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VACUUM DISTILLATION/VAPOR FILTRATION WATER RECOVERY

Interim Report for Phases I and II

Contract No. NAS 8-27467
GARD Project No. 1528

Chemical & Environmental Systems Group
Engineering Research Department

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FOREWORD

This report summarizes the results for the design, manufacture and checkout testing of a Vacuum Distillation/Vapor Filtration (VD/VF) water recovery system. The report is arranged in two parts. Part I describes the activities for developing an evaporator and catalytic oxidation unit during Phase I of the program. Part II describes the activities accomplished during Phase II for developing a condenser and integrating and testing the evaporator, catalytic oxidation unit, condenser and auxiliary components. The work was conducted for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration, under Contract No. NAS 8-27467 by the General American Research Division of the General American Transportation Corporation during the period from 25 June 1971 to 31 March 1973.

The NASA Project Monitor was Mr. James L. Moses of the Life Support and Environmental Branch, Propulsion and Thermodynamics Division. Personnel in the Chemical and Environmental Systems Group at GARD performed the activities under the direction of Mr. George A. Remus; Mr. Robert J. Honegger served as Project Engineer and Mr. Edwin K. Krug served as Engineering Assistant.

ABSTRACT

A vacuum distillation/vapor filtration (VD/VF) water recovery system was designed, fabricated, and check-out tested. The system employs vacuum distillation, vapor-phase catalytic oxidation, and condensation as the basic processes for recovering potable water from urine. Both the evaporator and condenser utilize a rotating impeller to create an artificial gravity for separation of liquid and vapor in zero gravity. Each impeller is driven through a magnetic coupling, thus eliminating shaft seals. A six-day performance test indicated good system thermal efficiency and water recovered from urine was of good quality as determined by selected analyses. Total organic carbon was less than 12 mg/l, pH varied between 6.0 and 6.9, turbidity was below 1 Jackson Unit, and ammonia concentration was less than 1 mg/l as indicated by daily analyses of recovered water.

TABLE OF CONTENTS

PART I: DESIGN, MANUFACTURE, AND CHECKOUT TESTING OF EVAPORATOR

TABLE OF CONTENTS

PART II: DESIGN, MANUFACTURE, AND TESTING OF ZERO-GRAVITY CONDENSER: INTEGRATION OF EVAPORATOR, CONDENSER, AND AUXILIARY COMPONENTS

LIST OF FIGURES AND ILLUSTRATIONS

LIST OF TABLES

PART I

DESIGN, MANUFACTURE, AND CHECKOUT TESTING OF EVAPORATOR

Section 1

INTRODUCTION AND SUMMARY

This report summarizes the activities of the General American Research Division (GARD) to develop an evaporator for vacuum distillation/vapor filtration (VD/VF) water reclamation. The evaporator development was conducted as Phase I of an anticipated program to develop a complete VD/VF water recovery system for spacecraft applications.

1.1 Background

Current manned space vehicles do not include water reclamation requirements and/or equipment because most of these vehicles utilize water-producing fuel cells for auxiliary power. Future space missions, such as the foreseeable Space Station, will most likely utilize solar cells instead of fuel cells; thus, another source of water must be provided. Life-support system requirements envision supporting 12 men continuously, using 180-day resupply intervals.

Studies conducted to determine the most economical approach for supplying the life-support needs of large-crew, long-duration space missions have indicated that it is essential to recover water from urine and respiration and perspiration condensates. The basic life-support systems can be modularized by using six-man capacity units, based on studies considering the overall integration of spacecraft systems.

1.2 Program Objectives

The ultimate program objectives were to develop and to evaluate a vacuum distillation/vapor filtration (VD/VF) water recovery system. As a functional model, the system is to convert urine and condensate waste water from six men into potable water on a steady-state basis. The system is to be designed for 180-day operating durations and to function on the ground, in zero-g aircraft, and in orbit.

In Phase I of the program, which is described in this part of the report, the objective was to develop an evaporator subsystem for water recovery by vacuum distillation/vapor filtration.

To accomplish this objective, a six-man capacity evaporator subsystem was designed, manufactured, and check-out tested. Prior to development of the evaporator, laboratory support tests were conducted to provide realistic information on which to base certain design features. These support tests provided information on distillation heat-transfer coefficients, operating characteristics of a magnetic coupling as compared to a rotary shaft seal, and operating characteristics of a bubble-type sensor for liquid level control in both normal and zero-gravity operation. Design calculations were prepared to determine the optimum size and shape of the evaporator. Based on laboratory support-test data and basic design calculations, the overall design for the evaporator was prepared and reviewed with NASA personnel for their approval. Detail drawings were then completed for fabrication of component parts and subassemblies. When assembled, the evaporator subsystem was check-out tested to verify the adequacy of its basic features.

1.3 System Description

The integrated water recovery system is to be comprised of the components shown on the block flow diagram, Figure 1. Of the items shown by solid lines, the evaporator wss designed, fabricated, and check-out tested in Phase I of this program. The remaining items shown by solid outline are components yet to be developed. Items shown by dotted outline were developed previously. under Contract F33615-69-C-1486 and will be used to complete the assembly of a totally integrated water recovery system.

The evaporator assembly developed in Phase I is made up of a vacuum evaporator still with a liquid heating jacket, a catalytic oxidation unit, and associated piping, valves, and controls. The still has an internal impeller that provides centrifugal acceleration of the boiling liquid for separation of liquid and vapor in zero gravity.

The impeller-operated at 100 rpm and required 70 watts of electrical power. The cylindrical vacuum still is 56 cm (22 inches) in diameter and 38 cm (15 inches) high; the free internal volume is sufficient to retain the residual urine sludge from 40 days of operation. To distill urine at a six-man rate, 660 watts of thermal power were required at a boiling temperature approximating 32°C (90°F).

The evaporator and catalyst bed assembly is shown in Figure 2.

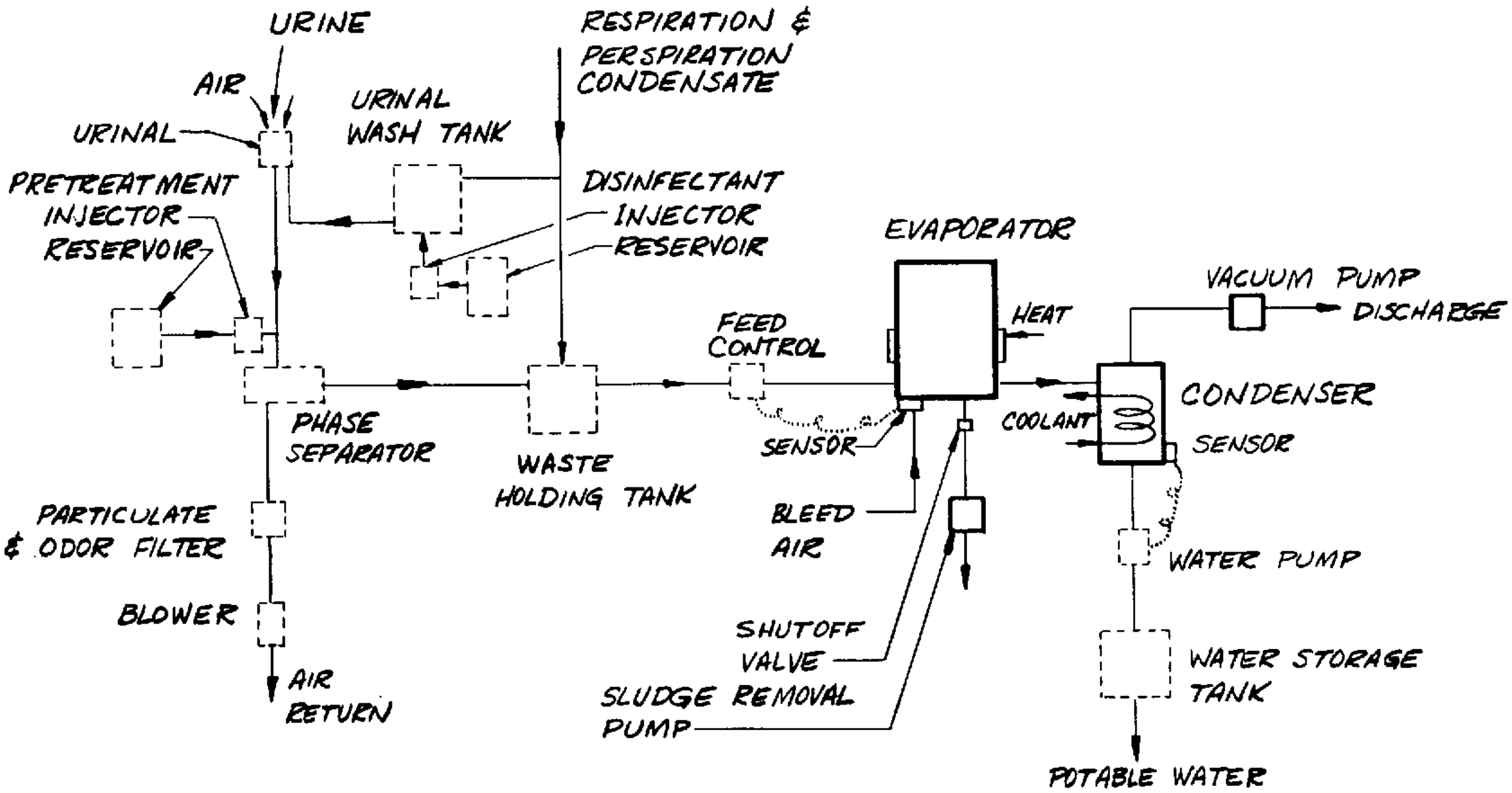

Figure 1 BLOCK FLOW DIAGRAM

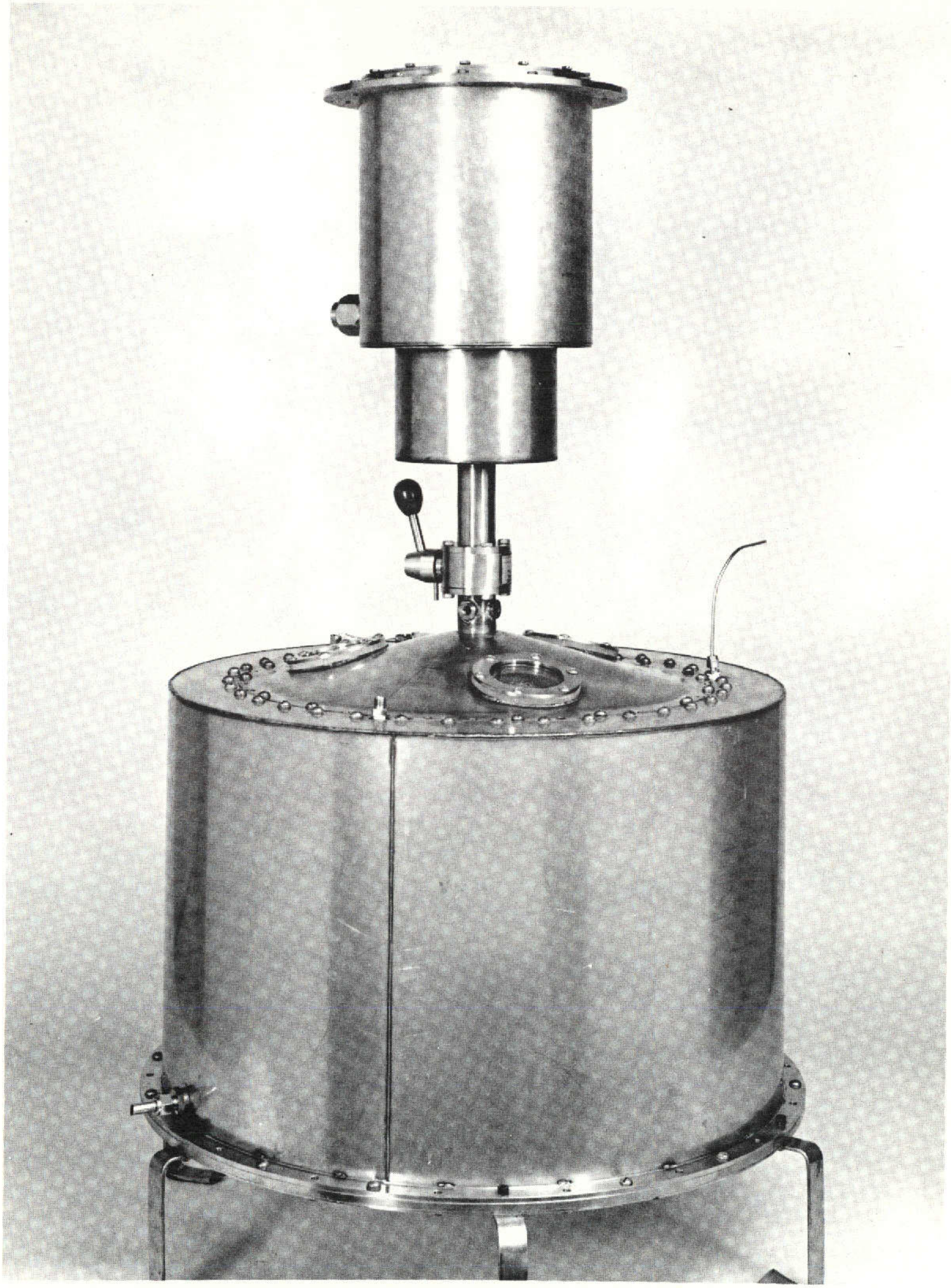

Figure 2 EVAPORATOR AND CATALYST BED ASSEMBLY

Section 2

WATER RECOVERY BY VACUUM DISTILLATION/VAPOR FILTRATION

2.1 Introduction

Water recovery by vacuum distillation/vapor filtration entails a distillation process in which urine is distilled under vacuum at a low temperature. As urine is distilled, solids are left behind and accumulate as residual sludge. The raw distilled vapor contains some small amounts of entrained mist and co-distilled organic vapors. The distilled vapor, along with oxygen fed into the vapor ducting, are passed through an oxidation catalyst operating at 150°C to remove the organic contaminant and then through a microporous vapor filter to remove bacteria and generate sterile vapor which is subsequently condensed to potable water.

2.2 Design Requirements

The design requirements for the evaporator developed in Phase I were as follows:

a) Incorporate a rotating vaned impeller to provide artificial gravity for liquid-vapor phase separation and improved heat transfer from the heating jacket surface to the liquid urine.

b) Have capacity to evaporate the combined urine and respiratory outputs, and recover water from these outputs at the same rate specified for the system under contract F33615-69-C-1486, namely, to recover 3.41 kg/day (7.5 lb/day) of water from the 1.58 kg (3.5 lb) of urine and 1.83 kg (5.0 lb) of respiratory water generated by each man. For the 6-man system the recovery rate was thus 20.4 kg/day

(45 lb/day) of water from the combined input total of 23.6 kg/day (51 lb/day). The evaporator volume was to be large enough to operate for 40 days without removing urine sludge, and to contain sufficient liquid volume so that the concentrated residue would maintain the accumulated solids in solution; the sludge could be removed after 40 days operation, or periodically at shorter intervals if desired, by means of a sludge removal pump.

c) Utilize the liquid-vapor interface to sense the quantity of liquid in the evaporator in conjunction with providing an automatic feed control; a pneumatic-mechanical sensor was to be used in the urine environment.

d) Utilize a water-filled jacket around the evaporator to transfer heat to the urine liquid. Heating elements were to be located in wells extending into the water jacket. Water can be circulated within the jacket to remove excess heat when required, thus providing positive temperature control when isotope heat sources are used.

e) Provide sufficient boiling liquid/vapor interface area to provide a low velocity for vapor leaving the liquid surface and thus minimize entrainment of droplets.

f) Rotate the impeller at low speed to minimize wear on rotating parts, but at sufficient speed to provide the necessary velocity for liquid/vapor separation and adequate boiling.

g) Attach mesh or sponge to the rotating impeller to be used to provide zero-gravity vapor de-misting capability.

h) Utilize a microporous membrane to filter entrained fine droplets from distilled vapor, and to act partially as a barrier to bacteria. The membrane was to be readily removed and replaced, if required, after thermal power shut-down and evaporator repressurization.

i) Include an oxidation catalyst bed designed to provide 40 days of operation without replacement. The housing was to be designed to permit easy removal and replacement of the catalyst cartridge after thermal power shut-down and evaporator repressurization.

j) Incorporate appropriately located sight glasses to permit both visual observation and camera-film recording of the liquid/vapor profile during laboratory or low-gravity testing, when appropriate.

SECTION 3

LABORATORY SUPPORT TESTING

Experimental investigations were conducted to evaluate: a) heat transfer rates between the heating bath and urine, b) a mechanical drive assembly for the rotating impeller, and c) a level sensing device for controlling the urine feed rate and liquid level in the vacuum still. Vapors from the lab distillation unit were also passed through a proprietary oxidation catalyst bed to evaluate the reduction of trace organic contaminants. The catalyst evaluation tasks were conducted under company sponsorship.

The system performed well mechanically with the exception of the rotary shaft seal for the impeller, which sporadically leaked seal-coolant water into the vacuum evaporator. The impeller drive for the laboratory unit was replaced by a magnetic coupling with a static vacuum barrier. The magnetic coupling and drive assembly were operated for a period of 218 hours with no apparent problems.

The bench-scale 3-man capacity evaluation evaporator was operated for a total of 442 hours with no residue removal. A total of 198 liters of feed was added to the system; 186 liters of water were recovered and 12 liters of residue containing 62% solids were accumulated. The bench-scale evaporator was then emptied and recharged with fresh pretreated urine and operated for an additional 110 hours. The vapors in both test runs were passed through the oxidation catalyst for a total of 552 hours.

As anticipated, the boiling temperature of the urine gradually increased relative to the distillate vapor temperature as the test progressed. Near the end of the first batch, the boiling point elevation increased at a more rapid rate; however, the 4°C (7°F) elevation at the end of the batch was lower than predicted for a 62% solids concentration. Since the heating jacket liquid temperature remained essentially constant, the gradual elevation of the urine boiling temperature resulted in a lower heating temperature difference and a gradual decrease in the water boil-off rate. The overall heat transfer coefficient remained constant, and the heating surface remained free of scale, during the entire test.

The liquid level sensor and feed control performed adequately throughout the 552 hours of testing with one exception. When the urine residue was concentrated beyond 40% solids, the feed line tended to plug with solids during overnight shutdown. Both the feed and liquid level sensing lines entered the evaporator at the bottom and were relatively small in size. Precipitated solids which settled on the bottom during overnight shutdown occasionally plugged the feed line and required manual unplugging on start-up of the next run. This was overcome in the final system by relocating and enlarging the feed and sensing lines.

The proprietary oxidation catalyst functioned satisfactorily throughout the 552 hours of operation; it reduced the total carbon and total organic carbon content of the product condensate to acceptable levels. During the course of testing the oxygen feed rate needed to reduce the total organic carbon content of the exit vapor was investigated by varying the oxygen feed rate between 10 cc/min and 230 cc/min (STP). Based on the organic carbon analyses of the recovered water, an oxygen flow of 150 cc/min (STP) is required for a six-man urine distillation rate.

3.1 Laboratory Test Apparatus and Procedures

3.1.1 Test Apparatus

The laboratory test apparatus consisted of hardware that was fabricated and/or purchased specifically for the program, plus standard laboratory equipment to support testing. Components of the system are listed in Table I, which also shows the function, model, and manufacturer of each item. The main components of the system were made of stainless steel, and all instrumentation was corrosion resistant. Figure 3 is a schematic representation of the test set-up and shows the relationship of the components as well as the flow path of the vapors. Figure 4 is a photograph of the entire system.

The evaporator was a 39-cm (15-3/8-inch) diameter by 19.7-cm (7-3/4-inch) high stainless steel cylinder with a 0.8-mm (1/32-inch) thick wall; the cylinder was flanged on both ends. The bottom flange was gasketed and bolted to a plate which also served as a mount for the impeller drive motor, shaft seal, bearings, and supports. The flanged top of the evaporator was covered by a transparent Lexan plate. The internal impeller had four identical vanes; there was approximately a 12.7-mm (1/2-inch) clearance between the vanes and the evaporator wall. A variable speed motor rotated the impeller through a water-jacketed dynamic shaft seal.

Two oxidation catalyst beds were mounted directly above the Lexan plate; one bed contained catalyst, while the other was empty and served as a control reference. Each bed was heated by an external wrap-around tape heater and controlled by a variable voltage transformer. A differential pressure gauge was connected at the inlet and outlet of each bed. The pressure differential indicated on each gauge served as a relative indicator of the instantaneous vapor flow rate through the respective bed. Oxygen flow for the beds was controlled by a fine needle valve and measured with a glass tube rotameter; the oxygen

TABLE I

LABORATORY TEST COMPONENTS

COMPONENT	FUNCTION	MODEL	MANUFACTURER
Evaporator	Evaporation	---	GARD-Fabricated
Heating Jacket	Supply heat to the evaporator wall	---	GARD-Fabricated
Adjustable Speed Drive Motor	To drive the impeller blades	JK1	Zero-Max
Ice Bath	To act as a reference for the potentiometer	---	---
Rotary Seal	---	---	Syntron Division, FMC Corporation
Condensate Receivers	To collect condensate delivered from the condensers	---	---
Glassware Condensers	To condense water vapors	---	---
Catalyst Bed	To oxidize organic material to CO_2, H_2O	---	GARD-Fabricated
Oxygen Flowmeter	To monitor O_2 flow to catalyst	1906D	Fisher-Porter Company
Thermocouples	To monitor evaporator liquid and vapor termperatures	Type K	---
Potentiometer	To give readout from thermocouples	2730	Rubicon Instruments
Magnehelic	To monitor pressure drop across beds	2005C	Dwyer Instrument Co.
Dry Ice-Acetone Trap	To condense vapors not condensed by glassware condensers	---	---
Urine Metering Control	Monitors the amount of urine to be added for each timer cycle	---	GARD-Fabricated

TABLE I

LABORATORY TEST COMPONENTS
(Concluded)

COMPONENT	FUNCTION	MODEL	MANUFACTURER
Variac	To adjust power to catalyst bed and heating jacket	236 Powerstat	Superior Electric Co.
Duoseal Vacuum Pump	To pull vacuum	1502	Welch Scientific Co.
Recirculating Water Bath	To circulate H_2O through H_2O jacket	3052	Lab Line Instrument Co.
Submersion Heater	To provide heat to recirculating H_2O bath	---	---
Chiller	Supply coolant for condensers	CFF50A	Remcor Products
Pressure Switch	To control liquid level by sensing ΔP	1822	E. W. Dwyer Manufacturing Company
Absolute and Differential Manometer	Monitor pressure in evaporator	---	Manostat Corporation
Manometer	Monitor pressure in condenser	---	Sargent-Welch
Feed Solenoid Valve	To allow urine feed from metering control	803436	ASCO
Repeat Cycle Timer	Control ON-OFF activity of feed solenoid valve	---	Industrial Timer Corp.
Pilot Strip	To plug in all major supporting electrical equipment	---	Cole Palmer
Thermocouples	To monitor water jacket, ambient, and catalyst temperatures	---	---

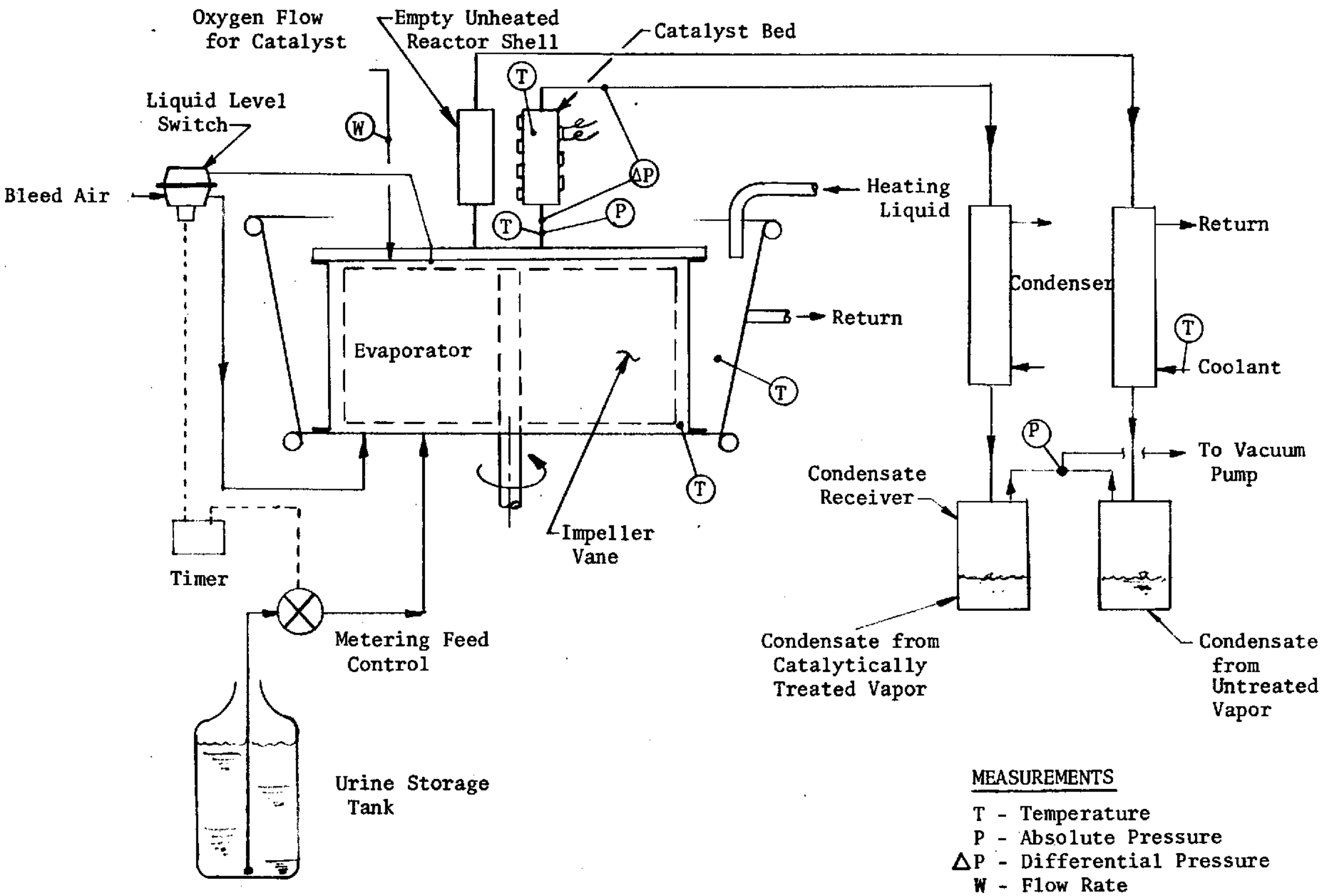

Figure 3 LAB TEST FLOW DIAGRAM

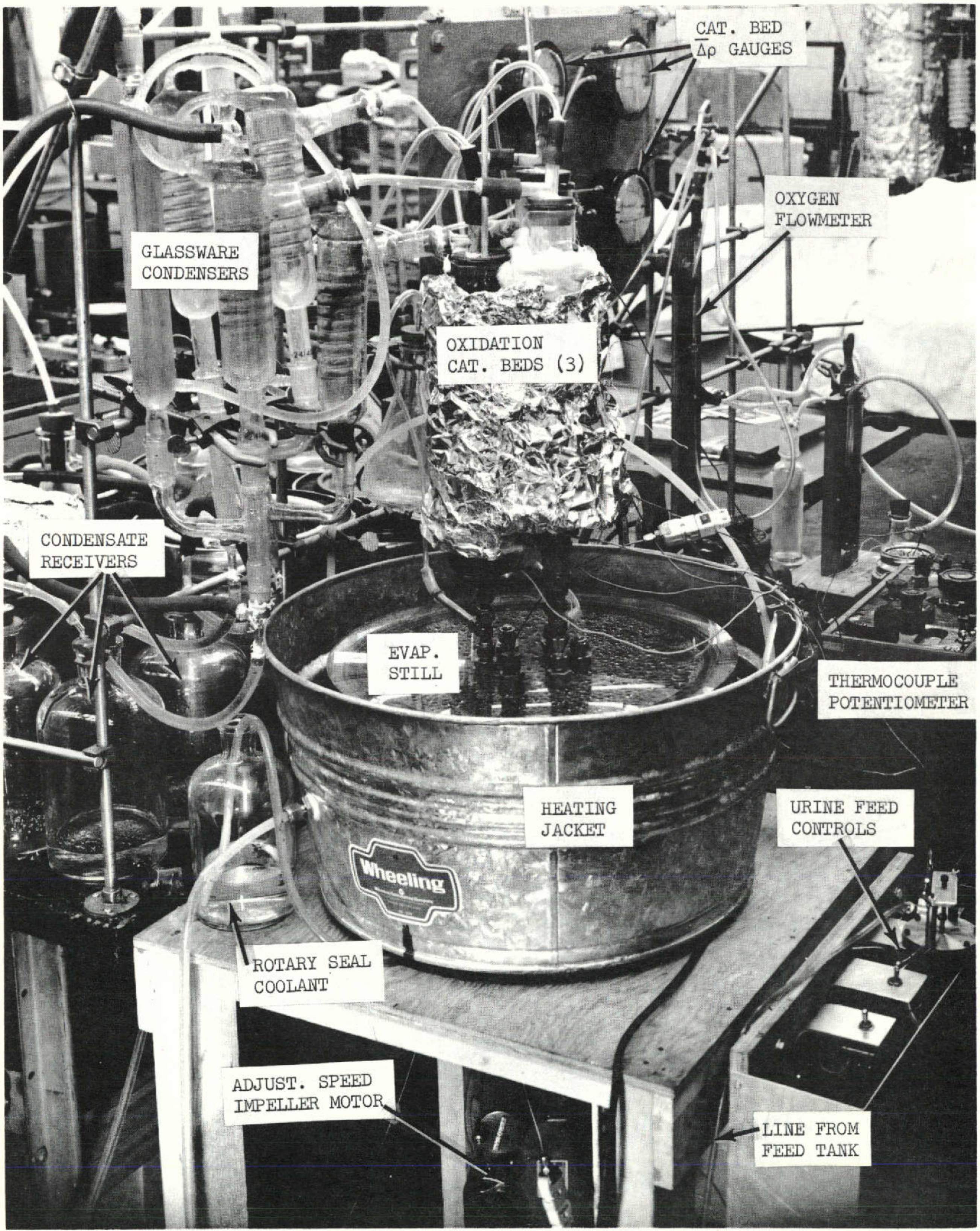

Figure 4 LABORATORY TEST SET-UP

entered both through the top of the still and through the liquid-level sensing system.

The liquid level control system consisted of a differential pressure switch measuring the head of liquid in the still, a metering pump, and a timer. One leg of the pressure switch connects to the vapor space in the evaporator; the other leg is submerged in the rotating body of liquid. Oxygen is fed into the evaporator through the submerged leg, and the difference in pressure between the vapor space and oxygen feed line actuates the switch. The switch allows the metering pump to feed approximately 100 cc of liquid at a given time interval determined by the timer setting. Feed liquid enters the evaporator at fixed intervals; however, if the level gets too high, the pressure switch cuts off power to the metering pump until the level drops to the desired level. Operation of this system is independent of ambient gravity levels.

A circulating water bath provided the thermal input to the heat transfer jacket. The open top jacket was constructed from 50.8-cm (20-inch) galvanized tub which was modified to attach to the bottom plate of the still.

Individual condensers and condensate receivers were connected to each catalyst bed to permit measurement and analysis of the condensate from each bed. The condensers were cooled by a water-glycol loop connected between the condensers and a small chiller. A laboratory vacuum pump was used for system pumpdown and to purge the noncondensable gases during operation.

Process temperatures were measured with mercury thermometers and/or thermocouples connected to a potentiometer. Absolute mercury manometers were connected to the vapor discharge line from the still and to the vacuum purge line from the condensers to indicate evaporator and condenser absolute pressures.

3.1.2 Test Procedures

All urine processed was collected from male in-plant personnel in approximately one-liter containers. Prior to setting out the collection flask, a 4-cc volume of chemical pretreatment was placed in it. Within 3 to 4 hours of the time the flask was set out, it was returned to the laboratory and the contents emptied into the urine feed tank.

The chemical pretreatment was a 4:1:4 mixture by weight of sulfuric acid, chromium trioxide, and distilled water. This particular pretreatment mixture has been used previously by GARD and other water recovery investigators and functions satisfactorily to inhibit biological decomposiiton of urea. (Without a suitable inhibitor, urea, the principle organic compound in urine, would decompose and give off unacceptable amounts of ammonia.)

At the initiation of the test, it was planned to mix an antifoam compound with the pretreatment acid at the time the acid was prepared and store this mixture in a single container. The intent was to make only one addition of pretreatment to the urine prior to distillation. In actual practice, however, the antifoam compound did not readily mix with the acid and it was necessary to separately treat the fresh urine with acid and with antifoam.

