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WATER RECLAMATION FROM URINE THERMOELECTRIC SYSTEM

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FOREWORD

This project was conducted at Research and Engineering Laboratories, Whirlpool Corporation, St. Joseph, Michigan, under Contract No. AF33 (657)-11479, "Research on the Recovery of Potable Water from Urine by Thermoelectric Distillation" for the Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson AFB, Ohio. The work was performed in support of Project No. 6373, "Equipment for Life Support in Aerospace," and Task No. 637304, "Waste Recovery and Utilization." Albert B. Hearld, Biomedical Laboratory, was the contract monitor for the Aerospace Medical Research Laboratories. The project was initiated in May 1963, and completed in October 1964. Principle investigator on this project was Duane C. Nichols, and significant contributions were made by the following Whirlpool personnel: J. T. Cross, Water Purification and Analysis; R. L. Eichhorn, Project Supervisor; L. W. Hayes, Engineering Design; R. G. Sickert, Electrical Controls and Testing; and R. Wheaton, Microbiology.

This technical report has been reviewed and is approved.

WAYNE H. McCANDLESS
Technical Director
Biomedical Laboratory

ABSTRACT

This project was initiated to design, fabricate, and test a thermoelectric system for the recovery of potable water from urine in aerospace applications. The unit built is an integral system, which yields quality potable water at a performance factor of 146 watt-hours per pound. It has a capacity of processing 12 liters of urine per day with a batch size of 1 liter per run. Further development work should be undertaken toward obtaining better efficiencies, a decrease in size, and a reduction in weight.

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SECTION I

INTRODUCTION

Background

Waste water, which is normally considered expendable, must be salvaged and processed for reuse on manned space missions of greater than a few days duration. Studies have been made which conclude that a distillation method is the most practical means of water recovery for the present state of the art.[1] A thermoelectric heat pump is one of several techniques for distillation which might provide a high-efficiency, lightweight, compact system. A heat pump operates by absorbing heat at one location, transporting it to another location, and releasing it there. Because a thermoelectric heat pump can utilize the latent heat released from the condensing steam by transferring it back to the boiler section for evolution of additional vapor, the method results in a very high efficiency relative to external input. A thermoelectric unit can also be easily miniaturized and is a static device. This project was initiated to evaluate the thermoelectric distillation process for recovery of potable water from urine for aerospace applications.

Scope

The scope of work performed included:

(1) A feasibility investigation to determine the potential effectiveness of thermoelectric distillation techniques for recovery of water from urine.

(2) A design study to establish and prepare design criteria for a thermoelectric distillation water recovery system including calculations, layouts, drawings, and other information necessary for the fabrication of a unit.

(3) The fabrication and testing of a thermoelectric distillation system.

Design Objectives

Within the framework of this scope, certain specific design objectives were to be met by the unit to be built on this project. These were:

(1) Minimum output of potable water per 24-hour period will be 5 liters.

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[1] Wallman, H. and S. M. Barnet, Water Recovery Systems (Multi-variable) WADD Technical Report 60-243, Wright Air Development Division, Wright-Patterson Air Force Base, Ohio, March 1960.

(2) Primary input to the system will be urine, with other liquid sources being of academic interest.

(3) Size, weight, and power are to be minimized.

(4) Percent recovery should be the maximum consistent with maintenance of a quality effluent.

(5) Unit must function under the following environmental conditions:

a) Variable ambient pressures between 1/3 and 1 atmospheres

b) Weightlessness

c) Temperatures of 60° and 75° Fahrenheit (16° to 24° C)

d) Relative humidities of 30 to 50 percent

e) Cabin atmosphere leakage rate of 1 pound per minute

(6) Unit should be designed to withstand the following G load applications:

a) Acceleration - 4.5 G peak axial and lateral with respect to the vehicle axis with possible 8 G peak axial - 10 minute duration

b) Deceleration - Less than during acceleration

c) Impact - 25 G axial and 10 G lateral

Special Test Requirements

Upon completion of the laboratory model, testing is to include a simulated 14-day run with the urine from three men (or equivalent) processed and the recovered water thoroughly tested. Standards for water potability are to be those established as the U. S. Public Health Standards (1961) for drinking water. The unit is to be tested under any of the variable environmental conditions of temperature, humidity, or cabin pressure which might affect the results of unit operation.

SECTION II

SYSTEM DESIGN

Feasibility Study

The feasibility of utilizing a distillation process for recovery of potable water from urine has been previously established and successfully accomplished with laboratory models. The object of this phase of the project was to establish the feasibility of building a high-efficiency thermoelectric distillation unit which would function under zero-gravity conditions. Although the distillation process is very simple, most apparatus designed for it are inefficient. The thermoelectric heat pump principle coupled with a good design will yield a high-efficiency device.

Figure 1 shows a thermoelectric distillation system in its simplest form. Liquid is vaporized in the boiler section; the vapor migrates to the condenser section where it condenses, and the latent heat of condensation is thermoelectrically pumped back to the boiler for reuse. The effectiveness of the heat pump is determined by the ratio of the quantity of heat pumped by the cold side of the unit to the power input to the unit. This efficiency of the basic thermoelectric module is termed the coefficient of performance (COP) and the maximum COP is given by equation 1.

$$COP_{max} = \frac{T_c}{T_h - T_c} \times \frac{\sqrt{1 + ZT_m} - \frac{T_h}{T_c}}{\sqrt{1 + ZT_m} + 1} \qquad (1)$$

In which:

T_c - Cold Side Temperature ($^\circ$ K)

T_h - Hot Side Temperature ($^\circ$ K)

