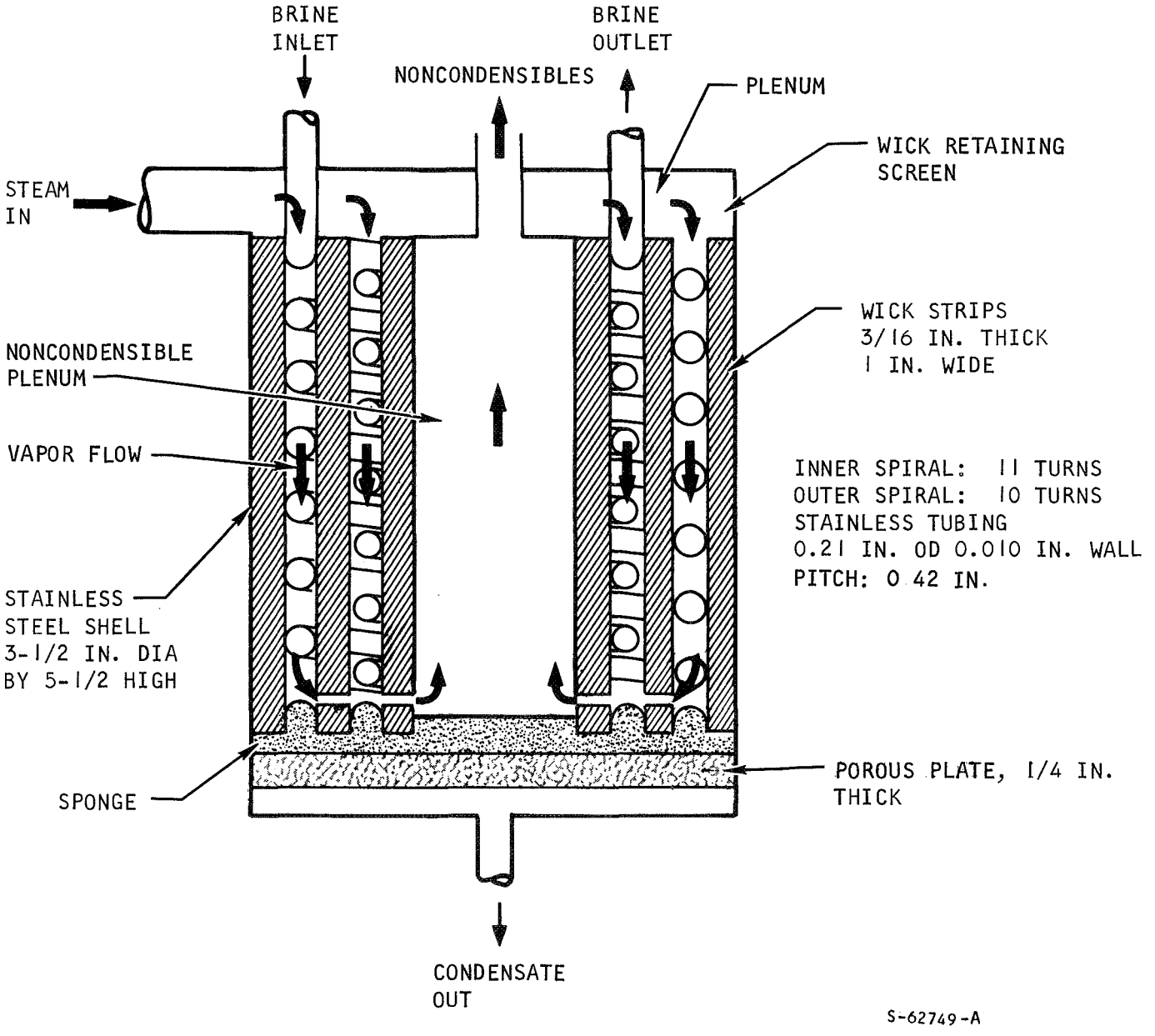


Figure 3-23. Flight Prototype Heater-Condenser

CATALYTIC REACTOR

Introduction

1. Background

The general guidelines established at the beginning of the IWRS development program specified that:

(a) The system should provide "hands off," completely automatic operation. As a corollary, no filters were to be used in the system; thus, the requirement for filter replacement and the hazards associated with such a task were eliminated.

(b) The system should produce water of the highest quality, free of bacteria. This requirement (considered together with the above) resulted in the selection of a catalytic reactor for the post-treatment process.

The first phase of the program (Task A of NAS 9-8460) was concerned with only a very minor effort on a catalytic reactor. A reactor was included as part of the system; however, reactor pressure drop was prohibitive and the unit was used only for a short run during system-level testing.

2. Scope of Present Programs

This phase of the program was concerned with (1) the selection of a catalyst suitable for use on the IWRS and (2) the design of a catalytic reactor for testing on the breadboard system. These goals were attained through the performance of the following tasks:

(a) Development of a catalyst test rig

(b) Catalyst screening program

(c) Catalyst evaluation and selection

(d) Limited life testing and reactor sizing

(e) Reactor testing in the breadboard system

Activities related to these tasks are summarized in the following paragraphs.

Experimental Apparatus

The test rig developed for the catalyst study is shown schematically in Figure 3-24 and photographically in Figure 3-25. To permit rapid screening and direct comparison of results, two catalytic units were installed in parallel on the test rig, thus permitting simultaneous, comparative, catalyst evaluation. Water was evaporated from urine into a five-liter, three-neck flask. The vapor passed through a high-vacuum stopcock (3 arms, hollow plug, 15-mm bore)

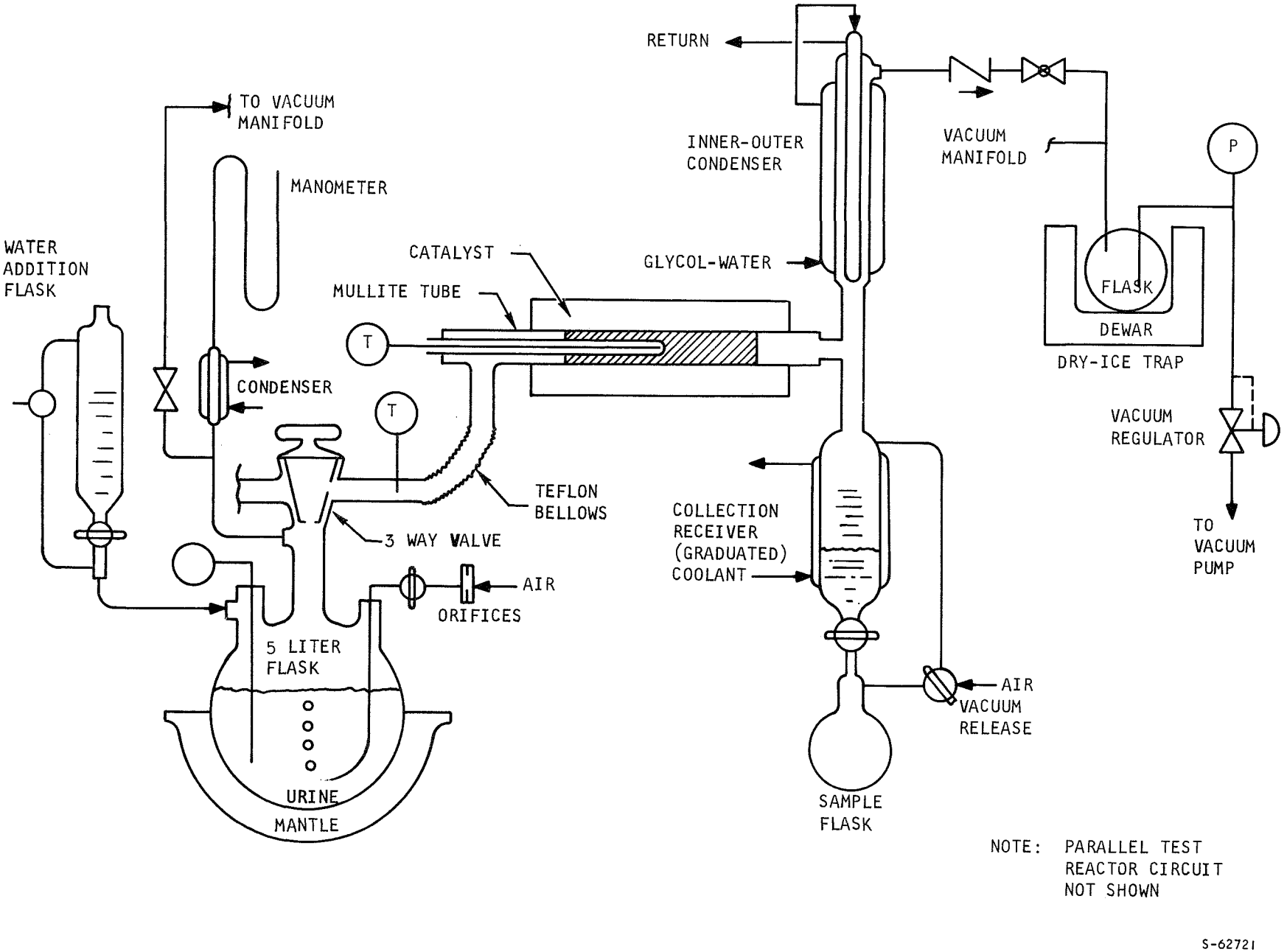
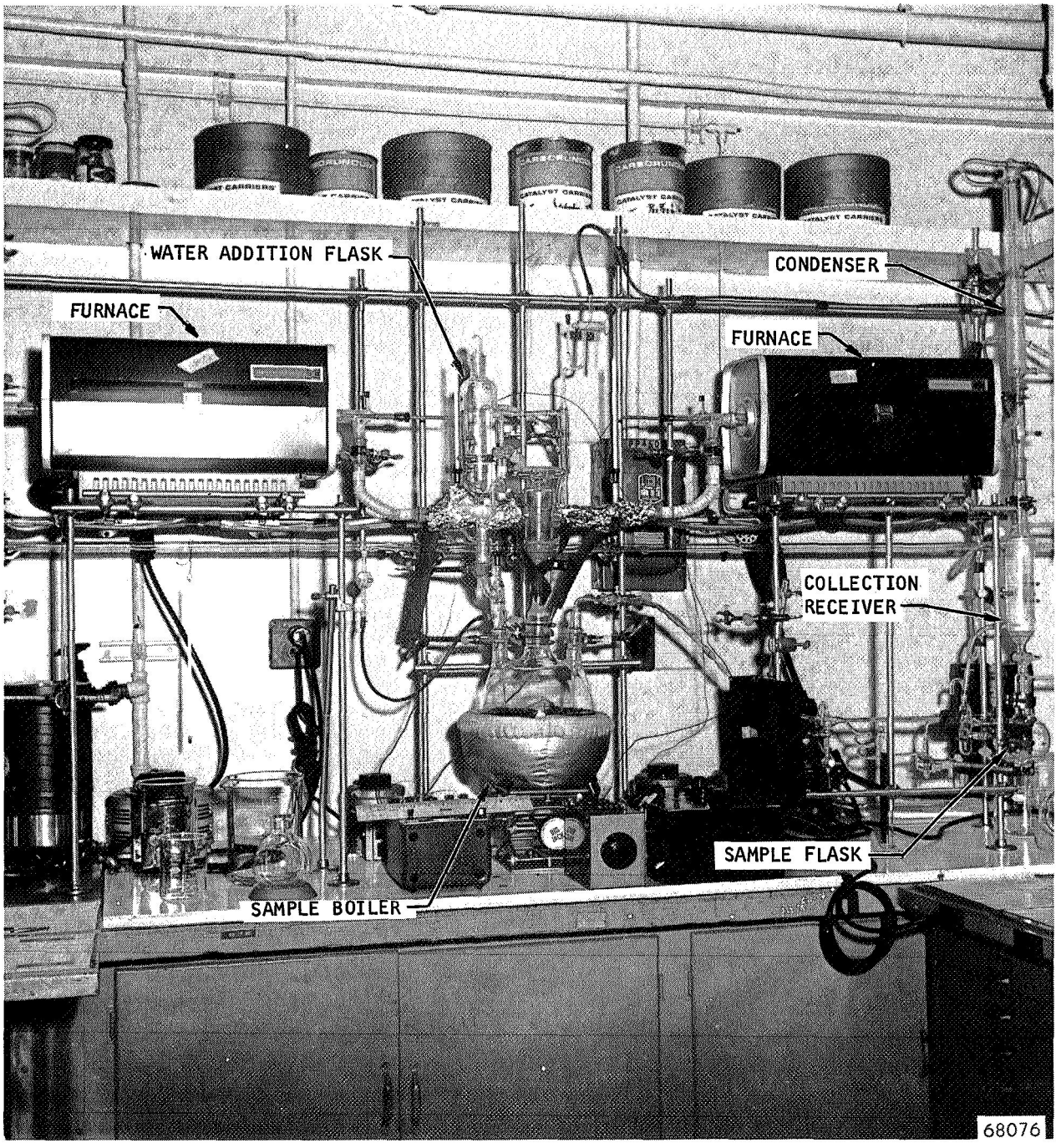


Figure 3-24. Apparatus for Investigation of Urine Vapor Pyrolysis



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Figure 3-25. Catalytic Reactor Test Rig

into a mullite tube (1-in. OD, 3/4-in. ID, 12-in. heated length) containing the catalyst under investigation; the tube was located in a furnace. A second mullite tube (1/4-in. ID), placed within the first one, was used to route a thermocouple halfway down the heated length of the catalyst bed. The vapor leaving the mullite tube was condensed in an inner-outer glass condenser (16-in. condensing length) and the condensate was collected in a jacketed, graduated, distillation receiver from which it could be drained into a sample flask. The condensate receiver and condenser were cooled by a refrigerated water-glycol recirculation unit.

The vacuum takeoff was located at the vent of the condenser. Check valves were installed in the vacuum lines from the individual condensers to the vacuum manifold, and a single dry-ice trap (a 1-liter flask in a suitable dewar) was installed in the vacuum manifold system. A vacuum regulator maintained the desired distillation pressure. A series of glass microcapillaries (suitably trapped) were installed ahead of a bubbler in the distillation flask so that, under vacuum conditions, a minute air flow (approximately 1.5 cc/min) bubbled through the urine to supply the required oxygen for contaminant oxidation. The air flow was measured by timing the passage of a water drop through a pipet and was found to be essentially constant during the test period.

Urine Test Solution for Screening Tests

A synthetic urine approximating the average analysis for human urine, was formulated for use in the catalyst screening tests. The synthetic mixture ensured that data for different catalysts were comparative. In addition, the use of the mixture made it possible to increase the proportions of various compounds so that odor and ammonia in the distillate could be maximized. To ensure that odiferous compound would be present in the distillate, camphor (dl-camphor, synthetic) was included since it has a penetrating odor in trace amounts; being insoluble in water, it also steam distills in the vapor.

Urine analyses which were the basis for the formulation of the synthetic mixture were obtained from the following sources:

(a) AiResearch Report 66-14-6

(b) Gray, P., "The Encyclopedia of Biological Sciences," Reinhold Publishing Co., N.Y., 1961, p. 368

(c) Altman and Dittmer, "Biology Data Book", Biophysics Laboratory, Aerospace Medical Division, Wright-Patterson AFB, Dayton, Ohio, AMRL-TR-64-100, October 1964, pp 186 ft.

(d) Webb,"Bioastronautics Data Book", NASA, Washington D.C., 1964, pp 216

Compilation of data from the literature indicated that synthetic urine having the composition shown in Table 3-4 would most nearly approximate an average urine composition and would provide the necessary sources of odor and ammonia. The mixed amino-acids, consisting of 24 amino acids (Table 3-5) in one-gram quantities, were thoroughly blended by ball milling. The odoriferous

TABLE 3-4

COMPOSITION OF SYNTHETIC URINE

CONSTITUENTS	MG/LITER	REMARKS
ORGANIC:		
Urea	25,000	
Phenol	1,500	
Amino Acids (mixed)	1,500	See Table 3-5
Lactic Acid	1,000	
Citric Acid	500	
Creatinine	1,000	
Uric Acid	1,000	
Hippuric Acid	500	
Odor Compounds (includes Camphor)	1,000	See Table 3-6
TOTAL	33,000	
INORGANIC:		
Sodium (N_a^+)	3,600	
Ammonium (NH_4^+)	1,500	
Potassium (K^+)	1,600	
Calcium (Ca^{++})	150	
Magnesium (Mg^{++})	100	
Chloride (Cl^-)	7,000	
Dihydrogen Phosphate ($H_2PO_4^-$)	2,900	930 mg P
Nitrate (NO_3^-)	450	
Sulfate ($SO_4^=$)	2,400	810 mg S Totals = 890 mg
Sulfide ($S^=$)	80	
Bicarbonate (HCO_3^-)	150	
TOTAL	20,000	
TOTAL SOLIDS = 53,000 mg/Liter		

TABLE 3-5

DL AMINO ACIDS*

DL Alpha Alanine
DL Arginine HCL
DL Asparagine
DL Aspartic Acid
DL Citrulline
DL Cystine
DL Dopa
DL Ethionine
DL Glutamic Acid
DL Histidine HCL
DL Isoleucine
DL Leucine
DL Lysine HCL
DL Methionine
DL Norleucine
DL Norvaline
DL Ornithine HCL
DL Phenylalanine
DL Proline
DL Threonine
DL Tryphophane
DL Tyrosine
DL Valine
DL Alpha Amino N Butyric Acid

*One gram of each of the above were used in the total amino acid mixture.

TABLE 3-6

ODOR COMPOUNDS USED IN SYNTHETIC URINE*

INGREDIENT	WEIGHT (Grams)
dl - Camphor	12.0
3 - Methyl Indole	1.0
Indole	1.0
2 - Imidazolidin Ethione	1.0
1 - Methylimidazole	1.0

*The above mixture was dissolved in 75 ml of Methyl Alcohol.

compounds (Table 3-6), including camphor, were dissolved in methanol and a proper quantity of this solution was added. All components were thoroughtly mixed before use. The uric acid proved to be relatively insoluble; it was necessary to adjust the pH to neutral (6.8) with about 15 cc of concentrated (30 percent) ammonium hydroxide solution for a 6-liter batch after all components were in solution.

The synthetic urine was made up to an initial solids concentration of about 53 g/liter. It was not changed during use, although odor or ammonia were added periodically. The distillate was returned to the still after sampling so that the concentration in the still probably did not exceed 100 g/liter at any time. The pH remained essentially neutral throughout the test period.

Toward the end of the program, human urine was substituted for final test evaluation of the selected catalyst. No detectable differences between the synthetic and the actual urine were found in the condensed water.

Analytical Methods

Analyses on the condensed water were restricted to qualitative or semi-quantitative tests that could be performed rapidly since comparative data only were required. A number of test papers specific for certain ions were obtained from the Gallard-Schlesinger Chemical Mfg. Corp., Carle Place, N. Y. The test paper most frequently used was specific for ammonia ion, with a limit of sensitivity of 10 mg NH_4^+ per liter (10 ppm). Other test papers specific for cyanide, sulfide, halogens, nitrates, and nitrites were used on infrequent occasions. In general, tests of the distillate were restricted to color, clarity, odor, pH (by test paper). ammonium ion (by test paper), and specific conductivity (micromho/cm). Little or no difference was detected between a good condensate and laboratory distilled water using these analytical techniques.

Catalyst Evaluated

The precious metal catalysts tested during the program are listed in Table 3-7. Some of the precious metal catalysts were obtained already deposited as a metal on alumina pellets. Others, particularly the oxides, were obtained as a powder.

A catalyst carrier (mullite pellets, 1/8-in. cylinders, MMN) was obtained from the Carborundum Co., Latrobe, Pa. The powders were rolled onto the pellets and then sieved to remove the excess powder. In certain instances, adherence of the powdered catalyst to the carrier was poor and accurate comparative performance data could not be obtained. The catalysts obtained as pellets were tested as such; only the powdered catalysts were loaded on the mullite pellets for testing.

Ruthenium (0.5 percent on 1/8-in. alumina pellets) was obtained from North American Rockwell, Downey, California. This catalyst was used in testing a General Electric unit at North American Rockwell and is reported to be a product of Engelhard.

TABLE 3-7

CANDIDATE PRECIOUS METAL CATALYSTS

CATALYST	DESCRIPTION	MFR	CATALOG NO.	PRICE, $/gram
Ruthenium (From North American, Downey, Calif.)	0.5% on Alumina Pellet	Engelhard	-	-
Platinum (90%) Rhodium (10%)	80 Mesh Gauge	Engelhard	-	-
Ruthenium	0.5% on Alumina Pellets	ESPI	PGC 325	0.72
Ruthenium	5% on Alumina Powder	ESPI	PMC 250	3.50
Platinum	0.5% on Alumina Pellets	ESPI	PGC 315	0.66
Platinum Oxide	Powder	ESPI	UPC 207	75.00
Palladium	0.5% on 1/8" Alumina Pellets	ESPI	PGC 305	0.45
Palladium Oxide	Powder (Reg'd grinding)	ESPI	UPC 205	5.40
Rhodium	5% on Alumina Powder	ESPI	PMC 240	7.75
Rhodium Sesquioxide	Powder	ESPI	K4450B	30.00
Iridium Dioxide	Powder	ESPI	K2893C	40.00
Rhenium	Metal Powder (-200 mesh)	ESPI	K4541E	13.00

NOTES:

(1) ESPI = Electronic Space Products Inc, Los Angeles, California
(2) Blacks of Platinum, Palladium, Rhodium, Ruthenium and Iridium also were available

All precious metals which could have been suitable as catalysts were evaluated with the exception of osmium, which forms a volatile toxic tetra-oxide. Rhenium, although not strictly a precious metal, was included; however, very little data was obtained. The rhenium powder would not adhere well to the catalyst carrier and the catalyst loading was too low to be effective in oxidizing any contaminants.

Test Procedure

No attempt was made to optimize space velocity or operating temperature during the screening tests. Condensate flow rates varied between 1.0 to 2.5 cc/min with a catalyst bed of 60 to 75 grams of pellets in the 3/4-in. ID mullite tube. Temperatures of 400°, 600°, and 800°C, were normally investigated for each catalyst. The desired flow rates were obtained by adjusting the heat input to the still and the condenser pressure in order to control the pressure drop across the catalyst bed. Properly controlled, the still temperature was essentially maintained between 115° and 120°F, (46° to 49°C); a still pressure between 65 and 80 mm Hg was obtained with the condenser pressure controlled at a nominal value of 50 mm Hg. Test bed pressure drop fluctuated considerably, depending on the type of catalyst carrier used and on the vapor flow rate. Boiling temperatures above 120°F (49°C) were not usually employed.

Initial tests of individual catalysts were undertaken using the test catalyst in one furnace and a similar catalyst carrier (generally 1/8-in. mullite cylinders) only in the second furnace so that a direct comparison could be made of distillate samples with and without catalytic purification.

Following screening of the candidate precious metal catalysts, the selected catalyst (rhodium on mullite pellets) was subjected to more extensive testing with ruthenium (GE catalyst) as the control catalyst. Life testing of the rhodium catalyst on mullite was performed with both synthetic and human urine. Rhodium was also tested as a metallic plating on stainless steel screen.

Screening Test Results

A summary of the screening test data is presented in Table 3-8. Ruthenium (0.5 percent on 1/8-in. alumina pellets) obtained from North American Rockwell was compared with ruthenium purchased commercially. Essentially similar results were obtained with the exception that an uncommonly low pH was obtained with the commercial material at temperatures in excess of 600°C. This change to a low pH with high temperatures was observed with other catalysts and is believed to be due to some false reaction of the pH paper rather than to the actual acidic nature of the water collected.

Palladium as a metal (0.5 percent on 1/8-in. alumina pellets) appeared to be an excellent catalytic at all temperatures from 400° to 800°C; in addition, it is the least expensive. This catalyst has previously been evaluated for high-temperature catalytic burners to be used for trace contamination control in space cabins and has proved effective for this purpose.

TABLE 3-8

PERFORMANCE OF PRECIOUS METAL CATALYSTS FOR URINE PYROLYSIS

Catalyst	Manufacturer	Support	Remarks
Ruthenium (from North American)	Engelhard	0.5 percent on 1/8 in. alumina pellets	Tested at 500° to 600°C. pH low at 4 to 4.5. Trace of NH_3 in one sample. Overall performance good.
Ruthenium	ESPI PGC325	0.5 percent on 1/8 in. alumina pellets	Above 600°C, pH of 2 to 4 obtained. Trace of NH_3 in one sample. Overall performance good.
Ruthenium	ESPI PMC250	5 percent on alumina powder dusted onto 1/8 in. mullite pellets	Used for comparative performance with rhodium on alumina powder. pH 5 to 6. Overall performance good.
Rhodium	ESPI PMC240		Compared with ruthenium also on alumina powder low catalyst loading (35 micrograms/gram). pH 5 to 6. Overall performance good.
Rhodium Black	Engelhard	Metallic black dusted on 1/8 in. mullite pellets	Used for more extensive testing of rhodium. Activated on O_2 atmosphere at 800°C. Overall performance good.
Rhodium Sesquioxide (Rh_2O_3)	ESPI K4550B	Powder dusted on 1/8 in. mullite pellets	Above 700°C, ph of 3 obtained in first samples. Overall performance good.
Platinum (90 percent) Rhodium (10 percent)	Engelhard	80 mesh wire gage	Not completely effective. Trace of odor and NH_3 still present in distillate. pH 7 to 8.
Platinum	ESPI PGC315	0.5 percent on 1/8 in. alumina pellets	Poor performance. Positive identification of NH_3 and odor in distillate. Obtained pH values 10 (400°C) to 2 (800°C)
Palladium	ESPI PGC305		Good performance at 400 to 600°C. Not tested at 800°C. pH 5 to 6.
Platinum Oxide	ESPI UPC207	Powder dusted on 1/8 in. mullite pellets	Trace of odor at 500 to 600°C. pH 5 to 6. Performance otherwise satisfactory.
Palladium Oxide	ESPI UPC205	Powder dusted on 1/8 in. mullite pellets	Coarse powder required grinding. Poor catalyst loading. Trace of NH_3 at 400° to 600°C. Satisfactory at 800°C. pH 6.
Iridium Dioxide	ESPI K2893C		Good performance at all temperatures. pH varied 2 to 5. Price very high.
Rhenium	ESPI K4541E	Metal powder (200 mesh) on 1/8 in. mullite pellets	Very poor catalyst loading. Definite odor and NH_3 in samples. pH values above 8.

Rhenium did not appear effective, but test results were inconclusive due to insufficient catalyst loading on the mullite pellets. Iridium dioxide was an excellent catalyst but pH values of the condensate ranged from 2 to 5. The reason for such acidic distillates has not been determined. Platinum-rhodium gauze (90 percent platinum and 10 percent rhodium on 80 mesh) proved only partially effective. Traces of odor and ammonia were found in the condensate. This was the catalyst employed on the breadboard system developed in the previous phase of IWRS program.

The choice was narrowed to palladium, rhodium, and ruthenium. Palladium is readily available as 0.5 percent metal on alumina, is relatively inexpensive, and is also very satisfactory. It was considered as an alternate. As expected, ruthenium was found to be a very effective catalyst. Rhodium was also quite effective, both as a metal and as an oxide. It was as good as ruthenium in comparative tests and gave satisfactory performance with a very low catalyst loading (35 micrograms/gram).

Rhodium was selected for further evaluation and for application to the breadboard system. The reasons for the selection are related to catalyst fabrication and system performance rather than catalyst activity. Rhodium is widely used commercially for plating of components which must be tarnish, corrosion, and abrasion resistant. Thus a wire screen (stainless steel) could be plated with rhodium and serve as the catalyst bed. This could reduce weight and pressure drop through the catalytic unit and thus reduce compressor power usage.

Selected Catalyst Evaluation

Following the screening of precious metal catalysts and the selection of rhodium for more extensive testing, the comparable ruthenium and rhodium catalysts (5 percent metal on alumina powder dusted on 1/8-in. mullite pellets, with essentially equal catalyst loading and weight) were subjected to a seven-day comparative test. No differences could be detected between the distillates processed over the two catalysts with the exception that an unexplained blue tint was found in ruthenium distillates toward the end of the test period. No evidence of acid condition was found (pH values of 5 to 6) and no deterioration in performance occurred. Conductivity values for the ruthenium distillates were slightly higher than those for the comparable rhodium distillates.

Testing of rhodium continued using rhodium black dusted onto mullite pellets (3.32 mg catalyst/gram of pellet) to obtain a more effective loading. An untreated catalyst bed was used in the parallel furnace to obtain an unpyrolyzed reference condensate. Initial tests were with synthetic urine for five days, and then human urine was substituted. It was thought desirable to activate the rhodium for two hours at 800°C in an oxygen atmosphere, although this procedure may not be necessary. The rhodium black was tested for six days with human urine, yielding essentially distilled water, after which time testing was continued with the additional requirement that the catalyst be kept in a nitrogen (inert) atmosphere when not is use so as to avoid possible excessive oxidation when cooling down at night. Testing continued for an additional six days with no deterioration in performance.

Rhodium was then plated onto stainless steel gauze (200 mesh; total weight of rhodium 0.159 grams). These screens were introduced into the mullite test tube; uncatalyzed stainless steel gauze was loaded into the parallel furnace for comparison. The catalyst was activated in oxygen at 800°C for two hours before use. Satisfactory operation was maintained for five days. It was found that with operating temperatures as low as 300°C employed contaminants could still be eliminated, although such low temperatures are not recommended for the breadboard unit until further test. Uncatalyzed condensate during these periods had a very obnoxious odor, high pH values, and gave a positive test for ammonium ion indicating that the rhodium was effective for purification. No deterioration of the rhodium-plated screens could be found following the five-day test.

Test data indicate that an oxygen input to the urine still of one std cc O_2/minute/astronaut should suffice to maintain catalytic activity at peak performance. The minimum oxygen requirements were not determined.

Breadboard Unit

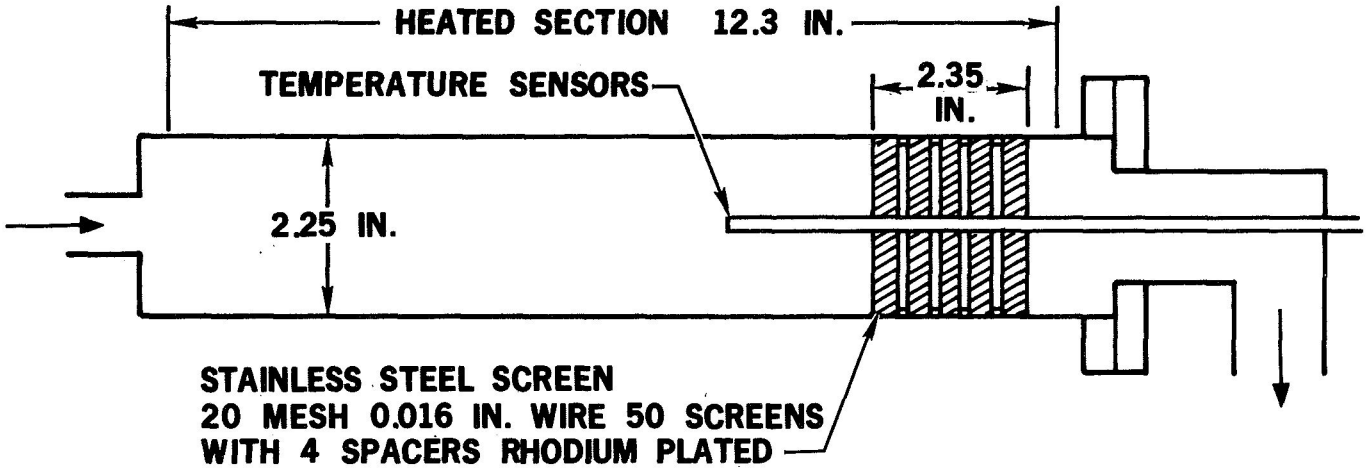
Upon satisfactory completion of the tests on rhodium-plated stainless steel screens, a reactor bed was designed for installation in the breadboard system. The bed was sized by scaling the test catalytic reactor, since no data were available to optimize bed size on the basis of space velocity and operating temperature.

Figure 3-26 shows a diagram and a photograph of the unit. The unit does not include a recuperator. In operation, the entire 2-1/4-in. tube is placed in a furnace which maintains the bed temperature at about 800°F. The front section of the tube serves as a preheater for the water vapor/air mixture flowing through the unit.

Previous to the accidental flooding of the breadboard system, the catalytic reactor performance was eminently satisfactory (see system test results). The reactor bed was very effective in oxidizing all contaminants and in producing water with absolutely no odor. Also, the reactor was equally effective in checking bacteria migration from the brine loop into the condenser during the entire duration of the tests.

Upon dismantling the breadboard reactor, examination of the screens revealed that flaking of the rhodium had occurred due to oxidation of the stainless steel carrier. The deterioration of the catalyst screens was limited to the area of the cylindrical screen bundle located at the bottom of the reactor. Corrosion at that location is believed to be due to the effect of liquid water left in the reactor for rather long periods (48 hours) after sterilization of the entire system with hot water. No catalyst damage is anticipated to occur under normal operation at high temperature.

PRESENT STATUS - VAPOR PYROLYSIS



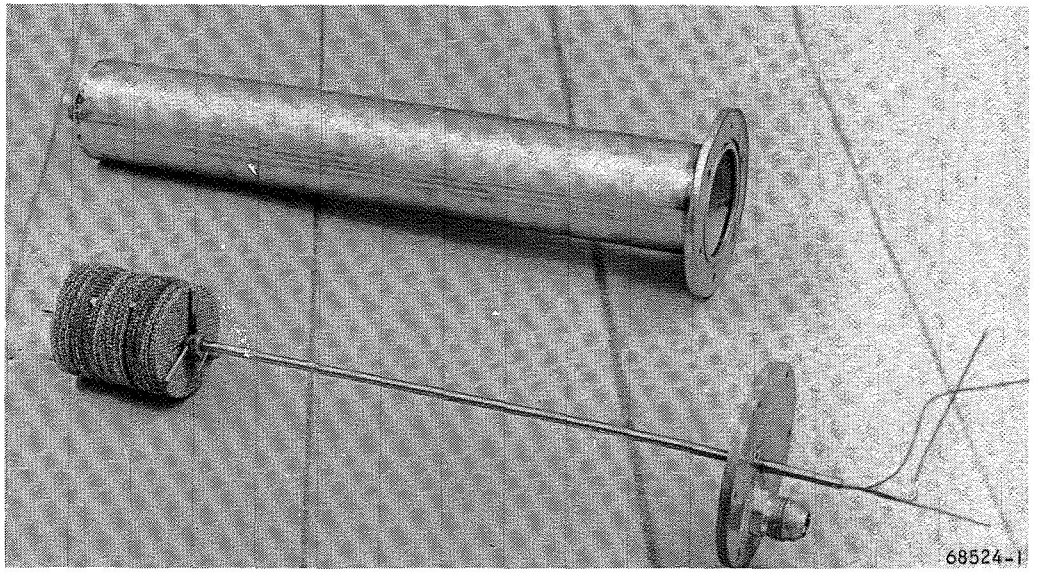


Figure 3-26. Breadboard Pyrolysis Unit

F-12466

Conclusions and Recommendations

Rhodium has been demonstrated to be very effective as a catalyst suitable for oxidizing trace contaminants produced in a low-temperature urine distillation process. More basic data are required to permit optimization of the reactor in order to:

(a) Minimize size, and heater power requirement of the unit

(b) Reduce pressure drop to a minimum thus alleviating the compressor design requirements

The data required involve catalyst testing in the existing rig with the modifications necessary for collection of the data. The test program will be aimed at establishing temperature-space velocity relationships using water vapor produced from urine brines at a temperature 10^0 to 15^0F higher than system distillation temperatures. These data will be used with appropriate safety factors to design the flight prototype unit.

Catalyst development tests have shown that about 1 std cc O_2/min/astronaut is adequate for contaminant oxidation. This represents only a very small quantity of oxygen, even over a period of a year (less than 1.5 lb/year/man), so that optimization of this parameter is not necessary. Note that the quantity of oxygen required by the process in terms of water recovered is about 0.015 percent; the effect of this amount of noncondensible on condenser performance does not appear to be significant.

In addition to catalyst performance data gathering, it is recommended that metals other than stainless steel be investigated as a suitable carrier for rhodium plating. As mentioned previously, oxidation of the substrate is not anticipated in normal operation because the phenomenon can only occur if liquid water is present; however, it appears safer to substitute some other material for the stainless steel screen. Candidate metals which warrant consideration include gold, gold plated stainless steel, silver, copper, tantalum, and titanium; others will be identified and evaluated. It is important to note here that the screen configuration is very attractive and should be retained for the flight prototype because it results in a very large catalyst surface and it is readily amenable to low pressure drop design.

LEVEL AND CONCENTRATION CONTROL SYSTEM

Introduction

The level and density controller provides two functions in the IWRS: (1) control of brine level in the liquid loop by addition of waste water and (2) removal of solids from the system by periodic dumping of a portion of the brine. The selection of a technique and of a system to accomplish these functions was a primary area of investigation under the IWRS program. The method of gaging and controlling the brine level and concentration has a very significant effect on system efficiency as will be shown later. Therefore, the effort in this task was oriented toward the development of a system which (1) minimized the performance requirements of other system elements, notably the compressor and condenser, and (2) provided a reliable gaging and control system.

1. Background

Early work on gaging and control systems for the brine loop established the requirements for a system which did not physically interface with the brine itself. This is primarily because (1) the brine contains large quantities of solids in suspension; therefore, secondary measurements, based on parameters other than density, are subject to significant errors, (2) the brine is abrasive and corrosive, and (3) any instrument physically located in the brine will tend to increase the possibility of solids deposition. After a survey of available approaches and feasibility testing of several candidate methods, a nucleonic technique was selected for development under the IWRS program.

During the Task A of NAS 9-8460, a prototype level and density control system was fabricated. This system was designed to (1) maintain the brine in the separators at a constant level, and (2) periodically dump brine at or near 50 percent concentration to remove solids. Essentially the level and concentration functions were performed independently and used the same monitoring technique. Both systems use low energy radiation sources (Americium 241) mounted on one side of the phase separator; the quantity of energy passing through the liquid contained in the separator and sensed by Geiger-Mueller tubes on the opposite side gives a measurement of the liquid density. In the case of the level controller the source and the sensor are placed at an angle to the surface of the liquid so that exposure of the source to the detector increases as the level of the liquid drops in the separator. Figures 3-27 and 3-28 show the location of the sources and sensors on the separator. Reference is made to AiResearch Report 69-5470 (Task A of NAS 9-8460) for details on the operation of the system.

Operation of these controls in the previous phase of the program demonstrated that the nucleonic technique for level and density control in the brine loop was very satisfactory. Early tests of the first breadboard in the present phase of the IWRS program confirmed these findings. During these runs the level controller performed as anticipated; however, some difficulties were experienced due to instability of the density controller. This was

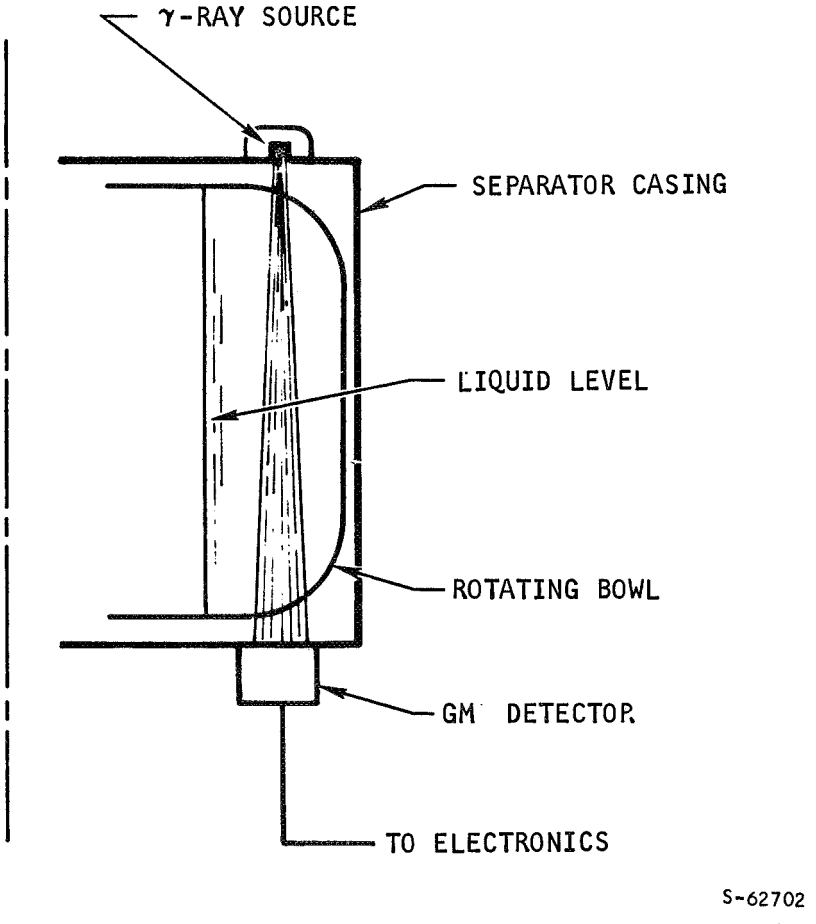
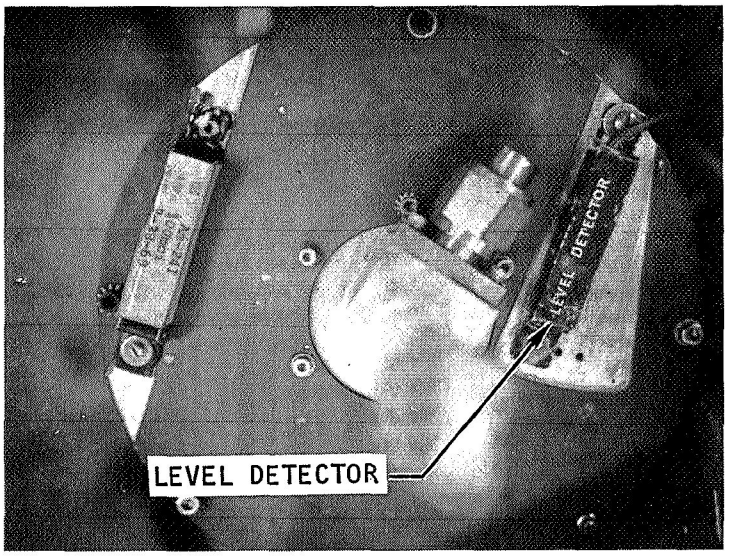
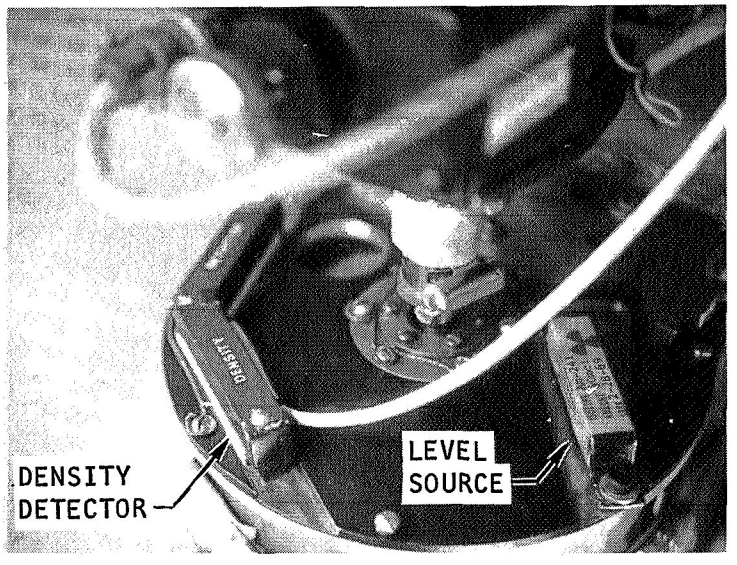


Figure 3-27. Location of Source and Detector on Separator



TOP OF SEPARATOR



F-12832

BOTTOM OF SEPARATOR

Figure 3-28. Detector and Source Placement

attributed to the electronic circuitry rather than to the source-sensor arrangement or the basic measurement technique.

