AMRL-TR-67-80

VACUUM DISTILLATION, VAPOR PYROLYSIS WATER RECOVERY SYSTEM UTILIZING RADIOISOTOPES FOR THERMAL ENERGY

H. ESTEN
R. W. MURRAY
L. COOPER

GENERAL ELECTRIC COMPANY

NOVEMBER 1967

Distribution of this document is unlimited. It may be released to the Clearinghouse, Department of Commerce, for sale to the general public.

AEROSPACE MEDICAL RESEARCH LABORATORIES
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

94

NOTICES

Federal Government agencies and their contractors registered with Defense Documentation Center (DDC) should direct requests for copies of this report to:

DDC
Cameron Station
Alexandria, Virginia 22314

Non-DDC users may purchase copies of this report from:

Chief, Storage and Dissemination Section
Clearinghouse for Federal Scientific & Technical Information (CFSTI)
Sills Building
5285 Port Royal Road
Springfield, Virginia 22151

Organizations and individuals receiving reports via the Aerospace Medical Research Laboratories' automatic mailing lists should submit the addressograph plate stamp on the report envelope or refer to the code number when corresponding about change of address or cancellation.

Do not return this copy. Retain or destroy.

600 - March 1968 - CO455 - 27-593

BLANK PAGE

AMRL-TR-67-80

VACUUM DISTILLATION, VAPOR PYROLYSIS WATER RECOVERY SYSTEM UTILIZING RADIOISOTOPES FOR THERMAL ENERGY

H. ESTEN
R. W. MURRAY
L. COOPER

Distribution of this document is unlimited. It may be released to the Clearinghouse, Department of Commerce, for sale to the general public.

FOREWORD

The Vacuum Distillation-Vapor Pyrolysis Water Recovery Unit was designed, developed, fabricated and tested by the Life Support Engineering Operation, Manned Orbiting Laboratory Department, General Electric Company, Philadelphia, Pennsylvania under Air Force Contract AF 33(615)-3308.

The program was monitored by Courtney A. Metzger, Biotechnology Branch, Life Support Division, Biomedical Laboratory, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. The contract was assigned Project No. 6373, "Equipment for Life Support in Aerospace", and Task No. 637305, "Analysis and Integration of Life Support Systems."

The Atomic Energy Commission furnished the radioisotopes and facility used in testing the system. The commission also provided the technical information and design data needed for installing and using the radioisotopes. Rufus Shivers, Division of Isotopes Development, Germantown, Maryland, served as program coordinator for the AEC. Dr. Donald Kelley and Dr. Ernest Johnson, Monsanto Research Corporation, were in charge of testing conducted at the Mound Laboratories, Miamisburg, Ohio for the AEC.

The technical report has been reviewed and is approved.

Wayne H. McCandless
Technical Director
Biomedical Laboratory
Aerspace Medical Research
Laboratories

ABSTRACT

A laboratory prototype system for producing, storing and dispensing potable water derived from urine and wash water has been designed, fabricated, and tested. The design incorporated the previously established technique of vacuum distillation of liquid wastes followed by pyrolysis of the steam in the presence of a catalyst. For the first time, radioisotope heat sources (containing Plutonium 238) were employed in both the evaporator and pyrolysis sections to minimize the electrical power requirements for a potential space application. The system was also designed to utilize electrical and waste heat sources and is capable of zero gravity operation. The basic process demonstrated its feasibility for long duration operation producing high quality potable water. Peripheral equipment, such as, liquid level sensors, and phase separators need further development. Unit weight was 120 pounds and power consumption was 56 watt-hours per pound of water recovered. A flight optimized design using isotopes would weigh 58 pounds and consume 8 watt hours per pound of water recovered.

TABLE OF CONTENTS

SECTION Page

Section Page

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION I

INTRODUCTION

1. BACKGROUND

Recovery and reuse of water from urine and wash water is essential to long duration space missions. This is due to the large amount of water consumed and used by man, and the booster thrust required to launch this weight of water. For example, 6 men on a one year mission will consume nearly 7 tons of water which would require nearly 20 billion pounds of thrust to launch on a space mission. If water is used for personal hygene as is presently indicated, the requirements are even more staggering.

Systems for manned space vehicles for recovery of water from urine are judged in relation to the following characteristics.

- Purity of recovered water
- Bacterial content of recovered water
- Amount of expendables required
- Electrical power required
- Weight and volume
- Maintenance required
- Reliability

Past systems have always been deficient or excessive in one or more of the above characteristics. Earlier activities (ACEL and Hydro-John) by General Electric using vacuum distillation and vapor pyrolysis for water recovery have been successful on all counts excepting electrical power requirements which were considered to be high. The advent of radioisotope heat sources to replace electrical heaters has relieved this problem. The system described in this report is designed to use radioisotope heat sources for the distillation and pyrolysis process of water recovery; therefore, electrical power is required only for controls and phase separators.

2. DESIGN OBJECTIVES

The objective of this program was to design, develop, fabricate, and test a prototype unit which recovers potable water from urine and wash water by distillation and pyrolysis processes. The unit was designed to use electrical or radioisotope heat sources for evaporation, and pyrolysis, and in addition, the evaporator was designed to use waste heat from a liquid heat transport medium. Specific objectives follow:

- Waste input rate: 15 pounds per day
- Waste liquid: Urine and/or wash water
- Possible crew size: 2 men
- Recovery processes: Vacuum distillation and vapor pyrolysis
- Expendables: Oxygen, for the pyrolysis process, 0.1 lb/day
- Storage capability:
    - Waste liquid: 5 pounds
    - Solid Wastes: 5 pounds
    - Hot potable water $71^{\circ}C$*($160^{\circ}F$): 5 pounds
    - Cold potable water $16^{\circ}C$* ($61^{\circ}F$): 10 pounds
        - * +2, $-5^{\circ}C$
- Electrical power available: 28 VDC and 115 VAC 60 cycle
- Period of operation: 30 days (5 missions)
- Environment:
    - Gravity: Normal earth gravity and design for Zero-g
    - Temperature: $15.6^{\circ}C$ ($60^{\circ}F$) to $35^{\circ}C$ ($95^{\circ}F$)
    - Pressure: 380 to 760 mm Hg
    - Humidity: 30 to 80% (relative
    - Atmosphere: Normal earth and design for 100% oxygen
    - Acceleration: Design for 15 cps at 8 "G" in any plane
- Power Requirement: 132 watt hours per liter
- Weight requirement: 50 pounds plus phase separator, urinal, waste storage container and controls

Volume requirement:	2.5 cubic feet design goal
Water yield:	90% recovery (minimum)

Standards for the recovered water were those established as U.S. Public Health Standards (1962) for drinking water. Criteria for monitoring for potability were:

Specific Conductance	500 umhos/cm
pH	5.5 - 9.0
Color	Less than 15 chloroplatinate units
Turbidity	Less than 25 Jackson units
Taste	Acceptable
Odor	Acceptable
Bacteria	None
Organics as Measured by Chemical Oxygen Demand	Less than 100 mg/l

In demonstration of compliance with design objectives, the system was operated to recover 7 liters of potable water from urine each day for a continuous 5 day period. Performance of the system was noted and the water recovered each day was monitored against the criteria given. The water recovered on the fifth day was tested for potability in accordance with U.S. Public Health Standards (1962). In addition, the water recovered on the fifth day was analyzed for organics by the gas chromatograph method. The test data is included in Table VII. No water recovery from wash water was tested since water recovered from urine is a more severe test.

Ethylene glycol at a temperature of 13°C (55°F) was utilized as the coolant in the systems condensing element.

Teflon-insulated, color coded, stranded wire was used for all electrical wiring, including leads, where practical. Circuits were properly fused; terminal strips and boards were eliminated when not essential. All "on-off" circuits, carrying more than 1/2 ampere and switched inside the test chamber, employed hermetic switches or relays, or a relay source external to the chamber. Electrical connectors for connecting the unit to the electrical system of the test chamber conformed to MIL-C-5015D, class R. All electrical parts have a minimum 5000 hour design life.

SECTION II
SYSTEM DESIGN

1. DESCRIPTION

The system is divided into three main subsystems; namely collection, processing, and storage. (See Figures 1 thru 5.) The collection subsystem consists of a urinal, phase separator, waste liquid storage reservoir, blower, air filter and controls.

The user micturates into the urinal after starting the phase separator and blower. The urinal has an adjustable orifice which provides a positive and gentle seal. The urine is conveyed (for zero-gravity operation) by a stream of cabin air which enters through the urinal. The urine-air mixture enters the phase separator where the air is centrifugally separated and is drawn through the blower, bacteria filter and charcoal, and is vented to the cabin. The urine is pumped to a storage reservoir from which it is metered into the processing subsystem .

The processing subsystem consists of an evaporator, pyrolysis unit, condenser, condenser water pump, solids storage reservoir and controls. The waste liquid is metered into the evaporator by a solenoid valve controlled by a liquid level sensor in the evaporator. The liquid is heated to 48.9°C (120°F) by 210 watts of either radioisotopic heat, electrical heat or waste heat and boils at the reduced pressure of approximately 87.5 mm Hg. (1.7 psia). The vapor is passed through a static phase separator or a centrifugal phase separator driven by the steam passing through an elemental turbine. The phase separator assures that liquid is not carried with the vapor flow. The vapor then passes through the pyrolysis unit where it is heated to 650°C (1200°F) in the presence of a catalyst. The heat is supplied by either a radioisotopic or an electrical heater with an output of 70 watts. The impurities in the water vapor are catalytically reduced or oxidized in the pyrolysis unit and are removed via the vacuum vent in the condenser as the water vapors are liquidified.

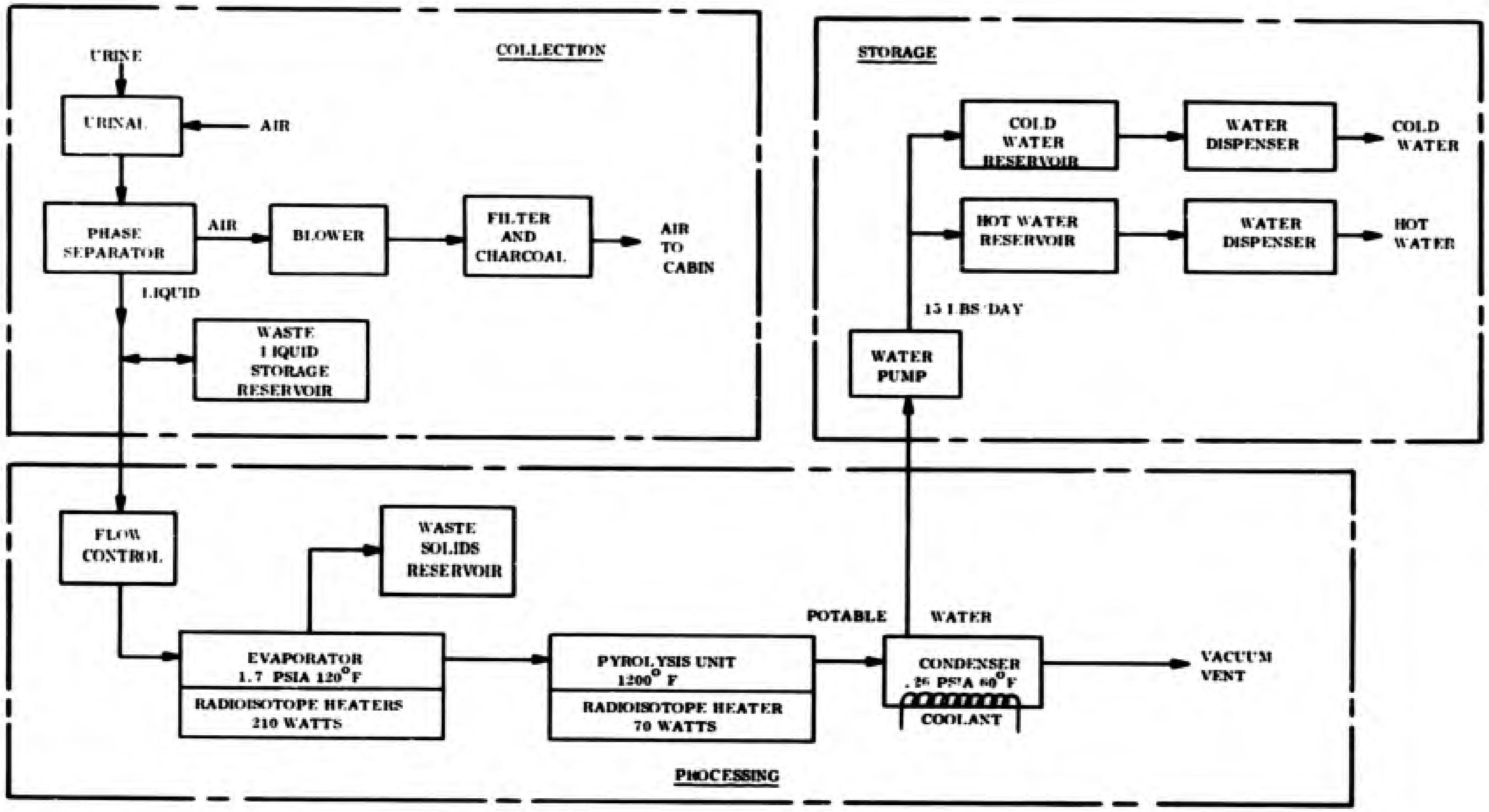


Figure 1. Vacuum Distillation - Vapor Pyrolysis Water Recovery Unit (Schematic)

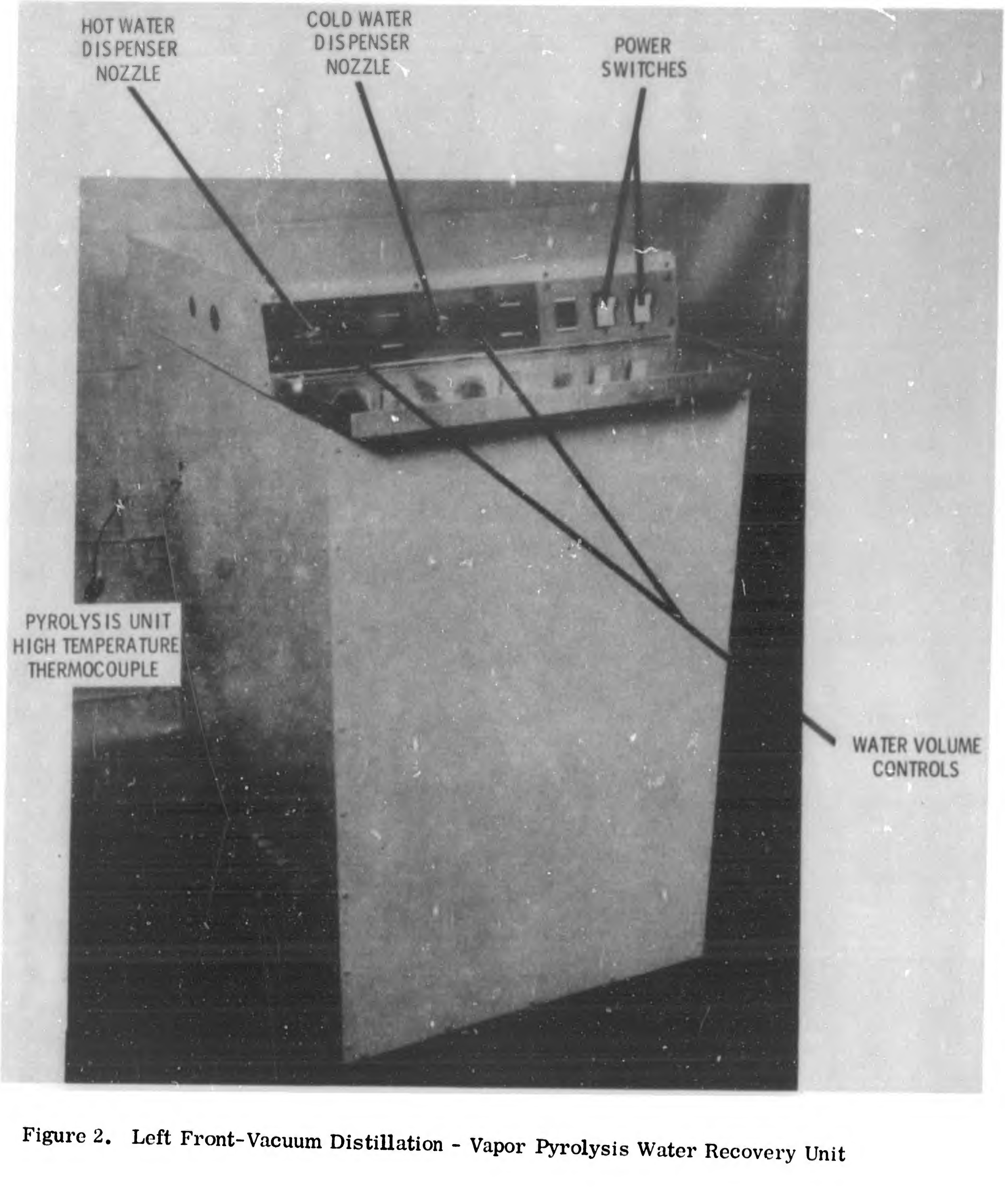


Figure 2. Left Front-Vacuum Distillation - Vapor Pyrolysis Water Recovery Unit

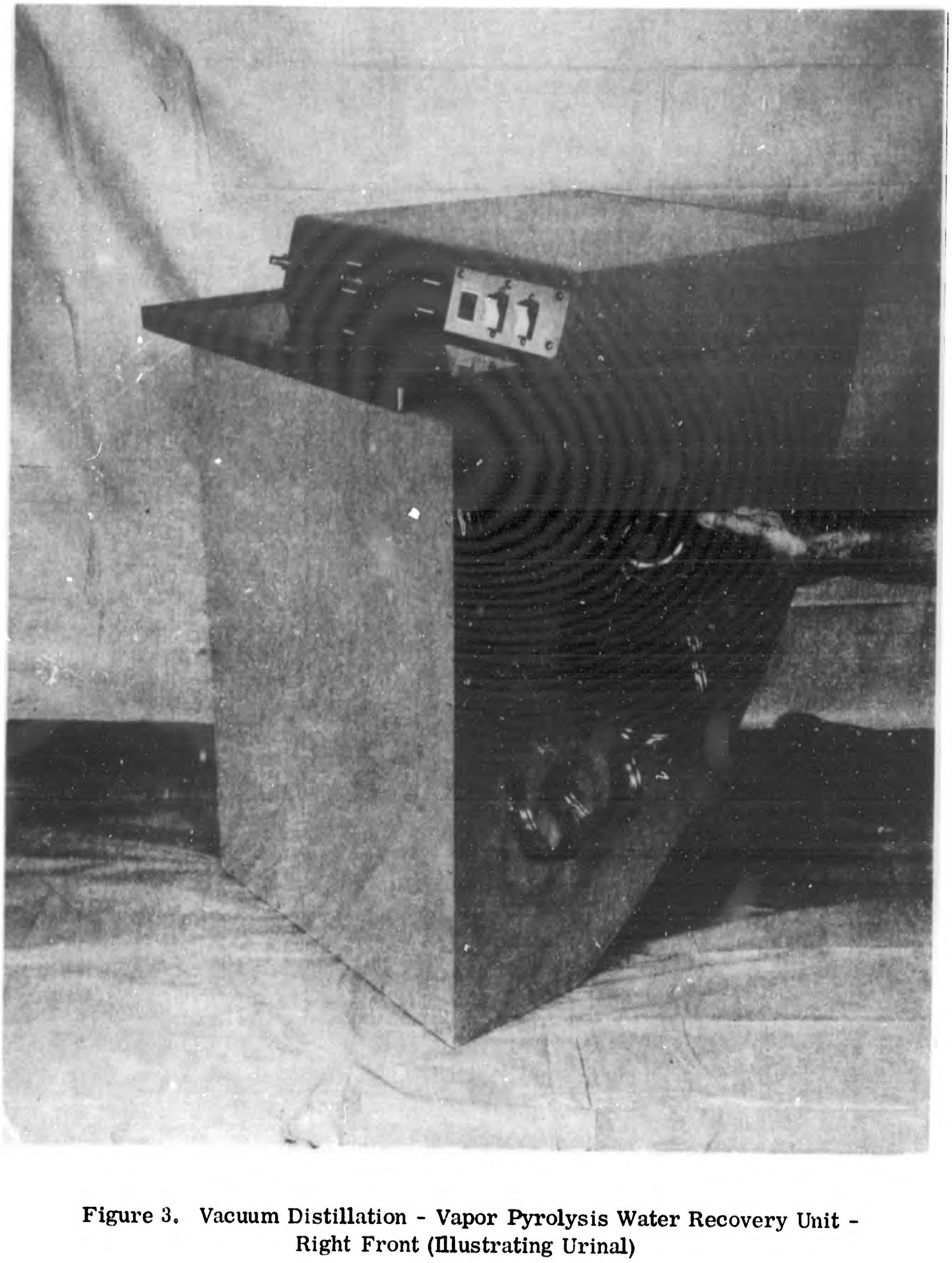


Figure 3. Vacuum Distillation - Vapor Pyrolysis Water Recovery Unit - Right Front (Illustrating Urinal)

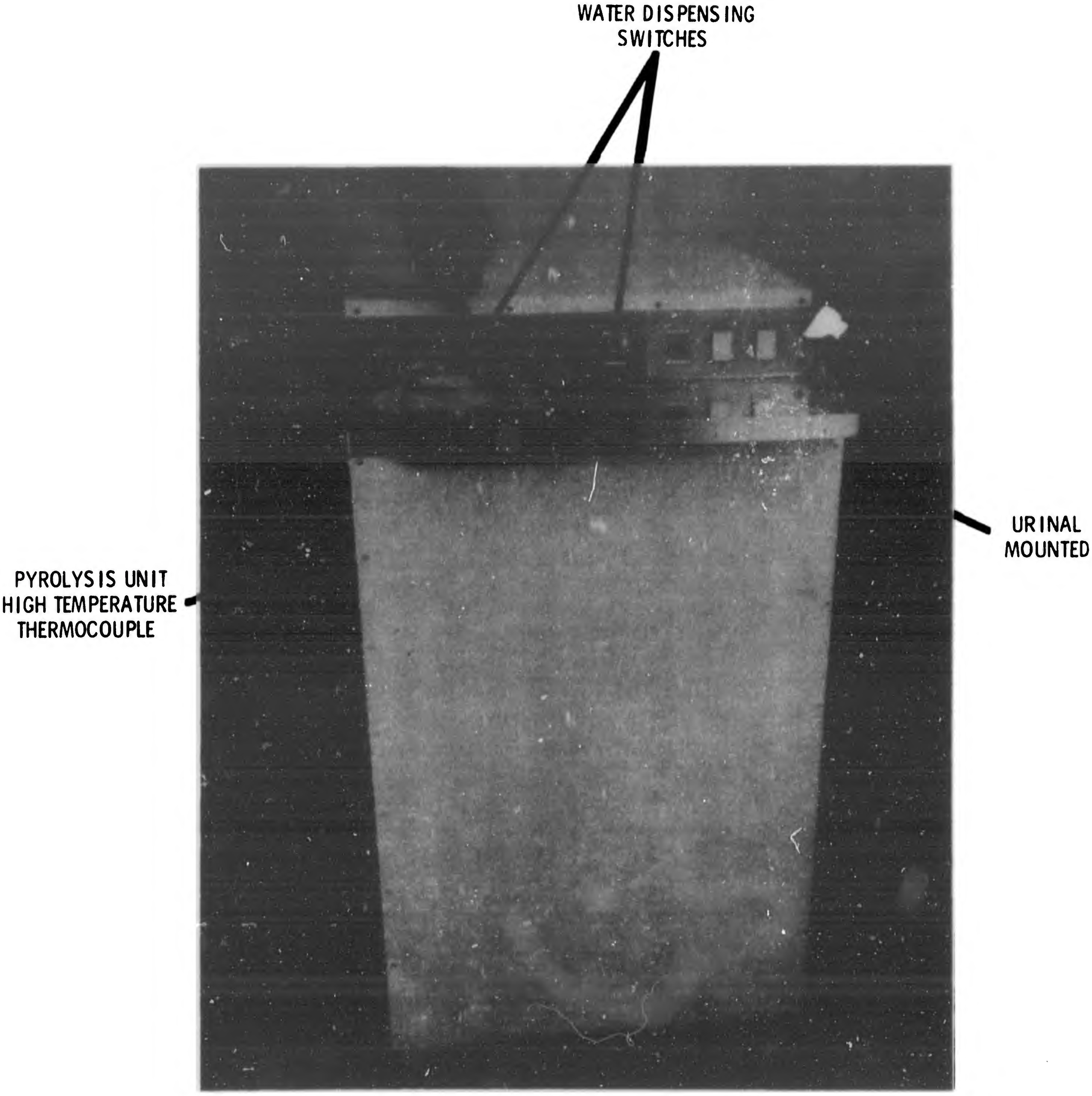


Figure 4. Vacuum Distillation - Vapor Pyrolysis Recovery Unit
(Front, illustrating hot water addition to food)