The laboratory test unit was operated approximately 8 hours/day during the normal working days of the week. During overnight and weekend shutdowns the still was repressurized to atmospheric pressure. At the beginning of each run, 1 cc of Dow Corning H-10 antifoam compound, diluted into 50 cc of water, was injected into the liquid within the still. As the tests progressed, additional antifoam was added during a run to reduce the amount of foam in the vapor space in the evaporator. Process measurements were taken and recorded at 3 to 4 hour intervals. Water samples for evaluating catalyst bed performance were obtained at the end of each day and represented the entire day's run. The performance of the catalyst bed was assessed by analyzing daily samples of condensate collected before and after the bed for total carbon, total organic carbon, pH, ammonia, conductivity, and turbidity.

3.2 Laboratory Test Results

3.2.1 Distillation Test Results

The first batching process required 443 hours to distill 167 liters of urine mixed with 28 liters of water and 3 liters of antifoaming compound. At the end of the test twelve liters remained as sludge, containing the concentrated urine solids. An analysis of the urine residue indicated 62% total solids by weight. The performance data for the first batch are summarized in Table II. No humidity condensate was used in these tests.

TABLE II

LABORATORY SYSTEM DISTILLATION PERFORMANCE SUMMARY

BATCH #1

ITEM		VALUE
Urine Input	167 liters	
Water Input (initial checkout)	28 liters	
Water Containing Antifoam	3 liters	
Total Input		198 liters
Recovered Water		186 liters
Residual Sludge		12 liters
Solids Concentration of Sludge		62% (weight)
Total Elapsed Time		443 hours

The first distillation batch was terminated after 443 hours because the residual sludge foamed excessively. On the last few days, as the evaporator was evacuated at the start of a daily run, the sludge foam would fill the entire vapor space in the evaporator and would carry over into the exit vapor line. The foaming action was so vigorous that it was not restrained by the rotating paddles when it filled the entire vapor space in the evaporator.

An initial objective of this test was to concentrate the residue to at least 50% solids and, secondly, to determine what is a practical limit of sludge concentration. The results of the first distillation batch indicate that approximately 60% is a practical limit. Two other areas of concern, boiling point elevation and heat transfer to the urine, were evaluated during these tests and are discussed below.

Boiling Point Elevation

For the first 110 hours the liquid and vapor temperatures were identical and varied between 25°C (77°F) and 28°C (82°F), but as the test progressed, a difference in temperature was noted between the boiling urine and vapor leaving the evaporator. During the next 220 hours, the liquid temperature was 0.5°C (1°F) to 1.4°C (2.5°F) higher than the vapor temperature; this demonstrated the anticipated boiling point elevation (BPE). In the final 110 hours of the first batch, the BPE increased to 4°C (7.5°F), which was indicative of the increased solids concentration in the evaporator liquid. The evaporator liquid and vapor temperatures and vapor pressure for 53-hour to 58-hour intervals are given in Table III. The rise in BPE as a function of hours of operation of the first batch is graphically depicted in Figure 5.

According to published data*, the solute weight fraction (or dissolved solids concentration) is approximately 45% for a BPE of 4°C (7°F). The

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* Putnam, D. F., Composition and Concentrative Properties of Human Urine, DAC-61125-F1, June 1970.

TABLE III

EVAPORATOR TEMPERATURE AND PRESSURE HISTORY

TIME hrs.	EVAPORATOR PRESSURE mm Hg	LIQUID TEMPERATURE C°	(°F)	VAPOR TEMPERATURE C°	(°F)	BOILING POINT ELEVATION C°	(°F)
FIRST BATCH							
0-57	24	26.6	(80)	26.6	(80)	---	---
57-110	24	26.1	(79)	26.1	(79)	---	---
110-166	23	27.2	(81)	26.6	(80)	0.6	(1.0)
166-222	23	28.2	(82.7)	27.2	(81)	1.0	(1.7)
222-276	24	29.8	(85.6)	28.4	(83.2)	1.4	(2.4)
276-334	22	29.3	(84.8)	27.9	(82.2)	1.4	(2.6)
334-388	23	30.5	(86.9)	28.3	(83)	2.2	(3.9)
388-443	22	31.6	(89)	27.4	(81.5)	4.2	(7.5)
SECOND BATCH							
0-54	30.5	31.4	(88.5)	31.4	(88.5)	---	---
54-110	29.2	31.2	(88)	30.9	(87.5)	0.3	(0.5)

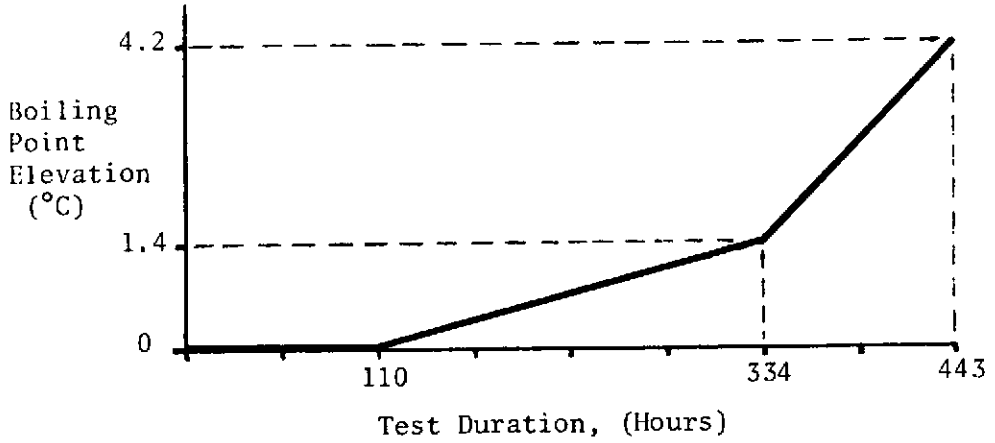

Figure 5 BPE vs. DURATION OF TEST

actual concentration of total solids was 62%. When the evaporator was drained after the first batch, it was noted that approximately 1.27 cm of precipitate covered the entire bottom of the evaporator. This precipitate was mixed into the residue drained from the evaporator and was included as part of the sample that was analyzed for total solids. Presumably, the precipitated solids in the residual sludge account for the difference between the 45% solids level expected for a 4°C BPE and the 62% solids actually measured.

When the second distillation batch was started with fresh urine, the liquid and vapor temperatures returned again to equal values--with no elevation of boiling point--for the first 54 hours. During the next 56 hour interval a slight boiling point elevation of 0.3°C was observed.

Overall Heat Transfer Coefficient

An objective of the distillation tests was to determine the overall heat transfer coefficient from the liquid heating jacket to the boiling urine and also to determine the variation of this coefficient as a function of hours of operation. It was found that the overall heat transfer coefficient remained essentially constant near 36.7 cal/hr-cm^2-°c (75 BTU/hr-ft^2-°F) for the duration of the tests.

The distillation rate, temperature difference (ΔT) for heat transfer, and overall heat transfer coefficient are given in Table IV for approximately 55-hour increments of the test duration. As the test progressed, the ΔT from heating fluid to urine decreased from a high value of 6.4 C (11.5 F) near the beginning of the test to a low value of 3.8 C (6.9 F) near the end of the test. Of significant note, the recovery rate varied in direct proportion to this ΔT, which indicates that the overall heat transfer coefficient remained essentially constant. The ΔT and distillation rate decreased mainly because the method of controlling heat input in the lab unit depended on control of the temperature level of the liquid heating jacket.

During the normal batch evaporation process, as the urine liquid temperature increases due to boiling point elevation, the available temperature difference for heat transfer decreases (assuming that both the evaporator pressure and liquid heating jacket temperature remain constant). To maintain a constant distillation rate the method of control should measure the ΔT between the evaporating liquid and the heating jacket rather than the temperature level of the heating jacket. On the basis of these tests, it appears that a ΔT-actuated control should be used to maintain the distillation rate on a full-scale system.

During the second distillation bath of 110 hours, the overall heat transfer coefficient remained essentially constant near 36.7 Cal/hr-cm^2-°C (75 Btu/hr-ft^2-°F). The average distillation rate of 5.2 cc/min and average ΔT of 3.8°C was lower than for the corresponding 110 hours of the first batch. The lower ΔT was probably due to carryover of foam in the vapor exit tube near the end of the first batch.

TABLE IV

DISTILLATION HEAT TRANSFER COEFFICIENT vs. TEST DURATION

TIME hrs.	DISTILLATION RATE cc/min	$\Delta T^{(1)}$ °C	($^{\circ}$F)	$U^{(2)}$ cal/hr-cm^2-C	(BTU/hr-ft^2-F)
FIRST BATCH					
0-57	8.9	5.6	(10.0)	43.0	(88)
57-110	8.8	6.4	(11.5)	37.7	(77)
110-166	7.1	5.0	(9.0)	38.2	(78)
166-222	7.5	5.4	(9.7)	37.7	(77)
222-276	7.3	4.9	(8.9)	39.6	(81)
276-334	5.8	4.2	(7.6)	37.2	(76)
334-388	5.5	3.8	(6.9)	38.6	(79)
388-443	5.3	3.9	(7.0)	36.7	(75)
SECOND BATCH					
0-54	5.5	3.9	(7.0)	38.2	(78)
54-110	4.9	3.6	(6.5)	36.7	(75)

[1] Temperature difference between liquid jacket and boiling urine.

[2] Overall heat transfer coefficient from liquid jacket to boiling urine.

The foam carryover apparently caused partial blockage in the oxidation catalyst bed; the required pressure differential for transporting vapor from the evaporator to the condenser was higher at the beginning of the second batch than in the first batch. The pressure drop through the catalyst bed was the operating parameter which limited the distillation rate rather than the temperature difference between heating jacket and evaporator liquid as in the first batch.

If the evaporator vapor pressure and temperature were allowed to increase further, the pressure differential between evaporator and condenser would increase and, as a result, the distillation rate could be increased. However, the vapor temperature in the evaporator would then be higher than ambient temperature and some of the generated vapor would condense within the evaporator and then need to be re-evaporatored again. Under these conditions the actual evaporation rate would be higher than the recovery rate. The calculations necessary to determine the overall heat transfer coefficient required that the evaporation rate be known. Since evaporation rate cannot be measured easily, but recovery rate is the same as evaporation rate if there is no refluxing of generated vapor within the evaporator, the recovery rate was measured and assumed equal to evaporation rate. Thus, an operational restraint to avoid refluxing was to maintain the evaporator pressure below 30 mm Hg absolute corresponding to a saturation pressure of 29°C (85°F).

3.2.2 Evaluation of Mechanical Features

The rotating impeller functioned adequately to keep the main body of liquid in motion. When the evaporator was drained after the first batching process, the boiling surface was free of scum and solids build-up.

The feed control and liquid level sensing system functioned satisfactorily. Near the end of the first batch, the sensing line and the feed line became plugged with urine solids, which settled out during overnight shutdown. The small line sizes and their vertical orientation were factors that contributed to the plugging.

Initially, the rotating impeller was driven through a rotary shaft seal. An assembly drawing of the rotary seal test configuration is shown in Figure 6. During testing, the rotary shaft seal assembly failed at the connection that seals the rotating shaft to the rotating seal face. Upon disassembly and repair, it was observed that a small slice into the rubber connection allowed gross leakage of seal coolant (water at atmospheric pressure) into the vacuum evaporator. From the nature of the seal defect, it appeared that the defect could have been initiated during assembly of the seal on the shaft. On numerous occasions there was sporadic leakage of the seal coolant into the evaporator.

Because of these problems the impeller drive for the laboratory unit was changed from a rotary seal system to a magnetic coupling. With the magnetic drive assembly a static barrier exists between the external drive and the internal impeller and its support bearings inside the vacuum chamber. An assembly drawing of the magnetic drive for the lab system is shown in Figure 7. After converting to the magnetic drive, the lab system was operated for 218 hours without apparent problems in the drive. As anticipated, the impeller speed had to be increased gradually from rest to normal rotation speed to prevent the magnets from uncoupling.

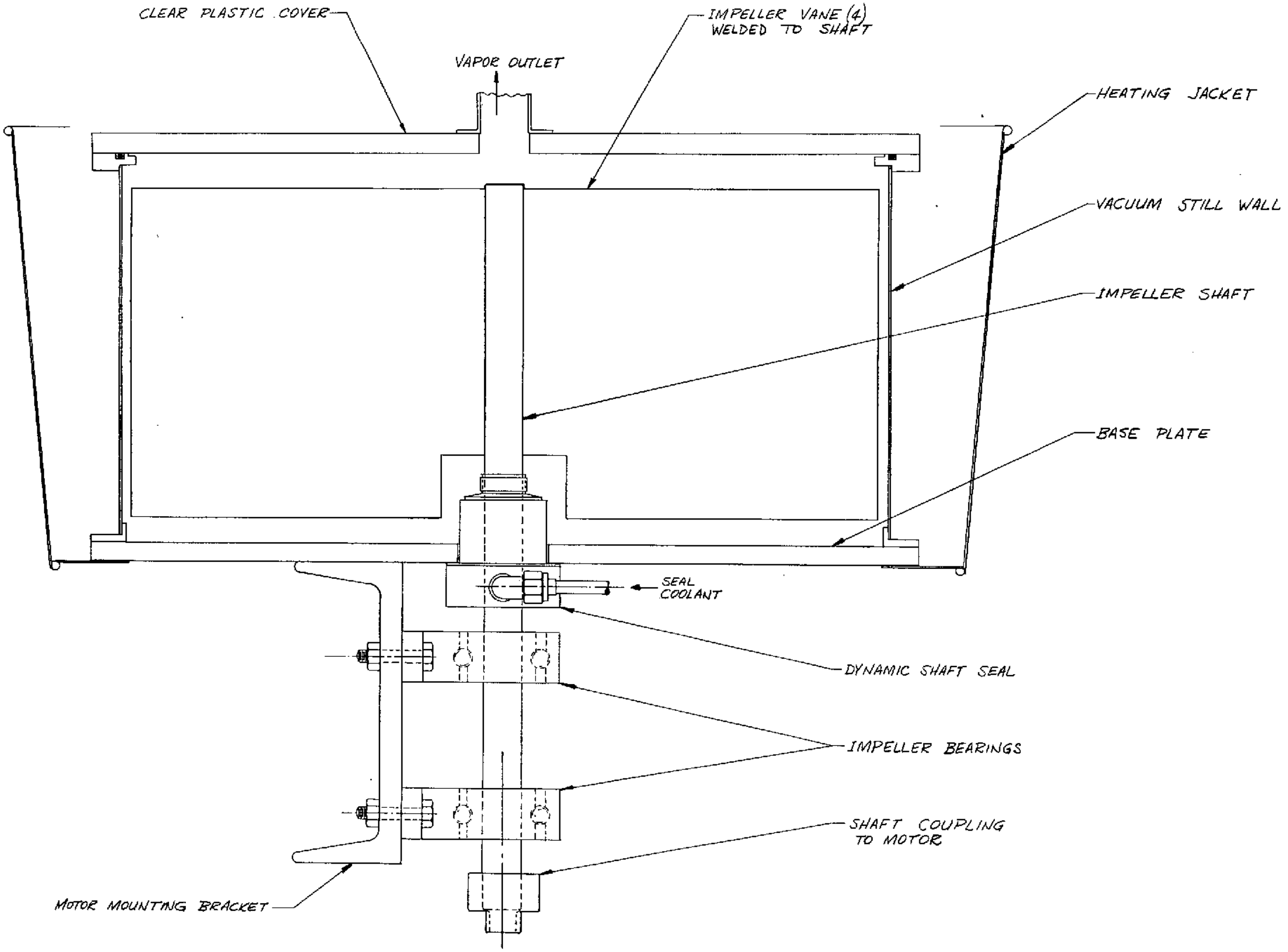

Figure 6 LAB DISTILLATION UNIT WITH ROTARY SHAFT SEAL

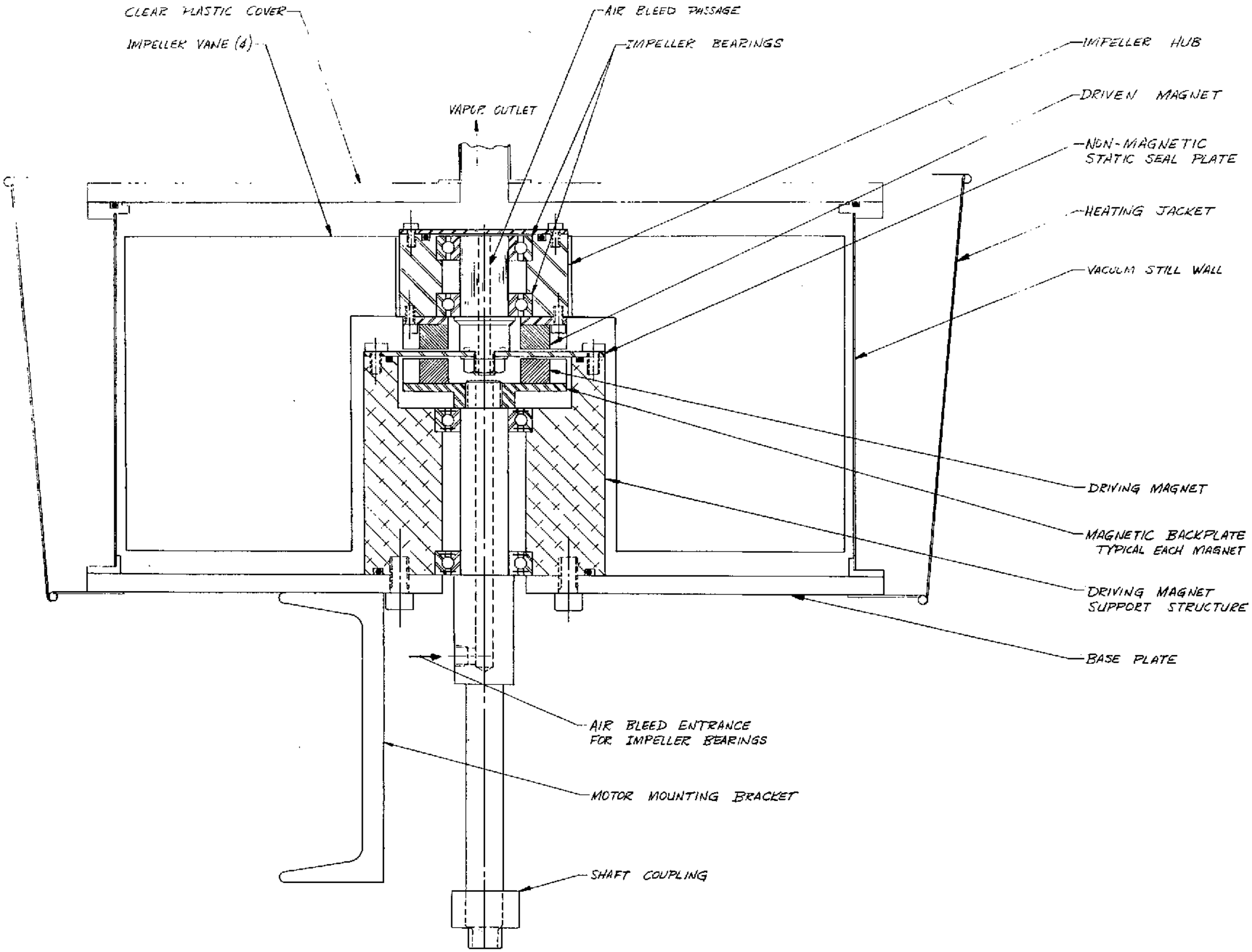

Figure 7 LAB DISTILLATION UNIT WITH MAGNETIC COUPLING

3.2.3 Oxidation Catalyst Test Results

The vapors from the lab distillation unit were passed through a proprietary catalyst bed to evaluate the catalyst's ability to promote oxidation of the trace contaminants in the distillate vapor. The catalyst evaluation was conducted under company sponsorship. The distillation system was operated for 443 hours with urine feed; 86 liters of condensate recovered from the vapor were passed through this catalyst bed during the first batching process. The daily analyses of the product water and pertinent operating parameters of the system are given in Table V.

The contaminant concentration level in the condensate collected from catalytically treated vapor was directly affected by the quantity of oxygen flow to the bed. By experimentally varying the oxygen flow, it was determined that 150 cc/min (STP) was required for a six-man urine distillation rate, with distillation at 32°C (90°F).

The daily variation of total carbon (TC) and total organic carbon (TOC) content is shown in Figures 8 and 9 respectively. The carbon containing contaminants are primarily organic carbon compounds in the condensate collected from raw vapor. Both TC and TOC concentration are reduced in the condensate from catalytically treated vapor, but the TC content is higher than TOC. Apparently some of the carbon containing compounds are converted to carbonates and possibly dissolved CO_2 which then appear as inorganic carbon in the water. The most significant result, however, is that TOC concentration is reduced to a very low and acceptable level.

Figures 10 and 11 illustrate the daily fluctuations of pH and ammonia concentration, respectively. These are discussed together because their fluctuations seem to be related; also, the pH and ammonia concentrations after

TABLE V

OXIDATION CATALYST TEST PARAMETERS AND TEST RESULTS

SAMPLE NUMBER	DATE (1971)	TEMPERATURE					PRESSURE		TOTAL CARBON		TOTAL ORGANIC CARBON		pH		AMMONIA		CONDUCTIVITY		TURBIDITY	
		AMBIENT °F	HEATING BATH °F	EVAP. LIQUID °F	EVAP. VAPOR °F	CATALYST BED °F	EVAP. mmHg	COND. mmHg	BEFORE CATALYST mg/1	AFTER CATALYST mg/1	BEFORE CATALYST mg/1	AFTER CATALYST mg/1	BEFORE CATALYST	AFTER CATALYST	BEFORE CATALYST mg/1	AFTER CATALYST mg/1	BEFORE CATALYST mhos	AFTER CATALYST mhos	BEFORE CATALYST JTU	AFTER CATALYST JTU
1	9/16	77	90	81	73	127	26	15	--	6	--	--	--	6.1	--	0	--	10	--	.4
2	9/17	--	--	--	--	--	--	--	--	3	--	--	--	6.1	--	0	--	15	--	.6
3	9/20	80	89	77	77	68	24	5	--	4	--	--	--	6.4	--	0	--	9	--	.5
4	9/22	82	89	79	79	109	23	5	--	1	--	--	--	5.8	--	0.5	--	14	--	.6
5	9/23	81	90	81	81	114	24	5	--	0	--	--	--	5.8	--	1.2	--	15	--	.4
6	9/24	75	89	80	80	101	22	5	--	0	--	--	--	6.0	--	.5	--	15	--	.4
7	9/27	78	91	81	81	98	25	4	--	12	--	--	--	8.4	--	7.5	--	45	--	.3
8	9/28	79	90	81	81	111	25	4	--	33	--	--	--	8.8	--	11.8	--	85	--	.5
9	9/29	76	91	82	82	114	26	12	--	22	--	--	--	8.4	--	7.3	--	58	--	.7
10	9/30	80	90	--	--	115	25	8	--	--	--	--	--	7.9	--	0	--	56	--	.4
11	10/1	80	91	79	79	109	25	8	--	--	--	--	--	6.3	--	2.5	--	40	--	.2
12	10/4	75	90	79	79	101	25	8	43	17	43	5	3.6	6.7	0	3.5	120	34	3.5	.2
13	10/5	75	90	78	78	120	24	7	37	0	37	0	3.6	6.5	0	3.6	130	22	2.0	.2
14	10/6	81	88	77	77	124	23	7	53	4	53	0	3.5	6.3	1.0	1.0	150	13	1.3	.3
15	10/7	83	91	78	78	120	24	7	60	3	60	2	3.7	6.3	0	1.5	150	11	25	.5
16	10/8	78	94	81	81	110	26	8	50	10	50	0	3.5	5.7	0	0	160	12	1.3	.9
17	10/13	73	90	80	80	129	24	6	51	10	51	6	3.6	5.9	2.5	.8	160	14	2.0	.8
18	10/14	74	91	82	81	150	24	7	68	12	68	4	3.7	6.2	7.8	5.5	190	43	13	.6
19	10/15	76	90	83	81	125	23	7	51	0	51	0	3.7	6.7	1.1	4.0	200	44	4.8	1.0
20	10/18	77	88	80	78	120	21	5	43	8	43	0	3.8	8.9	2.2	7.9	210	41	24	2.0
21	10/19	75	89	81	80	135	23	6	68	0	68	0	3.8	8.0	3.4	8.6	390	66	32	.5
22	10/20	79	91	--	--	123	23	6	25	2	25	0	3.9	8.4	1.2	5.8	85	37	2.0	.6
23	10/21	75	88	76	75	132	21	7	25	8	25	0	3.7	8.9	0	6.0	80	33	2.0	.4
24	10/22	72	90	81	80	134	22	7	58	0	58	0	3.7	7.1	1.5	7.7	340	60	13	.4
25	10/25	79	94	84	83	137	24	7	38	0	38	0	3.7	7.3	0.3	4.3	110	42	3	1.0
26	10/26	76	94	82	79	137	24	9	--	0	--	0	3.7	7.9	2.6	3.5	--	37	11	.8
27	10/27	75	92	84	81	134	24	9	--	0	--	0	3.8	6.8	--	3.0	--	36	6.5	1.0
28	10/28	77	92	84	82	134	23	8	54	0	54	0	3.6	7.5	1.8	4.0	140	26	1.5	1.2
29	10/29	75	92	82	80	141	22	8	--	0	--	0	3.8	6.6	--	2.8	--	31	10	1.2
30	11/1	76	89	81	81	134	21	7	29	5	29	0	4.0	6.6	1.0	2.0	--	29	1.0	1.3
31	11/2	77	92	83	81.5	134	21	7	27	0	27	0	3.8	6.8	0	3.8	100	36	2.2	.7
32	11/4	76	92	83	81.5	123	23	7	58	6	58	4	3.9	7.8	1.7	2.4	150	22	1.2	.7
33	11/5	81	94	84	81.5	135	22.5	8	80	0	80	0	3.8	6.5	2.4	2.8	300	32	.6	.5
34	11/8	76	93	86.5	83.5	150	24.5	--	52	0	52	0	3.7	7.9	0.5	4.0	150	42	.6	.8
35	11/9	76	93	84.5	82	143	23	7	42	5	42	1	3.7	6.6	0	2.8	170	30	.3	.8
36	11/10	78	94	85.5	83	134	24.5	7	53	3	53	3	3.8	7.1	0.3	2.8	110	26	.3	.9
37	11/11	75	96	85	84	143	24.5	7	53	0	53	0	3.6	6.7	0	2.5	130	20	.3	.9
38	11/12	75	94	85	83.5	136	24	7	38	1	38	1	3.9	6.4	0	4.0	120	43	.3	.8
39	11/15	82	98	88.5	85	141	25.5	7	57	13	57	11	3.6	6.8	0	5.5	115	52	.3	.8
40	11/16	82	92	84.5.	82.5	146	21	6	46	13	46	5	3.6	6.4	0	3.3	110	30	.5	1.3
41	11/17	82	90	83.5	81	150	20.5	6	50	13	50	7	3.7	6.4	0	2.5	100	28	.2	.9
42	11/18	80	96	87	84.5	139	24	7	57	13	57	0	3.7	7.2	0	2.5	100	32	.3	.7
43	11/19	79	91	84.5	82.5	142	23.5	7	55	5	55	3	3.7	6.5	0	3.9	110	32	.3	1.0
44	11/22	78	92	84.5	83	138	22	7	50	17	50	2	5.3	6.4	0	3.0	26	30	.7	.9
45	11/24	78	96	87	84.5	137	23.5	7	36	1	36	1	3.7	6.5	0	3.3	100	30	.3	.9
46	11/29	79	92	83.5	82	134	21.5	6	47	9	47	1	4.0	6.3	1.4	3.7	100	31	.3	.6
47	11/30	78	90	84	82	150	21	6	39	5	39	1	3.9	6.2	1.0	2.8	82	32	.2	.4
48	12/2	80	92	83.5	80.5	134	20	7	38	6	38	2	4.0	6.6	1.0	2.7	--	50	.2	.5
49	12/6	--	--	--	--	--	--	--	45	7	45	0	4.0	6.8	1.1	4.1	--	49	1.4	.8
50	12/8	78	97	88.5	83.5	152	23.5	14	40	3	40	0	4.0	6.8	5.0	2.0	--	62	.8	.8
51	12/9	80	93	85.5	83	160	23.5	9	40	10	40	0	--	6.9	--	6.0	--	60	--	.5
52	12/10	81	92	89	83.5	148	24	15	24	1	24	0	4.0	7.0	0.2	2.1	75	54	.5	.6
53	12/13	79	95	88	83.5	141	22	7	55	28.5	55	22	4.0	8.5	0	3.2	72	48	.5	.9
54	12/14	79	98	--	--	140	26	7	60	35	60	12	--	7.2	--	1.0	--	55	--	.7
55	12/15	82	102	92.5	88	146	26	7	137	11	137	7	4.2	7.9	7.5	2.3	510	36	5.5	.6
56	12/16	80	94	87	83	153	21	7	60	24	60	7	4.1	7.8	0	2.0	84	40	1.8	1.0
57	12/17	79	96	88	80.5	155	21	10	63	19	63	4	4.0	6.6	1.0	0	78	50	.5	.6
58	12/20	78	94	87.5	80	160	19	7	72	25	72	22	4.2	7.1	--	--	78	48	.7	1.0
59	12/21	78	94	--	--	155	20	7	73	32	73	5	4.2	6.9	.7	3.0	78	42	.7	3.0