2. Scope of the Present Programs

Initial work under the current contracts was concerned with improving the stability of the electronic circuitry associated with density control. System and component preliminary design studies and tests revealed early in the current program that operation at constant level and constant concentration resulted in significant system and component penalties. Consequently, a semi-batch mode of operation was devised whereby both level and concentration were allowed to vary according to a predetermined schedule. This involved redesign of the control logic circuitry. These improvements were incorporated in the breadboard system and this task was completed satisfactorily. The new control method is believed to constitute a significant improvement in the operation of the system. Details of these activities are presented in the following paragraphs.

Control System Requirements

In order to adequately define the requirements of a level and density control system, it is necessary to investigate the processing system and determine the effect of the level and density control parameters on system performance. This investigation was conducted, keeping in mind the primary importance of power and heat rejection of any system designed for use on a spacecraft.

The two primary power consuming elements of the system are the phase separator and the compressor, with the compressor being the most important. Because of this, a high-pressure ratio translates into a large system power penalty. Therefore, the level and density controls should be aimed at reducing the required compressor pressure ratio. The compressor pressure ratio necessary for operation is composed of several elements as follows:

(a) Pressure to overcome pressure-drop due to flow

(b) Pressure to overcome the temperature difference due to boiling point suppression of the brine as concentration increases

(c) Pressure to overcome the temperature rise of the brine loop as it picks up heat in the condenser

(d) Pressure to provide the temperature difference needed for heat transfer in the condenser

The first factor is dependent on system parameters which cannot be affected by the controls. The other elements are, however, directly related to the method of control.

The IWRS will be operated with the condenser pressure normally maintained at a constant level with a vacuum regulator. This parameter will be used in

the flight system to control the average water processing rate. Since condenser pressure is constant, any change which affects the pressure ratio from the separator to the condenser will result in a change in the pressure of the phase separator vapor cavity. Therefore, each of the aforementioned factors can be discussed in terms of their effect on separator pressure.

The pressure rise necessary to overcome boiling point suppression as the brine concentration increases is plotted in Figure 3-29. As shown, operation at 50 percent concentration results in a significant reduction in separator pressure, and thus an increase is required in pressure ratio by comparison with operation at lower concentrations (assuming constant water processing rate).

As the brine flows through the condenser, it is heated by the condensing water; the temperature rise of the brine in the condenser is significant. Since the vapor in the condenser is controlled at a constant pressure, the heat transfer process in the heater-condenser is bound by the constant temperature of the condensing water. At high concentration, the heat capacity of the brine is reduced due to reduced flow (caused by increase in viscosity) and reduced specific heat capacity. Thus, at high concentrations, the brine must be subjected to a higher change in temperature in the condenser for a given water processing rate. This effect is illustrated in Figure 3-30, showing brine temperature change required for 1.0 lb/hr water processing rate vs concentration.

The plot was prepared for a constant brine flow of 157 lb/hr and only reflects the drop in brine specific heat as concentration increases. The effect of this temperature rise can be realized by reference to Figure 3-29, showing the change in separator pressure corresponding to a given change in temperature.

The heat transfer process in the heat exchanger is almost totally governed by the brine heat transfer coefficient. Figure 3-20 shows the effect of concentration on this coefficient for the breadboard heat exchanger. A coefficient of 150 Btu/hr ^{0}F ft^{2} necessitates a difference of approximately 11^{0}F between the condensing vapor and the average brine temperature for a 1 lb/hr recovery rate. This high temperature difference at high brine concentration also results in a lowering of the separator pressure and an increase in required pressure ratio at high brine concentrations.

The three effects described above, are summarized in Table 3-9, showing the total pressure ratio requirement of the breadboard system at 20 percent and 50 percent concentrations. The contribution to this total from each of the above sources is shown in terms of temperature differences.

The data of Table 3-9 assumes a constant brine flow rate of 157 lb/hr in both cases. At high brine concentration the liquid loop pressure drop will increase considerably because of viscosity increase. This will require that the system separator speed be increased from 1800 rpm at 20 percent to 3000 rpm at 50 percent. The net effect is an increase in separator power of about 60 watts and also a severe liquid entrainment problem at the separator.

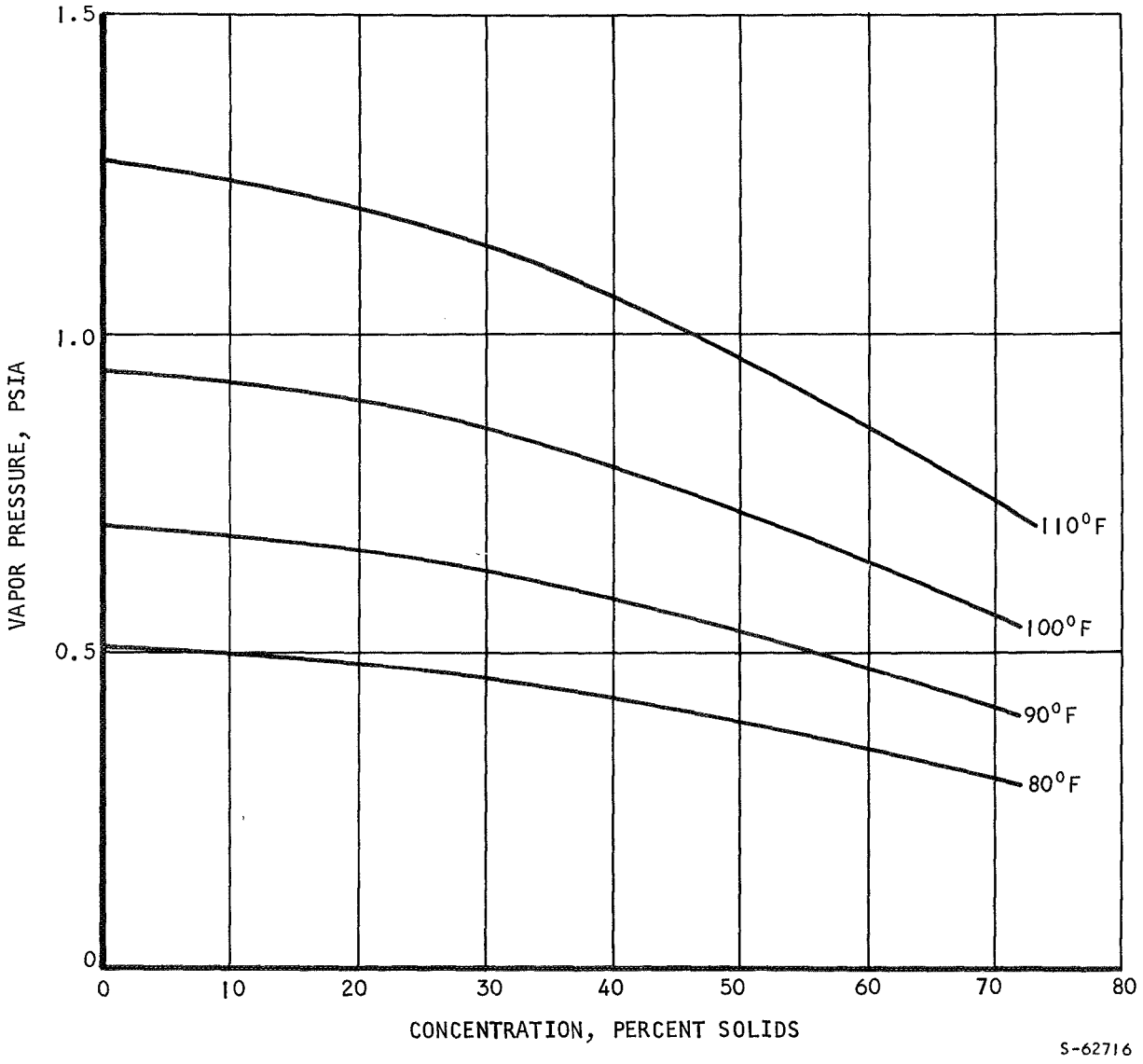


Figure 3-29. Vapor Pressure of Brine

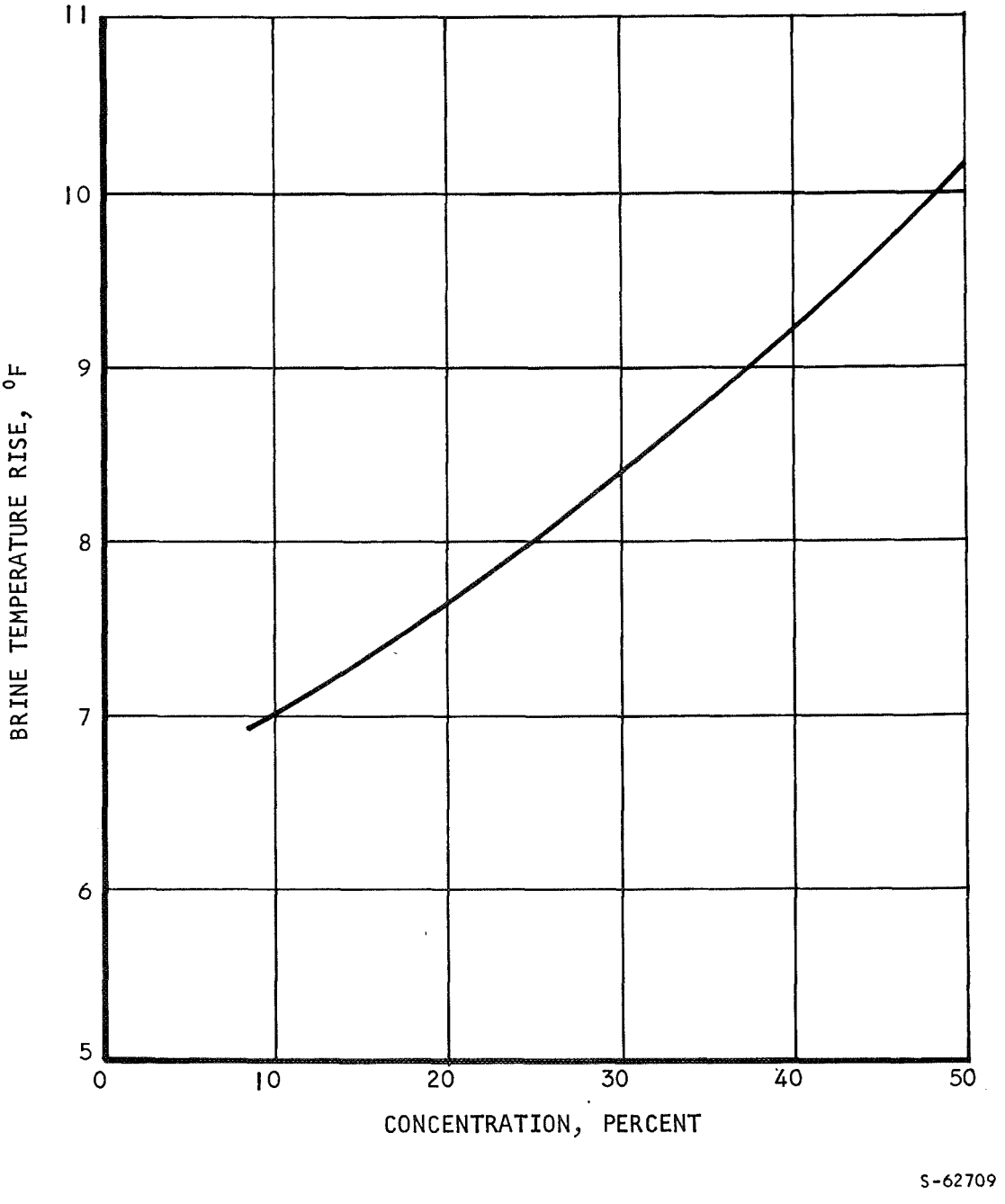


Figure 3-30. Brine Temperature Rise vs Concentration

TABLE 3-9

EFFECT OF BRINE CONCENTRATION ON
COMPRESSOR PRESSURE RATIO

Parameter	20 Percent Solids	50 Percent Solids
Water processing rate, lb/hr	1.0	1.0
Brine flow rate, lb/hr	157	157
Total pressure ratio	1.64	2.51
Saturation Temperature in condenser	116°F	116°F
ΔT for heat transfer	6°F	11°F
Brine temperature rise	7°F	10°F
Separator temperature	103°F	95°F
Separator pressure	0.977 psia	0.638 psia
Vapor pressure of water at separator temperature	1.04	0.841

Preceding discussions have demonstrated the desirability of operating the system at low concentration. However, high water recovery effectiveness requires that brine dump occur at high concentration. This apparent contradiction in requirements can be resolved by operation of the level and concentration controls in a semi-bath manner as illustrated in Figure 3-31.

Computer analyses were conducted to estimate system performance at 17, 25 and 50 percent concentration. Linear interpolation was used in the plot of Figure 3-31. The average water production rate over the entire 4.25 hr cycle is estimated to be 1.29 lb/hr which exceeds slightly the specification requirements. If the system were to be operated at constant level and constant concentration (50 percent) the water production rate would be only 0.84 lb/hr as shown in Figure 3-31.

Initially the liquid loop will be filled with urine; as vapor is drawn from the loop concentration will increase since the liquid content of the loop will be maintained constant by addition of urine. Cyclic repetitive semi-batch operation will start when the concentration of the brine reaches 17 percent. The sequence of events is as follows (see Figure 3-31):

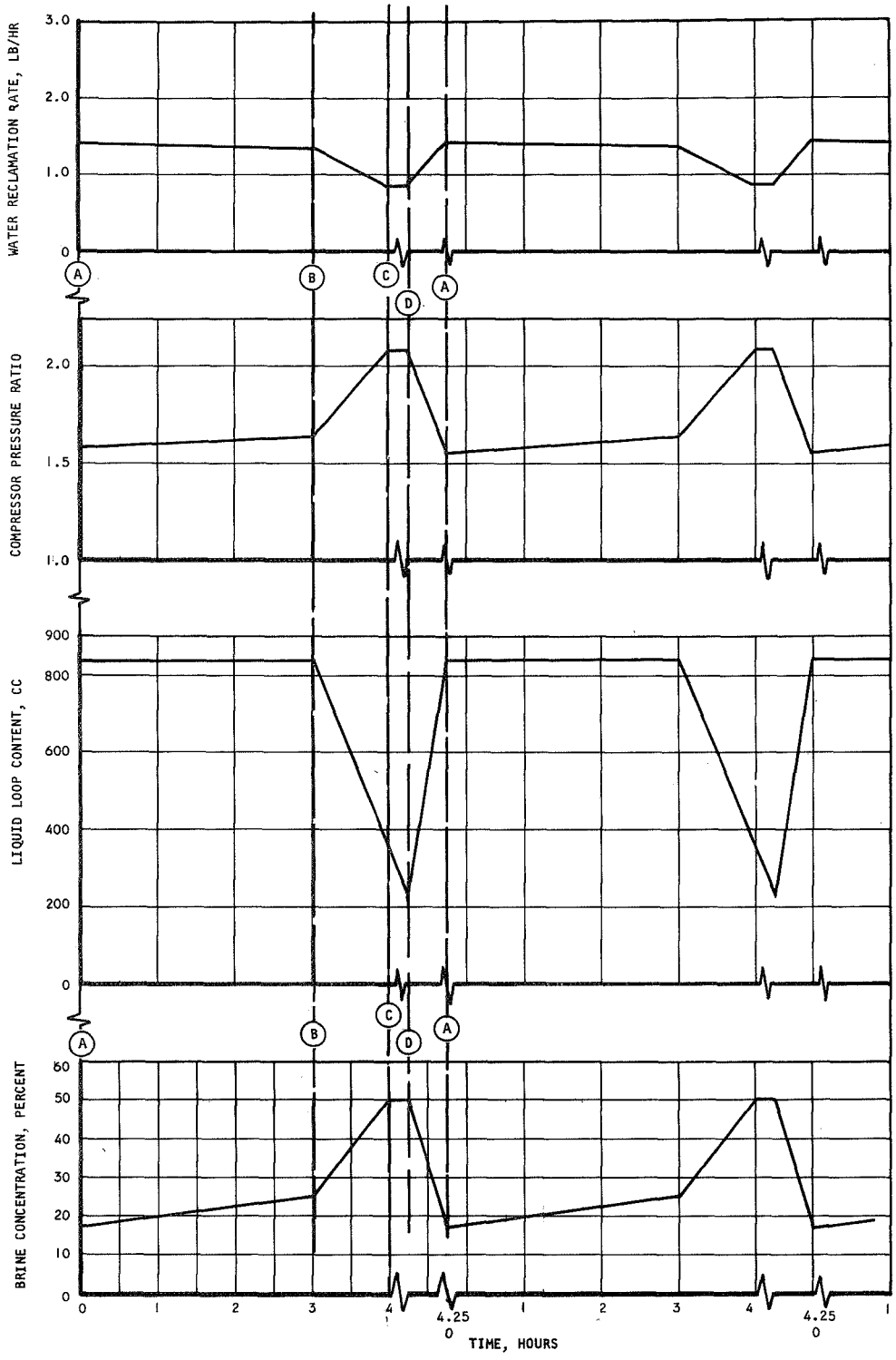


Figure 3-31. Semi-Batch Operational Sequence

A: Liquid level in loop: 830 cc

Brine concentration: 17 percent

Processing rate: 1.41 lb/hr

Compressor pressure ratio: 1.57

Brine flow rate: 201.3 lb/hr

A-B: Liquid level is maintained at 830 cc by addition of urine

Processing rate drops as concentration increases

Compressor pressure ratio increases

4.13 lb of water processed in 3.01 hr as concentration increases from 17 to 25 percent

B: Liquid level in separator: 830 cc

Brine concentration: 25 percent

Processing rate: 1.33 lb/hr

Compressor pressure ratio: 1.62

Brine flow rate: 201.8 lb/hr

B-C: Urine feed valve is closed during this period

Level drops as water is evaporated and concentration increases

Compressor pressure ratio increases sharply

1.01 lb of water processed as concentration increases to 50 percent

C: Liquid level in separator: 370 cc

Brine concentration: 50 percent

Processing rate: 0.84 lb/hr

Compressor pressure ratio: 2.07

Brine flow rate: 178.1 lb/hr

C-D: Dump valve opens and brine is discharged from the loop

Dump period: 5 min

D: Dump valve closes

Liquid level in separator: 225 cc

Brine concentration: 50 percent

Processing rate: 0.84 lb/hr

Compressor pressure ratio: 2.075

Brine flow rate: 178.1 lb/hr

D-A: Feed valve opens to raise the separator level to 750 cc

Feed period: 10 min

A: Operation starts again

Accuracy Considerations

To achieve the control functions described above, the sensors must provide the logic system with the correct count rate corresponding to the switch points of the operational sequence. The gamma rays from the source pass through several metallic interfaces as well as the fluid before reaching the sensor. An adequate count interval must be provided to achieve the required accuracy. The absorption of gamma rays can be represented by

$$I = Io \ (e)^{-\Sigma \rho \mu x} \qquad (1)$$

where I = beam intensity at counter

Io = beam intensity at source

ρ = material density

x = material thickness

μ = material mass absorption coefficient

Σ = summation over all the elements between the source and the sensor. Since all of the elements of the system are fixed as the prime density changes except the brine itself, this yields

$$I/Io = e^{-(C+\rho_B \mu_B x_B)} \qquad (2)$$

where C = constant

B : subscript referring to the brine

If Io is defined to be the intensity without any fluid in the bowl, then equation (2) becomes

$$I/Io = e^{-(\rho_B \mu_B x_B)} \qquad (3)$$

and μ_B can be determined from the data given in Figure 3-32. With x_B = 3.0 in., the mass absorption coefficient for the brine is 1.13 gm/cm. With this number, and the count rate with no fluid in the system, the count rate at any density can be determined. With the separator as configured for the upgraded breadboard, the count rate at 30 percent solids was 250 cps. From the geometry of the system, it is desired to have the density switch points at approximately 30 percent and 50 percent concentration for the breadboard system.

Since the emission of a photon is a random process, the accuracy of a count rate is determined by "random walk" statistics and is proportional to the square root of the number of counts. Thus, the accuracy of the count to within one standard deviation is given in percent as

$\frac{\sqrt{N}}{N}(100)$ where N is the total number of counts. To measure the 50 percent point to within ±1 percent,

$$\frac{\sqrt{N}}{N} = 0.01$$

or

$$N = 10^4 \text{ counts}$$

with a count rate of approximately 200 cps at 50 percent concentration, the time required to count is approximately 50 seconds. A similar analysis for the level control indicates a count interval of approximately 90 seconds at the high level to obtain 1 percent accuracy in level reading. However, since it is not important to maintain this level within that accuracy, a count interval for level measurement of several minutes would suffice. Source strength is therefore a determining factor in count accumulation time. Because it is desirable to utilize as small a source as is practical, the control system was configured to provide the required accuracy with sources of 10 and 30 millicurie for the level and density controls, respectively.

System Development

On the basis of the system requirements discussed above, an attempt was made to demonstrate the primary characteristics of this control system during

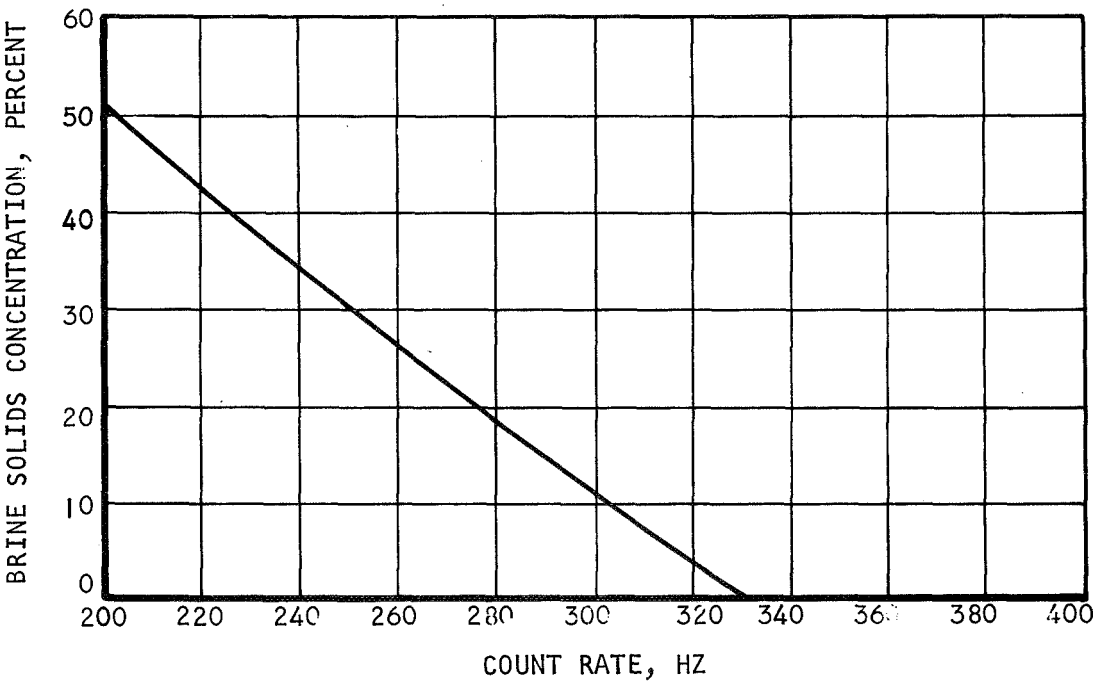


Figure 3-32. Density Control Calibration

the upgraded breadboard testing. The system was modified to provide the interconnecting logic necessary. The control in the final configuration used in the breadboard test is described below.

Control System Description

The function of the control system is to determine the level and density of the fluid present in the separator assembly, compare these inputs with preset levels, and to open or close solenoid valves as necessary to maintain the inputs at these preset levels. The Geiger tubes used as detectors produce large pulses when excited by gamma radiation. The pulse train from each tube is then converted to pulses of uniform amplitude by the input pulse conditioning circuits. The relations between the pulse count rates and density and level are shown in Figures 3-32 and 3-33.

In the case of the level control system, these pulses are first integrated to produce an analog level proportional to pulse rate. This analog level is then compared to high and low set points by analog comparators. The outputs of these comparators are connected to lamp drivers and buffer stages. The lamps give a visual indication of fluid level, while the buffers deliver logic signals to the valve logic panel. In the valve logic panel this fluid level analog information is compared with density information and with pre-programmed action data. The output of this comparison is routed to valve drivers which open or close solenoid valves to achieve control action.

In the case of density control, the conditioned pulses from the Geiger tubes are applied to a pulse totalizer which counts the pulses for a fixed time interval. At the end of the sample period the number stored in the totalizer is compared with preset limits by a digital comparator. The output of the digital comparator drives indicator lamps and provides logic signals to the valve logic panel. In the valve logic panel this density information is routed to the same pre-programmed comparator as the level information. The outputs of the programmed comparator turn on valve drivers which open or close feed and dump solenoid valves to achieve control action. Manual feed and dump switches are also incorporated in the valve logic panel. A functional diagram of this system is shown in Figure 3-34.

Geiger-Mueller tubes are used to determine level and density information. The Geiger tubes respond to incident radiation level. The incident radiation level reaching the tubes from the radioactive sources is dependent upon the amount of radiation absorbed by the fluid which is present between the source and the Geiger tubes. The output pulse frequencies of the tubes are then related to fluid level and density by the curves shown in Figures 3-32 and 3-33. The pulse train from either tube is coupled through a capacitor-diode network to the base of a transistor, which is connected with a series resistor across the 5 v logic supply. The output pulse trains are therefore of constant amplitude with varying frequencies.

The integrator circuit is used here as a frequency-to-analog converter. The input pulse train is fed to a one-shot circuit with a fixed output pulse width. This output pulse of constant width is then integrated by a capacitor-resistor network to produce a dc level which is proportional to frequency only,

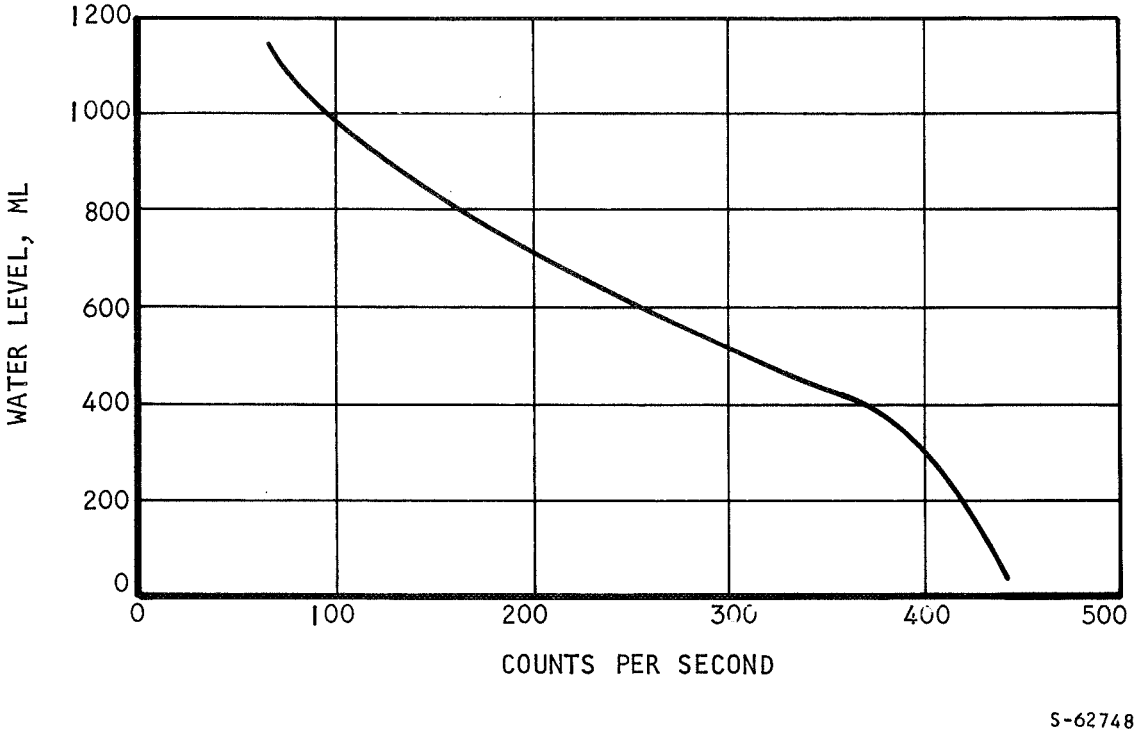


Figure 3-33. Level Control Calibration

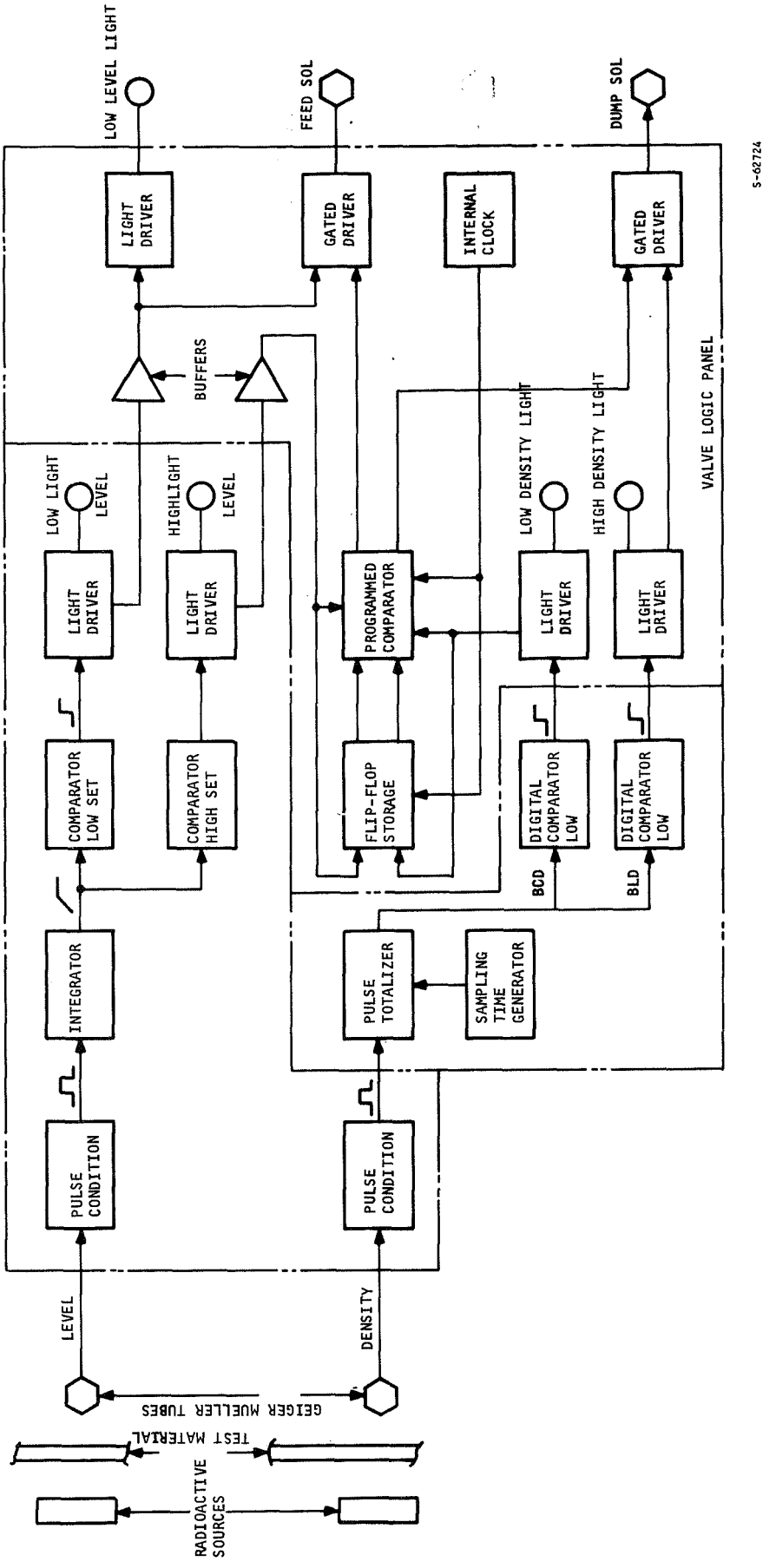


Figure 3-34. Control System Schematic

since the one-shot eliminates any amplitude effect. The dc level varies between zero and 10 v for zero to 1000 Hz input frequency.

The analog comparators accept the zero-to-10-v signal from the integrator and compare it to an adjustable reference voltage. The reference voltage is derived from a Zener diode and applied across a potentiometer. The output of the potentiometer is applied to the base of one transistor of a differential amplifier. The zero-to-10-v signal is applied to the other base. Because of the gain of this differential amplifier, the output transistor associated with the highest input signal saturates, giving a step output determined by the polarity of the difference signal at the transistor bases. The analog comparators provide the level information necessary for system control.

The light driver stages accept zero-to-5-v logic signals and provide the current and voltage amplification necessary to turn on panel lights. The light drivers also provide a zero-to-5-v output signal which is applied to the following stages. The current and voltage amplification are achieved by a switched current source driving two transistors for maximum current gain.

The gated drivers are similar to the light drivers except that an input gating feature has been added. The drivers are on if any input to them is low (0 volts). The gated drivers also have a manual input gate which allows the test operator to manually open or close the feed and dump solenoid valves.

A circuit is provided to accept a logic signal pulse train, totalize (count) these pulses over a time interval, and reset and repeat this function at the end of each sample interval. The sample interval should be adjustable from 10 sec to 1 min giving total count values ranging from 25,500 counts to 153,000 counts.

The digital comparator accepts the output of the pulse totalizer and compares this with preset values dialed in a front-panel-mounted thumbwheel switch. The comparator operates at the end of each sample period. The outputs from the comparator drive lamp drivers and provide logic signals to the valve logic panel. These signals enter the flip-flop storage and programmed comparator stages of the valve logic panel. The digital comparator determines the density information necessary for system control.

These stages are the heart of the valve logic panel. They accept level and density information, compare it to previous information and to programmed information, and give outputs necessary to provide control of the system according to a preset run profile.

During most of the system operation, with the density below the low set point and the separator level between the high and low set points, the system operates to feed urine in a pulsed mode. This pulse rate was approximately 4 pulses/min. This rate was used previously in this system and it was not changed. The rate can be reduced by a very large amount (on the order of 1 pulse every 5 to 10 min), without affecting the system operation noticeably.

System Test

Initially, the separator and the control system were designed for operation at essentially constant level and constant density. In this phase of the program the semi-batch scheme described previously was adopted for the IWRS. In terms of control system design, the semi-batch type of operation imposes requirements for accurate level and density measurement over a wide range of levels and densities combinations (see Figure 3-31).

Calibration of the density sensor prior to the 5-day test indicated that the density measurement was very much a function of the liquid level in the separator bowl. This is due primarily to the shape of the separator bowl and the placement of the density source and detector. The radiation beam from the density source becomes exposed to the vapor at low liquid level so that the density detector count rate increases rapidly (at constant density) as the separator liquid level drops below about 400 cc. Referring to Figure 3-31, the density gamma-ray beam travelled partially through vapor during operation from B to C and from C to D.

As a result the major portion of the 5-day test was devoted to the adjustment of the control feed and dump switch points to achieve a compromise in the operation of the semi-batch scheme. This, however, meant that the breadboard system would not meet the full range of operation described previously. In attempting to adjust the dump valve switch over count rate control and the overall control logic to accommodate the peculiarities of the density detector, difficulties were encountered which, resulted in automatic brine dump at concentration much lower (20-30 percent) than the desired value of 50 percent. Because of this and also because considerable quantities of brine were removed from the system for sampling purposes the average brine concentration was about 27 percent throughout the 5-day test (instead of the 20 percent design point).

Toward the end of the 5-day test settings were finally found, through trial and error, which appeared to more closely match the design switchover points and one complete automatic cycle was achieved. Brine dump then occured at an estimated concentration of 40 percent. This did, however, serve to demonstrate the soundness of the control technique.

Conclusions and Recommendations

The development work performed to date on the level and concentration controller has demonstrated the feasibility of the selected approach for the IWRS. This work, together with the system analysis, has also demonstrated that this system has a significant effect on operating efficiency and can be used to maximize that efficiency. Therefore, it is felt that the future efforts be directed toward refinement of this system to achieve prototype status. This refinement should be in two areas as follows:

(a) Design of the separator with the gaging provisions as a design requirement

(b) Refinement in design and packaging of the electronics

The first of these will ensure a stable and accurate fluid interface at each of the critical switch points in system operation. The second will enable extension of the range of the system to preclude the problems encountered in the breadboard test. Also, the system should be packaged as a single unit rather than two units as presently configured with a resulting savings in system volume, weight, and power.

PURITY MONITORING AND CONTROL

Introduction

The deliberations of the Space Science Board (SSB) have emphasized that a major problem in long duration space flight is that of quality standards for reclaimed water. As pointed out by the SSB, quality standards for water for spacecraft use require stringent control, especially in regard to biological quality. Drinking water supplies aboard the spacecraft will be regenerated from urine, wash water, and humidity condensate. The water reclamation system must ensure a safe potable water supply in regard to physical, chemical, and biological requirements. Sterility, or essential sterility, should be maintained throughout the entire regeneration unit. These stringent requirements pose a number of problems in the evaluation not only of ground-based systems, but also of systems to be used on board the spacecraft.

On board, the water recovery system must be reliable and easily monitored for chemical and biological contaminants. The SSB-suggested biological quality requirement is a maximum of 10 viable micro-organisms per milliliter of water; therefore, some positive form of sterilization is required after the phase separation step of the reclamation process. However, the concept of "essential sterility" throughout the system may not be a realistic approach to these various problems, as outgrowth in the holding tanks, resulting in large numbers of micro-organisms in a relatively short period of time, is a possibility not easily dismissed.

The objective of this task was to examine the requirements of the system in terms of potability monitoring equipment and to select instruments and techniques adequate to assure that the crew be accurately informed at all times of the quality of the potable water supply.

As a design goal, the water recovery system is required to produce reclaimed water that meets the potability requirements of Document MSC-SPEC-C35 entitled "Water, High Purity (Potable) and Sampling Procedure Specification for." As a minimum, the water purity levels must be higher than recommended by the SSB ad hoc panel on spacecraft water quality.

The results of the investigations conducted are summarized in the following paragraphs.

Chemical Composition Control

The statement of work specified that the following parameters be monitored as a minimum: pH, conductivity, turbidity, and specific ions (to be determined as part of the study). These parameters determine only the physical and chemical characteristics of the water. Other parameters affecting water quality levels are color, odor, chemical oxygen demand (COD), total solids, and microbiological content.

To assure adequate system monitoring and to permit timely repair action it is desirable to monitor the relative value of each parameter and its rate of change. By using the rate of change information, the crew will be warned early of any operational deterioration so that adequate safeguard action can be undertaken to minimize contamination of the reclaimed water portion of the circuit, including the potable water storage tanks.

The following discussions are concerned with the identification of parameters which form the purity monitoring criteria for the system:

1. Turbidity, Color, Odor and Taste

Of the physical characteristics such as color, taste, odor, and turbidity, only the last can be satisfactorily monitored on a continuous basis. As defined, turbidity is a measure of the optical property of the reclaimed water and is indicative of the number of suspended particles, of both chemical and biological nature in the water. To measure turbidity, light is transmitted through a water sample. Due to the suspended particles, light is scattered and absorbed and the scattered light, or the inline transmitted light, is detected by a light receiver such as a photocell. The resulting signal from the photocell is then compared with a reference to determine if the turbidity of the water is excessive.

There are two basic types of photoelectric turbidimeter; the nephelometer and the absorptometer. The nephelometer turbidimeter detects the intensity of light scattered from the particles and is insensitive to high turbidity levels in terms of the Jackson unit. The absorptometer directly measures the light passing through a water sample and is insensitive to low turbidities. Because of the relatively high turbidity level allowed for the water (5 Jackson units), only the absorptometer unit is acceptable for IWRS application.

In the present state-of-art, bacteria monitoring of the IWRS requires that a sample be drawn from the reclaimed water tank for bacteriological analysis. This sample could be used to visually monitor turbidity through a sight glass. In the IWRS, the porous plate employed for phase separation in the heater-condenser has a nominal pore size of 0.5 micron, so that it serves as a very effective filter in the reclaimed water stream. The presence of undissolved particles in the reclaimed water stream in quantities sufficient to result in objectionable turbidity level is therefore very unlikely. If it were to occur, other potability monitoring equipment such as the conductivity meter and the inorganic material monitor would most likely detect compounds whose presence would make the water unacceptable. At this time it is not recommended that a turbidity meter be incorporated in the system. It is also recommended that odor and taste be monitored as part of the reclaimed water test procedure at the tank level before the reclaimed water is pumped to the spacecraft supply.