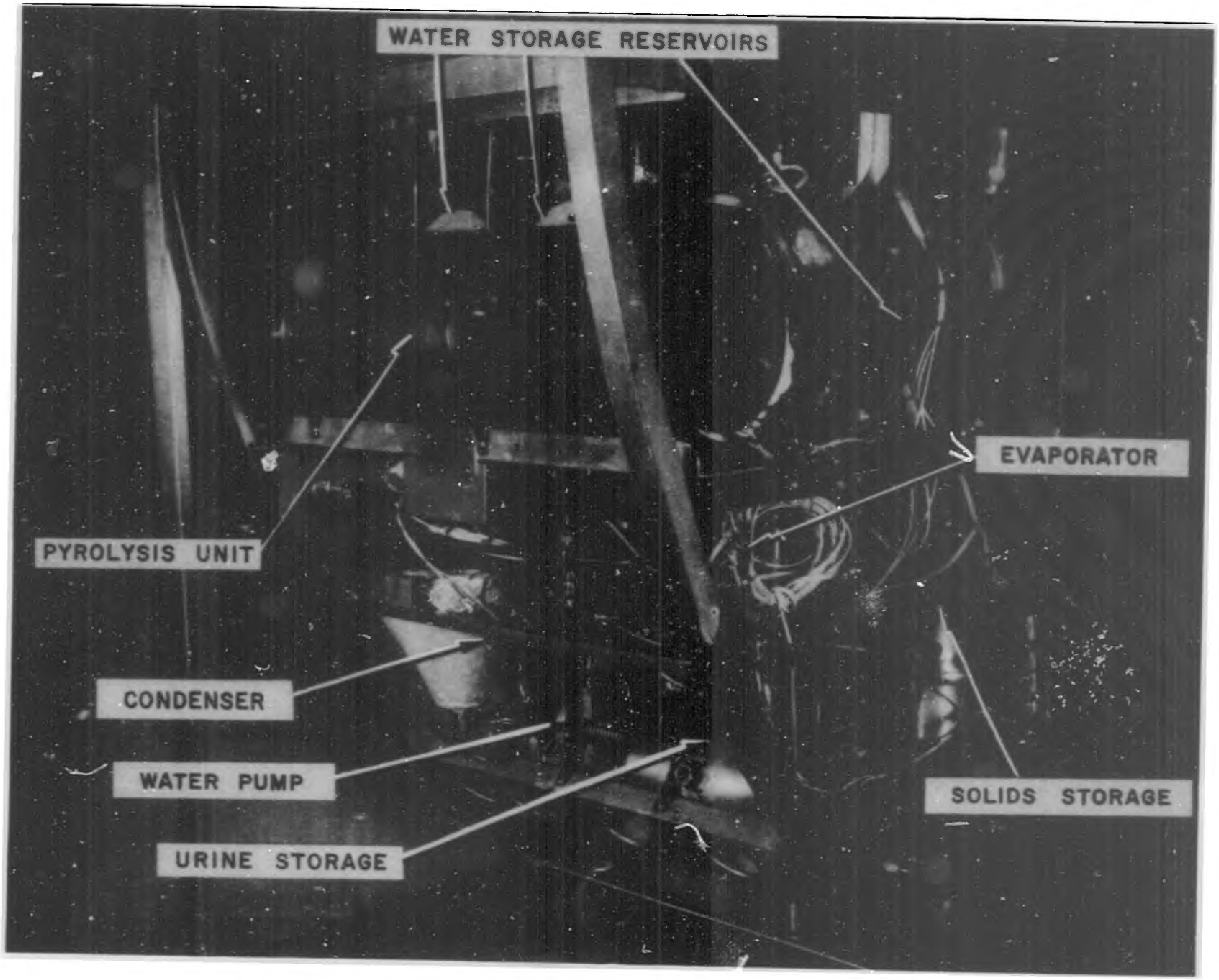


Figure 5. Vacuum Distillation Vapor Pyrolysis Recovery Unit
(Left rear, with skin and counter removed)

Also, any microorganisms in the vapor stream are incinerated, thus providing a sterile vapor. The vapor is condensed at approximately 15.6 C (60 F) which establishes vapor pressure of approximately 13.2 mm Hg. (0.26 psia). The vapor pressure differential between the evaporator and condenser is the driving force which causes the vapor to flow through the system.

The water pump is activated by a water level control in the condenser or a timed cycle. The positive displacement piston pump is pneumatically powered from a regulated 90 psig oxygen source. The oxygen is vented to the cabin after it is used to activate the pump; thus, it is consumed by the crew and not wasted.

The urine input into the evaporator contains approximately 5% solids which are separated from the liquid (vapor) by the distillation process. The solids are then centrifugally conveyed to the storage reservoir by the evaporator impeller.

The storage subsystem consists of hot and cold water reservoirs, water dispensers and controls. The water is pumped through check valves into storage reservoirs pressurized at 23.5 psig. The hot water reservoir check valve has a differential cracking pressure of 0.5 psi and the cold water reservoir check valve has a differential cracking pressure of 4.0 psi; therefore, the hot reservoir must be full before the cold reservoir will fill. This assures an ample supply of hot water. The hot water reservoir is heated by the steam from the pyrolysis unit or by electrical heaters and the cold water reservoir and condenser are cooled by a liquid coolant. The water is dispensed in calibrated amounts as required. This is accomplished by a variable time control which holds the water dispenser solenoid valve open until a calibrated amount of water is dispensed. For example, if 5 ounces of hot water is required to reconstitute a dried food, the user sets the selector switch to 5, attaches his food bag to the hot water dispenser and presses the hot water switch.

2. THERMODYNAMIC CYCLE

The thermodynamic cycle of the water recovery process is illustrated by Figure 6. Urine is transported from the storage vessel and a state point of 21.1°C (70°F), 760 mm Hg (14.7 psia), or lower, to the evaporator which effects boiling at 48.9°C (120°F) and 87.5 mn Hg (1.7 psia). The state points in the figures are 1 for the storage condition, 2 after the urine enters the evaporator, and 3 for the urine vapor leaving the evaporator. The steam entering the pyrolysis unit passes through a counter-flow heat exchanger which heats the vapor to the state point 4. After leaving the counter-flow exchanger the steam is further heated by electrical or radioisotope heaters to the condition 5 (with simultaneous and subsequent exposure to the ammonia decomposition catalyst). The steam then flows back through the counter-flow exchanger, giving up heat to the incoming steam, exiting the pyrolysis unit at the state point 6. Following pyrolysis, the steam is cooled and condensed. Partial cooling may be effected in the hot water tank's jacket bringing the steam to the state point 7', with the subsequent cooling in the condenser bringing the steam to the state point 7, 15.6°C (60°F), 13.2 mm Hg (0.26 psia) or (when the hot water is sufficiently hot) all of the cooling may be effected in the condenser. Following condensation, the recovered water is pumped to 12.13 mm Hg (23.5 psia) and stored in the hot and cold water tanks until dispensed upon demand.

3. MAJOR COMPONENTS

a. Urinal

The urinal (Figure 7) incorporates an adjustable orifice for effecting a positive gentle seal upon the user. Bleed orifices in the urinal housing permit induced air from the cabin to transport the urine down a three foot flexible tube to the phase separator.

Figure 8 depicts the entrainment air pressure drop required for transporting the maximum design urine flow rate of 50 cc/sec through a three foot tube, as a function of the amount of entrained air. Accordingly, with the 1/2 inch tubing connecting the urinal and phase separator, the head required shall be 3 inches of water with the maximum anticipated urine flow rate of 50 cc/sec.

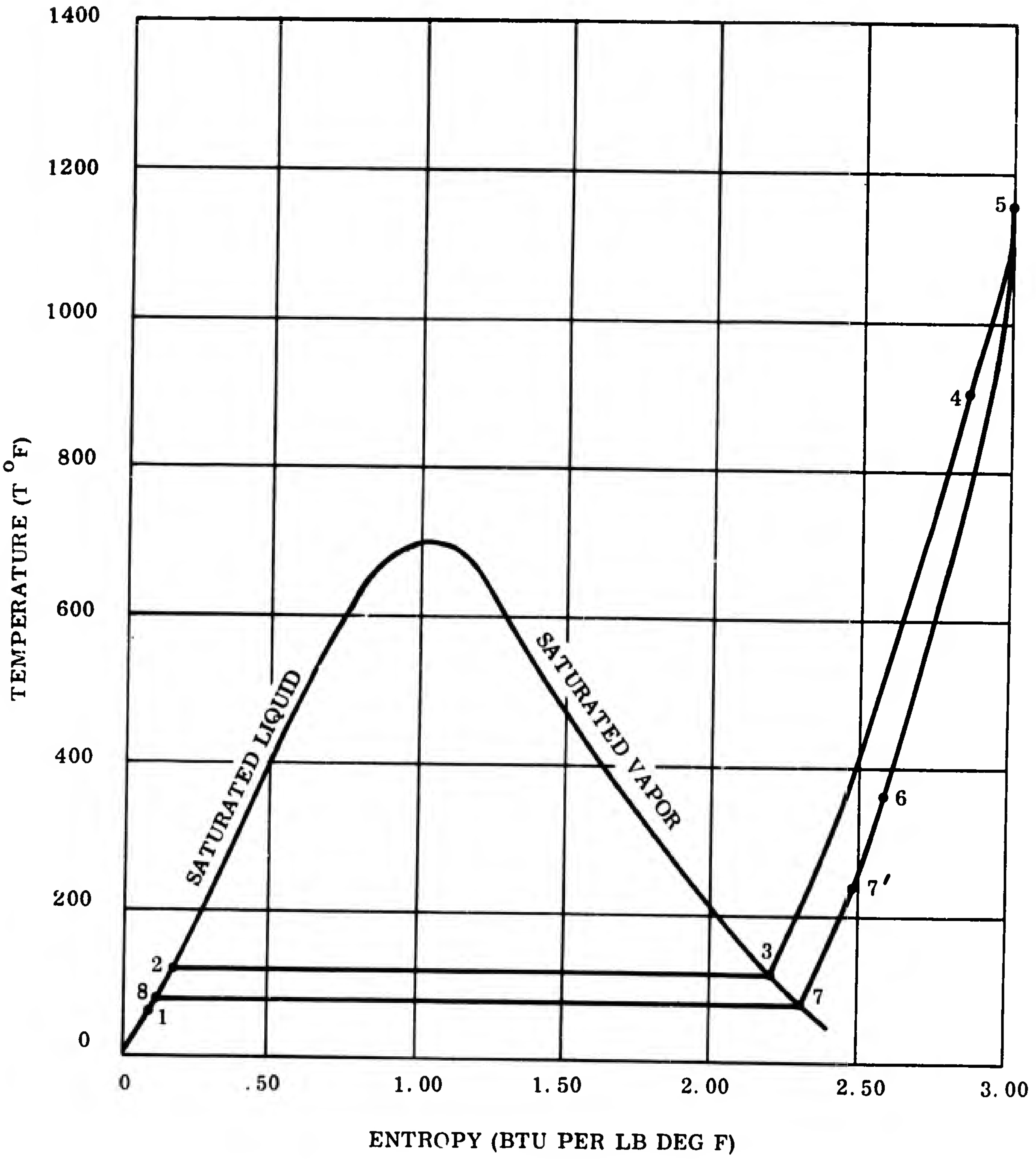


Figure 6. Thermodynamic Cycle of Water Vapor

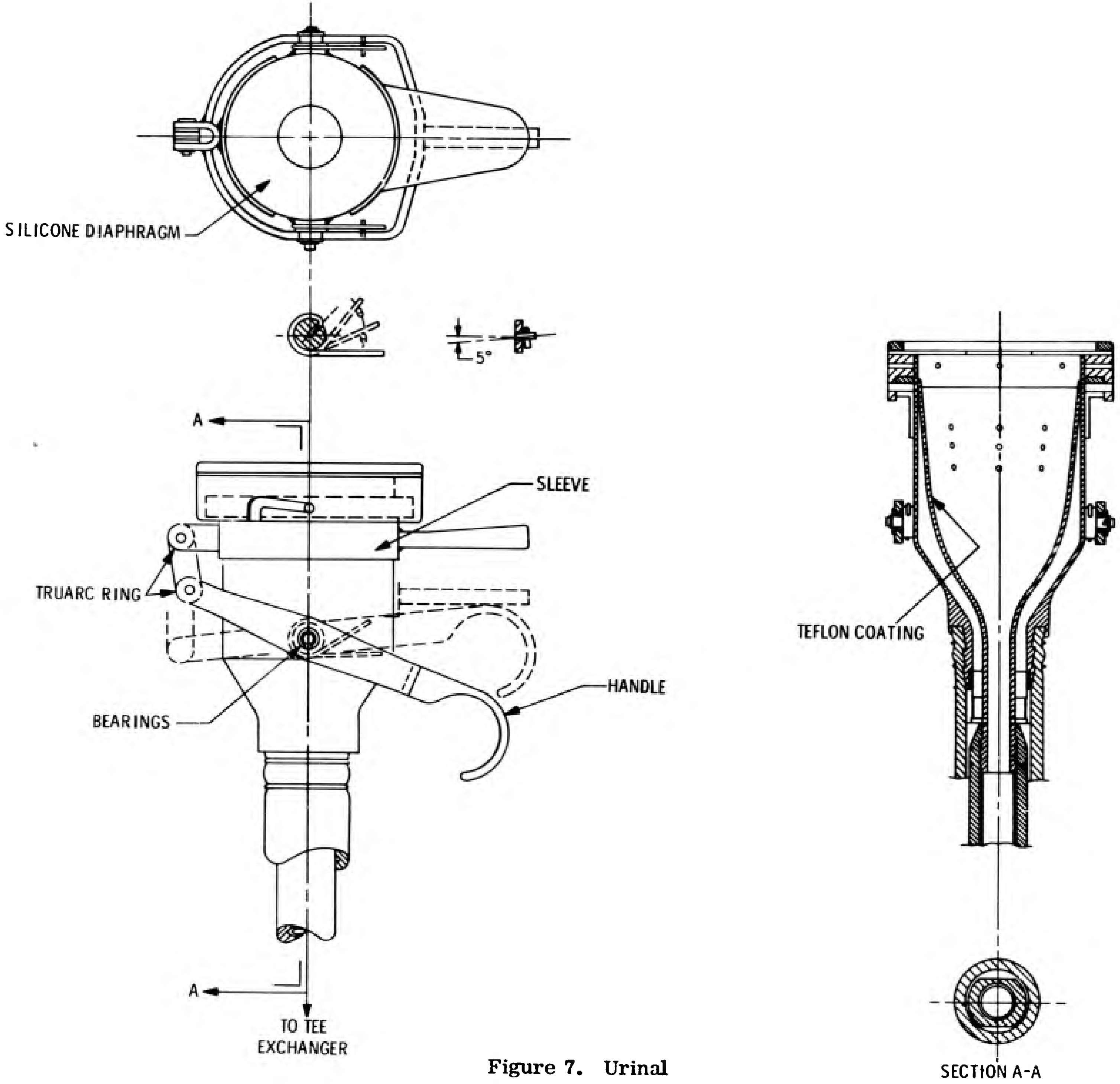


Figure 7. Urinal

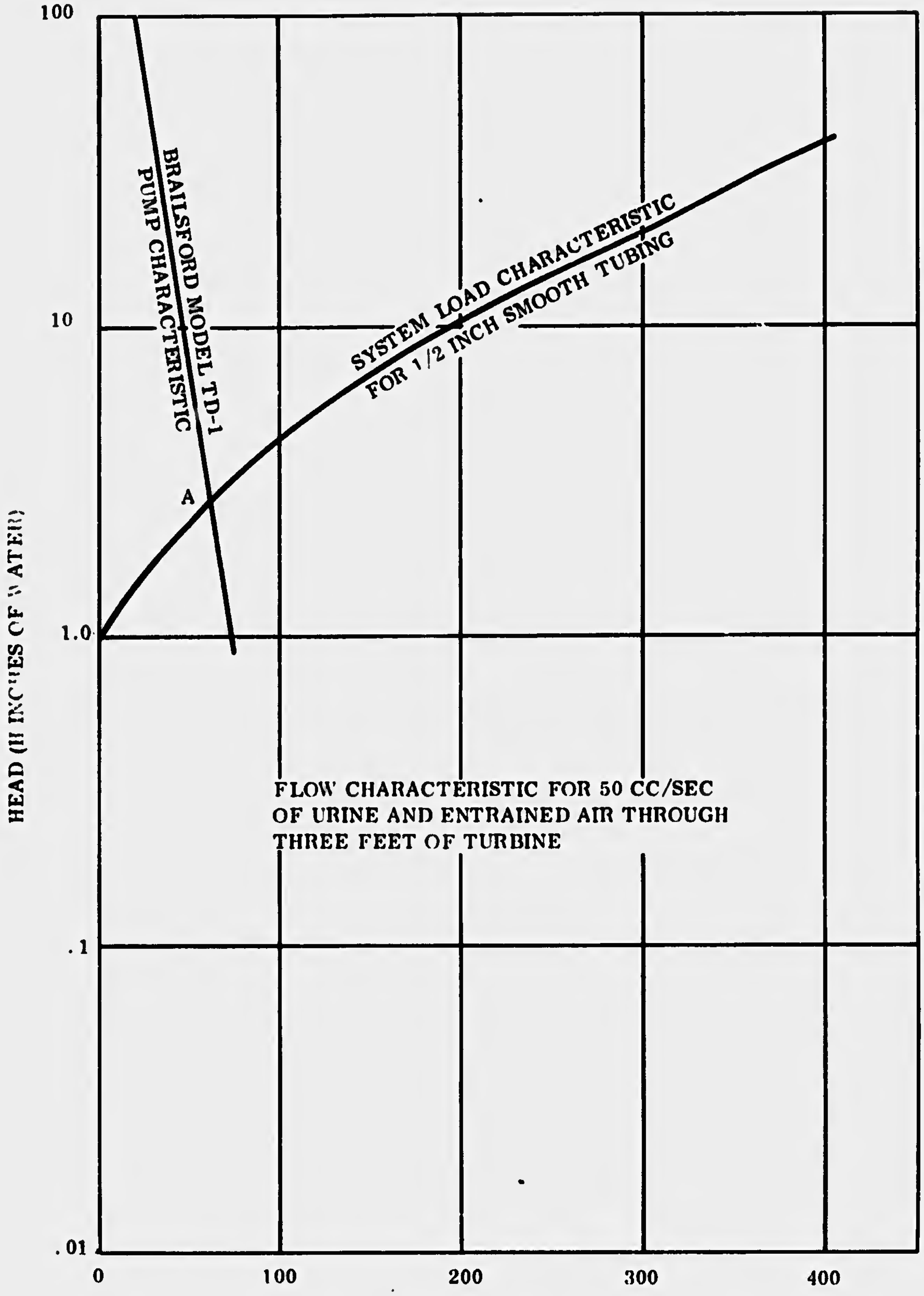


Figure 8. Flow Characteristics of Urine and Transport Air

A reduced liquid flow rate will simply reduce the required head of the two phase mixture.

b. Urine Transport

In the urinal, urine is entrained in air to effect its transport to the phase separator. The blower draws air from the phase separator and discharges it to the cabin through a filter. The filter incorporates bacterial and charcoal elements for removal of both bacteria and odor from the circulated air.

At the maximum air flow capable of being produced by the blower, the filter's pressure drop is less than 0.1 inches of water. With 50 cc/sec of urine flow (a reasonable maximum rate) in conjunction with 3 feet of 1/2 inch ID tubing, the head requirements for the urine entrainment are shown by Figure 8. Accordingly, the operating point for the system is the intersection of the system and pump's characteristic, point "A".

c. Phase Separator

The phase separator (Figure 9) consists of a bladed rotor and its stationary housing. The housing incorporates an inlet for the two-phase flow, an axial centrally located outlet for air and a peripheral outlet for the inertially separated liquid flow.

The phase separator rotor is driven by a toothed, timing belt at 1100 rpm from a 1725 rpm, 115 volt 60 cps induction motor. Operation is initiated by a relay controlled by a switch at the urinal's mounting. Accordingly, removal of the urinal from its mounting and activation of a switch, energizes relays bringing power to the separator motor and air blower motor. Operation is continued for 3 seconds after the urinal is remounted and switch is deactivated by time delay relay circuit which enables the phase separator to pump itself dry.

d. Waste Storage

The liquid from the phase separator is pumped through a solenoid valve into the waste storage reservoir (See Figure 10). The in line solenoid valve is energized from the same 115 volt source as the separator motor, ensuring the discharge line's being open when separation and pumping are required.

The stored fluid is contained within the bladder of the vented tank to prevent corrosion and to provide zero gravity storage capability.

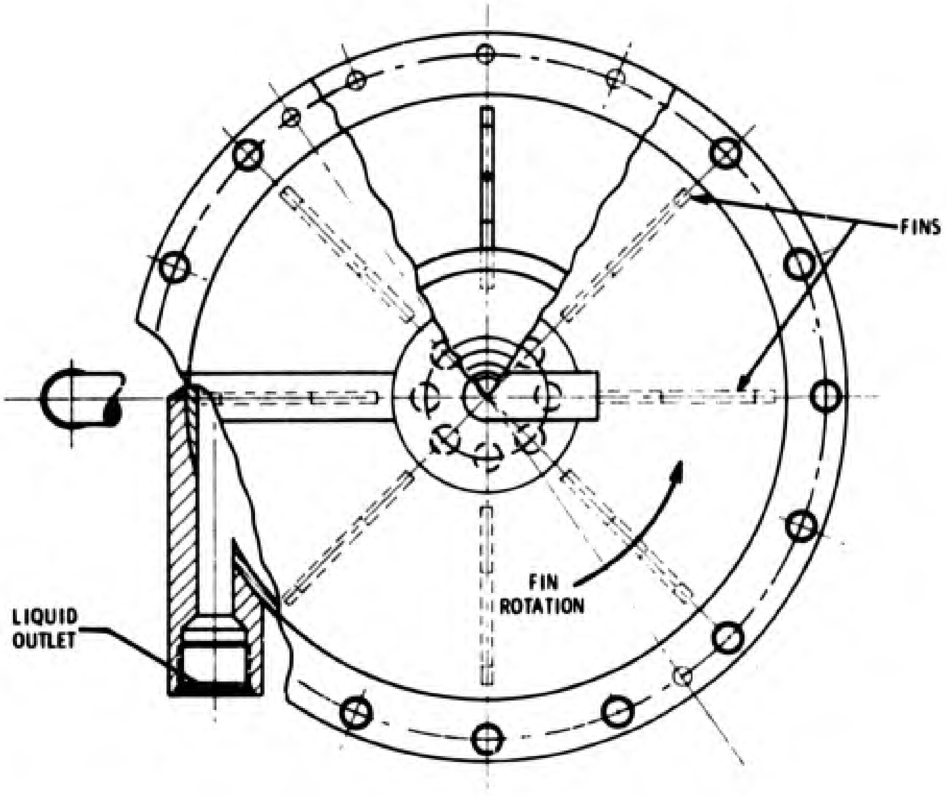


Figure 9. Urine Phase Separator

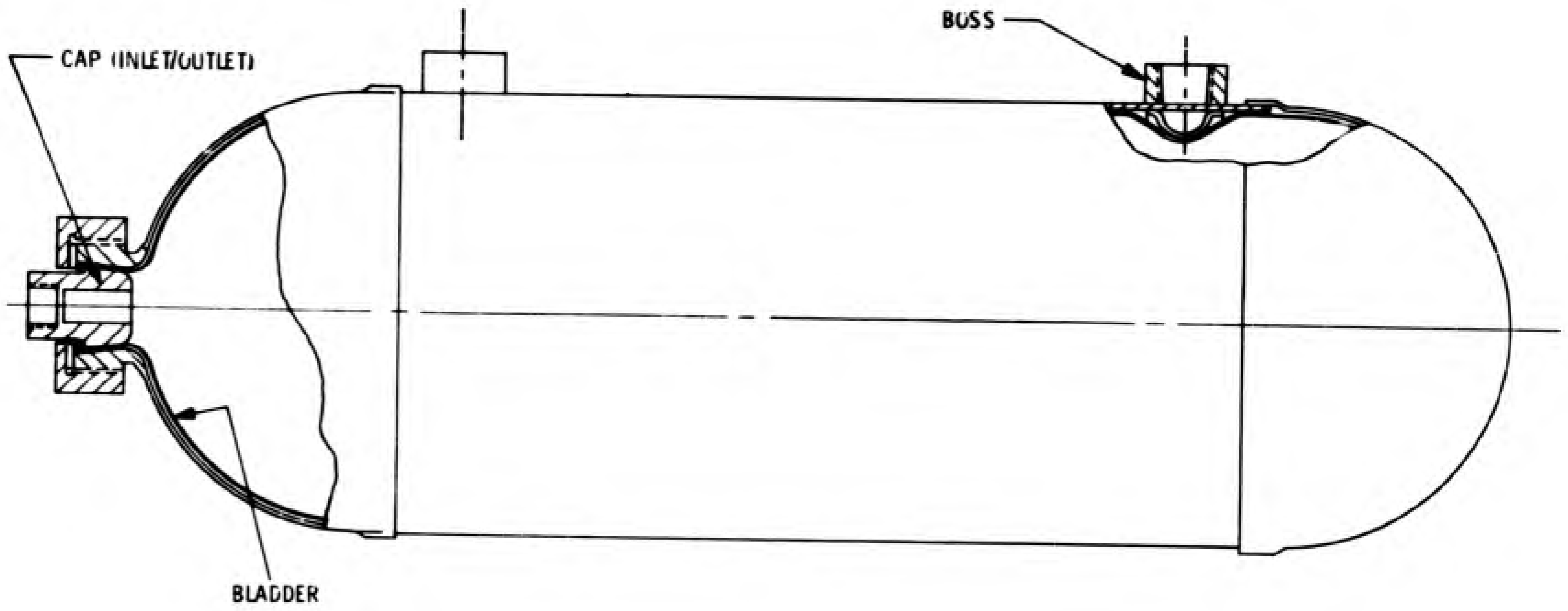


Figure 10. Waste Storage Reservoir

e. Evaporator

The urine evaporator (Figure 11 and 12) is a vessel containing ports for the admission of urine and discharge of steam and urine solids. Heat is provided by electrical heaters, a liquid waste heat exchanger or radioisotope heaters, with each heat source integral with its own heat exchanger. A bladed impeller, driven at 60 rpm by the evaporator motor and gear box, provides the gravitational field necessary to permit nucleate boiling. A "Quad-Ring" shaft seal is utilized.

f. Evaporator Phase Separator

The initial evaporator phase separator consists of a closed slinger similar to that of a conventional centrifugal pump's impeller, driven at high speed. Steam passed through the phase separator radially inwards to the eye, then through the hollow shaft to the upper section of the evaporator. Liquid carried with the steam, is separated from the steam by the phase separator's centrifugal action and returned to the evaporator. (See Figures 11 and 12.)