T_m - Mean Temperature $\frac{T_h + T_c}{2}$ ($^\circ$ K)

Z - Figure of Merit ($^\circ$ K $^{-1}$)

The figure of merit is a function of the basic thermoelectric material properties and represents the semiconductor quality. At 100° C, the operating figure of merit of current commercial thermoelectric materials is approximately 2.1×10^{-3} $^\circ$ K $^{-1}$. These materials are designed for use at refrigeration temperatures and would have improved

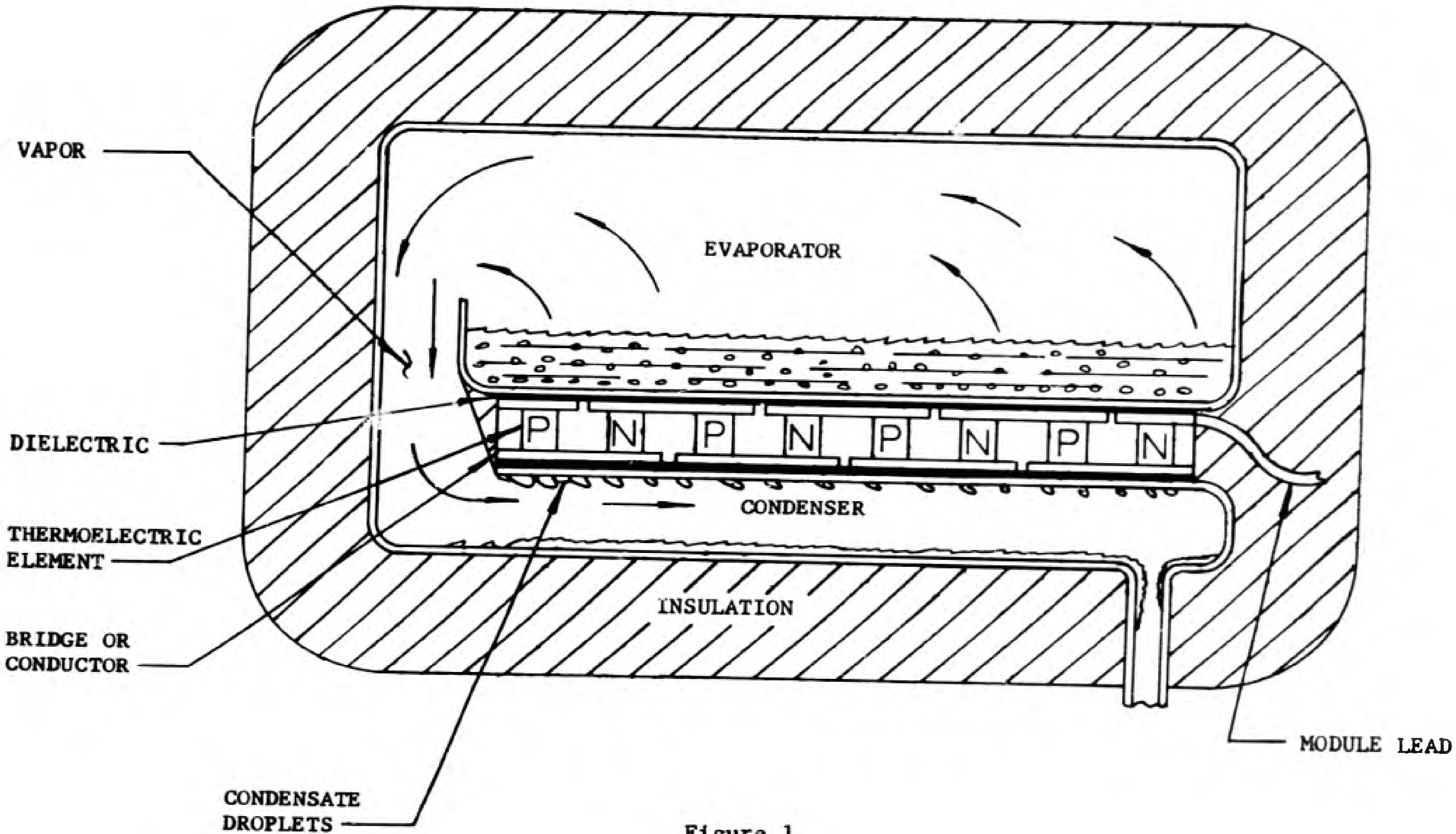

Figure 1

Cross Section of Thermoelectric Still

quality at lower operating temperatures with a maximum operation figure of merit of $2.6 \times 10^{-3}\ {}^{o}K^{-1}$. From equation 1 it is apparent that the efficiency of a thermoelectric heat pump is a function of three factors: the temperature level, the temperature differential, and the quality of the thermoelectric material. In a distillation system application, the temperature differential is the prime factor to be considered in obtaining a high efficiency. The quality of thermoelectric material is fixed by the quality available from vendors, and the temperature level is bracketed by the range of pressures at which the unit might operate. The total temperature differential across the thermoelectric system is the sum of several individual temperature drops within the distillation system. Each of these drops will be examined individually. The feasibility calculations will be based on a process time of 20 hours for the required 5 liters of water. This yields a rate of heat transfer of approximately 550 BTU/hr. Assuming that the boiler surface area will be 0.5 square feet, the heat flux will be 1100 BTU/hr ft^2.