2. pH

According to the literature, pH alone is not a good indicator of water quality. The reason for this is that in some samples of water reclaimed from urine, small amounts of contaminants of organic and inorganic nature were found at a pH level above 9. Yet, appreciable amounts of contaminants were found in some samples where the potability analysis indicated the pH was within acceptable limits. Although pH cannot be completely relied upon to determine relative quantities of impurities in the reclaimed water, its usefulness as an indicator of liquid acidity or alkalinity is apparent. Any abnormal change in pH would indicate a malfunction in the system or insufficient pretreatment of the urine supply to the system.

At this time a pH sensor developed by Beckman Instruments for zero-g space application appears to be suitable for the water recovery system. This instrument was incorporated on the breadboard system and found to operate satisfactorily. This device consists of a sensor-amplifier assembly and an amplifier. The sensor portion employs a miniature glass pH electrode and a reference electrode. The pH electrode consists of an internally sealed tube with a metallic electrode and an external tube containing electrolyte which contacts the electrode. The reference electrode is a silver-silver chloride element which is in contact with a reference solution of saturated potassium chloride. Basically, pH measurement is accomplished by measuring the potential developed between the reclaimed water sample and the potassium chloride solution. In operation, due to a positive head, there is a small continuous flow of the potassium chloride solution from the reference electrode into the reclaimed water stream. This quantity of potassium chloride is negligible (0.02 cc/day).

Beckman literature indicates the preamplifier assembly is about 4 in. long by 1.5 in. in diameter. A unit similar to that used on the breadboard system was qualified for the Apollo program. It is recommended that such a unit be incorporated in the flight prototype system. Such a pH sensor will detect small quantities of ammonia which constitutes one of the major potential water contaminants in event of system malfunction.

3. Conductivity

One of the best parameters for assessing water quality is electrical conductivity or specific conductance. Conductivity is a measure of the concentration of ionic species in solution; therefore, it mainly establishes the inorganic content of the reclaimed water.

MSC-SPEC-C35 specifies an allowable total solids content of 500 mg/liter. Using NaCl as the reference solid, 1000 mg/liter of NaCl at 25°C corresponds to a conductivity of about 1700 microohms/cm. Thus, on a proportional basis the equivalent allowable conductivity for the system is 850 microohms/cm corresponding to the allowed total solids of 500 mg/liter.

Conductivity information is most meaningful when the related pH of the water is between 6 and 9. Beyond these limits, conductivity is greatly influenced by the hydrogen and hydroxyl ions as compared to the other ions present in the water. As a result, conductivity at high and low pH does not accurately reflect the relative concentration of dissolved ionic compounds.

Conventional instruments available to monitor conductivity typically consist of a conductivity sensor and a monitor unit. The conductivity sensor employs two electrodes. During operation, low frequency ac voltage from a bridge circuit within the monitor unit is applied to the electrodes. The monitor unit is calibrated at zero baseline when the ionic concentration is minimum corresponding to minimum electrical conduction between the electrodes. As the ionic concentration increases, the resistance of the water between the electrodes decreases causing an increase in electrical conductance.

Fouling of the electrodes is one of the main disadvantages of the electrode-type of conductivity instrument, which is required to operate continuously over a long period of time. This disadvantage is practically eliminated with the Beckman toroidal-type conductivity analyzer, which operates at high audio frequencies without any electrodes in solution. Cylindrical metallic contacts are installed at each end of a nonmetallic, nonconducting tube and the contacts are wired to another toroid pickup to complete the circuit. In addition to being insensitive to fouling, the toroidal instrument has higher reliability, improved linearity, and lower power consumption than the conventional electrode-type conductivity instrument. On this basis, this type of instrument is recommended for IWRS.

Toroidal conductivity meters have been developed for commercial application, and the development of a flight prototype unit does not appear to be a problem.

4. Organic Monitoring Instrument

Knowledge of the organic content in the reclaimed water could provide valuable information when used and interpreted in conjunction with electrical conductivity information. To determine the organic content, parameters such as chemical oxygen demand (COD), carbon organics, total organic carbon (TOC), or dissolved organics can be monitored. However, procedures involved with these techniques require sampling and manipulation which are generally not compatible with space operations. Compact instruments have been developed for measuring dissolved organics. One such instrument, developed by the Aqua Test Corporation, is based on the ultraviolet radiation absorption of organic compounds. This ultraviolet radiation monitor, shown in Figure 3-35, was developed to measure relative amounts of organics likely to cause odors and

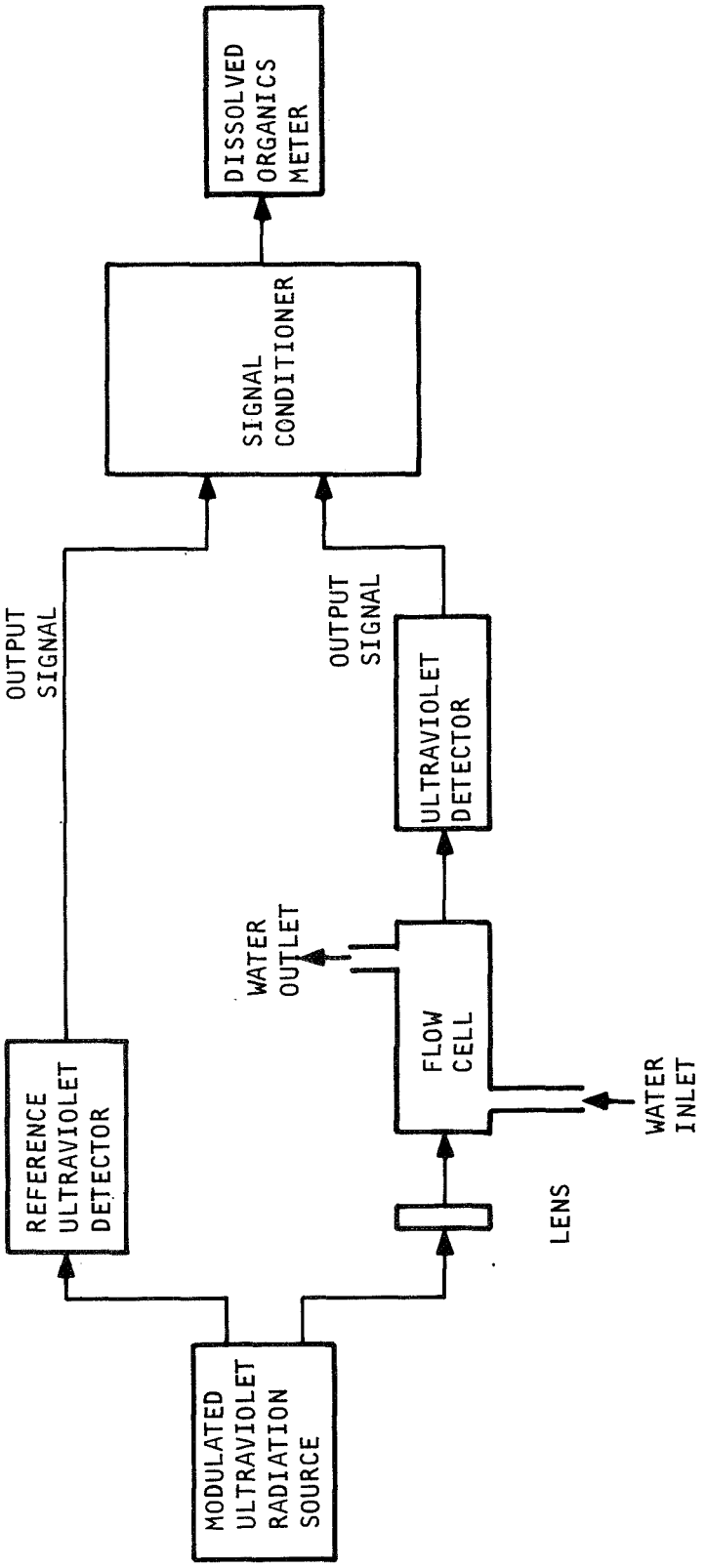


Figure 3-35. Aqua Test Water Quality Monitoring Arrangement

tastes in potable water. In the detection method, the output from the monitor is linear, with the absorption of ultraviolet radiation in the 254 millimicron wave length. The absorption, in turn, is proportional to the dissolved organic content in the water. For the best response, turbidity should be below the specified level. Until another suitable instrument becomes available for monitoring organics in the water, the method or instrument developed by Aqua Test appears desirable for the IWRS.

Bacteria Control and Sterilization

1. Reclaimed Water Sterility

The SSB has reviewed in detail the need for microbiological control of reclaimed water for human consumption. The SSB has suggested that the regenerated water be sterile, or essentially sterile; i.e., a maximum of 10 microorganisms per milliliter of water. To maintain this standard, positive sterilization must be maintained throughout the entire water recovery system (recovery-storage-delivery systems). Detection and monitoring of microbial contamination during space flight presents many problems. Sterilization of all components of the water regeneration system and the regenerated water also presents many unique problems.

The need to ensure sterility of the potable water is an obvious must. AiResearch does not agree with the SSB's criterion of "essential sterility." Although a count of 10 viable microorganisms per milliliter of potable water may be an acceptable standard, the possibility of microbial growth, through cross-feeding and a constant supply of nutrients into the water tanks, is an overriding possibility. The injestion of large numbers of microorganisms is not desirable; thus it is imperative that absolute sterility be maintained in the potable water tanks.

The SSB panel has suggested heat treatment, at least to pasteurization temperatures, as an acceptable method for sterilization at a point following the phase separation step of a distillation process. Normally, pasteurization is carried out at a temperature of 145° to 150°F for at least 30 minutes, or 161°F for at least 30 seconds.

Heat sterilization, as is true of most forms of sterilization, is dependent on several variables; e.g., temperature, time, physiological state of the cell (young, old, vegetative form, or spore), supporting menstruum, stability of the sterilizing agent in the supporting menstruum, etc. Not all micro-organisms are uniformly sensitive to heat treatment; therefore, the temperature used for sterilization must be high enough to kill not only vegetative forms but also spores. The percent and rate of kill will also depend on residence time at the desired sterilizing temperature, thus the higher the sterilizing temperature, the shorter the residence time required for complete kill. Pasteurization do not ensure 100-percent kill. Heat is

lethal to all forms of life; however, the power penalty for producing sufficiently high temperatures for sterility or "essential sterility" may be a deciding factor for using heat as the preferred method of sterilization. Sterilization of the regenerated water can be accomplished by other means, such as ultraviolet (UV) irradiation, mechanical filtering, and addition of biocidal agents to the water.

Sterilization with UV involves the immersion of a UV light source into the water supplies. The Barnstead Company manufactures such a unit which is placed into the water supply so that the UV rays reflect off the inner surfaces of the storage tank, thus permitting the maximum use of the irradiation. UV has poor penetration power and any dissolved solids will decrease the efficiency to kill. The major disadvantages lie in the power requirements, the effective life of the UV lamp (necessitating monitoring and occasional replacement of the lamp), and having practical application only in the reclaimed water holding tanks.

The use of mechanical filters placed at strategic points throughout the water recovery system is a possible means of maintaining the sterility of the recovered water after the phase separation stage. The primary drawback to this method is that filters of the pore size (0.2 μ) necessary for the retention of micro-organisms are easily clogged. Unless the filters are treated with a biocidal or biostatic agent, organisms may accumulate and grow on their surfaces (biocidal compounds in the water stream could serve the same purpose). The growth of organisms could have several deleterious effects. For example, the filters could break, releasing large quantities of accumulated micro-organisms into the water supply. Also, filters of such small pore size can cause severe pressure drop, especially when clogged. An additional disadvantage to the use of filters is that they must be removed and replaced, giving rise to possible contamination during the procedure.

A variety of chemical agents, such as chlorine and iodine, is available for disinfection of water. The use of such bacteriocidal or bacteriostatic compounds in the water supply would have to be carefully evaluated from the standpoint of possible toxic effects to the crew and possible corrosion of the water recovery system before use on a long term flight system. The major disadvantage of any liquid or powdered chemical disinfectant is the necessity of monitoring its concentration in the water and automatically dispensing it into the water, along with some means to ensure that thorough mixing of the agent will occur.

Ionized silver is a possibility as it is bacteriocidal and considered physiologically harmless to man. The concentrations of ionized silver required for killing of microorganisms is within Public Health standards for human consumption (50 to 100 ppm). Studies using electrolytically generated silver ions have shown a kill of over 99 percent in less than one hour for a variety of micro-organisms; however, more work is needed as little is known about the effects of ionized silver on viruses, fungal spores, and mycoplasma.

In the IWRS, pasteurization is accomplished upstream of the heater-condenser in the high temperature catalytic oxidizer, which is maintained at 800°F. This unit constitutes a very efficient barrier against bacteria migration from the brine loop into the potable water supply. Its use as a sterilizer requires that all equipment and lines downstream of the reactor be sterile at the start of operation and that positive means be provided to prevent bacteria migration from the reclaimed water storage tanks. System tests reported later have demonstrated the effectiveness of the catalytic reactor as a bacteria barrier. The approach recommended for the IWRS is depicted in Figure 3-36. The reactor assures sterile conditions in the condenser; a silver ion generator in the reclaimed water line provides a positive means of maintaining sterility downstream of the condenser, and bacteria filters check the migration of bacteria from the collection tank and the water recycling line.

Contamination of the water tap or spigot is not considered a serious problem. Although contamination of the potable water tank may occur when water is being drawn off or when the tap is not in use, the likelihood of this occurring is considered minimal for the following reasons: (1) turning on the water tap would mechanically flush out any micro-organisms trapped in the water spout; (2) although micro-organisms can gain access through the valve(s) into the water supply tank, the presence of ionized silver in the potable water will kill these organisms. If bacterial or fungal spores are considered a serious problem, mechanical filters (pore size, 0.22 μ) can be placed upstream of the water spout just ahead of the point of delivery into the spout itself. These filters would retain any vegetative cells as well as spores. Such filters could be routinely changed without contamination of the tank itself during the changing process.

2. Bacteria Detection and Monitoring

The complexity of solutions to the problems of detection and control of water-borne micro-organisms is a major problem area in any water regeneration system, especially if detection is to be rapid and simple, as it must be for space vehicle application. Standard methods for determining microbial counts in water require 18 to 24 hours for bacteria and longer for fungi. Detection of viruses is virtually impossible. Detection of very low counts, such as less than one micro-organism per milliliter, by standard dilution and plating methods presents additional problems as a rather large sample would be required to get meaningful data. As indicated, standard techniques require time for outgrowth of the initial population. During this time, a failure in the selected control method could result in a potentially serious problem as detection of a failure or malfunction would not be evident for 18 to 24 hours. Also, the use of standard dilution and plating methods for detection of water-borne micro-organisms not only requires a portable laboratory (incubator,

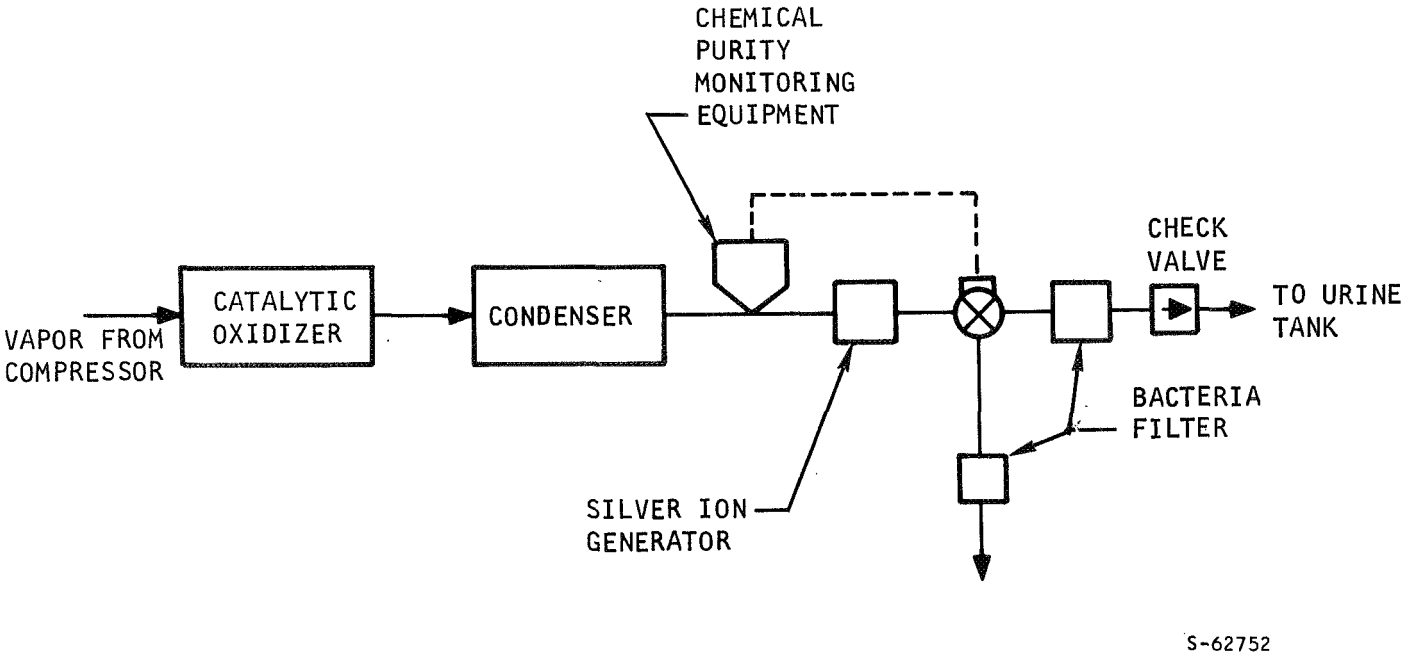


Figure 3-36. Recommended Bacteria Control Approach

growth medium, glassware, etc.), equipment not generally in keeping with space conservation, and extra work loads on the crew, but also creates the problem of disposal of any contaminated media. Thus, a method for on-line detection and monitoring of microbial contamination in the potable water supply system is very desirable. Several ways in which this problem may be approached are discussed below.

a. Particle Counters

Electronic particle counters, such as the Coulter counter of the Royco Model 340, are able to discriminate size and numbers of particles in a liquid system. Figure 3-37 shows a typical particle detector arrangement, such as is used in the Coulter counter. The instrument is installed in a line parallel to the main water stream. The operation of this detector depends upon the non-conducting characteristics of living micro-organisms. When the micro-organisms pass through the orifice, which is constructed from a plate of nonconducting material, their presence momentarily upsets the electrical conductance between the two electrodes and causes a voltage pulse to appear. The magnitude of this pulse is proportional to the population density of the micro-organisms.

This instrument has the advantage of speed of response for particles in the general size range of interest; however, differentiation of cells from organic or inorganic debris is not possible. To obviate this disadvantage, a baseline micro-organisms population can be monitored and then the population can be recounted after the sample water is exposed to an environment favorable to bacteria growth. A comparison of the results will indicate the presence or absence of micro-organisms. The present goal is total absence of any viable micro-organisms. As apparent, this condition is met only when the baseline and recounted micro-organism populations are the same.

General Electric studies using the Coulter counter indicate that the time required to analyze reclaimed water for micro-organism can be as low as 4 hours in comparison to a minimum of 18 hours required by the standard method of analysis.

b. Staining Methods

Staining methods for detection of micro-organisms have been under study for a number of years. One procedure consists of collecting suspended particles onto a porous tape and then staining these particles with a dye such as ethyl violet or crystal violet. The specimen is then treated with acetone or ethanol to remove excess dye and to remove dye from inorganic debris. The tape is then read-out automatically. A more sensitive type of staining method utilized I^{131} or a fluorescent dye conjugated antibody. The reaction of this antibody with specific bacteria (antigen) can be detected. Problems associated with this system are non-specific reactions as well as the necessity of presupposing knowledge of the exact kinds of micro-organisms which will be in the water system.

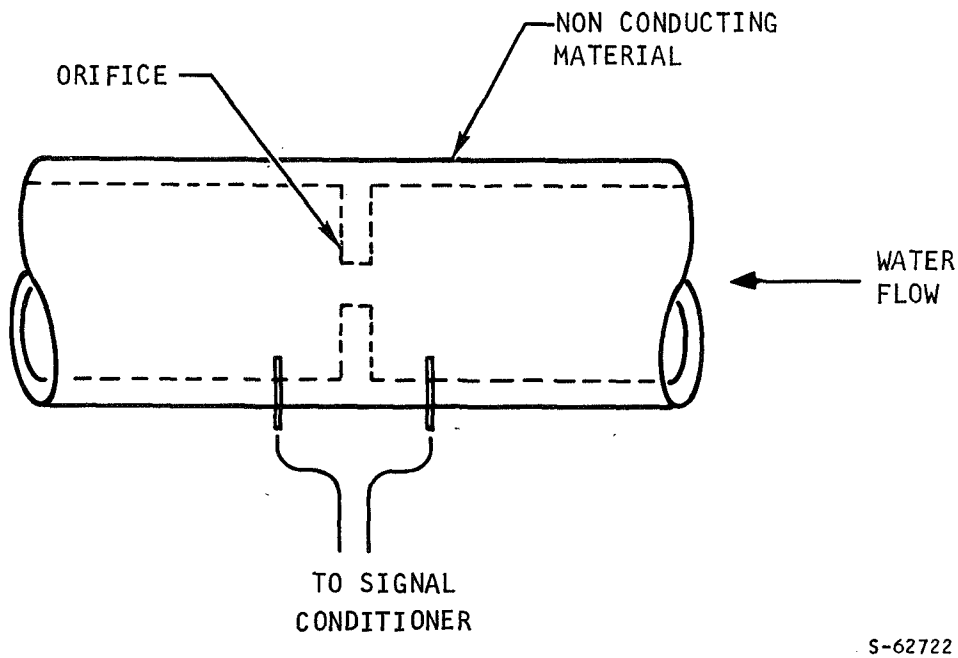


Figure 3-37. Micro-Organism/Particle Detector

c. Enzyme Methods

Enzyme methods for detection of micro-organisms are extremely sensitive. Two approaches are possible: (1) an anzyme assay of a known component of these organisms; e.g., adenosinetriphosphate detection utilizing a bioluminescent assay, and (2) the addition of some compound which will be acted upon by enzymes within the organisms. The first method requires a firefly bioluminescent assay for adenosinetriphosphate (ATP), which is common to all forms of life and is present in both living and dead cells. This assay is based upon the following reaction that produces light in firefly tails.

ATP + luciferin + luciferase + oxygen = light

If any of these components are missing, there can be no production of light. The peak light intensity from the reaction is directly proportional to the ATP quantity which is in turn proportional mainly to the live micro-organisms in the water sample.

Instrumentation for monitoring the bioluminescent light was developed by the North American Rockwell Corporation. Additional studies are required to determine the performance characteristics of this instrument and to upgrade its status for installation on a flight system. Another method of detection is based upon the oxidation reduction reactions of living cells, utilizing tetrazolium salts which are reduced to a colored precipitate; i.e., formazan.

d. Comparison of Approaches

No satisfactory techniques for on-line bacteria monitoring have been developed to date. The approach which appears to be the best is the electronic particle counter mentioned above. As discussed previously, no particles are anticipated downstream of the condenser separator plate, which acts as a very fine filter. Although the instrument is not specific to bacteria, such an instrument could be used in conjunction with the conductivity monitor and the organic content monitor to detect bacteria.

To establish confidence to this type of apparatus it is recommended that a Coulter counter be installed on the IWRS for evaluation in the next phase of the program. Pending long term testing of the device and its effectiveness as a specific bacteria detector for the IWRS, it is not recommended for the prototype system.

The method recommended invòlves the use of two reclaimed water tanks; while one if being filled, the other is isolated and on hold while a sample taken from it is being checked for bacteria content using the Coulter counter with injection of growth media in the test sample.

Urine Storage Vessel

Human urine is a excellent growth medium for many types of micro-organisms. Normal urine may be sterile or may contain up to 1,000 organisms per milliliter. The following organisms are commonly found in normal urine: staphylococci (coagulase-negative), diptheroid bacilli, coliform bacilli, enterococci, proteus species, alpha and beta hemolytic streptococci, saprophytic yeasts, and bacillus

species. Infected or pathologic urine may contain additional groups: pseudomonas aeruqinosa, alcaligenes species, mina polymorpha, candida albicans, gonococci, salnomella and shigella species, mycocbacterium tuberculosis and hemophilus species.

Previous studies on urine holding tanks conducted at AiResearch have shown that within 24 hours the microbial count may be greater than 10^8 organisms per milliliter. The daily addition of fresh urine to the holding tank ensures a fresh supply of nutrients to the organisms already present, as well as additional micro-organisms. Large populations of micro-organisms in the urine storage vessel is a potential hazard. As indicated above, urine can support the growth of many types of micro-organisms, some of which may be pathogenic, while some, although not considered pathogenic, may produce disease under given conditions. Although effective containment of these microbial populations may be achieved, bacterial debris, in the form of cell wall components, may contaminate the system and may be present in the product water. Such cell wall debris, if in high concentration, may result in pyrogenic effects.

From the above discussion, it is imperative that efforts be made to either sterilize the urine in the storage vessel or to effectively curb bacterial growth, thus holding the numbers of micro-organisms to an acceptable minimum. There are a number of possible solutions to this problem:

(a) Acid can be added to the urine to lower it to a pH of 1 to 2. Most bacteria and fungi will not grow under these conditions.

(b) Chemical disinfectants can be added to the urine. There are many chemical disinfectants and sterilants available; however, a careful analysis of their efficiency in urine would have to be carried out. The usefulness of such chemical poisons must be considered in terms of their effectiveness in the presence of organic matter, the concentration required, the temperature and pH at which disinfection is carried out, the time required for disinfection, and the effective life of the disinfectant.

(c) The urine can be chilled to 2^0 to 4^0C, which will effectively slow down microbial growth; however, refrigeration will be costly in terms of power penalties.

(d) The urine can be sterilized with heat; however heating the urine to sterilizing temperature will affect its composition and will require a costly power input.

The solution recommended by NASA is to check the growth of bacteria in the urine tank by the use of the following additive:

H_2SO_4, 39.8 percent
CrO_3, 9.8 percent
$CuSO_4$, 3.1 percent
H_2O, 47.3 percent

This mixture has been used successfully in the past, and can easily be introduced in the urine tank through the urinal during the urinal flush cycle. About 0.004 lb of mixture/lb urine is recommended on the basis of previous work.

Brine Storage Vessel

Unchecked growth of micro-organisms in the brine tank is undesirable as it also serves as a potential source of microbial contaminants. However, the increase in concentration of solids in the brine may be an effective check on microbial growth. Studies conducted during the pilot plant runs of the IWRS have revealed two interesting points; (1) organisms isolated from the urine feed were also present in the brine and (2) increasing brine concentrations showed a concomitant decrease in the number of micro-organisms. This decrease may be due to a drop in water activity (the amount of free, unbound, water available for microbial growth has dropped to a value incompatible with metabolic activity) or may reflect a buildup either bacteriocidal or static, of toxic metabolites in the brine. Both factors may be operative. Data collected showed that as the solids in the brine attained a concentration greater than 50 percent, the numbers of organisms decreased by more than 99.9 percent.

Although the data in regard to checking microbial growth in the brine storage vessel are encouraging, some consideration should be given to a more positive form of sterilization. Chemical disinfectants and sterilants might be ineffective here due to the high concentrations of solids.

Initial Sterilization

Prior to the startup of the water recovery system, sterilization of the entire unit is necessary. The two approaches possible with respect to this problem are heat sterilization and gas sterilization.

Heat sterilization, using live stream, will effectively sterilize the entire system; this technique was used effectively on the breadboard system. A disadvantage to using either wet or dry heat would be the presence of any heat labile components. Also a stream generator using considerable power will be necessary.

Gas sterilization, using ethylene oxide as the sterilizing gas, is an excellent method. The time required for complete sterilization depends on the temperature and humidity of the system. Subsequent to such sterilization, the entire system should be flushed out with large quantities of sterile, distilled water.

Sterility testing is performed by asceptically collecting water from various points in the system. This water is then filtered through bacteria retaining filters which are then placed on a suitable growth medium.

Further investigations are required to determine the optimum approach to system sterilization.

Maintenance

Should a failure in any part of the water recovery system occur, necessitating opening the system and allowing possible contamination during repairs, some means must be provided for sterilizing the entire recovery system or, as a minimum, the portion of the system downstream of the catalytic reactor. Here again, studies are necessary to permit selection of the best technique.

Conclusions and Recommendations

From the above discussion, two major problem areas are evident: (1) sterilization of the water supplies including not only ensuring sterility of the product water but also maintenance of sterility along the entire water regeneration system; and (2) detection and monitoring of possible microbial contamination. The latter problem area is of extreme importance, as failure of the sterilization process at any point in the system may not be immediately evident. The detection systems used must be simple, accurate, and rapid so as to give the crew continual monitoring of the water supplies.

The method or methods used for sterilization must meet certain requirements, including broad spectrum of activity, minimal power requirement, no damage to the health and safety of the crew, no corrosive effects on the water regeneration system, and an easily monitored operation.

Considerations as to the number of allowable viable organisms per millimeter in the water supply are still open to question. The criteria of "essential sterility" may be relaxed in the future, when more information becomes available on man-microbe interactions in space environments. Changes in normal flora under space conditions may induce a heightened sensitivity to the intake of even low numbers of micro-organism. At this time, the lack of such data does not warrant this conclusion. It is essential, however, to ensure that no buildup of micro-organisms occurs within the water supplies, as ingestion of large numbers of micro-organisms may produce severe gastric upsets. Therefore, as stated above, the major problems are those of effectively and safely sterilizing the water and a rapid and accurate means of monitoring the potable water supplies for viable micro-organisms. It should be noted that accumulation of non-viable cells in the water could be a potential hazard, e.g, gram-negative bacterial endotoxins may product gastric upsets and may also be pyrogenic.

Scrutiny of the approaches discussed for detection and monitoring of the water supplies in regard to microbial contamination suggests that very few of these methods would be practical. Enzyme assays, antigen-antibody systems, and oxidation reduction reactions require carefully controlled conditions for valid results and require time and laboratory space. On long-term missions, the lability of the reagents used, especially enzymes and antibody preparations, could be a limiting factor. At this time, the method of choice appears to be a particle counter used to check bacteria growth on a sample to which suitable nutrients have been added. Detection of low numbers of organisms by enzyme or immunological techniques would be a fortuitous event; however, with a particle counter, large volumes of water could be sampled in a relatively short period of time with accurate readout.

The following recommendations are made from the discussions given above:

(a) A thorough study should be made for controlling microbial growth in the urine storage vessels.

(b) Urine brine concentrates should be tested to determine if such concentrates are bactericidal or static. Available data would suggest a bactericidal property; however, additional study is necessary. (Also, can fungi thrive and grow in these brine concentrates?)

(c) To ensure sterility of the water recovery system downstream of the phase separation step, silver ion generators should be plumbed in at various critical points; i.e., downstream and upstream of valves which, if contaminated, may lead to contamination in the potable water storage vessels.

WATER COLLECTION, TRANSFER, AND STORAGE

Introduction

Preliminary design studies were conducted on all equipment concerned with collection, transfer, and storage of waste, reclaimed water, and brine, and preliminary specifications were prepared for each system component. These specifications are presented in Appendix A. The following paragraphs are concerned with overall water balance, based on data given in the work statement, and with sizing of the system tanks. Reference is made to Appendix A for the results of this task involving other components.

Water Balance

Figure 3-38 presents a summary of a daily water balance for the IWRS. The urine and the wash water recovery systems are considered together. The water balance was used to determine the spacecraft makeup potable water requirement and the storage tank capacity for the process liquids.

The water balance was based on the following requirements and guidelines:

Number of men	3
Drinking water and food preparation, lb/(man-day)	6.13
Water of oxidation, lb/(man-day)	0.66
Urine water (plus rinse water), lb/(man-day)	3.45 (2.00)
Fecal water, lb/(man-day)	0.25
Wash water, lb/(man-day)	5.45
Perspiration and respiration water, lb/(man-day)	3.09
Resupply interval, days	90
Nominal water recovery rate, lb/hr	1.0
Minimum water recovery efficiency, percent	95

The intermediate water recovery system is required to process 42.55 lb/day of waste liquid. Of the total, 9.27 lb/day is pretreated condensate; this water requires sterilization only by means of a silver ion generator before being transferred to the on-board potable water supply. The remainder (33.28 lb), which is processed by the two parallel water recovery systems, consists of 16.35 lb/day of wash water, 10.35 lb/day of urine water, 0.58 lb/day of wash water and urine solids, and 6 lb/day of urine rinse water.

The urine was considered to contain 5 percent solids and the wash water was considered to contain 0.18 percent solids. With these solids contents, the total

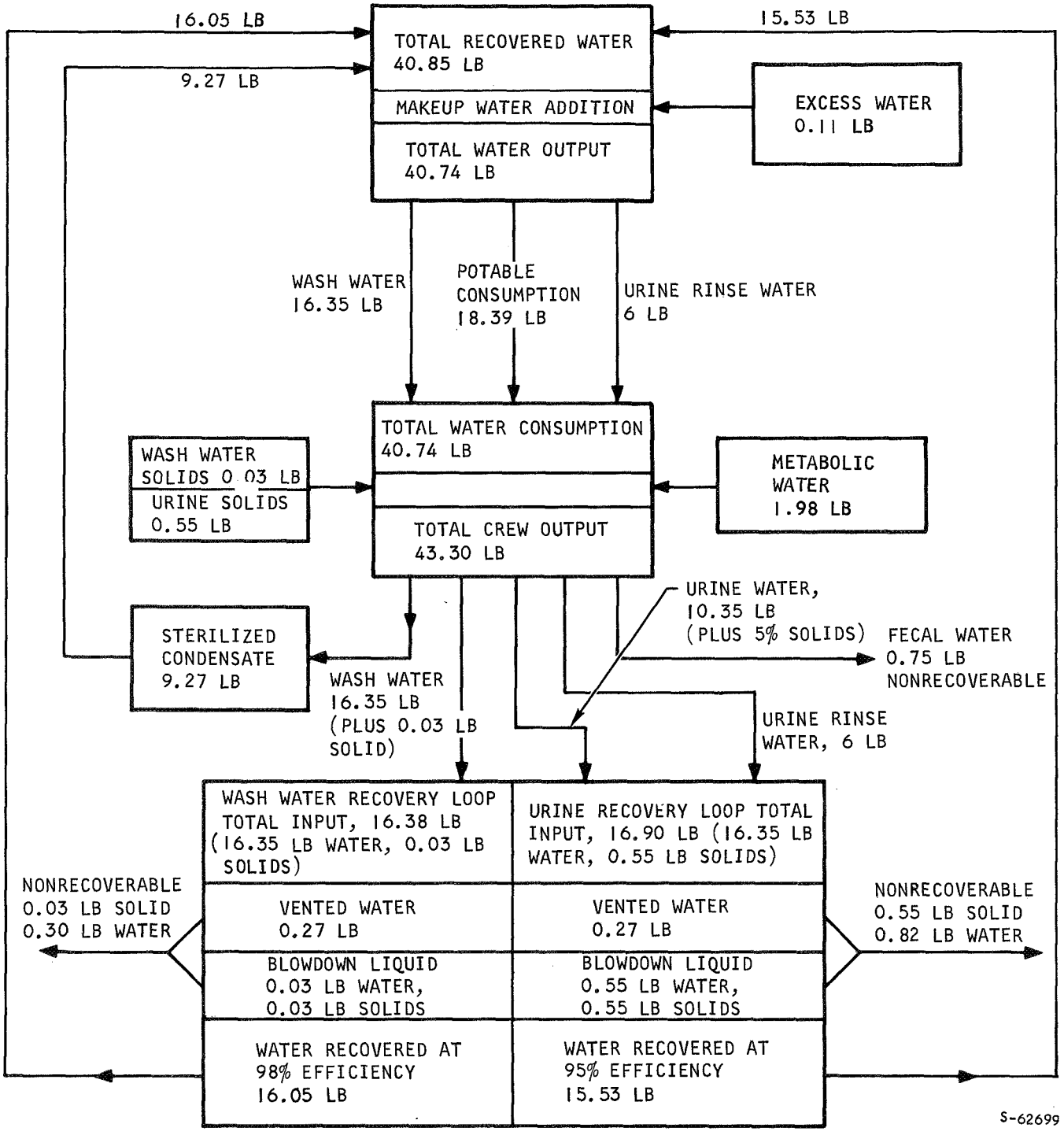


Figure 3-38. System Water Balance on a Daily Basis

input to the urine recovery and wash water recovery systems was calculated to be 16.90 lb/day and 16.38 lb/day, respectively. At a minimum urine recovery efficiency of 95 percent, a wash water recovery of 98 percent, and 100 percent condensate recovery a total of 40.85 lb of water should be reclaimed daily. The remaining 1.12 lb is lost in the brine waste transferred to the brine storage tank and in the gas vented overboard. Up to 0.54 lb/day of water loss through the recovery system vents is allowed.

Since the total recovered water is 40.33 lb/day (31.06 lb of reclaimed water and 9.27 lb of sterilized humidity condensate) while a total of 40.74 lb of water is consumed, there will be a daily shortage of 0.41 lb. Over a 90-day period this shortage will amount to 37 lb. To offset this condition, the spacecraft potable water supply (not part of the water recovery system) must include this amount of makeup water or the water must be provided by another subsystem within the spacecraft.

To effect a water balance without any makeup potable water, the wash water recovery system minimum efficiency must be 97.5 percent, corresponding to a vapor loss through the overboard vent of 0.38 lb/day. This appears reasonable since the urine recovery unit vent is 0.27 lb/day.

Calculations show that operating with a 1.5 psia vent pressure will result in a vented water loss of about 0.007 lb/hr or 0.168 lb/day. For this case, the concentration of noncondensible gases at the inlet of the heater-condenser in the urine recovery system is estimated at a maximum of 1 percent. At this vent rate, the recovery efficiency for the urine recovery system is 95.6 percent.

It is believed that the material balance of Figure 3-35 is conservative in terms of makeup water requirement. The 95-percent water recovery effectiveness from urine is within the IWRS capabilities; however, the wash water recovery unit should yield a higher overall efficiency because of the smaller quantity of solids in the wash water.

Waste Water Storage Tank Sizing

The urine (and wash water) storage tank is sized to hold a two-day supply of waste water. At the start of operation and in normal operation the tank content will correspond to a 1-day production of waste water. In this manner, should the waste water collection unit fail, the tank will maintain normal (or reduced) waste water flow to the reclamation unit, thus preventing shutdown. Similarly, should be reclamation unit fail, a one-day capacity is available while maintenance action is effected.

The urine (and wash water) collection tank required capacity is estimated at 37.6 lb (0.6 ft^3) including 15 percent ullage.

To assure expulsion, tank pressure will be maintained at 4.5 psia nominal by a bladder pressurized with nitrogen.

Assuming 5 daily micturations per man, 324 cc of urine is produced per micturation. This amount, plus 183 cc of rinse water, will enter the urine supply tank causing the expulsion pressure to increase. If the urine supply tank is initially half filled at 0.3 ft^3, the expulsion pressure will increase from 4.5 psia to 4.77 psia when the 507 cc of urine and rinse water is admitted to the tank. The relief pressure for the tank is about 7.0 psia nominal. Therefore, there will be no loss of nitrogen through pressure relief as a result of liquid inflow. Approximately 6 lb of liquid needs to be pumped into the tank at once to raise the pressure to the 7 psia relief level.

Reclaimed Water Tank Sizing

Two reclaimed water tanks are used in each water recovery unit. One tank is full and on hold while the other is being filled.

Once a tank is filled it is disconnected from the system and a sample of the recovered water is taken for bacteriological analysis. A minimum period of 18 hr is necessary to perform the bacteriological analysis. Therefore, each tank is sized for at least a one-day supply of reclaimed water. If, at the end of the 24-hr holding period, the water is found acceptable for consumption, the full tank is connected to the vehicle water supply, and the reclaimed water is transferred to the vehicle water storage system. If water is found unacceptable, then it is recycled for further processing. Alternately, an additive (bactericide) could be introduced into the tank to sterilize the water before transfer to the vehicle system.

While one tank in on hold, the second tank is connected to the IWRS and is being filled.

Returning the unacceptable water to the waste water tank for reprocessing will necessitate that the recovery rate be increased to reestablish tank content balance. Furthermore, the tank and lines of the contaminated tank will have to be sterilized. Sterilization of tank contents before transfer appears to be the most attractive solution. The optimum approach to tank sterilization requires further investigations.

The reclaimed water tank is designed with a 30-percent margin for overcapacity and ullage. Overcapacity is necessary if water is processed at a rate higher than design due to previous malfunction of the reclamation system. The reclaimed water tanks (2 per unit) have a total capacity of 20 lb of water corresponding to a volume of 0.327 ft^3.

Brine Storage Tank Sizing

The size of waste storage tanks for the urine and the wash water brines are not common due to the much smaller amount of waste brine output from the wash water recovery system. For the urine recovery system, the tank size was based on the storage requirement for urine brine, containing 50 percent solids. The urine brine waste tank will be replaced every 90 days. Therefore, 90-day capacity plus 15 percent for ullage were used to determine the

tank size. The usable tank size was calculated as 1.31 ft^3. Allowing for ullage, the design tank size is 1.51 ft^3.

It is estimated that at the end of 90 days, approximately 5.4 lb or 0.09 ft^3 of wash water waste brine will be collected. Adding 15 percent for ullage, the design tank size is 0.102 ft^3, which is slightly over 10 times smaller than the waste tank for the urine recovery system. A spherical tank of about 7.5 in. in dia could be used to store the wash water waste brine. An alternative would be to use a tank similar to the reclaimed water holding tank with its 0.26 ft^3 usable capacity. Replacement can be accomplished every 180 days instead of every 90 days. It is recommended that the two brine tanks be made identical so that the wash water reclamation system can serve as a backup to the urine reclamation unit in the event of a failure which cannot be repaired.

Pretreatment Fluid Tank Sizing

The pretreatment fluid used with the urinal rinse water is composed, by weight percent, of the following constituents:

H_2SO_4, 39.8 percent

CrO_3, 9.8 percent

$CuSO_4$, 3.1 percent

Water, 47.3 percent

About 0.004 lb of this mixture is needed for treatment of 1 lb of urine feed or wash water. Over a 90-day period, the estimated amount of pretreatment required is about 7 lb or 0.12 ft^3. A pressurized 8-in. spherical tank can be used to store the bactericide.