The slinger utilized a turbine drive whereby the steam flowing through the phase separator's hollow shaft passed through a pinwheel reaction turbine (See Appendix I for design criteria). Difficulties were encountered in holding the extremely close tolerances necessary to the impeller-turbine bearings. Accordingly, the active separator has been replaced with a passive one whereby stainless steel mesh is directly heated by the heat exchangers and completely fills the void volume of the evaporator. This ensures against carry-over of liquid with steam by providing a slight superheat to the vapor before it exits the evaporator.

g. Solids Removal

The initial solids removal design used a solids pump which admitted a slurry of urine and urine solids to a cam actuated pump.(See Figure 13.) With rotation of the pump, the piston advanced from bottom dead center towards top dead center, first squeezing the slurry and permitting liquid to permeate through a porous plug in the piston head and get behind the piston, simultaneously trapping the solids ahead of the piston. Further rotation exposed the trapped solids ahead of the piston to a discharge port, enabling them to be pumped to the solids storage reservoir. Rotation past the discharge port then results in retraction of the piston and back-flushing the fluid through the plug and the start of the next pumping cycle.

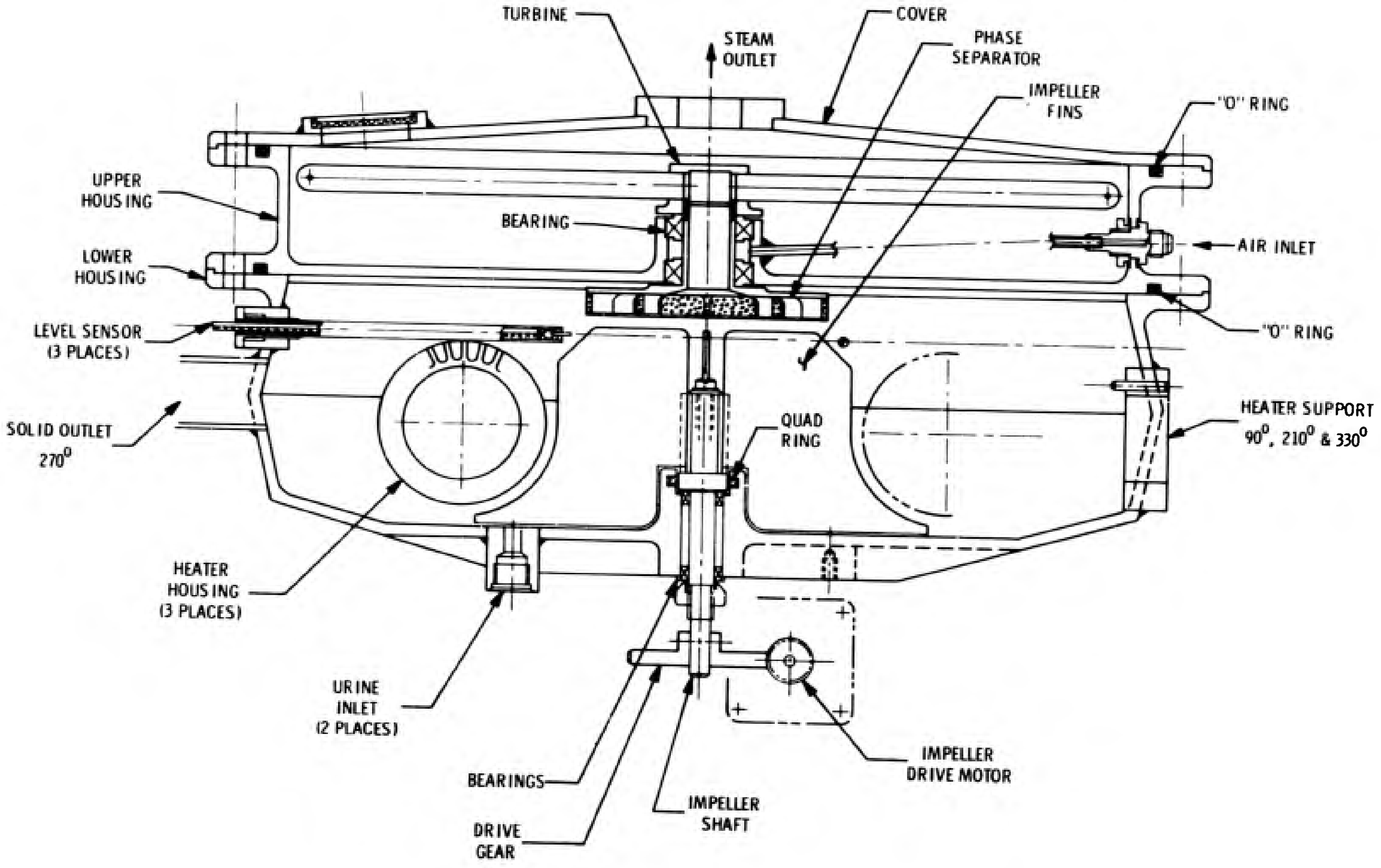
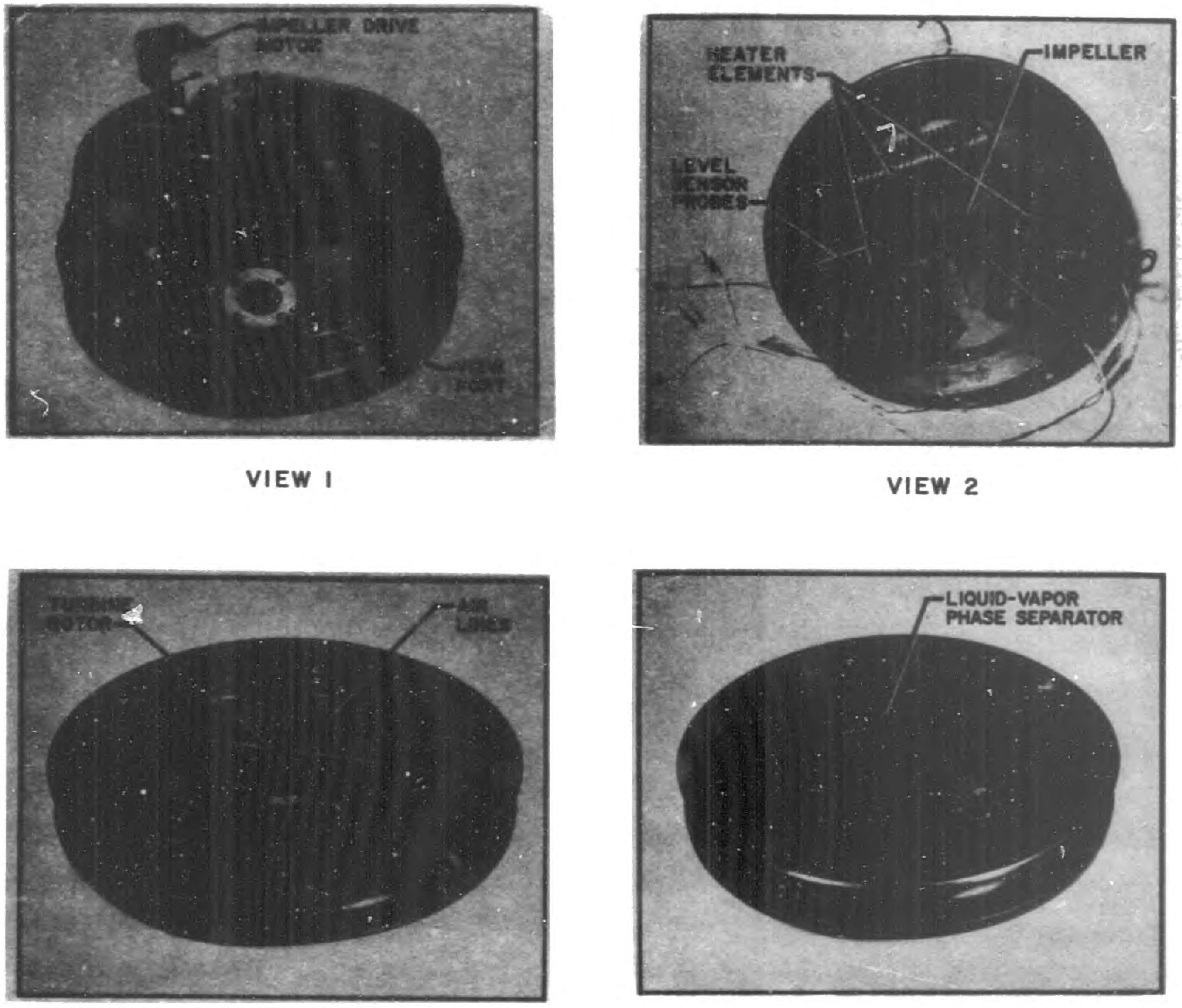


Figure 11. Evaporator Assembly



VIEW 1

VIEW 2

VIEW 3

VIEW 4

Figure 12. Evaporation Unit

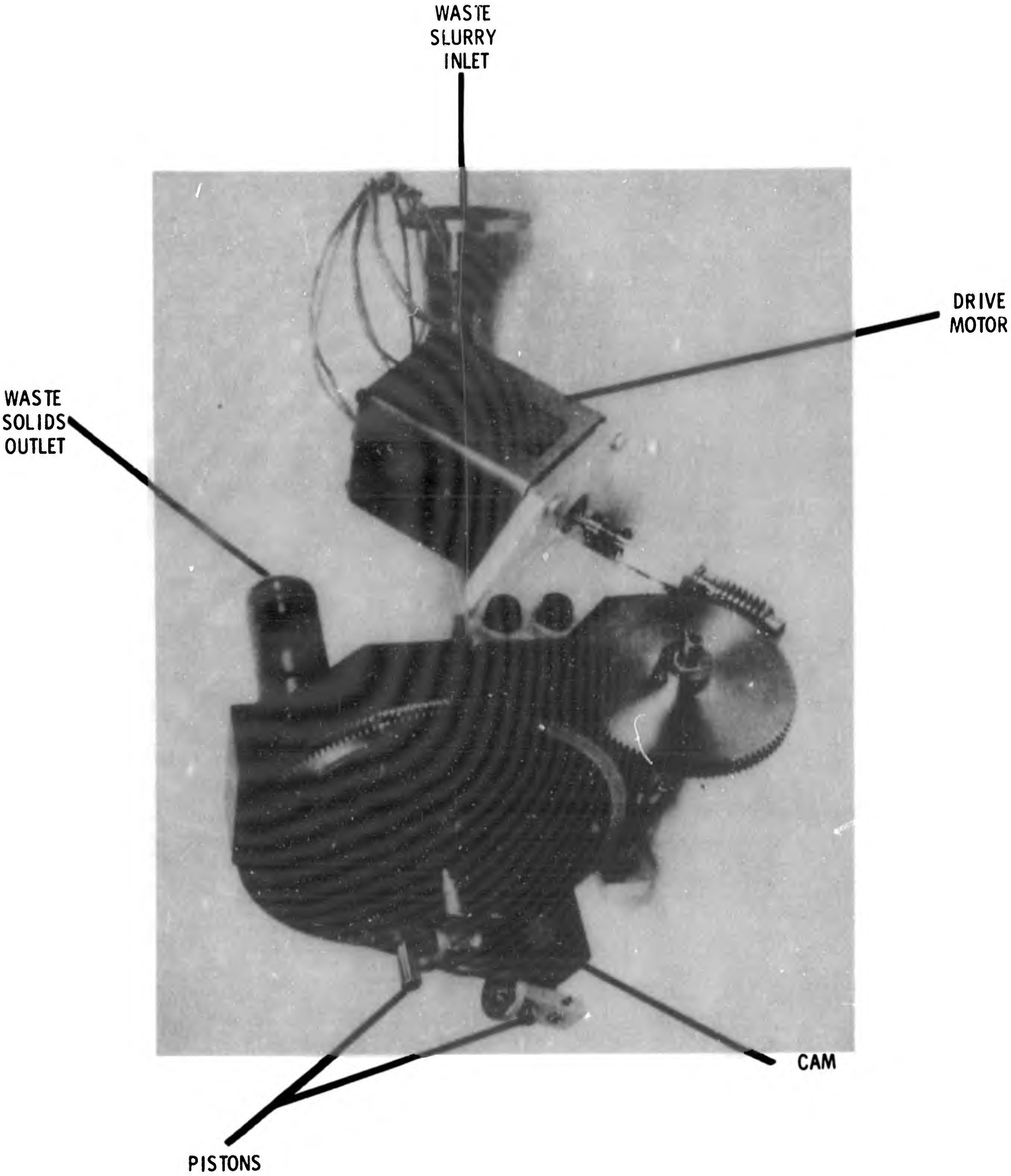


Figure 13. Solids Pump

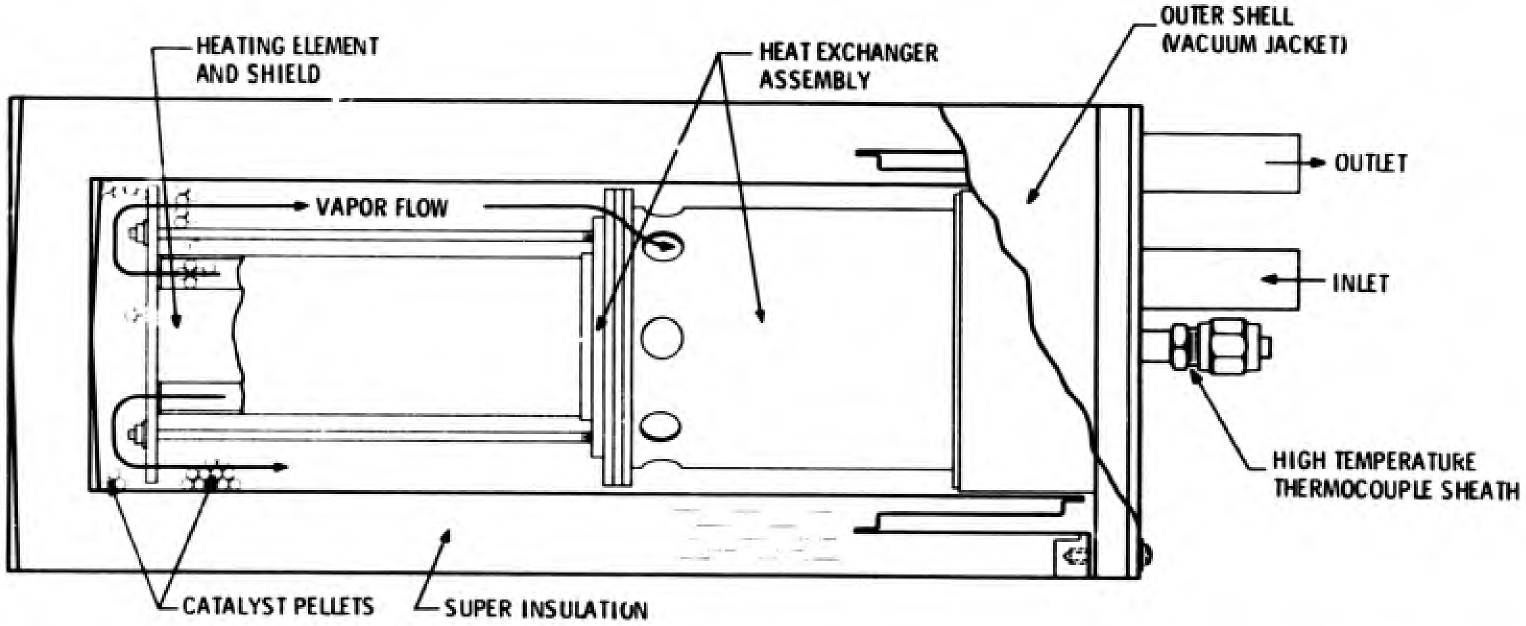


Figure 14. Pyrolysis Unit Assembly

Wear resulting from unanticipated, extremely abrasive action of the solids in the urine indicated the necessity for a different mechanism of solids separation. Accordingly, the port which previously led to the solids pump was directly connected to the solids reservoir, separation being effected inertially, utilizing the centrifugal field established by the evaporator rotor. Accordingly, separation was accomplished without the need for the separate solids pump, with the slight penalty of reduced recovery of liquid.

The solids storage vessel's design is identical with that of the liquid waste storage - Figure 10. As with the liquid storage, the waste is contained within the bladder to eliminate tank corrosion. However, since no pressure difference can be sustained across the bladder, a vacuum is drawn at the tank at one of its diametrical fittings.

h. Pyrolysis Unit

The pyrolysis unit (Figure 14 and 15) consists of a counter-flow heat exchanger, a heat source (either electrical or radioisotope), catalyst and an evacuated insulation jacket. Steam entering the pyrolysis unit initially flows through the tubes of the counter flow exchanger and is preheated by the earlier steam flow leaving the exchanger and pyrolysis unit. See Appendixes II, III and IV.

Exiting from the exchanger, the steam flows through a tube containing the centrally located heater surrounded by catalyst, the latter performing the additional function of assisting the heat transfer to the steam. Upon leaving the heater, the steam enters the catalyst bed completely surrounding the heater tube, turns and flows back through the catalyst bed to the counter-flow exchanger and out, giving up some of its heat to the incoming steam.

The super-insulation contained within this jacket was developed by General Electric's Space Power and Propulsion Section - Missile and Space Division. It consists of 37 consecutive layers of 3 mil NiChrome foil separated by NiChrome wire spacers.

i. Condenser

The condenser Figure 16, functions with a coolant supplied at 50^{o}F to 60^{o}F. Continuous venting of the non-condensibles is provided by a line 0.010 inches outside diameter. Accordingly, with a water vapor partial pressure of 0.26 psia (60^{o}F), the specific weight of the non-condensibles is 0.00109 lb/ft^3 and the amount of water lost daily is only 0.0162 lbs. See Appendix V.

The heat required daily to the condenser vent line to prevent freeze-up of the vapor in the lines is only 0.6 Btu. Accordingly, this has been considered as being provided by the heat transferred from the ambient to the vent line.

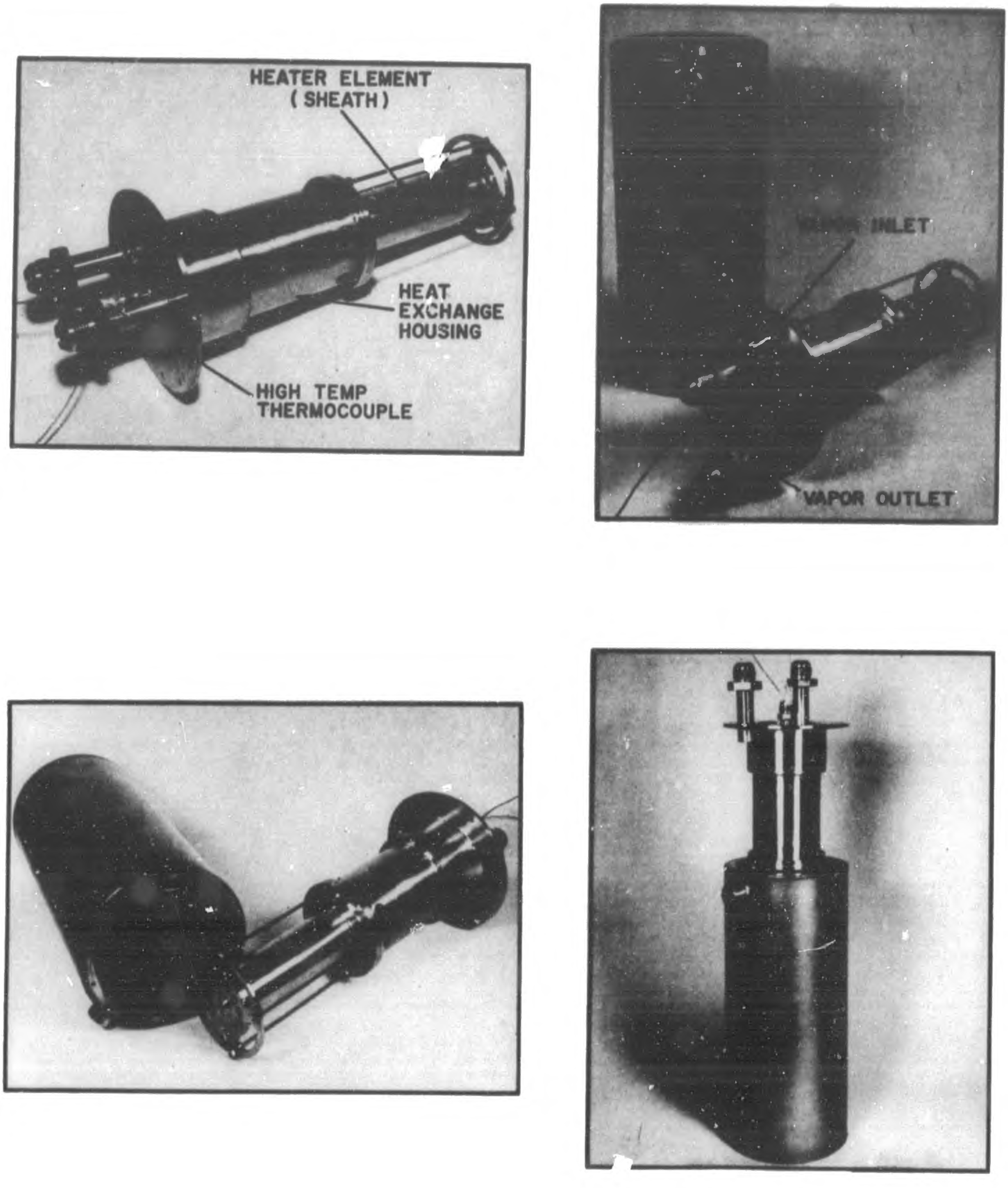


Figure 15. Pyrolysis Unit (Partially Assembled)