As the heat passes from the hot side of the thermoelectric module to the boiler, the first thermal barrier is encountered. It is a thermally conducting grease and dielectric film. One of the best dielectric materials for this film is an aluminum anodic coating because of its high thermal conductivity. Experience has shown that a realistic figure for the temperature drop for this barrier under the assumed conditions would be 0.1^o C. If the boiler plate is 0.062 inches (0.25 cm) thick and is made of aluminum, then the temperature drop through it would be 0.05^o C at 1100 BTU/hr ft^2. As the heat is transferred from the aluminum to the liquid, a significant temperature drop occurs. This drop is a function of the heat flux, the nature of the aluminum surface, the nature of the boiling mechanism, the operating pressure, and the concentration of the liquid solution. A study and analysis of literature on the transfer of heat to boiling liquids yielded a figure of 2.3^o C as being representative for the differential between the plate and the liquid.

It was necessary to empirically determine the difference in temperature levels between the boiling urine and the vapor. A typical curve of the results is shown in figure 2. Although the difference in temperature between boiling water and water vapor is normally only a few tenths of a degree Celsius, the constituents of urine raise its boiling point above that of water. As the concentration of the other constituents relative to water increase in the solution during the boiling process, the differential between the boiling liquid urine and vapor temperatures increases. From the simple laboratory tests, an average value for the temperature differential was calculated to be 1.1^o C for operation at atmospheric pressure.

The vapor temperature was 213^o F (100.5^o C). The differential between the vapor temperature and the expected boiling point of water (100.0^o C) was attributed to (1) superheat of the vapor, and (2) carry over of organic acids in the vapor.

As the vapor condenses, another temperature drop occurs which depends on the rate of condensation and the type of condensation. If dropwise condensation could be reliably obtained, very high transfer coefficients could be realized; however, it is unlikely that dropwise condensation can be maintained throughout the life of the unit; therefore, film condensation will be used for calculations. The same rate and flux assumptions will be

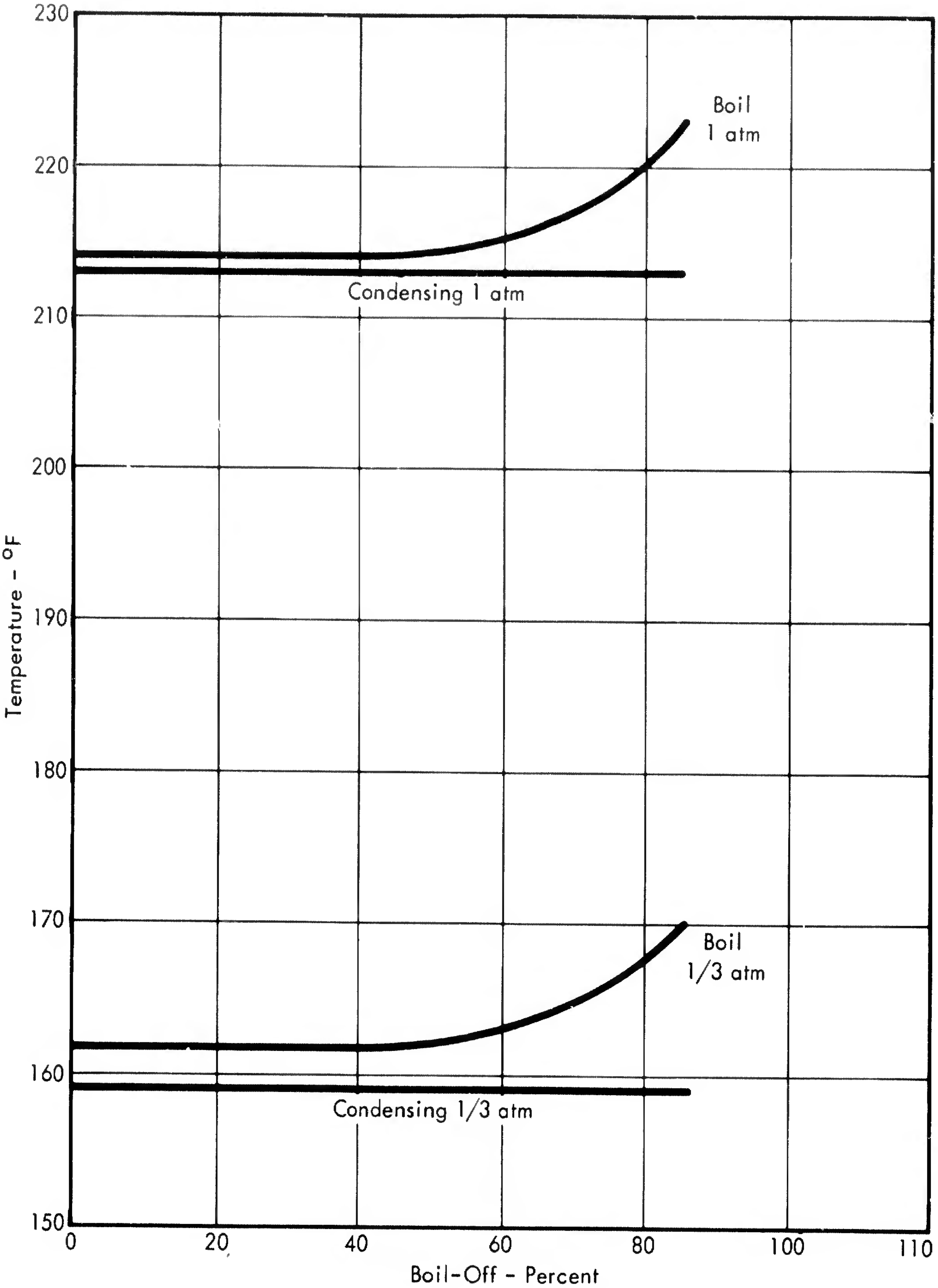

Figure 2

Urine Distillation Temperatures

made for the condenser as for the boiler. Available literature (see Bibliography) on the subject indicated a coefficient of heat transfer of 1700 BTU/hr ft^2 $^\circ$F would be realistic which will yield a value of 0.33° C temperature drop. The temperature drop across the dielectric film and through the condenser plate will be the same as for the hot side.