SECTION 4

SYSTEM DESIGN AND DEVELOPMENT

INTRODUCTION

The IWRS as defined in the NASA statement of work incorporates the following subsystems:

(a) Urine collection and transfer

(b) Urine storage and processing

(c) Wash water storage and processing

(d) Potable water collection and storage

Previous work conducted under company IR&D and NASA funds was entirely concerned with the water processing portion of the unit only. Early work was concerned with system conceptual design and with the development of a pilot plant to demonstrate system feasibility and assess major process parameters. Under that program the flash evaporation-vapor pyrolysis approach was found to be eminently satisfactory for the recovery of water from urine at high effectiveness.

The following phase of the program conducted under NASA sponsorship (Task A of contract NAS 9-8460) involved the development of breadboard hardware for incorporation in the pilot plant. That program culminated in system level tests which demonstrated the soundness of most hardware approaches selected. Recommendations were made for further breadboard system upgrading and testing.

The current programs (Task B of NAS 9-8460 and NAS 9-9981) were a continuation of the work done previously and were concerned with (1) the preliminary design of all the subsystems listed above, and (2) the upgrading of the breadboard test unit.

The preliminary design effort involved system analyses which resulted in the development of a performance prediction computer program for the water reclamation portion of the system. This program was employed to investigate the complex interactions between the system components and to define overall system operational parameters. Much of the analysis performed used the component/system test data as a basis.

Preliminary reliability analysis were conducted to identify single point failure which would endanger the system and the crew. Also maintainability guidelines were evolved. As a result of these reliability-maintainability studies, redundant components were defined and instrumention and other equipment were added to the system schematic for the purpose of fault detection and the performance of the maintenance tasks.

A system specification was prepared as part of this analytical effort. The specification also includes the urine collection and transfer subsystem. The description of the system evolved with its major characteristics are presented in Section 2. Performance optimization data are discussed in this section.

The system development effort was initially concerned with minor modifications of the breadboard unit used in the previous phase of the program to confirm test data and to elucidate certain system anomalies which were observed under Task A. Testing of this early breadboard system and analysis of the test data obtained indicated that this system was inadequate at this stage of the IWRS development. These tests identified the necessity for component level tests and also for a new breadboard unit. This upgraded unit demonstrated the capability of the system to produce water of a high quality. Also the performance capabilities of the system and of its components were successfully verified.

Much component data were gathered during the system level test program. These data are discussed in Section 3. It is important to note here that the interactions between the water processing system components are very complex and that component test data analysis can only be done in the light of the overall system operation. The system computer program is a very valuable tool in relating the performance characteristics of all these components and in resolving component interactions.

This report section summarizes system level activities. The development work conducted on the first breadboard system and on the upgraded unit is presented first. The results of the system optimization studies are also given.

EARLY BREADBOARD SYSTEM TESTS

Task A of Contract NAS 9-8460 concluded with a series of tests on the breadboard system developed by upgrading the IR&D pilot plant. The first efforts under Contract NAS 9-9981 were concerned with further upgrading of this unit and with system level testing. The objectives of this test program was to confirm the results of Task A and to investigate apparent anomalies identified under Task A. The test program was designed to provide additional component and system data to be used in system analysis and to provide guidance for component development efforts. Specifically the test program scope involved collection of the following data

(a) Detailed heat transfer data for evaluation of heat exchanger performance and overall system heat balance

(b) Visual observation of the spray patterns in the phase separator

(c) Operational verification of the level and density control system

(d) Data to support tradeoff studies of charcoal bed and catalytic oxidizer

(e) System performance with the diaphragm compressor

Test Setup

The early breadoard system test setup is shown schematically in Figure 4-1. Figure 4-2 is a photograph of the unit with the vane compressor. To accomplish the test program objectives listed above, the following modifications were incorporated in the breadboard unit.

(a) Installation of a flowmeter and additional temperature sensors in the brine loop to gather thermodynamic performance data for the heater-condenser and the entire recovery system

(b) Modification of the separator with the outer casing fabricated of of Plexiglass, so that the separation phenomenon could be observed visually

(c) Provisions for installation of the diaphragm compressor

(d) Repair of the electronic unit of the level of density control system

(e) Incorporation of a smaller charcoal bed

Test Results

With these modifications, the following series of tests were planned:

(a) Test of the system with the vane compressor with water to determine system thermal parameters

(b) Test of the system with water and the diaphragm compressor to determine system thermal parameters as a function of condenser vent pressure

(c) Test of the system with urine to determine separator performance, obtain additional thermal performance data, and evaluate the performance of the catalytic reactor and the charcoal bed

The initial test was conducted using the vane compressor. This was the first test in which the brine loop was instrumented for flow and temperature. The purpose of the test was to verify the instrumentation and to ascertain system thermal balance. The results of the test are summarized below, with the significant system level observations.

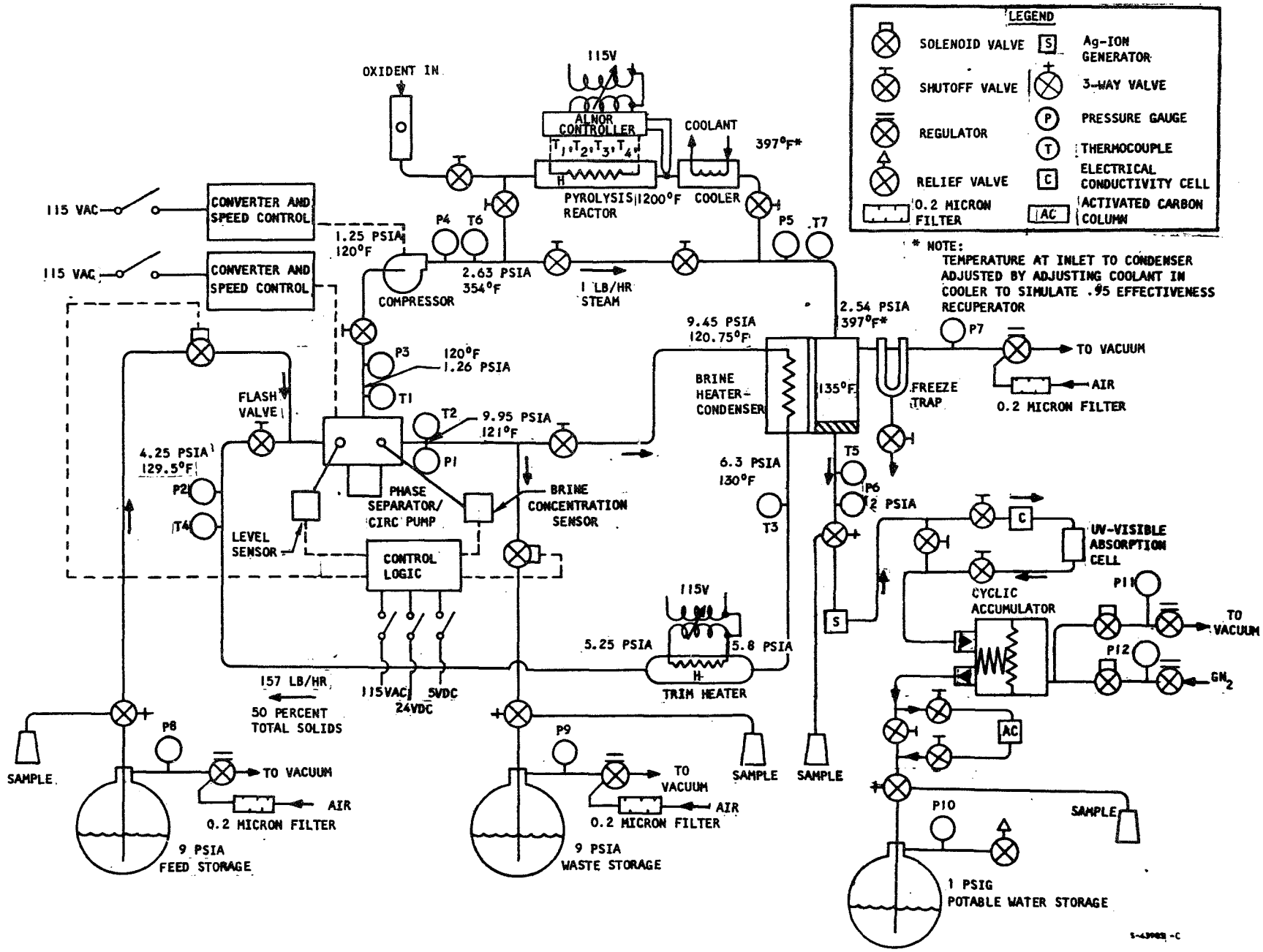


Figure 4-1. Early Breadboard Schematic

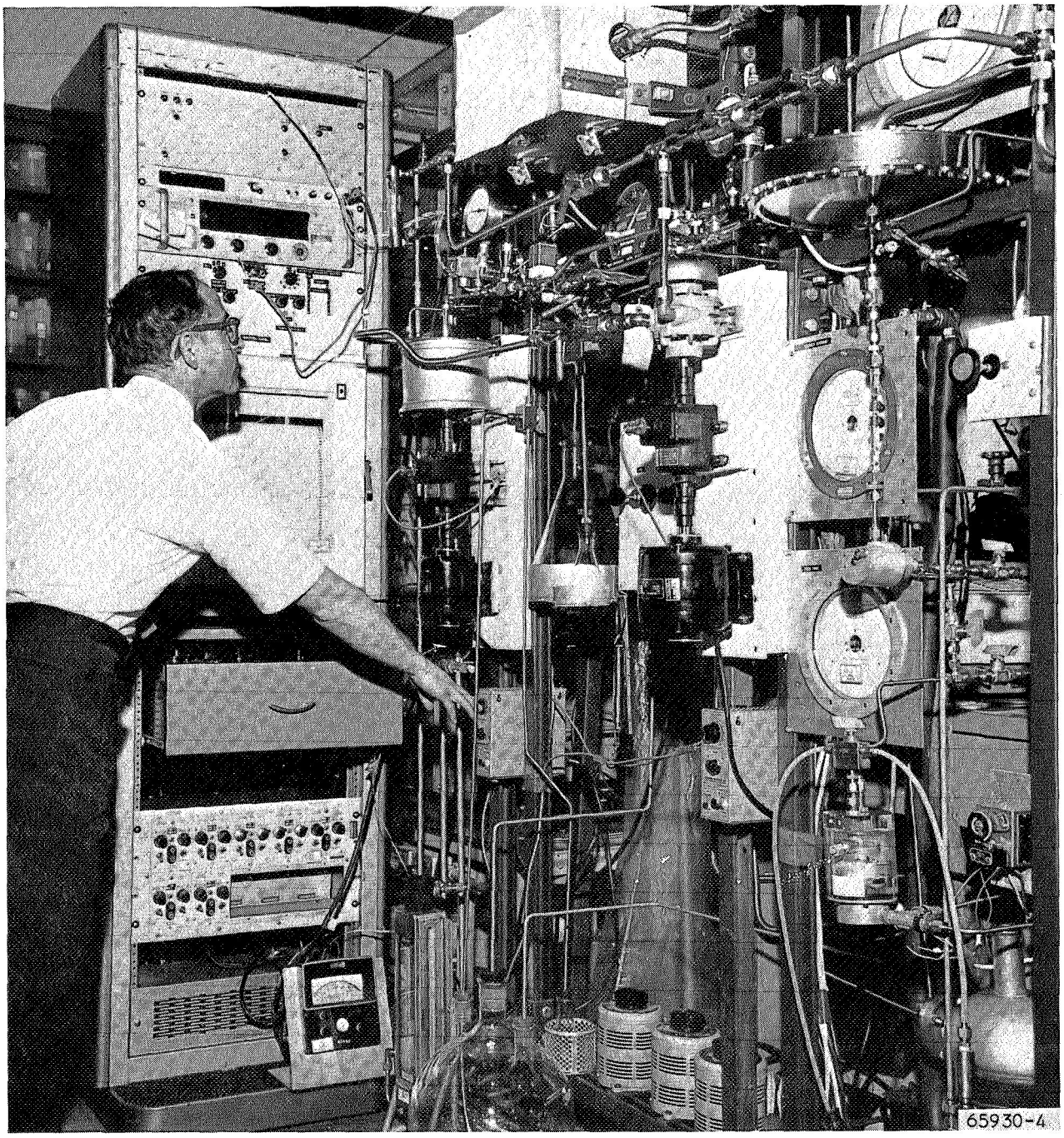


Figure 4-2. Early Breadboard Test Setup

(a) System achieved stable operation after five hours of operation

(b) A 45-watt heater in the brine loop was required to maintain stable operation

(c) Water production rate was 1.04 lb/hr

(d) Thermal balance in the brine loop was achieved

(e) Condenser inlet was at saturation temperature

These results verified the accuracy of the instrumentation in that a net system thermal balance was achieved. The fact that a trim heater was required in the brine loop and that the steam inlet to the condenser was saturated suggested that large quantities of thermal energy were lost to ambient through high leak in the lines and components. Also, in spite of the relatively high power consumption of the compressor (approximately 100 watts), there was sufficient heat loss in the vapor side of the system to cool the vapor to the condensing temperature before it entered the condenser. This test also indicated that the condenser performance was adequate, at least at low brine concentrations.

The diaphragm compressor was installed in the breadboard unit in place of the vane compressor, and breadboard testing was repeated. The results were similar to those of the first test with the exception that a heater set at approximately 25 watts was required on the compressor itself in order to prevent condensation in the compressor. This was due to the much larger area and lower power consumption (approximately 50 watts) of the diaphragm compressor. Figure 4-3 shows the results of this test. Significant results from this test are summarized below:

(a) 70 watts of trim heaters were required to sustain stable operation

(b) Water production rate was 1.03 lb/hr

(c) Thermal balance in the brine loop was achieved

(d) Condenser inlet was at saturation temperature

The results of this test confirmed the earlier conclusion of high system heat losses. For this test, approximately 30 percent of the energy added to the brine loop was lost through heat leak. Additional tests at other condenser pressures verified the heat loss as being proportional to system operating temperature level.

Following testing with water, urine was used to observe the operation of the separator, expand the system thermal performance data at higher brine concentrations, and obtain data on charcoal and catalyst bed performance. During these tests, several details of system and component performance became apparent, as discussed below.

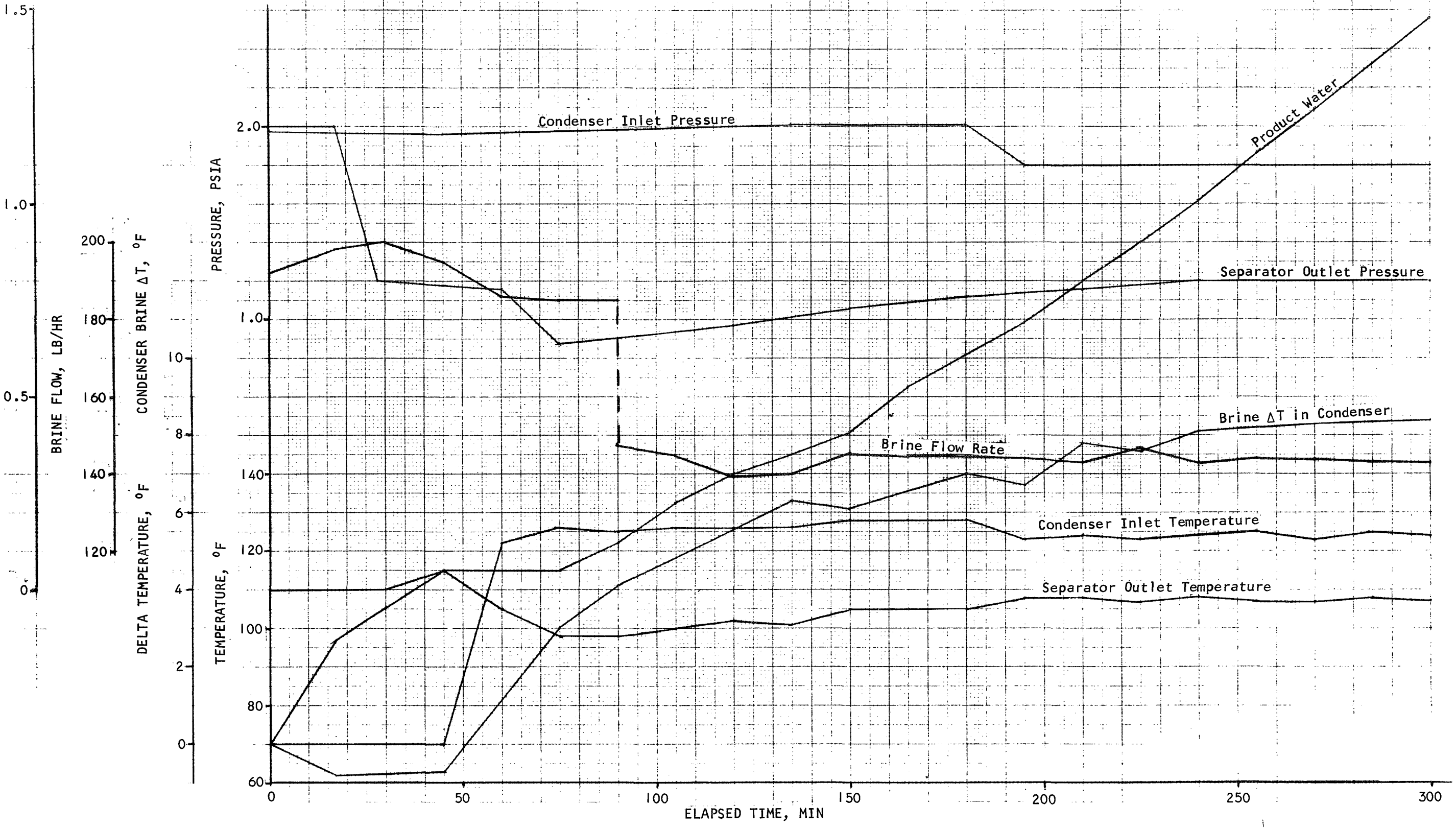


Figure 4-3. Early Breadboard Test Results

Visual observations of the separator during startup and steady state operation revealed two significant phenomena: (1) excessive foaming during startup and (2) direct spray impingement on the demistor. The foaming was attributed to gases, which were dissolved in the urine, coming out as the pressure of the urine was lowered. It was discovered that the amount of foaming could be controlled by the pumpdown rate of the system on startup. The direct impingement of spray on the demistor appeared to be the primary source of liquid phase carryover during steady-state operation of the system. Visual observations established the spray as originating from the pitot tube and the brine return tube. These observations suggested that baffling the separator could lead to a substantial reduction in steady-state liquid phase carryover. Baffle development was pursued at the component level (see Section 3).

The thermal performance of the system with urine was consistent with its performance with water. It should be noted however, that this was to be expected as the brine concentration during these tests did not exceed approximately 15 percent at any time. At this time, it was felt that further testing at higher concentrations would be of little value for the thermal performance analysis since the test rig introduced a substantial uncertainty into the results due to the high heat losses to ambient.

During operation with urine, an attempt was made to operate with the steam passing through the catalyst bed. After a short period of operation in this manner, it became apparent that the catalyst bed had insufficient flow capacity to allow operation at the desired flow rate of approximately 1 lb/hr. Because of this, and the recognition that any results of this test would be subject to significant error due to the large discrepancy in catalyst bed space velocities, catalyst bed testing was no longer pursued at the system level. Likewise, data on the absorption of contaminants in the charcoal bed was deferred until the separator carryover rates were reduced to a more reasonable level, allowing a more realistic evaluation.

During this period of testing, system analysis efforts had revealed the desirability of a semi-batch brine control system such as described in Section 3. Incorporation of this scheme would require modification of the density control logic unit. For this reason, the operation of the density control system was not fully tested. The level control system functioned satisfactorily during these tests.

Conclusions and Recommendations

Tests of the early breadboard system, together with concurrent system analyses, revealed that a new course of action should be taken if the objectives of the development program (NAS 9-9981) were to be met. Specifically the program should be reoriented to include the following tests:

(a) The breadboard system should be repackaged to overcome the problem of heat losses to ambient

(b) Component testing of the separator should be conducted to establish quantitative data on carryover and the effect of various baffle arrangements

(c) The level and density control system should be modified to incorporate the semi-batch control scheme

(d) The catalyst bed should be redesigned to reduce pressure drop

(e) Selected components (separator, condenser, and compressor) should be insulated to minimize heat losses

UPGRADED BREADOBARD SYSTEM TEST

As a result of the system tests conducted under Task A of Contract NAS 9-8460 and in the early part of Contract NAS 9-9981, the decision was made to upgrade the breadboard system to reduce heat losses from the lines and the major components and to minimize line pressure drops. Also, system data generated indicated the need for more comprehensive and more accurate instrumentation to enable better assessment of system and component thermodynamic performance. Finally, the existing test unit required major modifications for the installation of a new compressor and catalytic reactor.

Following limited component development test and concurrent system analyses, a new breadboard was assembled and instrumented. After a series of system shake-down runs to iron out component and instrumentation problems, the system was operated using water as the working fluid. Preliminary tests were then conducted with urine, prior to the start of a 5-day continuous run with urine.

The primary objectives of the breadboard tests were to establish

(a) The performance characteristics of the flash evaporation-vapor compression cycle, operating continuously with automatic controls, to achieve a cyclic semi-batch operation with brine solids concentration varying between 17 and 50 percent

(b) The performance of the phase separator/circulating pump and vapor compressor, the heat transfer performance of the brine heater/condenser, and the dynamics of the controls and their interaction of the system

(c) The potability of water distilled from pretreated and untreated urine with pyrolysis post treatment

(d) The control of microorganisms within the system, using the pyrolysis reactor

(e) The compatibility of materials, the scaling potential, and the identification of additional areas requiring improvement during the next phase of the program

The tests were generally conducted in accordance with the test plan presented in AiResearch Report 70-6219. Following the 5-day test, the system was dismantled and all components were critically examined for signs of wear or corrosion and for other signs of deterioration. The system was run for a total of 184 hours including the 5-day test, which accounted for about 100 hours.

The following paragraphs describe the breadboard unit and present the test data obtained, including water quality analyses. The data are discussed and solutions to the problems encountered during the system tests are presented.

System Description

The overall arrangement of the water reclamation unit assembled for the 5-day test is the same as that of the flight unit described in Section 2. Figure 4-4 is a schematic of the unit showing all components of the unit and identifying the instrumentation points. Photographs of the system are shown in Figures 4-5 and 4-6. The pyrolysis unit (Item 18) used in the breadboard unit did not incorporate a recuperator (see Figure 3-26); therefore, a cooler (Item 19) was incorporated to reduce vapor temperature upstream of the heater-condenser (Item 8).

The quality of the components of the urine processing unit was, in general, adequate for engineering development testing. All lines and tubing in the processing unit (brine and vapor loops) were stainless steel; the storage tanks and associated lines were essentially laboratory type equipment, as shown in the photographs of Figure 4-5 and 4-6.

The components assembled in the system incorporated the modifications which were deemed necessary as a result of earlier breadboard system tests and system-component analyses. Details of the component designs and performance data can be found in Section 3 of this report. Major component features are summarized below.

1. Vapor Compressor

A two-stage vortex machine (see Figure 3-7) was designed and tested with air prior to installation on the breadboard system. The compressor rotor is driven by an existing Apollo suit compressor motor through a magnetic coupling.

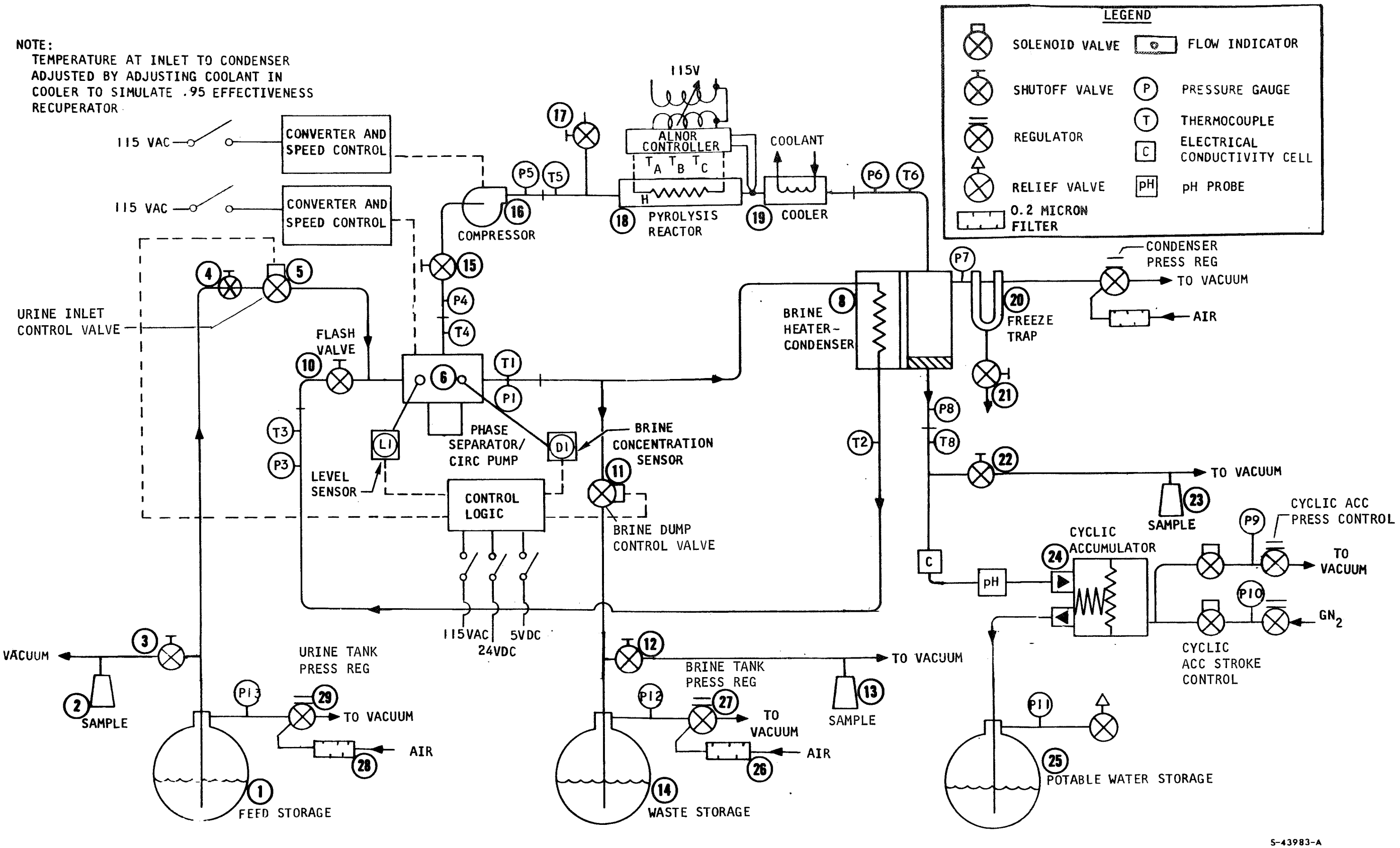
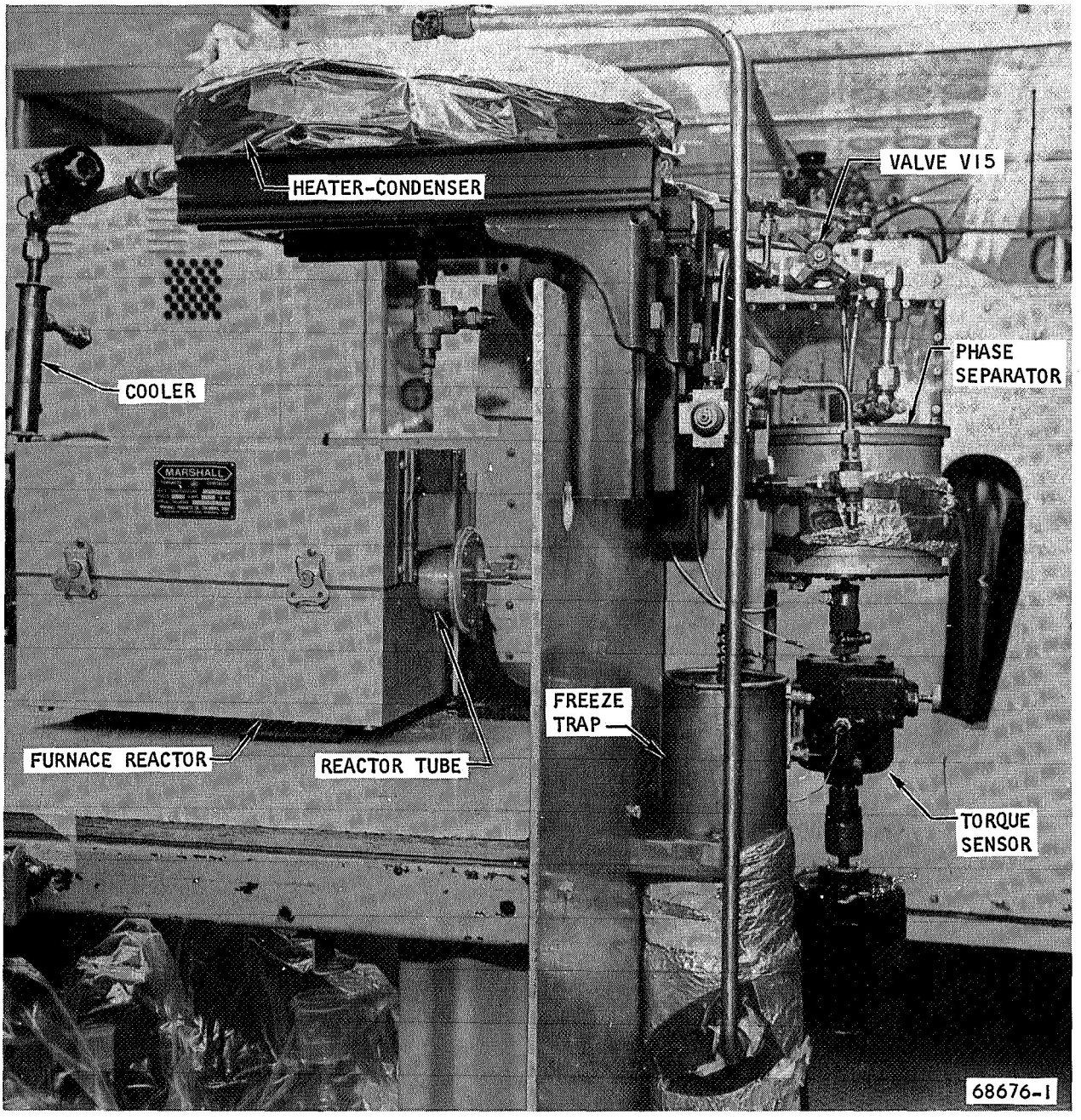
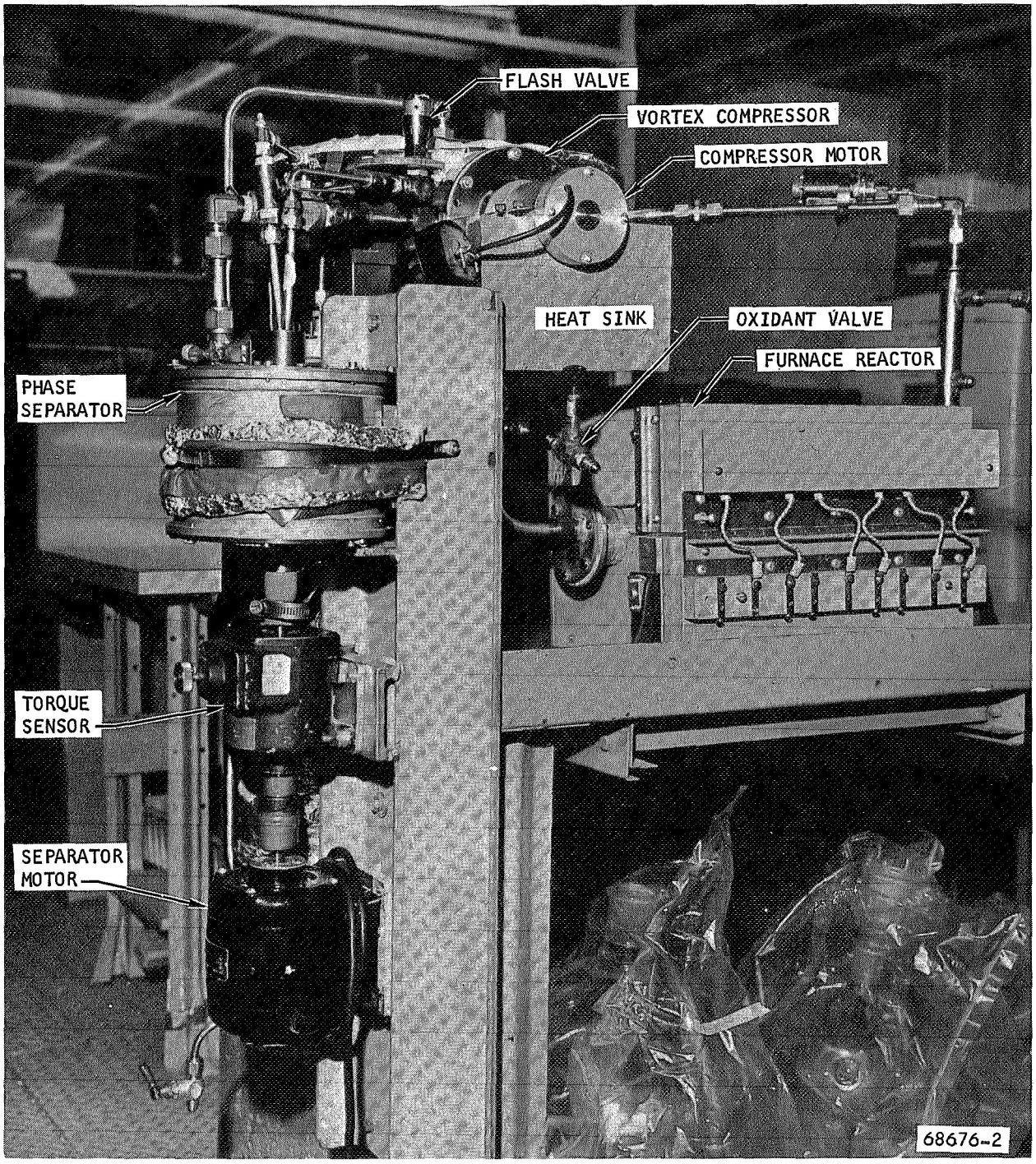


Figure 4-4. Breadboard Water Recovery System Schematic



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Figure 4-5. Breadboard Water Recovery System During Buildup (1 of 2)



F-12840

Figure 4-6. Breadboard Water Recovery System During Buildup (2 of 2)

2. Heater-Condenser (See Figures 3-18 and 3-19)

The heater-condenser is a single-tube unit similar to that used previously, refurbished to include a new tube designed with smoother inlet and outlet configurations. Tube length is 12 ft by comparison to 13.5 ft for the first breadboard unit.

3. Phase Separator (See Figures 3-10 and 3-11)

As a result of component-level testing, this unit was refurbished to include a baffle in conjunction with the demistor to reduce entrainment. The configuration of the tubes was also slightly modified.

4. Pyrolysis Reactor (See Figure 3-26)

A new reactor, using a rhodium catalyst, was designed and fabricated. No recuperator is used; the catalyst bed is installed in a furnace for temperature control. The furnace also provides the heat for vapor preheating. Vapor cooling is effected in a cooler between the reactor bed and the condenser.

5. Level and Concentration Controller (See Figure 3-27, 3-28, and 3-34)

The controller circuitry was redesigned to incorporate the semi-batch control scheme developed after the early breadboard tests.

Comprehensive instrumentation was incorporated on the breadboard. This instrumentation is identified on the schematic of Figure 4-4. Parameters not identified on the schematic, but which were monitored during the tests, include:

(a) Separator speed

(b) Separator shaft power

(c) Compressor speed

(d) Compressor motor current, voltage, frequency

(e) Compressor motor housing temperature

(f) Compressor casing temperature

High and low level warning lights, as well as a display of the detector counts, were provided for level and concentration monitoring. Product water quality was monitored continuously with Beckman pH and conductivity meters as shown on the schematic.

Provisions were made for on-line sampling of the urine feed, the brine waste, and the product water. Evacuated sterile bottles were used for collection of these samples, which were subjected to bacterial and chemical analyses.

Breadboard Shakedown Tests

Following completion of the component-level development test, the breadboard unit was assembled and preliminary runs were made prior to the 5-day test with urine. Initial runs were concerned with instrumentation check-out and general familiarization of the personnel with the various system operational peculiarities, including the supporting equipment. The integrity of the system was assured and component performance was ascertained and/or adjusted to meet the demands of the overall system. All these tests were run with water. Urine tests were then conducted prior to the 5-day run to evaluate overall system performance.

1. System Leakage

As discussed in Section 3, air leakage into the system was a major problem in previous system tests. Air leakage will deteriorate compressor performance by increasing compressor flow rate; more important yet, a small quantity of air mixed with the vapor will reduce heater-condenser performance drastically. To obviate this problem, the entire system was subjected to leak checks following system assembly.

Corrective measures were taken until the leakage of the processing unit (brine and vapor loops) was reduced to an acceptable level. Leakage was measured by evacuating the system to 0.5 psia and monitoring pressure build-up after all isolation valves were shut off. A final leakage rate lower than 0.0016 lb/hr was obtained. This represents 0.16 percent of the design water processing rate and was deemed adequate in terms of its effect on compressor and heater-condenser performance.

2. Level and Density Controller Calibration

The level and density control system was calibrated with water in the brine loop. This system had not been checked at the component level, since the system circuitry was not available at the time of the component level separator tests. Figures 4-7 and 4-8 show the level and density calibration curves obtained.

The density sensor calibration data indicate that with the present design of the separator bowl and the current location of the sensor, the level of liquid in the bowl has a very strong effect on the density detector count rate. This effect was much higher than anticipated; it was expected that the density sensor would operate satisfactorily to levels as low as 250 cc. The data show that the minimum level for accurate monitoring of brine density is between 400 and 500 cc. These data indicated that adjustment of the count rates at the low level switch points was necessary to accommodate the semi-

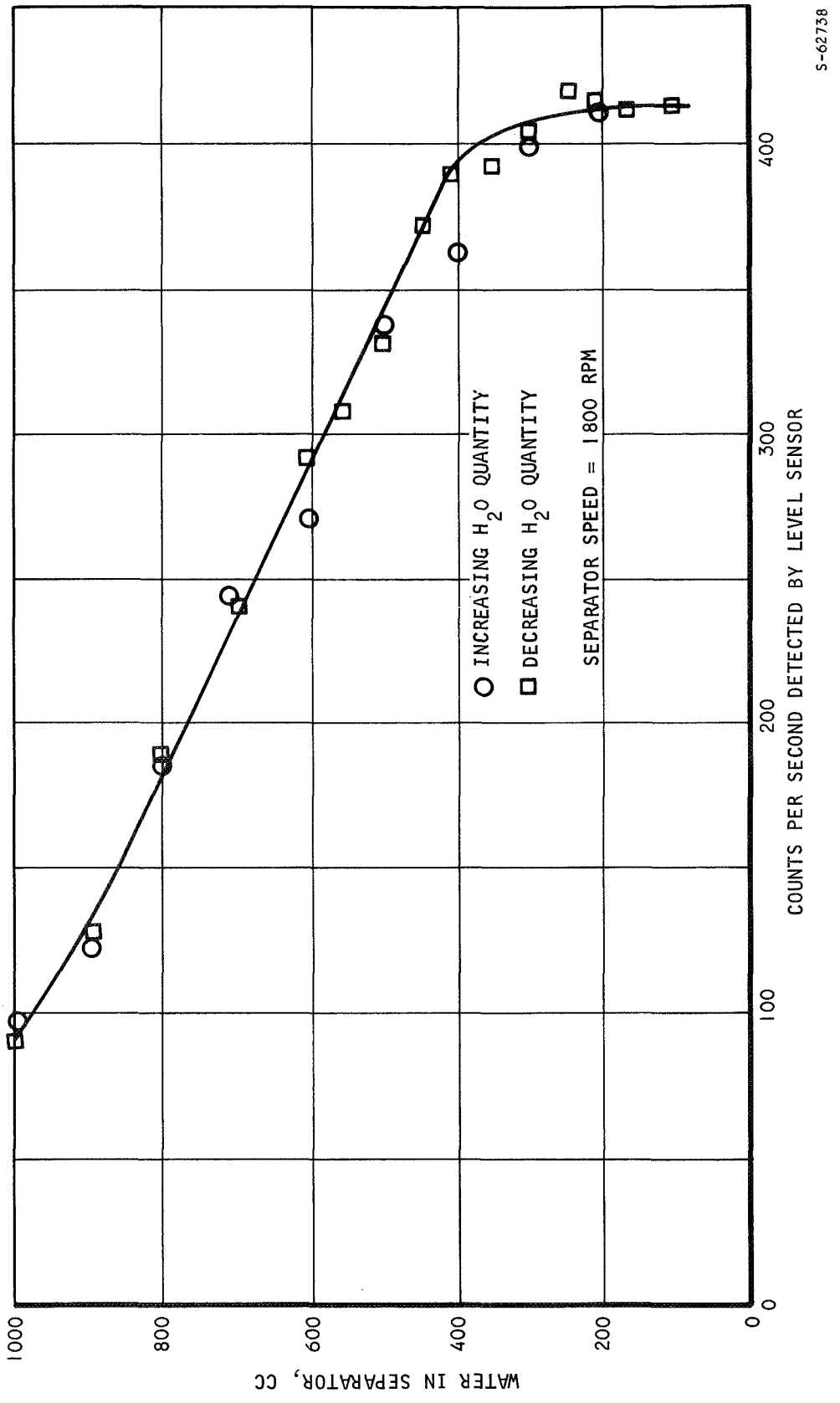


Figure 4-7. Separator Level Calibration with Distilled Water

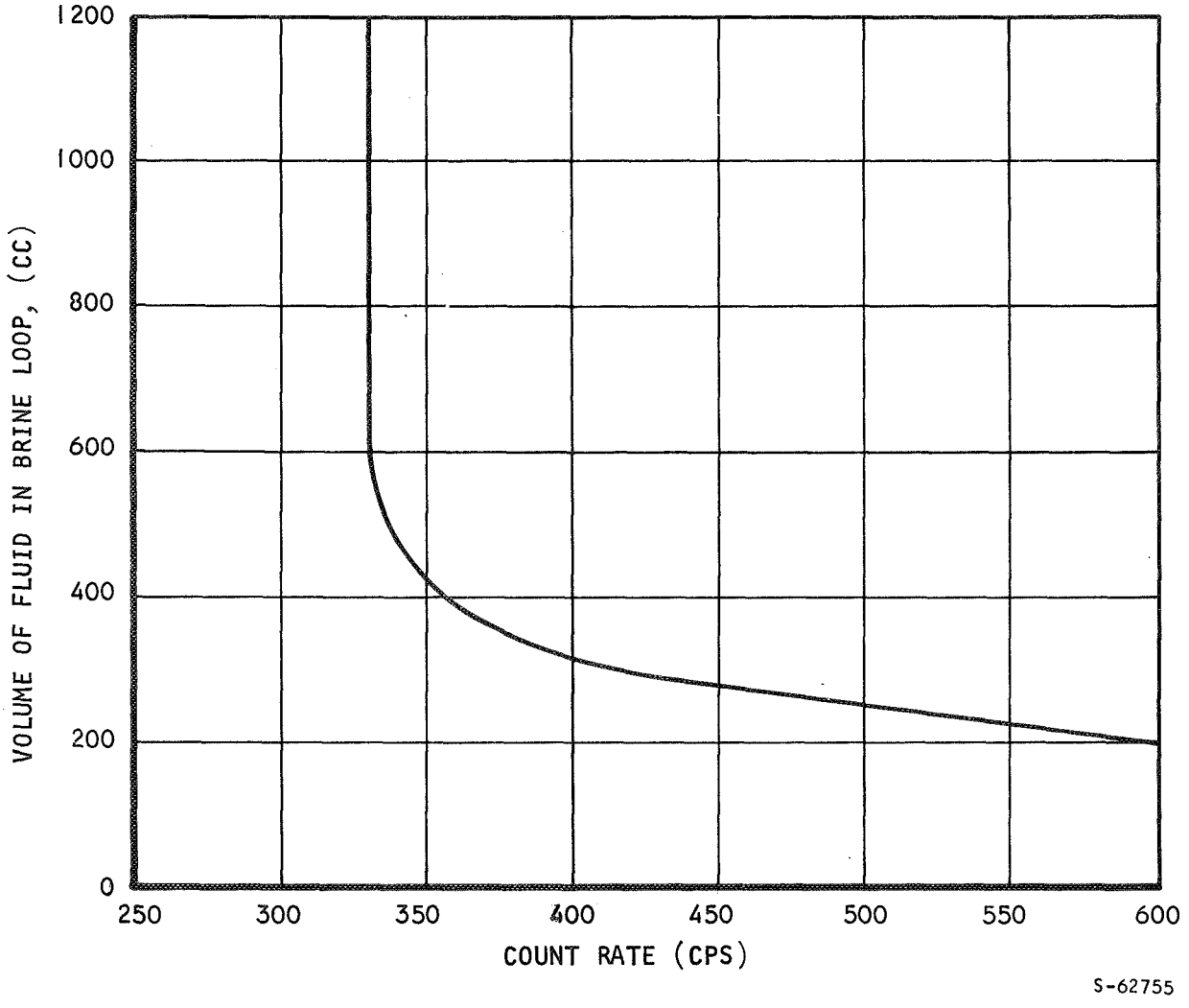


Figure 4-8. Effect of Liquid Level on Density Sensor Output

batch control scheme whereby brine dump starts at the 250 cc level and ends at 150 cc level. This adjustment was not made at this time, but was deferred until direct calibration data with high brine concentration were available in later tests with urine.