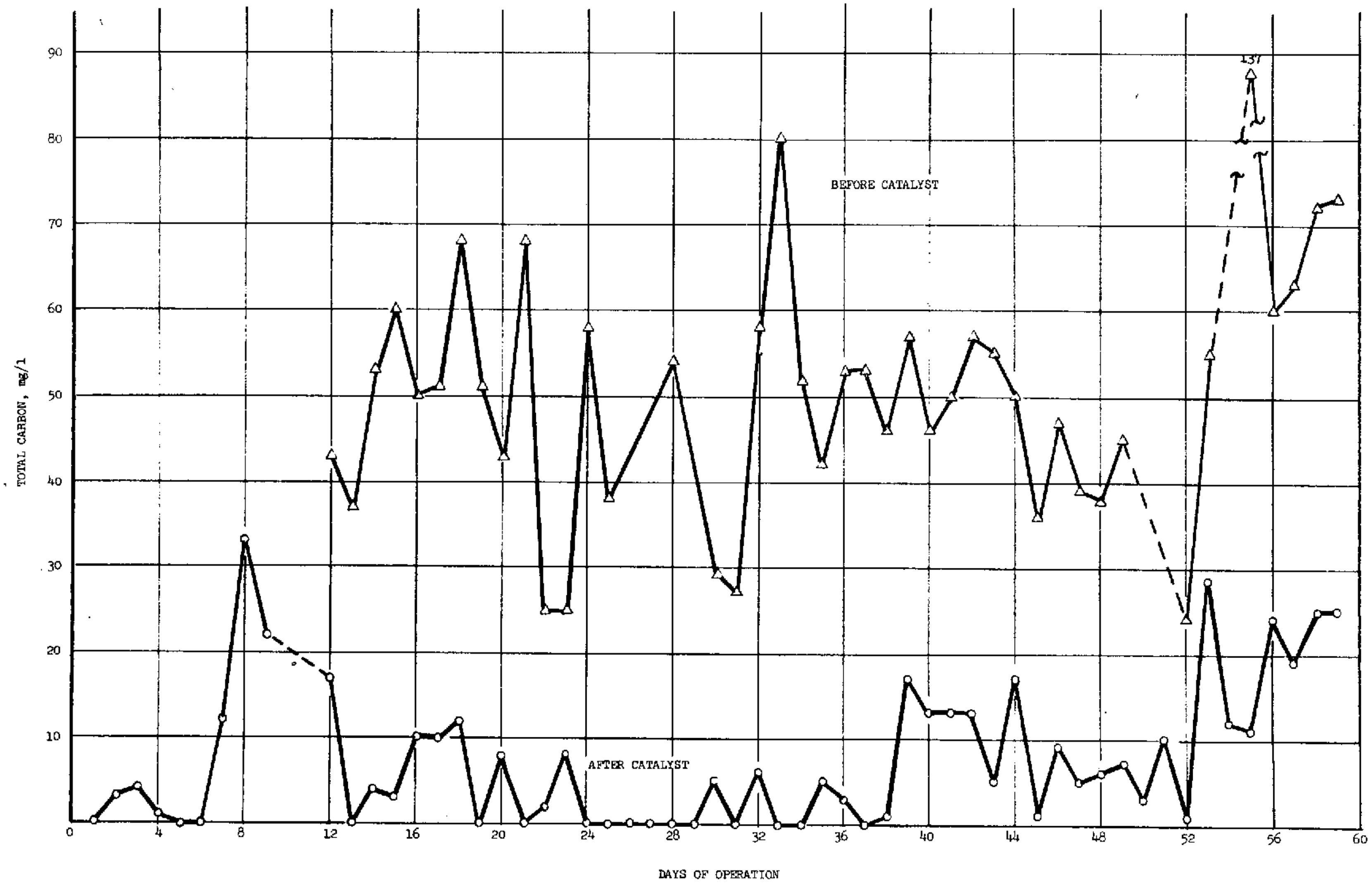

Figure 8 DAILY VARIATION OF TOTAL CARBON CONTENT

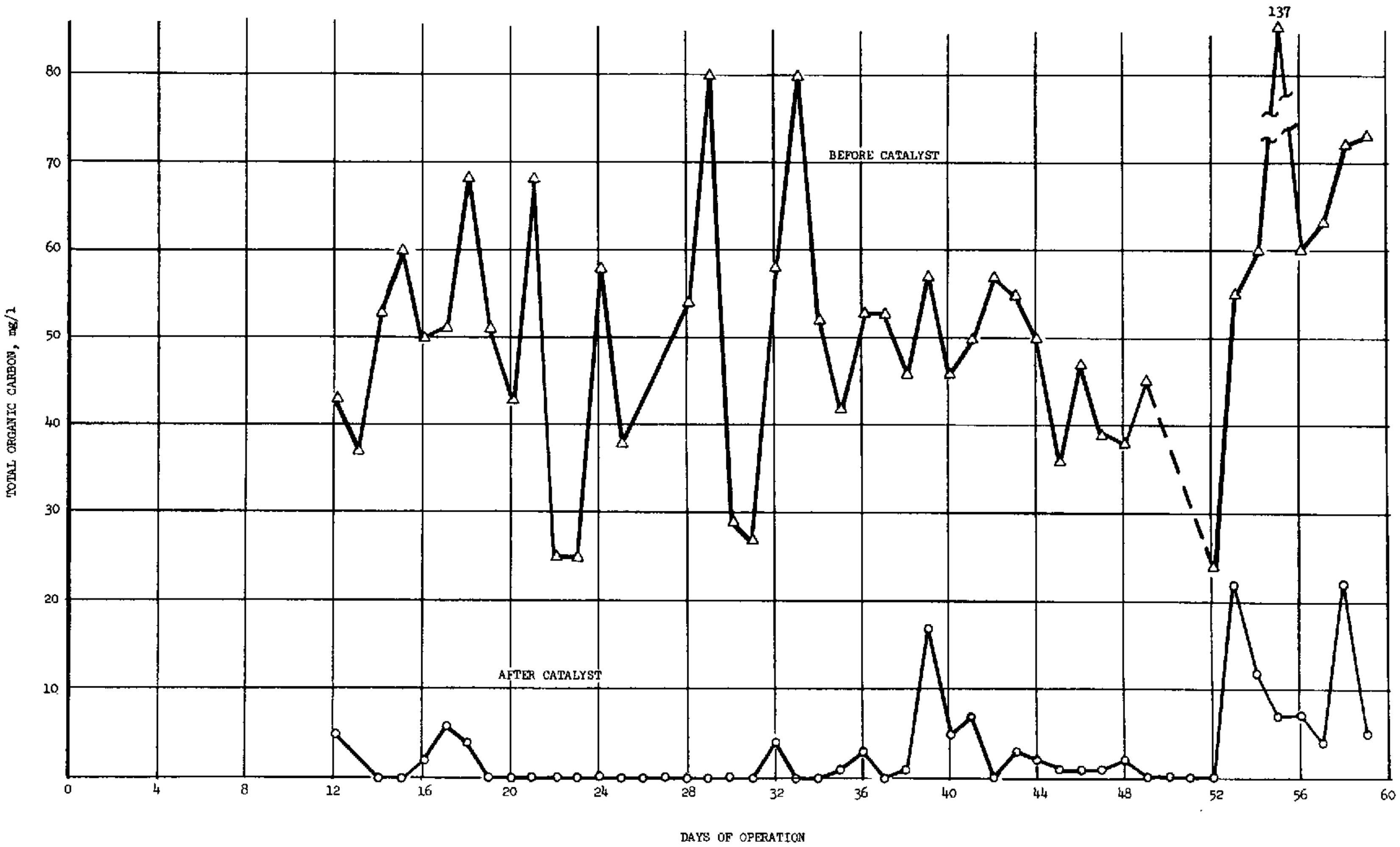

Figure 9 DAILY VARIATION OF TOTAL ORGANIC CARBON CONTENT

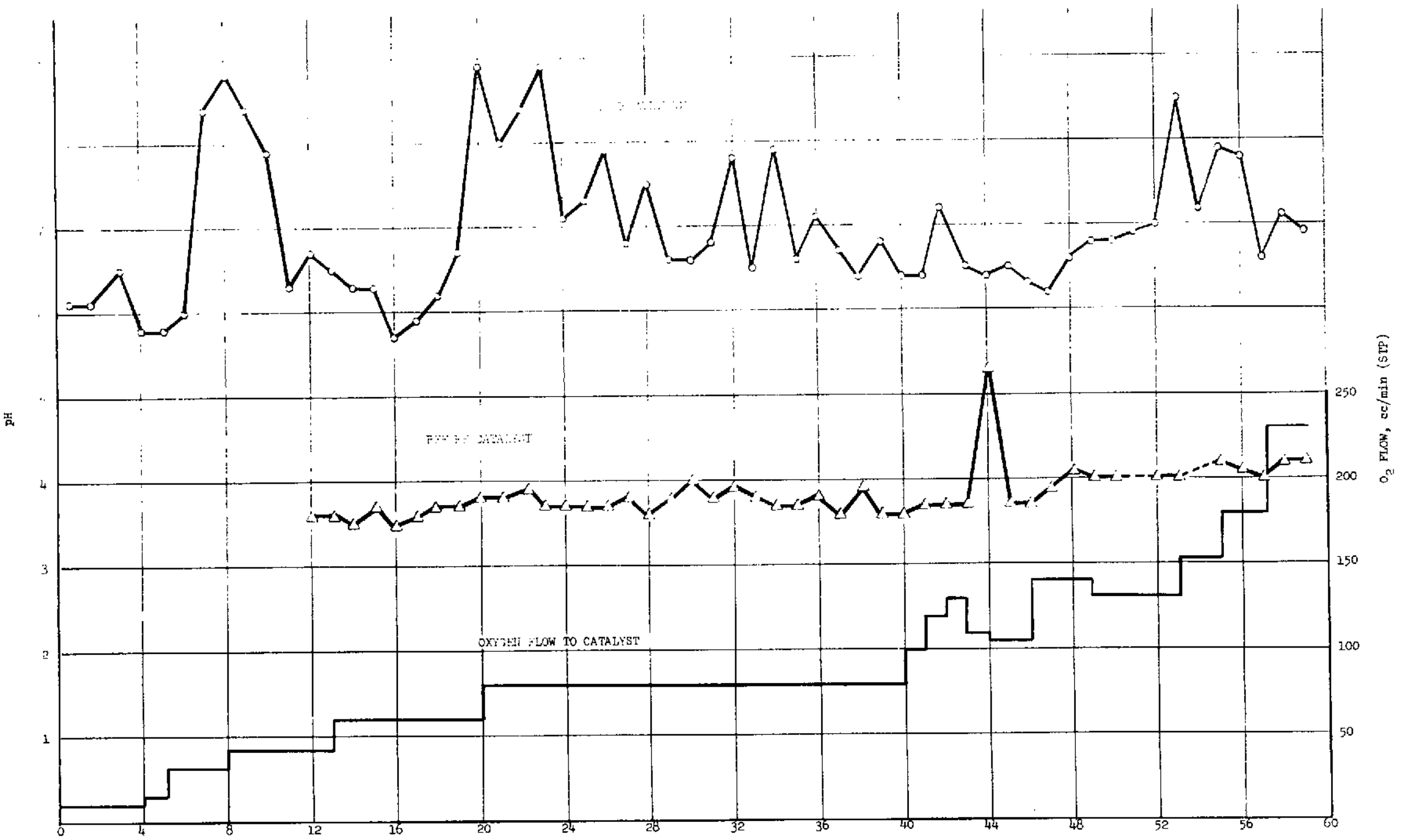

Figure 10 DAILY VARIATION OF pH

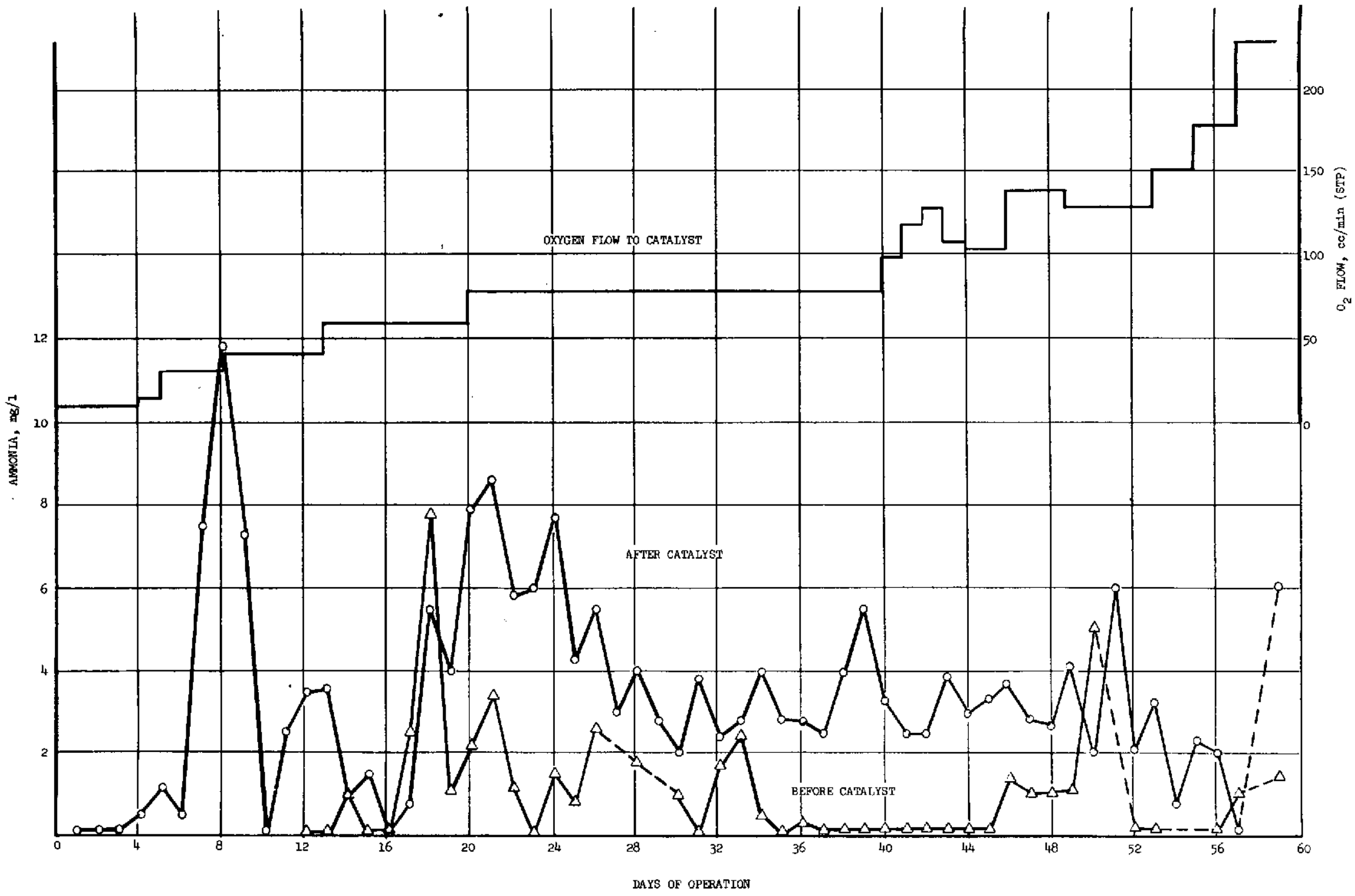

Figure 11 DAILY VARIATION OF AMMONIA CONTENT

treatment were generally higher than before treatment. This phenomenon is not readily explainable; it is known that it would not be possible to generate ammonia within the catalyst bed since it does not have any nitrogen or hydrogen containing compounds. It is possible that vapors or entrained mist contained compounds which were converted to ammonia by reaction or decomposition within the catalyst bed. This mechanism would have the effect of raising the ammonia concentration in the vapor passing through the catalyst.

Oxygen flow rate to the catalyst during system operation is also included on these figures since it appeared to have a relation to the concentration of ammonia in the condensate from catalytically treated vapor.

Figure 12 illustrates the daily variations in conductivity of the condensate. While there is no specified limit of conductivity for potability, it is generally desirable to have a conductivity value of less than 100 μmhos. The condensate collected from catalytically treated vapor was consistently below 100 and generally below 40 μmhos.

The daily variation in turbidity is shown in Figure 13. The relatively high values for days 12 through 30 for the condensate collected from raw vapor are probably attributed to the fact that these samples stood for an extended period of time before the particular analysis was conducted.

A summary of the catalyst performance in terms of the best, worst, and averaged value during the first batch is presented in Table VI. This table excludes the extreme values which occurred when foam carried over from the evaporator near the end of the first batch.

After the still was drained, a second batch of fresh urine was distilled for a short period. The vapors were again passed through the catalyst bed

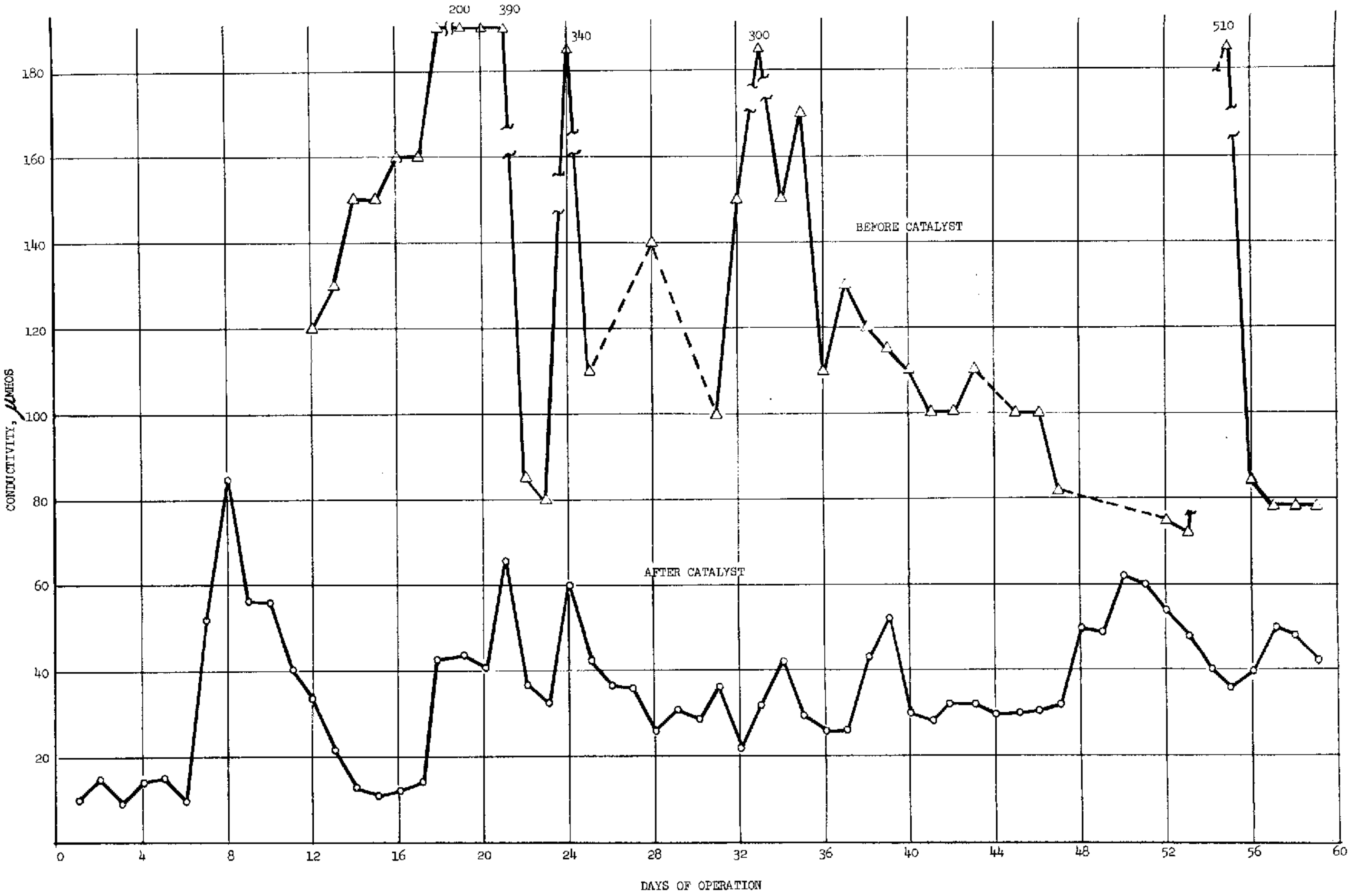

Figure 12 DAILY VARIATION OF CONDUCTIVITY

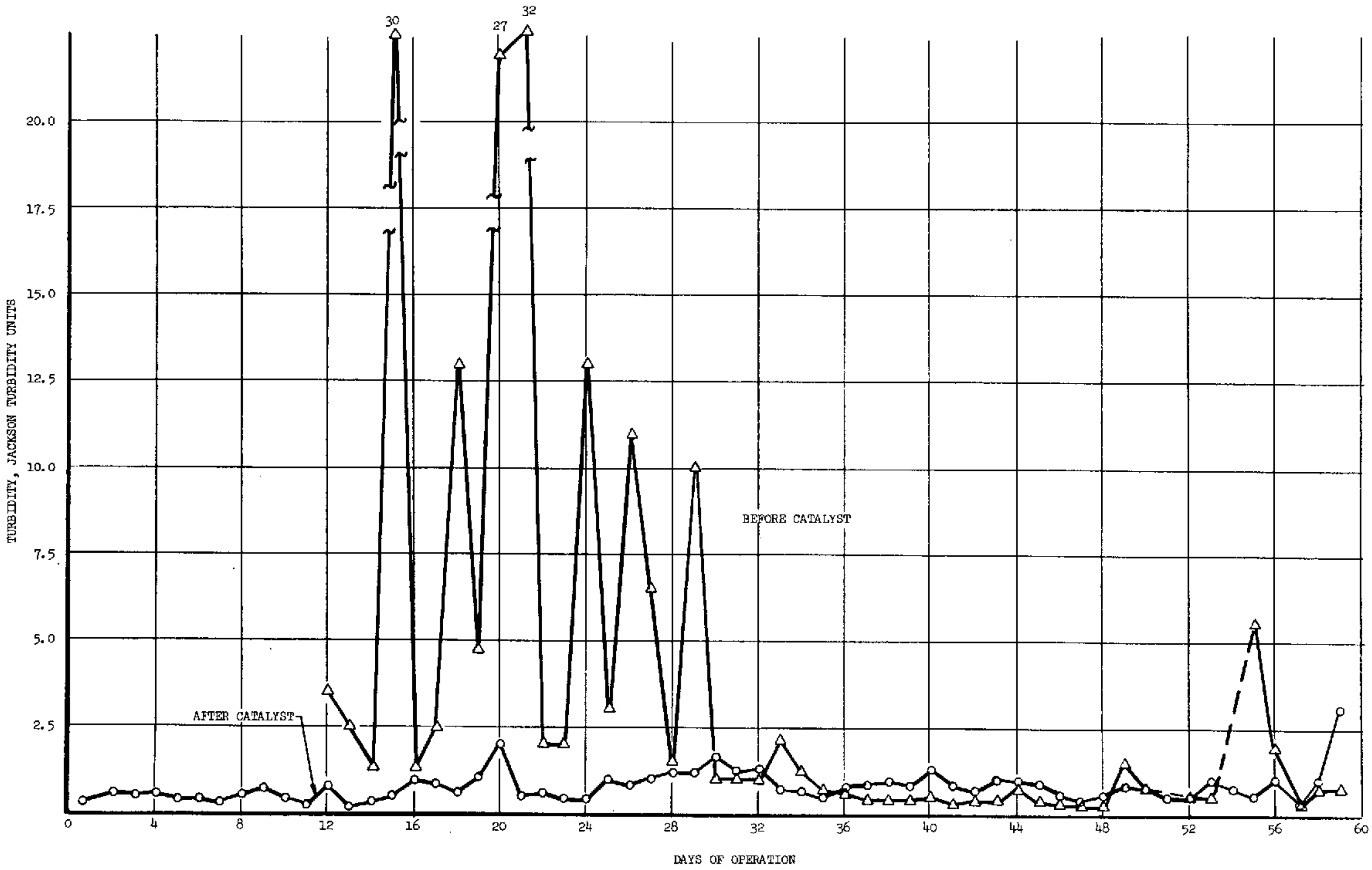

Figure 13 DAILY VARIATION OF TURBIDITY

TABLE VI

CATALYST PERFORMANCE SUMMARY: FIRST DISTILLATION BATCH

CONDENSATE ANALYSIS	BEST DAILY PERFORMANCE	WORST DAILY PERFORMANCE	AVERAGE FOR 443 HOURS
Total Carbon (mg/l)			
Before catalyst	24	80	50
After catalyst	0	36	6
Total Organic Carbon (mg/l)			
Before catalyst	24	80	50
After catalyst	0	33	3
pH			
Before catalyst	3.5	5.3	4.0
After catalyst	5.7	8.9	7.2
Ammonia (mg/l)			
Before catalyst	0	7.8	1.0
After catalyst	0	11.8	3.0
Conductivity (μ mhos)			
Before catalyst	72	390	140
After catalyst	7	66	44
Turbidity (JTU)			
Before catalyst	.5	32	2
After catalyst	.5	3	1

during 110 cumulative hours of operation, and 10.3 liters of condensate were collected from vapors passed through the catalyst. Evaluation of the results indicated the catalyst was still effective in reducing the concentration of trace contaminants in the product vapor. A summary of catalyst performance is presented in Table VII. There was no regeneration of the catalyst before starting the second batch. During the entire operation of the distillation system a total of 96.3 liters of condensate were collected from catalytically treated vapor.

TABLE VII

CATALYST PERFORMANCE SUMMARY:
SECOND DISTILLATION BATCH

CONDENSATE ANALYSIS	BEST DAILY PERFORMANCE	WORST DAILY PERFORMANCE	AVERAGE FOR 110 HOURS
Total Carbon (mg/l)			
Before catalyst	19.0	146	55.0
After catalyst	10.0	68	24.3
Total Organic Carbon (mg/l)			
Before catalyst	19.0	146	55.0
After catalyst	0.0	23	6.4
pH			
Before catalyst	6.7	4.2	6.1
After catalyst	6.7	9.3	7.5
Conductivity (μ mhos)			
Before catalyst	76	1000	259
After catalyst	42	300	130
Turbidity (JTU)			
Before catalyst	1.0	12.0	2.3
After catalyst	0.5	0.9	0.8

SECTION 4

EVAPORATOR DEVELOPMENT

4.1 Design

The vacuum distillation/vapor filtration unit shown in Figure 1-2 was designed in accordance with the general requirements for a six-man capacity zero "g" evaporator and the detail requirements listed in Section 2.2.

4.1.1 Evaporator Size Determination

To insure the adequacy of the evaporator design, calculations were made to determine tradeoffs between vacuum evaporator size, impeller speed, and sludge removal intervals. Calculations were made to determine the thermal energy requirement for a six-man recovery rate and to size the vapor and sludge removal lines. The calculations are included in the Appendix and are summarized as follows:

For 40 days batching duration,

Evaporator Diameter:	51.8 cm (20.4 inches)
Evaporator Height:	37.3 cm (14.7 inches)
Impeller Speed:	100 rpm is adequate for one-g demonstration of principle of operation.
Solids Concentration at End of Batch:	40% by weight
Area for Evaporation:	2740 cm^2 (2.96 ft^2) based on calculated boiling coefficient of (45 cal)/(hr cm^2°C) ((92 BTU)/(hr ft^2°F))
Vapor Duct Size:	20.9 mm (.824 inches) I.D.
Sludge Removal Line:	15.9 mm (.625 inches) I.D.

Utilizing information provided from the laboratory support test described in Section 3, a layout assembly drawing was prepared for the evaporator in accordance with the design calculations. The layout assembly drawing is shown in Figure 14. The layout design provides for heating and cooling coils located in the heating jacket. The evaporator, as constructed and shown in Figure 2 , does not include the coils but allows the recirculating heating liquid to flow directly into the jacket.

The configuration shown in Figure 14 includes three changes from the configuration described in GARD Proposal 91466. These are (a) addition of a shut-off valve at the vapor outlet of the evaporator, (b) the vapor filter located downsteaam of the catalyst instead of upstream, and (c) the vacuum evaporator and catalyst unit designed to utilize waste heat from a heat transport loop instead of only cartridge heaters.

The shut-off valve at the vapor outlet of the evaporator is intended to contain liquid within the evaporator in the event of power failure or stoppage of the centrifugal impeller, and to isolate the evaporator from the vapor components in the system during start-up with steam sterilization of the outlet vapor passage.

The vapor filter was relocated at the outlet of the catalyst bed to isolate the sterilized vapor components during periodic changing of the catalyst cartridge. The filter also serves as a bacteria removal mechanism in the system, and as a back-up to the catalyst bed.

From the standpoint of integrating all major subsystems in a spacecraft, it is anticipated that the water reclamation system could utilize waste heat from the Power Generating System. Accordingly, the configuration shown in Figure 14 was adjusted to utilize either waste heat or the originally proposed

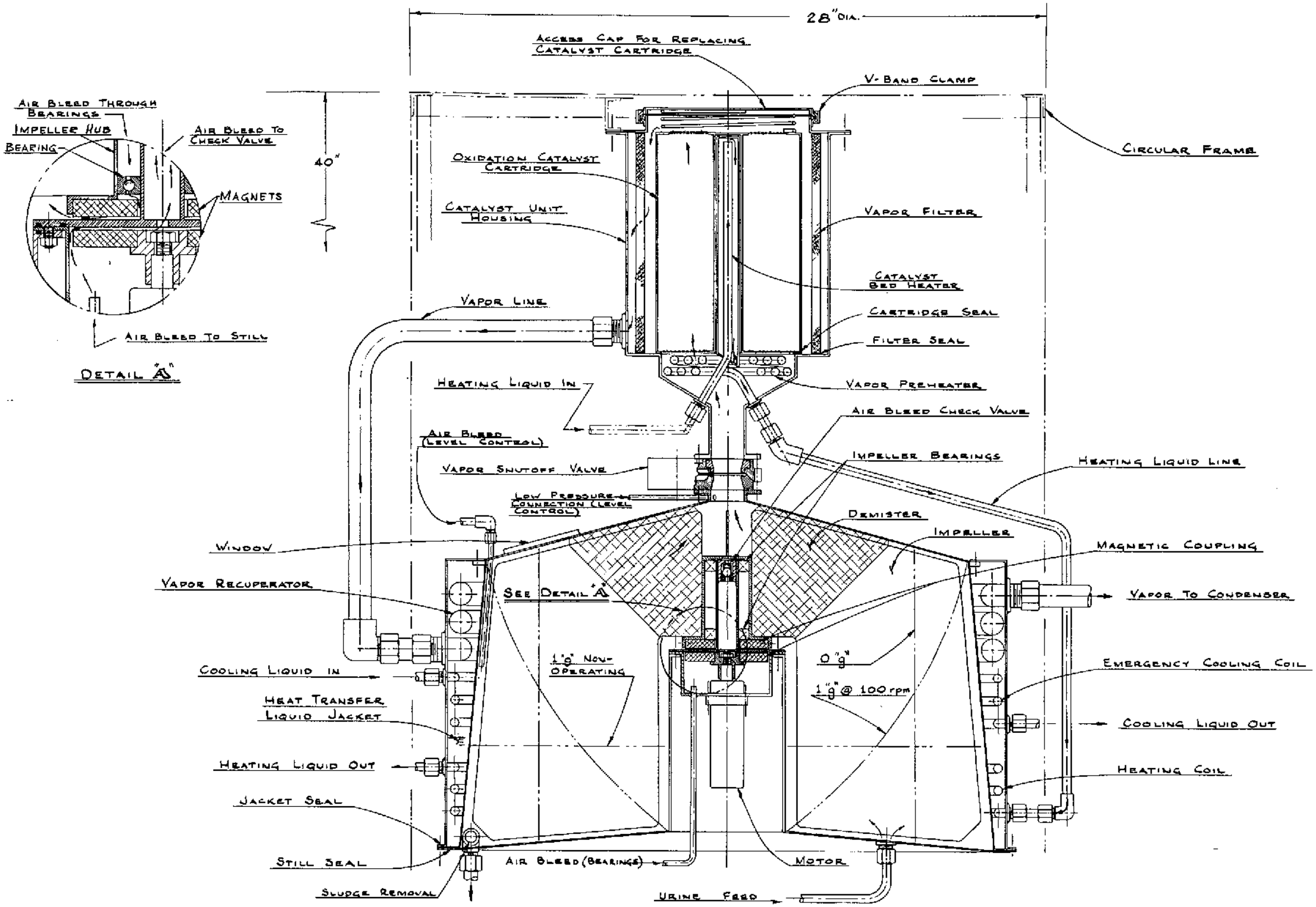

Figure 14 EVAPORATOR ASSEMBLY

cartridge heaters. These heaters would be located in a heat loop operating between the cartridges and the evaporator.

The internal dimensions of the six-man evaporator are 55.9 cm (22 inches) in diameter at the bottom and 38.1 cm (15 inches) high. The resulting volume of rotating liquid is sufficient to hold the urine sludge accumulated during 40 days of operation. Overall dimensions of the evaporator assembly are 71.1 cm (28 inches) in diameter and 101 cm (40 inches) high; these dimensions do not include local protrusions for fluid lines and connections.

4.1.2 Evaporator Components

The major items of the evaporator assembly and their respective function(s) are as follows:

	ITEM		FUNCTION
1.	Vacuum Evaporator	a)	Contains urine for distillation.
		b)	Houses the rotating impeller.
		c)	Provides visual inspection of liquid via sight glasses.
		d)	Provides for sludge removal, urine feed, liquid level sensing.
2.	Liquid Jacket	a)	Receives fluctuating heat input from heat loop and from vapor recuperator.
		b)	Provides a large uniform temperature area for heat transfer to the urine.
3.	Impeller	a)	Provides centrifugal effect and artificial gravity for vapor and liquid separation.
		b)	Constrains the evaporating urine against the heat transfer surface.
4.	Rotating Demister	a)	Prevents escape of fine mist in vapor by utilizing the centrifugal effect.
5.	Motor	a)	Drives impeller.

ITEM	FUNCTION
6. Magnetic Coupling	a) Transmits torque from motor to impeller across a static barrier
	b) Allows impeller and motor to uncouple when torque is above the safe limit for the gearbox
7. Impeller Bearings	a) Support impeller in the internal vacuum, urine sludge, and vapor environment
8. Air Bleed Line & Check Valve	a) Provides oxygen for catalytic oxidation of gases in distilled vapors
	b) Purges liquid leg of differential pressure switch sensing liquid level height in evaporator
	c) Continually purges a small quantity of air over impeller support bearings to prevent vapor and sludge from contacting bearings
	d) Provides for removing sludge and/or vapor from bearings in the event it contacts bearings during prolonged shut-down in zero "g"
	e) Check valve prevents back flow from the evaporator into motor housing
9. Heating Coil	a) Transfers heat from heat transport fluid to the liquid jacket
10. Vapor Shut-off Valve	a) Protects condenser, catalyst, filter and vapor passages by automatically closing when vacuum or electrical power is shut-off
	b) Manually closed when vapor components are being steam sterilized on initial start-up
11. Vapor Preheater	a) Transfers heat from heat loop to raise temperature of vapor to approximately 93°C (200°F) before entering catalyst bed

ITEM		FUNCTION
12. Catalyst Bed Heater (Utilizes heat loop)	a)	Initially heats catalyst bed to approximately 149°C (300°F) at start-up
	b)	Heats vapor to approximately 121°C (250°F)
13. Oxidation Catalyst Cartridge	a)	Contains oxidation catalyst in a readily replaceable cartridge
14. Oxidation Catalyst Bed	a)	Removes trace organic compounds from the process vapor
	b)	Subjects the vapor to sterilization temperature
15. Vapor Filter	a)	Filters bacteria and other particulates from the process vapor
	b)	Maintains a sterile barrier to condenser during the interval of catalyst replacement
16. Vapor Recuperator	a)	Transfers heat from process vapor to the heat transfer liquid jacket

The vacuum evaporator, catalytic oxidation unit housing, heating coils, and liquid jacket are stainless steel components fabricated from machinings, formed sheet, spinnings, tubing, and heliarc weldments. All mechanical joints which seal against vacuum utilize static O-ring face seals and bolts, except the access cover for the catalyst cartridge. A V-band clamp and O-ring seal at the cover permits access at this point.