The sum of the various temperature drops discussed in the proceeding paragraphs is 4.0° C and is $(T_h - T_c)$.

Substituting the above values into the maximum COP equation (equation 1) yields a value of 12.8, which means for every watt input in electrical energy, 12.8 watts of heat energy will be recovered from the condensing vapor. The actual efficiency of the distillation unit will be COP + 1 or 13.8 times that of a unit in which no heat is recovered. Translated into boiling efficiency, this is equivalent to 21 watt-hours per pound. It is apparent that a high efficiency thermoelectric unit could be built; however, it should be cautioned that the feasibility efficiency developed above is an ultimate value which would require a perfect design. In practice, this value could not be achieved, because such design factors as heat balance, etc, could not be controlled to achieve the ultimate.

Because of the zero-gravity-operation specification, additional forces or constraining means will have to be used as necessary in the system. Some possibilities are: centrifugal forces, capillary action, and semipermeable membranes. The zero-gravity specification will complicate the design and possibly lower the efficiency, but will not place any restrictions on a thermoelectric design that it would not place on any other approach to a distillation process.

The ability of a thermoelectric unit to withstand the acceleration and impact forces depends on the specific design. Thermoelectric modules installed in other units built by Whirlpool Corporation have been tested for shock in accordance with Military Specification Mil-E-5272C, procedure IV, paragraph 4.15 at an inpact of 50 G for 11 milliseconds, and have successfully passed with no adverse effects.

Preliminary Design

Several approaches that could fulfill the basic operational requirements were investigated. After evaluating each approach, we decided that: (1) a batch process would be used, (2) the unit would be operated at an absolute pressure of approximately 3.5 inches of mercury, (3) the filter would be an integral part of the unit, and (4) the effects of zero gravity would be overcome by rotation of the entire unit.

A batch process provides the simplest approach to the design and also results in the highest efficiency. The efficiency of the unit is a function of temperature differential which, in turn, is a function of the concentration of the various constituents in the urine. As the water is selectively distilled from the urine, this concentration increases and, consequently, the temperature differential increases. Use of a batch process results in both a slower rate of concentration increase than a continuous process and a better average efficiency.

However, the use of a batch process precludes taking full advantage of recovery of heat from the effluent water. Therefore, to maintain a high efficiency by keeping heat-up to a minimum, a low temperature boil is advisable. Operating at the low temperature or low pressure offers additional advantages. At the low temperature, the distillate is of a much better quality, because the urea does not decompose. The higher quality distillate can be made taste-and-odor-free by passing it through a charcoal filter, whereas the distillate of an atmospheric pressure process must also be passed through an ion-exchange resin bed. Pretreatment of the urine is also necessary to minimize ammonia carry-over and to control foaming and scaling in the boiler for atmospheric distillation. A second definite advantage of low pressure boiling in this application is a constant boiling temperature. If the unit pressure were allowed to follow the cabin pressure, the boiling point would continuously change, drastically reducing efficiency. Also, a special vapor vent would be required to dispose of disagreeable odors produced by the decomposition of the urine constituents for an atmospheric boil. In the low pressure system, space vacuum will be utilized and any odors, which have been minimized by a low temperature boil, will be discharged to the vacuum.

The distillate will require treatment with a charcoal filter to reduce any adverse odor or taste to a minimum. A column 1 square inch in cross section and 54 inches long will adequately process the required quantity of distillate for the full 14-day period. Integration of this posttreatment column in the device minimizes water handling problems, since the output of the unit will be quality potable water.

Rotation of the unit is the simplest technique to effectively maintain separation of the liquid and vapor phases. Rotation will also be used to induce fluid flow in the system.

Based on the foregoing approach, a unit was designed and built which consists of five major components. These are: (1) boiler (2) thermoelectric heat pump, (3) condenser, (4) filter, and (5) storage tank. The boiler is located at the center of the concentric design. (See figure 3.) Several important factors influenced the basic design of this component. First, the internal surface of the boiler is critical because of the potentially high temperature drops which can occur at the interface, and within the liquid, during boiling. Both ribs and grooves were used on this surface to minimize this drop. The ribs have a further function of being structural members for the boiler walls. The boiler cross section is an octagon to permit the best application of the heat pump modules to the unit.

Although rotation of the unit will keep the liquid against the wall during normal operation, the possibility of random spillover of urine exists when the unit is being filled under zero gravity. Prevention of this spillover is accomplished by a series of concentric interleaved baffles at the vapor outlet of the boiler. The vapor outlet of the boiler discharges the steam to a distribution chamber which is connected to the eight condenser tanks. These tanks are also interconnected on an extreme perimeter to permit fluid flow and discharge. Internal extended surfaces are used to obtain a maximum efficiency from the condenser tanks by minimizing the temperature drops.