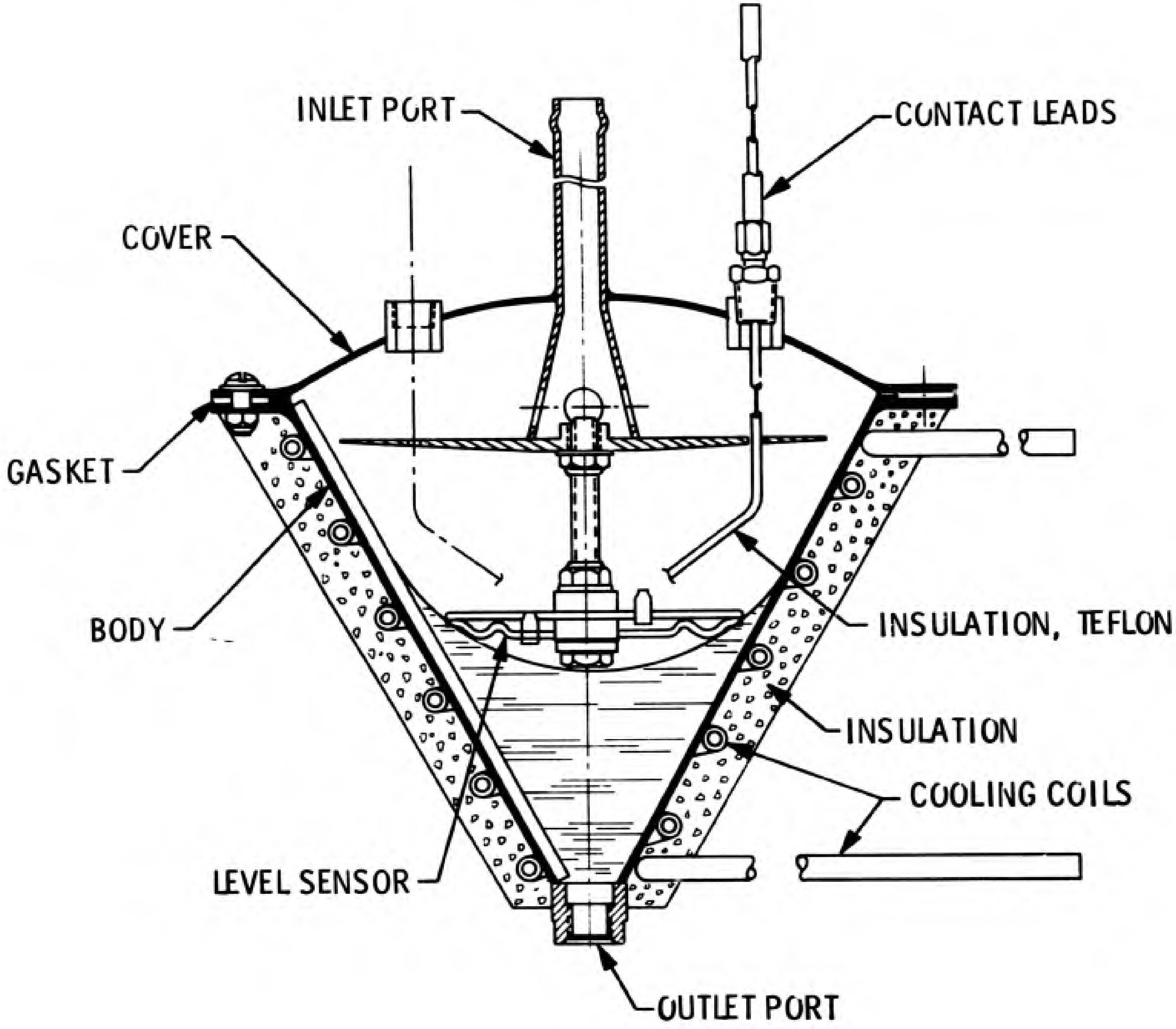


Figure 16. Condenser Assembly

j. Water Pump

The water pump Figure 17, is a positive displacement piston pump utilizing reed valves for inlet and outlet check valves. The pump is operated by 90 psi regulated oxygen pressure which is admitted to the back-side of the piston. This drives the piston to top head center discharging water through a check valve. The oxygen behind the piston is continuously vented. Shut-off of the O_2 solenoid valve permits the oxygen to bleed off and a spring to return the piston to bottom head center admitting water to the cylinder for the subsequent operating cycle.

k. Water Reservoirs

Pressurized bladder type of water storage reservoir are used for the two cold and the one hot water tanks, Figure 18 and 19. Bladder pressure is established with oxygen and provided by a low pressure (23.5 psi) regulator. Each reservoir's capacity is just over 140 in^3, hence, they can contain slightly more than 5 pounds of water, See Appendix VI. Working stresses in the aluminum material are conservative, only about 4,000 psi. The cold water tank is cooled by circulating through a jacket the same coolant which flows to the condenser. The hot water tank employs an electrical heater wrapped around the tank for heating the water. Initially the steam from the pyrolysis unit was used to heat the water. In order to reduce the heating and cooling loads on the tanks, an insulation jacket of a foamed silicone rubber, is utilized.

l. Controls

1. Hot Water Temperature

The temperature of the hot water is controlled by a bimetallic, snap acting thermal switch attached to the tank. Operation of the switch completes the circuit to a relay which energizes an electric heater integral with the tank. Accordingly, heat remains "on" until the water temperature actuates the switch, opening the heating circuit.

2. Water Dispenser

Water dispensing control is effected with a time delay relay, in conjunction with the water's regulated pressure of 23.5 psia. One through six ounces of water are dispensed as desired by selecting the quantity with a variable resistance switch, then operating a push button switch. The switch energizes the Agastat relay which, in turn energizes the solenoid valve, holding it open sufficiently long to discharge the preselected amount of water.

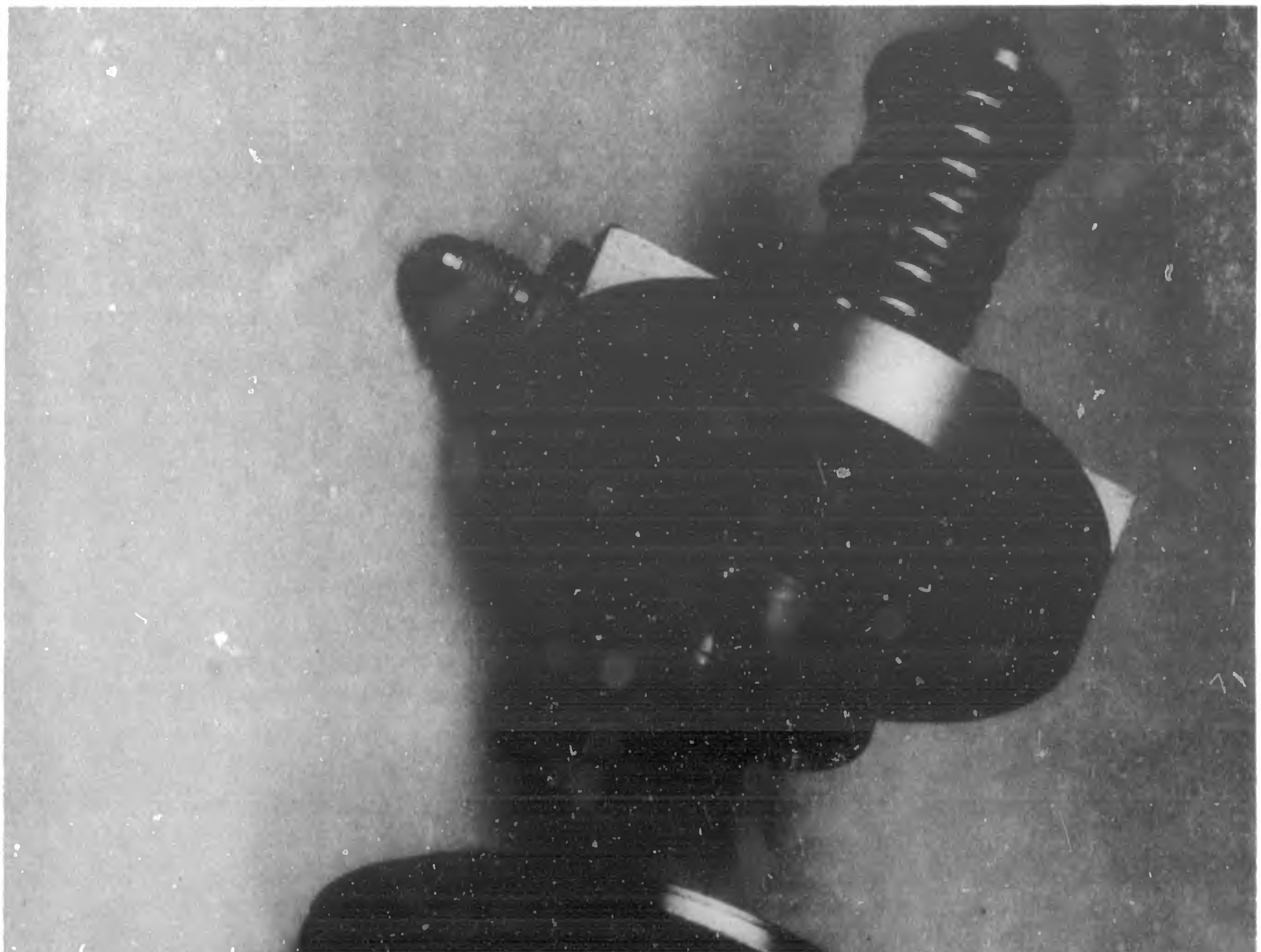


Figure 17. Pump (Partially assembled, illustrating inlet and outlet piston, spring and gas inlet)

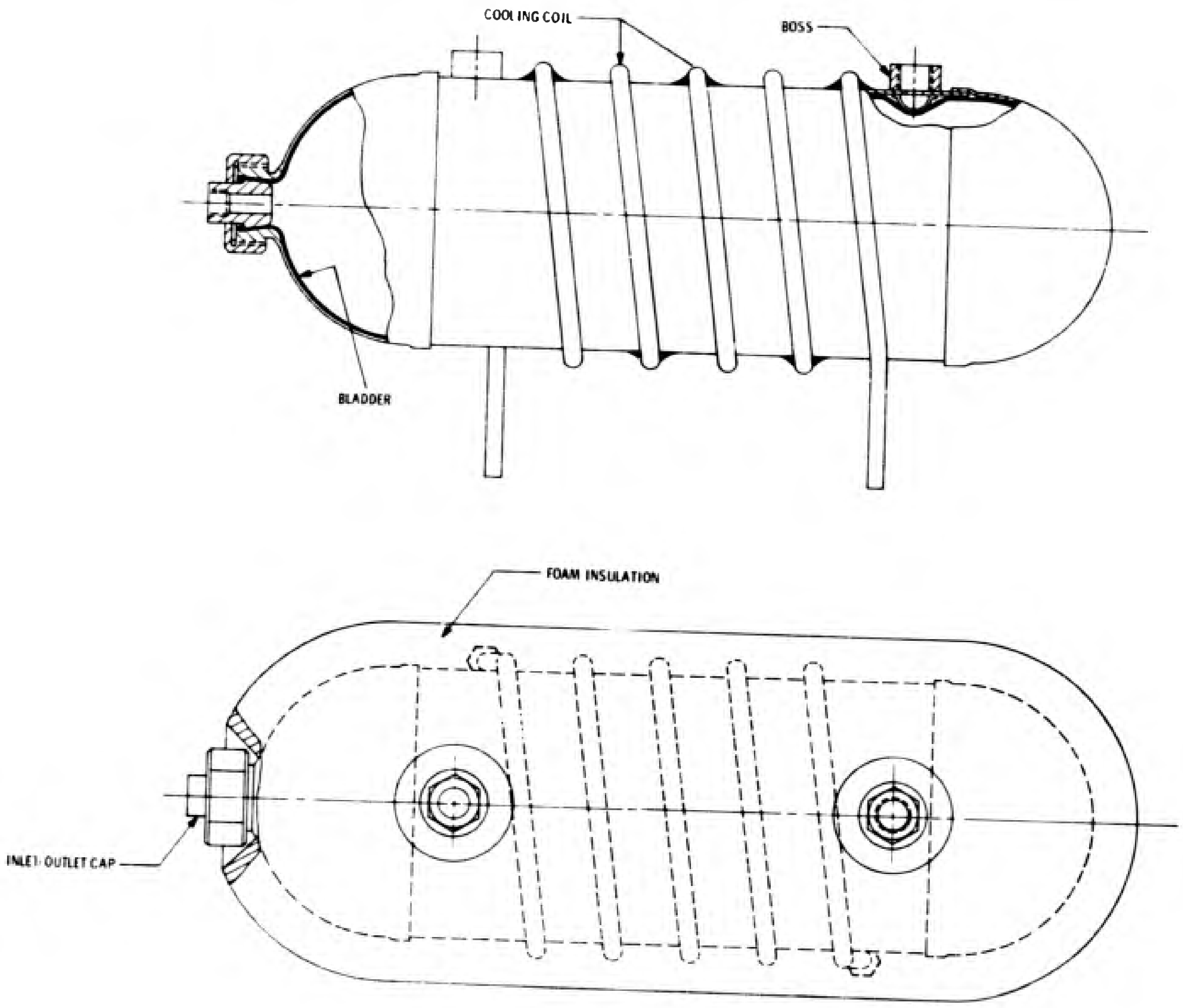


Figure 18. Cold Water Reservoir

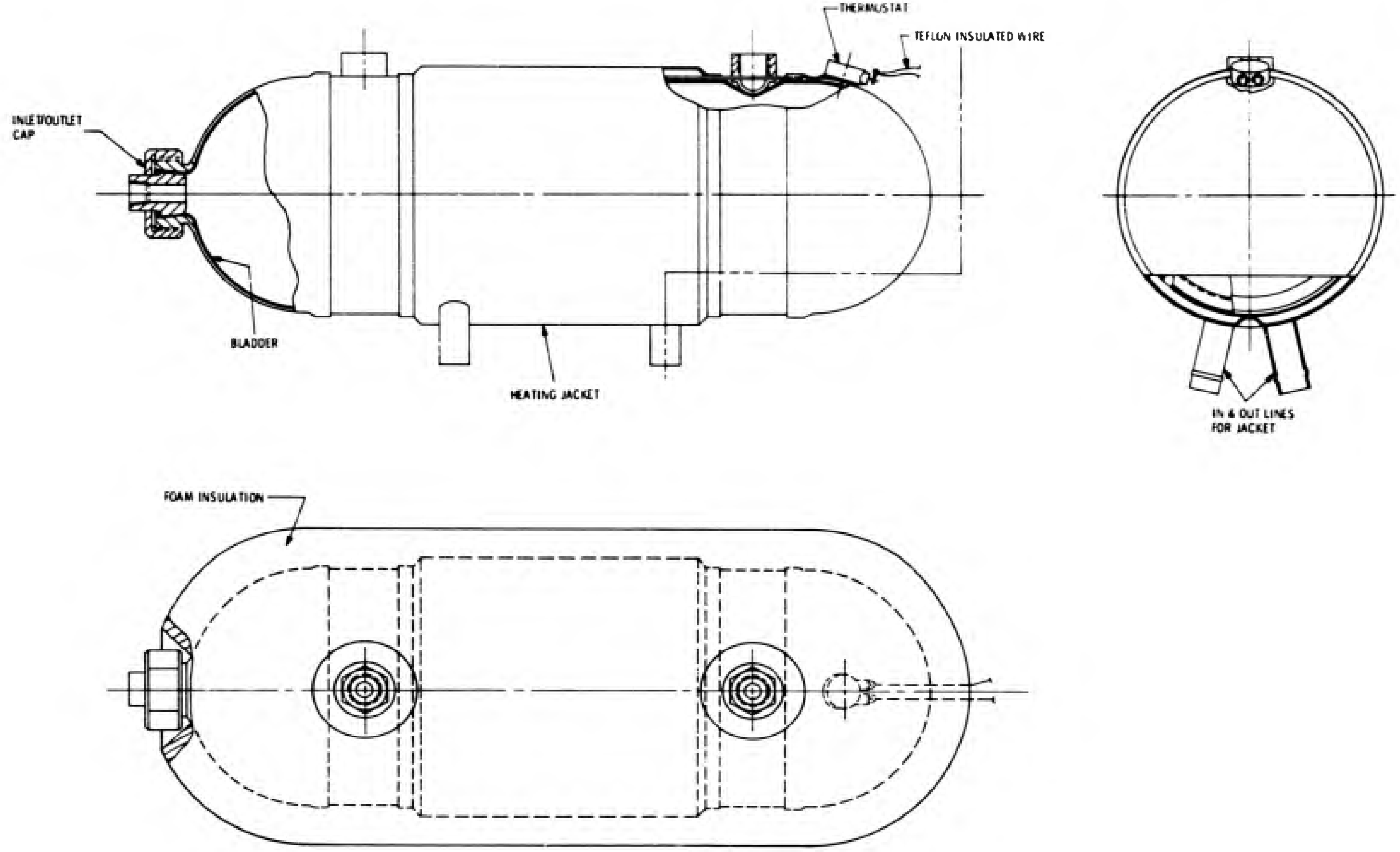


Figure 19. Hot Water Reservoir

3. Evaporator Level Sensor

The urine level in the evaporator was originally controlled by conductive probes. Three probes were used to average out errors which might result from agitation of the liquid's free surface. When the probes were not in contact with urine, infinite resistance was sensed and the urine solenoid supply valve was opened. When sufficient urine had been admitted to cause the sensors to conduct, the solenoid supply valve shut. Difficulties encountered with solids in the evaporator shorting out the conductive probes resulted in a change to an ultrasonic control. Accordingly, the new type sensors were installed. These sensed the presence of a liquid interface, suitably energizing a relay as a function of the liquid level with respect to the sensing element. The relay was then used to turn on the urine supply solenoid valve.

4. Condenser Level Control

The original condenser level control consisted of a capacitance type level sensor. Utilizing the difference in capacitance between steam and water, condensate covering the probes turned the condenser pump on. Accordingly, the pump's solenoid valve admitted 90 psi oxygen to the backside of the piston, driving it forward for one pumping stroke. Upon completion of the stroke, with the solenoid valve off, a spring returns the piston to bottom dead center for subsequent operations. A failure of the control necessitated a change to a constant speed timing motor being used for turning "on" the pump's O_2 solenoid valve for fixed intervals. This has been set to afford a greater pumping rate than is required in the condenser. Accordingly, the pump operates cyclicly, depleting the liquid in the condenser.

5. Electrical Schematic

An electrical schematic for the unit is shown in Figure 20.

6. Weight, and Power

Table I delineates the weight, and power for the elements of, and the complete water recovery system. The total system weight and power, respectively stands at 120 lbs and 56 watt - hrs/ lb of produced potable water. This is not a flight optimized system. A flight unit is estimated to weigh 58 lbs and operate with a power input of 8 watt-hours per pound of potable water.

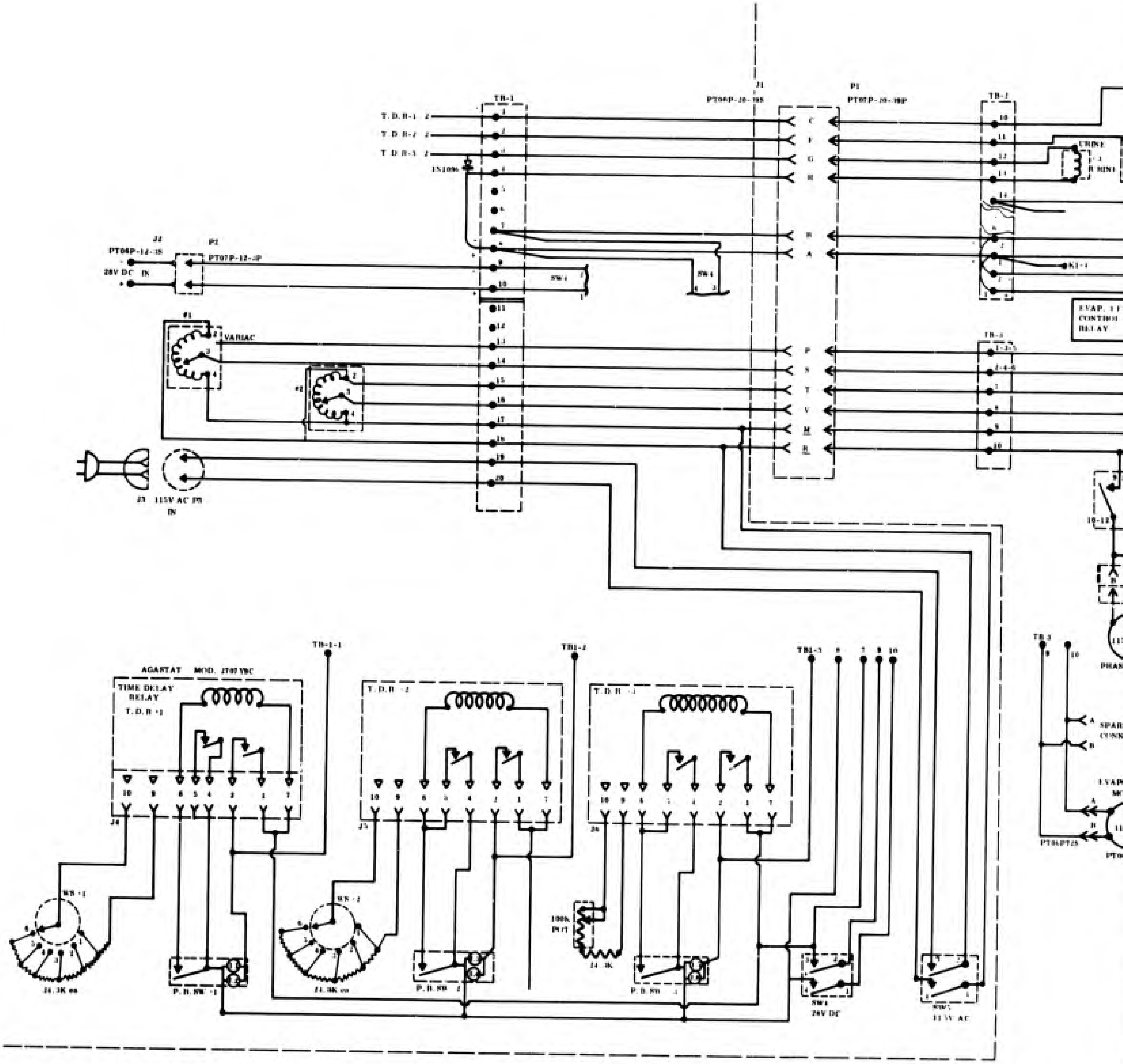
7. Reliability Analysis

The reliability estimated for the system, based upon satisfactory performance for 720 hours is 0.962. This is determined by the failure rates for the individual elements of the system as shown by Table II, with the system reliability given by

$$R = r_1 \times r_2 \times r_3 \quad \times \ldots r_n$$

m. Structure

Basic framework is welded, 1" x 1" extruded aluminum angle. Brackets for internal components are also of aluminum angle with the heavier elements mounted on aluminum channel. Aluminum was chosen for its light weight and some degree of corrosion resistance. The approximate weight of the framework is 12 pounds with the control panel weighing 7 pounds and additional brackets and supports at 6 pounds. The internal mounting and structural brackets are bolted to the frame as is the control panel. The skin is mounted with screws.