The impeller is supported by internal bearings which are continually purged during operation with the air used in the catalytic oxidation process. The inner race is stationary and secured to the bottom of the evaporator. The outer race is attached to the impeller hub and is the rotating member. The bearings are fabricated from a cobalt base, chrome, tungsten alloy and are designed for wear resistance while operating without a lubricant. A small quantity of air is admitted through the hollow inner post and through a check valve at the end of the post. The bleed air continually passes over the bearings and blocks water vapor, urine droplets, or particles from entering the bearing chamber. The check valve prevents reverse flow of vapor from the still into the motor housing during prolonged shut-down.

The impeller is driven by a 28-vdc motor located in a well in the bottom plate of the still. The top end of the well is a statically sealed nonmagnetic plate which supports the mount tube for the inner bearing races. Motor torque is transmitted across the nonmagnetic plate by a magnetic coupling. The coupling consists of a matched pair of ceramic permanent magnets attached to magnetic backplates. The backplates attach the magnets to the impeller and motor output shaft.

The vapor shut-off valve is a stainless steel gate valve with a penumatic actuator. A 3-way solenoid pilot valve connects the actuator cylinder to either the system vacuum pump or to ambient pressure. When vacuum is applied, the gate valve is open; when ambient pressure is admitted, the actuator's return spring closes the valve.

The oxidation catalyst cartridge is designed to fit over the catalyst heater and to seal with an O-ring at the lower outside wall. The cartridge seal is spring-loaded by the upper access cap. When the access cap and V-band clamp are positioned in place, the spring-loaded O-ring seal prevents vapors from bypassing the catalyst. Radial fins within the catalyst cartridge aid the distribution of heat outward from the central heater.

The vapor filter is a cylindrical cartridge of Pall Corporation Ultipor pleated filter media rated for removal of 0.08-micron size particles from the gases and vapors. This is generally accepted as "absolute" removal of bacteria from vapors and gases. The filter cartridge is constructed of pleated filter media bonded to end caps. Each end cap has an O-ring seal to prevent by-passing of flow around the filter. The filter media and bonding material are suitable for continuous exposure to 135°C (275°F).

4.1.3 Evaporator Operation

Description of Operation

Referring to Figure 14, the system operation is as follows:

Pretreated urine and humidity condensate solution are metered into the evaporator via a three-way solenoid valve, metering pump, and timer. The metering accumulator volume and timer interval realtionship are adjusted to feed slightly more than the nominal feed rate. The three mechanical items, in conjunction with a differential pressure switch sensing the liquid level in the evaporator, comprise the urine feed control. The liquid-level sensor also serves as the heat input control, by acting as part of the heating-liquid feed-valve circuit.

A small amount of air continually bleeds in through one leg of the liquid-level sensor; the air back-pressure is transmitted to a pressure switch. When the volume of liquid in the still reaches a maximum set-point, the sensor transmits a higher back-pressure due to the increased liquid height. Increased pressure actuates a high-level switch and closes the urine feed solenoid valve until the boiling process returns the liquid interface to the normal operating level. Air entering through the level sensor probe also prevents fouling and clogging, and eventually reacts in the catalytic oxidizer with volatiles generated during urine evaporation.

The main body of liquid is driven outward to the vacuum still wall by the vaned impeller. The entire body of liquid moves at the impeller speed and continually washes past the heat input surface. Heat input is provided through a waste-heat liquid loop to the liquid jacket; the heating-liquid transfers heat across the still wall to the urine. The liquid jacket also receives from the vapor recuperator at up to 149°C (300°F); the liquid in the jacket acts as a large uniform temperature bath operating at approximately 38°C (100°F) to boil urine.

The overall heating rate is controlled with a bypass valve in the heating liquid loop. When the bath temperature is below 43°C (110°F) and the urine level in the still is within normal operating limits, the bypass valve allows the heating liquid to enter the liquid jacket. When either the bath temperature is above 43°C (110°F) or the urine liquid level is below the low operating limit, the bypass valve prevents flow to the liquid jacket and no heat is received for evaporation.

The heating jacket also includes an emergency cooling coil. In the event of a malfunction of the heat loop controls or an abnormally high waste-heat liquid temperature, the emergency heat removal loop can be actuated to keep the heating jacket temperature below 49°C (120°F). The controls for the heating and cooling loops will be designed as part of the evaporator and condenser assembly in Phase II of the program.

The impeller is driven by a 28-vdc motor located outside the evaporator. The motor controls include a rheostat to reduce the applied voltage during start-up. Normal operating torque required to drive the impeller is relatively low--1.356 joules (1 ft-lb) as compared to the torque required for instantaneous start-up from rest to 100 rpm. To circumvent the requirement for a large magnetic coupling for start-up only, the motor voltage is reduced at start-up and gradually increased with increasing impeller speed. The impeller includes a de-misting sponge to coalesce mist or aerosols into larger droplets, which will then be driven outward to the main body of liquid by the centrifugal force of rotation.

The evaporator is operated with a liquor solution that increases in concentration until approximately 40% solids by weight are accumulated in solution after 40 days. In normal operation the sludge is removed by utilizing the pumping action of the impeller to either transfer the sludge directly to a storage container, which is at the same absolute pressure, or alternately, to feed the sludge to a removal pump, which transfers the sludge to the desired location and pressure level.

Distilled vapors pass through the vapor shut-off valve, which is open during normal operation, and pass over a preheater tubing coil. The tubing coil contains circulated waste-heat liquid at approximately 149°C (300°F), which heats the vapor from 32°C (90°F) to approximately 93°C (200°F). As the vapors pass through the oxidation catalyst bed, entrained organic compounds are oxidized and the entire flow stream is heated to a nominal temperature level of 121°C (250°F). The oxygen required for this process is provided by bleed flow into the still through the liquid-level sensor and by the main bearings purge flow.

The vapor leaving the catalyst bed is filtered through a microporous membrane (Pall Ultipor .9 filter media at 93-121°C (200-250°F). The filter retains particles 0.08 microns and larger. The viable bacteria which escape the catalyst bed are retained by the filter and should be destroyed by prolonged exposure to 93-121°C (200-250°F).

The filtered vapor then passes through the coiled-tube recuperator and is cooled by the heating jacket liquid. The sterile, potable vapor leaves the recuperator and evaporator assembly at approximately 49°C (120°F) and is ready for subsequent condensing into potable water.

4.2 Fabrication and Assembly

The evaporator shell structure was fabricated from stainless steel formed sheet, spinnings, machined flanges, and port fittings. Heliarc welding was employed throughout for joining the parts of each subassembly.

The vacuum evaporator and heating jacket assembly are shown in Figure 15. Upper and lower closures are spinnings which are bolted to machined flanges with O-ring seal grooves. The inner side wall was rolled from sheet and butt seam welded into a conical shape.

Major parts of the rotating impeller and de-mister assembly are: 1) two ball bearings and bearing support structure, 2) four radial vanes, 3) vapor de-misting mesh, 4) driven magnet, and 5) a nonmagnetic plate between the magnets. The plate mounts to the lower closure of the vacuum still shell and forms a part of the barrier structure between ambient pressure and vacuum. The impeller and de-mister assembly is shown in Figure 16.

Input torque to rotate the impeller is supplied by the power drive assembly shown in Figure 17. A brushless 28-volt dc motor operates nominally at 5000 rpm to drive a 3-stage gearbox, which reduces the speed to 100 rpm. The driving magnet, mounted on the gearbox output shaft, is identical in shape to the driven magnet.

The catalytic oxidation unit was fabricated in a similar manner to that for the vacuum still. This assembly has individual access caps for removal of the catalyst cartridge and the vapor filter. Appropriately located instrumentation bosses are included as shown in Figure 18.

Figure 15 VACUUM EVAPORATOR ASSEMBLY

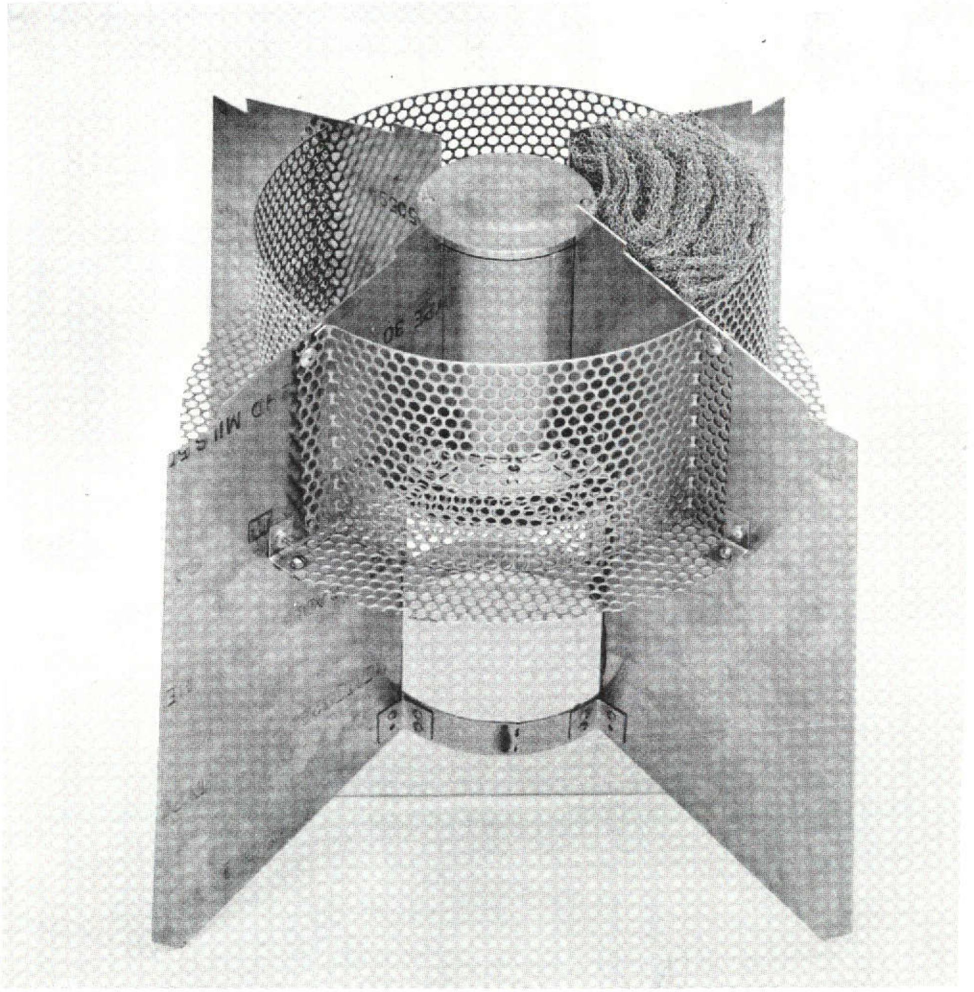

Figure 16 IMPELLER/DEMISTER ASSEMBLY

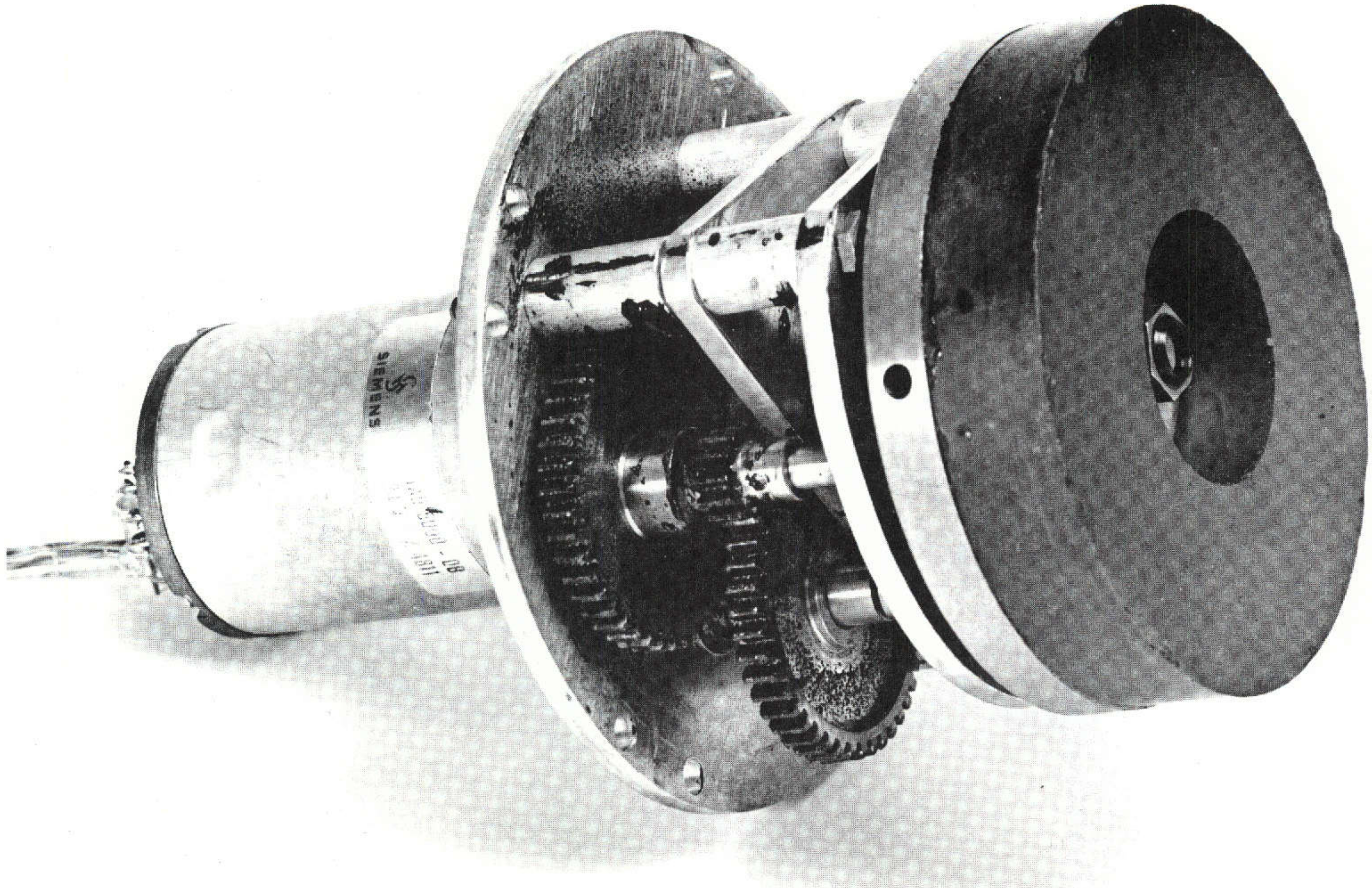

Figure 17 POWER DRIVE ASSEMBLY

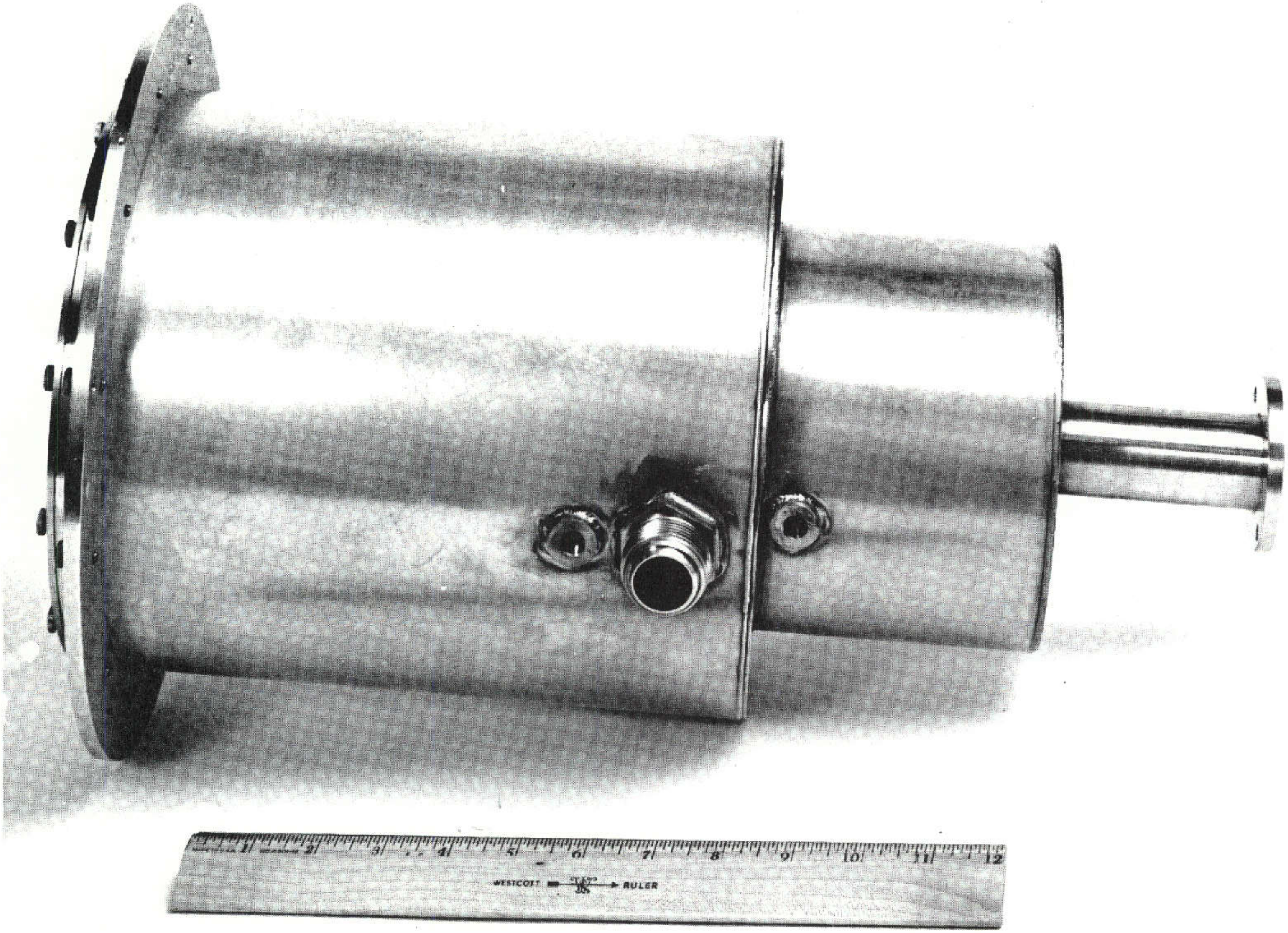

Figure 18 CATALYTIC OXIDATION UNIT

4.3 System Check-Out Tests

The full-scale evaporator was connected with a standard shell and tube condenser, and a series of short duration check-out tests were conducted. The raw urine feed controls, and the electrical controls for the impeller drive motor were mounted on a temporary frame. Product condensate was collected in a 55-liter glassware receiver located directly beneath the condenser. The check-out test set-up is shown in Figure 19.

Temperature sensors were mounted on the system to record temperature levels of the heating liquid, evaporating (boiling) liquid, and condenser coolant. A pressure sensor located at the vacuum still outlet measured the absolute pressure above the boiling liquid.

This series of check-out tests was conducted first with water and then with urine, primarily to verify the adequacy of various operating and control features, and to evaluate the following:

a) Distillation rate as a function of heating liquid inlet and outlet temperatures, and flow rate.

b) Drive motor power required.

c) Profile of liquid/vapor interface during rotation.

d) Liquid-level sensor and switch performance to control feed to the distillation unit.

The water check-out tests were conducted for six days, while urine check-out tests were conducted for an additional five days. Performance data are given in Tables VIII and IX.

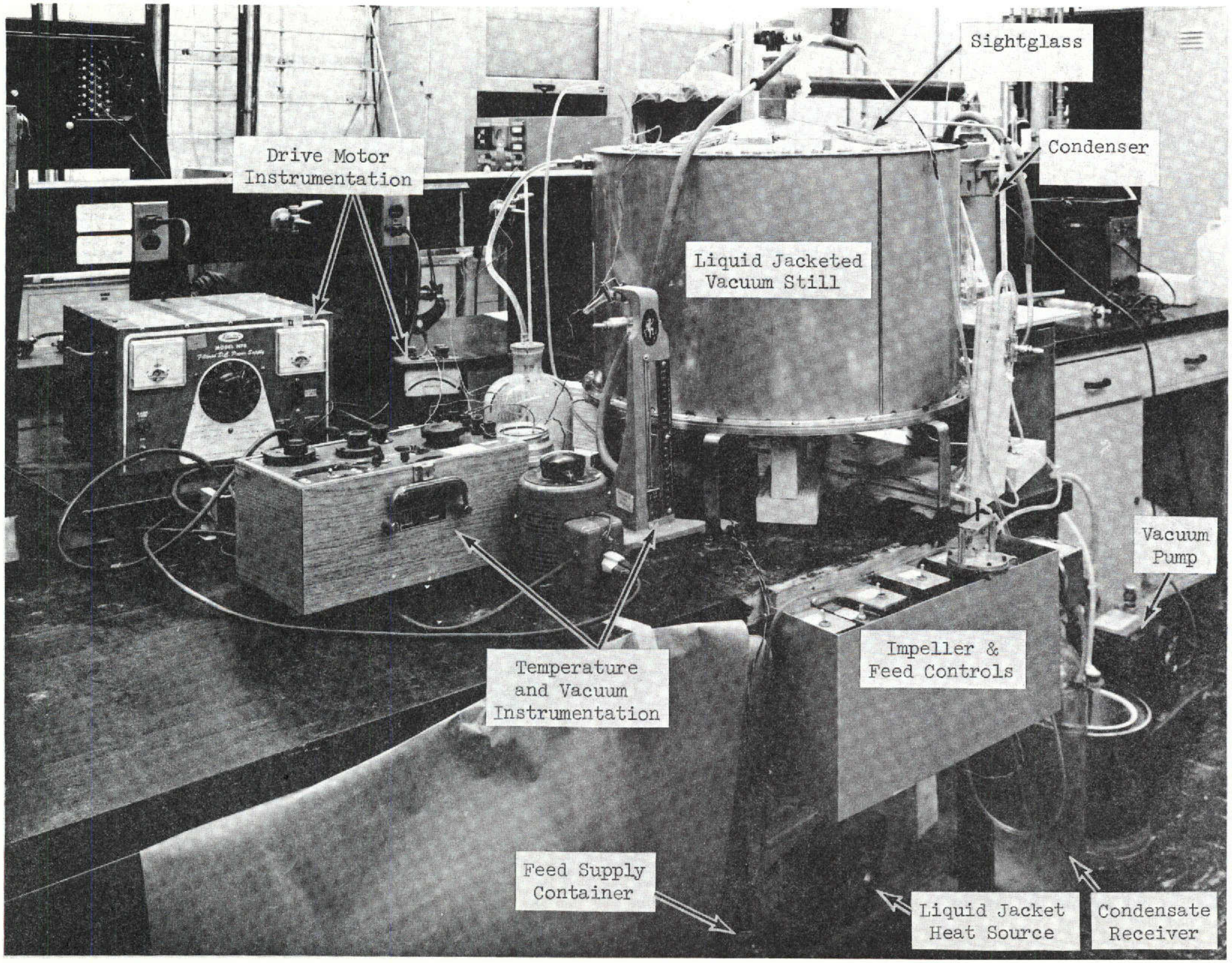

Figure 19 CHECK-OUT TEST SET-UP

Table VIII EVAPORATOR CHECK-OUT TEST WITH WATER

		LIQUID HEATING JACKET					EVAPORATOR				CONDENSER			
		TEMPERATURE						TEMPERATURE				RECOVERED WATER		
DATE	OPERATION (Hrs.)	IN (°F)	OUT (°F)	AVG (°F)	FLOW RATE (liters/ min)	EQUIV. POWER (watts)	FEED (liters)	LIQUID (°F)	ΔT* (°F)	PRESS. (mm Hg abs)	COOLANT SUPPLY TEMP. (°F)	AMOUNT (liters)	AVG. RATE (lb/hr)	REMARKS
2/10							39							Initial Evaporator Fill
2/10	7.9	89.6	85.5	87.5	1.90	302	13	85.5	2.0	27	40.5	5.7	1.59	
2/11	9.0	72.7	63.5	68.1	1.84	654	5	63.0	5.1	11	40.0	9.8	2.14	
2/12	8.6	85.5	65.5	75.5	1.84	1421	15	60.0	14.5	10	41.0	17.8	4.53	
2/14														Replaced worn brass gear with steel gear in impeller drive unit.
2/14 & 2/15,	10.0	73.6	64.2	68.9	1.88	679	9.8	63.0	5.9	11	41.0	10.2	2.24	

* ΔT - Difference between evaporator liquid temperature and average heating jacket temperature

1. Impeller drive motor power: 70 watts

2. Impeller speed: 96 rpm

Table IX EVAPORATOR CHECK-OUT TEST WITH URINE

DATE	OPERATION (Hrs.)	LIQUID HEATING JACKET					EVAPORATOR				CONDENSER			REMARKS
		TEMPERATURE			FLOW RATE (liters/min)	EQUIV. POWER (watts)	FEED (liters)	TEMPERATURE		PRESS. (mm Hg abs)	COOLANT SUPPLY TEMP. (°F)	RECOVERED WATER		
		IN °F	OUT °F	AVG °F				LIQUID (°F)	ΔT* (°F)			AMOUNT (liters)	AVG. RATE (lb/hr)	
4/12							39							Initial Evaporator Fill
4/12	10.0	90.4	82.0	86.2	1.88	597	8	80.0	6.2	25	45	9.0	1.92	
4/13	8.0	94.5	86.0	90.2	1.82	600	5	82.0	6.2	26	49	6.5	1.8	
4/14	7.0	92.0	83.0	87.5	1.88	655	7.5	82.0	5.5	25	47	6.4	2.01	
4/17 & 4/18	15.5	93.6	84.6	89.1	1.88	655	18.0	81.0	8.1	27	46	14.6	2.07	

* ΔT - Difference between evaporator liquid temperature and average heating jacket temperature

1. Impeller motor power: 55 watts

2. Impeller speed: 80 rpm

a) Distillation Rate

The six-man unit recovered water at 0.97 to 1.02 kg/hr (2.14 to 2.24 lb/hr) which is slightly in excess of the required six-man rate of 0.85 kg/hr (1.88 lb/hr). With the jacket heating liquid entering at 23°C (73.3°F) and flowing at 1.86 kg/min (4.1 lb/min), the jacket liquid outlet temperature averaged 17.8°C (64°F). With this approximate 5.5°C (10°F) temperature drop the heat input was equivalent to 668 watts of thermal power, while the heat absorbed in boiling an average of 1.0 kg/hr (2.19 lb/hr) of water was 688 watts. These power levels are essentially equivalent within experimental measurement error, and show that all of the heat input was utilized in distillation. When operating near the six-man recovery rate, the absolute pressure within the still was maintained essentially constant at 11 mmHg abs (b.pt. = 17.8°C (64°F)) while the actual boiling temperature was 17.2°C (63°F).

The still was operated at this lower temperature and pressure because the temporary condenser was operated at 4.4°C (40°F). The pressure drop from the still to the condenser was lower than expected and the boiling pressure in the still was resultingly lower. However, the temperature difference between the heating jacket liquid and boiling water was maintaned at the desired 2.8 to 3.3°C (5 to 6°F) level to show proper boiling rate capability. The temperature difference between the everage heating jacket liquid and evaporator liquid was 2.8 to 3.3°C (5.1 to 5.9°F). The heat transfer rate is approximately 39 Cal/hr-cm^2-°C (80 BTU/hr-ft^2-°F) under these conditions.

During the water check-out tests the unit was also operated to recover water at an average rate of 2.06 kg/hr (4.53 lb/hr) during an 8.6-hour run; this is slightly above the twelve-man recovery rate of 1.72 kg/hr (3.76 lb/hr). Operating conditions were about the same as for the six-man recovery rate except the heating jacket inlet to outlet temperature difference was 11.1°C (20°F); accordingly, the temperature difference between the average heating jacket liquid of 24.2°C (75.5°F) and evaporator liquid at 16°C (60°F) was 8°C (14.5°F).

The full scale unit was check-out tested with urine feed and the performance data are presented in Table IX. With heating liquid supplied at 33 to 34°C (92 to 93.6°F) and at a rate of 1.88 kg/min (4.1 lb/min), its temperature dropped 5°C (9°F) through the jacket; this is equivalent to 655 watts of thermal power. The measured recovery rate was .93 kg/hr (2.04 lb/hr) at 27 mmHg absolute pressure corresponding to 28°C (82°F). The theoretical heat of vaporization rate for .93 kg/hr at 27 mmHg is 635 watts, which is slightly lower but essentially equivalent to the actual measured power. The fact that measured power was slightly greater than theoretical during the urine tests, but slightly lower than theoretical power during the water tests, can probably be attributed to the operating temperature level of the evaporator still. The water check-out tests were conducted with the evaporator liquid at approximately 16°C (60°F) as compared to the urine tests with liquid at 27°C (70°F). During the water check-out tests the evaporator received a small unmeasured amount of heat from the ambient and during the urine tests a small unmeasured amount was lost to ambient. In both circumstances the measured and theoretical values are essentially equivalent, which demonstrates that the still was performing as anticipated.

b) Drive Motor Power

The power drive assembly functioned properly with the exception of a brass gear in the speed-reducing gearbox which was worn excessively after 24 hours. During the water check-out tests the torque required to rotate the impeller and liquid within the still was higher than anticipated. The motor consumed 70 watts at an impeller speed of 96 rpm, whereas the anticipated requirement as determined from calculations was 50 watts at 100 rpm. The higher load presumably contributed to the gear wear. The brass gear was replaced by a steel gear and all gears were lubricated with Texaco Unitemp 500 grease. This lubricant has a greater ability to remain on the gear teeth than the initially installed grease. After another 10 hours of operation during the water checkout tests and 40 hours of operation during the urine tests, the gearbox was functioning satisfactorily and with no apparent wear of the steel gears.

c) Liquid Profile

The rotating impeller functioned properly to constrain the liquid against the heat transfer surface of the still. As observed through sightglasses on the top cover of the evaporator, the liquid/vapor profile was the parabolic shape anticipated for 1-g operation. The scope of visibility into the evaporator was limited by the size of the sightglasses. The 7-cm (2-3/4-inch) diameter sightglasses permitted observing the impeller rotation and the general profile of the rotating liquid.

d) Liquid Level Control

The feed control and level sensor functioned properly throughout the entire test. The level sensor functioned as required to prevent the feed control from adding more feed liquid when it was at the maximum desired level.

The feed control was originally designed to feed 100 cc maximum every 5 minutes. This was insufficient when the unit was operated in excess of a 12-man recovery rate. For this particular test, the timer was modified to actuate the solenoid valve every 2-1/2 minutes. The level sensor functioned to prevent over-filling the evaporator by controlling the metering accumulator to feed only part or none of the 100 cc when the liquid level was at the maximum desired level.

The overall performance of the level control was satisfactory and presented no difficulties. Proper operation is not gravity dependent, and the control should perform satisfactorily in zero-gravity.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the development and testing activities conducted in Phase I of the program the following conclusions have been reached:

1) A liquid jacket around the evaporator is a very desirable method of controlling the temperature level and rate of heat transferred to the boiling urine.

2) The distillation rate varies in direct proportion to the temperature difference between the heating liquid and the boiling urine for essentially the complete distillation period.

3) The boiling surface remains clean and free of scum or solids build-up when the liquid is rotated within the evaporator; the liquid velocity at the impeller tip was 6.7 ft/sec during the tests conducted.

4) Although solids precipitate out of the sludge mixture, they do not cling to the surfaces that are continually washed by the rotating liquid.

5) Approximately 60% solids in the final sludge is a reasonable operating limit for vacuum distillation batching.

6) Dow Corning H-10 antifoaming compound is required at a rate of 0.1 cc/hr to prevent excess foaming; at 40% solids concentration and above antifoam was required at each vacuum pumpdown after the still was repressurized.

7) The overall heat transfer coefficient, U, from the liquid jacket to the urine remains essentially steady at approximately 36.7 Cal/hr-cm^2-°C (75 BTU/hr-ft^2-°F) during the entire batching process.

8) The particular dynamic shaft seal evaluated for the impeller drive provided a nominal seal between the ambient and vacuum environments but sporadically leaked seal coolant into the vacuum still.

9) A magnetic coupling drive functioned satisfactorily in both the lab support test unit and the 6-man evaporator.

10) A differential pressure switch functioned satisfactorily as a liquid level sensor when air was bled through the high-pressure line and bubbled through the liquid.

11) A proprietary oxidation catalyst, evaluated under GARD sponsorship, effectively reduced trace contaminants by 90% in the still effluent vapor when oxygen flow was 150 cc/min (STP) for the six-man urine distillation rate.

5.2 Recommendations

Based on the observations and conclusions drawn from this phase of the program, the following recommendations are made concerning the use, operation, evaluation, and future testing of the VD/VF evaporator.