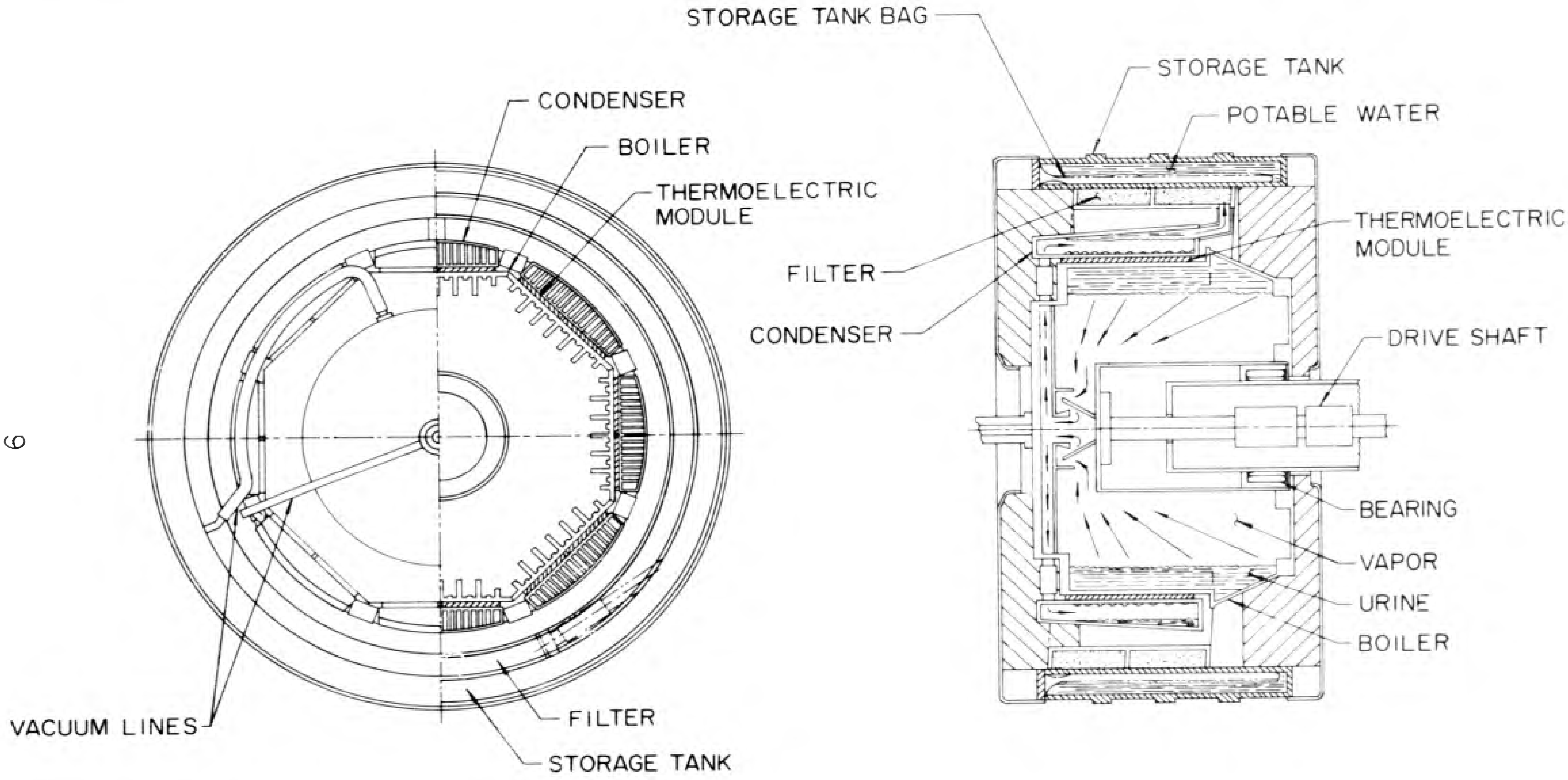

FIGURE 3
SCHEMATIC SECTION
MAIN ASSEMBLY
THERMOELECTRIC DISTILLATION UNIT

The thermoelectric heat pump module is sandwiched between the boiler and condenser tanks. Its design was optimized for operation at a temperature differential of 4.5° C and a current of 7 amperes to produce the required 5 liters of potable water per day.

The condensed liquid flows from the condenser tanks through a helical charcoal filter and into the storage tank. A plastic bag within the storage tank provides the means for expelling the potable water under zero-gravity conditions and maintains separation between the air and water.

Design Development

During initial testing of the device, it became apparent that three problem areas existed. One of these was urine spillover from the boiler into the rest of the system. Although the baffles fulfilled the primary function of preventing spillover when the unit was not rotating, urine was being forced into the condenser section whenever a pressure differential existed between the boiler and condenser while the unit was in operation. This pressure differential existed under three conditions: (1) during initial evacuation of the system, (2) whenever the boiler was not vacuum tight, and (3) during boiling. Apparently, splashing was occurring in the unit under normal running conditions and the clearances were not sufficient between baffles. Consequently, a water (urine) seal was developing between baffles, and whenever a pressure differential was created across the network, the liquid forming the water seal was forced through the baffles into the condenser section. Although increasing the clearances between baffles would have eliminated the pumping action, it would have required major rework on the boiler section. Therefore, two alternate steps were taken; the speed of rotation was increased to 200 rpm and the batch size was reduced to 1 liter. The combination of changing both these operating conditions eliminated the splashing and, hence, spillover of urine.

The increase in rotational speed further complicated the second problem area, the rotational drive. Originally it was planned to manually spin the device to overcome inertial forces and static friction. However, the inertia of the unit was too great to achieve 120 rpm with a manual start. Investigation revealed that a minimum torque of 8 inch-pounds was needed to accelerate the apparatus to the required speed. Of course, once the unit has reached speed, the torque requirement is significantly decreased. A commercially available gear motor was installed to facilitate evaluation of the remainder of the device.

Later testing of the unit showed another area that needed refinement. It was very difficult to obtain a completely air-free state in the charcoal filter and storage tank, and even more difficult to maintain it. The design of the unit demanded that these sections be completely air-free. The problem was easily overcome by the addition of a vacuum tap on the storage tank.