These preliminary data indicate that in redesigning the separator the peculiarities of the density control system should be a determining factor in establishing bowl geometry.

3. Compressor Performance

Compressor performance with water was checked and found to be somewhat lower than design performance. This was anticipated since component level testing with air had also shown lower performance than anticipated. As a result, the compressor speed was increased from 23,500 to 26,400 rpm by changing the frequency of the power input to the unit. Compressor performance data is given in Section 3.

4. System Thermodynamic Performance

Initial tests with water were conducted on the system to establish baseline performance parameters. The results of this test are shown in Table 4-1; computer data are also shown for comparison. The average water production rate was approximately 0.5 lb/hr, which was somewhat lower than anticipated. It was theorized that the reason for the low production rate was an imbalance in the system thermal control. Excessive heat leaks from the brine loop would result in significant reduction in water production rate. This condition was experienced on the early breadboard tests.

In an attempt to correct this situation, the separator was insulated and the brine line was wrapped around the compressor casing; cooling the compressor in this manner not only increased the brine temperature but also improved compressor performance.

The first two columns of Table 4-2 show the results of the test conducted with this configuration. As indicated, the water production rate was very greatly increased over that previously obtained. However, an appreciable amount (approximately 1.5 percent) of water was carried into the vacuum vent from the condenser. This was attributed to heater-condenser thermal imbalance due to excessive heat addition to the brine loop from the compressor.

The insulation was removed from the condenser in an attempt to reestablish thermal equilibrium by rejecting more heat from the condenser. The results of the test run with this configuration are shown in the last two columns of Table 4-2. The desired results were not achieved and the vent carryover remained approximately the same as before.

These tests on the thermal balance of the system in various configuration indicated that some phenomenon other than thermal balance was responsible for

TABLE 4-I

PERFORMANCE OF BREADBOARD WATER RECOVERY SYSTEM WITH DISTILLED WATER

Parameter	Computer Results	Date/Time 9/3/70 1115	9/3/70 1315	9/3/70 1415
Separator				
Brine Outlet Pressure, P1, psia	10.38	9.6	10.0	9.2
Brine Outlet Temperature, T1, °F	107.84	98.5	104	104
Vapor Outlet Pressure, P4, psia	1.20	0.90	1.1	1.1
Vapor Outlet Temperature, T4, °F	107.84	100.4	106	106
Separator Speed, rpm	1800	1800	1800	1800
Input Shaft Power, watts	31.7	55.8	55.8	50.5
Level, cc	820	770	640	400
Brine Solids Concentration, %	0	0	0	0
Compressor				
Outlet Pressure, P5, psia	1.676	1.68	1.75	1.72
Outlet Temperature, T5, °F	242.6	224.5	233	227.5
Speed, rpm	--	27060	27060	27120
Input Current, amp	--	0.45	0.45	0.44
Pressure Ratio, P5/P4	1.46	1.87	1.59	1.56
Heater-Condenser				
Vapor Inlet Pressure, P6, psia	1.51	1.38*	1.36*	1.34*
Vapor Inlet Temperature, T6, °F	147.4	251	231	247
Vent Pressure, P7, psia	1.50	1.48	1.53	1.50
Condensate Outlet Pressure, P8, psia	--	0.75	1.00	1.04
Condensate Outlet Temperature, T8, °F	--	98	106	107.5
Condensate Production Rate, lb/hr	1.432	0.562	0.463	0.507
Brine Side Flow Rate, lb/hr	191.3	NR	NR	NR
Brine Side Temperature Rise, °F	7.57	3.5	4.0	6.0
Flash Valve				
Inlet Pressure, P3, psia	3.01	2.3	2.5	2.4
Inlet Temperature, T3, °F	115.19	102	108	110

NOTE: NR = Not Recorded
* = Calibration Error

TABLE 4-2

PERFORMANCE OF MODIFIED BREADBOARD WATER RECOVERY SYSTEM WITH DISTILLED WATER

Parameter	Date/Time 9/9/70 1215	9/9/70 1345	9/10/70 1230	9/10/70 1430
Separator				
Brine Outlet Pressure, P1, psia	9.2	9.4	10.0	10.1
Brine Outlet Temperature, T1, °F	109	111	104	104
Vapor Outlet Pressure, P4, psia	1.1	1.2	1.25	1.25
Vapor Outlet Temperature, T4, °F	111	113	107	106
Separator Speed, rpm	1800	1800	1800	1800
Input Shaft Power, watts	48.1	48.1	57.0	57.0
Level, cc	760	800	820	780
Brine Solids Concentration, %	0	0	0	0
Compressor				
Outlet Pressure, P5, psia	1.81	1.80	1.87	1.79
Outlet Temperature, T5, °F	213	205	211	207
Speed, rpm	27360	27240	27060	26920
Input Current, amps	0.42	0.41	0.41	0.45
Pressure Ratio, P5/P4	1.65	1.50	1.50	1.43
Heater-Condenser				
Vapor Inlet Pressure, P6, psia	1.49*	1.30*	1.64	1.50
Vapor Inlet Temperature, T6, °F	247	277	214	257
Vent Pressure, P7, psia	1.52	1.46	1.52	1.44
Condensate Outlet Pressure, P8, psia	1.15	1.3	1.03	1.10
Condensate Outlet Temperature, T8, °F	111	112	104	106
Condensate Production Rate, lb/hr	1.232	1.255	1.39	1.5
Brine Side Temperature Rise, °F	9.0	7.0	6.0	6.0
Flash Valve				
Inlet Pressure, P3, psia	2.4	2.8	2.5	3.0
Inlet Temperature, T3, °F	118	118	110	110
System Modification	Brine tubing on compressor. Insulation placed on separator.		Brine tubing on compressor. Insulation removed from condenser.	

* = Calibration Error

the system performance being at variance to the expected performance. A subsequent leak check of the system revealed a leak in the catalyst bed thermocouple tube. A leak into the vapor side of the condenser could significantly affect performance by degrading the vapor side heat transfer coefficient. The discussion on the condenser performance presented in Section 3 gives details of the effect of leakage on condenser performance. It was therefore decided to revert the system to the earlier configuration (insulation on the condenser; no compressor cooling with the brine loop) and to continue the system test program. An additional heat exchanger was installed downstream of the catalyst bed to provide better control of condenser inlet temperature.

5. System Sterilization

The next phase of the test program was to conduct a shakedown run with urine. Prior to this run, the system was sterilized. Sterilization at this point in the test program was performed to demonstrate that the system could be sterilized effectively with hot water and that carryover of microorganisms from the brine loop into the product water could be checked by the pyrolysis reactor.

Sterilization was accomplished by injecting hot water into the vapor loop through the oxidizer shutoff valve (Item 17 in Figure 4-4). The water was routed through the catalyst bed, into the condenser, and out of the condenser product water port and vacuum vent port. Hot water from the product water port was circulated through the cyclic accumulator and all the plumbing to the product and waste storage tanks and sample ports. Flow was continued until all the system was above 220°F for at least 20 minutes. At the end of this sterilizing period a sample of the sterilizing water was withdrawn from the product water sample port for microbiological analysis. No microorganisms were found.

6. Shakedown Tests With Urine

Initial shakedown runs with urine were performed to evaluate system performance prior to the start of the long term test with urine. The results of two 6-hour tests are shown in Table 4-3. The first test was conducted at the same conditions as the earlier water tests. The system performance at these conditions is consistent with that obtained earlier, although the water production rate is not as high as expected.

The second test was conducted with a condenser vent pressure of 1.75 psia instead of the previous 1.5 psia. It was felt that if the compressor was limiting system performance, the higher operating pressure would allow the compressor to develop a higher pressure ratio due to a lower volumetric flow rate. However, the water production rate actually decreased. Analysis of the system test data reveals that the cause of this unexpected behavior is the high air leakage rate into the separator. This is discussed in greater detail later in this section as well as in Section 3. Water samples were taken during each test for microbiological and chemical analysis. The results

TABLE 4-3

PERFORMANCE OF BREADBOARD WATER RECOVERY SYSTEM WITH URINE BRINE

Parameter	Date/Time 10/1/70 1315	Date/Time 10/2/70 1315
Separator		
Brine Outlet Pressure, P1, psia	10.2	10.8
Brine Outlet Temperature, T1, °F	100	102
Vapor Outlet Pressure, P4, psia	0.7	0.8
Vapor Outlet Temperature, T4, °F	100	102.4
Separator Speed, rpm	1804	1791
Input Shaft Power, watts	45.2	58.2
Level, cc	760	760
Brine Solids Concentration, %	9	--
Compressor		
Outlet Pressure, P5, psia	1.56	1.88
Outlet Temperature, T5, °F	210	214.5
Speed, rpm	25880	25560
Input Current, amp	0.37	0.45
Pressure Ratio, P5/P4	2.23	2.35
Heater-Condenser		
Vapor Inlet Pressure, P6, psia	1.35*	1.77
Vapor Inlet Temperature, T6, °F	--	160
Vent Pressure, P7, psia	1.5	1.75
Condensate Outlet Pressure, P8, psia	0.79	0.81
Condensate Production Rate, lb/hr	0.74	0.59
Brine Side Temperature Rise, °F	3.38	2.89
Condensate Conductivity, micromho/cm	8	33
Condensate, pH	7.65	7.60
Vented Water, cc/hr	5	40
Flash Valve		
Inlet Pressure, P3, psia	2.59	2.62
Inlet Temperature, T3, °F	103.4	104.9

* = Error in Instrumentation

of these analyses indicate the ability of the system to produce high quality water. These data, together with the data from the other tests, are discussed later in this section of the report.

Continuous 5-Day Test With Urine

Following the shakedown tests with urine, the system was tested continuously for 100 hours with urine. This test was started after the shakedown tests described above. Following these preliminary tests, the brine loop was flushed, the system pressure was raised to ambient, and the catalyst bed was kept at high temperature (between 600° and 900°F) to serve as a barrier to migration of microorganisms to the product water side of the system. Dry nitrogen was circulated at a low flow rate through the vapor side of the system to maintain the system at a slight positive pressure. These conditions were maintained for two days prior to the start of the 5-day run.

The thermodynamic system data, system water production rate and urine feed, and product water conductivity are plotted in Figures 4-9 and 4-10 for the entire five-day test. These data are discussed in the following paragraphs.

From the startup at approximately 0930 on 10/5/70, until early on 10/6/70, the system operated in a nominal condition and separator level was being maintained with the level control system. There was no dump of the brine during this time since concentration had not reached the required level. Table 4-4 shows system operating conditions during this period. Performance was as expected, based on the results of the previous shakedown and calibration tests. At approximately 0200 on 10/6/70 (point B on Figure 4-9 and 4-10), the density control system signaled the solenoid valve to dump a portion of the brine. Due to an oversight in the operation of the system, the brine storage tank was at ambient pressure and not evacuated to 7 psia as required according to test procedures. Opening of the dump valve under these conditions resulted in the introduction of air into the brine loop. This condition was corrected, a sample of the brine fluid was taken, and operation was continued. Samples of the product water were taken periodically. The results of the microbiological and chemical analyses demonstrated that the system was producing water of very high quality, with no bacteria during this period. Detailed water analysis is given later in this section.

At approximately 1000 on 10/6/70, problems were encountered with the compressor motor, resulting in reduced compressor speed and a very short (10 min.) period of compressor shutdown due to overload (1200, point C). These compressor problems account for the lower water production rate during that period (from 1000 to 1720 hr). The urine feed rate remained the same to make up for the brine samples taken during that period.

During this period (point C to point D), a check of the density control calibration was made. A brine sample was removed and the count rate from the density sensor was monitored. This count rate, compared to the expected rate



Figure 4-9. Water Recovery System Test Results--10/5/70 to 10/9/70 (1 of 2)

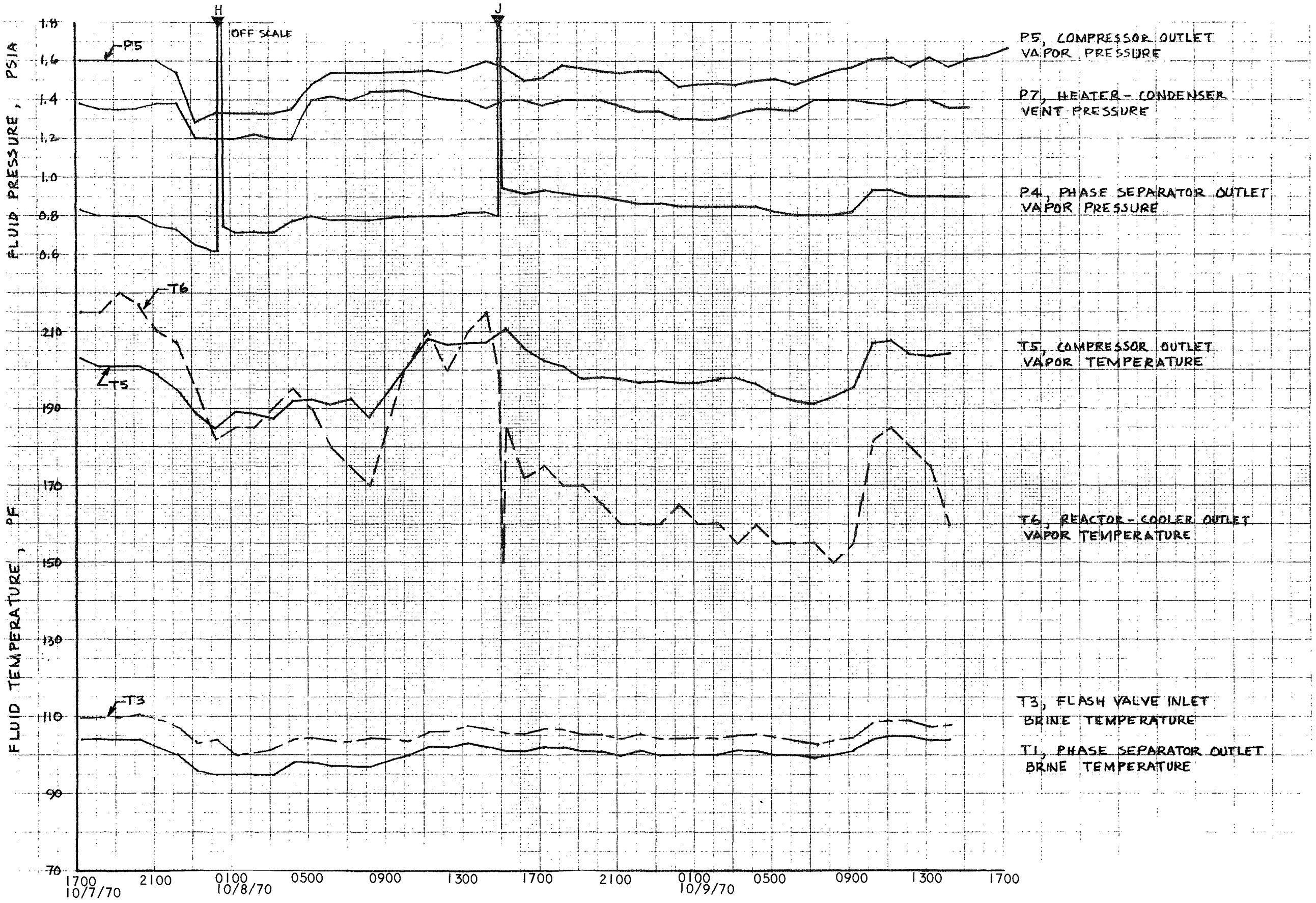


Figure 4-9 (Continued) (2 of 2)

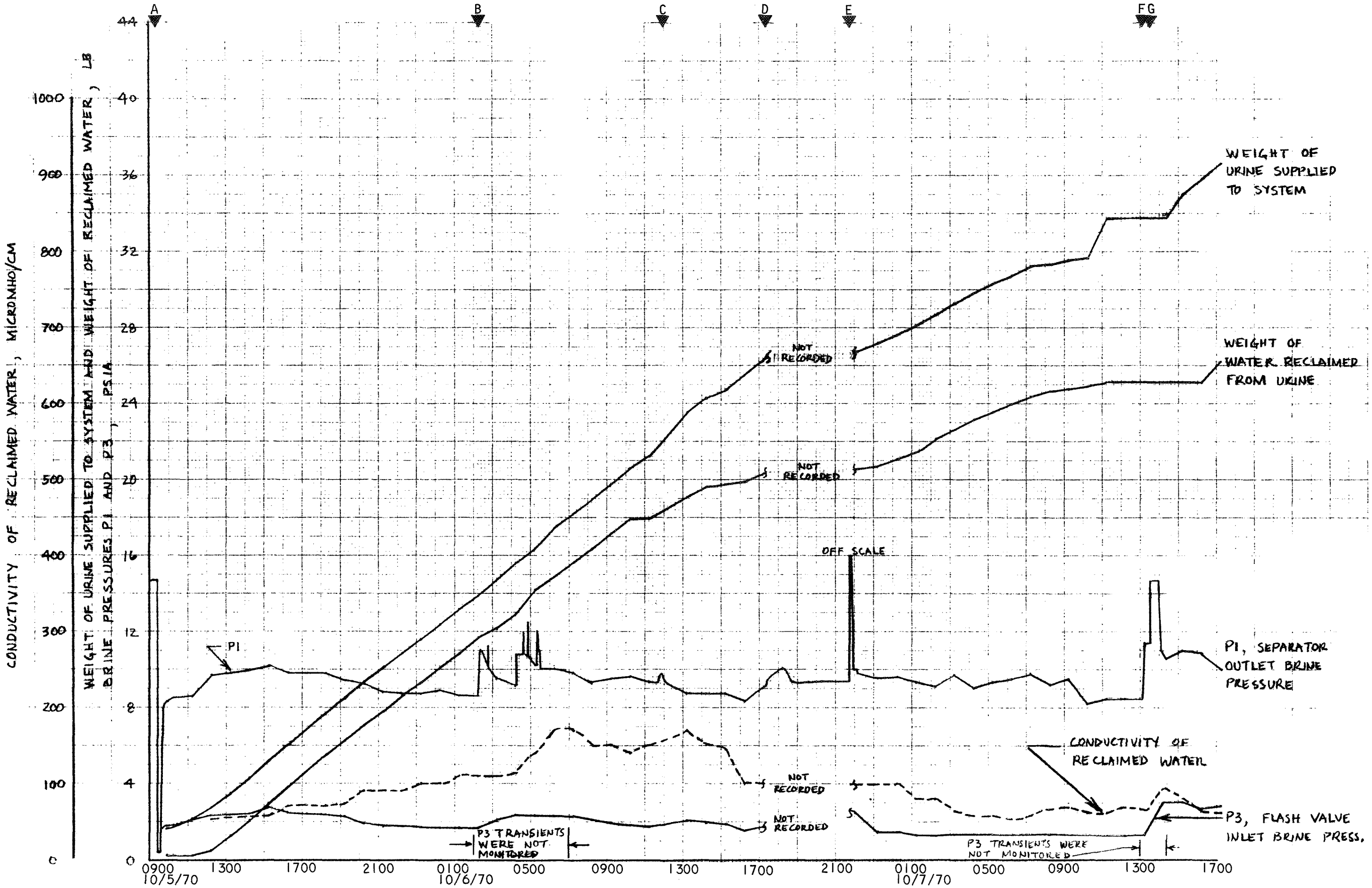


Figure 4-10. Water Recovery System Test Results--10/5/70 to 10/9/70 (1 of 2)

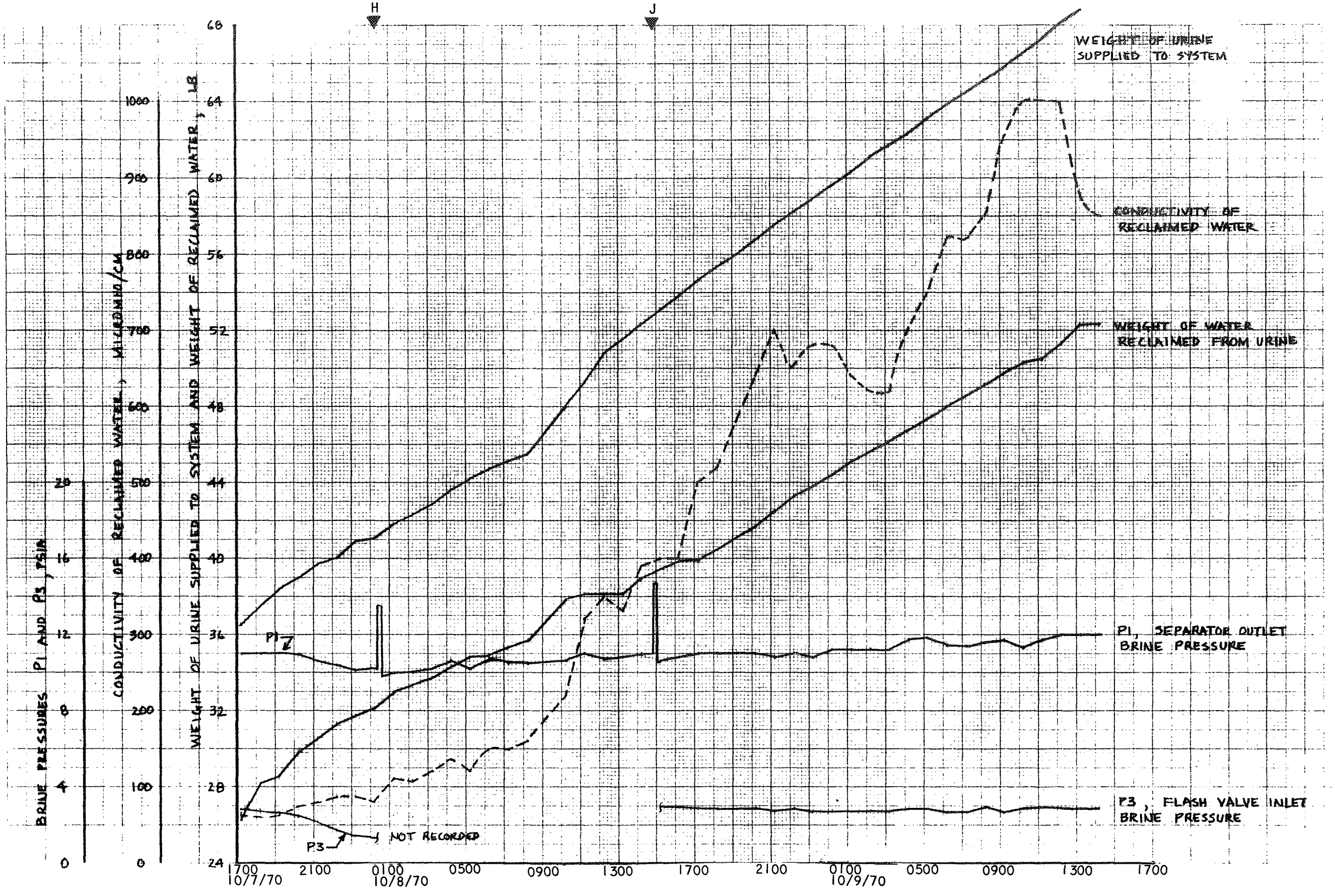


Figure 4-10 (Continued)(2 of 2)

TABLE 4-4

TYPICAL PERFORMANCE OF BREADBOARD WATER RECOVERY SYSTEM WITH URINE BRINE (5-DAY TEST)

Parameter	Date/Time 10/6/70 0115
Separator	
Brine Outlet Pressure, P1, psia	8.6
Brine Outlet Temperature, T1, °F	100
Vapor Outlet Pressure, P4, psia	0.72
Vapor Outlet Temperature, T4, °F	101.8
Separator Sepeed, rpm	1815
Input Shaft Power, watts	37.5
Level, cc	780
Brine Solids Concentration, %	--
Compressor	
Outlet Pressure, P5, psia	1.43
Outlet Temperature, T5, °F	198
Speed, rpm	26480
Input Current at 135 vac, amp	0.42
Pressure Ratio, P5/P4	1.99
Heater-Condenser	
Vapor Inlet Pressure, P6, psia	1.49
Vapor Inlet Temperature, T6, °F	180
Vent Pressure, P7, psia	1.40
Condensate Outlet Pressure, P8, pisa	0.90
Condensate Production Rate, lb/hr	0.75
Brine Side Temperature Rise, °F	5.78
Condensate Conductivity, microhmo/cm	110
Condensate pH	7.68
Vented Water, cc/hr	8.1
Flash Valve	
Inlet Pressure, P3, psia	1.70
Inlet Temperature, T3, °F	105.8

at the measured density of the brine sample, revealed that an adjustment should be made in the density control system switch points. This corrective action was taken, thus allowing the density sensor to measure the high brine concentration before the separator level fell below the minimum level at which brine dumping should have taken place.

At 1720 on 10/6/70 (point D on Figures 4-9 and 4-10), the compressor speed dropped to 14,000 rpm. The compressor was shut down and the compressor motor removed. The motor bearings were replaced and the compressor reactivated at 2200 on 10/6/70 (point E of Figures 4-9 and 4-10). This occurence and the resulting effects on the system, are discussed in more detail later in this section.

After system reactivation following the compressor shutdown, the temperature rise of the brine loop in the condenser started to increase. This occurred with the water production rate decreasing to less than 0.5 lb/hr, indicating a significant decrease in brine flowrate. At 0900 on 10/7/70, the separator speed was increased from 1800 to 2000 rpm and the brine temperature rise in the condenser decreased to levels nearer normal, but still high for the water production of the system. At 1300 (point F) with the temperature rise continuing to increase, it was obvious that a flow restriction had developed in the brine loop. The separator was desctivated and the brine loop was found to be plugged. The obstruction was removed by opening the loop and inserting a flexible wire in the heater tube and operation was reinitiated (point G). This blockage is associated with the period of shutdown during repair of the compressor motor, as discussed in Section 3. It was concluded that this problem was a direct result of interrupted operation and would not occur except under the low temperature-high concentration which occurred as a result of compressor failure.

System operation continued from this point until the end of the test at 1400 on 1/9/70. From 1300 on 10/7/70 to 1400 on 10/9/70, system operation was normal except for a thermal control problem in regulating condenser inlet temperature, and the failure of pressure transducer P3. The thermal control problems were due to the difficulties experienced in regulating the condenser inlet temperature with the catalyst bed outlet cooler. Attempts to control the vapor temperature with nitrogen gas flow through the cooler proved unsuccessful during that period (point G to point H); the nitrogen gas flow was shut off and the temperature was regulated by removing insulation from the cooler and the line to the condenser. This method proved somewhat successful, but did not achieve the degree of control desired for the test. This problem is one of the contributing factors to the existence of a finite amount of water carryover into the vacuum vent. The flight system recuperator is designed to cool the vapor to 154°F; losses in the line from the recuperator to the condenser will further reduce the vapor temperature to an estimated value of 121°F. On the breadboard system the condenser inlet temperature varied from about 160 to 210°F. It was observed that operation at temperatures above 170°F would result in sizeable quantities of water vapor carryover to vacuum.

The pressure transducer on the brine loop at the inlet to the flash valve failed and was removed at approximately 0030 on 10/8/70 (point H). It was replaced at 1500 on 10/8/70 (point J). During removal and replacement the vapor valve (Item 15 in Figure 4-4) between the separator and compressor was closed and the brine loop brought to ambient pressure to remove and replace the transducer. Operation was resumed by opening valve 15. Although these actions appeared to have no effect on system operation, careful analysis of the test data indicates that the transient pressure surges imposed on the system (especially those associated with opening of the vapor valve 15) contributed to system contamination by excessive carryover from the separator due to rapid deaeration of the brine. This phenomenon is discussed more fully in the following paragraphs on system overall performance.

A total water balance of the system during this test was conducted. The results are summarized below.

Total feed, 69.4 lb

Product water, 52.2 lb

Waste brine, 9.3 lb (includes fluid remaining in brine loop at end of test)

Overboard vent, 4.6 lb

Water remaining in condenser 3.3 lb

Post-Test Inspection

After completion of the 5-day run, the system was flushed with water at 250°F for a period of 4 hours. The breadboard system was then dismantled for inspection. At that time, a total running time of 184 hours had been recorded on the system. All components were examined carefully for signs of wear, corrosion, and, in the liquid loop, solids deposits. A summary of the observations made during this post-test inspection is presented below.

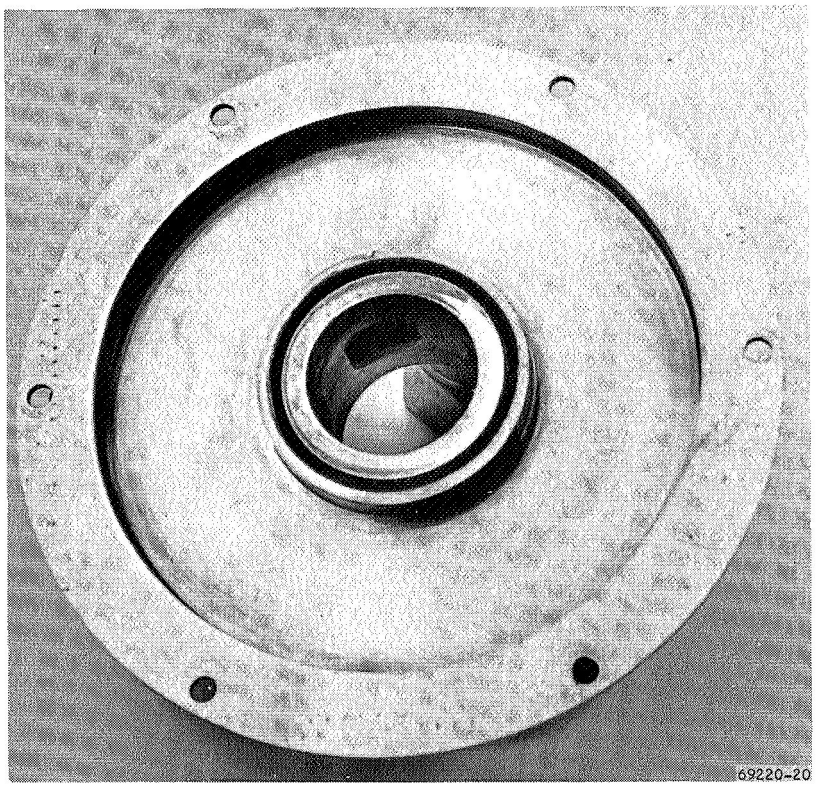
1. Phase Separator

Prior to installation of the separator in the upgraded breadboard unit, evidence of corrosion had been observed in a braze-joint area of the bowl. As anticipated, the corroded area at that location had increased to a surface of about 1 $in.^2$; otherwise the bowl was clean. This problem could easily be eliminated in the fabrication of a flight system by elimination of the braze joint.

Examination of the carbon face seal revealed extensive damage. The upper housing of the seat which interfaces with the carbon seal was worn unevenly, as shown in Figure 4-11. In addition, the face of carbon seal itself was badly chipped. This could easily have been the source of air leakage experienced during the 5-day run.

The pitot tube and the brine return tube were free of obstruction.

A thin layer of a black greasy substance was found on the wall of the vapor tube, indicative of carry over.





F-12842

Figure 4-11. Carbon Face Seal After 5-Day Test

2. Compressor

No indication of wear or corrosion was noticed on any of the components. A slight quantity of lubricant was found to have leaked from the bearings. The motor bearings were found to be damaged.

3. Pyrolysis Reactor

Figure 4-12 shows the reactor as it appeared after the 5-day test. No damage to the reactor housing was noticed. Upon disassembly a thermocouple probe tube was found to be broken. Leakage through this tube had been detected prior to the 5-day run and the tube had been plugged at that time.

Examination of the catalyst screens revealed that corrosion of the stainless steel substrate had taken place, resulting in flaking of the rhodium plating. This damage was limited to a very small area at the bottom of the reactor. Not all of the screens showed such deterioration. Corrosion of the stainless steel substrate is due to the presence of liquid water in the reactor. Vapor condensation within the reactor during periods of inactivity or following sterilization would result in the accumulation of liquid water at the bottom of the reactor.

This problem would not exist on a flight unit when the reactor is continuously on stream.

4. Heater-Condenser

All components of the heater-condenser were examined. No evidence of obstruction were found in the brine tube. The tube, the screen, and the housing showed no signs of corrosion except in weld areas, where the brine and vapor inlet tubes penetrate the housing. The hydrophilic porous plate showed very little evidence of corrosion. Wick discoloration was found, as shown in Figure 4-13, indicative of carryover into the condenser during the system tests. It is interesting to note here that although the product water had a definite odor in the latter part of the 5-day test, no such odor could be detected within the condenser.

Microbiological Analysis

The following paragraphs describe the methods and procedures used in the performance of the microbiological analysis conducted in support of the 5-day test. Test data are presented with a discussion of the test results.

1. Methods and Materials

(a) Collection of Urine--Urine was collected from acceptable donors in sterile, polypropylene bottles and refrigerated until used.

(b) Screening of Urine Donors--Urine from perspective donors was carefully screened as to the following criteria:

(1) Microscopic examination for evidence of any pathology such as red or white blood cells, casts, etc.

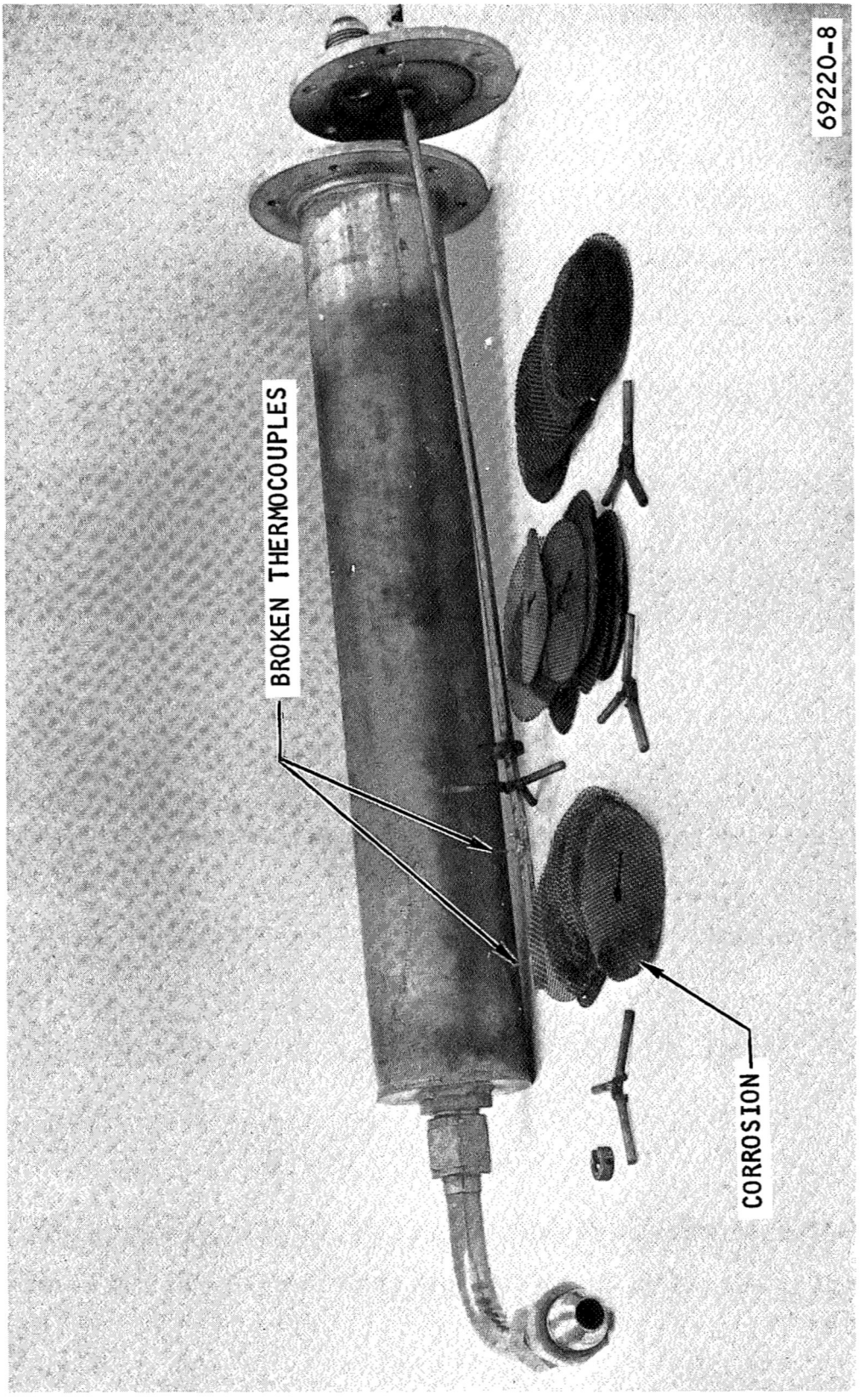


Figure 4-12. Reactor After 5-Day Test

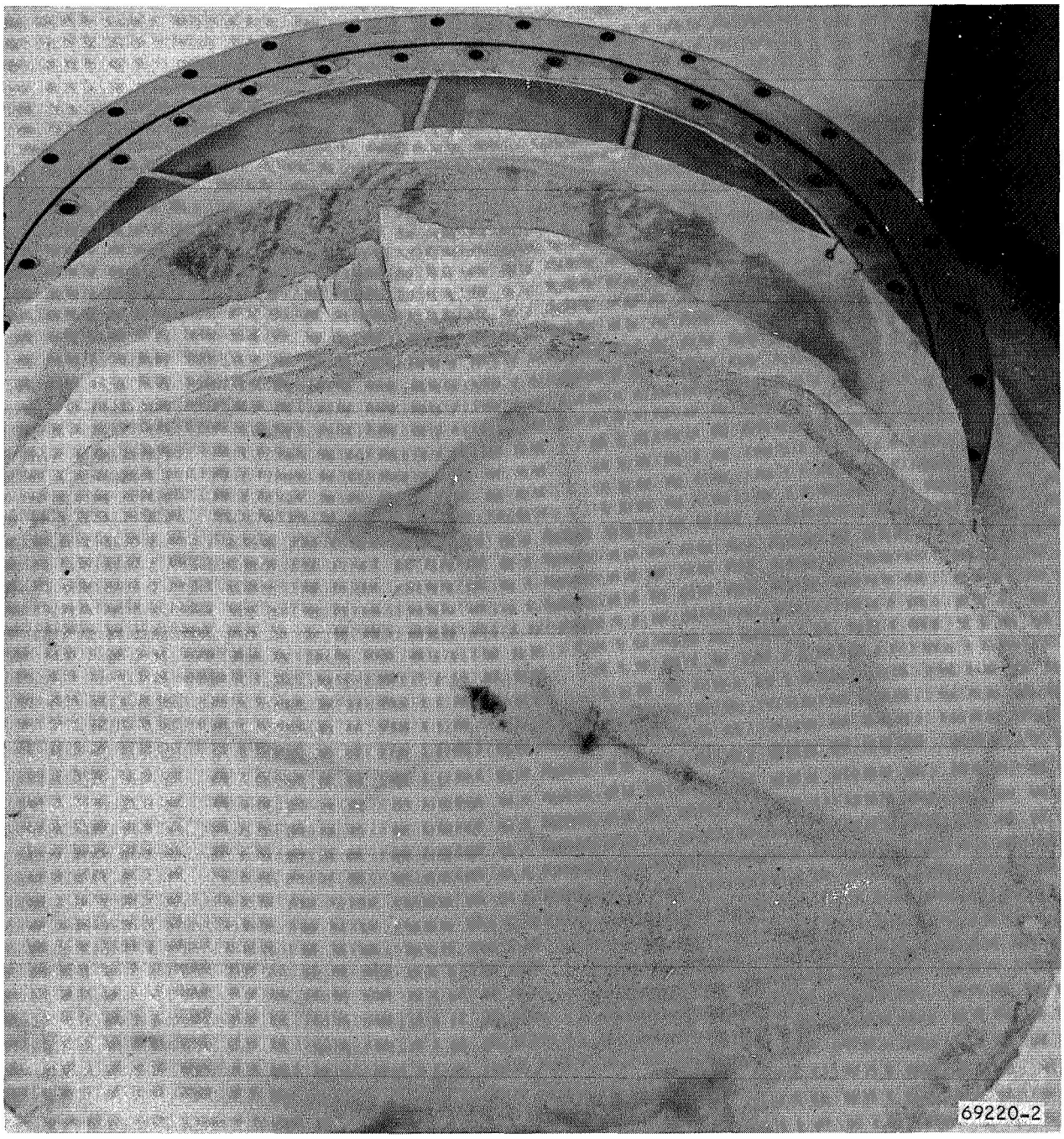


Figure 4-13. Condenser Wick After 5-Day Test

(2) Chemical tests for presence of sugar, proteins, ketones and occult blood.