1) To provide an equivalent basis for comparison, it is recommended that both ARDOX* catalyst, as used in prior VD/VF systems, and the proprietary GARD catalyst evaluated concurrently with Phase I be employed alternately in future tests.

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*Manufactured by ARDE, Inc. - Mahwah, New Jersey

2) A magnetic coupling should be used to drive the impeller within the vacuum environment.

3) The vaned impeller should be accelerated gradually from its rest position to prevent uncoupling of the magnetic drive.

4) Oxygen flow for the GARD oxidation catalyst should be 150 cc/min (STP) for a six-man urine distillation rate.

5) Means should be provided for storing antifoam compound separately from the pretreatment acid.

6) The temperature difference between the heating jacket liquid and the boiling urine should be utilized as the basic parameter for controlling distillation (and water recovery) rate.

7) Air should be bubbled through the liquid level sensing tube to prevent fouling and clogging of the differential pressure switch used for level control.

PART II

DESIGN, MANUFACTURE, AND TESTING OF ZERO-GRAVITY CONDENSER: INTEGRATION OF EVAPORATOR, CONDENSER, AND AUXILIARY COMPONENTS

Section 1

INTRODUCTION AND SUMMARY

Part II summarizes the activities of the General American Research Division (GARD) to develop a zero-gravity condenser for vacuum distillation/vapor filtration (VD/VF) water reclamation. The condenser development and subsequent integration and testing of the evaporator, condenser and auxiliary components were conducted as Phase II of a program to develop a functional model VD/VF water recovery system. A zero-gravity evaporator had been developed during Phase I of the program.

Program Objectives

The overall program objectives were to develop and evaluate a vacuum distillation/vapor filtration (VD/VF) water recovery system. As a functional model, the system converts urine and condensate waste water from six men to potable water on a steady-state basis. The system is designed for 180-day operating durations and for function on the ground, in zero-g aircraft, and in orbit.

In Phase II of the program, described in this part of the report, the objectives were to develop a condenser and to integrate the condenser and auxiliary components with the evaporator developed in Phase I.

Program Summary

The VD/VF water recovery system is comprised of the components shown on the block flow diagram, in Figure 1. Of the items shown by solid outline, the evaporator (including a catalytic oxidation unit) was developed in Phase I and the condenser was developed in Phase II. The remaining items shown by solid outline, namely (a) sludge removal pump and shut-off valve and (b) vacuum pump, were procured as purchased components and integrated with the feed control, evaporator, condenser, water pump, and water storage tank to form an integrated VD/VF water recovery system. The remaining items shown by dotted outline were developed previously under Contract F 33615-69-C-1486, and comprise the urine collection and storage subsystems.

The zero-gravity condenser is made up of smooth condensing surfaces with coolant passages directly in contact with each condenser surface. A rotating impeller with wiper blades continually wipes the condensate from the condensing surfaces, and provides centrifugal force to separate the condensate from non-condensible gases in zero gravity. The impeller is driven by an electric motor, and the motor torque is transmitted to the impeller through a magnetic coupling which eliminates shaft seals. The zero gravity condenser is shown in Figure 20.

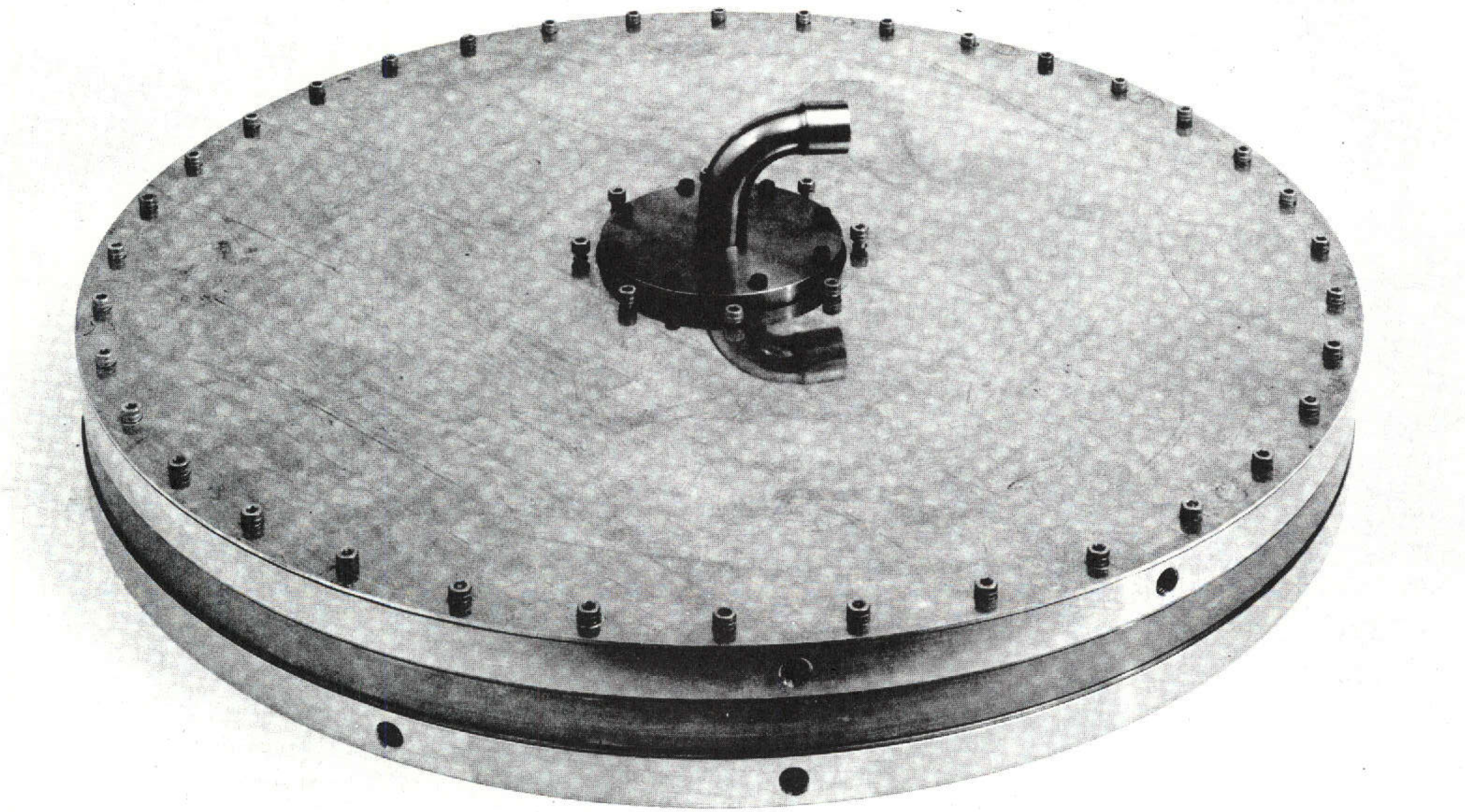


Figure 20 ZERO-GRAVITY CONDENSER

Section 2

CONDENSER DEVELOPMENT

A primary component of the vacuum distillation/vapor filtration water recovery process is the system condenser. The function of the condenser is to convert the vapor from the evaporator and catalyst unit into potable water, and to effect separation of the condensed water from noncondensable gases mixed with the incoming vapors. These operating factors required special design considerations for the condenser to be functional in zero gravity.

2.1 Design Requirements

The design requirements for the zero-gravity condenser were as follows:

(a) Utilize a rotating vaned impeller to provide artificial gravity for (1) separation of liquid from noncondensible gases and (2) improved heat transfer from the condensing vapors to a cooling jacket.

(b) Provide capacity to continuously remove the vapor generated in an evaporator with a nominal 6-man feed rate of urine and humidity condensate. The nominal inlet flow conditions to be used in designing the condenser were as follows:

Flow	0.9 kg/hr (2 lb/hr) of water vapor plus 250-500 cc/min (STP) noncondensable gases
Temperature	49°C to 66°C (120°F to 150°F)
Pressure	10-15 mm Hg absolute

(c) Utilize the vapor/liquid interface to sense the quantity of liquid in the condenser and provide automatic drain control.

(d) Utilize a coolant-filled jacket around the condenser to receive the heat from the condensing vapors.

(e) Configure the condenser to allow for the use of a drive motor common with the evaporator; alternately, the condenser may use a separate drive motor.

(f) Incorporate appropriately located sight glasses to permit visual observation of the liquid/vapor profile during laboratory testing.

2.2 Support Testing of Lab Condenser

The design requirements delineated the type of condenser needed and the condensing capacity expected. To determine the size of the zero-gravity condenser precise data were needed to properly specify the necessary heat transfer area. Useful data are published on heat transfer with condensation, including data on special cases which consider a deviation from condensing only pure vapors. The conditions for the VD/VF condenser, however, simultaneously combined several influencing factors which were:

(1) Condensation at reduced pressure of 0.01-0.03 atmospheres.

(2) Condensation of superheated vapor

(3) Condensation in the presence of noncondensable gases

(4) Condensation with artificial removal of condensate from condensing surface.

When considered as a summation of individual influencing factors, an overall heat transfer coefficient was calculated to be in the area of 98 Cal/hr-cm^2-°C (200 Btu/hr-ft^2-°F).

To determine a realistic heat transfer coefficient for the basic design of the zero gravity unit, a lab model condenser was constructed and operated at various test points near the actual conditions anticipated for the zero-gravity condenser.

A laboratory test condenser unit was fabricated, assembled, and operated to determine heat transfer coefficients for the same conditions at which the full-scale zero-g condenser was to be operated. The lab model condenser was not designed for a specific recovery rate but rather to obtain heat transfer data for known operating conditions and for a heat transfer area of 0.23 m^2 (2.5 ft^2). Test results indicated the actual heat transfer coefficient was approximately 49 Cal/hr-cm^2-°C (100 Btu/hr-ft^2-°F).

Parts for the lab condenser included a vacuum shell, heat transfer jacket, drive motor and magnetic coupling, and transparent plastic cover which previously comprised part of the lab distillation unit operated during Phase I. A new impeller was fabricated to fit the internal dimensions of the vacuum shell and was shaped to provide the desired flow path of the vapor along the condensing surface. The impeller incorporated four flexible wipers in a rotating wheel which continually moved past the heat transfer surface. Four small radial vanes were attached to the bottom edge of the impeller; these vanes kept the condensate rotating with the impeller and in this manner provided zero gravity separation of the product condensate from noncondensible gases which were drawn off near the center-line of rotation. The lab condenser unit is shown in Figure 21 with the transparent plastic cover and impeller removed.

The overall flow diagram for testing the lab condenser is shown in Figure 22. Water was boiled in the vacuum evaporator, with the boiling rate controlled by a variable voltage transformer supplying power to four electrical heating elements. A measured quantity of bleed air was fed into the vapor stream leaving the evaporator; this air simulated the air flow which would be required for the oxidation catalyst in the actual system.

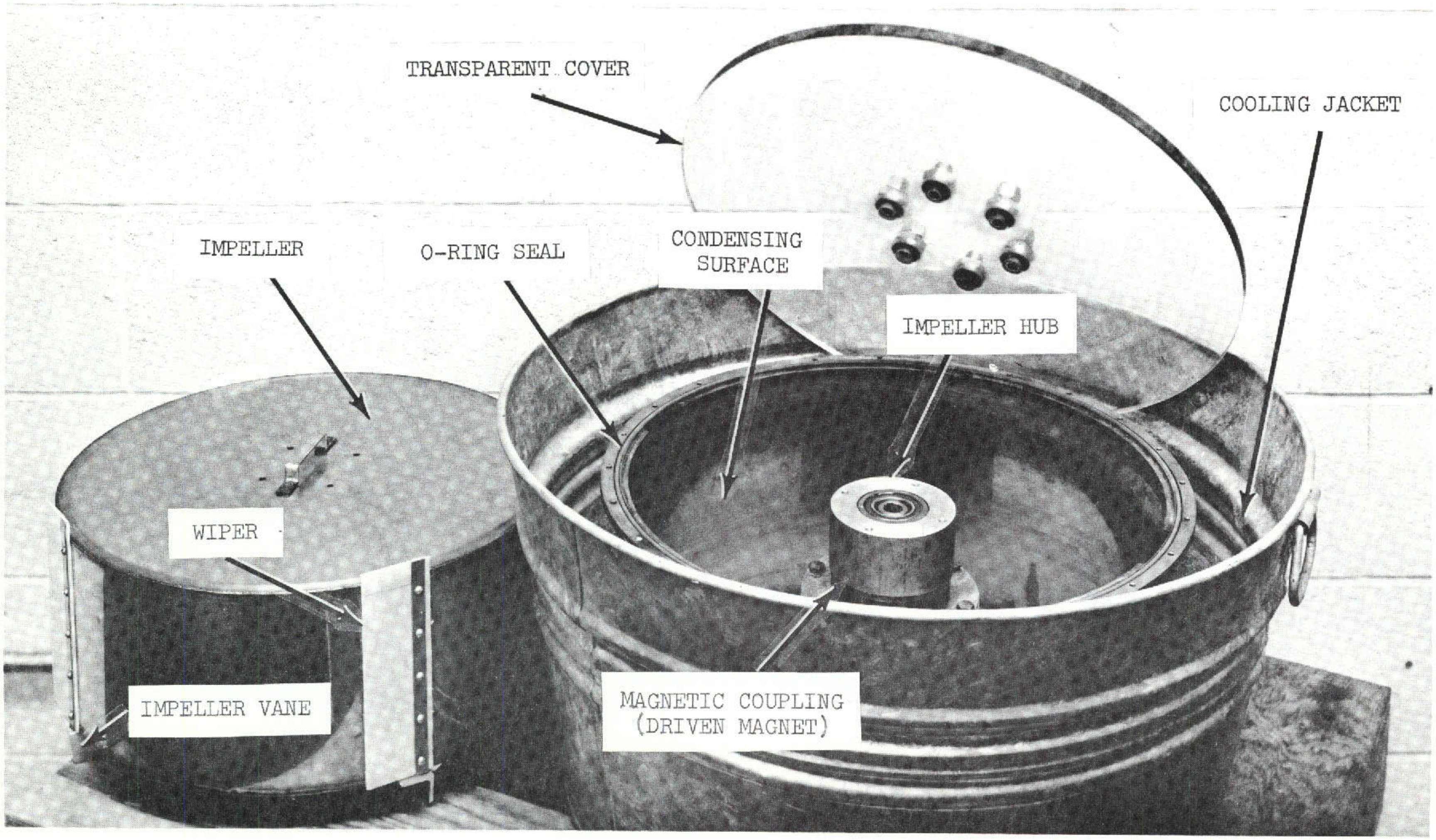


Figure 21 LABORATORY TEST CONDENSER UNIT

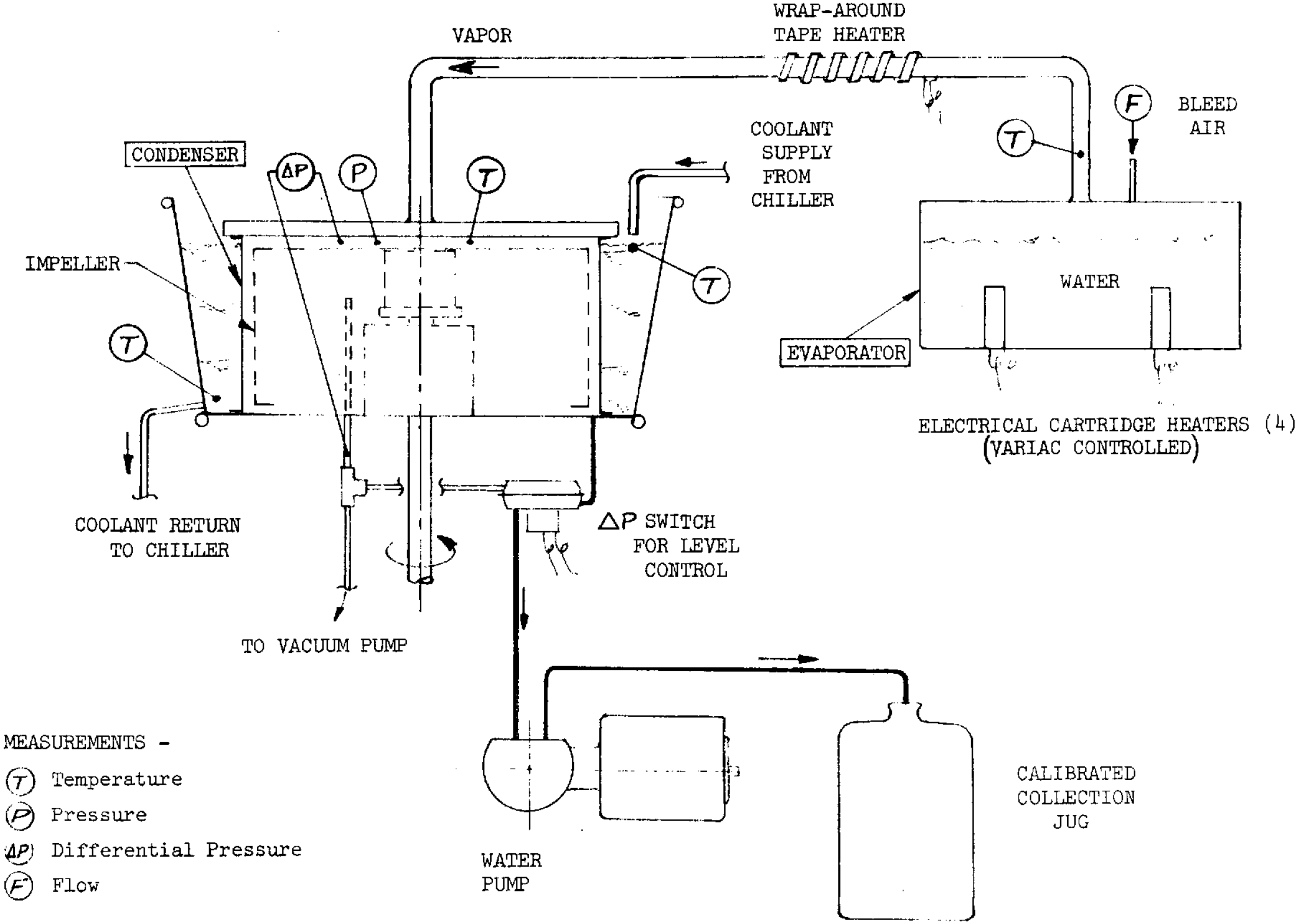


Figure 22 FLOW DIAGRAM FOR LAB TEST CONDENSER

The vapor and air were heated by a wrap-around tape heater to simulate the superheat of the product vapor anticipated after passing through the catalyst bed.

The superheated vapor and air entered the top of the condenser through the transparent cover. The flow was directed outward and constrained to flow past the liquid-jacket-cooled heated transfer surface where condensation occurred. The product condensate collected in the bottom of the condenser and increased in quantity until a differential pressure switch which sensed the height of liquid level was actuated. The pressure switch acted as a level control and energized the water pump to transfer the product condensate to storage. Noncondensable gases were drawn from the condenser through a vacuum purge line located near the center of rotation.

The significant measurements which were obtained during each test run were as follows:

(1) Duration of test run

(2) Quantity of condensate collected

(3) Temperature

  (a) Condenser inlet temperature

  (b) Coolant inlet temperature

  (c) Coolant discharge temperature

(4) Absolute pressure in condenser

(5) Bleed air flow rate into vapor leaving evaporator.

The condenser performance was assessed by comparing the amount of condensate collected to the amount of water boiled for that particular test run. The overall heat transfer coefficient was calculated from the temperature measurements and recovery rate for that particular run.

The overall heat transfer coefficient from the condensing vapor to the coolant liquid in the jacket was determined from the relationships:

$$Q = UA\Delta T$$

and, $Q = Wh_{fg}$

so that, $U = Wh_{fg}/A\Delta T$

where, Q = Heat transfer rate, Btu/hr

U = Heat transfer coefficient, Btu/hr-ft^2-°F

h_{fg} = Latent heat of evaporation, Btu/lb

A = Heat transfer area, ft^2

ΔT = Temperature difference between condensing vapor and average coolant temperature in jacket

and, W = Liquid condensed, lb/hr

The overall coefficient, U, is a series addition of three heat transfer coefficients, namely, the condensation coefficient from the condensing vapor to the metal wall, the thermal conductivity through the wall, and the coefficient from the wall to the coolant liquid, and is expressed by the equation:

$$\frac{1}{U} = \frac{1}{h_{cond}} + \frac{1}{(k/t)_{wall}} + \frac{1}{h_{cool}}$$

where, U = Overall heat transfer coefficient from condensing vapor to coolant liquid

h_{cond} = Condensation coefficient of heat transfer including the desuperheating of the vapor

$(k/t)_{wall}$ = Thermal conductivity through the wall separating vapor from coolant

and, h_{cool} = Convection coefficient between the metal wall and coolant liquid.

The effect on U of the metal wall, $(k/t)_{wall}$, is negligible compared to the condensation and convection coefficients. In essence, U is determined by the heat transfer coefficients on each side of the wall.

The lab condenser was operated at the conditions anticipated for the zero gravity condenser, which were:

Vapor Temperature	20°C to 85°C (75°F to 185°F)
Condenser Pressure	9 to 23 mm Hg absolute
Coolant Supply Temperature	-3.0°C to 18.5°C (27°F to 65°F)
Noncondensable Gas Flow	0 to 350 cc/min.

Initially, the condenser was operated with the coolant jacket configuration as shown in Figure 21. Coolant was supplied from an external chiller to an annular jacket 7.6 cm (3 inches) wide and 20.3 cm (8 inches) high. The jacket was maintained full at all times; the return line was located directly opposite the supply line. The average pumped velocity was <0.30 cm/sec (<0.01 fps). With this arrangement, U values were 19.5 to 29.3 Cal/hr-cm^2-°C) (40 to 60 Btu/hr-ft^2-°F), which were much lower than anticipated. Test data and results of two typical runs are given in Table X.

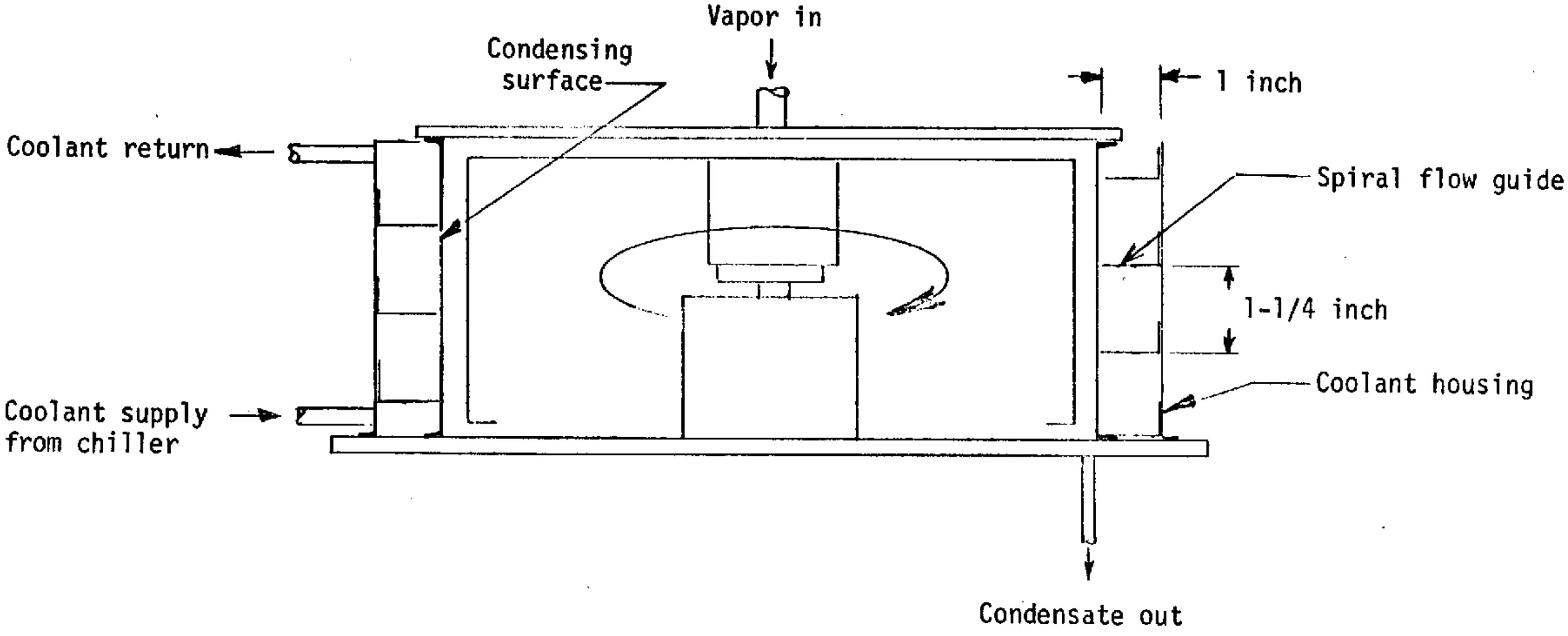
The results from the initial test runs indicated the rate of heat transfer was influenced greatly by the coolant heat convection coefficient. To improve the overall heat transfer rate, a modification was made to the coolant jacket; the modified configuration is shown in Figure 23. The primary differences were: (1) annular area was decreased, and (2) flow rate of coolant was increased; the combined result was that coolant velocity past the heat transfer surface was increased. Coolant flow rate was 5.3 lpm (1.4 gpm) through the 2.5 by 3.2-cm (1-inch by 1-1/4-inch) rectangular area; the average coolant velocity was 10.7 cm/sec (0.35 fps).

TABLE X

LAB CONDENSER TEST DATA AND RESULTS

LOW COOLANT VELOCITY, ∼.01 FPS

1. TEST RUN	1	2
2. DURATION, minutes	450	450
3. TEMPERATURE, °C (°F)		
a. Vapor leaving evaporator	24.0 (75.2)	23.5 (74.3)
b. Vapor entering condenser	24.5 (76.1)	27.0 (80.6)
c. Coolant entering jacket	9.0 (48.2)	7.0 (44.6)
d. Coolant leaving jacket	9.0 (48.2)	7.0 (44.6)
e. Ambient	---	30.0 (86.6)
4. PRESSURE		
a. Vapor entering condenser, mm Hg abs	14.0	13.0
b. Differential between vapor entering condenser and vacuum purge line, mm Hg	5.0	4.5
5. BLEED AIR FLOW INTO VAPOR, cc/min STP	125	125
6. HEAT SUPPLIED TO EVAPORATOR, watts	417	338
7. QUANTITY OF CONDENSATE COLLECTED, cc		
a. From condenser	4580	3850
b. From freeze-out trap	170	110
c. Total condensate	4750	3960
8. AVERAGE RECOVERY RATE, kg/hr (lbs/hr)	0.61 (1.35)	0.51 (1.13)
9. CONDENSER EFFICIENCY, %	96.4	97.2
10. OVERALL HEAT TRANSFER COEFFICIENT, $\frac{\text{Cal}}{\text{hr-cm}^2\text{-°C}}$ $\left(\frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}\right)$	28.4 (58)	19.6 (40)



(Cross-section through condenser diameter)

Figure 23 MODIFIED CONFIGURATION OF COOLANT JACKET: LAB TEST CONDENSER

With the improved coolant jacket configuration, U values were 49 to 59 Cal/hr-cm^2-°C (100 to 120 Btu/hr-ft^2-°F); these values were approximately twice those obtained when the coolant velocity within the jacket was essentially stagnant. Test data and results of typical runs after the coolant jacket modification are given in Table XI. The lab condenser tests indicated that an overall heat transfer coefficient of 49 Cal/hr-cm^2-°C (100 Btu/hr-ft^2-°F) was appropriate for designing the zero-gravity condenser.

2.3 Design of Zero-Gravity Condenser

The zero-gravity condenser shown in Figure 20 was designed in accordance with the detail requirements listed in Section 2.1. In accordance with these tests, a layout assembly drawing was prepared as shown in Figure 24. During normal operation of the zero-gravity condenser, vapor flow from the evaporator and catalytic oxidation unit enters near the center of the unit and is distributed near the center of the impeller by an inlet manifold. Vapors are then constrained to flow radially outward between the upper condensing surface and the rotating impeller plate. The vapor flows radially out and along the heat transfer surface with condensation occurring as the vapor contacts the cool surface. Flexible wiper blades, attached to the rotating impeller, continually wipe the condensing surface and collect the condensation droplets along the wiper. The rotating impeller and wiper blades impart a centrifugal force to the condensate to direct it radially outward to the outer housing of the condenser. Any vapor which is not condensed during the upper pass along the condensing surface flows down and then radially inward along the opposite cool surface to effect complete condensation. Noncondensable gases are removed at the center of the unit on the side opposite the vapor inlet.

TABLE XI

LAB CONDENSER TEST DATA AND RESULTS

IMPROVED COOLANT VELOCITY, ~.35 FPS

1. TEST RUN	1	2	3
2. DURATION, minutes	420	420	350
3. TEMPERATURE, °C (°F)			
a. Vapor leaving evaporator	26.0 (78.8)	28.0 (82.4)	29.0 (84.4)
b. Vapor entering condenser	53.0 (127.5)	82.0 (180.0)	85.0 (185.0)
c. Coolant entering jacket	12.0 (51.8)	8.5 (47.3)	8.0 (46.4)
d. Coolant leaving jacket	12.0 (51.8)	8.5 (47.3)	8.0 (46.4)
4. PRESSURE			
a. Vapor entering condenser, mm Hg abs	14.0	12.0	14.0
b. Differential between vapor entering condenser and vacuum purge line, mm Hg	3.1	2.8	2.8
c. Differential between vapor above and underneath impeller, mm Hg	0.0	0.0	0.0
5. BLEED AIR FLOW INTO VAPOR, cc/min STP	142	149	210
6. HEAT SUPLLIED TO EVAPORATOR, watts	529	597	597
7. QUANTITY OF CONDENSATE COLLECTED, cc			
a. From condenser	5800	6570	5450
b. From freeze-out trap	150	90	70
c. Total condensate	5950	6660	5520
8. AVERAGE RECOVERY RATE, kg/hr (lb/hr)	0.83 (1.82)	0.94 (2.06)	0.94 (2.06)
9. CONDENSER EFFICIENCY, %	97.5	98.8	98.7
10. OVERALL HEAT TRANSFER COEFFICIENT, $\frac{\text{Cal}}{\text{hr-cm}^2\text{-°C}} \left(\frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}\right)$	60.0 (122.0)	47.4 (97.0)	28.0 (57.4)

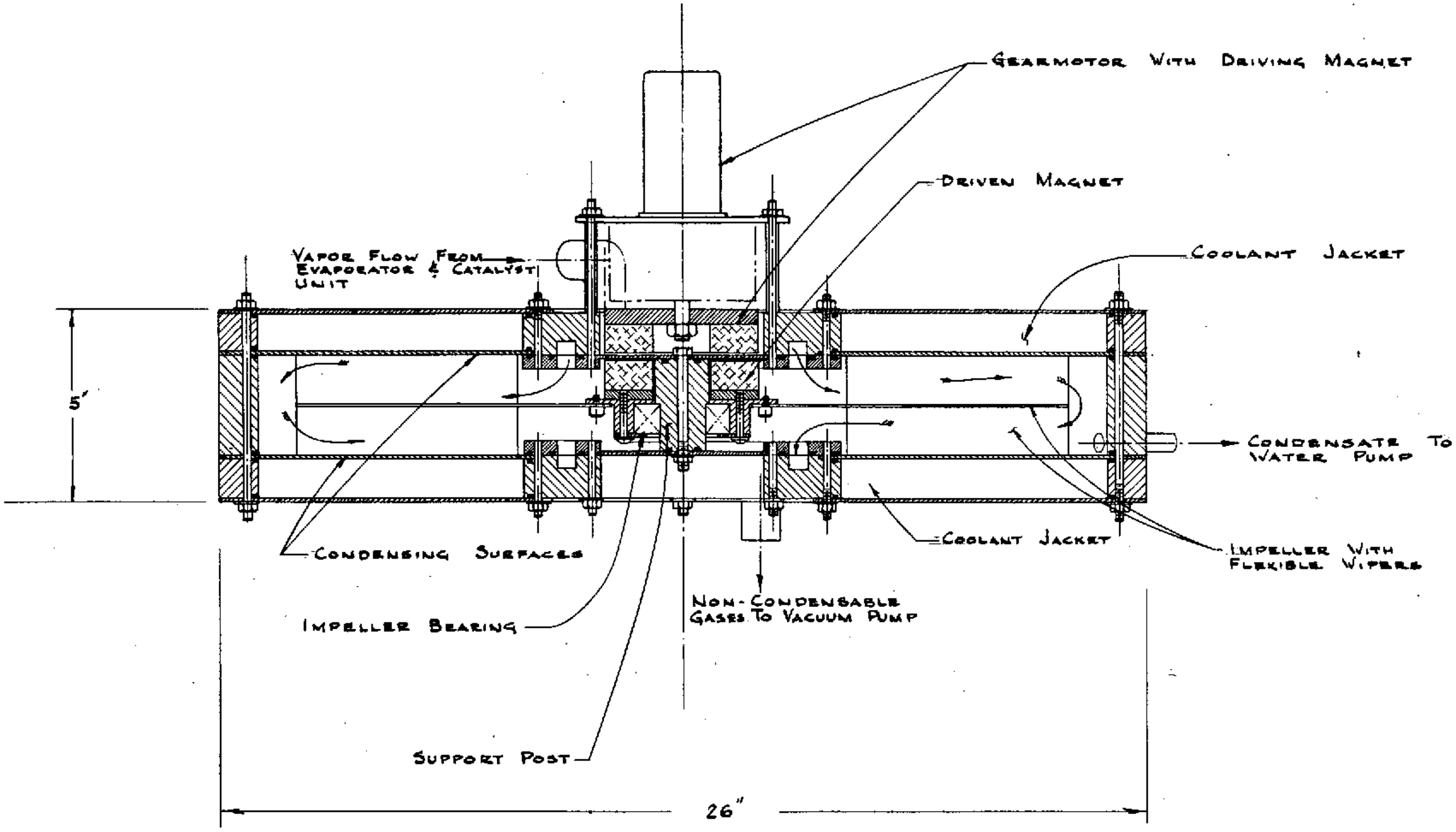


Figure 24 ZERO-G CONDENSER ASSEMBLY

The condensate within the condenser collects along the inside surface of the housing; a timer periodically actuates a pump to transfer the condensate from low pressure to storage at ambient pressure. The pump is started by the timer but continues to operate until all the condensate is removed and the pump discharge pressure drops; this drop is sensed by a pressure switch located at the pump discharge; actuation of the switch shuts off the pump.