After some preliminary tests, during which an operating level was determined for highest efficiency, evaluation tests were run. The operating current for best efficiency was higher than the initial design, and it was possible to obtain almost twice the required process volume from the unit.

The operating current was high because the temperature differential was slightly lower than had been used in design calculations, and the optimum heat balance was not obtained. The deviation from optimum heat balance also affected the efficiency of the thermoelectric heat pump.

The power supply and control system for the system consisted of a full wave, filtered, direct-current power supply and a three-cam-timer system. The timer controlled the boiling cycle according to a preset schedule as explained in section III.

The thermoelectric distillation unit built during this project is shown in figure 4. The main assembly and frame is 24 inches wide by 18 inches deep by 18 inches high, and weighs 49 pounds.

Although the unit was designed specifically for processing of urine, it can be used for recovery of water from other types of waste water in aerospace missions. However, water which has any type of oil in it should not be used; since the oil may coat the interior surfaces of the boiler and reduce the unit's efficiency.

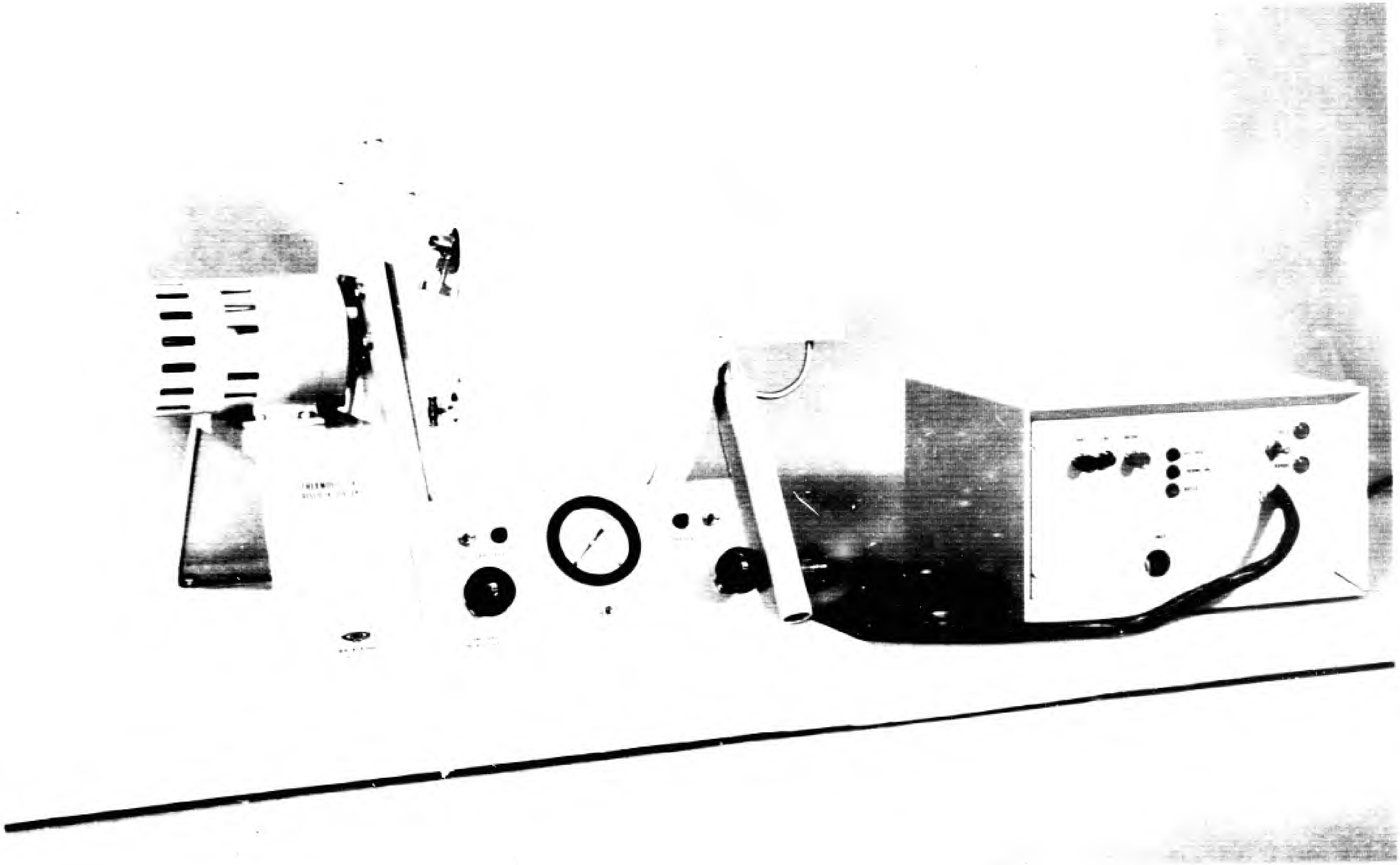

Figure 4

Thermoelectric Distillation Unit

SECTION III

SYSTEM EVALUATION

Test Program

The test program was performed in two phases: (1) shakedown test phase, and (2) the 14-day-performance test phase. During the shakedown tests, operating specifications were established and monitoring systems were checked. The 14-day test was a simulated run to both evaluate performance and system reliability.

Shakedown Tests

Shakedown testing of the distillation system was accomplished using urine and colored deionized water as the test charge temperature, and approximate boil time was established.