Each prospective donor was also questioned as to recent infections and asked if he was currently on antibiotic therapy.

(c) Sterilization of the Urine Distillation System--The entire system was sterilized prior to the start of testing by circulating 250°F water through the test setup for 4 hours. Sterility testing was performed by inoculating Thioglycollate broth and by filtering 500 ml of water obtained from the test setup through 0.45μ millipore filters.

(d) Collection of Specimens--Samples for microbiological analysis were collected asceptically in sterile containers. Feed, brine, and product water samples were collected on a daily basis.

(e) Enumeration and Identification Procedures--Quantitation of urine feed and brine was carried out by the pour plate method. Ten-fold dilutions were carried out in sterile distilled water blanks. All counts were done in duplicate and the counts averaged. Anaerobic counts were performed on undiluted samples. If dilution was necessary, these were performed in Thioglycollate broth. Product water samples were handled as above and also filtered through a 0.45μ millipore filters.

Identification of isolates was performed according to routine procedures utilizing general, selective, and differential media, as well as biochemical tests for speciation. Incubation was carred out at 37°C for 24 and 48 hours, depending on the type of medium and the type of test performed.

Anaerobic incubation was carried out in a BBL anaerobic jar utilizing gas packets containing 95-percent H_2 and 5-percent CO_2.

2. Results

Prior to the start of the 5-day test, water samples were obtained subsequent to the sterilization of the system. Sterility testing of two such samples was performed by inoculating Thioglycollate broth and by filtration of 500 ml of the water sample through a 0.45μ millipore filter. The filter was placed on Tryptic Soy Agar plate and both the Thioglycollate and filter were incubated aerobically for seven days at 37°C. No growth was evident in either culture.

The actual test run was started on 10/5/70 and ended on 10/9/70. Urine feed, brine, and product water samples were collected on a daily basis. Both quantitation and identification of isolates were performed on all samples. Samples were quantitated using Tryptic Soy Agar. Samples for identification were inoculated to the following media: Phenylethylalcohol blood agar (5 percent sheep red blood cells), Eosin-Methylene blue agar, Sabouraud's Dextrose agar, Mannitol Salt agar, and Thioglycollate broth.

Table 4-5 shows the total counts for the 5-day test of both the urine feed and brine concentrate. During most of the 5-day run the brine concentration was between 20 and 30 percent due to difficulties with the density sensor and the requirements for brine sampling. The data of Table 4-5 are given for this concentration range.

TABLE 4-5

URINE AND BRINE MICROBIOLOGICAL ANALYSIS DATA

Day	Micro-organisms/ml.	
	Urine Feed	Brine Concentrate
1	5.2×10^7	No sample collected
2	1.01×10^8	1.83×10^8
3	2.55×10^8	2.7×10^8
4	2.5×10^8	2.35×10^8
5	1.75×10^8	1.12×10^8

As shown in Table 4-5, both the urine feed and brine concentrate contained considerable microbial populations. The significance of this data is discussed later.

Table 4-6 shows the viable counts obtained from the product water. Pour plates were made of undiluted samples.

TABLE 4-6

QUANTITATION OF PRODUCT WATER

Day	Pour Plate		Millipore Filter		Thioglycollate Broth
	Aerobic	Anaerobic	Quantity Filtered (ml)	Total Micro-organisms	
1	0	0	100	2	No Growth
2	0	0	500	37	Growth
3	0	0	500	0	Growth
4	0	0	500	0	No Growth
5	0	0	250	0	No Growth

As is evident from Table 4-6, counts obtained in the product water were very low.

Identification of isolates was performed on all three daily samples. The following micro-organisms were obtained from the urine feed and brine concentrate: Escherichia coli, Micrococci, Enterococci, Proteus vulgaris and Candida albicans. No attempt was made to quantitate the various groups of micro-organisms, thus no conclusions can be drawn concerning predominating species. However, the same organisms were isolated in both the urine feed and brine concentrate.

3. Discussion and Conclusions

Microbial counts were performed on both the urine feed and brine concentrate. It is evident from the high counts (10^8/ml) obtained in the urine feed that some effective biocide should be incorporated into the urine feed to keep microbial growth at a minimum. Such a biocide must be effective in urine for considerable periods of time and also must not appear as harmful products in the product water either as the original biocide or as breakdown products thereof as a result of the distillation process or heating process in the pyrolysis bed.

The build-up of microbial flora in the brine concentrate was not surprising. It was expected that, as the brine increased in total solids content, a concomitant decrease in the microbial population would have occurred. However, high brine concentrations were not reached during the five day run due to withdrawal of brine samples and, as a result, this effect was not noted. The data in Table 4-5 does indicate a drop of about 59.0 percent in the microbial population occurring from the third day to the fifth day. Whether or not this reflects an increase in the total solids content of the brine is not clear from the present data. A similar decrease in microbial counts was observed in the urine feed and thus may reflect a build-up of toxic conditions in both the urine feed and brine concentrate. Further work is required to elucidate this problem.

Microbiological analysis of the product water showed that the water was well within the limits suggested by the Space Science Board (no more than 10 viable micro-organisms per milliliter). Three methods were employed to detect viable micro-organisms in the product water. Undiluted samples (1.0 ml) were analyzed by the pour plate method, these plates being incubated both aerobically and anaerobically. No micro-organisms were detected, as was shown in Table 4-6. Since the numbers of micro-organisms were expected to be low, large quantities of the product water were filtered through 0.45μ millipore filters, with the filters subsequently placed on Tryptic Soy Agar plates. Growth was obtained on the first and second days of the test run. Colony counts showed that the water contained less than 1 micro-organism per milliliter. Identification of these isolates was performed and compared to those species found in both the urine feed and brine concentrate. The organism found in the product water was not found in either the urine feed or brine concentrate, thus it is assumed that the organism isolated from the product water on days 1 and 2 was a chance contaminant and thus does not reflect a breakdown in the system allowing

organisms to obtain entrance to the product water. If such were the case, it would be expected that the microbial counts would be considerably higher and would also reflect the microbial population in kind as found in the urine feed and brine concentrate.

Product water was also inoculated into Thioglycollate broth. Growth in the broth occurred on the second and third days. Identification of the organisms from the broth on day 2 showed it to be the same as that isolated from the millipore filter. Growth in the broth on day 3 was identified as Proteus vulgaris, an organism found in both the urine feed and brine concentrate. However, no growth was obtained on the millipore filter (500 ml product water tested). As is apparent from Table 4-6 it is unlikely that the product water was contaminated either from the urine or the feed tanks. Rather contamination is believed to have occurred during sampling or testing.

The following points summarize the results and conclusions obtained from the microbiological analysis.

Microbial growth in the urine feed is extensive. Further studies are required to reduce this growth, most probably utilizing a biocide. This testing is planned for a later date.

From the microbiological analysis performed on the product water, it is concluded that the quality of the water conformed to both Public Health Standards and to those put forth by NASA.

Chemical Analysis of the Product Water

1. Scope

Chemical analyses of the product water were conducted throughout the test period to evaluate the overall performance of the system. As mentioned previously, pH and conductivity were monitored continuously. Daily samples of the product water were drawn for more comprehensive analysis. Chemical analyses involved determination of the following contaminants:

Nitrate ions

Ammonium nitrogen

Phosphate ions

Urea nitrogen

Phenols

Metal ions (Ni, Fe, Cr, Cu, Zn, Pb, Si)

In addition, total solids content was measured.

2. Methods

Nitrates, ammonium nitrogen, phosphates, urea nitrogen, and phenols were determined by colorimetric techniques. These are procedures which involve reacting the substance to be determined with some compound to produce a color. The intensity of the color produced is directly proportional to the amount of the unknown substance to be determined. The intensity of the color is measured on a spectrophotometer by absorption, and compared to standards of known quantities.

(a) Nitrates--ASTM D 992-52--Colorimetric test using brucine alkaloid and read at 470 mμ on a Beckman DB Spectrophotometer. Standard prepared from potassium nitrate. Accuracy: 0.3 ppm.

(b) Ammonium Nitrogen--ASTM D 1426--Colorimetric test using Nesslers reagent and read at 460 mμ on Beckman DB Spectrophotometer. Accuracy: 1/2 ppm.

(c) Phosphates--ASTM D515--Colormetric test using Vanadomolybdate to develop yellow color and read at 400 mμ on Beckman DB Spectrophotometer. Accuracy: 2 ppm.

(d) Phenols--ASTM D 1783--Colorimetric test using 4-aminoantipyrine to develop color and read at 460 mμ on Beckman DB Spectrophotometer. Accuracy: 5 ppb.

(e) Urea Nitrogen--Dow Diagnostest--Colorimetric test to determine the amount of nitrogen associated with urea in sample. The amount of urea present may be obtained by dividing this number by the molecular weight of nitrogen (14) and multiplying by the molecular weight of urea (60.06). Determination made on Beckman DB Spectrophotometer.

All metal ions were determined by atomic absorption methods. When elements are excited by a flame, they have the ability to absorb light energy of a specific wave length. The amount of energy absorbed is proportional to the amount of ion present, thus providing a method of quantative analysis for that ion. The samples were read directly without dilution or concentration.

Total solids were determined by accurately weighing an empty beaker, boiling 100 ml of the product water to dryness in the beaker, and then re-weighing the beaker to determine the difference (the weight of the solids).

3. Results

The results of the product water quality tests are presented in Table 4-7. Also shown for comparison are the water purity requirements of NASA specification MSC-SPEC-C35 and the water purity standards recommended by the ad hoc panel.

TABLE 4-7

CHEMICAL WATER ANALYSIS

Properties or Constituents	Breadboard Product Water						MSC-SPEC-35 Specification	Ad hoc Panel Standards
	10/5/20	10/7/70	10/8/70	10/9/70	10/9/70	Mixed* Sample		
pH	7.5-7.68	7.6-8.6	7.6-8.8	7.8-8.2	7.8-8.2	7.8-8.2	6-8	5-10
Bacteria, no/ml	None	None	None	None	None	-	None	None
Odor	None	Strong	Strong	Strong	Strong	Strong	None	None
Color (platinum-cobalt units)	None	None	None	None	None	None	15	15
Specific Conductance, μ mhos/cm	70	65	390	1000	-	-	-	1700
Total dissolved solids, ppm	19	52	53	65	-	20	500	1000
Nitrate, ppm	1	2	18	2	1	1	-	10 (as Na)
Ammonia nitrogen ppm	1	2.5	25	15	1000	50	-	-
Phosphate, ppm	<2	<2	<2	<2	30	<2	-	-
Urea nitrogen, mg/ml	-	-	1.82	4.82	9.8	-	-	-
Phenols, ppm	<5	<5	<5	<5	<5	<5	-	-
Nickel, ppm	<0.3	<0.3	-	-	<0.3	<0.3	0.05	-
Iron, ppm	<0.5	<0.5	-	-	<0.5	<0.5	0.3	1.0
Chromium, ppm	<0.2	<0.2	-	-	<0.2	<0.2	0.05	0.05
Copper, ppm	<0.5	<0.5	-	-	<0.5	<0.5	1.0	3.0
Zinc, ppm	<0.2	<0.2	-	-	<0.2	<0.2	5.0	15
Sodium, ppm	0.3	0.5	-	-	<3	<3	-	-
Lead, ppm	<3	<3	-	-	<3	<3	0.05	0.2
Silicon, ppm	16	16	-	-	<4	<16	-	-
Surface Tension, dynes/cm^2	72	71	-	-	52	67	-	-

*Sample taken from product water tank at completion of test.

4. Discussions

As shown in Table 4-7, the water was generally of a high quality with the exception of odors, which were due to overloading the catalytic reactor when large quantities of brine were entrained from the separator. The first occurrence of entrainment was on the second day of the 5-day test, when the brine dump valve opened upon a signal from the controller. Since the waste brine tank was at atmospheric pressure at the time, air entered the brine loop, resulting in large quantities of brine carryover into the vapor loop.

Brine carryover also occurred when the system was shut down momentarily for minor repairs. These incidences were discussed previously. Evidence of heavy carryover was found during inspection of the hardware after the 5-day test.

In the development of the schematic for the flight configuration of the IWRS, provisions were incorporated in the system to prevent carryover which could occur due to

(a) Separator flooding--A solenoid shutoff valve in the feed line will close automatically when separator level reaches a maximum value. This valve serves as a back-up for the normal control valve.

(b) Separator failure--Should the separator fail due to motor failure or separator bearing seizure, a valve in the vapor line will close automatically.

(c) Rapid depressurization of the brine loop--A bleed valve in parallel with the condenser pressure regulator will be used to limit the rate of depressurization of the entire system. Procedures will require that both the vapor and liquid loops be depressurized simultaneously from ambient.

(d) Brine tank overpressurization--A check valve is incorporated in the brine dump line to prevent reverse flow to the brine loop.

With the exception of the presence of ammonia and urea (see Table 4-7) during the latter part of the test, the water quality was exceptionally good and met all the requirements of the specification. Water produced during the shakedown tests with urine had no odor; the two water samples taken during the first day of the 5-day test (before separator flooding) also had a very low ammonia content and no odor.

The problems encountered during the latter part of the test do not involve the process per se, but rather are the result of errors in procedures and oversights in system design. In future development work, provisions will be incorporated in the breadboard unit to prevent such occurrences.

Discussion of System Test Data

Several unique factors contributed to performance characteristic at variance with the expected results. In spite of these anomalies, the system was successful in performing its primary function--production of potable water from urine. In the early part of the test, the water produced met the standards of potability defined by NASA in both chemical and microbiological composition. As mentioned above, procedural problems in the latter part of the test resulted in brine carryover into the vapor loop and contamination of this portion of the breadboard unit.

Throughout the test period, the product water contained no bacteria which had passed through the system from the feed. These results constitute a demonstration of system capability and a verification of the concepts employed.

As a result of the system breadboard tests, greater insight was gained into the processing system performance and operation. The results of the analyses conducted after completion of the 5-day tests are discussed in the following paragraphs. Major topics include

(a) Separator air leakage

(b) Brine carryover

(c) Compressor performance

(d) System thermal performance

1. Separator Air Leakage

Several system operational and performance problems encountered during the 5-day test were a direct result of the phase separator performance. As discussed in Section 3, the condenser vapor side heat transfer coefficient is strongly affected by the amount of non-condensible gases in the vapor. While initial tests showed the separator face seal leakage to be acceptably low (0.0016 lb/hr), separator leakage increased progressively; estimates (from system pressure buildup) of separator leakage made during the 5-day test indicate that as much as 0.15 lb/hr of air leaked through the face seal. Examination of the face seal after the 5-day test showed the separator seal to be badly damaged and supports this estimate. The high leakage rate reduced the vapor heat transfer coefficient by a factor of about 3 to 4, as shown in the data analysis presented in Section 3. It also resulted in a reduction in the partial pressure of the water in the condenser, since the total pressure remained at the selected value of 1.5 psia with the non-condensibles accounting for 15 percent of the total pressure in the condenser, the condensing temperature is lowered from 116 to 110^{0}F, thus reducing the temperature difference from the condensing steam to the brine by approximately 50 percent. The degraded condenser performance caused a shift in the system operating point to a lower mass flow rate. This was brought about because of the higher pressure ratio needed to transfer the

heat in the condenser. This higher pressure ratio moved the operating point of the compressor to a lower flow rate, an off-design condition. Operation at a higher pressure ratio and lower flow rate than optimum, together with compression of the air leaking into the separator, caused a significant increase in compressor power. These performance characteristics, all a result of the single problem--air leakage into the separator--can be averted by utilizing a separator design not requiring rotating seals.

2. Brine Carryover

Generally, the phase separator performed properly during steady-state operation; however, rapid depressurization of the brine loop accounted for the decrease in water quality noted at several points during the test.

Several times during the system test with urine, the gas flow rate in the separator was excessive, causing carryover of brine into the vapor side of the system. This occurred when air was introduced into the system through the dump valve (point B on Figures 4-9 and 4-10) and during rapid depressurization of the separator (points G, H and J on Figures 4-9 and 4-10). The effect of these procedural problems can be seen by noting the conductivity of the reclaimed water in Figure 4-10. The conductivity data also agree with the chemical water analyses of Table 4-7, which show the nitrogen content of the product water increasing from 10/7/70 through 10/9/70. Throughout the three days of testing with urine, prior to point B (two days of which were the urine shakedown test), the water conductivity remained below 100 micromhos/cm. Following the introduction of air into the brine loop at point B, the conductivity of the water increased to about 150 micromhos/cm. The elapsed time between point B and the rapid rise in water conductivity is consistent with the residence time of water in the condenser. Similar responses occurred following the rapid depressurization of the separator at points G, H, and J. The incorporation of a system bleed valve in parallel to the system pressure regulator will preclude this from happening in a flight system. The flow of air into the system through the brine dump valve can be corrected by use of a check valve in the dump line. It should also be noted that the proposed separator design, with a magnetic coupling and pressure shell separate from the rotating bowl, will be less susceptible to these occurrences. The volume between the bowl and shell will provide a plenum chamber with a large surface area for evaporation of any liquid brine which might be carried out of the separator bowl.

3. Compressor Performance

As a result of the increased performance requirements imposed on the compressor by the air leakage problems, it was necessary to operate the compressor at a higher speed. This increase in compressor speed, together with a higher operating temperature than in normal usage, caused a failure of the compressor motor bearings. Failure of these bearings has no significance whatever on the performance as the life of the vortex unit, since in a flight system, a motor designed specifically for this application would be employed. This failure did, however, have an effect on the system test. As indicated in the discussion in Section 3, it is felt that the system shutdown during repair

of the compressor motor contributed directly to the condenser tube fouling experienced shortly thereafter. Tube fouling was a direct result of operation at low temperature and high brine concentration; it is estimated that brine flow rates as low as 70 lb/hr were experienced in the liquid loop following system startup after compressor motor failure.

4. Thermal Performance

As indicated earlier, approximately 6 percent of the water supplied during the system test was carried overboard through the vacuum vent on the condenser. This carryover, excessive for a spacecraft system, is a result of an imbalance in the power and heat leak of the system. If an excess of energy is supplied to the brine loop outside of the condenser, the vapor flow rate will be too high to be totally condensed in the condenser. This condition is aggravated by low heat transfer rates in the condenser and by the prescence of air, as explained above. With low condenser heat transfer rates, the pressure ratio required between the separator and condenser is high, with a fixed condenser pressure; this implies a lower separator pressure and, therefore, a lower liquid loop temperature. The separator temperature will be an average of about 10^{0}F too low. This means that the heat leak from the brine loop is about 25 percent less than anticipated. The total brine loop heat leak is on the order of 150 Btu/hr; therefore, the excess energy of the brine loop over that anticipated is approximately 40 Btu/hr., approximately that required for the amount of carryover experienced. This was further aggravated by the inability to properly control the condenser vapor inlet temperature. As indicated by Figure 4-9, the inlet temperature was consistently in excess of 150^{0}F, the value desired for simulation of the recuperator performance. This contributed an average of 10 to 15 Btu/hr in excess energy, also adding to the water carryover to vacuum. The heat balance of the system is significant only when it is in excess of that which can be absorbed by the brine loop and heat leak in the condenser. When the heat balance is slightly the other way, heat losses exceed power input at the nominal operating condition, the production rate will decrease slightly and system temperatures will adjust to provide a correct balance. When the heat losses are very much larger than the power inputs, as was the case in the early breadboard tests, additional energy must be supplied by heaters to obtain reasonable production rates.

Detailed analyses of heat losses were conducted as part of the preliminary design efforts. The results of these analyses were incorporated in the performance prediction computer program.

By elimination of the air leakage into the separator, the heat transfer capability of the heater-condenser will be increased significantly. It is recommended that the heater-condenser be over-designed to provide a margin of safety so that slight thermal imbalances in the system will not result in water vapor carryover.

5. Semi-Batch Process Control

As mentioned previously, the density sensor count rate was found to be dependent on the liquid level in the phase separator and accurate density measurement at brine loop liquid contents lower than about 500 cc could not be achieved. As a result it was decided to override the automatic control circuitry by manually increasing the count rate at which the brine valve should be signaled to open. This manual adjustment was necessary to prevent brine dump at low salt content.

The characteristics of the density sensor is essentially dependent on the separator bowl geometry and on the internal volume of the entire liquid loop. Redesign of this separator bowl so that the density source x-ray beam be submerged at liquid loop contents as low as 250 cc would improve the density sensor characteristics and divorce density sensing from separator level in the range of liquid volumes encountered in the semi-batch mode of operation.

Many brine samples were drawn from the liquid loop during the 5-day test. The volume of the samples and the sampling frequency had to be reduced to permit buildup of the brine concentration above 25 percent. On the last day of the 5-day test the controller cycled the brine dump valve open at a brine concentration of 40 percent. At that time the control count rate had been adjusted upwards to accommodate the poor density sensor characteristic. Although this adjustment was necessary the semi-automatic cycling of the dump valve by the controller circuitry was demonstrated.

It is recommended that in redesigning the separator attention be paid to the bowl shape to permit density monitoring in the level range from 1000 to 150 cc.

Conclusions and Recommendations

The following conclusions can be drawn from the test data and the discussions presented above:

(a) The system capability to produce very pure water, free of bacteria, has been demonstrated.

(b) The basic hardware approaches selected are satisfactory. Extensive testing at the system level has established the requirements for design improvements, especially to eliminate phase separator air leakage.

(c) Generally, the system arrangement and control scheme has been demonstrated successfully. Addition of hardware to prevent brine carryover in the liquid loop, due to component failure or procedural error, is indicated.

On the basis of the system-level test program conducted and the analyses performed to elucidate the system behavior and the performance of specific components in the system, the following recommendations are made. These recommendations involve system arrangement as well as component design, since the performance of any of the major system components is very much related to the performance of the entire system. Components are considered here in terms of system effects; reference is made to Section 3 for further component-level recommendations.

(a) Provisions must be incorporated to prevent air leakage. In this respect, particular attention must be paid to the brine loop where air leakage could result in liquid carryover.

(b) Hardware must be included in the system to prevent brine carryover into the vapor loop due to failure or operator error. The following equipment is recommended:

(1) A check valve in the brine dump line to prevent reverse flow.

(2) A solenoid shutoff valve in the vapor delivery line to the compressor. This valve would be actuated closed in the event of separator malfunction.

(3) A solenoid shutoff valve in the brine loop feed line. This valve is a backup to the normal control valve.

(4) A bleed valve to provide limited and controlled depressurization capability of the brine loop.

(c) In packaging the system components, careful attention must be paid to thermal energy balance to obviate water vent overboard. Insulation will be required consistent with the power expended in the system components and the thermodynamic limitations of the heater-condenser.

(d) Compressor performance improvement is desirable. A motor specifically designed for this unit is necessary to assure long life.

(e) The phase separator proved to be very troublesome during system tests. Component-level tests indicated the need for redesign to reduce entrainment. System-level tests showed conclusively that the unit as currently designed is not suitable for even a breadboard unit, due to high air leakage through the face seal. Design improvement recommended involve complete redesign to (1) eliminate the face seal by use of a magnetic drive, (2) accommodate the density controller, and (3) eliminate braze joints to prevent corrosion.

(f) The heater-condenser should be improved. The low thermal performance of the system during tests (as manifested by lower processing rate than design and relatively high vapor sent overboard) are not attributed to this unit, but rather to the large air leakage into the phase separator. Improvements are recommended to include (1) a new configuration to reduce heat leak to a minimum (see Figure 3-23) and (2) a larger unit with increased heat transfer performance to provide a safety factor and eliminate the possibility of vapor venting overboard.

(g) The reactor performed satisfactorily except when carryover occurred. Even under overload conditions, the reactor proved to be an effective barrier in preventing bacteria entrainment to the potable water portion of the loop. Component-level development requirements are given in Section 3.

(h) The control system performance is judged to be satisfactory. The nucleonic technique of level and density control was demonstrated with the limitations imposed on the density sensor by the phase separator bowl geometry. The level sensor performed in a very satisfactory manner. The logic circuitry designed and developed for semi-batch control of the water recovery process was demonstrated satisfactory.

COMPONENT DETAIL DESIGNS

Component detail-design activities were held at a minimum compatible with fabrication under the direct supervision of program engineering personnel.

All drawings and sketches, from which the system components were built, are transmitted to NASA under separate package. A complete list of these drawings is given below.

811300	Accumulator Outline - Cyclic
811301	Accumulator Assembly - Cyclic
PA110312	Coil - Condenser
PA97015	Water Condenser/Separator Assembly
PA97012-1	Condenser Assembly
PA97012-2	Condenser Assembly
PA97008	Coil Assembly
PA97009	Ring
PA97010	Cover Assembly
PA97011	Pan Assembly
PA97013	Plate Porous
PA97014	Gasket
PA97016-A	Absorbent Strip
PA97017-A	Absorbent Pad
PA97018	Adapter
PA97042	Filter
X801391	Compressor, Vortex, Two Stage
PA110315	Separator, H_2O Recovery
PA77081	Upper Housing Separator
PA77082	Sleeve Separator
PA77083	Cover Outer Container
PA77084	Face Seal, Upper
PA77085	Face Seal, Lower
PA77086	Drum Cover Centrifuge
PA77087	Flange Drum Upper
PA77088	Cover Lower Outer Container

PA77089	Housing Flange
PA77091	Bottom Flange, Drum
PA77092	Flange Main Housing
PA77094	Drum Half
PA77095	Drum Centrifuge
PA77096	Braze Assembly, Drum
PA80274	Pitot Tube
PA80275	End Plate
PA80276	Return Tube
PA90340	Tube, Outer Housing
PA90341	Main Housing
PA90342	Fitting End
PA90344	Nut
PA95440	Frame Demistor
PA110314	Shaft
PA80278	Filter Support
PA95472	Plate Drum
PA90343	Spacer
SK 041670	Heater Assembly
SK 041770	Spacer Heater
SK 040070	Water Control Electronics
SK 050070	Water Control Logic

SYSTEM PERFORMANCE OPTIMIZATION

Introduction

The system computer program, described in detail in Appendix B of this report, was used to investigate system performance variations as a result of component performance or configuration changes and system operating parameter changes. The variations considered in this analysis were:

(a) Component variations:

Condenser tube diameter

Compressor pressure ratio

Separator speed/brine flow rate

(b) Operating condition variations:

Condenser vent pressure

Brine concentration

Baseline System

The system defined as the baseline for this analysis is described here to provide a point of reference to evaluate the variations listed above. The analysis was restricted to the IWRS processing loop, including the following components:

(a) Separator

(b) Compressor

(c) Recuperator-Reactor

(d) Flash Valve

(e) Heater-Condenser

(f) Interconnecting lines

1. Separator

The separator configuration assumed for this analysis is that which was described as the recommended separator in Section 3 of this report. The primary characteristics significant in this analysis are:

Drum diameter, 6.0 in.

Drum length, 4.0 in.

Pitot tube radius, 2.7 in.

Heat leak, 1.0 Btu/hr ^{o}F

2. Compressor

The performance of the compressor used as the baseline for the performance analysis is shown in Figure 4-14. The power curve of Figure 4-14 is the power required by the compressor only and does not include the power losses of the bearings, the magnetic coupling, or the motor. The bearing and coupling losses are determined separately in the computer program.

3. Recuperator-Reactor

The baseline recuperator design is a shell-and-tube, cross-counter-flow heat exchanger. The unit contains a catalyst bed at one end. Inlet flow is over the tube bundle. An electrical heater is imbedded in the catalyst bed to maintain the hot end temperature. The entire unit is insulated to minimize heat loss to ambient. Table 4-8 below summarizes the characteristics of the recuperator/catalyst bed unit.

4. Heater-Condenser

The condenser is a single-tube heat exchanger with brine flowing on the inside and vapor flowing over the outside of the tube. The flow is arranged in a counter-flow pattern to provide the maximum effectiveness. The tube is arranged in a cylindrical coil with the vapor flowing between adjacent passes of the tube. The spacing of the tubing is varied to provide a reasonable vapor velocity throughout the length. The spacing is maximum at the inlet and minimum at the outlet.

The computer program treats the condenser tube in seven increments and performs heat transfer analysis on each increment. Table 4-9 below shows the tube length and spacing for these increments. The tube dimensions are: length, 144 in.; diameter, 0.219 O.D.; wall thickness, 0.016 in. The computer program uses the heater-condenser geometry of the breadboard unit rather than that shown in Figure 3-23. Because of the nature of the process taking place in that unit the actual geometry of the heater-condenser will not affect performance appreciably.

Interconnecting Lines

The lines joining the system components are also considered in this analysis. The line lengths used for the baseline system are summarized below in Table 4-10. Very conservative tube lengths were assumed.

In addition to the line lengths listed below, an equivalent length of line is used in the program to simulate a shutoff valve between the separator and compressor. Equivalent lengths are also used in the brine line to simulate two 90-degree bends between the separator and condenser and also two 90-degree bends within the condenser.

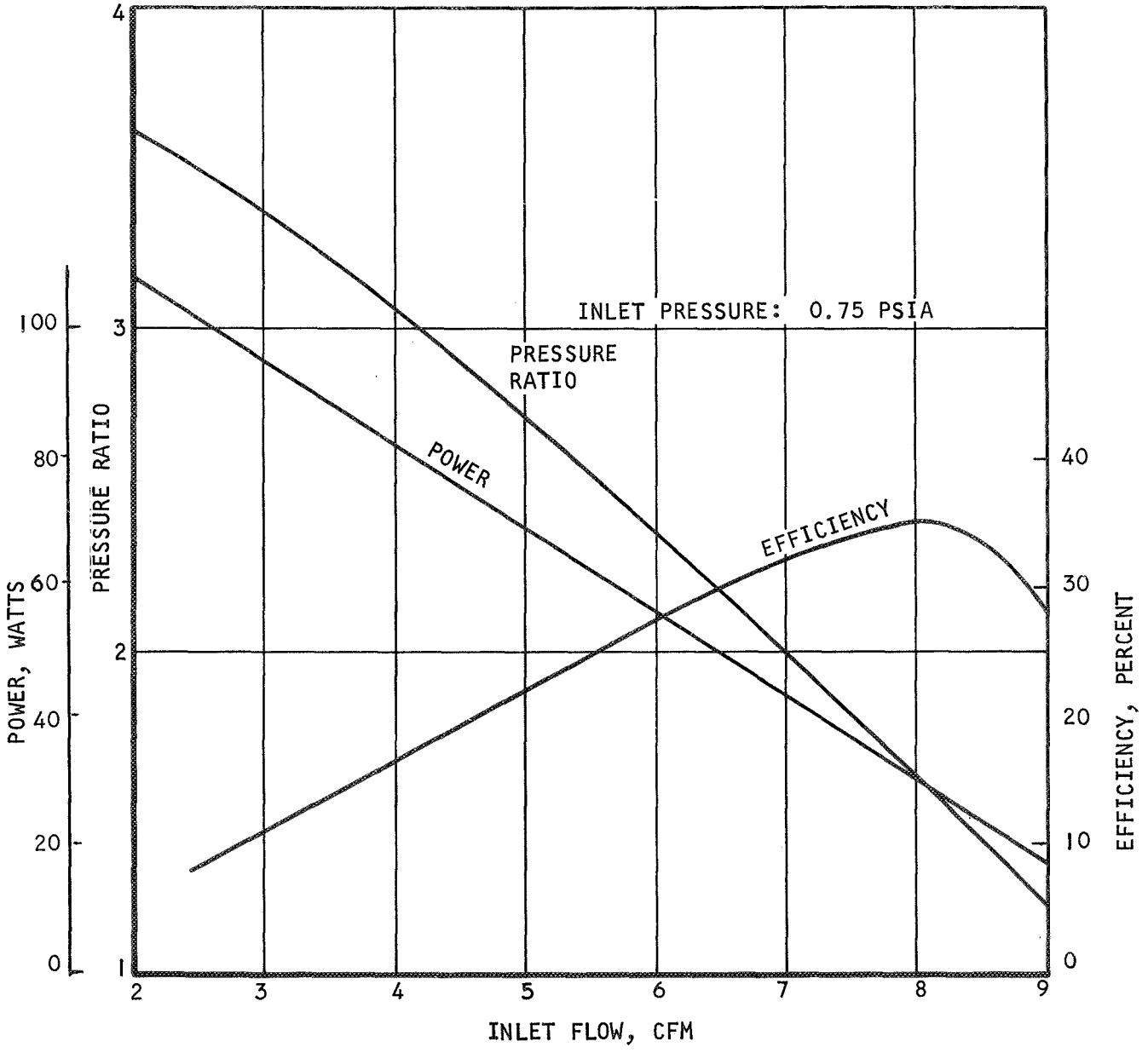


Figure 4-14. Compressor Performance

TABLE 4-8

RECUPERATOR AND CATALYST BED CHARACTERISTICS

Recuperator	
Number of tubes	124
Tube length	20 in.
Tube diameter	0.125 in. O.D.
Tube wall thickness	0.005 in.
Tube bundle pitch (1)	0.1875 in.
Number of passes on shell side	16
Flow area/pass	0.94 $in.^2$
Number of baffles	15
Flow area/baffle	2.16 $in.^2$
Shell diameter	3.0 in.
Shell thickness	0.030 in.
Catalyst Bed	
Bed diameter	2.25 in.
Bed length	3.0 in.
Screen mesh	20 wires/in.
Wire diameter	0.016 in.
Number of screens	94

(1) Tubes are arranged in the form of an equilateral triangle with the pitch, defined as the length of one side of the triangle (center to center).

TABLE 4-9

CONDENSER CHARACTERISTICS

Increment	Length, in.	Spacing, in.
1	32.7	0.50
2	27.7	0.50
3	23.3	0.40
4	19.5	0.40
5	16.1	0.22
6	13.2	0.22
7	11.5	0.22

TABLE 4-10

INTERCONNECTING LINES CHARACTERISTICS

Line	Length, ft	Inside Diameter, in.
Vapor Lines:		
Separator to compressor	2	0.45
Compressor to recuperator	6	0.45
Recuperator to condenser	6	0.45
Brine Lines:		
Separator to condenser	6	0.20
Condenser to separator	6	0.20

Performance Analysis

With the system configured as described above, the control system will function in a semi-batch mode of operation where the brine concentration will vary from essentially zero at start of operation to 50 percent just prior to the dump cycle. During continuous operation, the system will operate between 17 and 50 percent concentration. However, the majority of water will be removed with brine concentration between 17 and 25 percent. Therefore, during the investigation of other system parameters, the brine concentration will be fixed at 20 percent. This concentration was selected as the design point for the system. Performance as a function of brine concentration is discussed later in this section.

Figure 4-15 is a schematic of the processing unit performance at 20 percent brine concentration. Figure 4-16 shows the computer printout for this case. The case represents a nominal run situation for the processing unit and will be the basis for comparison of the other cases. The power of the compressor and separator given in Figure 4-14 does not include the motor efficiency. A motor efficiency of 70 percent was assumed to obtain the power numbers shown in Figure 4-15.

1. Component Variations

Since one of the critical components in the system is the compressor, the effect of the compressor performance on system performance was examined. The baseline compressor performance curve was increased by 10 and 20 percent (10 and 20 percent higher pressure ratio at a given flow rate). Figure 4-17 shows the water production rate as a function of compressor performance. As indicated by Figure 4-17, although the pressure ratio for a given flow was increased by 20 percent, the resulting increase in water production rate is only about six percent. This is the result of an adjustment of the entire system operating level to accommodate the change in compressor performance. The separator pressure is slightly lower, with the result that the compressor pressure ratio is 1.64 versus 1.59 for the nominal compressor performance. These data as well as other system parameters are shown in Figure 4-18, showing system performance with compressor performance 20 percent greater than nominal.

The second critical component which was analyzed is the condenser. This component, more than any other, controls the overall production rate of the system. In order to increase the system efficiency, a higher brine flow rate and more heat transfer area would be beneficial. Both of these are achieved by increasing the diameter of the heat exchanger tube. The resulting system performance is shown in Figure 4-19. As indicated by Figure 4-19, there is significant potential for improved system efficiency by increasing the heat exchanger tube diameter. This, however, cannot be realized on the system because, in spite of the increased brine flow rate, the fluid velocity in the tube is decreased. The fluid velocity must be maintained in order to prevent deposition of solids and blockage of the tube.