Identical coolant jackets located on each side of the unit have radial flow guides to direct the coolant over the entire heat transfer surface. The flow guides not only direct coolant flow but also give this surface the structural rigidity needed to remain flat when the internal pressure is reduced to 10-20 mm Hg absolute operating level.

2.4 Fabrication and Assembly

The vacuum condenser was fabricated from stainless steel sheet and machined parts and is shown in Figure 25. The flat, disc-shaped condenser surfaces were bolted to the machined elements and sealed by static O-ring gaskets.

The rotating impeller subassembly is comprised of: (1) inner support post, (2) ball bearing, (3) driven magnet, (4) impeller disc with four radial wipers on each side of the impeller, and (5) fastener hardware. The impeller subassembly is shown in Figure 26.

2.5 Condenser Check-Out Testing

The unit was initially check-out tested to verify that the essential subcomponents performed satisfactorily. The rotating impeller, drive motor, and the condensate pump were operated to determine (1) that proper assembly clearances were maintained between the impeller and housing, (2) the variation in speed and motor power for operation at no-load and full-load with water

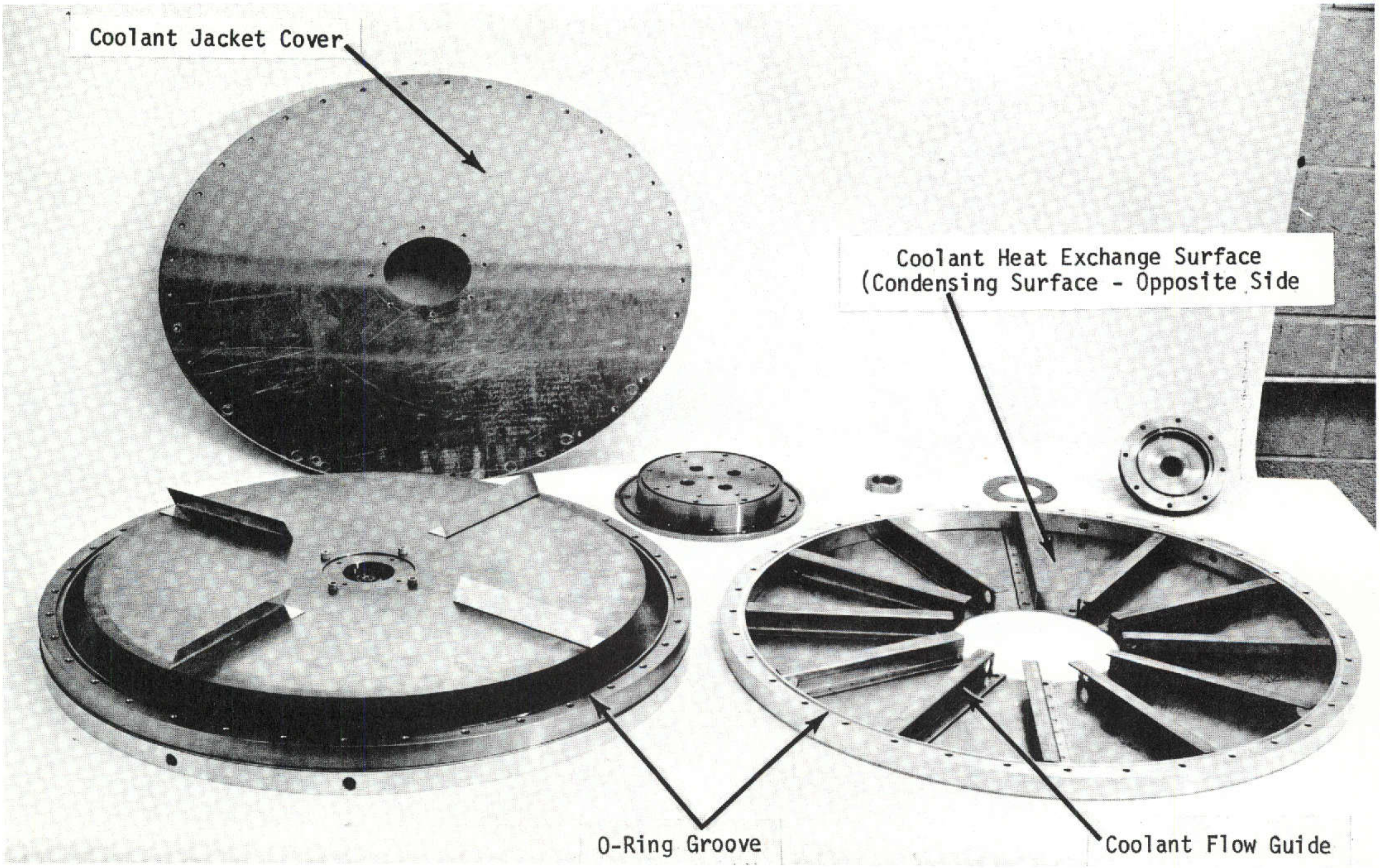


Figure 25 CONDENSER WITH COOLANT JACKET REMOVED

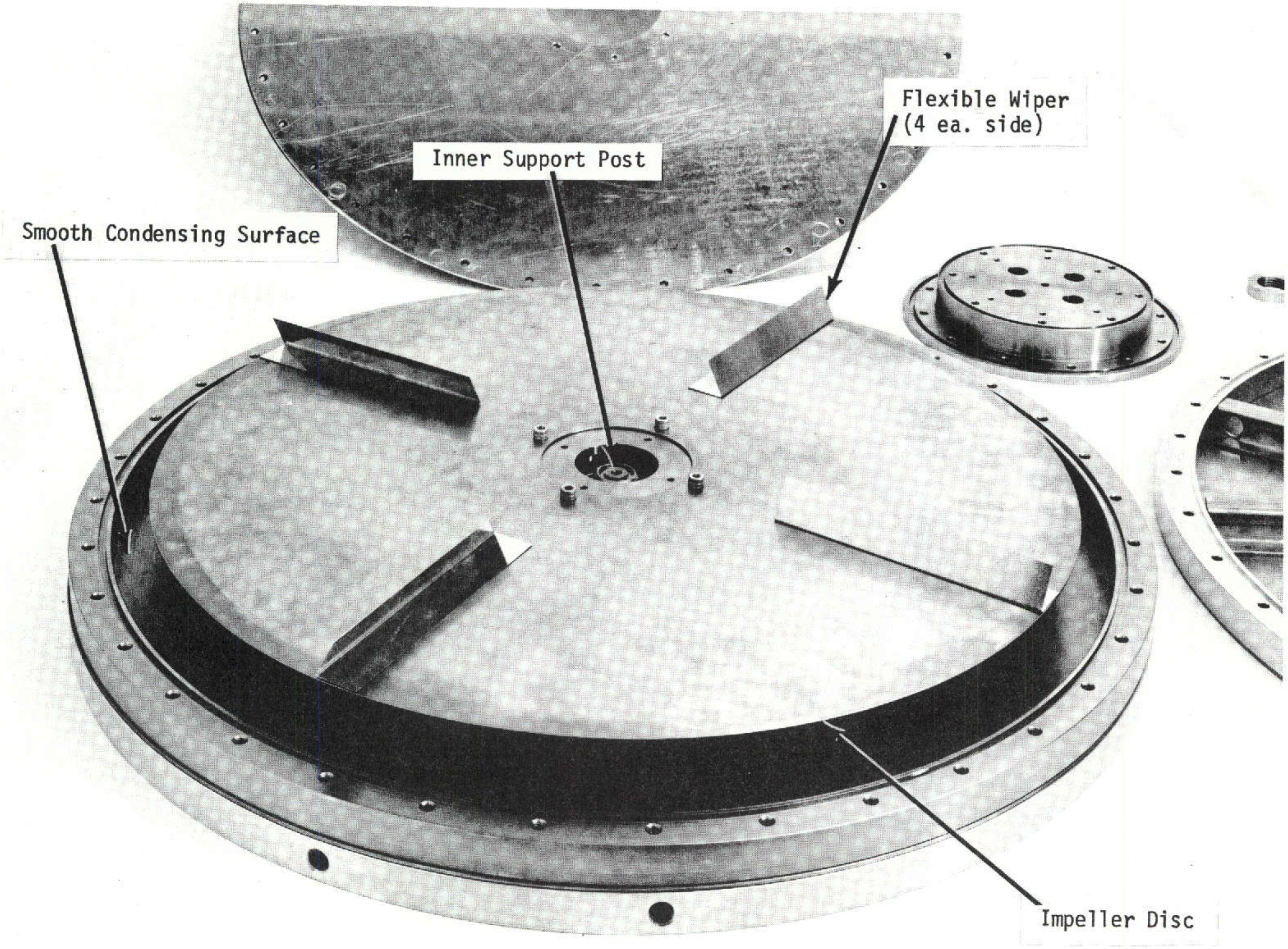


Figure 26 IMPELLER SUBASSEMBLY

inside the condenser, (3) the pumpout rate of water from the vacuum condenser to the storage tank, and (4) that the control for the water pump functioned automatically and continuously.

Rotating Impeller Operation. The rotating impeller was operated at various speeds up to 110 rpm, the maximum speed of the drive motor with the original speed reduction gearbox. The flexible wipers on the impeller were adjusted to lightly contact and wipe the condensing surface. By visual and audio observation, it was determined that the rotating impeller was operating properly. Subsequent to the initial check-out tests, a higher speed motor was used and the impeller was operated at speeds up to 200 rpm.

Drive Motor Performance. Initially, the power drive unit consisted of a brushless dc motor coupled to a speed reduction gearbox which had three stages of spur gears. When the motor was operated at its top speed of approximately 6000 rpm, the output speed of the gearbox was 110 rpm. When driving the impeller, without water in the condenser, the speed was 110 rpm and the motor required 40 watts. When water was introduced into the condenser (simulating the condensate which collects during actual operation), the impeller speed was 110 rpm and the motor required 65 watts. Although the actual torque was not measured, the motor manufacturer's performance chart indicated that motor output torque was approximately 324 cm-gm (4.5 oz-in). The torque is stepped up in the speed reduction gearbox by a 55:1 ratio, resulting in an output torque of approximately 18,000 cm-gm (250 oz-in). The gearbox torque rating was 250 oz-in, indicating marginal performance ability. Since the nominal load was close to the rated capacity and since there was a gearbox failure between the output gear and output shaft, the condenser power drive unit was changed to a gear motor with a worm gear speed reduction box.

The worm gear reduction unit torque rating is 430 oz-in and functioned satisfactorily at output speeds between 160 and 200 rpm.

Water Pump Performance. A magnetically coupled gear pump is used to pump the condensate from the vacuum condenser to a storage container at atmospheric pressure. An initial bench check-out test of the pump indicated its pumping rate was 0.61 liters per minute (0.16 gallons per minute) when pumping from atmospheric pressure to 1.41 kg/cm^2 (20 psig). However, when the pump was assembled into the system and operated as part of the condenser check-out tests, the pump was not capable of removing the condensate when the condenser vacuum was 10 mm Hg absolute.

The pump was removed from the condenser and bench-tested under actual vacuum conditions. The pump was connected via a flexible vacuum tube to a small bell jar. The bell jar was partially filled with water and the vapor space above the water was evacuated to and maintained at 10 mm Hg absolute. The pump was placed at various vertical distances below the water level and its pumping rate was measured for each height of static inlet head. The measured rate was 0.12 lpm (0.032 gpm) when the inlet static head was 50 mm Hg (27 inches of water) above the 10 mm Hg vapor pressure.

To obtain 50 mm Hg (27 inches of water) or more static head above the 10 mm Hg vapor pressure in the condenser, a Pitot tube (right angle scoop) was added to the pump inlet port. The Pitot tube served to convert the kinetic energy of the rotating pool of condensate into potential energy or static head in the pump intake tube.

With the new worm gear-reduction gearmotor, the rotating impeller operated at approximately 200 rpm without water in the condenser; with condensate in the condenser, the speed was 160 rpm. If there were no slippage between the rotating water and the rotating impeller, the 160-rpm speed would produce 97 mm Hg (52 inches of water) or static head. Actually, there was some slip between the water and impeller so the static head appeared to be approximately 75 mm Hg (40 inches of water).

The water discharge pump and inlet Pitot tube were reassembled with the condenser. The pump initially functioned satisfactorily to transfer the condensate from the vacuum condenser to atmospheric pressure storage tank. However, after approximately 8 hours of system operation, the pumping capacity dropped off until the pump was unable to pump out the condensate. The apparent reason for loss of capacity was wearing of the plastic pump gears within the pump.

To circumvent a shutdown of zero-g condenser testing due to the decrease in gear pump performance, a secondary pump was added to the outlet of the gear pump. The secondary pump -- a peristaltic pump -- lowered the pressure differential required across the gear pump. The two pumps in series performed satisfactorily to pump out condensate to atmoshperic pressure.

Automatic Control of Water Pump. The electrical controls which function automatically to start and stop the condensate pump consisted of a repeat cycle timer, which started the pump every 2-1/2 minutes, and a pump discharge pressure switch and motor relay, which kept the pump running as long as water was available at the pump inlet. When essentially all the condensate was pumped from the condenser, the pressure differential decreased sharply, and the differential pressure switch shut off the pump. The pressure switch employs an adjustable set point which was readily adjusted to obtain satisfactory automatic performance. The automatic controls functioned satisfactorily and without incident.

Section 3

SYSTEM TESTING

The VD/VF water recovery system was tested to evaluate processing performance and quality of recovered water during six continuous days of operation. The objectives of these tests were to evaluate system performance by assessing the following:

(1) Water recovery rate versus time
(2) Water yield versus time
(3) Heating efficiency
(4) Water quality versus time
(5) Power consumption
(6) Effects of random temperature and pressure variations.

3.1 Test Set-Up and Instrumentation

Tests were conducted at GARD's Chemical & Environmental Systems Laboratory.

The water recovery system was set up as shown in the schematic flow diagram, Figure 27. The test instruments used to determine the process conditions are listed in Table XII.

3.2 Operation and Monitoring

During the nominal six-day performance test the system was operated for 145 cumulative hours and recovered 151 kg (333 lbs) of water from 160 kg (351 lbs) of urine feed.

Urine was collected from male in-plant personnel and added to the urine storage tank on a daily basis. Prior to setting out the urine collection receiver, an acid pretreatment solution was placed in the receiver; in this

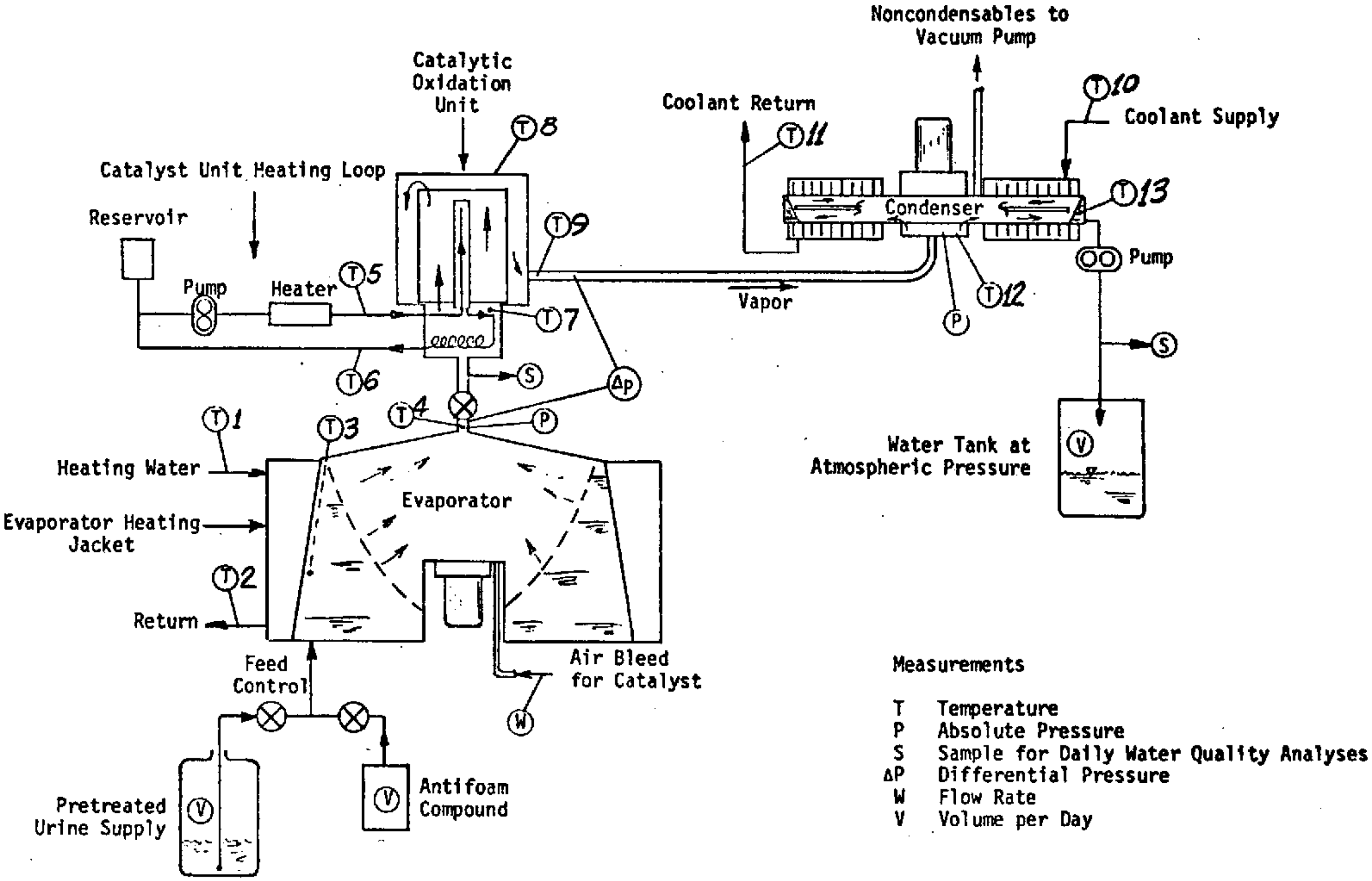


Figure 27 FLOW DIAGRAM FOR SYSTEM PERFORMANCE TESTS

TABLE XII

PROCESS TEST PARAMETERS AND INSTRUMENTATION

	Test Measurement	Instrument
(a)	Process Temperatures	Iron-Constantan Thermocouple and Honeywell Multipoint Recorder
(b)	Evaporator Pressure	Absolute Mercury Manometer
	Condenser Pressure	Absolute Mercury Manometer
(c)	Catalyst Unit Differential Pressure	Magnehelic $\overline{\Delta p}$ Gauge
(d)	Oxygen Feed to Catalyst Unit	Rotameter (0-2000 cc/min)
	Air Bleed to Evaporator	Rotameter (0-80 cc/min)
	Level Sensor	
(e)	Urine Input Antifoam Compound Added Water Produced Vacuum Line Freeze Trap Water	Graduated Beaker and/or Balance Scale
(f)	Heat Transport Liquid Flow Rate - Evaporator Heating Water - Catalyst Heating Oil - Condenser Glycol/Water Coolant	Graduated Beaker Stop Watch
(g)	Test Duration	Clock
(h)	Input Power	Voltmeter Ammeter
(i)	Water Samples	Pre-Sterilized Sample Jar

manner the pretreatment was mixed witn the raw urine immediately upon being voided from the donor.

The acid pretreatment was a mixture of 44% by weight sulfuric acid, 11% chromium trioxide, and 45% distilled water. This mixture has been found to satisfactorily inhibit biological decomposition of the raw urine.

As the freshly collected urine was transferred to the urine storage tank, a small quantity of Dow Corning H-10 antifoam compound was mixed into the pretreated urine. For the six-day test the antifoam addition rate was 4 drops antifoam per liter of urine.

Samples were collected daily of the raw vapor leaving the evaporator, and of the condensate pumped from the condenser. The product condensate was tested for viable bacteria density and for a few prominent indicators of water quality. The sample condensate from raw vapor was also analyzed to obtain an indication of the performance of the oxidation catalyst bed in reducing total carbon and total organic carbon concentrations.

Process temperatures were recorded on a continuous basis by a multipoint recorder. Other process parameters were monitored and recorded at 2-4 hour intervals during the 8:00 am to 5:00 pm period of each test day.

3.3 Water Quality Analysis Procedures

The water quality monitoring program consisted of the following analyses and measurements:

(1) Total carbon
(2) Total organic carbon
(3) pH
(4) Ammonia
(5) Conductivity

(6) Turbidity

(7) Viable bacteria density.

Total carbon (TC) and total organic carbon (TOC) analyses were performed with a Beckman Model 915 Total Organic Carbon Analyzer. The TOC determination is made by subtracting the measurement of inorganic carbon from total carbon.

Product water, pH, conductivity, and turbidity were measured with standard laboratory instruments. A Beckman Expandomatic Model 76A pH meter was used to give a direct read-out of the sample pH. An Industrial Instruments Model RC 16 B 2 Conductivity Bridge with calibrated conductivity probes and a Hach Model 1860 Turbidimeter were used for measuring conductivity and turbidity, respectively.

Analyses for ammonia were performed by colorimetry. The procedure required that the sample be treated with a reagent composed of phenol, nitroprusside, and hypochlorite. The reagent, in the presence of ammonia, produces a blue color which was measured at 630 mμ by a Bausch & Lomb Spectronic 20 Colorimeter.

Bacteria analyses were determined by using a modified most probable number (MPN) technique. For each sample, fifteen tubes of thioglycolate broth along with control tubes were incubated at 35°C for 72 hours. Prior to incubation, 5 of the 15 tubes were innoculated with 1 ml of sample, 5 tubes were innoculated with 1 ml of sample diluted 10:1, and 5 tubes were innoculated with 1 ml of sample diluted 100:1. The tubes were checked for growth after 48 hours and after 72 hours. Viable bacteria density was determined from MPN tables on the basis of the number of positive tubes in each dilution level. Gas formation within the broth was considered a positive indication of coliform organisms.

3.4 Processing Test Results

Performance test data for inputs, outputs, and process flow conditions are given in Table XIII. During the 145 cumulative hours of operation, the urine distillation temperature varied between 23°C (74°F) and 26°C (78°F), the vapor oxidation temperature varied between 142°C (287°F) and 148°C (299°F), and the potable water was condensed at 5.5°C (42°F) to 10°C (50°F). The average recovery rate remained constant at 1.04 kg/hr (2.3 lbs/hr).

3.4.1 Evaporator Heat Utilization

Warm water was circulated to the evaporator heating jacket at a constant rate of 2.1 kg/min (4.6 lb/min). The water temperature entering the jacket varied between 31°C (87°F) and 33°C (91°F); the temperature difference between inlet and outlet averaged 4.7°C (8.5°F). The heat transport rate to the evaporator jacket from 2.1 kg/min (4.6 lbs/min) of water flowing through 4.7°C (8.5°)ΔT was 592 kcal/hr (2350 Btu/hr).

Heat required to evaporate 1.04 kg/hr (2.3 lbs/hr) of vapor at 20 mm Hg was 605 kcal/hr (2400 Btu/hr). This was in close agreement with the measured heat input rate and indicated that essentially all of the heat supplied to the heating jacket was utilized to evaporate urine inside the vacuum evaporator.

3.4.2 Urine Distillation

Urine distillation occurred in the 23°C (74°F) to 26°C (78°F) range. The actual vapor pressure immediately above the liquid surface was not measured; the vapor pressure in the outlet duct was measured, but this location was down stream of the demister. It appears that there was approximately 3 mm Hg Δp across the demister mesh. This approximation is based on the observation that the vapor pressure in the evaporator outlet duct was about 3 mm Hg below that anticipated for the measured urine liquid temperature. For example, near

TABLE XIII

PERFORMANCE TEST DATA AND RESULTS

Date	Time of Recording	Cumulative Data				Temperature °C (°F)													Pressure - mm Hg			REMARKS
		Test Time	Urine Feed	Water Produced	Freeze Trap	Evaporator				Catalyst Unit					Condenser				Evap. Absolute	Cond. Absolute	Cata. Differential	
		hrs.	kg (lb)	kg (lb)	kg (lb)	Heating Liquid In	Heating Liquid Out	Urine Liquid	Exit Vapor	Heating Liquid In	Heating Liquid Out	Vapor Into Bed	Metal Housing	Exit Vapor	Coolant In	Coolant Out	Vapor In	Condensate				
1-8-73	1015	-0-	19.7 (43.3)																			Start of test; Evaporator liquid ≈12% solids.
	1610		37.3 (82.0)			31 (88)	26 (79)	24 (74.5)	28 (82.5)	166 (330)	139 (282)	145 (293)	111 (232)	117 (242)	4 (39)	7 (44)	18 (64)	11 (52)	19.5	15	2.6	
1-9-73	815	22.0				31 (88)	26 (79)	24 (75)	26 (79)	166 (330)	139 (282)	145 (294)	111 (232)	121 (249)	1 (33)	4 (38.5)	18 (65)	6 (42)	20.5	16	2.3	
	1215	26.0	55.4 (122.2)	27.9 (61.4)	.36 (.79)	31 (87)	26 (78)	23 (74)	27 (80)	166 (330)	139 (282)	145 (293)	111 (232)	121 (249)	2 (35)	4 (39.5)	17 (62.5)	7 (44.5)	18.5	14.5	2.4	
	1900	32.75																				Distillation stopped at 1900 due to loss of vacuum; apparently freeze trap blockage. Operation resumed at 845.
1-10-73	845	32.75																				
	1047	35.78	75.2 (165.7)	38.2 (84.0)	.62 (1.36)	32 (89)	28 (82.5)	24 (76)	32 (89)	163 (325)	133 (272)	142 (287)	116 (241)	126 (259)	6 (42)	9 (47.5)	18 (64)	15 (60)	20.5	15	2.6	
	1816					31 (88)	27 (80)	24 (75)	28 (83)	166 (330)	139 (283)	146 (295)	112 (234)	120 (248)	3 (37)	6 (42)	18 (64)	8 (47)	19.5	15	2.3	
1-11-73	820		94.8 (209.0)		.95 (2.09)	31 (87)	26 (79)	23 (74)	27 (81)	166 (330)	137 (279)	144 (291)	110 (230)	118 (244)	1 (33)	4 (38)	18 (64)	6 (42)	19.5	15.5	2.3	
	1530	64.5	114.2 (251.50)	67.4 (148.3)		31 (87)	26 (79)	23 (74)	28 (83)	166 (330)	139 (283)	145 (294)	113 (235)	121 (250)	2 (35)	5 (40)	17 (63)	8 (46)	18.5	14	2.4	
1-12-73	830					32 (90)	27 (81)	25 (77)	28 (83)	166 (330)	139 (283)	146 (295)	112 (233)	120 (248)	1 (34)	4 (39)	19 (66)	6 (42.5)	19.5	15	2.3	
	1530	88.5	149.2 (329.0)	98.4 (216.5)	1.30 (2.86)	31 (88)	26 (79)	24 (75)	28 (83)	166 (330)	137 (280)	145 (293)	114 (238)	123 (253)	3 (38)	6 (43)	17 (62.5)	10 (50)	18	14	2.4	
1-13-73	400	101.0		103.3 (227.5)	1.69 (3.73)																	Distillation stopped at 400 due to blown fuse on condenser water pump. Operation resumed at 1200.
1-15-73	1200	101.0																				
	1648					33 (91)	28 (82)	26 (78)	32 (89)	168 (335)	143 (289)	148 (299)	113 (236)	122 (252)	3 (37)	5 (41)	19 (66)	8 (47)	19	15	2.3	
1-16-73	830					33 (92)	28 (83)	26 (78)	32 (90)	168 (335)	143 (289)	147 (297)	114 (238)	123 (253)	3 (38)	6 (43)	18 (64)	9 (49)	19.5	15.5	2.3	
	1430	127.5	159.3 (351.0)	133.6 (249.0)	2.01 (4.42)	33 (91)	28 (82)	26 (78)	32 (89)	171 (340)	143 (289)	148 (298)	113 (236)	122 (252)	3 (37)	5 (41)	19 (66)	8 (46)	19	15	2.3	
1-17-73	800	145.0	159.3 (351.0)	151.4 (333.0)	2.31 (5.08)	33 (92)	28 (83)	26 (78)	32 (90)	166 (330)	138 (281)	145 (293)	111 (232)	117 (243)	4 (39)	7 (44)	18 (65)	10 (50)	19.5	15.5	2.4	

1 Urine feed data includes amounts in feed supply container.
Urine feed included 4 cc acid pretreatment per liter of urine plus 0.2 cc antifoam (Dow Corning H-10) per liter of urine.

2 Oxygen feed to catalyst unit: 500 cc/min (STP)
Air bleed to evaporator sensor: 7 cc/min (STP)

3 Evaporator heating liquid flow: 2.1 kg/min (4.6 lb/min) of water
Catalyst heating liquid flow: 9.1 lph (2.4 gph) of silicone oil
Condenser coolant flow: 6.4 lpm (1.7 gpm) of ethylene glycol and 50% water

4 Evaporator impeller: 80 rpm, 55 watts
Condenser Impeller: 160 rpm, 45 watts

the end of the test, the urine temperature was 26°C (78°F) and the pressure in the outlet duct was 19 mm absolute. The solids concentration in the urine was 26%; at this concentration and 26°C temperature the equilibrium vapor pressure is 22 mm Hg absolute. This was 3 mm Hg above the 19 mm Hg measured pressure in the outlet duct. Based on the measurements taken, there appeared to be 3 mm Hg $\overline{\Delta p}$ across the demister mesh.

The solids concentration in the evaporator was estimated from the urine feed rate, and assumed the fresh pretreated urine was 4% solids by weight. The solids concentration progressed from 12% to 26% during the 145 hours of operation.

3.4.3 Evaporator Heat Transfer Coefficient

The overall heat transfer coefficient between the liquid heating jacket and boiling urine remained constant during the change in solids concentration from 12-26%. Although the temperature level rose slightly during the test, both the temperature difference between heating liquid and urine and the distillation rate remained constant, indicating that the heat transfer coefficient remained constant. For the recovery rate of 1.04 kg/hr (2.3 lbs/hr), and an average temperature difference of 5°C (9°F), the overall heat transfer coefficient, U, was 23.7 Cal/hr-cm^2-°C (48.5 Btu/hr-ft^2-°F).

3.4.4 Water Yield

Water yield is defined as the amount of water recovered from the amount of water available in the feed. The water which is not recovered represents that amount lost in the residual sludge.

Because the unrecovered water is part of the residual sludge, the ultimate water yield is largely determined by the final concentration of residue at the end of the evaporator batching cycle. When recovering water from urine and humidity condensate (respiration and perspiration condensate) from six men, and concentrating the residues to 45%-50%, the water yield should be 98% or greater. The system was designed for concentrating the residues to 45%-50% after 45 to 50 cumulative days of operation.

Based on the results of urine distillation tests conducted during Phase I, approximately 60% solids in the final sludge is a reasonable operating limit for vacuum distillation batching. At 60% solids concentration at the end of a distillation batch and with essentially no water lost through the condenser vent to the vacuum pump (as will be the case in a closed spacecraft environment), the ultimate recovery capability is 99% by weight, based on the amount of water available in the urine and humidity condensate feed.