The complete system was initially instrumented as follows:

Pressure Measurement	-	Gage Located in Still Frame
Thermoelectric Unit Input	-	Recording D-C Ammeter Recording D-C Voltmeter
Auxiliary Heat Input	-	A-C Wattmeter
Drive Motor Input	-	A-C Wattmeter
Temperature Measurement	-	Recording D-C Millivoltmeter

Boiler temperature was measured with a copper-constantan couple using an ice bath reference. Boiler-condenser temperature difference was measured using a differentially connected thermocouple. Output of this thermocouple relates directly to temperature difference.

With this instrumentation, it was possible to continually monitor performance of the system through an operating cycle and, therefore, make possible a quick evaluation of performance at various inputs.

A typical operating cycle is shown in figure 5. Because the still cycle is solely controlled by the time, entry temperature of the urine is important to insure that the time allowed for application of auxiliary heat is adequate to insure initiation of charge boil. The portion of the time cycle designated "preheat" is devoted to bringing the urine charge to boil temperature. During preheat, the temperature difference between boiler and condenser increases to a maximum value at which the heat pump is in thermal balance. As boiling starts, the temperature difference

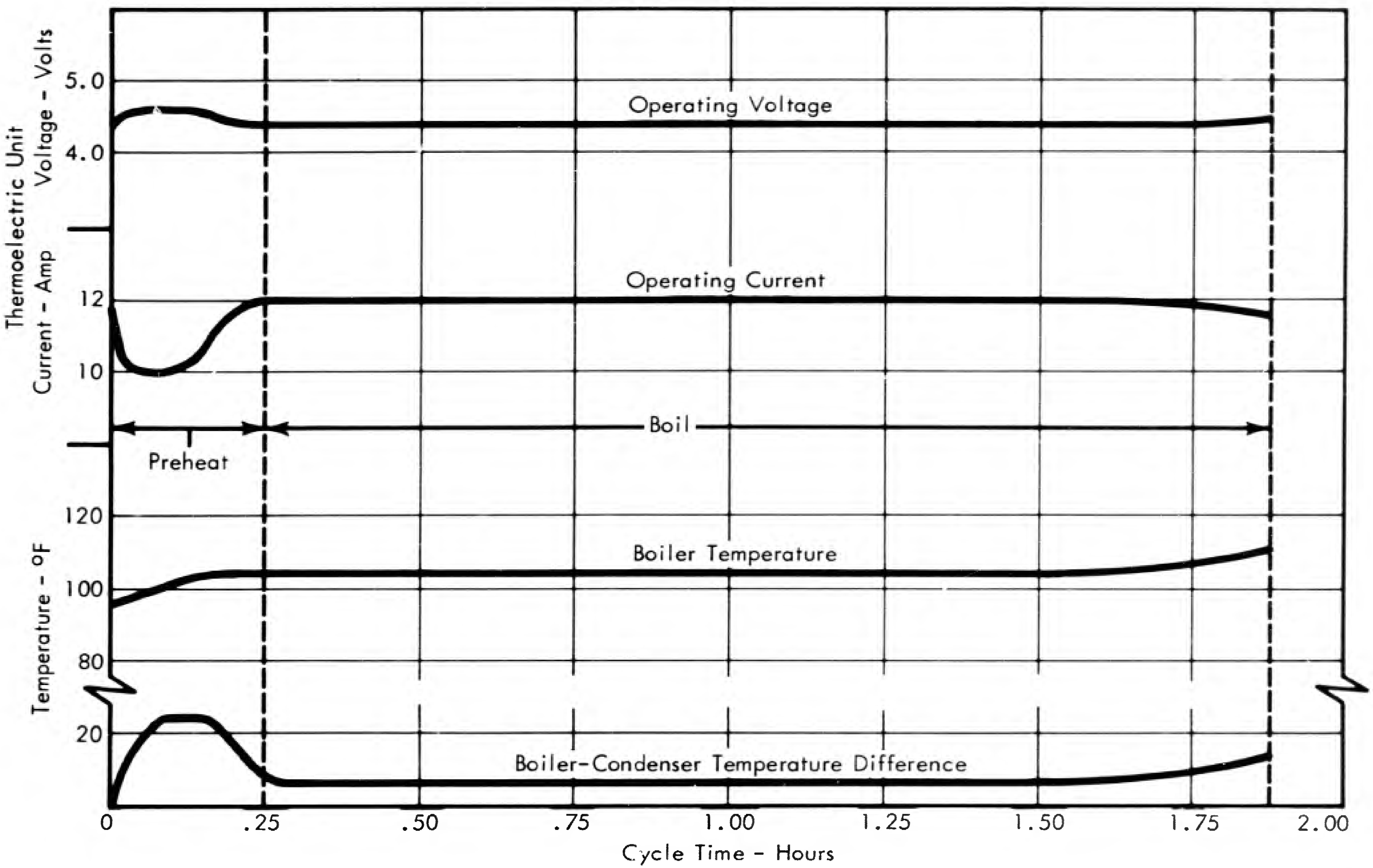

Figure 5

Typical Operating Cycle

decreases because of the heat load imposed by water vapor condensing in the condenser tanks. This temperature difference then remains relatively constant, as does boiler temperature, until termination of the cycle. The auxiliary heat input is terminated when the temperature difference reaches the constant low level. Near the end of the operating cycle, the temperature difference and boiler temperature increase, due to a reduction in effective boiler heat transfer area caused by the decreasing charge level and by the increasing concentration of solids. The cycle is terminated at such a time as will yield approximately an 85-percent boiloff.

The following cycle and set of operating conditions were established for the initial portion of the 14-day run.