TB-1
T.D.R-1 2
T.D.R-2 2
T.D.R-3 2
1N1096
J2
PT06P-12-3S
P2
PT07P-12-3P
28V DC IN
SW4
#1
VARIAC
#2
J3 115V AC P3
IN
J1
PT06P-20-16S
P1
PT07P-20-16P
C
F
G
H
B
A
P
S
T
V
M
R
TB-2
URINE
K1-1
EVAP.
CONTROL
RELAY
TB-3
1-3-5
2-4-6
10-12
TB-1-1
TB1-2
TB1-3
AGASTAT MOD. 2707YBC
TIME DELAY RELAY
T.D.R-1
T.D.R-2
T.D.R-3
J4
J5
J6
WS-1
WS-2
21.3K ea
100K POT
21.3K
P.B.SW-1
P.B.SW-2
P.B.SW-3
SW1
28V DC
SW2
115V AC
SPARE
CONN
EVAP
PT06P725
PHAS

A

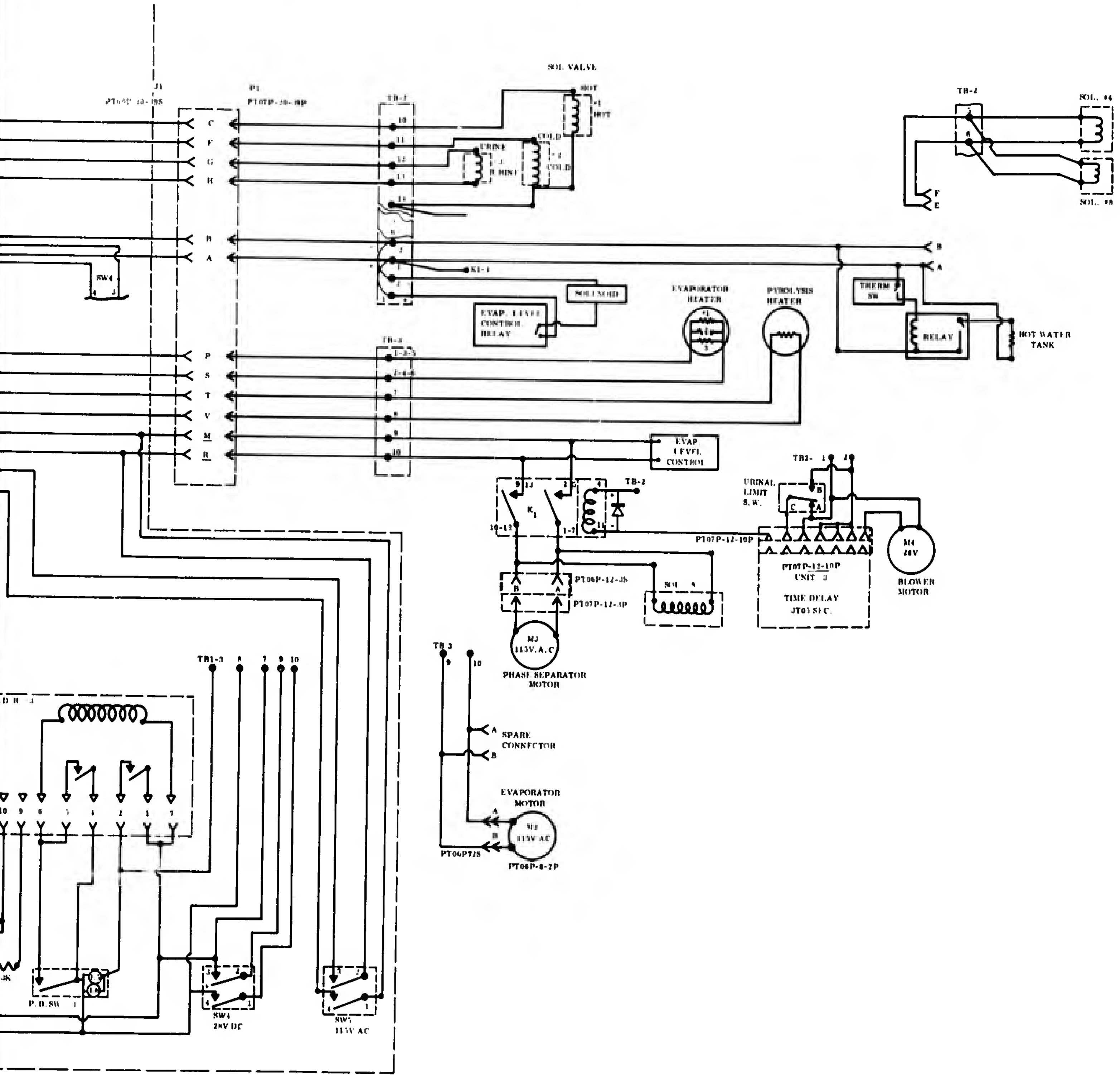


Figure 20. Electrical Schematic

13

Table I. Weight and Power

COMPONENT	PROTOTYPE UNIT WEIGHT (LB)	FLIGHT UNIT WEIGHT (LB) (ESTIMATE)	PROTOTYPE UNIT POWER (WATTS)	FLIGHT UNIT POWER (WATTS) (ESTIMATE)
Collection				
Urinal	0.4	0.4		
Hose	0.5	0.5		
Phase Separator and Motor	8.0	4.0	150 (3)	30 (3)
Blower	0.6	0.6	2 (3)	2 (3)
Filter	0.15	0.15		
Check Valve	0.05	0.05		
Waste Liquid Res.	1.0	1.0		
Controls	20.0	3.0 (2)		
Processing				
Flow Control and Valve	0.4	0.4	10 (3)	3 (3)
Evaporator and Motor	9.0 (1)	5.0 (1)	30	2
Solids Reservoir	1.9	1.9		
Pyrolysis Unit	25.0 (1)	10.0 (1)		
Condenser	4.0	2.0		
Storage				
Condensate Pump	1.2	1.2		
O_2 Valve	0.5	0.5	7 (3)	1 (3)
H_2O Valve	0.5	0.5		
Check Valve	0.05	0.05		
Level Sensor	0.3	0.3	5 (3)	2 (3)
Cold Water Reservoir (2)	3.8	3.8		
Hot Water Reservoir	2.0	2.0		
Dispenser Valves (2)	1.0	1.0	7 each (3)	1 each (3)
Bypass Filter	1.0	1.0		
Flush Valve (1)(Solenoid)	0.15	0.15	7 (3)	1 (3)
Dispensing Control	0.5	0.5	5 each (3)	1 each (3)
Misc. (Fittings, tubes, etc.)	8.0	4.0		
Enclosure	5.0	3.0		
Structure	25.0	12.0		
Total	120.00 lb	58.00 (1) lb	Average 35 watts at 0.625 lb water/hr equals 56 watt-hrs/lb	Average 5 watts at 0.625 lb water/hr equals 8 watt-hrs/lb

(1) Excluding Isotope Heaters
(2) 2 Variacs Eliminated
(3) Intermittant Use

Table II. Reliability Analysis for 720 Hours Operation

ELEMENT	FAILURE RATE	CYCLES	HOURS	RELIABILITY	NOTE
Urinal	0	1,440		1.0000	a
Blower Switch	0.12×10^{-6} F/C	1,440		1.0000	
Phase Separator Switch	0.12×10^{-6} F/C	1,440		1.0000	
Phase Separator Seal (2)	0.7×10^{-6} F/C	$1,728 \times 10^{3}$		1.0000	b
Phase Separator Bearings (2)	0.05×10^{-5} F/H		96	1.0000	
Phase Separator Rotor Ass'y	0		48	1.0000	
Phase Separator Motor	0.45×10^{-5} F/H		48	1.0000	
Blower Ass'y	0.45×10^{-5} F/H		48	1.0000	
Bacterial Filter	0.001×10^{-5} F/H		48	1.0000	
Urinal Water Sol. Valve	0.11×10^{-5} F/C	1,440		0.9984	
Conductivity Probe (3)	0		2,160	1.0000	
Solenoid Water Valve (3)	0.11×10^{-5} F/C	14,400		0.9842	
Turbine Bearings (2)	0.05×10^{-5} F/H		1,440	0.9993	
Oxygen Bleed Valve	0		720	1.0000	
Evaporator Drive Motor	0.45×10^{-5} F/H		720	0.9968	
Evaporator Seal	0.7×10^{-6} F/C	86,400		1.0000	c
Evaporator Bearings	0.05×10^{-5} F/H		1,440	0.9993	
Solids Pump Bearings (2)	0.05×10^{-5} F/H		1,440	0.9993	
Cam Followers (2)	0		1,440	1.0000	
Springs (2)	0		1,440	1.0000	
Pyrolysis Assembly	0		720	1.0000	
Condenser Assembly	0		720	1.0000	
Condenser Pump	0.49×10^{-5} F/H		720	0.9964	
Pump Control	0		720	1.0000	
Water Reservoirs (3)	0		2,160	1.0000	
Urine and Solids Reservoirs (2)	0		1,440	1.0000	
Oxygen Pressure Regulator	0.08×10^{-5} F/C	14,400		0.9885	
Oxygen Relief Valve	0.005×10^{-5} F/C	14,400		0.9994	
Tank Selector Switch (2)	0.12×10^{-6} F/C	4,800		0.9994	
Filter	0.001×10^{-5} F/H		720	1.0000	
Limit Switches, Pump (2)	0.12×10^{-6} F/C	14,400		0.9982	
Relay	0.12×10^{-6} F/C	1,440		0.9998	
Solenoid Valve, Air	0.11×10^{-5} F/C	720		0.9992	
Check Valve	0.005×10^{-5} F/C	720		1.0000	

a. Operational cycles estimated as 10 uses/man-day

b. Since the seal will function satisfactorily even after wear sufficient to cause a gap between the normally rubbing parts, the reliability of this element is estimated as 1.0000.

c. Redundancy of elements of the Quad Ring Seal results in 1.0000 for the element's overall reliability. In contrast a single element, O-Ring type seal would provide 0.9395 reliability.

R. System reliability

$$R = 0.9984 \times 0.9842 \times 0.9993 \times 0.9968 \times 0.9993 \times 0.9993 \times 0.9993 \times$$
$$0.9964 \times 0.9885 \times 0.9994 \times 0.9994 \times 0.9982 \times 0.9998 \times 0.9992 = 0.962$$

SECTION III

SYSTEM EVALUATION

1. GENERAL ELECTRIC TEST

a. Test Procedure

For details of the test procedure used, see Appendix VII, Systems Operation.

b. Equipment Performance - Electrical Power

During the five day test, difficulties were experienced with the liquid level control for the evaporator, the bearings for the turbine slinger, and the solids pump. All other elements of the system performed satisfactorily.

Difficulties with this liquid level control were mainly a consequence of a solids build-up within the evaporator, in particular, deposits forming upon the elements of the sensors and shorting them out. This resulted in the erroneous signal that the evaporator was "full". Accordingly, the urine supply valve was not energized and the evaporator tended to run dry.

The drive for the slinger required urine-free bearings for the turbine. In turn, this necessitated extremely close running clearances between the rotor hub and the housing to prevent a flow of steam and entrained urine into the bearings. Test results indicate that the required clearances were not consistently met, resulting in bearing failures. Subsequently, the turbine-slinger configuration was removed, with a baffle installed to prevent direct entrainment of liquid with steam and attendant "carry-over".

The Solids Pump failed as a consequence of excessive wear. This resulted in air leaking into the evaporator and preventing solids slurry from reaching the pump. Accordingly, the pump's inlet was starved from the solids it was intended to pump. The abrasive wear encountered was far more severe than had originally been anticipated. Hence, it does not appear likely that any fix short of a complete re-fabrication with, say, Stellite, would suffice. To circumvent this difficulty, operation was continued without the pump, using the mechanism which originally transported the solids to the pump as the separation mechanism--the evaporator stirrer's centrifugal field. Operation was continued satisfactorily without the solids pump for the remainder of the GE tests.

c. Water Analyses Results

Five water samples were obtained during the test at the General Electric Company's facility. The results of the water analyses are listed in Tables III and IV. The analyses were conducted by Betz Laboratories in accordance with US Public Health Standards (1962).

2. MOUND LABORATORY TESTS

a. Test Procedure

For details of the test procedures used, see Appendix VII, Systems Operation.

b. Equipment Performance - Electrical Power

The purpose of the electrical tests were twofold:

- To assure the satisfactory operation of the system and the auxiliary test equipment for the subsequent radioisotope tests.
- To demonstrate that any system failure which might result in a complete loss of stream flow through the pyrolysis unit would not result in an unsafe pyrolysis isotope temperature.

During the testing several difficulties developed with the system and the auxiliary test equipment which was subsequently corrected. This included the installation of a cold trap in the vacuum line, and the replacement of the piston in the water pump which had been leaking.

Upon completion of the run, the power input to the evaporator was cut-off, reducing the system flow to essentially zero. Accordingly, the thermocouple within the heater (located within the far, hot end of the heater, the position of maximum temperature) indicated a temperature of 955 °C which was less than the upper design limit of 1200 °C for the radioisotope heater.

Table III. Chemical Analyses - Water Samples General Electric Tests (Electrical)

SAMPLE DATE	10-14-66	10-22-66	10-23-66	10-24-66	10-26-66
Ammonia as N, ppm	5.0	3.5	0.03	0.03	0.4
Carbon Dioxide	0.0	56.0	26.0	18.0	20.0
Total Hardness		5.9	1.0	1.3	—
Alkalinity ① as $CaCO_3$, ppm	0.0	0.0	0.0	0.0	0.0
Alkalinity ② as $CaCO_3$, ppm	0.0	0.0	0.0	1.0	6.0
Chloride as Cl, ppm	8.0	38.0	12.0	3.0	3.5
Sulphate as SO_4, ppm	5.5	—	—	—	0.0
pH	3.8	4.2	3.9	4.5	5.3
Specific Conductance ③	120.0	130.0	100.0	25.0	14.0
Nitrate as N, ppm	—	—	—	—	0.0
Nitrite as N, ppm	—	—	—	—	0.22
Color (Units)	—	5.0	5.0	5.0	5.0
Turbidity (Units)	—	5.0	1.0	2.0	2.0
Total Solids, ppm	—	—	—	—	10.0
Odor	None	None	None	None	None
C.O.D., ppm	18.0	144.0	40.0	16.0	23.0
F.M.A. ④	13.5	2.3	9.0	0.0	—

① Phenolphthalein

② Methyl Orange

③ Micro-mhos 18°C (corrected)

④ Free Mineral Acids

Table IV. Bacteriological Analyses General Electric Tests (Electrical)

SAMPLE DATE	10/14/66		10/22/66		10/23/66		10/24/66		10/26/66	
Incubation Period (hrs)	24	48	24	48	24	48	24	48	24	48
Total Number of Bacteria per ML on Agar	0		37		0		0		0	
Presumptive Test (Coliform Group) Volume of Sample										
10.0 ML	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5
1.0 ML		0/5		0/5		0/5		0/5		0/5
0.1 ML		0/5		0/5		0/5		0/5		0/5
Most Probable Number (M.P.N.)		0		0		0		0		0

REMARKS: The presumptive test for members of the Coliform Group was negative in all of the five 10 ML portions of the sample. The samples tested conformed with the bacteriological requirement of the US Public Health Service Drinking Water Standards.

c. Equipment Performance - Radioisotope Power

Operation of the system with radioisotope heating for the evaporator and pyrolysis unit resulted in some equipment failures. However, none of these were a consequence of the heat source used. Both evaporator and condenser level controls failed, the former as a consequence of solids build up which created a parallel shorting path through the electrical sensor; the latter experienced a part failure in the capacitive sensor. In addition, two other equipment failures which occurred included the phase separator's outlet solenoid valve being held open by a foreign particle and a shaft seal which wore out.

Corrective action resulted in the substitution of a timing motor-programmer for the condenser control which then worked satisfactorily. The solenoid valve, held open, was flushed, permitting it to then shut sufficiently tight. The shaft seal was fixed temporarily by the addition of an external, face-sealing element.

No permanent fix was available for the evaporator's level control. Hence, following the noted difficulty, manual filling was effected. This was satisfactory for the most part, but did result in difficulties as a consequence of human error, causing a flooding of the system.

d. Water Analyses Results

The analyses of the water samples obtained during the Mound Laboratory tests are listed in Table V. These analyses were conduced by the U.S. Department of Interior at Cincinnati, Ohio.

e. Mass Spectrometric Gas Analysis

Gas samples which were drawn off the system just ahead of the condenser contained large amounts of hydrogen, nitrogen and carbon dioxide. Presumably the nitrogen and hydrogen resulted from the decomposition of ammonia. When the system operated properly, it was the carbon dioxide which apparently caused the low pH in the water. A detailed analysis of the gas samples is contained in Table VI of the text. These tests were conduced by Mound Labs.

Table V. Chemical Analyses - Mound Laboratory Tests

SAMPLE NUMBER		313	314	315	316 ②	317 ③	318 ④	319 ④	320	321	322
SAMPLE DATE		11/18/66	11/18/66	11/18/66	12/6/66	12/6/66	12/3-4/66	12/5-6/66	12/13/66	12/15/66	12/15/66
HEAT SOURCE		E	E	E	RI	RI	RI	RI	RI	RI	RI
COMPONENTS											
Zinc	PPB	36.	130.	26.	200.	250.	14.	38.			
Cadmium	PPB	< 5.	< 5.	< 5.	< 5.	< 5.	< 5.	< 5.	35	63	< 5
Arsenic	PPB	< 25.	< 25.	< 25.	< 25.	< 25.	< 50.	< 50.	< 5	< 5	< 5
Boron	PPB	18.	30.	18.	8.	< 3.	14.	< 5.	< 25	< 25	< 25
Phosphorus	PPB	< 20.	105.	< 20.	90.	60.	< 25.	< 25.	7	7	< 5
Iron	PPB	5.	73.	7.	75.	75.	26.	20.	55	55	30
Molybdenum	PPB	①	①	①	①	①	①	< 10.	40	25	9
Manganese	PPB	< 3.	9.	< 3.	8.5	< 2.5	< 2.5	3.5	< 10	< 10	< 10
Aluminum	PPB	1375.	>1500.	1500.	2250.	1500.	1000.	465.	< 3	< 3	< 3
Beryllium	PPB	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	1000	525	70
Copper	PPB	500.	500.	350.	225.	175.	6.	7.	< 0.03	< 0.03	< 0.03
Silver	PPB	< 0.5	5.	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	25	< 3	< 3
Nickel	PPB	< 5.0	20.	< 5.	16.	< 5.	5.	< 5.	4	< 0.5	3
Cobalt	PPB	< 5.	< 5.	< 5.	< 5.	< 5.	5.	< 5.	< 5	< 5	< 5
Lead	PPB	< 10.	< 10.	< 10.	45.	< 10.	15.	15.	< 5	< 5	< 5
Chromium	PPB	< 3.	17.	< 3.	21.	10.	5.	< 5.	40	< 10	30
Vanadium	PPB	< 10.	< 10.	< 10.	< 10.	< 10.	10.	< 10.	< 3	< 3	< 3
Barium	PPB	4.	12.	4.	5.	14.	1.	4.	< 10	< 10	< 10
Strontium	PPB	< 1.	< 1.	< 1.	< 1.	< 1.	1.	< 1.	80	< 1	< 1
Calcium	PPM	< 1.	< 1.	< 1.	—	—	—	—	< 1	< 1	< 1
Magnesium	PPM	< 1.	< 0.2	< 1.	—	—	—	—	—	—	—
Sodium	PPM	< 1.	1.0	< 1.	5.	3.1	< 1.	4.	—	—	—
Potassium	PPM	< 0.5	< 0.5	< 0.5	3.1	3.1	0.4	1.	< 1	< 1	< 1
Sulfate	PPM	45.	10.0	3.5	12.	9.	11.	21.	0.1	0.1	0.1
Chloride	PPM	9.	250	7.5	48.	36.	6.5	6.5	25	< 1	7
Ammonia(NH_3/N)	PPM	87.	250.	7.5	10.	6.3	17.	8.	1500	4.2	3.0
Total Phosphate	PPM	0.06	0.06	—	0.28	0.28	0.06	0.35	0.02	< 0.01	< 0.01
Total Carbon	PPM	710	25	2800	135.	2000.	5.2	4.	45	12	5
Total Hardness	PPM	< 1	< 1	< 1	14.	5.	6.0	6.	< 1	< 1	< 1
Total Alkalinity	PPM	298	1300	356	0.0	0.0	226.	86.	6200	38	52
Turbidity (Jackson Units)		—	—	—	0	0	0	0	—	—	—
Color (Units)		—	—	—	0	0	0	0	—	—	—
Conductivity (μ mhos)		270	1570	260	205	165.	175.	170	2400	77	116
pH (Units)		9.2	9.2	9.1	4.1	4.4	8.9	8.2	9.7	4.0	8.3
Urea	PPM	88	< 0.1	< 1.	10.	10.	< 0.1	< 0.1	80	< 0.1	< 0.1
					②	③	④	④			

① Interference from high aluminum content.

② Odor free

③ Sample had sweet odor.

④ Sample did not deteriorate standing at room temp.

Table VI. Spectrometric Analyses Gas Samples - Mound Laboratory Tests

SAMPLE DATE		11-17-66	11-22-66	11-24-66	12-5-66	12-8-66	12-16-66	12-16-66
TIME DRAWN (HR)		0900	0930	1000	1300	1000	1032	1500
HEAT SOURCE								
COMPONENTS	WT							
H_2	2	24.4	0.01	31.3	0.0	30.3	58.5	5.0
CH_4	16	0.8	9.2	0.7	0.5	0.1	0.2	0.1
CH_4	17	0.0	0.1	0.0	0.0	0.0	0.0	0.0
H_2O	18	4.3	0.7	0.4	1.1	0.0	0.0	0.0
C_2H_2	26	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO	28	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO	29	0.2	0.0	0.0	0.0	0.4	0.3	0.4
CO	30	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2	28	27.4	27.8	24.9	54.0	31.4	22.0	76.5
C_2H_4	28	0.0	0.0	0.3	0.0	0.0	0.0	0.0
C_2H_6	30	1.0	5.2	0.9	25.4	0.0	0.0	0.0
C_2	32	5.7	0.7	6.6	2.8	2.1	1.2	1.3
HR	40	0.7	0.9	0.2	5.0	1.4	0.1	0.8
CO_2	44	33.0	0.0	29.3	10.3	14.1	17.6	15.5
CO_2	45	1.8	3.9	2.7	0.1	0.1	0.1	0.3
CO_2	46	0.7	1.7	1.1	0.0	0.0	0.0	0.0
C_3H_8	44	0.0	49.8	1.6	0.7	0.0	0.0	0.0

BLANK PAGE

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

- Radioisotope heat sources have characteristics (e.g. reliability, long life, ease of maintenance) which make them attractive for use in space vehicle life support systems.

- No detectable amount of radioactivity is transferred to the urine or water when operating with Plutonium 238 radioisotope heaters.

- The vacuum distillation - vapor pyrolysis water recovery process produces potable and sterile water from urine. Recovery efficiencies (urine in versus water out) are very good, averaging 93% for the two longest runs. Of the 15 water samples taken and analyzed throughout the various tests, (see Table I) four (4) were obviously contaminated when the evaporator liquid level sensor failed and four (4) were slightly contaminated by improper cleaning after a control failure. This leaves seven (7) good samples on which the success of the system is based. Subsequently, the system controls were modified and several tests were conducted utilizing simulated urine (5000 ppm NH_3 in water). These tests confirmed the previous good test results.

- With no steam flow, the maximum temperature reached by the electrical heater elements is 955°C.

- Susceptibility of the Evaporator Level Control to failure, in conjunction with human error, necessitated the shut downs which limited the duration of the individual runs. Simplified methods with minimal electronics proved to be the best approach.

- Pyrolysis steam temperature is a direct function of the amount of flow. Accordingly, over the range of flows capable of being produced, the greater the flow the higher the temperature and vice versa.

Urine solids are extremely abrasive and require special handling procedures. The solids are detrimental to seals, bearings and close tolerance devices.

Static phase separators in the urine evaporator are preferable to dynamic devices because of power considerations and the abrasive effects of the urine solids on moving parts.

- Long duration operation of the Vapor Pyrolysis system is feasible; however, the reliability of the condenser and evaporator level controls requires further investigation. Further mechanical improvements to the system would be in areas such as solids removal evaporator phase separation, and evaporator shaft seals.

2. RECOMMENDATIONS

- More evaluation is required to determine the optimum catalyst for the pyrolysis process in the water recovery system. Catalysts such as platinum, ruthenium, and rhodium have been used successfully. Better catalysts may lower the required operating temperature, but lower temperatures may not sterilize the vapor.

- Both reducing and oxidizing atmospheres have been used in the pyrolysis chamber. Exact benefits of each are not known and require further study.

- More activity in the area of controls, especially liquid level sensors for zero gravity environments, is required.

- More evaluation of static and dynamic phase separators in a zero gravity environment is required.

- The system described herein is sufficiently developed to show its desirability as a flight system. It is recommended that a flight experiment of this type be incorporated in near future space flights so that the unit will be space proven before it is required for long duration space missions.

APPENDIX I

TURBINE DESIGN

The turbine is a "pinwheel" type characterized by 100 percent reaction. Steam flows through the hollow shaft from the evaporator's slinger to two spokes, then radially outward within the spokes. An orifice at the end of each spoke permits the steam to expand imparting a reaction force to the assembly.