Testing conditions deviated slightly from the nominal design conditions in that (1) only urine was fed to the evaporator instead of a urine-humidity condensate mixture, and (2) the final concentration of residue was not reached during the six cumulative days of testing. Also, because the system was operated as a bench test with an oil-type vacuum pump and water trap, rather than in a closed environment with a dry vacuum pump and adsorbent bed, the water vapor vented from the condenser along with noncondensable gases appeared as unrecovered water. Prior to the six-day test, the system was operated to recover 74.4 kg (163.8 lbs) of water from 108.2 kg (238 lbs) of urine; this was a yield of 71.7%. During the six-day test, the system recovered 151.5 kg (333 lbs) of water from 159.5 kg (351 lbs) of urine feed. For the total system operation in which 225.9 kg of water was recovered from 267.7 kg of urine feed, the water yield was 87.9%. Water yield as a function of sludge concentration is shown in Figure 28.

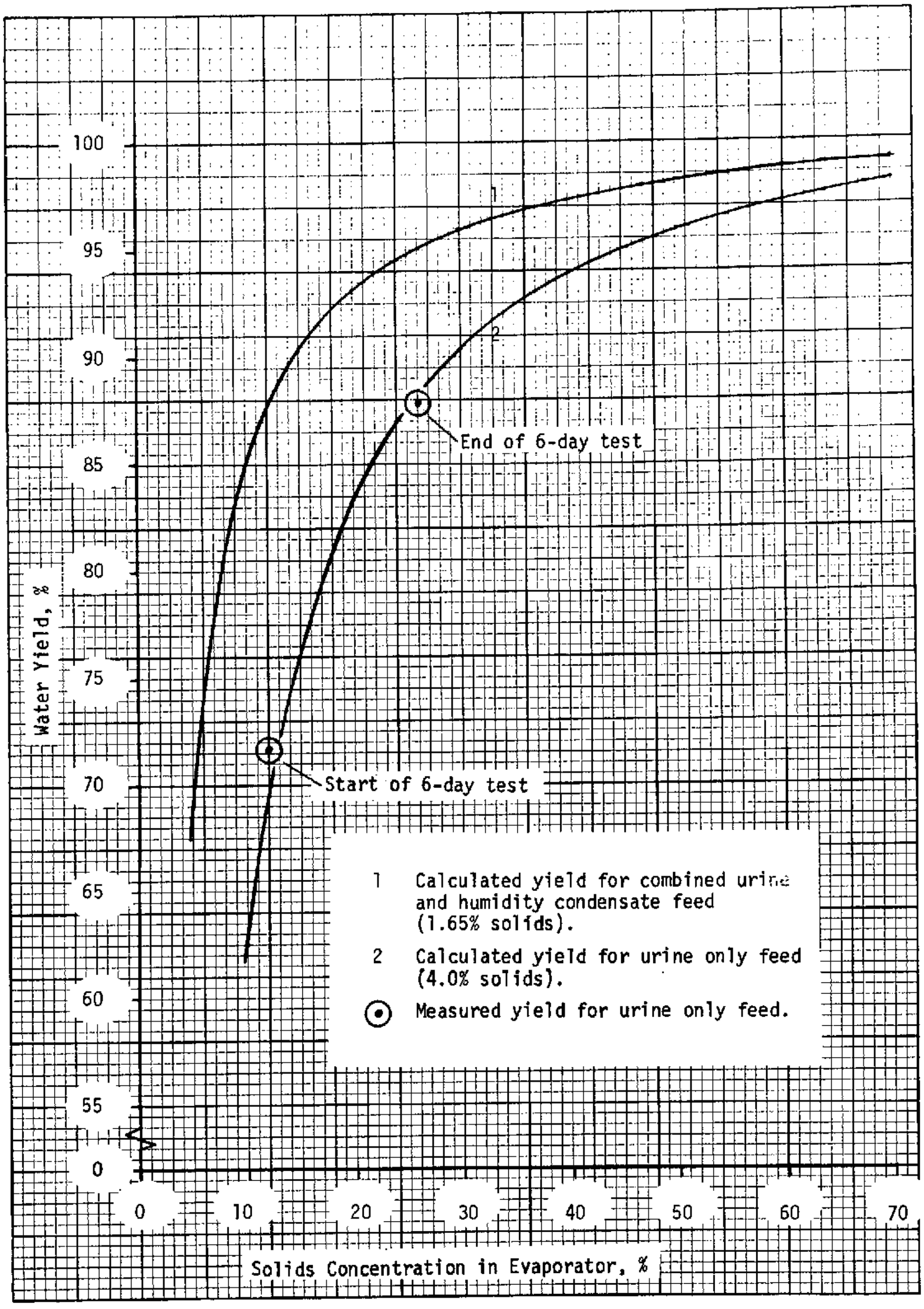


Figure 28 WATER YIELD VS. SLUDGE SOLIDS CONCENTRATION

3.4.5 Catalyst Heat Utilization

The catalyst unit and process vapor were heated to 120°C (250°F) by a closed recirculation heating loop. Heating liquid flow was maintained at 9.1 lph (2.4 gph); heating fluid was Dow Corning 550 Silicone Oil which has a heat capacity of 0.38 cal/gm-°C (0.38 Btu/lb-°F). The temperature difference between the 166°C (330°F) inlet to the catalyst unit and the 138°C (280°F) outlet is 28°C (50°F); this represents 96 kcal/hr (380 Btu/hr) heat input to the catalyst unit. After the catalyst unit was heated, the heat input from the recirculating liquid loop was needed to heat the vapor and the small amount of oxidation gas. To heat 1.04 kg/hr (2.3 lbs/hr) of vapor plus 500 cc/min (STP) of oxygen from 27°C (80°F) to 140°C (290°F) required 56 kcal/hr (220 Btu/hr). The remainder of the heat input, or 40 kcal/hr (160 Btu/hr), was lost to the ambient as insulation losses. Expressed as a percentage, 56 of 96 kcal/hr is 58% heat utilization.

3.4.6 Condenser Heat Rejection

The system process heat was removed in the condenser by an ethylene glycol-50% water coolant loop operating between the condenser and a freon-cycle chiller unit. Coolant flow was constant at 6.4 lpm (1.7 gpm) and the temperature pick-up in the condenser was 2.2°C (4°F). This represents a measured heat rejection rate of 696 kcal/hr (2720 Btu/hr). Heat removal required to cool the 120°C (250°F) incoming vapor to the 10°C (50°F) condensing temperature and to condense the 1.04 kg/hr (2.3 lbs/hr) of vapor was 666 kcal/hr (2640 Btu/hr). Since the condenser temperature level was slightly below ambient temperature, this small difference could readily have been the amount of heat picked up from ambient air.

3.4.7 Condenser Heat Transfer Coefficient

The condenser heat load of 696 kcal/hr (2720 Btu/hr) was transferred to the coolant through 0.55 m^2 (6 ft^2) of heat exchange area. Referring to Table XIII, the condensate temperature within the condenser was generally 3° to 4°C (5° to 7°F) above the coolant exit temperature. On the basis of the average coolant temperature, the temperature difference between condensing vapor and coolant was 4.4°C (8°F). These conditions indicate the overall heat transfer coefficient was 28 Cal/hr-cm^2-°C (57 Btu/hr-ft^2-°F). This is approximately one-half the value obtained in the lab test condenser; however, the average coolant velocity in the zero-g condenser was 4.3 cm/sec (0.14 fps) as contrasted to the coolant velocity of 10.7 cm/sec (0.35 fps) in the modified lab test condenser.

3.4.8 Condenser Venting and Condensing Efficiency

Removal of noncondensable gases from the condenser included some water removal along with the gases and resulted in a condenser inefficiency.

The oxygen feed to the catalyst unit vented from the system through the condenser and vacuum pump; since it was mixed in the steam flow, the air was saturated at the condensing temperature. From the psychrometric relationship for air-water vapor mixtures, the minimum amount of water loss could be predicted. For the average test conditions of 15 mm Hg pressure, 7°C (45°F) condensing temperature and 500 cc/min (STP) noncondensable gas flow rate, the water loss rate was 0.028 kg/hr (0.05 lbs/hr). This represented 2% of the product vapor being removed through the vacuum vent line.

The vapor and gases leaving through the vent line and vacuum pump mix with the surrounding atmosphere. In a closed environment, as a spacecraft cabin, this vapor is condensed and fed to the evaporator along with respiration and perspiration condensate from the atmosphere humidity control system. Although the vented vapor is not lost, it does result in a system inefficiency because of the additional burden it places on the humidity control system and the water recovery evaporator.

3.5 Product Water Quality

The quality of water is shown by analyses in Table XIV. These analyses provided indicators of water quality but were not sufficient in duration to give assurance that the water would conform to standards for potability over long range use. These general indicators demonstrated that the recovered water from these specific tests was of high quality.

During the six days of operation, the total organic carbon (TOC) concentration, as measured daily, varied between 0.8 and 12.0 mg/l. This indicated that the organic contaminant level was kept very low in concentration. In comparing the TOC of product water to the TOC concentration of raw condensate, the TOC levels were reduced by 68% to 92%.

The TOC analysis was used in place of another analysis, chemical oxygen demand (COD), to determine the organic contaminant level of the recovered water. The standards for potability require that COD be below 100 mg/l while TOC limits are not defined. Both the TOC and the COD analysis provides a measure of organic contaminant level but the modus operandi of each method is completely different and therefore no direct correlation between the analyses for all samples exists. However, for water recovered by distillation of urine, it has been found that COD values are of the order of 2-1/2 to 3-1/2 times the TOC values for the same sample. Using a 2-1/2 to 3-1/2 correlation factor when considering the COD potability limit of 100 mg/l, the corresponding limit for TOC would be 28 to 40 mg/l. On the basis that TOC values were

TABLE XIV
WATER QUALITY ANALYSES

SAMPLE / COMPOUND	#1		#2		#3		#4		#5		#6	
	Raw	Prod.	Raw	Prod.	Raw	Prod.	Raw	Prod.	Raw	Prod.	Raw	Prod.
1) Total Carbon, mg/l	27.0	10.5	19.0	4.8	21.0	5.1	25.0	9.2	22.5	8.5	---	16.5
2) Total Organic Carbon, mg/l	27.0	5.5	18.0	1.3	19.0	0.8	24.5	5.2	20.5	6.5	---	12.0
3) pH	4.0	6.7	4.1	6.0	4.9	6.4	3.5	6.4	3.7	6.9	---	6.3
4) Ammonia, mg/l	<0.1	0.8	1.2	0.8	<0.1	0.5	<0.1	0.9	<0.1	0.2	---	<0.1
5) Conductivity, μmhos	110	56	96	38	----	32	145	35	36	22	---	15
6) Turbidity, JTU	0.3	0.4	0.5	0.9	---	0.08	0.08	0.08	0.04	0.08	---	0.4
7) Viable bacteria density, MPN/ml	---	*	---	<0.2	---	<0.2	---	<0.2	---	4.9	---	0.7

*Undeterminable

significantly below the 28-40 mg/l range, it can be assumed that the organic contaminant levels were within acceptable limits.

Ammonia concentrations were consistently below 1 mg/l. Conductivity varied between 15 and 56 μmhos. While there are no limits on these parameters for potability, it is generally desirable to maintain ammonia content below 10 mg/l and for conductivity to be below 100 μmhos.

The product water pH varied between 6.0 and 6.7, thus falling within a generally acceptable range of 6.0 to 8.0. Turbidity levels were consistently below 1 JTU and within the maximum potability standards of 10 JTU.

With the exception of the first sample, viable bacteria density, as determined by the most probable number technique, was below 10 organisms per milliliter. The first sample had all positive tubes in all three dilution levels, indicating an indeterminate result, and was possibly due to contamination in the testing equipment. The first sample as well as the remaining five samples did not exhibit growth nor generate any odor upon standing for several weeks.

3.6 Mechanical Performance

During the six-day performance test, the water recovery system was operated on a continuous basis. The urine feed control and evaporator liquid level sensing subassembly which was developed and checkout tested in Phase I functioned satisfactorily to automatically maintain the desired liquid level in the evaporator. The evaporator impeller was operated at 80 rpm and required 55 watts of electrical power.

The condenser impeller was operated at 160 rpm and required 45 watts of electrical power. The 160-rpm speed was determined during checkout testing of the condenser as the speed necessary to assure repetitive performance of the water pump (condensate pumpout from vacuum condenser to storage at one atmosphere). The condensate pumpout was accomplished by two pumps connected in series -- a gear pump and a secondary peristaltic pump. The water pump controls which were initially evaluated during checkout testing of the zero-g condenser continued to perform satisfactorily.

Section 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Based on the development and testing activities conducted in Phase II of the program the following conclusions have been reached:

(1) A condenser with an internal rotating impeller and coolant surfaces directly opposite the condensing surfaces is an effective condenser insofar as could be evaluated in normal gravity.

(2) The overall heat transfer coefficient from the condensing vapor to the liquid coolant is approximately 49 Cal/hr-cm^2- C (100 Btu/hr-ft^2- F).

(3) The VD/VF evaporator, catalyst unit and condenser functioned satisfactorily based on thermal, mechanical and recovery performance during a 145-hour evaluation test.

(4) The quality of recovered water, as measured by analyses for total organic carbon, pH, conductivity, turbidity, and viable bacteria density (with one exception) was within established limits for potability.

(5) The measured evaporator heat utilization and condenser heat rejection were equivalent to anticipated theoretical values for given distillation rates.

(6) The catalytic oxidation unit utilized 56% of the heat supplied to it by a closed recirculating hot liquid loop. The remaining 44% was lost to the surrounding environment.

(7) The evaporator impeller rotating at 80 rpm required 55 watts of electrical power; the condenser impeller operated at 160 rpm and required 45 watts.

(8) A timer-actuated and pressure switch cut-out method of automatic control of water pumpout was satisfactory.

4.2 Recommendations

Based on the observations and conclusions drawn from this phase of the program, the following recommendations are made concerning the use, operation, evaluation, and future testing of the VD/VF water recovery system.

(1) Further testing of the VD/VF water recovery process should be carried out to evaluate:

  (a) Distillation performance during one or more evaporator batching cycles in which the sludge is concentrated to the range of 50%-60% solids.

  (b) Water quality variations during batching cycles.

  (c) Mechanical performance and durability of the complete system during batching cycles over a sustained period, nominally 90 to 180 days.

(2) The VD/VF water recovery process should be evaluated with respect to integrating this process into a total water management subsystem for long duration missions.

APPENDIX

DESIGN CALCULATIONS

I. Vacuum Still Sizing Calculations

The variables to consider in determining still size are:

1. Required heat transfer area
2. Diameter of still
3. Liquid-vapor profile in 1 "g" which is a function of diameter and rotor speed, and
4. Volume of liquid in still

The equations for each of these variables must be determined before optimum still size and shape can be determined.

Heat Transfer Area - The required area for heat transfer to boil the urine is determined by the distillation rate and the boiling coefficient of heat transfer.

The specified feed rate for a 6-man system is:

21#/day urine comprised of 20#/day of water
1#/day of solids
and 30#/day humidity condensate.

Maximum possible distillation rate is 20 plus 30 = 50#/day of water

Latent heat of vaporization = 1045 BTU/# @ 85°F

$$\text{Thermal input rate required} = \frac{(1045\ \text{BTU/\#})\ (50\ \text{\#/day})}{24\ \text{hr/day}}$$

$$= 2180\ \text{BTU/hr}$$

The anticipated boiling coefficient may be between 100 and 1000 $\dfrac{\text{BTU}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$

depending mainly on the liquid velocity at the heat transfer surface and the effects of fouling.

References: Jakob & Hawkins, Elements of Heat Transfer, (3rd Ed.) Pp. 206-210.

J. H. Perry, Editor, Chemical Engineers Handbook, (4th Ed.) Section 10, Table 10-2.

For a temperature difference of 8°F from metal surface to liquid, $h = 1250$ BTU/hr-ft^2-°F for water at 1 atmosphere.

To consider fouling effects, $h = 500$ BTU/hr-ft^2-°F for the equivalent coefficient of the deposit. This is a recommended value for heating and vaporizing organic and inorganic liquids.

The overall coefficient including deposits is:

$$h = \frac{1}{\frac{1}{1250} + \frac{1}{500}} = 357 \frac{\text{BTU}}{\text{hr-ft}^2\text{-°F}} \quad @ \text{ 1 atmosphere}$$

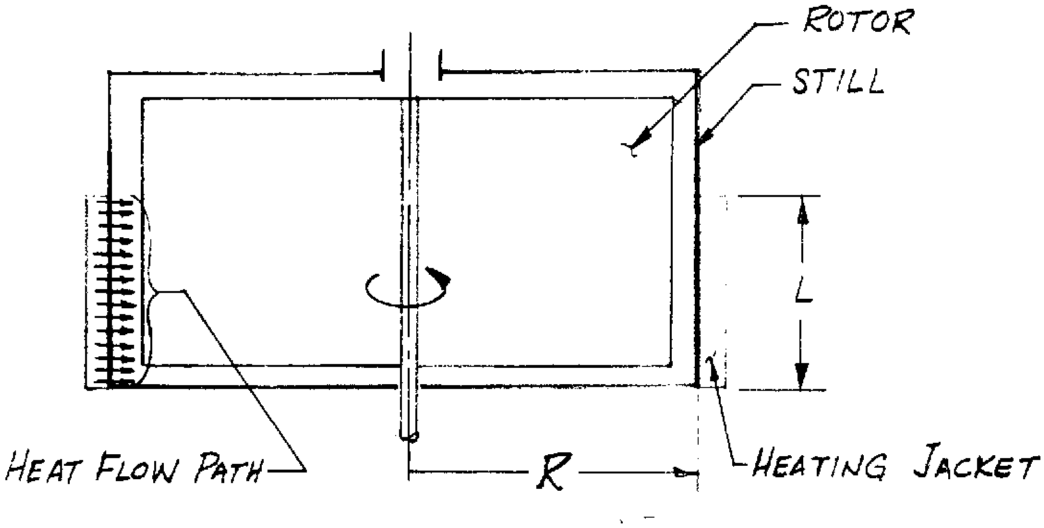
To correct for boiling at reduced pressure:

$$h = (357) \left[\frac{0.5 \text{ psia}}{14.7 \text{ psia}}\right]^{0.4} = (357)\ (.259) = 92 \frac{\text{BTU}}{\text{hr-ft}^2\text{-°F}}$$

Thermal input, $Q = h \cdot A \cdot \Delta T$

$$A = \frac{2180 \text{ BTU/hr}}{92 \text{ BTU/hr-ft}^2\text{-°F}\ (8° \text{F})} = 2.96 \text{ ft}^2$$

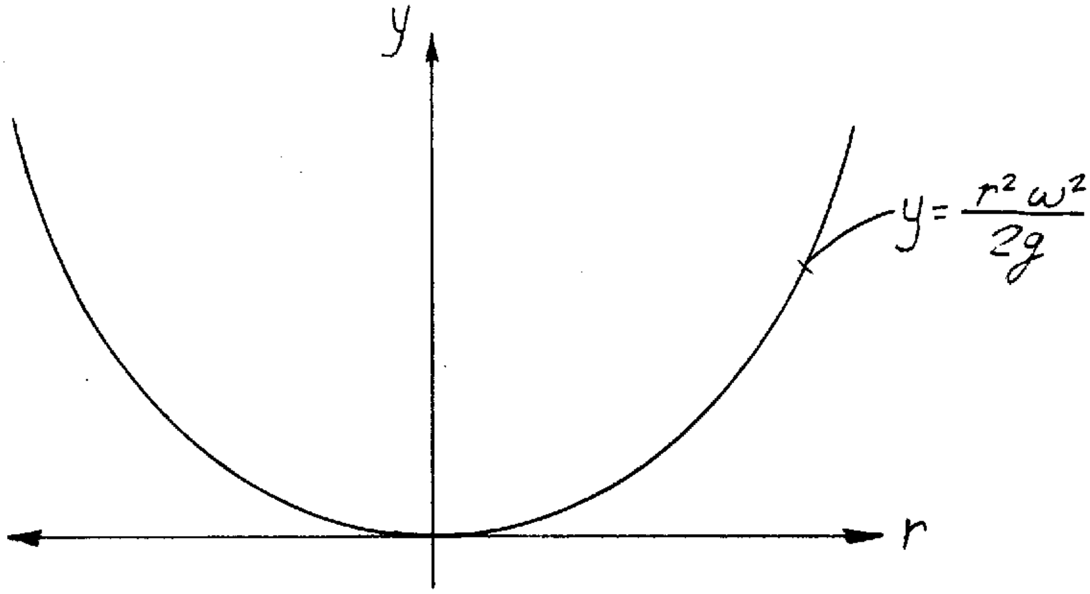
$$A = (2\pi R) \cdot (L)$$

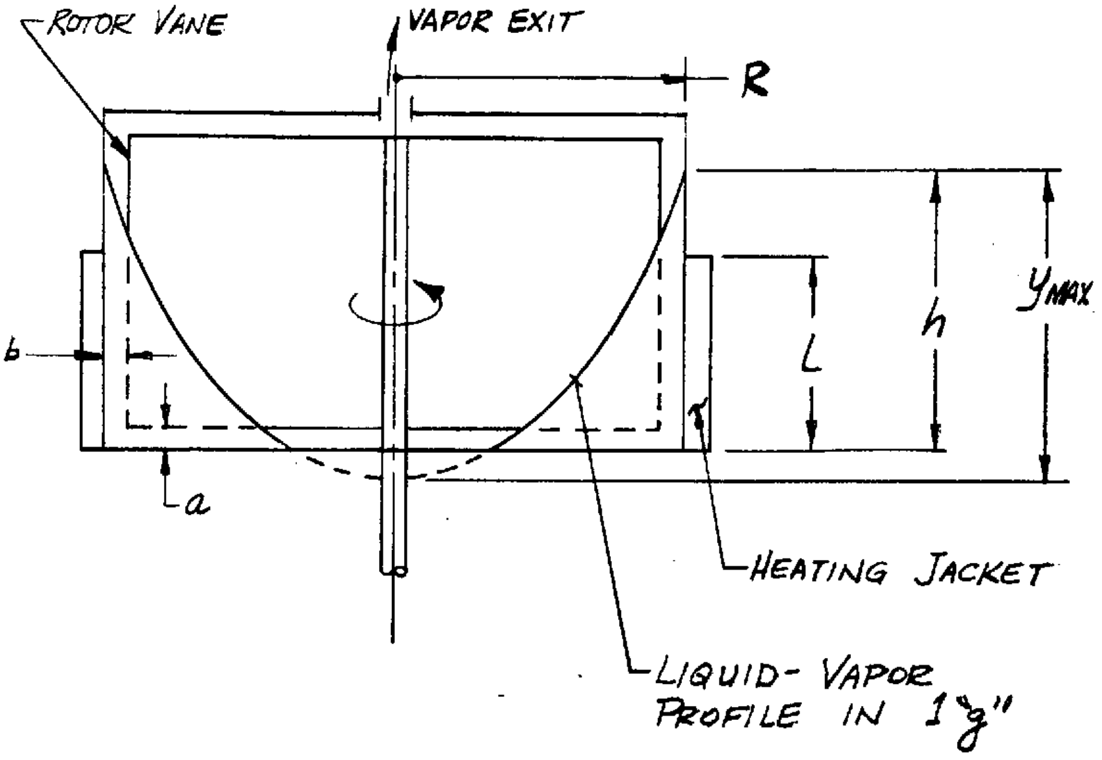


"R", the radius of the still, is also a variable in determining motor speed and liquid volume, The length of heating jacket, L, may be determined after these other factors are considered in determining their dependence on "R".

The configuration of the still and rotor assembly are shown in Figure A-1.

Liquid-Vapor Profile - The equation for a spinning body of liquid in one "g" is a parabola expressed by: $y = \frac{r^2 W^2}{2g}$





SYMBOLS:

N = Rotor Speed, RPM
W = Rotor Speed, Rad/sec
L = Length of heat transfer jacket
R = Radius of still and, approximately, radius of rotor
$\bar{V}$ = Velocity of rotor tip, ft/sec
a = Clearance between rotor and face of still
b = Clearance between rotor and radial wall of still

Figure A-1 EVAPORATOR STILL AND ROTOR CONFIGURATION

In terms of "N" and "R", $y_{MAX} = (14.25\text{in}) \left[\frac{N}{100\ \text{RPM}} \times \frac{R}{10\text{in}} \right]^2$

This must be known to be sure the heating jacket is covered with liquid.

Liquid Volume - The equation relating liquid volume to rotor speed and liquid profile is

$$\text{Volume} = \frac{gh^2}{W^2} \quad \text{where } h \leq y_{MAX}$$

This expression includes only the volume between the bottom of the parabola and the constraining wall and assumes that "h" will be less than y_{MAX} which is the maximum height the rotor is capable of producing in 1 "g". In terms of "N" and "h", Volume = $\dfrac{(11.05\text{in}^3)(h/\text{in})^2}{\left(\frac{N}{100\ \text{RPM}}\right)^2}$

Batching Duration - The length of duration of the batching process is limited by the rate of solids addition, the final concentration of sludge and the volume of sludge to be removed. The weight of solids at end of batch is:

W_s = (solids feed rate) x (No. of days of batching)

also,

W_s = (Vol. if Sludge) x (sp. Gravity) x (Solids Weight Friction)

The latter equation neglects the precipitated solids which can be expected to be approximately 2% when the solids weight friction is 40%. Equating these expressions and solving for "No. of days of batching":

$$\text{No. of days of batching} = \frac{(\text{Vol. of Sludge}) \times (\text{sp. Gravity}) \times (\text{Solids Weight Friction})}{\text{Solids feed rate}}$$

For a six-man rate of urine feed the solids feed rate is:

$$3.5 \frac{\#\ \text{urine}}{\text{man-day}} \times (6\ \text{men}) \times .05 \frac{\#\ \text{solids}}{\#\ \text{urine}} = 1 \frac{\#\ \text{solids}}{\text{day}}$$

Rotor Speed - The tip velocity of the rotor is expressed by

$$\bar{V} = (w) \times (R)$$

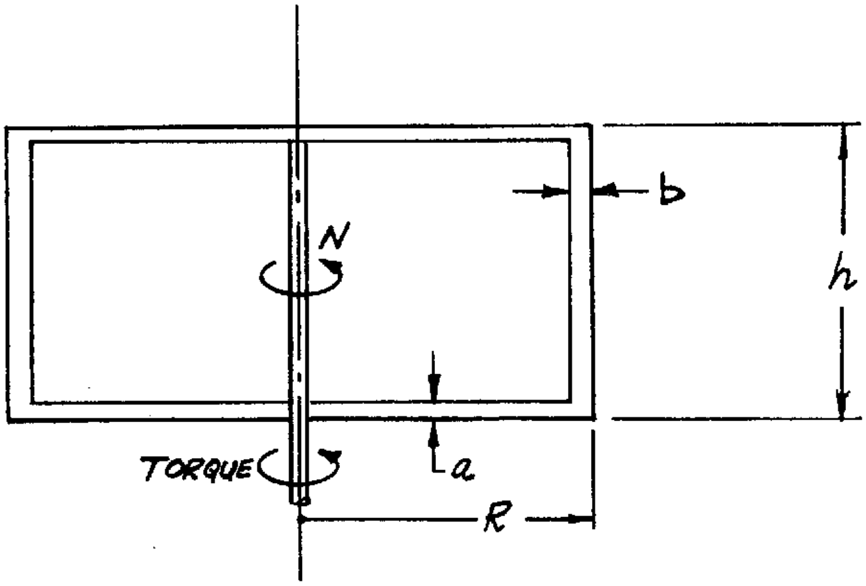
$$\text{or } \bar{V} = (8.73 \text{ ft/sec}) \ \frac{N}{100 \text{ RPM}} \times \frac{R}{10\text{in}}$$

It is desirable to have a liquid velocity of 3 ft/sec or greater past the heater transfer surface to minimize the effects of fouling.

Fluid Torque - The fluid torque required to shear the liquid along the constraining walls is:

$$\text{Torque} = (1.53^{03\text{-in}}) \left(\frac{\mu}{\text{centipoise}}\right)\left(\frac{N}{100 \text{ RPM}}\right)\frac{R}{10\text{in}}$$

$$\times \left[\frac{(R/10)^2}{4 \ a/\text{in}} + \frac{(R/10\text{in}) \ (h/10\text{in})}{b/\text{in}}\right]$$



Ref: Streeter, Fluid Mechanics, Chapter 4.

NOTE: This equation accounts for fluid torque only; the actual motor torque required will also have to consider bearing friction, inertial effects at start-up and from external accelerations during operation, etc.

Application of equations - To apply the foregoing equations in sizing the evaporator still, further constraints must be made to reduce the number of variables. First, it is desirable to limit the weight fraction of solids of the end of the batching cycle to approximately 40%. The major factors which contribute to this limitation are sludge viscosity, precipitated solids, and weight fraction of extracted water. Typical values of these properties are listed below for 30, 40, 50, and 60% concentrations. (Ref: Putnam, Composition and Concentrative Properties of Human Urine).

X $\frac{\text{\# Solids (Solute)}}{\text{\# Urine}}$	Precipitated Solids $\frac{\text{\# Precipitate}}{\text{\# Solutes}}$	Viscosity Centipoise	Extracted Water $\frac{\text{\# water extracted}}{\text{\# water content}}$
30%	1.5%	1.71	91.0%
40%	2.1%	2.45	94.1%
50%	2.9%	4.03	96.2%
60%	6.5%	5.98	97.4%

Both viscosity and weight fraction of precipitated solids start rising at an increasing rate at 40-50% solids concentration. Increased viscosity makes the sludge more difficult to spin inside the still. As solids precipitate out of solution, they will tend to foul the heat input surface; also, the precipitated solids are more abrasive on the components which must transport the sludge from the still to a storage container. The 40-50% limitation on solids concentration yields a weight fraction of extracted water of 94 to

96% which is within the desired range of performance. Using 40% as the concentration at end of batch,

$$\text{No. of days of batching} = (\text{Vol. of sludge}) \times \left(1.184 \times 0.0361 \frac{\#\ \text{urine}}{\text{in}^3}\right)$$

$$\times \left(.40 \frac{\#\ \text{solids}}{\#\ \text{urine}}\right)$$

$$\div \left(1 \frac{\#\ \text{solids}}{\text{days}}\right)$$

$$\text{No. of days of batching} = (.0171\ \text{days}) \left(\frac{\text{Volume of Sludge}}{\text{in}^3}\right)$$

for 20 days of batching, Volume $= \frac{20}{.0171} = 1170^{\text{in}^3}$ (Trial 1)

for 40 days of batching, Volume $= \frac{40}{.0171} = 2340^{\text{in}^3}$ (Trial 2)

From the equation of liquid volume as a function of the liquid-vapor profile,

$$\text{Volume} = \frac{(11.05^{\text{in}^3})\ (h/\text{in})^2}{(N/100\ \text{RPM})^2}$$

$$h = \frac{\text{Volume}}{11.05^{\text{in}^3}} \times (N/100\ \text{RPM})\ \text{inches}$$

for volume $= 1170^{\text{in}^3}$ and $N = 100$ RPM:

$h = 10.3^{\text{in}}$ (Trial 1)

for volume $= 2340^{\text{in}^3}$ and $N = 100$ RPM:

$h = 14.7^{\text{in}}$ (Trial 2)

Letting $h = y_{MAX} = (14.25^{in}) \quad (N/100\ RPM) \times (R/10^{in})^{2}$

and solving for R,

$$R = \frac{10^{in}}{(N/100\ RPM)} \qquad \frac{10.3^{in}}{14.25} \qquad \text{for } h = 10.3^{in}$$

$$R = 8.5^{in} \qquad \text{(Trial 1)}$$

$$R = \frac{10^{in}}{(N/100\ RPM)} \qquad \frac{14.7^{in}}{14.25} \qquad \text{for } h = 14.7^{in}$$

$$R = 10.2^{in} \qquad \text{(Trial 2)}$$

For each of these cases, the liquid velocity past the heat transfer surface is:

$$\bar{V} = (8.73\ \text{ft/sec}) \left(\frac{N}{100\ RPM}\right) \times \left(\frac{R}{10^{in}}\right)$$

$$= (8.73) \left(\frac{100}{100}\right) \left(\frac{8.5}{10}\right) = 7.4\ \text{ft/sec} \qquad \text{(Trial 1)}$$

$$\bar{V} = (8.73) \left(\frac{100}{100}\right) \left(\frac{10.2}{10}\right) = 8.9\ \text{ft/sec} \qquad \text{(Trial 2)}$$

This is in the desired range to aid in preventing fouling.
Heat transfer area required in 2.96 ft^2:

$$A = (2\pi R)L$$

$$L = \frac{(2.96)(144)}{(2\pi)(8.5)} = 8.0^{in} \qquad \text{(Trial 1)}$$

$$L = \frac{(2.96)(144)}{(2\pi)(10.2)} = 6.65^{in} \qquad \text{(Trial 2)}$$

For both cases, the height of liquid, h, is greater than the height of the heat transfer jacket, L, thus assuring that the heating area is covered with liquid.

From the foregoing calculations, the still dimensions should be 8.5 inches radius by 10.3 inches high for 20 days batching duration or 10.2 inches radius by 14.7 inches high for 40 days duration.