Entry Urine Temperature	-	38° C (100° F)
Urine Charge	-	1 Liter
Still Pressure	-	3.5 Inches Mercury Absolute
Total Run Time	-	1.97 Hours
Auxiliary Heat Time	-	0.25 Hour
Boiling Time	-	1.72 Hours
T. E. Input at Boil	-	12.0 Amps at 4.2 VDC
Auxiliary Heat Input	-	35 Watts

Performance Test

The performance test was a simulated 14-day run in which an average of 6 liters of urine were processed per day. Each run processed 1 liter of urine which had been pretreated with 2 grams of Tris (hydroxymethyl) nitromethane to kill any bacteria. A complete run took approximately 2 hours including filling and emptying operations. Although the test was initially operated under the conditions given in the previous section, the cycle was altered slightly to obtain the best results. The resultant cycle was a total operating time of 1.87 hours with a 0.17-hour preheat period. The preheat was manually controlled for the first cycle of each day to preheat the system to the boiling temperature.

Although it did not appear that bacteria would be a problem from shakedown test results, the total count had risen so high by the 7th day an attempt was made to sterilize the system by flushing with a bactericide. The unit was backwashed with paradiisobutylphenoxyethoxyethyl dimethylbenzyl ammonium chloride. Although the presence of bacteria was not again detected for several runs, they reappeared and rapidly multiplied. At the end of the 10th day, the distillation unit was placed in an autoclave and sterilized. Also at this time, an air filter was added to the vacuum release line to prohibit airborne bacteria from entering the system and recontaminating it.

No evidence of bacteria was detected during the remainder of the tests. However, both color and turbidity were increased for one run after the sterilization.

Discussion of Test Results

A summary of the test results is shown in table I. The values given are averages for the tests made during a given day unless otherwise specified. Maximum values are the highest values obtained during analysis of individual runs for the day.

The high turbidity values for the 3rd through 7th day reflect the very high bacteria count. Once the bacteria had been cleaned from the system, the effluent water fell well within desirable limits until the filter became loaded on the 14th day. The filter is designed for over 14 days, but several days preliminary testing had been done with this filter before the 14-day test started. The odor threshold of 3 B_s on the 6th day was attributed to the use of old urine, but no specific reason for a high threshold on the 3rd day could be determined. The analytical tests were performed by the procedures outlined in Standard Methods for Examination of Wastewater. (See Bibliography.)

The average direct current power to the thermoelectric heat pump during boil was 49 watt-hours per pound. An additional 7 watt-hours per pound was required during the preheat portion of the cycle to bring the urine from 100° F to boiling temperature. During the 14-day test a motor was used which consumed 132 watt-hours per pound, but this was later replaced with a commercial unit which required 90 watt-hours per pound. Using the smaller motor, it was necessary to initiate the rotation of the system by manually spinning. The total input to the unit was 146 watt-hours per pound.

The actual energy required to rotate the system after it has reached the 200 rpm is less than 0.15 foot-pound which would be 4.3 watt-hours per pound for the test operation conditions. It is apparent that the overall energy consumption of the unit would be significantly reduced through the use of a special high efficiency drive system. For operation under zero gravity the energy requirement to rotate the system would be decreased because of less frictional loss, and could be further reduced by lowering the speed of rotation since it would no longer have to be 200 rpm. It should be possible also to lower the energy consumed by the thermoelectric unit because, during the current test program, optimum heat balance for maximum efficiency was not obtained. If a critical heat balance is achieved, vapor should be occasionally evident in the vacuum system, due to a temporary excess of evaporation over condensation capability. However, this condition was not reached on this unit, which would indicate that heat losses of the boiler were causing recondensation within it. This would decrease the apparent system efficiency. It should be possible to completely eliminate the power required for preheat, by utilizing waste heat to obtain the best efficiency for a distillation system.

TABLE I

WATER ANALYSIS

Day	Percent Boil-Off	Odor Thres-hold (max)	Color (max units)	Tur-bidity (max units)	Evap. Residue (ppm)	Cl (ppm)	NH_3-N (ppm)	pH	Alk-alinity (ppm)	Conduct-ivity (10^{-4} mhos)	Bacterial Count (org./ml) *
1	80	0	0	0	186	16	17	8.3	88	2.7	100×10^3
2	86	0	0	0	149	13	17	8.5	88	2.3	100×10^3
3	89	24 B_s +	0	14	146	31	16	8.5	86	3.0	100×10^3
4	88	0	0	16	104	13	9	8.0	77	2.4	100×10^3
5	87	0	0	12	163	39	15	8.2	88	3.9	130×10^3
6	89	3 B_s	0	19	219	29	17	8.1	90	3.3	270×10^4
7	87	0	0	38	183	18	4	8.1	71	2.4	70×10^5
8	88	0	0	4	187	32	2	8.1	63	2.5	0×10^2
9	85	0	0	0	112	9	8	8.5	71	1.6	110×10^2
10	86	0	0	0	119	3	6	8.6	78	1.3	35×10^3
11	85	0	30	15	199	38	2	8.5	67	4.1	0×10^2
12	82	0	0	0	236	59	7	8.8	98	3.8	0×10^1
13	82	0	0	0	192	40	6	9.1	93	2.7	0×10^1
14	77 ‡	0	0	0	481	211	13	9.1	116	8.1	0×10^1

* Coliform not present in any samples

\+ Balsmic, Sweet

‡ Low initial urine temperature

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A high efficiency system for the recovery of potable water from urine has been built. However, further development work should be done to increase efficiency and reduce weight and size. Further development work on efficiency should concentrate on the elimination of, or a significant reduction in, the power requirement for the rotational drive, and optimization of heat balance to fully utilize the capability of the thermoelectric system.

Although the integral charcoal filter worked well in this unit, it is recommended it be made a separate component on future designs because of problems presented during sterilization of the charcoal.

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