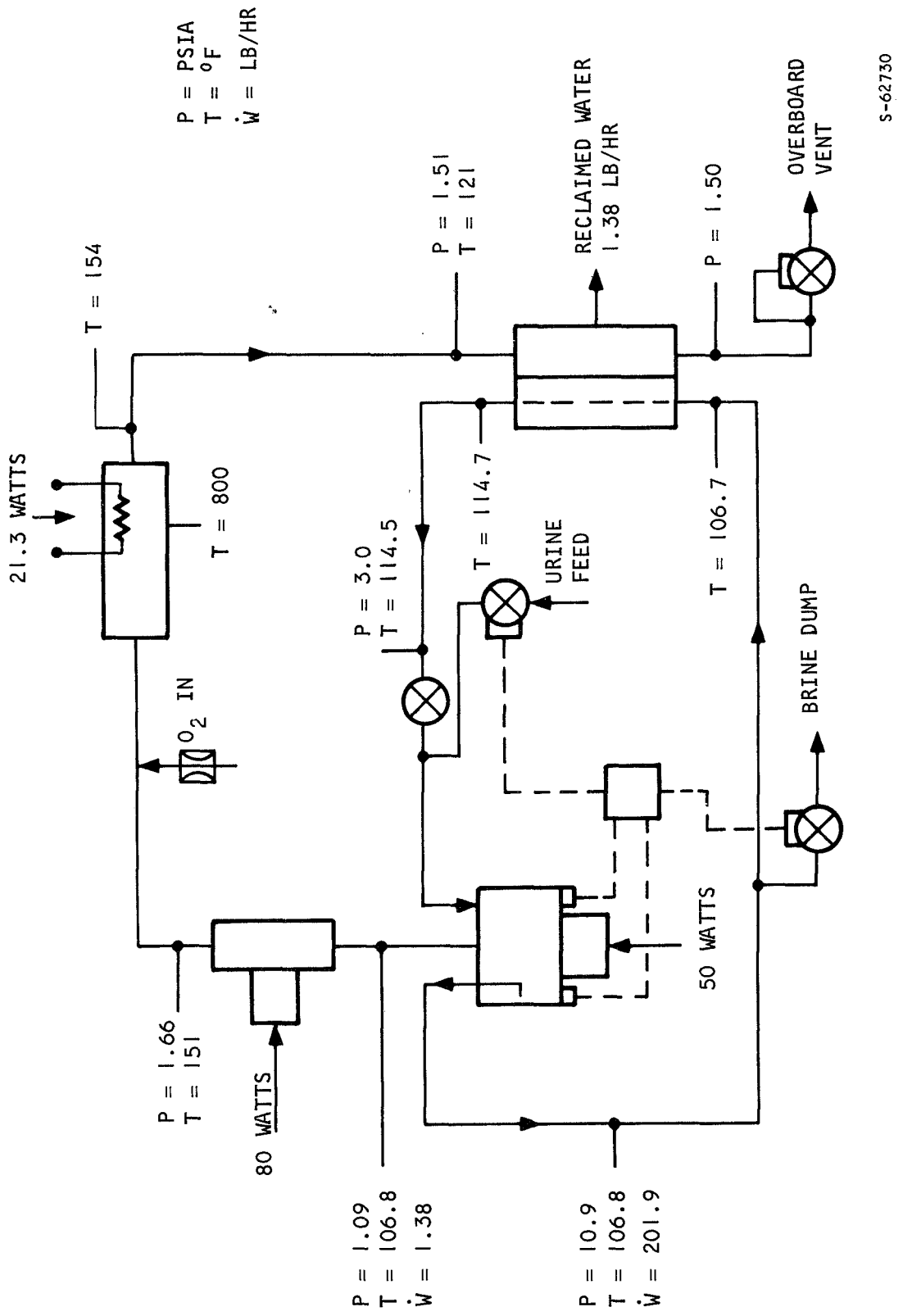


Figure 4-15. Baseline System Performance

SYSTEM OPTIMIZATION NOMINAL SYSTEM RUN

CONFIGURATION DATA

SEPARATOR

ROTATING DRUM WITH PITOT TUBE LIQUID PICKUP

DRUM DIAMETER	=	6.0000 INCHES	PITOT HEAD COEFFICIENT	=	.1354
DRUM LENGTH	=	4.0000 INCHES	PITOT DRAG COEFFICIENT	=	.1256
PITOT TUBE RADIUS	=	2.7000 INCHES	MINIMUM SEPARATOR VOLUME	=	14.1372 CU.IN.
HEAT LEAK TO AMBIENT	=	1.0000 BTU/HR/F			

COMPRESSOR

TWO STAGE VORTEX WITH SINGLE SIDED WHEELS

HEAT LEAK TO AMBIENT = 2.0000 BTU/HR/F

FLOW(CFM)	PRESS RATIO	POWER(WATTS)
2.0000	3.6000	108.0000
3.0000	3.3600	95.0000
4.0000	3.0600	82.0000
5.0000	2.7200	69.0000
6.0000	2.3600	56.0000
7.0000	2.0000	43.0000
8.0000	1.6000	30.0000
9.0000	1.2200	17.0000

RECUPERATOR

CROSS-COUNTER FLOW SHELL TUBE EXCHANGER WITH INLET ON SHELL SIDE

NUMBER OF TUBES	=	124.0000	FLOW AREA ON SHELL SIDE	=	.0065 FT-FT
NUMBER OF PASSES	=	16.0000	FRONTAL AREA SHELL SIDE	=	.0200 FT-FT
TUBE LENGTH	=	20.0040 INCHES	BAFFLE FLOW AREA	=	.0150 FT-FT
TUBE DIAMETER	=	.1100 INCHES	AXIAL CONDUCTION AREA	=	.0041 FT-FT
HEAT LEAK TO AMBIENT	=	.1200 BTU/HR/F	AXIAL COND CONDUCTIVITY	=	7.0000 BTU/HR/FT/F

CATALYST BED

WIRE MESH CATALYST BED WITH FLOW ALONG AXIS

BED LENGTH	=	3.0000 INCHES	WIRE DIAMETER	=	.0160 INCHES
BED DIAMETER	=	2.2500 INCHES	MESH SIZE	=	20.0000 WIRES/IN

CONDENSER

SPIRAL TUBE HX-BRINE ON INSIDE-STEAMON OUTSIDE -COUNTER FLOW

TUBE LENGTH	=	144.1000 INCHES	FOULING FACTOR	=	.0001
TUBE DIAMETER	=	.1870 INCHES	HEAT LEAK TO AMBIENT	=	1.3000 BTU/HR/F

Figure 4-16. Baseline System Configuration and Performance

FLUID LINES

	LENGTH(FT)	DIAMETER(IN)	UA(BTU/HR/F)
BRINE LINES			
CONDENSER TO FEED	2.0000	.2000	.2600
FEED TO SEPARATOR	2.0000	.2000	.2600
SEPARATOR TO DUMP	2.0000	.2000	.2600
DUMP TO CONDENSER	2.0000	.2000	.2600
VAPOR LINES			
SEPARATOR TO COMPRESSOR	14.0000	.4500	.0000
COMPRESSOR TO RECUPERATOR	6.0000	.4500	.4000
RECUPERATOR TO CONDENSER	6.0000	.4500	.3000

PERFORMANCE DATA

OPERATING CONDTIONS

SEPARATOR LEVEL	=	50.0000 CU.IN	AMBIENT TEMPERATURE	=	70.0000 DEG F
BRINE CONCENTRATION	=	20.0000 PERCENT SOLIDS	FEED TEMPERATURE	=	70.0000 DEG F
FEED CONCENTRATION	=	4.0000 PERCENT SOLIDS	VENT PRESSURE	=	1.5000 PSIA
CATALYST TEMPERATURE	=	800.0000			

SYSTEM PERFORMANCE SUMMARY

WATER PROD. RATE	=	1.3836 LB/HR	SEPARATOR POWER	=	34.8470 WATTS
SEPARATOR PRESSURE	=	1.0940 PSIA	COMPRESSOR POWER	=	55.5105 WATTS
COMPRESSOR PRESS RATIO	=	1.5882	CATALYST/RECUP. POWER	=	21.2819 WATTS
BRINE FLOW RATE	=	201.8750 LB/HR	VAPOR CARRYOVER	=	.0000 LB/HR

SYSTEM STATE POINTS		PRESSURE(PSIA)	TEMPERATURE(DEG F)
1	INLET TO FLASH VALVE	2.9957	114.5610
2	OUTLET OF PITOT TUBE	10.9626	106.8489
3	BRINE INLET TO CONDENSER	10.0441	106.7386
4	BRINE OUTLET FROM CONDENSER	5.6858	114.6948
5	SEPARATOR VAPOR OUTLET	1.0940	106.8489
6	INLET TO COMPRESSOR	1.0453	106.8489
7	OUTLET OF COMPRESSOR	1.6601	150.9893
8	RECUPERATOR INLET	1.6459	119.3063
9	CATALYST BED INLET	1.6227	765.3000
10	CATALYST BED OUTLET	1.5219	800.0000
11	RECUPERATOR OUTLET	1.5194	154.0062
12	CONDENSER VAPOR INLET	1.5038	121.3625

COMPONENT PERFORMANCE DATA

SEPARATOR

SPEED	=	1800.0000 RPM	BRINE OUTLET PRES	=	10.9626 PSIA
POWER	=	34.8470 WATTS	BRINE TEMPERATURE	=	106.8489 DEG F
VAPOR PRESSURE	=	1.0940 PSIA	HEAT LEAK	=	36.8489 BTU/HR

Figure 4-16 (Continued)

COMPONENT PERFORMANCE DATA

COMPRESSOR

INLET PRESS	= 1.0453	PSIA	POWER	= 55.5105	WATTS
OUTLET PRESS	= 1.6601	PSIA	ADIABATIC EFF.	= 24.1417	PERCENT
PRESS RATIO	= 1.5882		HOUSING TEMP.	= 150.9893	DEG F
VOLUME FLOW	= 8.0309	CFM	HEAT LEAK	= 161.9141	BTU/HR

COMPONENT PERFORMANCE DATA

RECUPERATOR

INLET TEMP.	= 119.3063	DEG F	INLET PRESS.	= 1.6459	PSIA
OUTLET TEMP.	= 154.0062	DEG F	OUTLET PRESS.	= 1.5194	PSIA
EFFECTIVENESS	= .9490		SHELL SIDE DEL P	= .0232	PSID
HEAT LEAK	= 48.8404	BTU/HR	TUBE SIDE DEL P	= .0025	PSID
POWER	= 21.2819	WATTS			

CATALYST BED

INLET TEMP.	= 765.3000	DEG F	BED DELTA P	= .1009	PSID
INLET PRESS.	= 1.6227	PSIA			

COMPONENT PERFORMANCE DATA

CONDENSER

BRINE FLOW	= 201.8750	LB/HR	VAPOR FLOW	= 1.3836	LB/HR
BRINE DELTA P	= 4.3583	PSID	VAPOR INLET P	= 1.5038	PSIA
BRINE DELTA T	= 7.9562	DEG F	VAPOR DELTA P	= .0073	PSID
BRINE H	= 850.7368	BTU/HR/FT/FT/F	VAPOR SATUR T	= 115.6034	DEG F
BRINE INLET T	= 106.7386	DEG F	VAPOR H	= 2214.9348	BTU/HR/FT/FT/F
HEAT LEAK	= 59.2943	BTU/HR			

LINE DATA

	PRESSURE DROP(PSID)	HEAT LEAK(BTU/HR)
CONDENSER TO FEED	.4483	11.6206
FEED TO SEPARATOR	.4484	11.6032
SEPARATOR TO DUMP	.4592	9.5807
DUMP TO CONDENSER	.4593	9.5664
SEPARATOR TO COMPRESSOR	.0488	-.0000
COMPRESSOR TO RECUPERATOR	.0142	26.0591
RECUPERATOR TO CONDENSER	.0156	20.3053

Figure 4-16 (Continued)

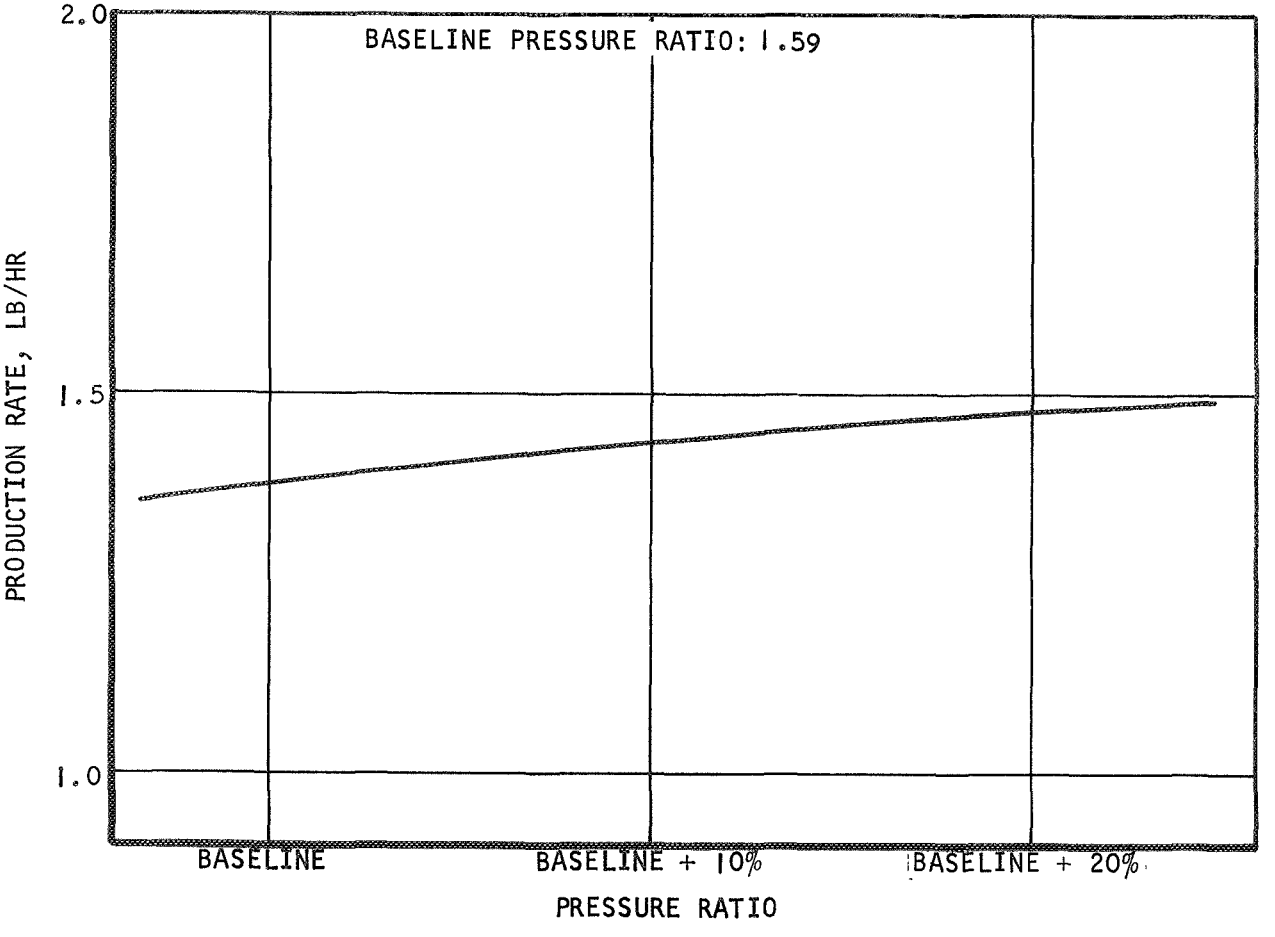


Figure 4-17. Effect of Compressor Performance

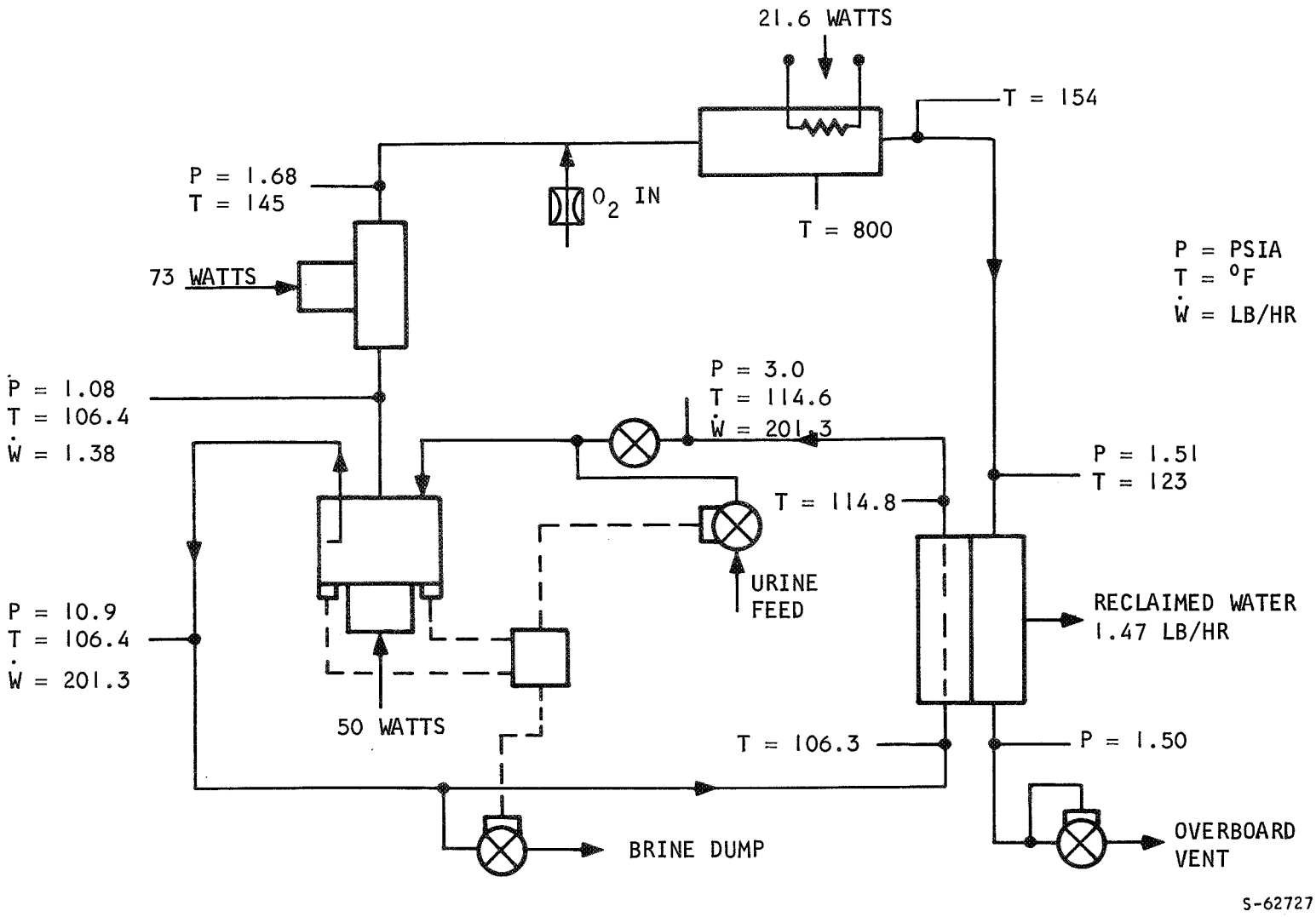


Figure 4-18. System Performance with 20 Percent Increase in Compressor Pressure Ratio

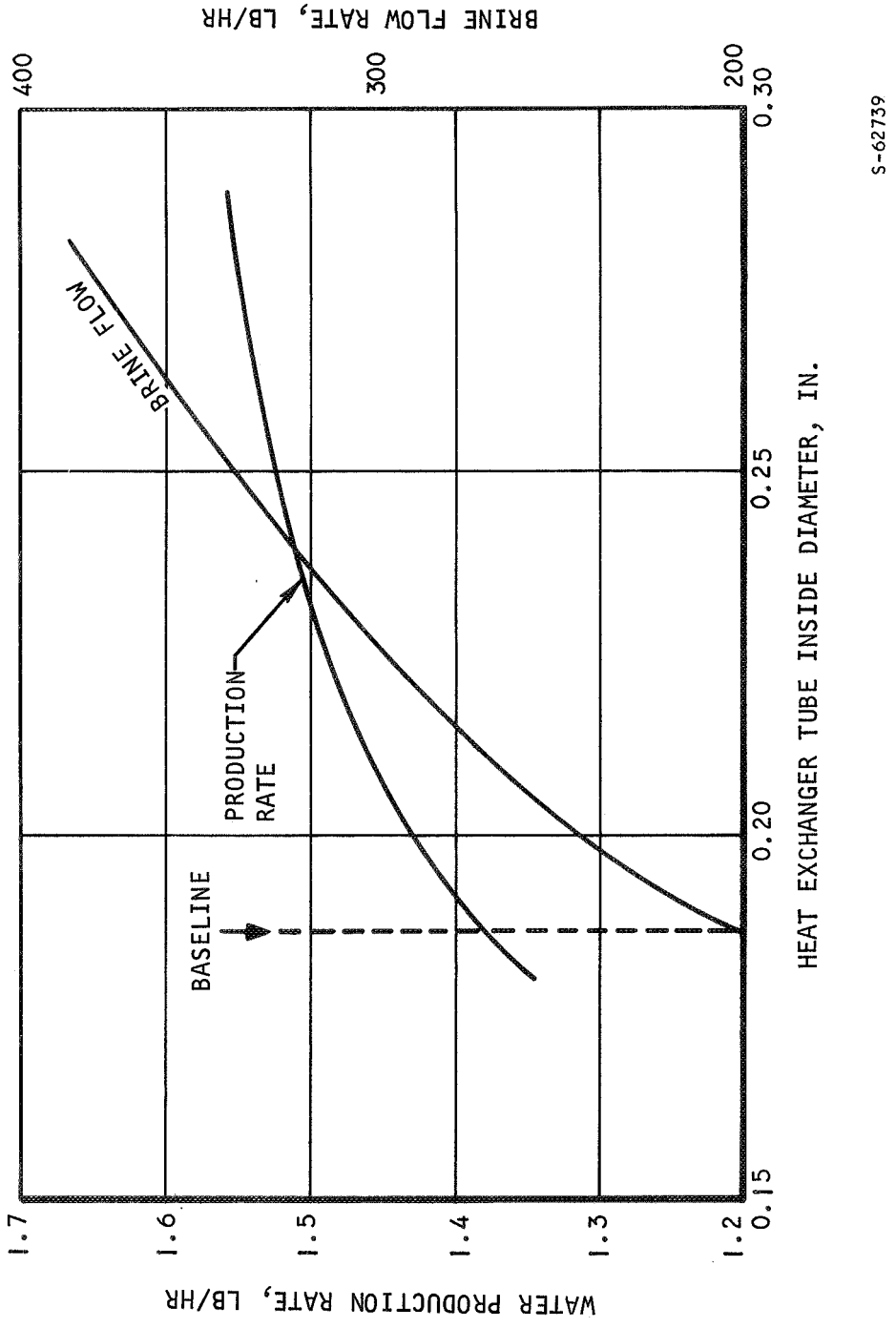


Figure 4-19. Effect of Heater-Condenser Tube Diameter

Separator speed was also varied to determine the effect on system performance. This has much the same effect as increasing the heat exchanger tube diameter without decreasing the fluid velocity. Figure 4-20 shows the system performance for a separator speed of 2000 rpm (from the design value of 1800 rpm). The water production rate is increased from 1.38 to 1.44 lb/hr. This, however, requires an increase in system power of 11 watts. This represents a disproportionate power increase by comparison with production rate increase and therefore a decrease in system efficiency.

2. Operational Variations

The system described as the baseline system represents a near optimum design within the limitations of the performance of the components. Increased system efficiency can be obtained only by increasing the efficiency of individual components. It is therefore of interest to investigate the system performance in response to variations in operating parameters. Essentially two parameters, brine concentration and condenser pressure, can be varied during system operation. Condenser pressure can be adjusted to vary system output to maintain the proper water inventory. Brine concentration will vary during operation in response to the system feed and dump control.

If the system will operate satisfactorily over a range of condenser vent pressures, the water production rate can be adjusted to meet the desired rate determined by waste water production. A system such as this must be able to accommodate a range of production rates since starting and shutdown to control process rate of the system require somewhat extensive procedures. Computer simulation runs were made with system vent pressures of 1.0 to 2.0 psia. Figure 4-21 shows the resulting water production rate versus vent pressure. As indicated, the water production rate will vary from 1.0 lb/hr at 1.0 psia vent pressure to 1.73 lb/hr at 2.0 psia vent pressure. The variation will be adequate for good inventory control of waste and product water storage. Figure 4-22 shows system performance at 1.0 psia vent pressure. Although the production rate is variable, the specific power consumption (power consumption/water production rate) is higher at the lower pressures. Figure 4-23 shows specific power consumption as a function of condenser pressure. The specific power consumption decreases as the pressure, hence flow rate, is increased. This is primarily due to spreading the fixed power of the system (the separator and the heat leak of the recuperator) over a higher flow rate. This benefit tends to disappear as the operating pressure significantly differs from the nominal value due to operation of the compressor at off-design conditions.

During normal system operation, the brine concentration will vary in response to the control system feed and dump cycling. The control sequence is discussed in some detail earlier in this report. From the control system analysis and the volume of brine in the separator and brine lines, it was determined that the brine concentration will vary from 17 to 25 percent while urine is fed into the system. Between 25 and 50 percent, no feed is provided and the separator level is decreased. At 50 percent, some brine is dumped; the remaining brine is diluted with feed urine to bring the concentration back to 17 percent.

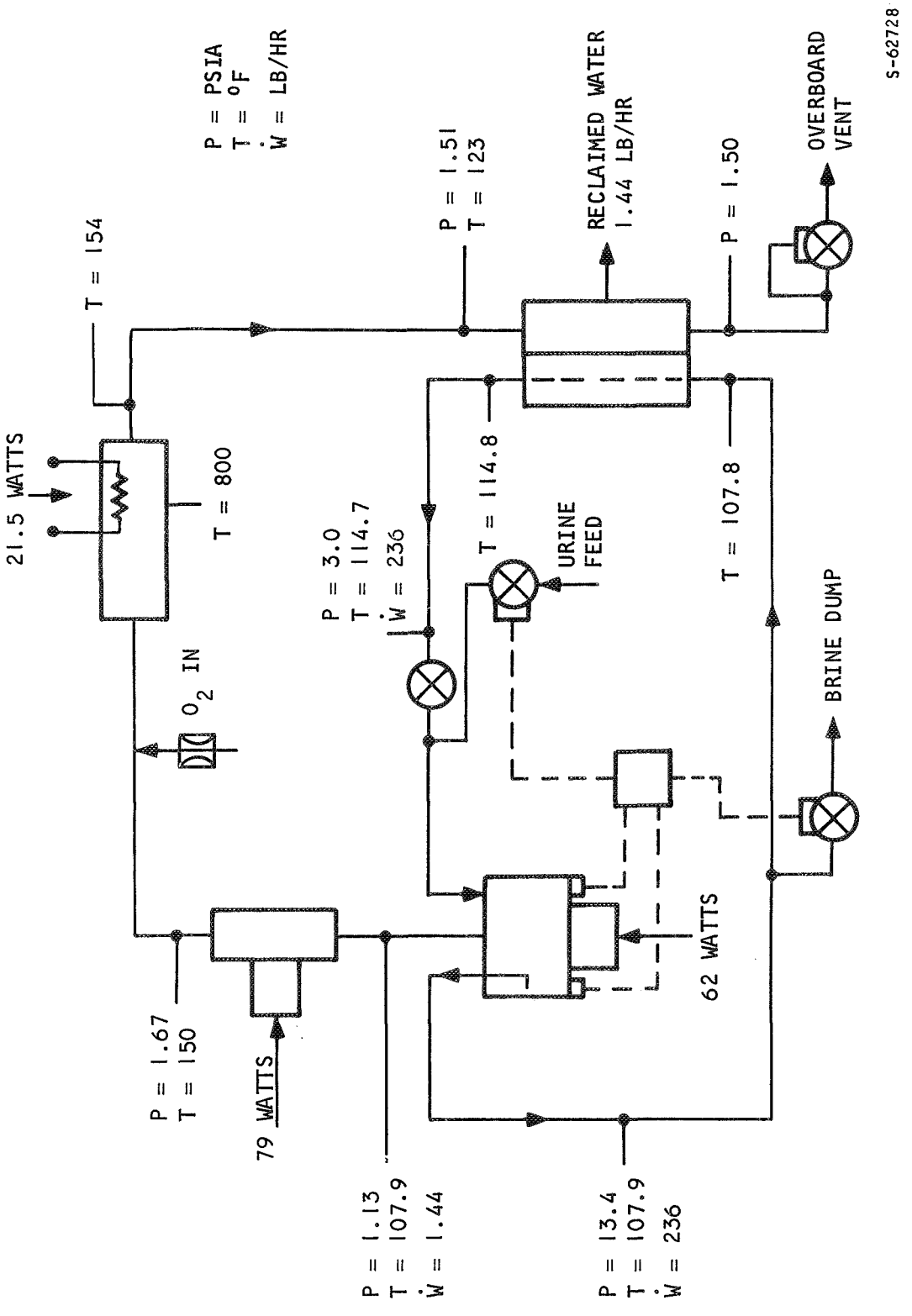


Figure 4-20. System Performance with Separator Speed of 2000 rpm

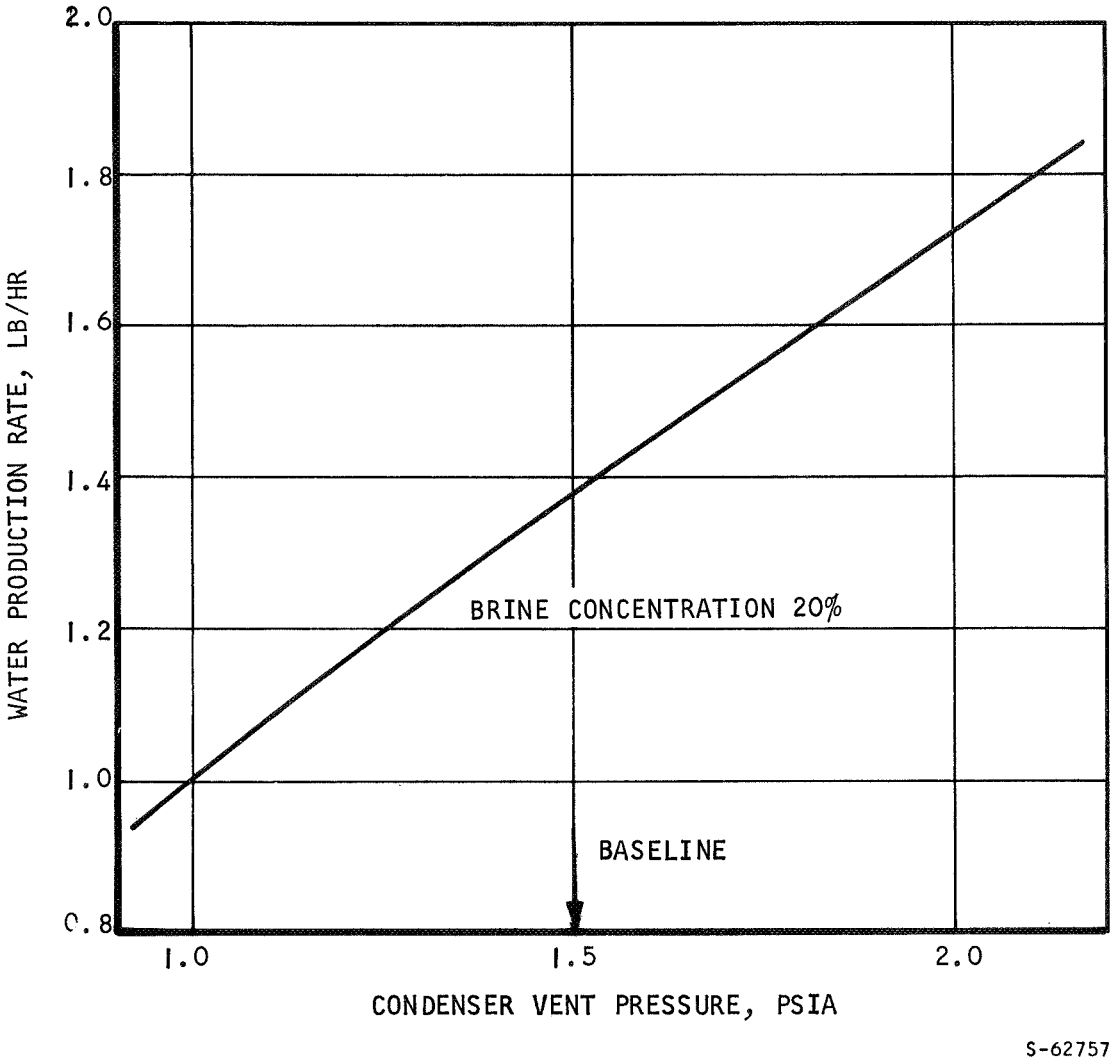


Figure 4-21. Water Production Rate vs Condenser Vent Pressure

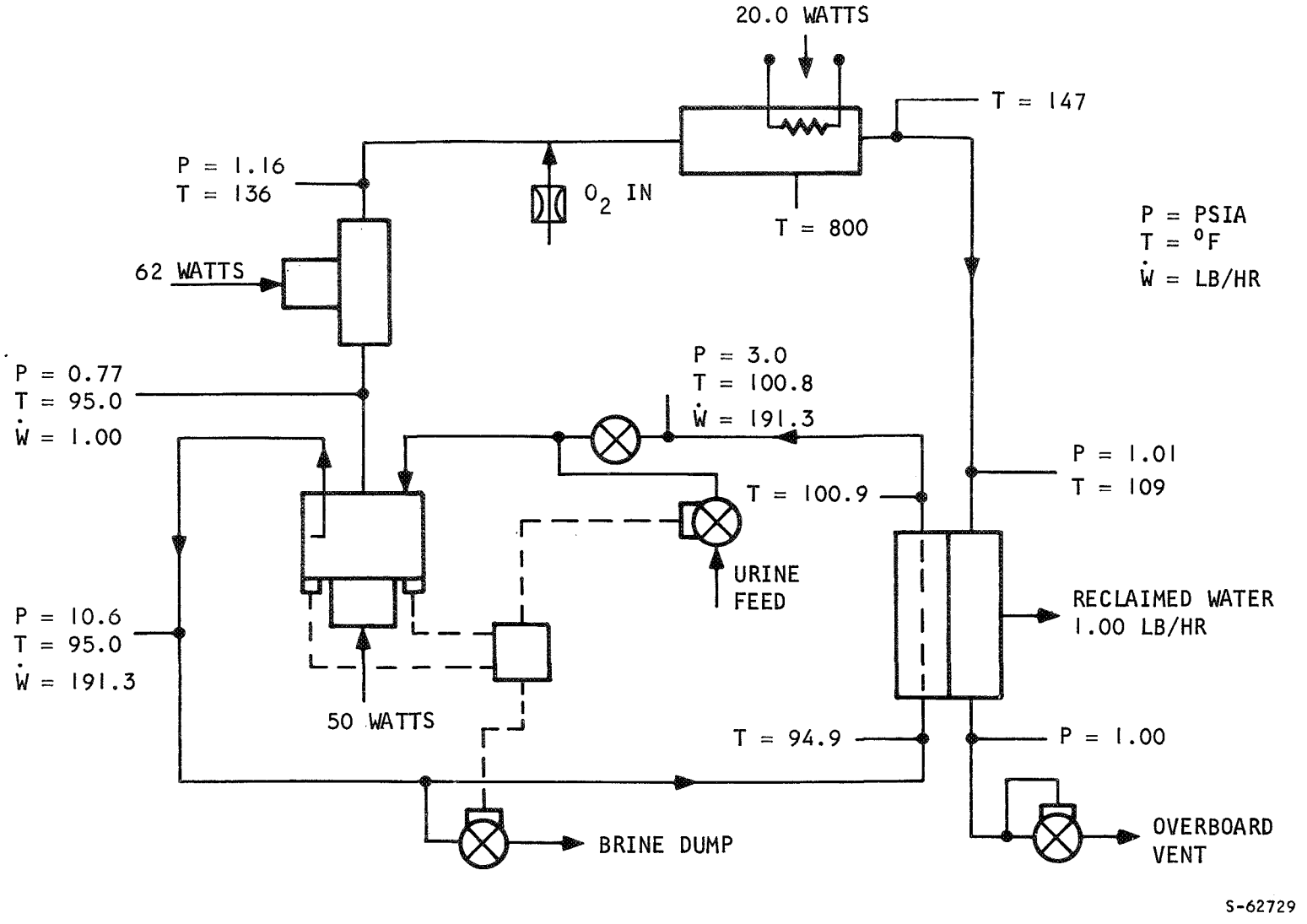


Figure 4-22. System Performance at 1.0 psia Condenser Vent Pressure

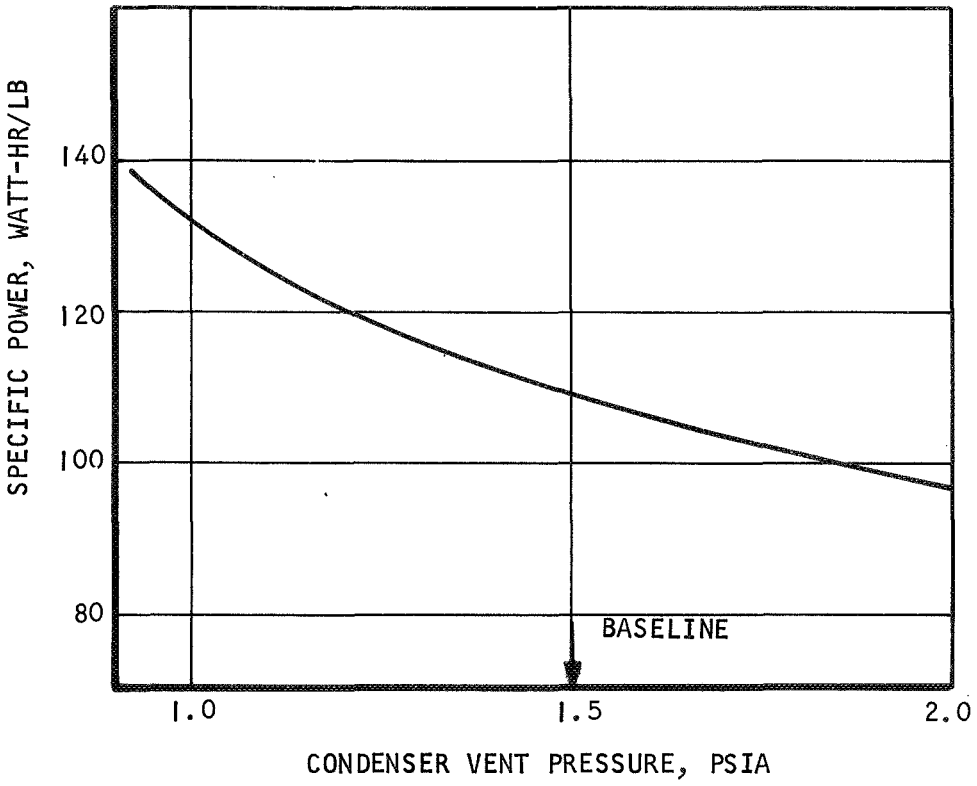


Figure 4-23. Specific Power vs Vent Pressure

The limits of the operational cycle are summarized in Table 4-11 below.

TABLE 4-11

SYSTEM PARAMETERS AT LIMITS OF CONTROL SYSTEM

System Phase	Brine Concentration, percent	Separator Level, $in.^3$
Startup	0	50
End of Dilution	17	50
End of Feed	25	50
Start of Dump	50	25

Figure 4-24 shows the water production rate as a function of brine concentration. This figure clearly shows the penalty involved in continuous operation at high concentrations. Figures 4-25, 4-26, 4-27, and 4-28 show the system performance for the state points corresponding to the control limits (0, 17, 25 and 50 percent brine concentration). An even more significant indication of the penalty involved in operation at high brine concentrations is given by Figure 4-29. This shows that although system power does not vary significantly over the operational range of brine concentrations, the specific power of the system nearly doubles in going from concentrations near zero to concentrations near 50 percent. Computer output of the system analysis for brine concentrations of 0 and 50 percent are shown in Figures 4-30 and 4-31, respectively. These can be compared to Figure 4-16 to ascertain the variation of individual system parameters with concentration.