II. Evaporator Assembly Heating Analysis

The heating loop temperatures and process fluid temperatures are summarized on the evaporator heating diagram Figure A-2. This diagram and the accompanying analyses assume waste heating liquid flow through interconnected loops for the catalytic oxidation unit and the vacuum still assembly.

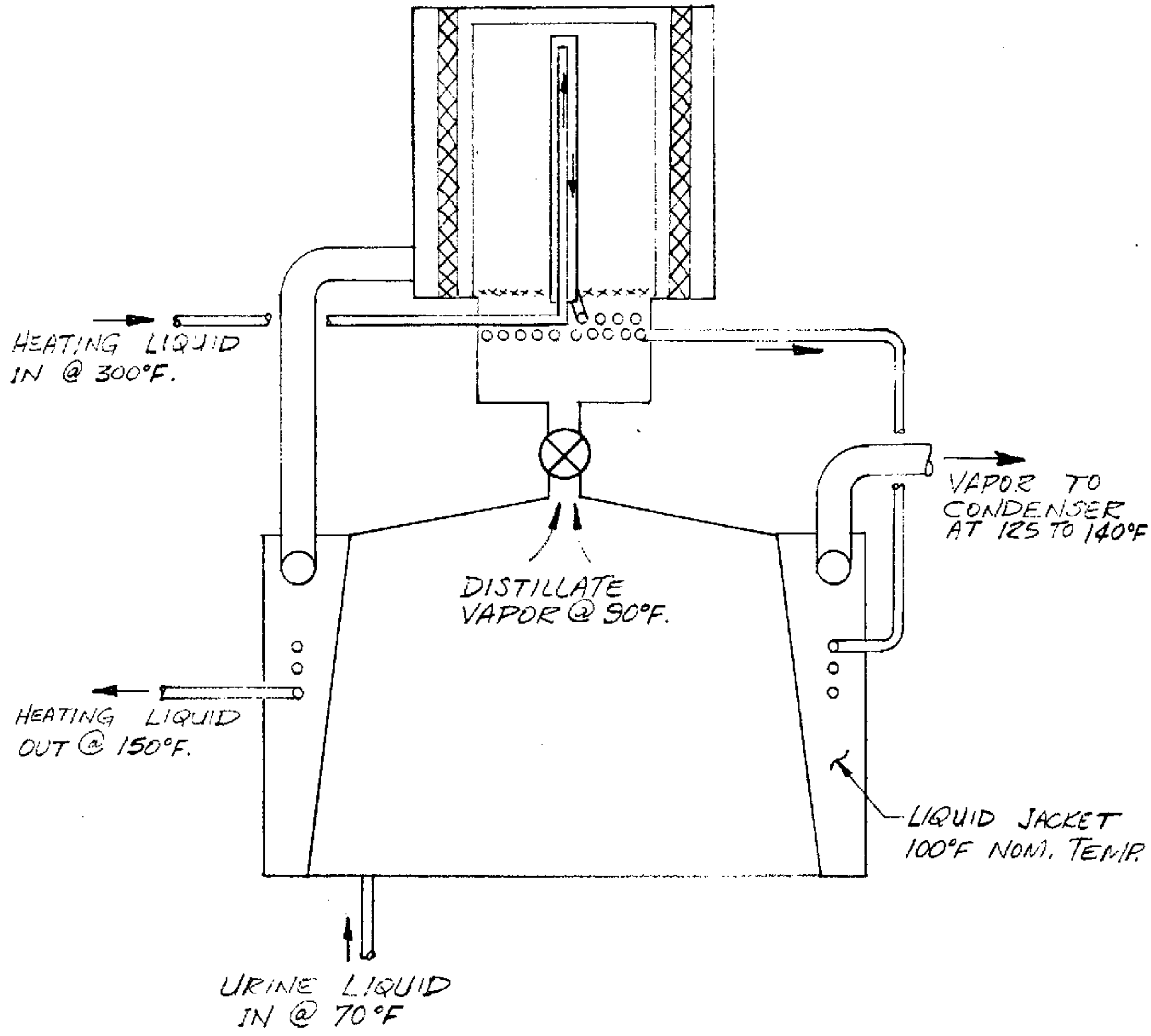


Figure A-2 EVAPORATOR HEATING DIAGRAM

Total heat requirements are:

Sensible heating of liquid = $(2\#/\text{hr})(1\frac{\text{BTU}}{\#\ ^\circ\text{F}})(90^\circ - 70^\circ\text{F})$ = 40

Boiling of urine = $(2\#/\text{hr})(1045\ \text{BTU}/\#)$ = 2090

Sensible heating of vapor = $(2\#/\text{hr})(.45)(120 - 90)$ = 27

2157

Heat losses through insulation (See p. A-18) = 136

2293

$$\text{Flow} = \frac{Q}{Cp \cdot \Delta T}$$

For heating liquid in @ 300°F, $Cp = .6\frac{\text{BTU}}{\#\ ^\circ\text{F}}$

out @ 150°F

$$\text{Flow} = \frac{2260\ \text{BTU/hr}}{(.6\ \frac{\text{BTU}}{\#\ ^\circ\text{F}})(150^\circ\text{F})} \approx 25\#/\text{hr}$$

$$\text{Volume flow} = (25\#/\text{hr}) \times \frac{1\ \text{gal}}{8.34\#} = 3\ \text{gal/hr}$$

Heat Required in Catalyst Bed:

$(2\#/\text{hr})(.45)(250^\circ\text{F} - 90^\circ\text{F})$ = 144

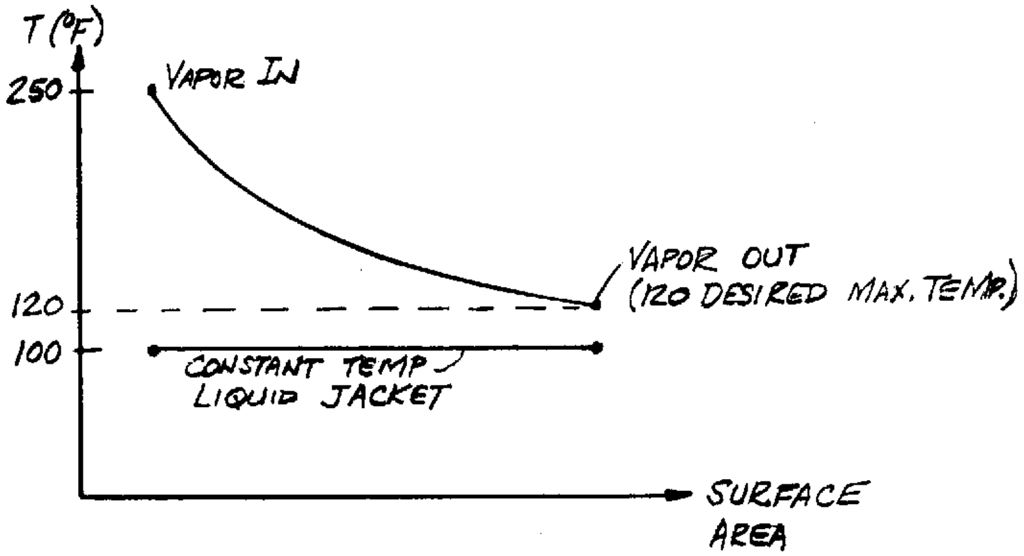
plus 40 watts losses = 136

280 BTU/hr (82 watts)

$$\text{Heating Liquid } \Delta T \text{ in Catalyst Bed} = \frac{280\ \text{BTU/hr}}{(.6\ \frac{\text{BTU}}{\#\ ^\circ\text{F}})(25\ \#/\text{hr})}$$

$$= 19^\circ\text{F}$$

VAPOR RECUPERATOR AREA REQUIRED



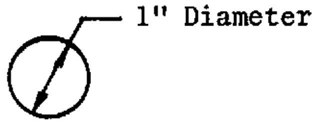
$$Q = hA\ (\Delta T)\ln: \quad (\Delta T)_{ln} = \frac{(250-100) - (120-100)}{\ln \frac{250-1}{120-100}}$$

$$= \frac{130}{\ln \frac{150}{20}} = \frac{130}{2} = 65°F$$

h vapor $\approx$ 1 BTU/hr-ft^2-°F

h vapor << h water bath

$$A = \frac{(2\#/hr)\ (.45\ \frac{BTU}{\#\ F})\ (130°F)}{(1\ \frac{BTU}{hr\text{-}ft^2\text{-}°F})\ (65°F)} = 1.8\ ft^2$$

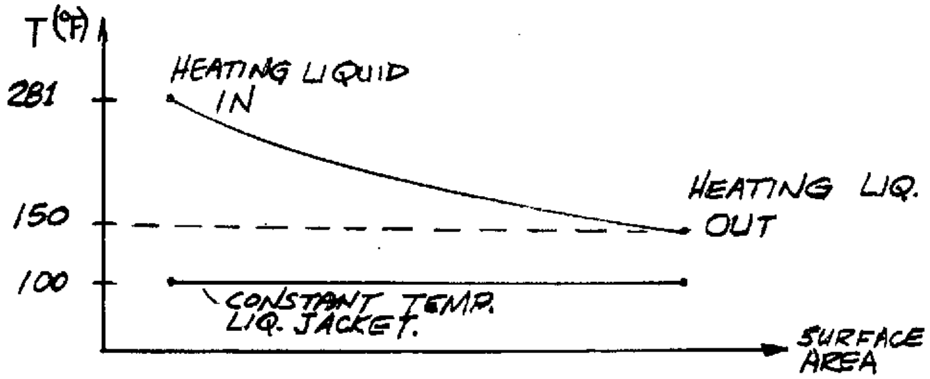


$$L = \frac{A}{\pi D} = \frac{1.8\ ft^2}{\pi (1")} \times 12\ in/ft = 6.9\ ft$$

L = π (Diameter of coil) (No. of coils); Coil Diameter $\approx$ 22 in

$$\text{No. of Coils} = \frac{6.9\ ft}{(\pi)\ 22\ in} \times 12\ in/ft = 1.2\ \text{Coils}$$

HEATING COIL AREA REQUIRED FOR HEAT TRANSFER TO LIQUID JACKET:



$$Q = (2\#/\text{hr})\left[(1\ \frac{\text{BTU}}{\#^\circ\text{F}})(90-70)(^\circ\text{F}) + 1045\ \text{BTU}/\#\right] = 2130\ \text{BTU/hr}$$

$$Q = UA\ (\Delta T)\ \ln$$

$$(\Delta T)\ln = \frac{(281-100) - (150-100)}{\ln \frac{281-100}{150-100}} = \frac{134}{\ln \frac{181}{50}} = \frac{134}{1.27} = 105^\circ\text{F}$$

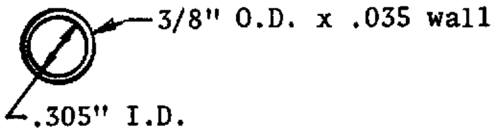
$$U = \frac{1}{\frac{1}{h_{(\text{jacket})}} + \frac{1}{h_{(\text{heating liquid})}}}\ ;\quad h_{\text{jacket}} \approx h_{\text{heating liquid}}$$

$$h \approx 100\ \text{BTU/hr-ft}^2\text{-}^\circ\text{F}$$

$$U = 50$$

$$A = \frac{2130\ \text{BTU/hr}}{(50\ \frac{\text{BTU}}{\text{hr-ft}^2\text{-}^\circ\text{F}})(105^\circ\text{F})} = .41\ \text{ft}^2$$

$$A = \pi \cdot D \cdot L$$

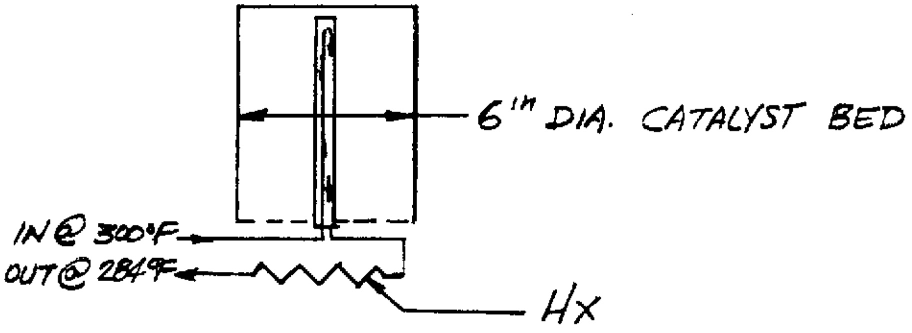


$$L = \frac{.41\ \text{ft}^2}{(\pi)(.305\text{in})} \times 12\ \text{in/ft} = 5.1\ \text{ft}$$

$$L = \pi\ (\text{Coil Diameter})(\text{No. Coils})$$

$$\text{No. Coils} = \frac{L}{\pi \cdot D} = \frac{5.1\ \text{ft}}{\pi\ (2\ \text{ft})} = .8\ \text{Coils}$$

Heat Dissipation in Catalyst Bed:



$$\text{Catalyst Bed Flow Area} = (\pi/4)(6)^2 = 28.2 \text{ ln}^2$$

If H_x Area is 1/2 of Flow Area,

$$H_x \text{ Area} = (1/2)(28.2) = 14.1 \text{ in}^2$$

$$Q = h \cdot A \cdot (\Delta T)_{ln} = (2\#/hr)(.45 \frac{BTU}{\# \cdot °F})(T_{exit} - 90°F)$$

$$(\Delta T)_{ln} \text{ is approximately: } 280 - (\frac{T_{exit} + 90}{2}) = (\Delta T)_{Avg}$$

$$h \approx 1 \text{ BTU/hr-ft}^2\text{-}°F$$

Solving for T_{exit}:

$$\frac{(1 \text{ BTU/hr-ft}^2 °F)(14.1 \text{in}^2)}{144 \text{in}^2/\text{ft}^2}(280 - \frac{T + 90}{2}) = (2)(.45)(T-90) \text{ BTU/hr}$$

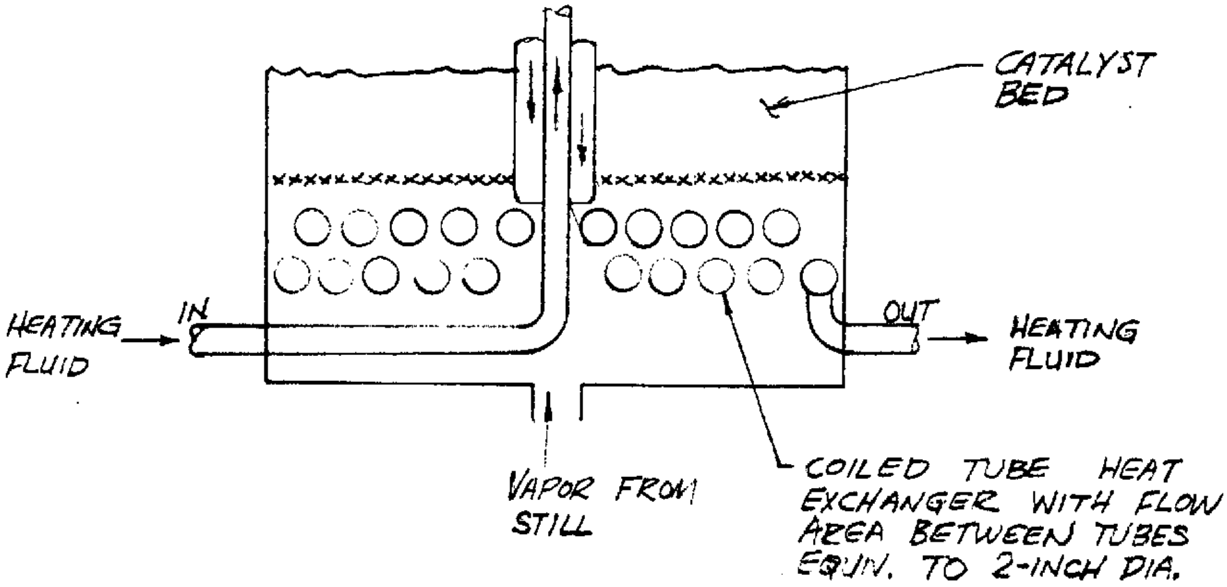
$$(.098)(560 - T + 90) = (1.8)(T - 90)$$

$$650 - T = 18.4T - 1650$$

$$19.4 T = 1650 + 650$$

$$19.4 T = 2300$$

$$T = 119°F \quad \text{(too low)}$$



$$H_x \text{ Area} = \left(\frac{\pi}{4}\right)\left[(6)^2 - (2)^2\right] \times \left[\frac{(\pi/2)(D)}{D}\right] = 39.4^{in^2}/\text{Row}$$

2 Rows = 78.8^{in^2}

For 78.8^{in^2} of area (preheater):

$$\frac{(1 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F})(78.8^{in^2})}{144^{in^2}/\text{ft}^2}\left(280 - \frac{T + 90}{2}\right) = (2)(.45)(T - 90)$$

$$(.547)(560 - T + 90) = (1.8)(T - 90)$$

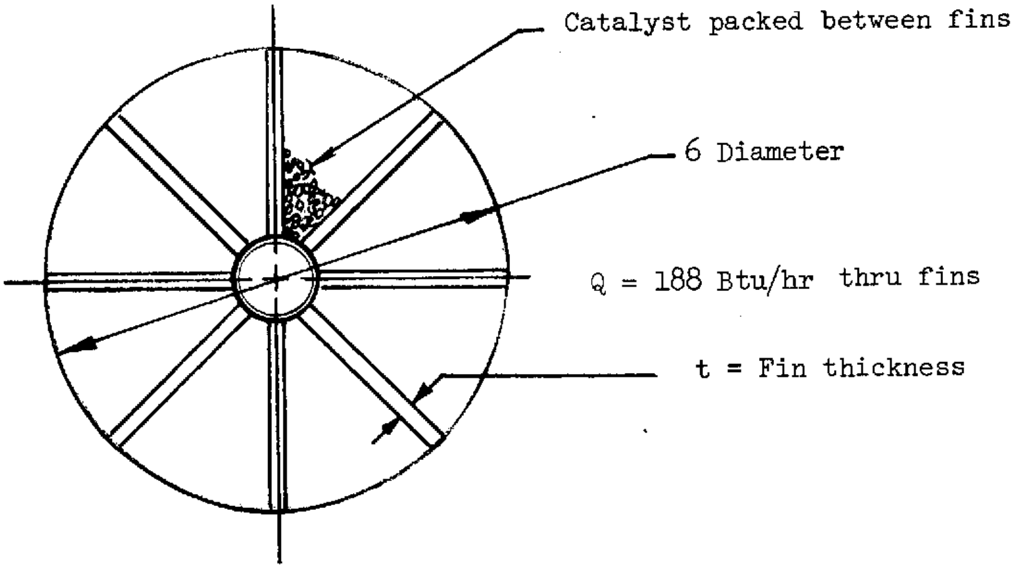
$$650 - T = 3.29\ T - 164$$

$$814 = 4.29\ T$$

$$T = 190$$

$$Q_{\text{Preheater}} = (2\#/\text{hr})(.45 \frac{\text{BTU}}{\# \ ^{\circ}\text{F}})(190 - 90)^{\circ}\text{F} = 90 \text{ BTU/hr}$$

$$Q_{\substack{\text{Catalyst}\\ \text{Bed Conduction}}} = 278 - 90 = 188 \text{ BTU/hr}$$



$$Q = \frac{kA}{x}(\Delta T)$$

$$k = 10 \frac{\text{BTU/ft}}{\text{hr-ft}^2\text{-}^{\circ}\text{F}}$$

$$\Delta t = 100^{\circ}\text{F}$$

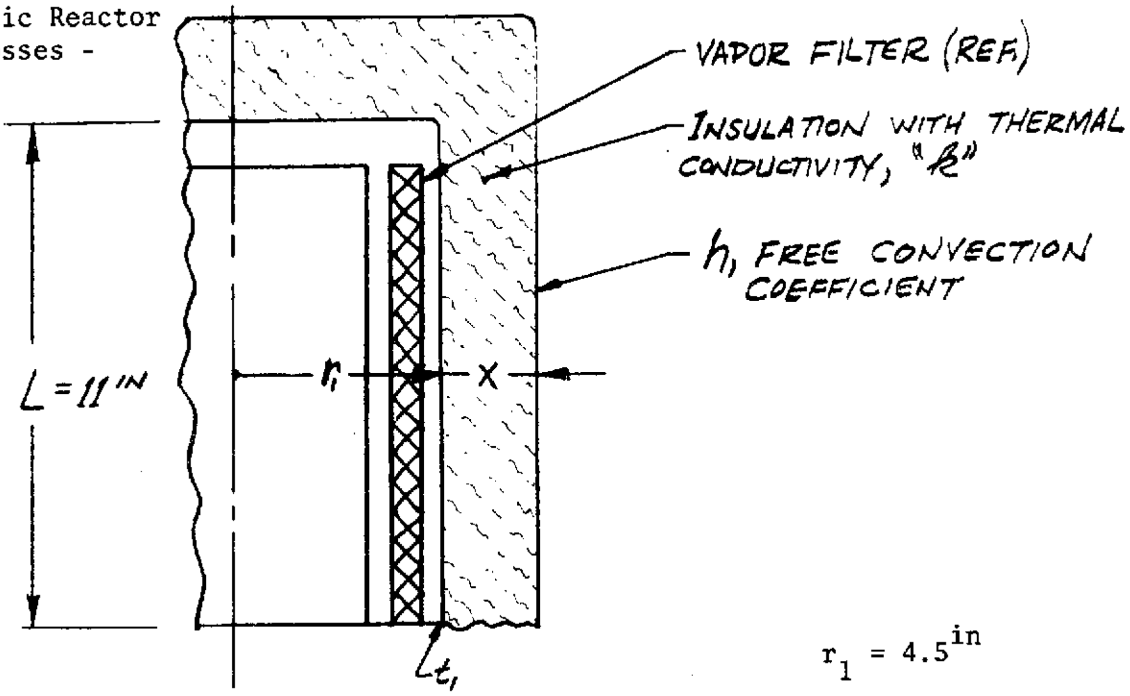
$$x = (6'' - 1'')/2 = 2.5^{\text{in}}$$

$$A = (8 \text{ fins})(10^{\text{in}} \text{ high})t$$

$$(188 \text{ BTU/hr}) = \frac{(10 \frac{\text{BTU-ft}}{\text{hr-ft}^2\text{-}^{\circ}\text{F}})(8)(10^{\text{in}})(t)(100^{\circ}\text{F})}{2.5^{\text{in}}} \times \frac{1 \text{ ft}}{12^{\text{in}}}$$

$$t = .0705$$

Catalytic Reactor Heat Losses -



$r_1 = 4.5^{in}$

$r_2 = r_1 + x$

$$\text{Heat Loss, } Q = \frac{2\pi L}{\frac{\ln {r_2}/{r_1}}{k} + \frac{1}{r_2 h}} + \frac{\pi (r_1)^2}{\frac{r_2 - r_1}{k} + \frac{1}{h}} \quad (t_i - t_{amb})$$

$t_1 = 300°F \text{ max}$

$t_{amb} = 70°F$

$k = .25 \dfrac{BTU\text{-}in}{hr\text{-}ft^2\text{-}°F}$

$h = 1 \dfrac{BTU}{hr\text{-}ft^2\text{-}°F}$

For $x = 1^{in}$, $V_2 = 4.5 + 1 = 5.5$ in

$$Q = \left[\frac{(2\pi)(11^{in})}{\frac{\ln(5.5/4.5)}{.25} + \frac{1}{(5.5)(1)}} + \frac{(\pi)(4.5^{in})^2}{\frac{1^{in}}{.25} + \frac{1}{1}}\right](300 - 70)(F \frac{BTU^{in}}{hr\text{-}ft^{2.4}}) \times \frac{1 \ ft^2}{144^{in}}$$

$$= \left[\frac{69.1}{.796 + .182} + \frac{63.7}{4 + 1}\right] \times \frac{230}{144}$$

$$= \left[\frac{69.1}{.972} + \frac{63.7}{5}\right] \times \frac{230}{144}$$

$$= (71.1 + 12.74) \frac{230}{144}$$

$$= (83.84) \frac{230}{144} \qquad = 136 \text{ BTU/hr}$$

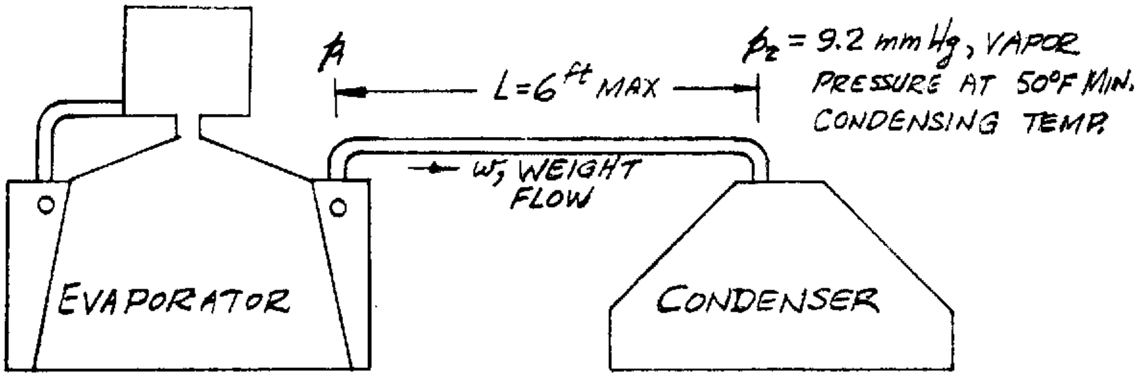
Heat losses thru insulation ≈ 40 watts

III. Vapor Line Sizing Calculations

Pressure Drop in Evaporator to Condenser Vapor Line:

Poiseuille's Equation for compressible flow

$$p_1^2 - p_2^2 = \frac{256\ \mu L\ wRT}{\pi D^4}$$



ALLOWABLE Δp = 1mm Hg
VAPOR TEMPERATURE LEAVING RECUPERATOR = 125 TO 140°F.

140 °F = 60 °C

@ 60 °C, μ = 110 micropoises

$$1\ \frac{\text{lbf-sec}}{\text{ft}^2} = 478 \text{ poises}$$

$$(110 \times 10^{-6} \text{ poises}) \times \left[\frac{1\ \frac{\text{lbf-sec}}{\text{ft}^2}}{478 \text{ poises}}\right] = .23 \times 10^{-6}\ \frac{\text{lbf-sec}}{\text{ft}^2}$$

$$p_1^2 - p_2^2 = (p_1 + p_2)(p_1 - p_2) = (10.2 + 9.2)(1) = 19.4\ \overline{\text{mmHg}}^2$$

Solve for D:

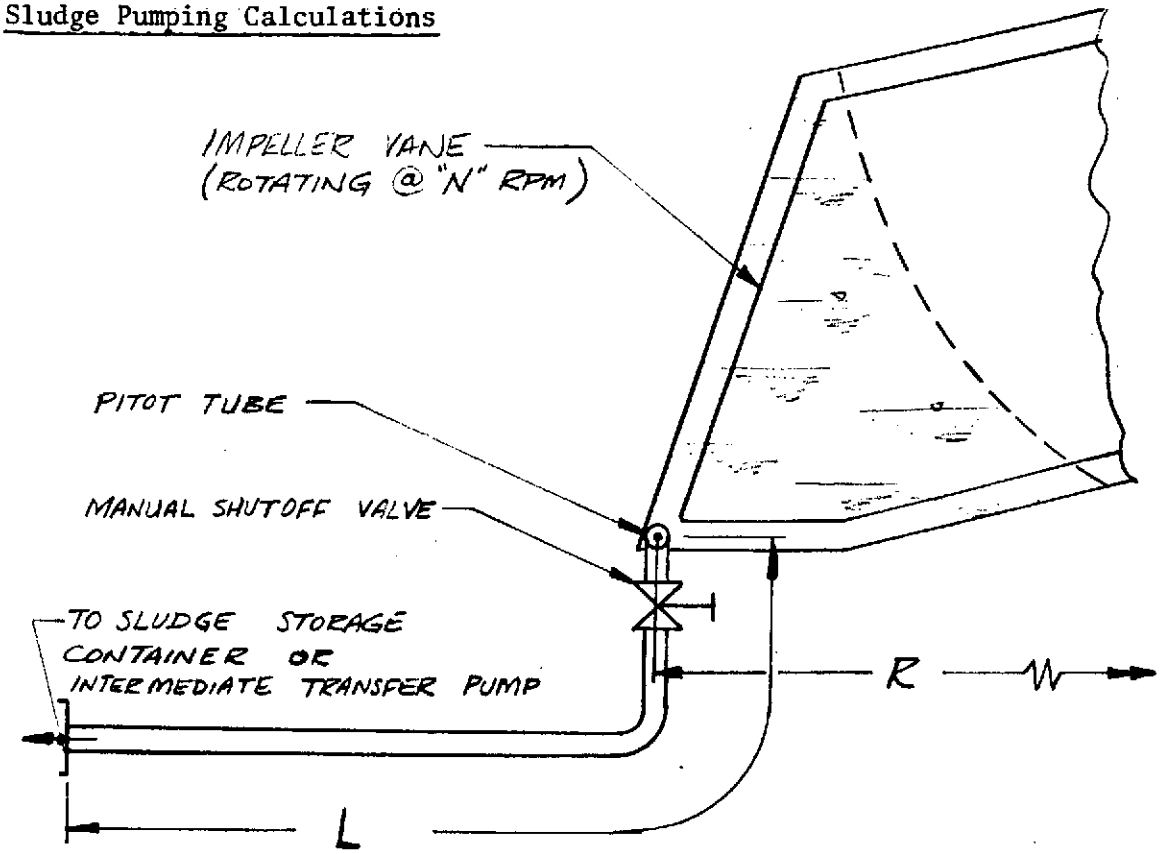
$$D^4 = \frac{256\ \mu L\ wRT}{\pi\ (p_1^{\,2} - p_2^{\,2})}$$

$$= \frac{(256)(.23 \times 10^{-6}\ \frac{\text{lbf-sec}}{\text{ft}^2})(6\ \text{ft})(85.7\ \frac{\text{ft lbf}}{\text{lbm}\ {}^\circ\text{R}})(600\ {}^\circ\text{R})(50\ \#/\text{day})}{(\pi)(19.4)(\text{mmHg})^2(\frac{1\ \text{lbf/in}^2}{51.7\ \text{mmHg}})^2 \times \frac{3600\ \text{sec}}{\text{hr}} \times \frac{24\ \text{hr}}{\text{day}}}$$

$$D^4 = \frac{(256)(.23)(10^{-6})(6)(85.7)(600)(33)(2675)}{(\pi)(19.4)(3600)(24)}$$

D = .824 (I.D.) Use 1 Nom O.D. Lines

IV. Sludge Pumping Calculations



Pressure Head Developed @ Pitot Tube

$$q = (.518 \text{ psi})(\text{Sp. Gravity})\left[\left(\frac{R}{10}\right)\left(\frac{N}{100}\right)\right]^2$$

$$q = (.518 \text{ psi})(1.184)\left[\left(\frac{12}{10}\right)\left(\frac{100}{100}\right)\right]^2 = .88 \text{ psi for fluid velocity equal to impeller velocity}$$

$R = 12^{in}$

$N = 100$ RPM

Sp.Gr. = 1.184 @ 40%

$q_{actual} = (1/2)(.88 \text{ psi}) = .44$ psi allowing for fluid slippage.

For laminar flow through pipes:

$$\overline{\Delta p} = \frac{32\ \mu L \bar{V}}{D^2} \quad \text{(Equation of Poiseuille)}$$

$$\bar{V} = Q/A; \quad A = (\pi/4)D^2$$

$$\overline{\Delta p} = \left(\frac{128}{\pi}\right)\frac{\mu L Q}{D^4}$$

Q = volume flow rate

D = I.D. of pump-out tube

L = Length of line

μ = viscosity of sludge

For 40 days of batching; 40% concentration at end of batch:

$\mu = 2.45$ centipoise

Volume of sludge = 2340 in^3

Try D = .625 in (3/4 O.D. x 1/16 wall)

$L = 10^{ft}$

$$Q = \frac{(\overline{\Delta p})(D^4)}{128\ \mu L}$$

Allowing 1/10 of available $\overline{\Delta p}$ for friction drop and 9/10 for losses in valves, elbows; $\overline{\Delta p}_{line} = .044$

$$Q = \frac{(.044 \text{ psi})(.625 \text{ in})^4}{(128)(2.45)(10 \text{ ft})} \times \frac{47{,}800}{\text{lb sec/ft}^2} \times \frac{12 \text{ in}}{\text{ft}}$$

$$= 3.86 \text{ in}^3/\text{sec}$$

Volume flow rate, $Q = \frac{\text{volume}}{\text{time}}$

or time $= \frac{\text{volume}}{Q}$

time $= \frac{2340 \text{ in}^3}{3.86 \text{ in}^3/\text{sec}}$ = 600 sec; 3/4 diameter line is ok.