The torque developed (at zero angular velocity) equals the time rate of change in angular momentum, or

$$T_t = \frac{rWs}{g} \Delta v_s,$$

where T_t is the turbine torque, lb-ft,

W_s is the steam flow rate, lbs/sec

Δv_s is the change in velocity across the turbine nozzle, ft/sec

r is the radius of the nozzle, ft

Since 0.5 psi drop is taken in the turbine,

$\Delta v_s = 800$ ft/sec for a given orifice size

with r = 4.5 in.,

$W_s = 0.625$ lbs/hr.,

$$T_t = \frac{4.5}{12} \times \frac{.625}{3600 \times 32.2} \times 800 = .001584 \text{ lb-ft} = .30 \text{ oz-in.}$$

The aerodynamic drag torque of the rotor can be estimated using a drag coefficient of unity. Then the retarding force acting on a differential element of area

$$dF = \frac{\rho v^2}{2} dA$$

where F = drag force

ρ = atmosphere density

v = rotor velocity

A = rotor area

and the drag torque for this differential area

$$dT = \frac{pv^2}{2} rdA = \frac{\rho \omega^2 r^3 d\, dr}{2}$$

where T = drag torque
d = tube diameter
ω = rotational velocity

$$\text{then } T = 2 \frac{{}^{r}_{o} \rho \omega^2 r^3 d\, dr}{2} = \frac{\rho \omega^2 d\, r^4}{4}$$

Since $\rho = \frac{1}{vg} = 1 \times 10^{-5}$ slugs/ ft^3,
and $r_o = .375$ ft, $r_o^4 = .02$ ft^4
and d = .25 inches = .02 ft.

Accordingly, for the turbine geometry chosen, the drag is a function of the rotational speed as shown by the table below:

n(rpm)	T (lb-ft)	T (oz-in)
1000	1.1×10^{-5}	2.1×10^{-3}
2000	4.4×10^{-5}	10.95×10^{-3}
4000	17.6×10^{-5}	4.4×10^{-2}
8000	70.4×10^{-5}	.176
12000	208×10^{-5}	.400

No torque will be developed when the rotor's tip speed equals the nozzle efflux velocity, or when

$$\omega r_o = 800 \text{ ft/sec}$$

$$\omega = \frac{800}{r_o} = \frac{800}{4.5 \text{ in.}} = 2140 \text{ rad/sec},$$

$$\text{Since } n = \frac{60\,\omega}{2\pi} = \frac{60 \times 2140}{2\pi} = 20{,}600,$$

the turbine nozzles developes no torque at 20,600 rpm.

Figure 21 depicts the turbine as a function of speed, and also the rotor aerodynamic drag. Included, also, is an estimate for the bearing torque. At a constant speed, the turbine must be in equilibrium between the developed torque and the load. Accordingly, at any operating condition the difference between the turbine torque and the sum of the individual bearing and aerodynamic torques represents the torque available for the slinger's separating action in the evaporator.

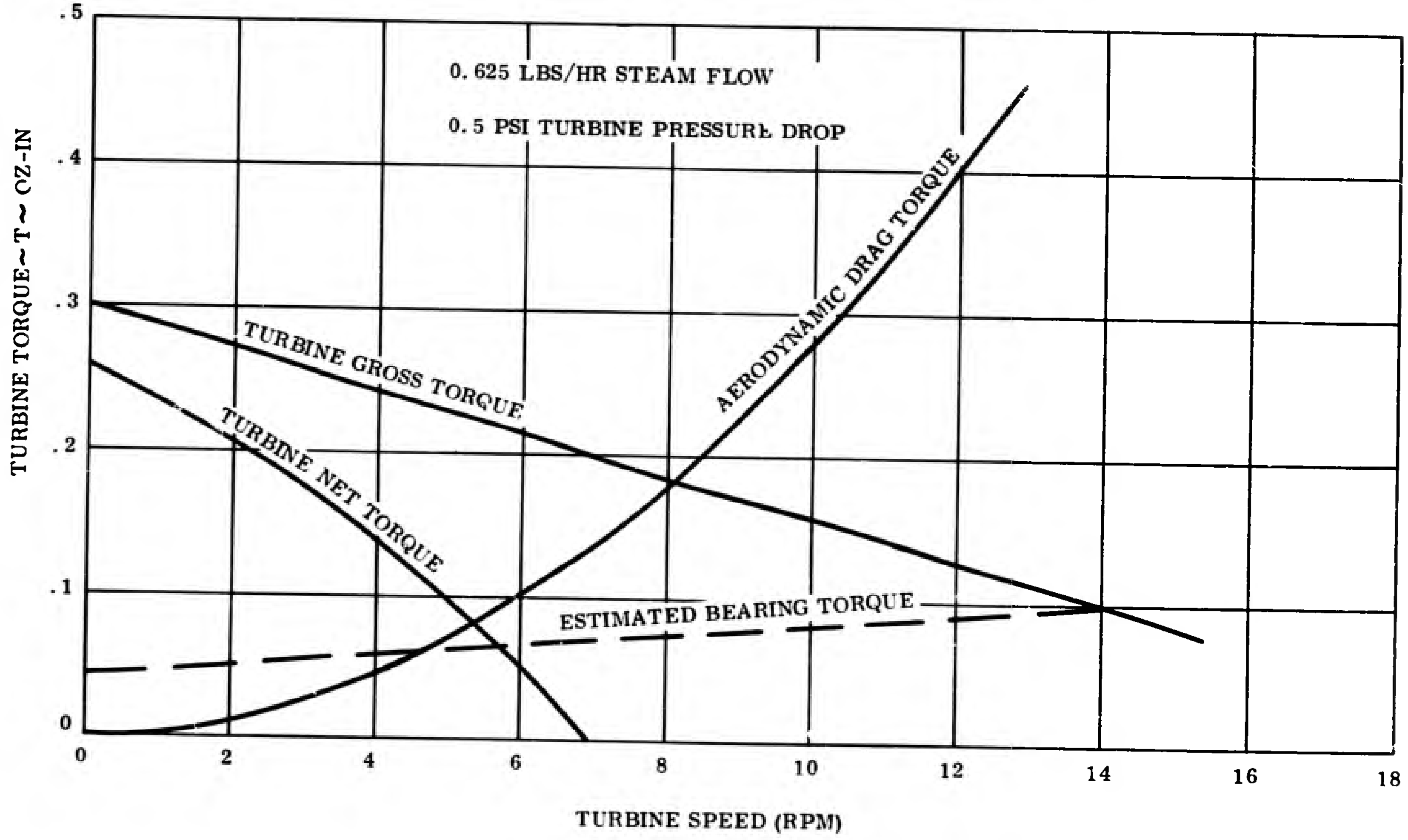


Figure 21. Turbine Speed-Torque Characteristics

BLANK PAGE

APPENDIX II

PYROLYSIS UNIT - MATERIALS SELECTION STUDY

1. CORROSION STUDY

Early in the design phase of the program, it was believed that a steam temperature of 1800°F was required to effect complete ammonia decomposition with a platinum catalyst. Accordingly, Hastelloy X was chosen for the fabrication material, based upon its strength at that temperature and its resistance to corrosion. Since no materials performance data was available for Hastelloy X in an ammoniacal environment, tests were run upon TIG welded lap joints (with and without Hastelloy X filler wire) and electron beam butt welded joints and tube to bulkhead joints. The test set up was as shown by figure 22. Urine placed in a distillation flask which was kept within an electric heating blanket whose voltage was adjusted to maintain a constant boiling temperature within the flask. The urine vapor was passed through a quartz furnace tube which utilized a thermocouple for monitoring furnace temperature. Throughout the test, 1950°F to 2050°F was maintained. Three duplicate sets of 5 test specimens were evaluated. One set was removed from the test after one week's exposure (Group 1). The second set was removed after two week's exposure (Group II) and the third set of specimens was removed after 500 hours exposure.

The weight of each specimen before and after test was noted. The specimen types are identified as follows:

a. Lap joint 0.035" - Hastelloy X Sheet - No filler wire

b. Lap joint 0.035" - Hastelloy X Sheet - Hastelloy X filler wire

c. Butt joint 0.035" - Hastelloy X Sheet - Electron Beam Welded

d. Tube to Sheet Joint - Hastelloy X Sheet - Electron Beam Welded

e. Platinum Mesh - Simulated Catalyst Material

Figure 22. Pyrolysis Corrosion Test Set-up

2. TEST RESULTS

a. Weld Joint Study

Weld test specimens a, b, c, and d are shown in cross-section in Figure 23. Ample weld penetration was achieved with each welding method as exemplified by the enlargements of joints a, b, and d in this exhibit. Similar suitability of weld penetration was observed in specimen c.

Comparisons were made between cross-sectioned joints a, b, c, and d at high magnifications before and after the 500 hour test, see figure 24. The specimens were free of local pitting and intergranular corrosion attack. However, a small amount of oxidation occurred during the test. This oxidation appeared equal in severity along the weld, heat affected zone, and base metal surfaces. The visual appearance of these surfaces after 500 hours' exposure is recorded in figure 25. The microstructure of Hastelloy X in the prior-to-test condition contains a fine particle size second phase, well dispersed throughout the matrix. Coarsening of the second phase was noted after the test. This coarsening has apparently little effect on corrosion during the time duration of this test. The surface oxide and dispersed secondary phase are illustrated in Figure 26.

b. Weight Change Consideration

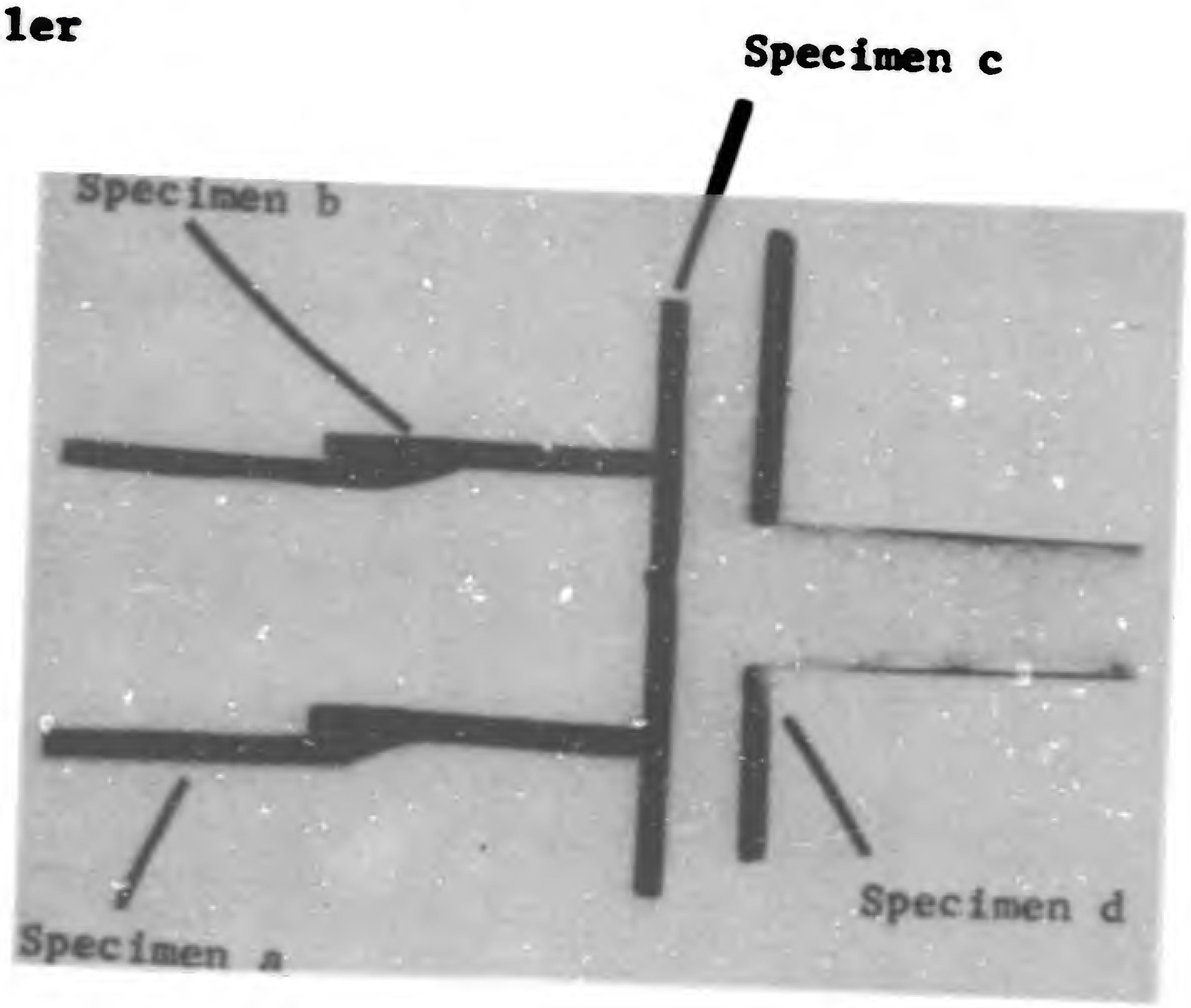
The weight change after one week, two weeks and 500 hour exposures are compiled in Table VII. The weight in grams for each specimen before and after test were compared and the weight loss or gain listed in the subsequent horizontal comumn in the after test column. The percent change in weight is listed for the 500 hour test specimens only and appear in the final vertical column of the table. The first week specimens show a small weight loss and after 2 weeks exposure a slight weight gain is recorded. This weight gain is attributed to oxidation which was visually observed on the specimen surfaces. The Group III specimens (500 hour exposure) show small weight changes. The platinum specimens underwent a 2% weight gain and visual surface discoloration.

3. DISCUSSION OF RESULTS

The Hastelloy X material underwent surface oxidation and microstructural change during the 500 hour high temperature corrosion test. The time duration of this test was a fraction of the time required during an actual space mission. Although no local pitting or intergranular attack took place the effect of longer time exposure on the material cannot be extrapolated. Corrosion data with time-data points over a longer time period, with the

Specimen b 4X

TIG Welded with Filler



2X

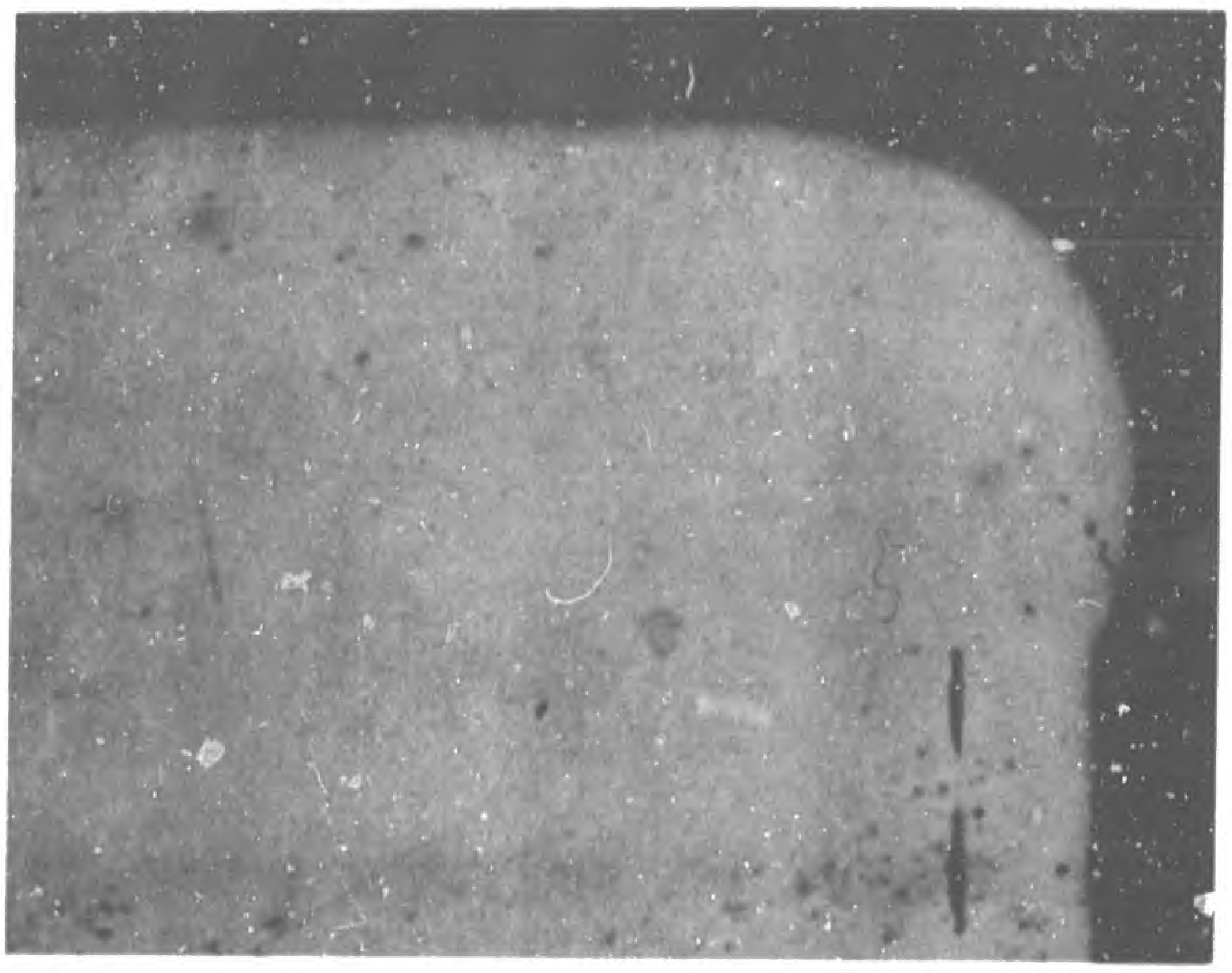
Specimen d 125X

Tube to Sheet Joint
Electron Beam Welded

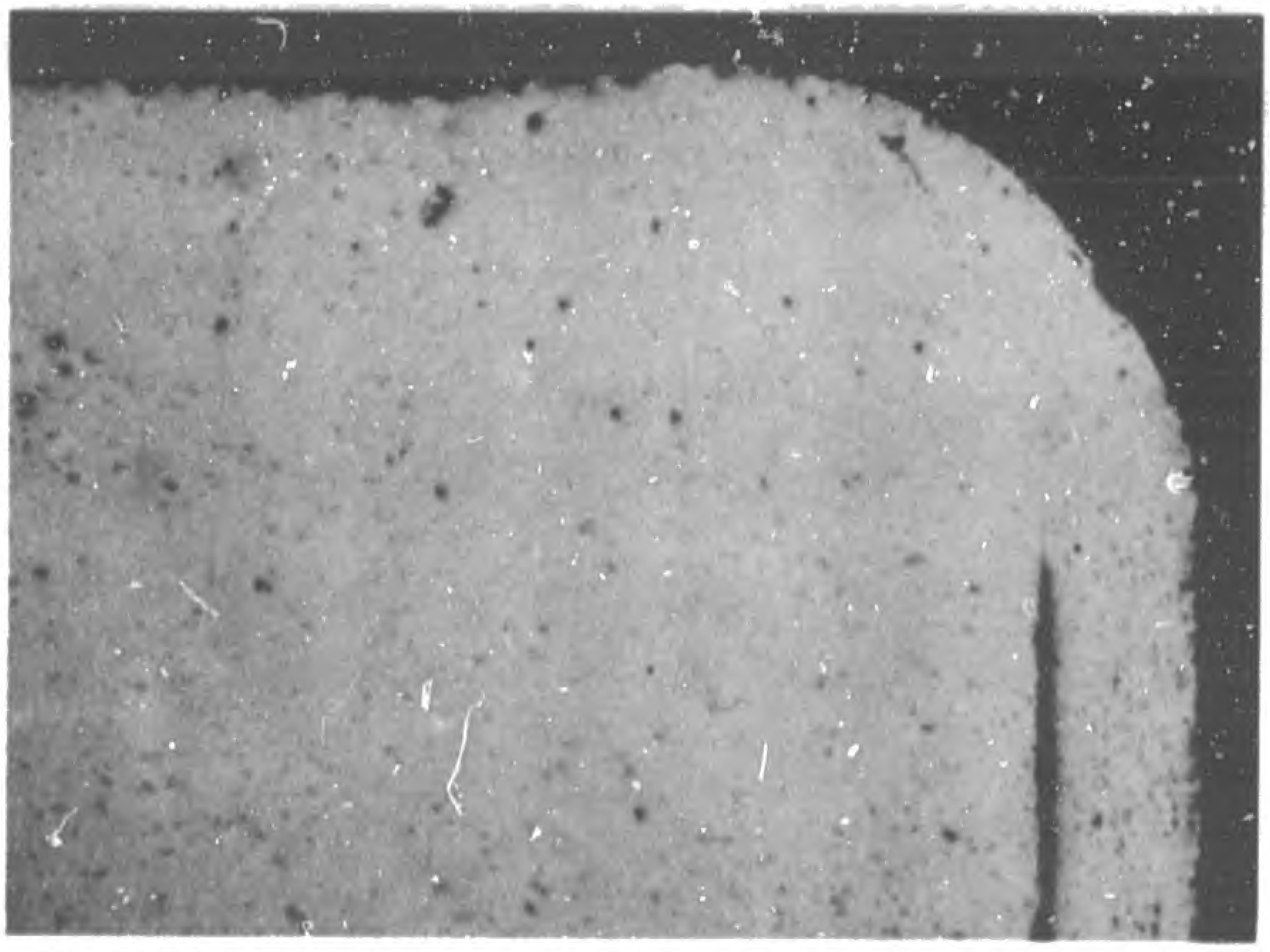
Specimen a 4X

TIG Welded - No Filler

Figure 23. Weld Penetration Study



JOINT d BEFORE TEST



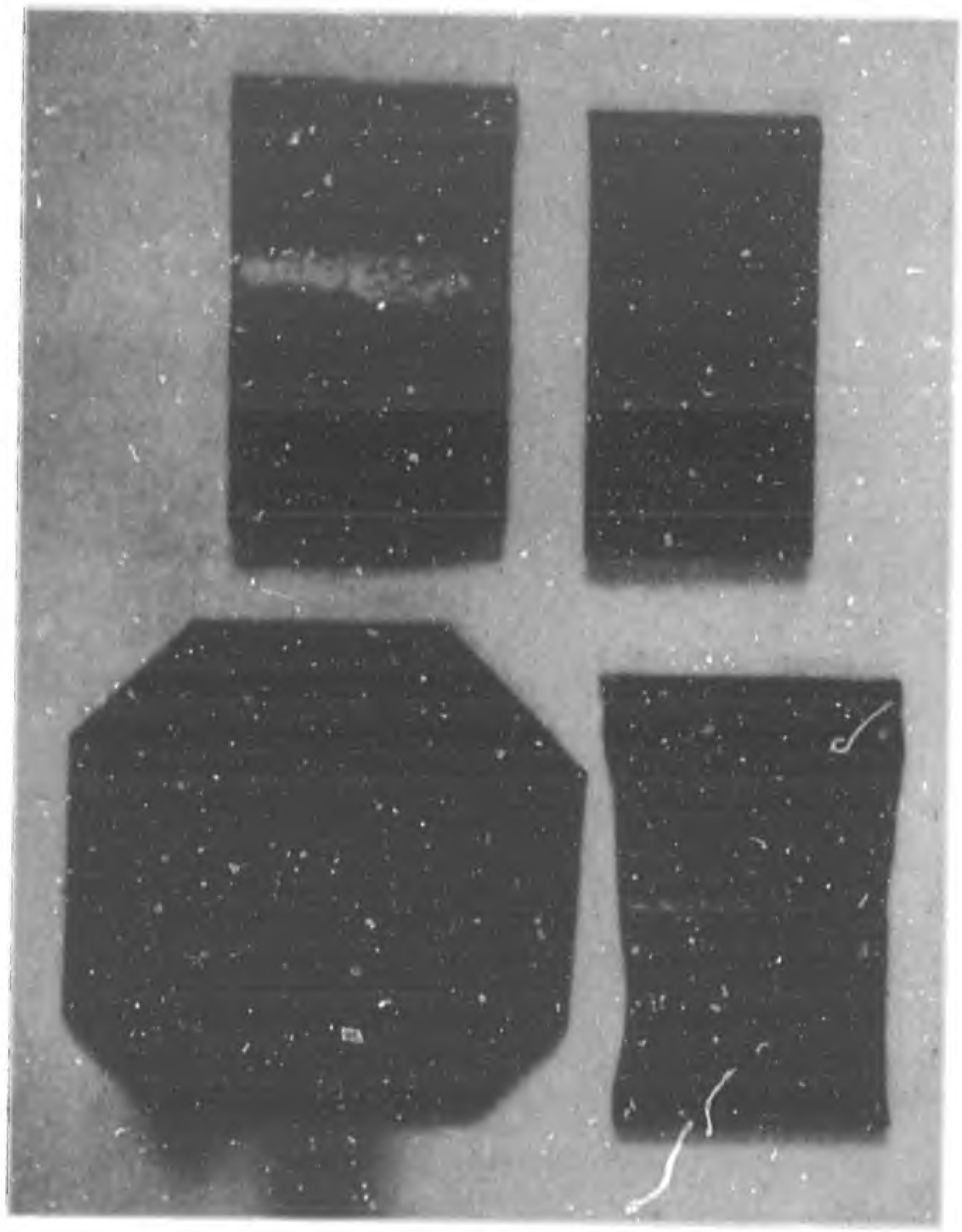
JOINT d AFTER TEST

JOINT d EXEMPLIFIES THE SUPERFICIAL SCALING ON THE SURFACE OF HASTELLOY X SPECIMENS a, b, c, and d AFTER 500 HOURS OF TEST EXPOSURE.