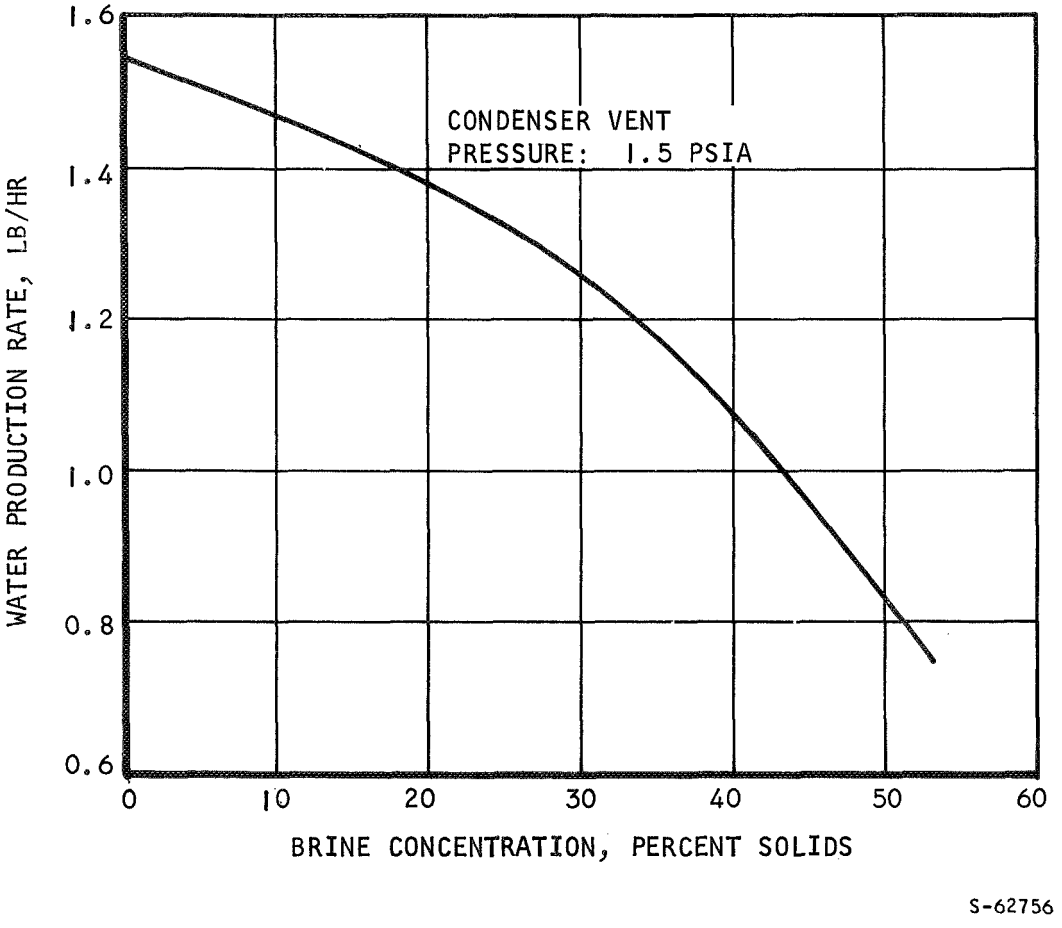


Figure 4-24. Water Production Rate vs Brine Concentration

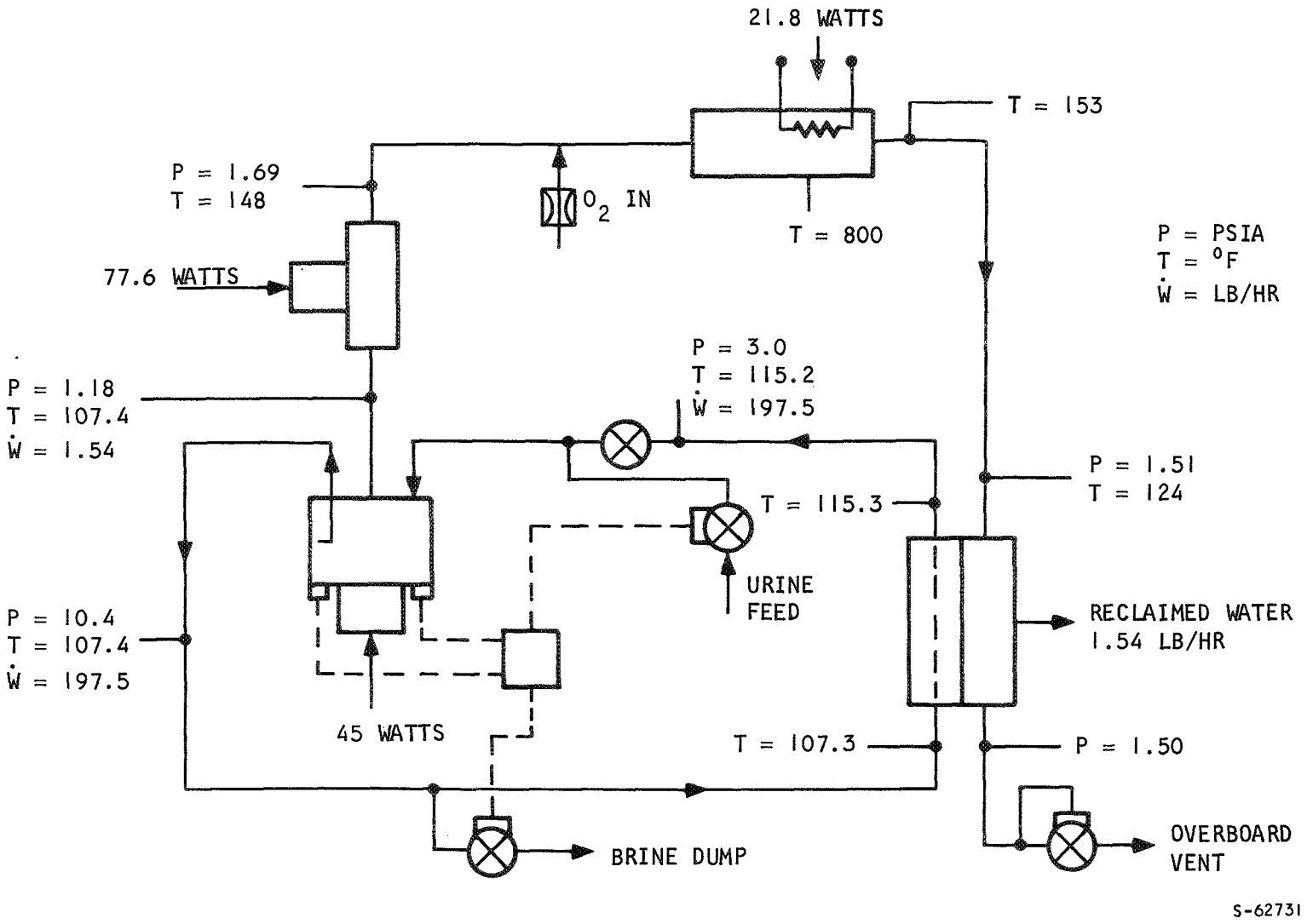


Figure 4-25. System Performance at 0 Percent Brine Concentration

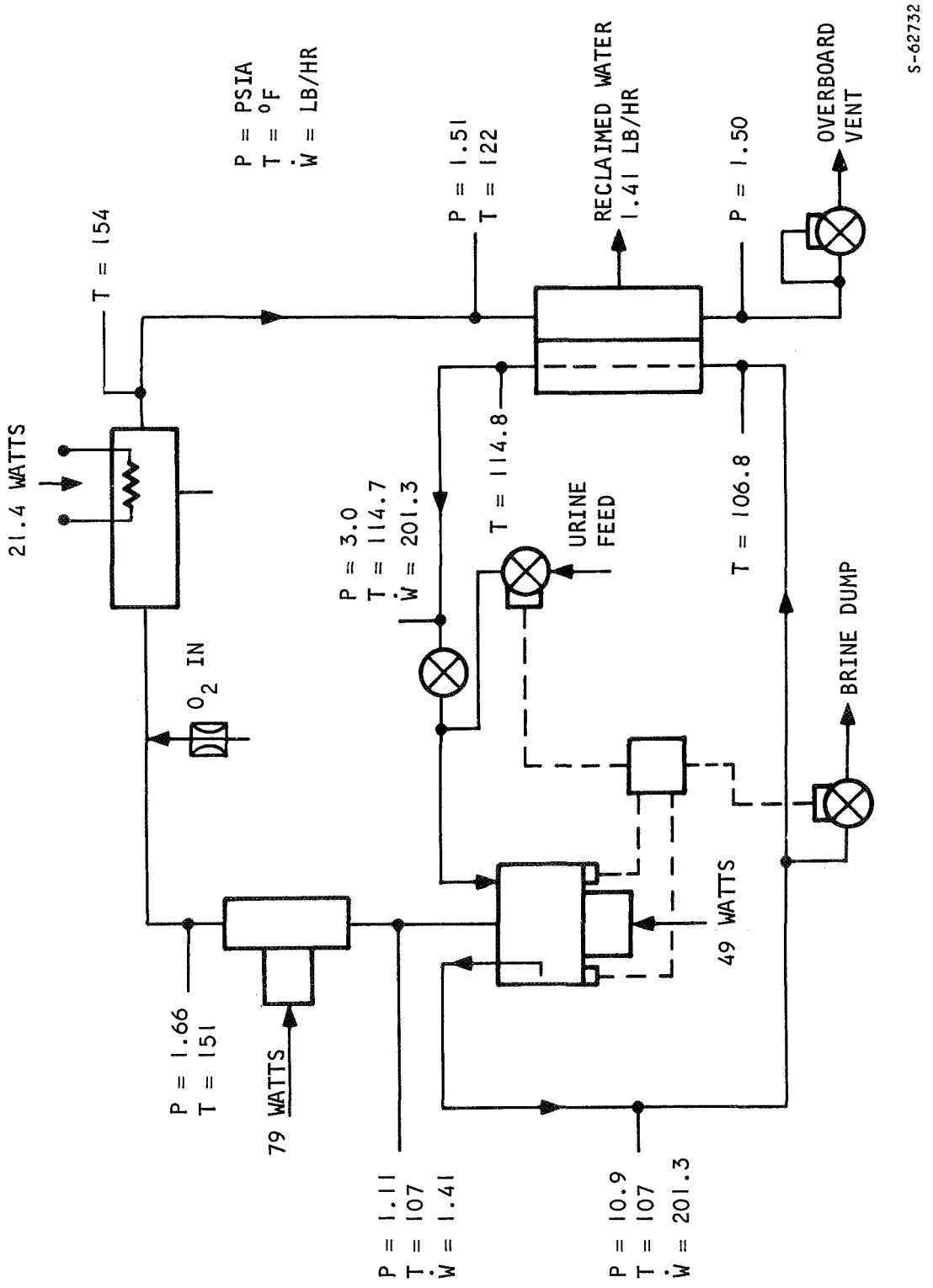


Figure 4-26. System Performance at 17 Percent Brine Concentration

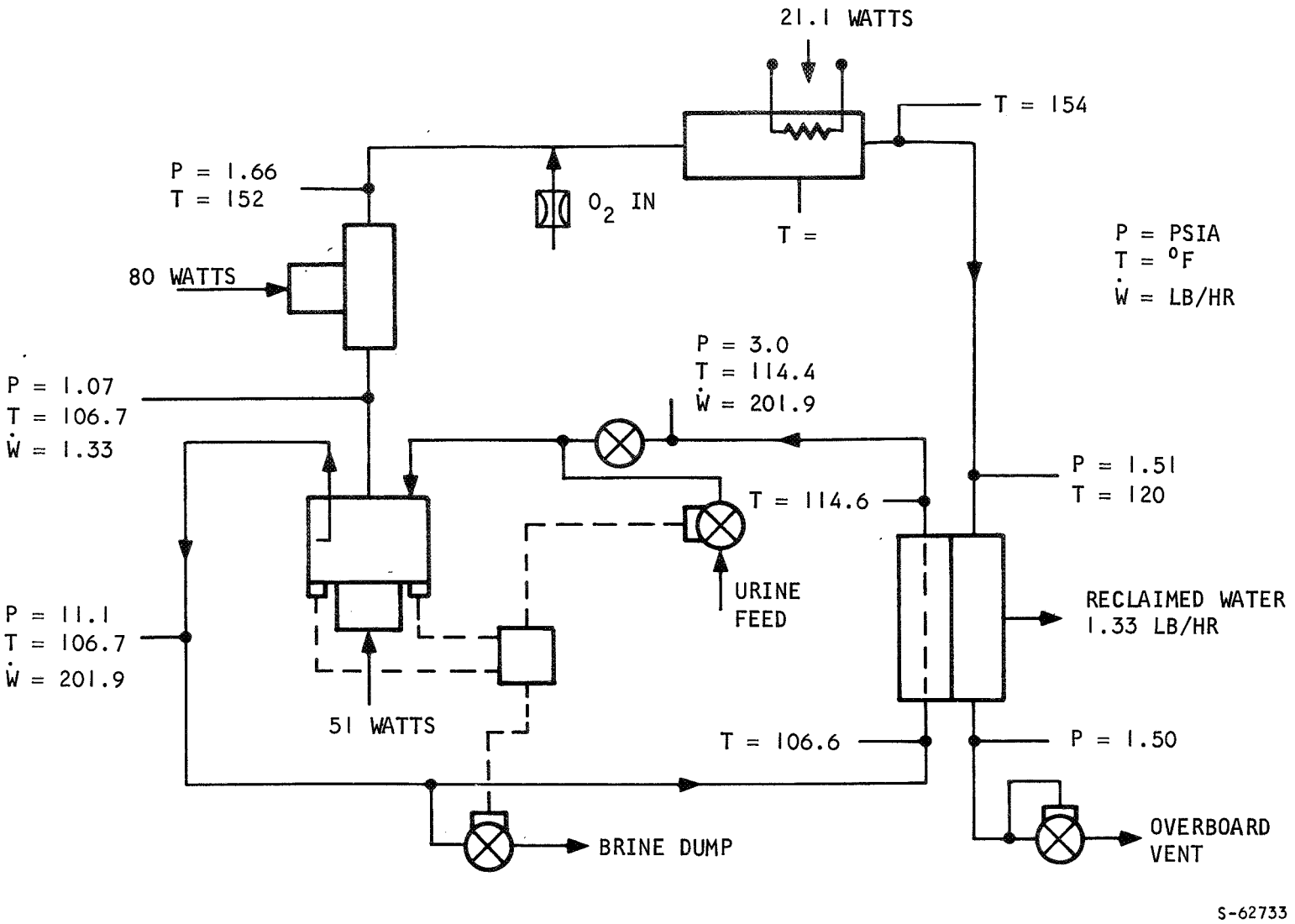


Figure 4-27. System Performance at 25 Percent Brine Concentration

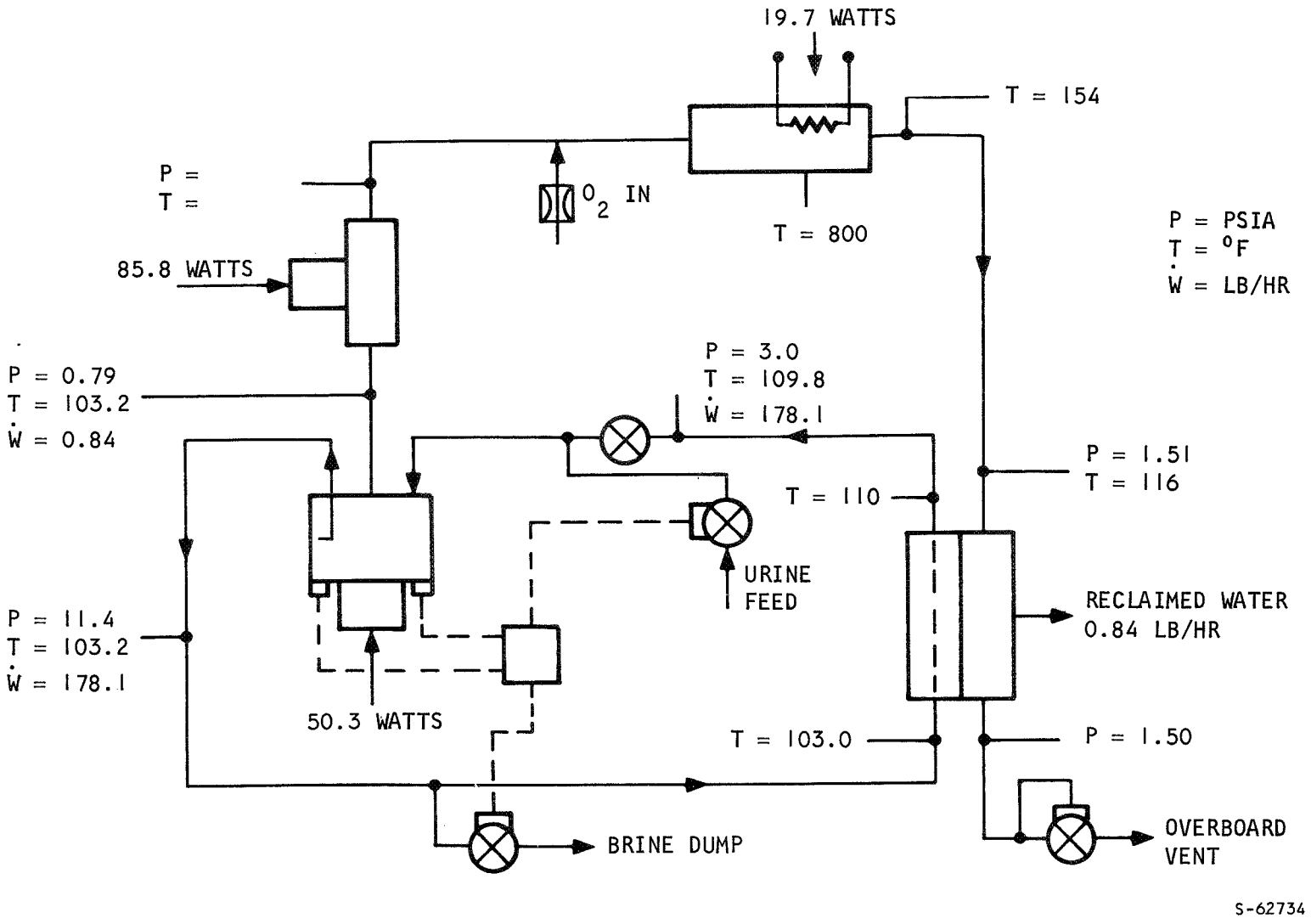


Figure 4-28. System Performance at 50 Percent Brine Concentration

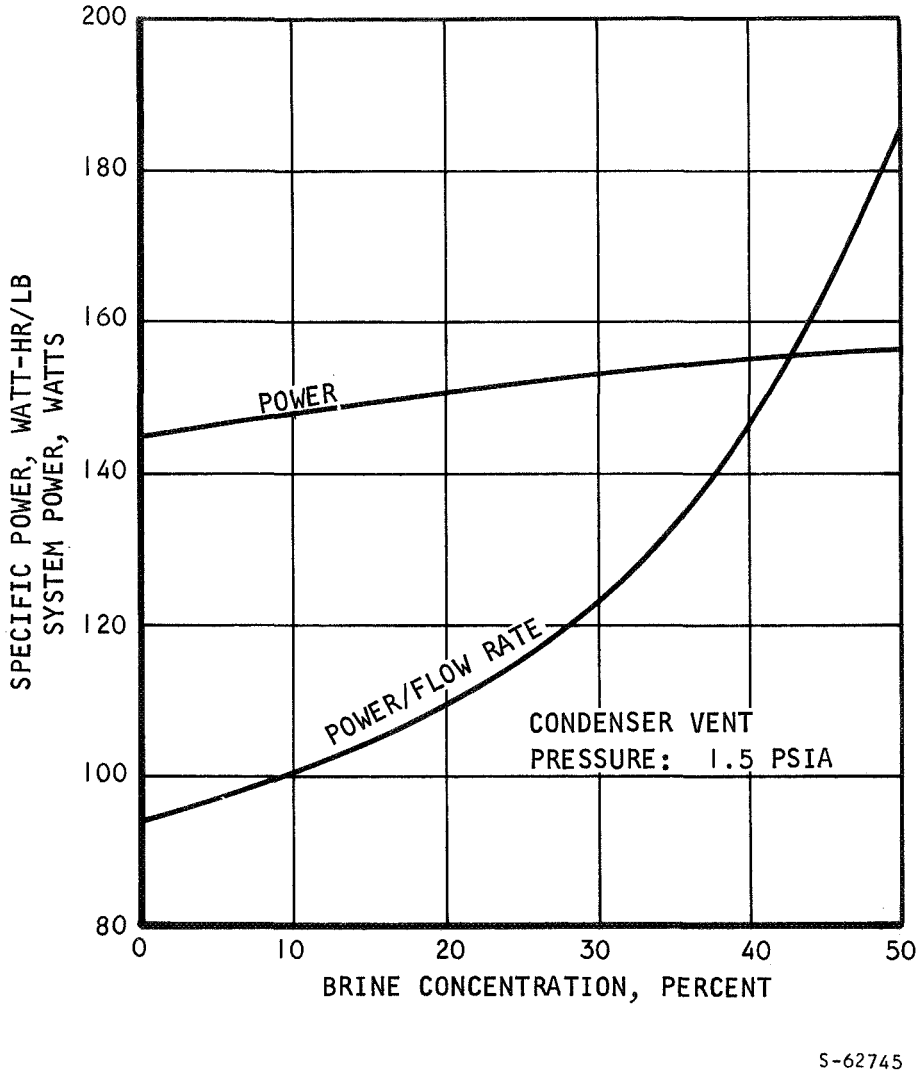


Figure 4-29. System Total Power and Specific Power Consumption vs Brine Concentration

SYSTEM OPTIMIZATION NOMINAL SYSTEM RUN

CONFIGURATION DATA

SEPARATOR

ROTATING DRUM WITH PITOT TUBE LIQUID PICKUP

DRUM DIAMETER	=	6.0000 INCHES	PITOT HEAD COEFFICIENT	=	.1270
DRUM LENGTH	=	4.0000 INCHES	PITOT DRAG COEFFICIENT	=	.1174
PITOT TUBE RADIUS	=	2.7000 INCHES	MINIMUM SEPARATOR VOLUME	=	14.1372 CU.IN.
HEAT LEAK TO AMBIENT	=	1.0000 BTU/HR/F			

COMPRESSOR

TWO STAGE VORTEX WITH SINGLE SIDED WHEELS

HEAT LEAK TO AMBIENT = 2.0000 BTU/HR/F

FLOW(CFM)	PRESS RATIO	POWER(WATTS)
2.0000	3.6000	108.0000
3.0000	3.3600	95.0000
4.0000	3.0600	82.0000
5.0000	2.7200	69.0000
6.0000	2.3600	56.0000
7.0000	2.0000	43.0000
8.0000	1.6000	30.0000
9.0000	1.2200	17.0000

RECUPERATOR

CROSS-COUNTER FLOW SHELL TUBE EXCHANGER WITH INLET ON SHELL SIDE

NUMBER OF TUBES	=	124.0000	FLOW AREA ON SHELL SIDE	=	.0065 FT-FT
NUMBER OF PASSES	=	16.0000	FRONTAL AREA SHELL SIDE	=	.0200 FT-FT
TUBE LENGTH	=	20.0040 INCHES	BAFFLE FLOW AREA	=	.0150 FT-FT
TUBE DIAMETER	=	.1100 INCHES	AXIAL CONDUCTION AREA	=	.0041 FT-FT
HEAT LEAK TO AMBIENT	=	.1200 BTU/HR/F	AXIAL COND CONDUCTIVITY	=	7.0000 BTU/HR/FT/F

CATALYST BED

WIRE MESH CATALYST BED WITH FLOW ALONG AXIS

BED LENGTH	=	3.0000 INCHES	WIRE DIAMETER	=	.0160 INCHES
BED DIAMETER	=	2.2500 INCHES	MESH SIZE	=	20.0000 WIRES/IN

CONDENSER

SPIRAL TUBE HX-BRINE ON INSIDE-STEAMON OUTSIDE -COUNTER FLOW

TUBE LENGTH	=	144.1000 INCHES	FOULING FACTOR	=	.0001
TUBE DIAMETER	=	.1870 INCHES	HEAT LEAK TO AMBIENT	=	1.3000 BTU/HR/F

Figure 4-30. System Performance with 4 Percent Brine Concentration

FLUID LINES

	LENGTH(FT)	DIAMETER(IN)	UA(BTU/HR/F)
BRINE LINES			
CONDENSER TO FEED	2.0000	.2000	.2600
FEED TO SEPARATOR	2.0000	.2000	.2600
SEPARATOR TO DUMP	2.0000	.2000	.2600
DUMP TO CONDENSER	2.0000	.2000	.2600
VAPOR LINES			
SEPARATOR TO COMPRESSOR	14.0000	.4500	.0000
COMPRESSOR TO RECUPERATOR	6.0000	.4500	.4000
RECUPERATOR TO CONDENSER	6.0000	.4500	.3000

PERFORMANCE DATA

OPERATING CONDTIONS

SEPARATOR LEVEL	= 50.0000	CU.IN	AMBIENT TEMPERATURE	= 70.0000 DEG F
BRINE CONCENTRATION	= .0000	PERCENT SOLIDS	FEED TEMPERATURE	= 70.0000 DEG F
FEED CONCENTRATION	= 4.0000	PERCENT SOLIDS	VENT PRESSURE	= 1.5000 PSIA
CATALYST TEMPERATURE	= 800.0000			

SYSTEM PERFORMANCE SUMMARY

WATER PROD. RATE	= 1.5427	LB/HR	SEPARATOR POWER	= 31.6933 WATTS
SEPARATOR PRESSURE	= 1.1839	PSIA	COMPRESSOR POWER	= 54.3505 WATTS
COMPRESSOR PRESS RATIO	= 1.4989		CATALYST/RECUP, POWER	= 21.7998 WATTS
BRINE FLOW RATE	= 197.5000	LB/HR	VAPOR CARRYOVER	= .0000 LB/HR

SYSTEM STATE POINTS		PRESSURE(PSIA)	TEMPERATURE(DEG F)
1	INLET TO FLASH VALUE	3.0120	115.1582
2	OUTLET OF PITOT TUBE	10.3619	107.4499
3	BRINE INLET TO CONDENSER	9.5214	107.3513
4	BRINE OUTLET FROM CONDENSER	5.4932	115.2773
5	SEPARATOR VAPOR OUTLET	1.1839	107.4499
6	INLET TO COMPRESSOR	1.1277	107.4499
7	OUTLET OF COMPRESSOR	1.6903	148.4963
8	RECUPERATOR INLET	1.6730	119.9550
9	CATALYST BED INLET	1.6447	766.5188
10	CATALYST BED OUTLET	1.5338	800.0000
11	RECUPERATOR OUTLET	1.5308	153.4361
12	CONDENSER VAPOR INLET	1.5115	123.6896

COMPONENT PERFORMANCE DATA

SEPARATOR

SPEED	= 1800.0000 RPM	BRINE OUTLET PRES	= 10.3619 PSIA
POWER	= 31.6933 WATTS	BRINE TEMPERATURE	= 107.4499 DEG F
VAPOR PRESSURE	= 1.1839 PSIA	HEAT LEAK	= 37.4499 BTU/HR

Figure 4-30 (Continued)

COMPONENT PERFORMANCE DATA

COMPRESSOR

INLET PRESS	=	1.1277 PSIA	POWER	=	54.3505 WATTS
OUTLET PRESS	=	1.6903 PSIA	ADIABATIC EFF.	=	23.7816 PERCENT
PRESS RATIO	=	1.4989	HOUSING TEMP.	=	148.4963 DEG F
VOLUME FLOW	=	8.2662 CFM	HEAT LEAK	=	156.9531 BTU/HR

COMPONENT PERFORMANCE DATA

RECUPERATOR

INLET TEMP.	=	119.9550 DEG F	INLET PRESS.	=	1.6730 PSIA
OUTLET TEMP.	=	153.4361 DEG F	OUTLET PRESS.	=	1.5308 PSIA
EFFECTIVENESS	=	.9508	SHELL SIDE DEL P	=	.0282 PSID
HEAT LEAK	=	48.8062 BTU/HR	TUBE SIDE DEL P	=	.0030 PSID
POWER	=	21.7998 WATTS			

CATALYST BED

INLET TEMP.	=	766.5188 DEG F	BED DELTA P	=	.1109 PSID
INLET PRESS.	=	1.6447 PSIA			

COMPONENT PERFORMANCE DATA

CONDENSER

BRINE FLOW	=	197.5000 LB/HR	VAPOR FLOW	=	1.5427 LB/HR
BRINE DELTA P	=	4.0281 PSID	VAPOR INLET P	=	1.5115 PSIA
BRINE DELTA T	=	7.9260 DEG F	VAPOR DELTA P	=	.0099 PSID
BRINE H	=	1267.8380 BTU/HR/FT/FT/F	VAPOR SATUR T	=	115.7859 DEG F
BRINE INLET T	=	107.3513 DEG F	VAPOR H	=	2382.5050 BTU/HR/FT/FT/F
HEAT LEAK	=	59.5361 BTU/HR			

LINE DATA

	PRESSURE DROP(PSID)	HEAT LEAK(BTU/HR)
CONDENSER TO FEED	.4135	11.7721
FEED TO SEPARATOR	.4136	11.7566
SEPARATOR TO DUMP	.4202	9.7370
DUMP TO CONDENSER	.4203	9.7241
SEPARATOR TO COMPRESSOR	.0561	-.0000
COMPRESSOR TO RECUPERATOR	.0173	25.6903
RECUPERATOR TO CONDENSER	.0193	20.5689

Figure 4-30 (Continued)

SYSTEM OPTIMIZATION NOMINAL SYSTEM RUN

CONFIGURATION DATA

SEPARATOR

ROTATING DRUM WITH PITOT TUBE LIQUID PICKUP

DRUM DIAMETER	=	6.0000 INCHES	PITOT HEAD COEFFICIENT	=	.1584
DRUM LENGTH	=	4.0000 INCHES	PITOT DRAG COEFFICIENT	=	.1486
PITOT TUBE RADIUS	=	2.7000 INCHES	MINIMUM SEPARATOR VOLUME	=	14.1372 CU.IN.
HEAT LEAK TO AMBIENT	=	1.0000 BTU/HR/F			

COMPRESSOR

TWO STAGE VORTEX WITH SINGLE SIDED WHEELS

HEAT LEAK TO AMBIENT = 2.0000 BTU/HR/F

FLOW(CFM)	PRESS RATIO	POWER(WATTS)
2.0000	3.6000	108.0000
3.0000	3.3600	95.0000
4.0000	3.0600	82.0000
5.0000	2.7200	69.0000
6.0000	2.3600	56.0000
7.0000	2.0000	43.0000
8.0000	1.6000	30.0000
9.0000	1.2200	17.0000

RECUPERATOR

CROSS-COUNTER FLOW SHELL TUBE EXCHANGER WITH INLET ON SHELL SIDE

NUMBER OF TUBES	=	124.0000	FLOW AREA ON SHELL SIDE	=	.0065 FT-FT
NUMBER OF PASSES	=	16.0000	FRONTAL AREA SHELL SIDE	=	.0200 FT-FT
TUBE LENGTH	=	20.0040 INCHES	BAFFLE FLOW AREA	=	.0150 FT-FT
TUBE DIAMETER	=	.1100 INCHES	AXIAL CONDUCTION AREA	=	.0041 FT-FT
HEAT LEAK TO AMBIENT	=	.1200 BTU/HR/F	AXIAL COND CONDUCTIVITY	=	7.0000 BTU/HR/FT/F

CATALYST BED

WIRE MESH CATALYST BED WITH FLOW ALONG AXIS

BED LENGTH	=	3.0000 INCHES	WIRE DIAMETER	=	.0160 INCHES
BED DIAMETER	=	2.2500 INCHES	MESH SIZE	=	20.0000 WIRES/IN

CONDENSER

SPIRAL TUBE HX-BRINE ON INSIDE-STEAMON OUTSIDE -COUNTER FLOW

TUBE LENGTH	=	144.1000 INCHES	FOULING FACTOR	=	.0001
TUBE DIAMETER	=	.1870 INCHES	HEAT LEAK TO AMBIENT	=	1.3000 BTU/HR/F

Figure 4-31. System Performance with 50 Percent Brine Concentration

FLUID LINES

	LENGTH(FT)	DIAMETER(IN)	UA(BTU/HR/F)
BRINE LINES			
CONDENSER TO FEED	2.0000	.2000	.2600
FEED TO SEPARATOR	2.0000	.2000	.2600
SEPARATOR TO DUMP	2.0000	.2000	.2600
DUMP TO CONDENSER	2.0000	.2000	.2600
VAPOR LINES			
SEPARATOR TO COMPRESSOR	14.0000	.4500	.0000
COMPRESSOR TO RECUPERATOR	6.0000	.4500	.4000
RECUPERATOR TO CONDENSER	6.0000	.4500	.3000

PERFORMANCE DATA

OPERATING CONDTIONS

SEPARATOR LEVEL	=	25.0000 CU.IN	AMBIENT TEMPERATURE	=	70.0000 DEG F
BRINE CONCENTRATION	=	50.0000 PERCENT SOLIDS	FEED TEMPERATURE	=	70.0000 DEG F
FEED CONCENTRATION	=	4.0000 PERCENT SOLIDS	VENT PRESSURE	=	1.5000 PSIA
CATALYST TEMPERATURE	=	800.0000			

SYSTEM PERFORMANCE SUMMARY

WATER PROD. RATE	=	.8404 LB/HR	SEPARATOR POWER	=	35.2357 WATTS
SEPARATOR PRESSURE	=	.7883 PSIA	COMPRESSOR POWER	=	59.9634 WATTS
COMPRESSOR PRESS RATIO	=	2.0755	CATALYST/RECUP. POWER	=	19.6876 WATTS
BRINE FLOW RATE	=	178.1250 LB/HR	VAPOR CARRYOVER	=	.0000 LB/HR

SYSTEM STATE POINTS		PRESSURE(PSIA)	TEMPERATURE(DEG F)
1	INLET TO FLASH VALVE	2.9886	109.7845
2	OUTLET OF PITOT TUBE	11.3675	103.1636
3	BRINE INLET TO CONDENSER	10.3863	103.0148
4	BRINE OUTLET FROM CONDENSER	5.8054	109.9638
5	SEPARATOR VAPOR OUTLET	.7883	103.1636
6	INLET TO COMPRESSOR	.7636	103.1636
7	OUTLET OF COMPRESSOR	1.5849	161.3084
8	RECUPERATOR INLET	1.5794	117.6461
9	CATALYST BED INLET	1.5698	756.9300
10	CATALYST BED OUTLET	1.5064	800.0000
11	RECUPERATOR OUTLET	1.5054	160.7161
12	CONDENSER VAPOR INLET	1.4996	115.8194

Figure 4-31 (Continued)

COMPONENT PERFORMANCE DATA

SEPARATOR

SPEED	= 1800.0000	RPM	BRINE OUTLET PRES=	11.3675	PSIA
POWER	= 35.2357	WATTS	BRINE TEMPERATURE=	103.1636	DEG F
VAPOR PRESSURE	= .7883	PSIA	HEAT LEAK =	33.1636	BTU/HR

COMPONENT PERFORMANCE DATA

COMPRESSOR

INLET PRESS	= .7636	PSIA	POWER =	59.9634	WATTS
OUTLET PRESS	= 1.5849	PSIA	ADIABATIC EFF. =	22.5288	PERCENT
PRESS RATIO	= 2.0755		HOUSING TEMP. =	161.3084	DEG F
VOLUME FLOW	= 6.7902	CFM	HEAT LEAK =	182.5586	BTU/HR

COMPONENT PERFORMANCE DATA

RECUPERATOR

INLET TEMP.	= 117.6461	DEG F	INLET PRESS. =	1.5794	PSIA
OUTLET TEMP.	= 160.7161	DEG F	OUTLET PRESS. =	1.5054	PSIA
EFFECTIVENESS	= .9369		SHELL SIDE DEL P =	.0096	PSID
HEAT LEAK	= 49.2430	BTU/HR	TUBE SIDE DEL P =	.0010	PSID
POWER	= 19.6876	WATTS			

CATALYST BED

INLET TEMP.	= 756.9300	DEG F	BED DELTA P =	.0634	PSID
INLET PRESS.	= 1.5698	PSIA			

COMPONENT PERFORMANCE DATA

CONDENSER

BRINE FLOW	= 178.1250	LB/HR	VAPOR FLOW =	.8404	LB/HR
BRINE DELTA P	= 4.5809	PSID	VAPOR INLET P =	1.4996	PSIA
BRINE DELTA T	= 6.9490	DEG F	VAPOR DELTA P =	.0019	PSID
BRINE H	= 165.6870	BTU/HR/FT/FT/F	VAPOR SATUR T =	115.6816	DEG F
BRINE INLET T	= 103.0148	DEG F	VAPOR H =	1591.4343	BTU/HR/FT/FT/F
HEAT LEAK	= 59.3879	BTU/HR			

LINE DATA

	PRESSURE DROP(PSID)	HEAT LEAK(BTU/HR)
CONDENSER TO FEED	.4693	10.3906
FEED TO SEPARATOR	.4696	10.3673
SEPARATOR TO DUMP	.4904	8.6225
DUMP TO CONDENSER	.4908	8.6032
SEPARATOR TO COMPRESSOR	.0247	-.0000
COMPRESSOR TO RECUPERATOR	.0055	27.7909
RECUPERATOR TO CONDENSER	.0058	20.4803

Figure 4-31 (Continued)

MAINTAINABILITY

General Considerations

In designing a system for long term spaceflight, equipment reliability becomes a factor which is more important than the normal optimization parameters of weight and power. Numerous studies have demonstrated that for mission duration on the order of one year, high reliability can only be achieved by providing maintenance capability such that, upon failure of a component, the system can be restored to its normal configuration through repair action. This involves positive action on the part of the astronauts and requires that the system design be optimized in terms of the maintenance tasks. These tasks will be performed in the space environment by astronauts who will be trained to perform such maintenance action, yet cannot be experts on all subsystems installed on board a spacecraft. In terms of man-machine interfaces, the maintainable system must be designed to:

(a) Eliminate any contamination hazard, either bacterial or chemical

(b) Require a realistic level of training, including fault detection, by the astronaut

(c) Obviate the necessity for immediate action upon the occurrence of a failure

(d) Require only simple tools

(e) Minimize potential human error (the probability of the astronaut successfully performing repair must be considered in determining overall system reliability)

In general, maintainability does not constitute an alternative for high reliability. On the contrary, system equipment must be designed for long life and high reliability to minimize (1) the time expended in repairing the system, (2) the quantity of spares to be carried on board, and (3) the psychological stress which will accompany each failure. A better criterion for the evaluation of a maintainable system is its availability. For high availability, the number of failures must be minimized through the use of highly reliable hardware. The IWRS operating life is specified as one year (8770 hours). Rotary equipment designed for the Apollo and Gemini programs have been demonstrated on test to have a life adequate for such a mission; e.g., the Apollo glycol pump (> 10,000 hours) and the Gemini cabin fan (> 20,000 hours). These data are given here to illustrate that the technology is available for the design of long life rotary equipment. This technology should be used in the design of any long duration maintainable subsystem, including the IWRS.

Another aspect of maintainability which warrants much attention is the addition of equipment to the system to make it maintainable. This additional equipment includes:

(a) Instrumentation to permit fault isolation at the replaceable package level

(b) Equipment which will permit easy removal and replacement of the defective part

(c) Equipment which will prevent failure propagation

In a non-maintainable system, instrumentation is provided for the purpose of monitoring performance, switching-on redundant units, or selecting degraded operational mode in the event of malfunction. In general, a malfunction on a system like the Apollo ECS can be detected by its effect on the environment: high temperature, high humidity, low flow, etc., so that even in the event of instrumentation breakdown, overall system reliability is not impaired. In the case of a long term maintainable system, failures will occur and must be detected and diagnosed timely so that repair can be effected. Instrumentation is thus necessary for system operation through the mission. On this basis, the instrumentation becomes an integral part of the system and its unreliability must be considered as part of the total system unreliability. An instrumentation failure corresponds to a system failure and must be corrected. This poses a problem, since spaceflights to date have demonstrated clearly that instrumentation probably constitutes the most unreliable class of equipment on board a spacecraft. Much instrumentation is desirable for fault isolation; on the other hand, addition of instrumentation adds to the unreliability of the overall system. It should be noted that the addition of any kind of equipment to make the system maintainable degrades overall reliability. Thus an optimum exists which is difficult to define in terms of weight and volume. Much engineering judgment must be exercised together with human factors considerations, in the definition of the maintenance level.

Another factor of importance in the development of a maintainable system involves hardware packaging. New concepts are required here which will result in rather large volume penalties. The packages must be designed to facilitate the performance of maintenance tasks in a timely manner without requiring the use of complex tools. In general, all replaceable items should easily be accessible with attention paid to the components most likely to fail.

IWRS Maintainability Features

In this phase of the program, no special emphasis was placed on the maintainability--reliability aspect of the system. However, the guidelines briefly discussed above were generally followed in the evaluation of the system schematic and package described in Section 2 of this report. Maintenance of the IWRS presents a particular problem by comparison to other spacecraft EC/LS subsystems. This results from the nature of the subsystem itself and of the fluids involved:

(a) The urine and the brine pose bacterial and chemical contamination problems. Spillage of brine, in particular, would result in a most undesirable odor problem in the spacecraft. Thus the brine must be carefully contained.

(b) The reclaimed water portion of the loop is normally kept under absolute sterility conditions. Repair action will require very special procedures which might include sterilization of this entire portion of the loop after repair.

(c) The high temperature reactor normally operates at 800°F. Cooldown will be necessary before repair action is initiated.

(d) Water is at a premium on board the spacecraft. Overboard loss of this fluid due to repair action must be obviated.

(e) The urine collection function cannot be interrupted.

(f) Shutdown of the water reclamation process results in the use of emergency stores. If these stores are to be replenished at a later date, the waste water must be stored as such during shutdown, resulting in large waste water collection tanks.

The system incorporates many provisions which were considered necessary to enhance its maintainability-reliability. First, all system components should be designed for a 2-year life. As mentioned previously, this is within the state-of-the-art technology. Shelf life should be 5 years mininum. This will assure high intrinsic reliability.

Second, the arrangement of the system provides high reliability through the operation of two parallel water reclamation units: one for urine and one for wash water. The urine reclamation unit is essential; the wash water unit is not. In the event of a failure in the urine reclamation loop, which cannot be repaired in the time normally alloted for such maintenance action, the urine collection subsystem could be connected to the wash water reclamation unit. Since the reclamation loop can be operated at processing rates as high as 1.75 lb/hr by simple adjustment of condenser pressure, operation in this manner (on a single reclamation loop) would permit urine processing and wash water processing at a reduced rate.

Third, the storage tanks will permit a one-day downtime following interruption of the reclamation function. The urine storage tank capacity is sufficient to store a two-day production of urine. Normally, the tank is half full so that failure of the reclamation unit will not necessitate immediate urinal outflow switchover to the wash water loop. Upon restarting the urine reclamation unit, the processing rate should be adjusted to restore this capability. Conversely, failure of the urine collection subsystem will not necessitate shutdown of the reclamation unit since a one-day charge is available in the waste tank. Note that this feature obviates the necessity for subsystem shutdown and startup because of a malfunction in another subsystem. It is recommended that a redundant urine collection loop be provided, or that provisions be incorporated in the system for emergency backup of the urine collection function. This could be a simple overboard dump urinal of the type developed for Apollo.

Finally, many features were incorporated in the design of the components and subsystem which will obviate and facilitate maintenance tasks. Some of these are mentioned below:

(a) All motor driven rotating equipment is statically sealed. Power is transmitted through magnetic couplings. Thus motors can be replaced without compromising the integrity of the fluid lines. Ammeters monitor current draw of each motor. Impending failure should be detected before it occurs.

(b) All temperature transducers are mounted externally so that they can also be replaced without opening the fluid loops.

(c) All check valves are made redundant. The normal failure mode for these valves is in the open mode. Very little weight penalty is involved.

(d) All tank pressure regulators incorporate a relief valve. A pressure sensor on the line will detect regulator or relief valve failure opened or closed.

(e) All lines connected to vacuum incorporates a shutoff valve as the last item on the line.

(f) The brine loop controller incorporates circuitry to prevent flooding of the phase separator by closing a solenoid valve on the urine feed line.

(g) Redundant heater and control circuits are used on the catalytic reactor.

(h) The hydrophilic porous plate of the condenser is a replaceable item.

At this time maintenance at the component level in the brine loop was ruled out for the following reasons:

(a) The brine loop comprise three components: the flash valve, the heater tube, and the phase separator. Failure of the flash valve (an orifice) and of the heater-condenser tube is very unlikely. Failure of the separator bearings is the most likely failure mode. These bearings will be designed for long life with ample safety factors, so that failure is unlikely to occur.

(b) Any repair action within the brine loop will necessitate flushing the loop to eliminate the possibility of brine spillage. System tests have demonstrated that odors from the brine are extremely strong and unpleasant; also, the brine contains large quantities of bacteria potentially pathogenic. Adequate flushing of the brine loop will require (1.) unknown quantities of water with bactericide and (2) disposal of the brine and flushing solution. The penalties involved in flushing this loop might exceed the advantages realized

through the capability for replacement of the separator and the heater-condenser as separator units. Pending detailed tests and analyses of brine loop maintenance, the approach has been taken that, should there be a failure in that loop the entire loop will be replaced. Six quick-disconnects are provided for this purpose.

System parameters which are monitored are displayed on a monitor-control panel. The only manual system controls are the switches for activation of the motors, controllers, and recuperator--reactor heater. The condenser pressure regulator can also be set manually to control water processing rates. All system shutoff valves (with the exception of the tank isolation valves) can be operated from the control panel.

Manual operation of the system controls would require the continous attention of an astronaut very familiar with the complex interactions between the various system parameters. This could be done, however, this approach is not recommended in view of (1) the maintainable aspect of the system, (2) the existence of two reclamation units in the IWRS, and (3) the allowable downtime provided by the system tanks. In the event of a malfunction, the system should be shut down and repair action should be scheduled and performed. The capability for doing this is an essential requirement in the design of a maintainable unit.

While maintenance in the brine loop constitutes a hazard to the astronauts, maintenance of any portion of the system downstream of the catalytic oxidizer constitutes a hazard to the system because of the possibility of bacterial contamination. Such actions will have to be followed by sterilization of the portion of the system which has been contaminated. At this time, procedures for sterilization prior to startup or following maintenance have not been definitized. Steam sterilization, although very effective, is not attractive for space application primarily because of the high power requirement, heat loads, and probable humidity loads. Sterilization with hydrogen peroxide offers many advantages which should be studied in detail.

Following maintenance action which involves opening the loop, the pressure integrity of the loop will have to be checked. This can be done by pressurizing the system with nitrogen and monitoring pressure decay.

One of the guidelines used in the conceptual design of the IWRS was that the system be a "hands off" unit with minimum scheduled and unscheduled maintenance and minimal system-crew interfaces. The system described in Section 2 of this report conforms to this early requirement. The water reclamation unit itself involves only one scheduled maintenance action: replacement of the brine tank at the 90-day resupply period (this could be obviated by the use of a larger tank). Other scheduled maintenance tasks involve the urine collection subsystem replacement of the bactericide tank and of the charcoal filter at 90-day intervals. Also, bacteriological tests of the product water will have to be performed daily. Whether this is an essential requirement will have to be demonstrated by extensive development tests on flight prototype hardware incorporating all the bacteria control features of the system described in Section 2.

RELIABILITY

Early in the development of the schematic, described in Section 2, preliminary reliability analyses were conducted. These analysis consisted of system-level failure modes and effects analyses (FMEA) and subsystem-level logic diagrams. The FMEA's were concerned only with the water reclamation and purity monitoring portion of the system; however, logic diagrams were prepared for all three functional subsystems as defined in Section 2.

As a result of the FMEA's, a number of changes were incorporated in the design of the system. These changes included the need for displays and the incorporation of alarms. Other FMEA conclusions were not implemented because of insufficient data to resolve a particular problem. For example, brine carryover into the vapor loop due to separator failure was identified as a major failure mode because of the extensive maintenance tasks involved in flushing the brine from the entire system. Such a separator failure could propagate to all components of the vapor loop and might not be repairable. As a result, a tentative solution was selected to prevent vapor loop fouling because of separator failure. Although no supporting test data are available, the assumption was made that inputs from the density and level sensors could be used to rapidly detect such a failure. This signal could be used to immediately shutoff a solenoid valve in the vapor loop, thus isolating the loop from the brine circuit.

Another failure identified as difficult to isolate involves the cyclic accumulator. In this case, a ΔP transducer was incorporated in the system to monitor the suction pressure of the accumulator.

In general, the FMEA's illustrated that failure identification might be a very serious problem which would require extensive knowledge of the operation of the system on the part of the astronauts. It is strongly recommended that failure diagnostic diagrams be prepared in the next phase of the program.

As mentioned above, the FMEA's were performed early in the program and were used as a tool in the development of the system schematic. The results of these analyses were transmitted to NASA at the time. No attempts were made to upgrade these analyses as the program proceeded and the schematic evolved into its final configuration. For this reason the FMEA's are not incorporated as part of this report.