Figure 24. Joint d Before and After Test

Specimen b
Lap Join 7
Hastelloy X-Filler Wire
(TIG)

Specimen a
Lap Joint
No filler wire
(TIG)



Specimen d
Tube to Sheet Joint
Hastelloy X
Electron Beam Welded

Specimen c
Butt joint
Hastelloy X
Electron Beam Welded

2X

Figure 25. 500 Hour Corrosion Test Welded Specimens

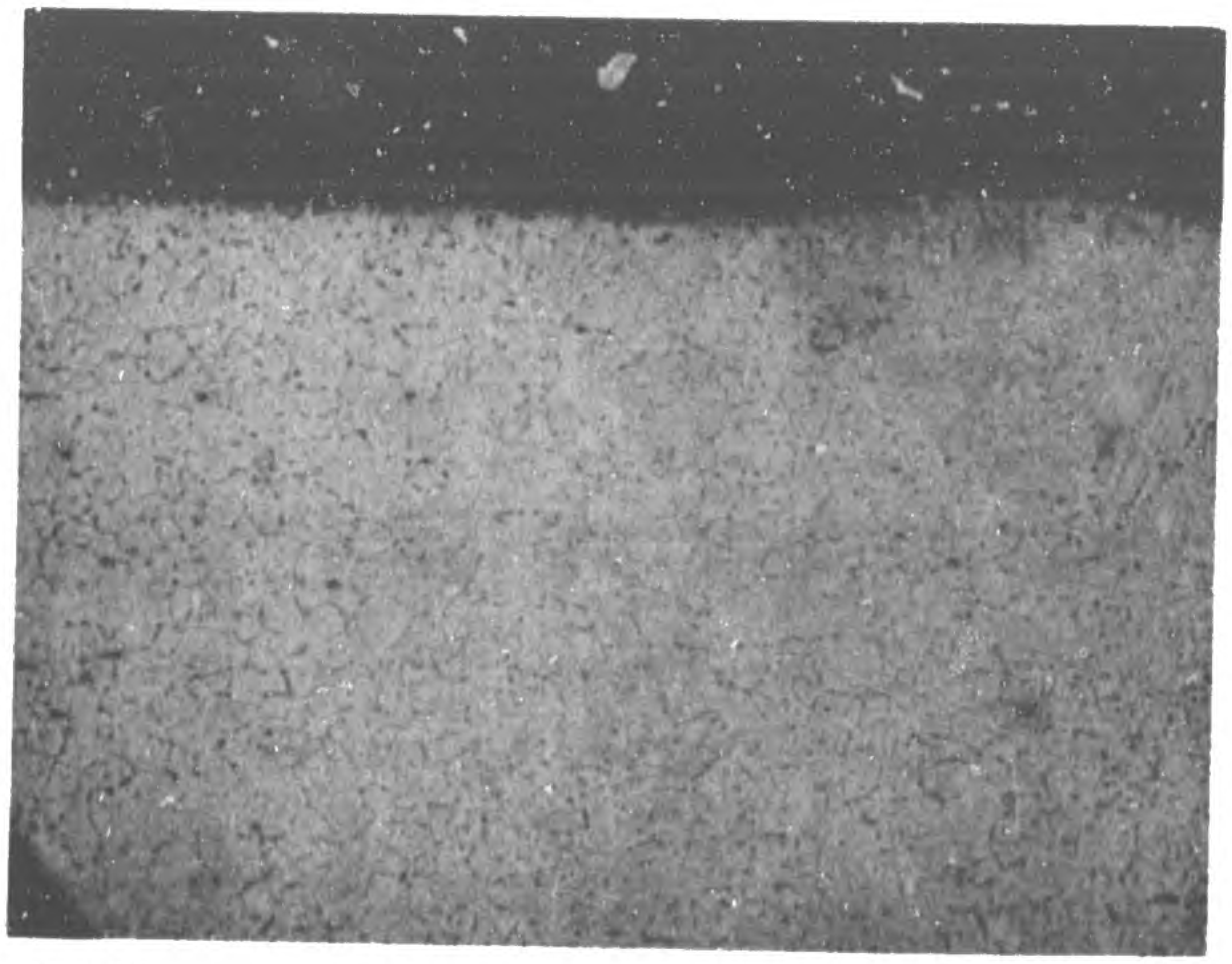


Figure 26. Joint d After Test-Etched Electrolytically With 10% HCl

Table VII. Weight Change

Sample Weights

	Group I		Group II		Group III	
	Before	After 168 hrs.	Before	After 336 hrs.	Before	After 500 hrs.
No Filler	1.62002	1.61858	1.41400	1.42496	1.77000	1.76630
Weight Change		-0.00144		+0.01096		-0.00370 (0.2%)
Filler	1.80708	1.80604	1.72384	1.73501	1.52435	1.52882
Weight Change		-0.00104		+0.01117		+0.00447 (0.28%)
Electron Beam	1.48743	1.48462	1.48589	1.49406	1.60676	1.60939
Weight Change		-0.00281		+0.00815		+0.00263 (0.16%)
Tubes	2.97985	2.98534	2.93732	2.99548	3.14266	3.18005
Weight Change		+0.00549		+0.05816		+0.03739 (0.11%)
Platinum Mesh	0.13172	0.12781	0.13974	0.14291	0.12883	0.13152
Weight Change		-0.01391		+0.00317		+0.00269 (2.0%)

object of establishing time vs. material property change relations, are needed. In this test constant flow conditions were maintained, however, in a flight situation a no-flow condition may occur. In this case the temperature near the isotope heating element will rise. This could be serious since the present operating temperature is approaching the peak useful temperature for Hastelloy X alloy. Therefore, consideration must be given to newer alloys which might perform at higher temperatures or methods to protect Hastelloy X from such high temperature exposure. The customer has been given material exposed to the 500 hour test for microprobe analysis studies of the Hastelloy X surface oxide.

Test monitoring data, such as, consumption of raw material during test were recorded and periodic samples of the distillate were collected. This data was used to determine the purity of the water obtained by the operating temperatures.

The increased weight of the platinum gauze is of concern. Additional studies are needed to determine the nature of the adherent deposit (or oxidation products) on the gauze. The use of platinum and other materials requires additional studies since their catalytic action is a function of surface condition.

APPENDIX III

INITIAL PYROLYSIS UNIT HEAT LOSS ANALYSIS

The heat losses from the pyrolysis unit are assumed to be comprised of three facets: (1) The radial heat transfer through the superinsulation jacket; (2) The conductive heat transfer axially along the inner shell; (3) The conductive heat transfer axially along the counter flow heat exchanger.

1. RADIAL HEAT TRANSFER

The Union Carbide Co.'s brochure on superinsulation, F 1757-8 provides curves which indicate that at 1800°F the thermal conductivity

$$k \approx .0025 \quad \frac{\text{BTU}}{\text{Hr. ft}^2 - {}^\circ\text{F/ft}}$$

This value is somewhat conservative for our configuration, since it assumes 15 psi contact pressure between the insulation layers, and also neglects the reduction in k that accompanies the axial temperature drop.

Considering our configuration as co-axial cylindrical shells with hemispherical heads (at the hot end), 12 inches cylindrical length and with the inner shell's 6 inch diameter, then the heat transferred (Q) across the one inch of superinsulation between the shells,

$$\begin{aligned} Q \text{ hemi} &= k\,A\,\frac{dT}{t} \\ &= .0025 \times 2\,\pi\,R^2 \times \frac{1700}{1/12} \\ &= .0025 \times 2\,\pi\,\frac{(3)^2}{12} \times \frac{1700}{1/12} \end{aligned}$$

where:

A = area ft^2

dT = temperature difference ^oF

t = insulation thickness, ft

Q hemi = 20 BTU/HR.

and Q cylinder $= k \frac{dT}{t} A$

where $A = 2 \pi Rl$

l = length

average $dT = \frac{1700}{2} = 850^oF$

$= .0025 \times \frac{850}{1/12} \times 2 \pi (3/12) 12$

$= .0025 \times 12 \times 850 \times 6 \times 3.14$

Q cylinder = 48 BTU/hr

Hence, the total heat transfer across the superinsulation is, conservatively, 68 BTU/HR.

2. AXIAL, CONDUCTIVE HEAT TRANSFER

The Universal Cyclops Steel Corporation cites the thermal conductivity of Unitemp HX (Universal's designation of Hastelloy X) as:

Temperature - (^oF)	Thermal Conductivity $\left(\frac{BTU - Inch}{hr. - ft^2 - {}^oF}\right)$
70	63.0
600	100.0
1000	136.0
1500	173.5
1700	188.5

To simplify the analysis and to assure conservatism, it is assumed that the radial heat transfer has no effect upon the axial transfer, and further, that no significant thermal resistance exists between the base of the unit and its heat sink. Accordingly, the base is assumed as 100°F.

The conductive axial heat transfer then

$$Q_{axial} = k\ A\ \frac{dT}{dl} \qquad (1)$$

With the assumption that the radial heat transfer does not affect

$$Q\ \text{axial} = \text{Constant} \qquad (2)$$

and since the area A is a constant,

$$k\ \frac{dT}{dl} = \frac{Q}{A} = C_1\ \text{(constant)} \qquad (3)$$

The Universal Cyclops Conductivity data permits the approximate description of the conductivity as

$$k \approx 56 + .08\ T\ (^{o}F) \qquad (4)$$

Accordingly,

$$k\ dT = C_1\ d\ell = (56 + .08T)\ dT \qquad (5)$$

and $56\ T + .04\ T^2 = C_1 \ell + C_2$ (6)

Considering that $T = 100^{\circ}F$ at $\ell = 0$

$$C_2 = 56\,(100) + .04\,(10{,}000) = 6{,}000 \qquad (7)$$

At the hot end where $\ell = 12$ and $T = 1800^{\circ}F$

$$C_1 = 18{,}700$$

Substituting the value for C_1 into (3),

$$\text{and with the area } A = \frac{2\,\pi\,R}{12} \times \frac{t}{12} = \frac{2 \times 3.14 \times 3 \times .040}{144} = .00522 \text{ ft}^2$$

$$Q \text{ axial} = .00522 \times 18{,}700 = 97 \text{ BTU/hr.}$$

3. HEAT BALANCE

The analyses indicate that the heat loss is conservatively, 165 BTU/hr. The estimated heat requirements of the steam are 46 BTU/lb (from 1700°F to 1800°F), and with .625 lb/hr steam flow, this becomes 29 BTU/hr. Hot water heating requires an additional 40 BTU/hr. Accordingly, the total pyrolysis heat load is estimated as 234 BTU/hr. A seventy watt heat source provides 239 BTU/hr., and in view of the conservative nature previous calculations, should be adequate.

APPENDIX IV

PYROLYSIS UNIT HEAT EXCHANGER ANALYSIS

1. STEAM FLUID FLOW ANALYSIS

A pressure of 1.2 psia was selected as the condition at the inlet to the counter flow exchanger, based upon the known temperature, the flow from the evaporator and practical line sizes. Accordingly, with 0.625 lbs/hr of flow, at 1.2 psia and 120°F, the volume flow

$$F = Wv = 0.625 \frac{\text{lbs}}{\text{hr}} \times 281 \frac{\text{ft}^3}{\text{lb}} = 176.0 \frac{\text{ft}^3}{\text{hr}}, \quad (1)$$

$$\text{or } F = \frac{176.0 \text{ ft}^3/\text{hr}}{3600 \text{ sec/hr}} = 0.0488 \text{ ft}^3/\text{sec} \quad (1a)$$

Assuming a 1/4 inch line size, the cross sectional area

$$A = 0.0491 \text{ in}^2 = 3.40 \times 10^{-4} \text{ ft}^2 \quad (2)$$

Then the velocity through the tube

$$V = \frac{F}{A} = \frac{0.0488 \text{ ft}^3/\text{sec}}{3.40 \times 10^{-4} \text{ ft}^2} = 144 \text{ ft/sec} \quad (3)$$

Considering the tube length between the discharge of the evaporator and the inlet to the counter flow exchanger to be small, the pressure drop is approximately equal to the velocity head.

$$\text{Thus } \Delta k = \frac{\rho v^2}{2g} = \frac{1}{281} \times \frac{(144)^2}{64.4} = 1.15 \frac{\text{lbs}}{\text{ft}^2} = 0.008 \frac{\text{lbs}}{\text{in}^2} \quad (4)$$

The energy available for producing this velocity change results from the change in enthalpy of the steam is it expands from 1.7 psia to 1.2 psia, 22 Btu/lb, which results in a velocity capability of 1050 ft/sec. Accordingly, 1/4 inch tubing is adequate for the pressure drop available, with an orifice required to reduce the pressure to the proper value at the design flow.

Heating requirements for the hot water necessitates 360°F vapor from the counter-flow exchanger. This results in a 240°F Δ T through the exchanger, and since the discharge temperature from the pyrolysis unit is 1800°F, the inlet to the pyrolysis unit is 1540°F. Consulting figure 6 at the point 6, with 3/16 inch ID, 54 tubes the flow area

$$Ai = 54\ \frac{\pi}{4}\ Di^2 = 54\ \frac{\pi}{4}(0.1875)^2 = 1.49^2\ in = 0.0104\ ft^2, \qquad (5)$$

and the tube distribution has been selected to afford equal area for the counter flow. At point 6 then, since v = 1,072 ft ^{3}/lb,

$$V = \frac{Wv}{A} = \frac{0.625 \times 1{,}072}{0.010 \times 3600} = 18.0\ ft/sec, \qquad (6)$$

and the head loss between points 5 and 6

$$\Delta P \approx \frac{\rho v_6^2}{2g} \approx \frac{1}{1072} \times \frac{1}{64.4} \times (18.0)^2 \times \frac{1}{144} = 0.34 \times 10^{-4}\ \frac{lbs}{in^2} \qquad (7)$$

With this configuration, then, the pressure at point 6 is slightly less than 1.2 psia, essentially identical with point 5. Similar calculations show that the pressure point 8 is also 1.1 psia. In accordance with these temperature-pressure values for the steam through the exchanger, the necessary tube length can be estimated.

2. COUNTER FLOW EXCHANGER TUBE LENGTH

Utilizing the procedure in the G E Heat Transfer Manual (Section G 503,) the weight flow per unit area

$$G = \frac{W}{A} = \frac{0.625}{0.0104} = 60.3\ \frac{lbs}{ft^2\ hr.} \qquad (8)$$

The Reynold's number

$$R = \frac{GD}{\mu}\ \frac{TB}{T_F} \qquad (9)$$

where the correction ${}^{T}{}_{B}/{}^{T}{}_{F}$ represents the ratio of the fluid's bulk temperature to its film temperature, with

$$T_F = \frac{0.7\ T_B}{0.3\ T_w} \qquad (10)$$

and T_w, the wall temperature, is assumed as the mean of the gas temperature on each side of the wall.

Figure 27 provides the data for the steam properties necessary to the calculation of the Reynold's Number. With these values and Figure 28 (extrapolated from G503. 2p.2 Figure 1A) the dimensionless quantity

$$j = \frac{h}{(C_p \rho)\ V_b} \left(\frac{C_p u}{k} \right)^{0.6} \qquad (11)$$

can be determined, and subsequently the film coefficient be calcualted. Accordingly, the fluid properties at each statepoint in figure 6 are as shown in the following Table VIII

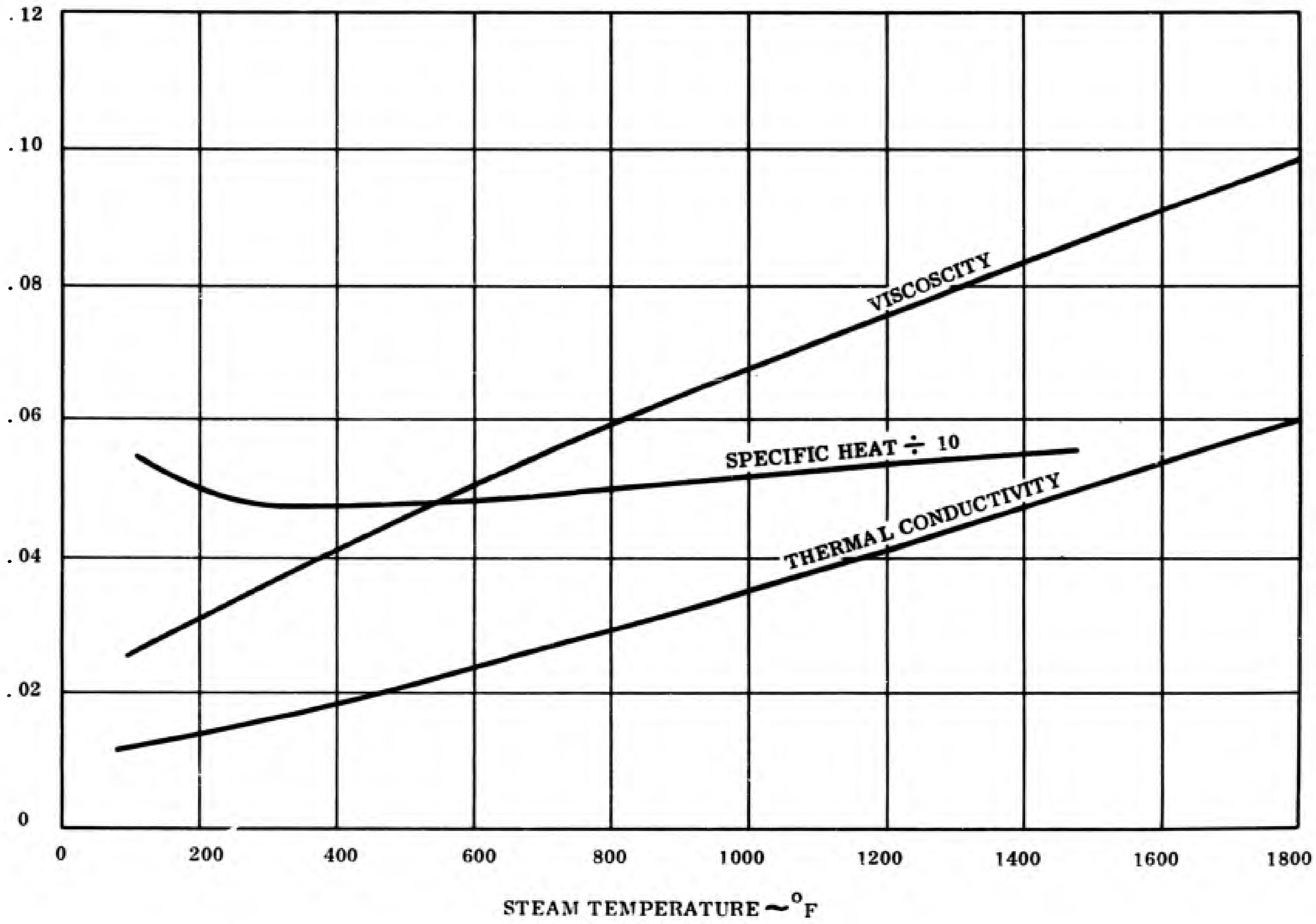


Figure 27. Steam Properties

EXTRAPOLATION OF CURVES FROM GE HEAT TRANSFER MANUAL G503.2. P.2. FIG 1A.
FOR L/D≫1

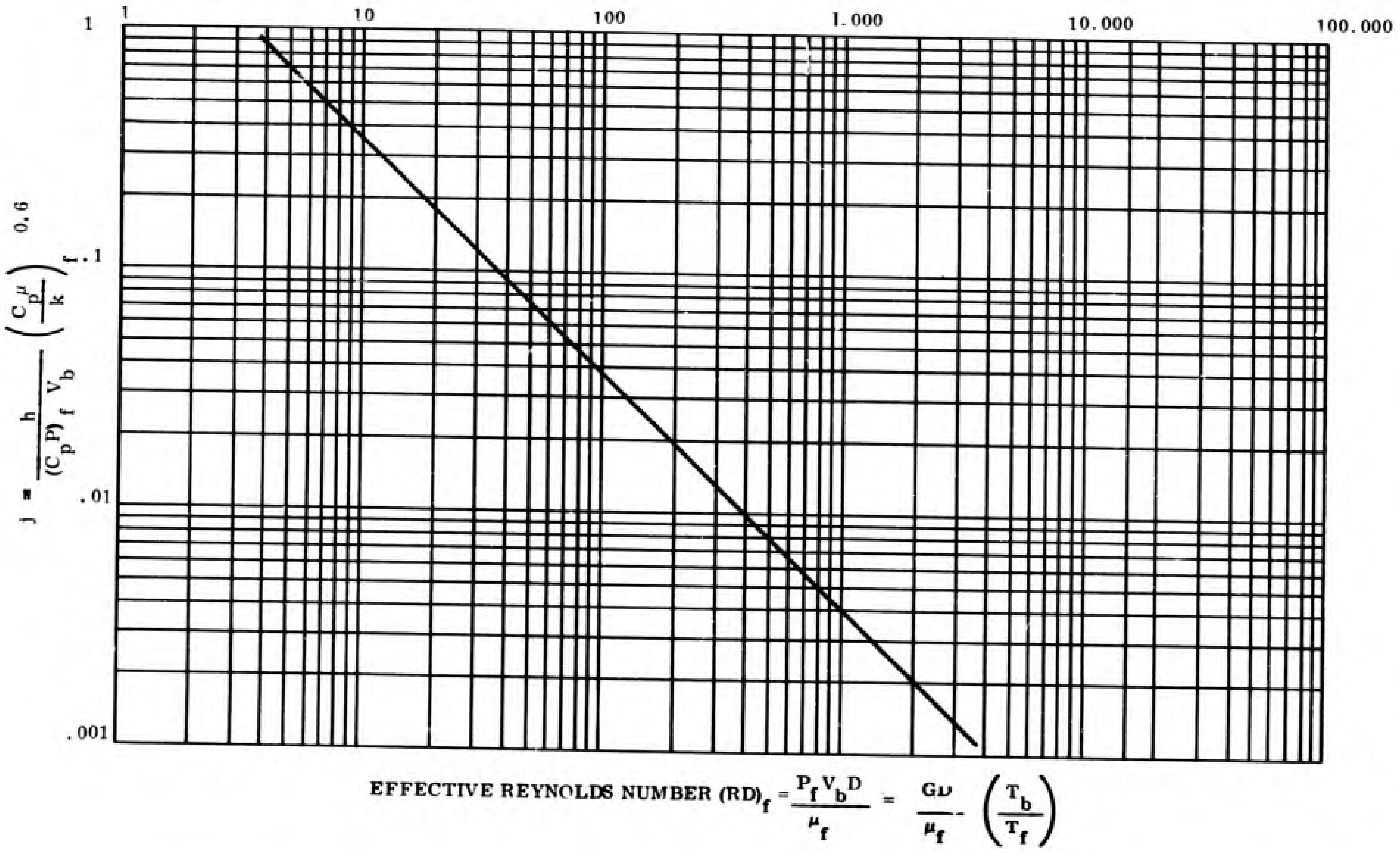


Figure 28. Steam Reynolds Number versus Heat Transfer Factor j

TABLE VIII STEAM PROPERTIES (FIGURE 6)

$T_5 = 120^{\circ}F$	$T_6 = 1540$	$T_7 = 1800$	$T_8 = 360$
$p_5 = 1.2$ psia	$p_6 = 1.2$	$p_7 = 1.1$	$p_8 = 1.1$
$\rho_5 = .00356 \frac{lbs}{ft\ 3}$	$\rho_6 = .000933$	$\rho_7 = .00780$	$\rho_8 = .00215$
$v_5 = 281 \frac{ft^3}{lb}$	$v_6 = 1072$	$v_7 = 1281$	$v_8 = 464$
$\mu_5 = .0264 \frac{lbs}{ft\text{-}hr}$	$\mu_6 = .089$	$\mu_7 = .089$	$\mu_8 = .039$
$R_5 = 34.7$	$R_6 = 10.4$	$R_7 = 8.58$	$R_8 = 26.4$
$J_5 = .105$	$J_6 = .35$	$J_7 = .42$	$J_8 = .140$
$k_5 = .012 \frac{Btu}{hr\text{-}ft^2\text{-}{}^{\circ}F/in}$	$k_6 = .052$	$k_n = .060$	$k_8 = .0175$
$V_5 = 16,960$ ft/hr	$V_6 = 64,750$	$V_7 = 77,400$	$V_8 = 28,000$
$h_5 = 3.09 \frac{Btu}{hr\text{-}ft\ 2\text{-}{}^{\circ}F}$	$h_6 = 12.1$	$h_7 = 15.1$	$h_8 = 3.85$

An analogue computer was necessary to the calculation of the tubing length. Accordingly, equating the heat transferred from the hot fluid at temperature T_h to the tubing wall temperature to the heat gradient of the hot fluid

$$k_H \pi d \left(T_H - T\right) = - \frac{WC_H}{\mu} \frac{dT_H}{dx} \qquad (12)$$

Similarly, for the heat transferred from the hot wall to the cooler fluid

$$h_c \pi d (T - T_c) = - \frac{WC_C}{\mu} \frac{dT_C}{dx} , \qquad (13)$$

And finally for steady state conditions the heat into the tube equals the heat out of the tube, giving

$$k \pi d t \frac{d^2T}{dx^2} - \frac{WC_H}{\mu} \frac{dT_H}{dx} + \frac{WC_C}{\mu} \frac{dT_C}{dx} = 0 . \qquad (14)$$

In these equations, the coefficients h_H, h_C, C_C, and h are not linear but may be approximated as functions of temperature as shown by Figure 6. Accordingly, solving (12), (13) and (14) simultaneously with the aid of a Reeves Analogue Computer enabled the length to be determined for 0.010 inch wall thickness as 5.20 inches (It is interesting to note that an approximate analysis which neglects tube conductivity indicates 2.0 inches to be adequate. This helps to explain why counter flow exchangers generally have very great length to tube diameter ratios, since then conductivity can be more safely ignored).

3. COUNTER-FLOW EXCHANGER AND PYROLYSIS UNIT THERMAL BALANCE

Considering that the input to the pyrolysis unit is 70 watts (239 Btu/hr), the thermal losses from the unit plus the useful output must total 239 Btu/hr, where the useful output is the difference in enthalpy between the inlet and outlet steam flows, 68 Btu/hr.

The heat losses from the unit consist of radiation losses through the superinsulation and conduction losses to the base. For one inch of insulation wrapped on a 4 inch diameter cylinder, 14 inches long capped with a 2 inch radius hemisphere

$$Q_R = k_R A \frac{\Delta T}{\Delta l},$$

$$\text{or } Q_R = .0025 \left[\frac{2\pi \times 2 \times 14}{144} + \frac{2\pi (2)^2}{144} \right] \frac{1730}{1/12} = 72.5 \frac{\text{BTU}}{\text{HR.}} \qquad (5)$$

The conductive heat transfer consists of two parts, the axial heat flow down the inner superinsulation-wrapped jacket, then to the base, and flow from the header at the cold end, down the element of the counter-flow exchanger to the base. Accordingly, the conductive losses are to a heat sink attached to the base. Considering the base to be at a uniform temperature, the conductive losses

$$Q_c = \frac{T_B - T_S}{R_C} A_C \qquad (16)$$

where

T_B is the temperature of the base,

T_S is the sink temperature (considered as 70°F)

A_C is the heat conduction area from the base to the sink,

and R_C is the thermal resistance.

Hence the conduction is proportional to the temperature drop across a fixed resistance, or

$$Q_C = C\,(T_b - 70^{\circ}F). \qquad (17)$$

Our thermal balance permits

$$Q_C = 239\text{-}68\text{-}72.5 = 98.5 \text{ BTU/HR} \qquad (18)$$

which it is intended will be accomplished by suitably insulating the base from the sink by "cut and try". It should be recognized that a base of 120°F is assumed here, consistent with the 120°F inlet temperature, while the inlet base is assumed designed to "float" or be isolated from the outlet.

In summary:

Losses	$Q_C = 98.5$ BTU/HR
	$Q_R = 72.5$ BTU/HR
Total	$Q_{tot\ loss} = 171$ BTU/HR
Input	$Q_{in} = 239$ BTU/HR

This gives a 40% safety factor.

APPENDIX V

CONDENSER VENTING

Continuous venting is feasible, since the loss of water appears to be trivial. Analysis indicates that a vent sized to discharge the condenser gas mixture will lose water at the daily rate given by:

$$\text{Venting rate of non-condensibles (lbs/day)} \times \frac{\text{specific wt. of water vapor}}{\text{specific wt. of non-condensibles}}$$

Approximating the non-condensible venting rate as the weight flow of O_2 into the system, and considering it to be 5 cc/min at STP conditions, the non-condensible venting rate

$$\dot{W}_{nc} = 5\ \text{cc/min} \times \frac{60\ \text{min}}{\text{hr}} \times \frac{24\ \text{hrs}}{\text{day}} \times \frac{1\ \text{in}^3}{16.4\ \text{cc}} \times \frac{1\ \text{ft}^3}{1728\ \text{in}^3} \times 0.0842 \frac{\text{lbs}}{\text{ft}^3}$$

$$= 0.0213\ \text{lbs/day}$$

Considering the partial pressure of the water vapor in the condenser to be 0.26 PSIA, and its temperature 60°F, and assuming three non-condensible partial pressures of 0.09, 0.19 and 0.29 PSIA. Then the specific weight of the non-condensibles are, respectively, 0.000517, 0.00109 and 0.001668 (lbs/ft^3). Accordingly, with the steam specific weight of 0.000828 lbs/ft^3, the daily water loss is shown by the following table:

Partial Pressure of Non-Condensibles, P_{nc}, PSIA	Spec. Wt. of Non-Condensibles W_{nc}, lbs/ft^3	Daily Water Loss $\dot{W}_{H_2O}$, lbs/day
0.09	0.000517	0.0341
0.19	0.00109	0.0162
0.29	0.001668	0.0106

These water loss figures indicate that the condenser can be operated with only about 0.5 lbs water loss during thirty days if the non-condensibles partial pressure is around 0.2 PSIA. Since venting will be to vacuum, supersonic flow will occur in the throat of the vent line. Considering the gas mixture will have a ratio of specific heat $\left(\frac{Cp}{C} = \gamma\right)$ of about 1.35, then $\frac{T_t}{T_s} = 1.18$, where T_t is the total temperature and T_s the static temperature.

Accordingly, with $T_t = 60^\circ F = 520^\circ R$

$$T_s = \frac{520}{1.18} = 440^\circ R = -20^\circ F$$

Thus the gas mixture, unless heated, will freeze in the discharge line.

Since the water loss is 0.0162 lbs/day which must be heated $50^\circ F$ to prevent freezing (along with the non-condensibles). Thus the heat required per day

$$Q_{vent} = (W\ Cp)_{gas} \times 50 + (W\ Cp)_{vapor} \times 50$$

$$= 0.0213 \times 0.217 \times 50 + 0.0162 \times 0.46 \times 50$$

$$Q_{vent} = 0.231 + 0.373 = 0.6 \text{ BTU/day}$$

This of course is so little it suggests merely securing the vent in close proximity to a warm body to prevent freeze-up.

The flow area required of the vent is estimated as the sum of the areas necessary to the vapor flow and the non-condensibles. Accordingly the vent orifice diameter is:

$D_{vent} = 0.008$ inches.

APPENDIX VI

WATER STORAGE RESERVOIRS

1. **REQUIRED VOLUME: (EACH RESERVOIR MUST HOLD 5 lbs H_2O)**

$$\frac{5\text{lbs}}{62.4} \times 1728 = 138.5\ \text{in}^3$$

Using 4" DIA (0.04 wall) spherical ended cylinder:

$$V_s = 4/3\,\pi\,(2)^3 = 33.5\ \text{in}^3 = 33.5\ \text{in}^3$$

$$Ac = \frac{\pi\,(4)^2}{4} = 12.57\ \text{in}^2$$

$$Vol_c = 138.5 - 33.5 = 105$$

$$Length_c = \frac{105}{12.57} = 7.95\ \text{in (make 8.5")}$$

using 0.04" thick bladder material, the bladder vol is:

$$V_s = \frac{4}{3}\,\pi\,(2^3 - 1.96^3) = 1.93\ \text{in}^3$$

$$V_c = 8.5\,\pi\,(4^2 - 3.92^2) = \frac{4.20}{6.13\ \text{in}^3}$$

The 8.5" length from (2) above allowed 12.57 (0.55) = 6.91 in^3 spare which is greater than 6.13 in^3.

2. SURFACE AREA RESERVOIR:

$$A_s = 4\pi\,(2.08)^2 = 54.4$$

$$A_c = 8.5\pi\,(4.08) = \underline{109.0}$$

$$\text{Total} \quad 163.4 \text{ in}^2 = 1.14 \text{ ft}^2$$

Stress:

P working = 25 PSID

P design = 100 PSID

S allow = 35,000 PSI

In cylinder (p. 268 Roark)

$$t = \frac{PR}{S} = \frac{100\ (2)}{35{,}000} = 0.00572 \text{ in} \qquad 0.04 \text{ in O.K.}$$

In spherical ends (p. 281 Roark)

$$t = \frac{PR}{S} = \frac{100\ (2)}{2(35{,}000)(1)} = 0.00286 \text{ in} \qquad 0.04 \text{ in O.K.}$$

3. WEIGHT

$$V_s = 4/3\pi(2.04^3 - 2^3) = 2.02$$

$$V_c = 8.5\pi\,(4.08^2 - 4^2) = \underline{4.34}$$

$$6.43 \text{ in}^3$$

Reservoir wt. = 6.43 (0.1) = 0.643lb

Bladder wt. = 6.17 (0.07) = 0.429lb (maximum) (assume SP.G. Rubber = 1.94)

Fittings 4.00 (0.1) = $\frac{0.400}{1.472\text{lb}}$ Total

4. THERMAL LOSSES (160°F RESERVOIR):

Using 1/2" thick covering of polyurethane insulation with K = $0.13 \frac{\text{BTU-in}}{\text{hr ft}^2\ {}^\circ\text{F}}$

Outside area = $4 (2.5)^2 + 5 (8.5) = 212 \text{ in}^2 = 1.47 \text{ ft}^2$

$$A = \frac{1.47 - 1.14}{2.3 \text{ LOG } \frac{1.47}{1.14}} = \frac{0.34}{0.255} = 1.34 \text{ ft}^3$$

T_s = Surface temperature of insulation

Q_1 = Conduction losses

Q_2 = Convection losses (72°F air @ 1 F.P.S.)

Q_3 = Radiation losses (75°F cabin walls)

$$Q_1 = Q_2 + Q_3$$

If $T_s = 89^\circ$F

$T_1 = 160 - T_s$

$$Q_1 - \frac{K}{r} A \ T_1 = \frac{0.13}{0.15} (1.34) (71) = 24.8 \text{ BTU/hr}$$

(p. 197 GEIDT)

$$N_{re} = dV = \frac{5 (6140)}{12} = 2550 \quad \text{and} \quad h = \frac{25}{\frac{5}{12}} (0.0148) = 0.89 \ \frac{\text{BTU}}{\text{hr ft}^2 \ {}^{\circ}\text{F}}$$

$$\Delta \ T_2 = T_s = 72$$

$$Q_2 = h \ A \ T_2 = 0.89 \ (1.47) \ (17) = 22.30 \text{ BTU/hr}$$ (p. 269 GEIDT)

$$\Delta \ T_3 = T_s - 75$$

$$Q_3 = h \ A \ T_3 = 0.11 \ (1.47) \ (14) = 2.27 \text{ BTU/hr}$$

$$Q_2 + Q_3 = 24.57 \text{ BTU/hr} \qquad 24.8 \text{ BTU/hr}$$

Therefore use 25 BTU/hr loss

5. REQUIRED THERMAL INPUT (160° RESERVOIR):

Must raise $\frac{5}{24}$ lb/hr of 61°F saturated liquid to 160°F

$$h_{100} = \frac{5}{24} (127.89) = 26.65$$

$$h_{69} = \frac{5}{24} (29.06) = \frac{6.05}{20.6} \sim \text{ 21 BTU/hr required}$$

Therefore

21 required input

25 losses

8 spare

54 $\frac{\text{BTU}}{\text{hr}}$ Total

6. HEATING LOOP (160°F RESERVOIR):

Lowering 625 lb/hr of 160°F saturated vapor from the condenser to 170°F

$$\Delta T_{LM} = \frac{200 - 10}{2.3 \text{ LOG} \frac{200}{10}} = 63.5$$

Using a heating jacket:

$$h_{vapor} = 30 \text{ (estimated from Hydro-John calculations)}$$

$$h_{water} = \frac{K}{t} = \frac{0.387}{0.166} = 2.34 \text{ (assuming t - 2 in. - 0.166 ft.)}$$

$$h_{alum} = \frac{100}{t} = \frac{100}{\frac{0.04}{12}} = 30{,}000$$

$$\frac{1}{U} = \frac{1}{30} + \frac{1}{2.34} + \frac{1}{30{,}000} = \frac{13{,}301}{30{,}000}$$

$$U = \frac{30{,}000}{13{,}801} = 2.17 \frac{\text{BTU}}{\text{hr ft}^2 \text{ }^\circ\text{F}}$$

$$A = \frac{54}{2.17\ (63.5)} = 0.392\ ft^2 < \text{Than } 0.75\ ft^2\ {}^oF \text{ cylindrical portion of reservoir}$$

7. THERMAL GAINS (61°F RESERVOIR):

Using the same approach as in Section 7 for the 160°F reservoir and assuming $T_3 = 70^oF$ (on surface of 1/2" insulation)

$$Q_2 + Q_3 = 2.62 + 0.81 = 3.43 \text{ BTU/hr and } Q_1 = 3.14 \text{ BTU/hr}$$

$$3.43 \sim 3.14$$

Heat gain is approximately 3.3 BTU/hr

Design to remove 5 BTU/hr

8. REQUIRED COOLING (61°F RESERVOIR):

From previous calculations the condenser cooling loop will deliver 430 lb/hr of 38% by weight ethylene glycol solution at 57°F and h = 1140 BTU/hr $ft^2\ {}^oF$ in 0.180 I.D. (0.035 wall) aluminum tubing.

Assuming a 1°F rise in the glycol solution

$$\Delta T_{lm} = \frac{3 - 4}{2.3\ \text{LOG} \frac{3}{4}} = 3.5^oF$$

With tubing spaced at 4 in C.T.C. distance

Longest path = 0.04 + 1.875 + 0.125 + 0.035 = 2.075 in. or 0.1725 ft

$$h_{al} = \frac{K}{t} = \frac{100}{0.1725} = 580$$

$h_{glyc} = 1140$

$h_{water} = \frac{K}{t} = \frac{0.339}{0.166} = 2.02$ (using t = 2" - 0.166 ft)

$\frac{1}{U} = \frac{1}{580} + \frac{1}{1140} + \frac{1}{2.02} = \frac{568}{1140}$

$U = \frac{1140}{568} = 2$

$A = \frac{Q}{U \Delta t_{LM}} = \frac{5}{2\ (3.5)} = 0.715\ ft^2 < 0.757\ ft^2$ of cylindrical portion of reservoir

BLANK PAGE

APPENDIX VII

SYSTEMS OPERATION

1. PREPARATION FOR OPERATION

The system is prepared for operation by providing electrical, pneumatic, coolant and vacuum connections, and the recorders for temperature measurements as follows:

a. Electrical Power

115 VAC, 60 cps electrical power is required. Total power required is less than 350 watts, including surges. A 28VDC supply is required. Power is about 50 watts with electrical heating of hot water reservoir.

b. Pneumatic Power - Nitrogen

A nitrogen supply is connected at the bulkhead fitting. The supply can be any pressure between 100 and 2250 psig.

c. Vacuum - Rough

The rough vacuum connection is made at the bulkhead. Connection shall be to a roughing pump capable of pumping at least 40 liters/minute at 29.5 in. Hg. vacuum.

d. Vacuum - Hard

A combination mechanical and diffusion pump, provides the continuous pumping required by the vacuum insulated jacket of the pyrolysis unit. Connection for this is made at the bulkhead fitting.

e. Coolant Connections

The coolant (water or aqueous glycol) for the condenser and cool water reservoirs is brought to and from the bulkhead fittings.

2. OPERATION OF THE SYSTEM (Electrical Heating)

a. Start-Up

The start-up procedure is to accomplish the following:

1. Provide a sequence of operations whereby all of the water collected is potable;
2. Accomplish this without inducing adverse effects upon the equipment.

Accordingly, the sequence of operations is as follows:

- a. Pump the vacuum jacket - initially, rough down the jacket. When the pressure is on the discharge vacuum gage scale, the diffusion pump is turned on. Adjust the coolant flow through the diffusion pump until it results in the line being warm to the touch. Satisfactory operation occurs with the jacket being in the 10^{-4} mm Hg. pressure range.
- b. Turn on the evaporator roughing pump.
- c. Turn on AC power, then apply voltage through the variac to the electrical heaters of the pyrolysis unit. Adjust the voltage as necessary to assure the jacket's pressure staying "on scale," or less than 25×10^{-3} mm Hg. abs.
- d. Sufficient time (approximately 4-8 hours) to permit the pyrolysis unit to achieve a temperature of 1200°F or hotter.
- e. Turn on DC power.
- f. Turn on the evaporator's electrical heaters through the evaporator variac.
- g. When the evaporator urine temperature reaches 120°F, steam is generated in the evaporator, flows through the pyrolysis unit to the condenser and is then pumped into potable water storage tanks. With a continuous supply of urine, normal operation will result.

3. OPERATION OF THE SYSTEM (Waste Heat)

Operation of the system using waste heat for evaporation of urine requires the replacement of the electrical heating units of the evaporator with the finned coil for waste heat. The start-up procedure then consists of all of the steps followed using electrical heat, except step f. Instead of turning on the evaporator's electrical heaters, the waste heat working fluid is circulated through the evaporator's heating coil.

4. OPERATION OF THE SYSTEM (Isotope Heating)

Preparation for isotope heating in lieu of electrical heating requires the replacement of the electrical heating units in the evaporator (3) and pyrolysis unit (1) by isotope heaters.

The start-up procedure is altered from that of the electrical heating. Accordingly, the start-up consists of:

a. Pump the vacuum jacket as in 2a.

b. Turn on the evaporator roughing pump.

c. Turn on AC power

d. After the pyrolysis unit is at temperature, 1200°F or higher, turn on DC power admitting urine to the evaporator.

e. When the urine temperature reaches 120°F, operation should be automatic as with electrical heating.

5. EMERGENCY OPERATIONAL PROCEDURES

Analysis and tests have indicated that no induced failures will result from thermal causes, even in the event of a failure causing 100% of the design flow to cease. Accordingly, though temperatures will rise, the components in which the isotopes are packages (evaporator and pyrolysis unit) will not fail.

Emergency operating procedures, then, are aimed at rectifying difficulties which arise with the system exclusive of the heating source.

a. Hard Vacuum Failure

If the hard vacuum should fail, for either pump causes or jacket leakage reasons, the hard vacuum valve should be shut and a bleed valve opened to permit an air flow to reduce the temperature of the pyrolysis unit to save the superinsulation from oxidation.

b. Rough Vacuum Failure

Failure of the evaporator's roughing pump, or leakage causing a rise in system pressure will result in a decreased generation of potable water. No catastrophic effects will be induced. Operation may be continued so long as hard vacuum is maintained and pyrolysis temperature remains greater than 1200°F.

c. Cooling Supply Failure

Failure of the coolant supply will raise the system pressures and simply reduce the rate of collection of potable water. No catastrophic effects are anticipated. In the event of this failure, the repair should be effected with no shut-down of the unit.

d. Liquid Supply Failure

Two failures are included in this category. One, the urine or processed water does not get to the evaporator; or two, an excess of urine gets to the evaporator. In the former case, no steam is generated. An immediate fix, restoring the urine supply is all that is necessary. No supplementary emergency action is necessary.

If the supply failure causes an excess of liquid to be admitted to the evaporator, this could result in liquid reaching the phase separator and eventually carrying over solids to the pyrolysis unit. Accordingly, it is essential that this condition be corrected. The immediate corrective action is to open the 28VDC supply to the system, shutting the urine inlet solenoid valves, permitting repair to the system.

e. Heater Failure

An electrical heater failure will consist of either a shorted heater element or an open heater element. If the former occurs, excessive power demand might open the circuit breaker on the variac. However, if the breaker does not open, the heating element will burn out. With a shorted heater, the fix is to remove that heater's electrical power input and continue operation on 2 heaters (if the failure is in the evaporator). Of course, if an open heater element occurs, no need exists for removing the power input to that heater.

If the failure occurs in the pyrolysis unit, operation must be stopped to avoid contaminating the collection system with non-potable water. Accordingly, the power is to be removed from the heater, then the by-pass valve is to be opened at a rate whereby the valve is full open when the pyrolysis temperature becomes 1200°F or lower.

f. Water Pump Failure

A failure of the water pump will be indicated by a rise in system pressure. If delayed sufficiently, water will reach the roughing pump. However, no catastrophic failure will be induced.

The fix is the correction of the difficulty in the pump.

g. Water Dispensing System Failure

A failure in the collected water's dispensing system would occur with either a single solenoid dispenser failure (manifesting itself as continuous flow from that dispenser or no flow obtainable from that dispenser), or a failure of the water pressurization system (which would affect all dispensers equally). Neither case causes catastrophic failure. The former case, involving a single dispenser, necessitates a DC power shut-off while the solenoid valve is replaced. The latter case, involving a pneumatic failure, necessitates the shut off of the nitrogen supply and the replacement of the failed element, i.e., tank bladder, valve, etc.

5. SHUT-DOWN

The shut-down procedure is to enable the ceasing of normal operation without contamination of the system downstream of the condenser which would require subsequent sterilization. Accordingly, shut-down steps are as follows:

a. Open the air bleed valve.

b. When the pyrolysis temperature drops below $1000^{\circ}F$, open the bypass valve.

c. If electrical heaters are used, shut these off.

d. Turn off DC and AC power.

e. Turn off the evaporator roughing pump.

f. Turn off the heater of the diffusion pump.

g. When the diffusion pump heater is cool to the touch, turn off its mechanical backing pump.

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
General Electric Company
Philadelphia, Pennsylvania 19101

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP
N/A

3. REPORT TITLE
VACUUM DISTILLATION, VAPOR PYROLYSIS WATER RECOVERY SYSTEM UTILIZING RADIOISOTOPES FOR THERMAL ENERGY

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final Report, 5 May - 4 July 1967

5. AUTHOR(S) *(First name, middle initial, last name)*
H. Esten
R. W. Murray
L. Cooper

6. REPORT DATE
November 1967

7a. TOTAL NO. OF PAGES
82

7b. NO. OF REFS
0

8a. CONTRACT OR GRANT NO. AF 33(615)-3308

b. PROJECT NO. 6373

c. Task No. 637305

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
General Electric Co. No. 67SD8124

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
AMRL-TR-67-80

10. DISTRIBUTION STATEMENT
Distribution of this document is unlimited. It may be released to the Clearinghouse, Department of Commerce, for sale to the general public.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Aerospace Medical Research Laboratories
Aerospace Medical Div., Air Force Systems Command, Wright-Patterson AFB, O. 45433

13. ABSTRACT

A laboratory prototype system for producing, storing and dispensing potable water derived from urine and wash water has been designed, fabricated, and tested. The design incorporated the previously established technique of vacuum distillation of liquid wastes followed by pyrolysis of the steam in the presence of a catalyst. For the first time, radioisotope heat sources (containing Plutonium 238) were employed in both the evaporator and pyrolysis sections to minimize the electrical power requirements for a potential space application. The system was also designed to utilize electrical and waste heat sources and is capable of zero gravity operation. The basic process demonstrated its feasibility for long duration operation producing high quality potable water. Peripheral equipment, such as, liquid level sensors, and phase separators need further development. Unit weight was 120 pounds and power consumption was 56 watt-hours per pound of water recovered. A flight optimized design using isotopes would weigh 58 pounds and consume 8 watt hours per pound of water recovered.

DD FORM 1 NOV 65 1473

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Life Support						
Vapor Pyrolysis						
Radioisotope						
Water Recovery						
Zero Gravity						
Water System						

Security Classification