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AUTOMATIC WATER RECOVERY SYSTEM

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FOREWORD

This study was initiated by the Biomedical Laboratory of the Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. The research was conducted by the General American Research Division (GARD) of the General American Transportation Corporation, 7449 North Natchez Avenue, Niles, Illinois 60648. Mr. P. P. Nuccio was the principal investigator for GARD. Mr. Courtney A. Metzger of the Biotechnology Branch, Life Support Division, was the contract monitor for the Aerospace Medical Research Laboratories. The Work was performed under contract AF 33(615)-2124 in support of project 6373, "Equipment for Life Support in Aerospace," and task 637304, "Waste Recovery and Utilization." The research sponsored by this contract was started in October 1964 and was completed in December 1966.

The research covered herein was performed by personnel within the Life Support Systems Group of GARD under the direction of Mr. R. A. Bambenek and supervision of Mr. P. P. Nuccio. Principal contributors were Messrs. J. F. Berninger and E. B. Watts for mechanical design, and Messrs. W. J. Jasionowski and T. L. Hurley for chemical consultation and analysis.

This technical report has been reviewed and is approved.

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ABSTRACT

A water recovery system for reclaiming potable water from urine and other waste waters was designed, fabricated and tested. The system operates on the vacuum distillation principle with vapor compression for the recovery of latent heat. Chemical pretreatment of the waste liquid is employed and the condensate is post-treated by adsorption and filtration. A unique waste-liquid recycle technique was developed. The technique maintains clean evaporator surfaces (thus eliminating the need for periodic cleaning), and permits continuous automatic operation for an indefinite period. The system is designated GARD Model 1271 Automatic Water Recovery System. The materials, finishes, and built-in artificial gravity required for a flight qualifiable system were incorporated into the model which weighs 98 pounds and occupies less than 2.5 cubic feet. Electrical energy consumption varied according to the solids concentration of the feed liquid, and ranged from 34.6 watt-hours per pound of potable water recovered from low-solids urine to 55.4 watt-hours per pound when processing urine concentrated to 32 percent solids. During a 14-day acceptance test performed on the model, 421 pounds of potable water were recovered from 490 pounds of urine for a yield efficiency of 86 percent.

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INTRODUCTION AND SUMMARY

The significant achievement of the program was the development of a recycle loop and its application to a vapor compression vacuum distillation water recovery system. The recycle loop permits long-term operation by automatically removing, diluting and recycling urine concentrated by the evaporation process. If the urine remained in the evaporator, it would increase in solids concentration and cause sludging and fouling of the evaporator surface. Periodic removal of urine solids from the evaporators of other recovery systems is a normal operating requirement. With the recycle loop, accumulated solids can be disposed by dumping part of the recycle concentrate. This can be done without stopping the operation of the system. The water loss is no greater than that experienced with other solids removal techniques, and the recovery rate of potable water remains continuously high because the evaporator surface remains free of contaminants.

The operation of the system is as follows: The evaporator and condenser are maintained at the saturation pressure of water at the local ambient temperature by a small vacuum pump drawing from the condenser (in space a capillary tube vent line to space vacuum will replace the pump). Waste water is metered to the evaporator at four times the evaporation rate. The water vapor generated in the evaporator is compressed and pumped to the condenser (which envelopes the evaporator) by the compressor. The higher pressure, higher temperature vapor condenses upon contacting the cooler evaporator wall. The heat released by the condensing vapors travels through the evaporator wall to the waste water to continue the evaporation process. Meanwhile condensate is pumped from the condenser through an activated carbon bed, then through a 0.15-micron filter to a potable water tank. The unevaporated liquid, which contains dissolved urine solids left by the vapor, is pumped from the evaporator to an external tank. In that tank, the concentrated liquor is mixed with fresh urine and the diluted liquid is recycled back to the evaporator for another exposure to the evaporation process.

A 17-day (3 days with tap water, plus 14 days with urine) acceptance test run on the system proved the recycle concept to be an acceptable method for extending indefinitely the operation of a water recovery system. After the test, the evaporator was opened and found clean and free of deposits. Daily analysis for coliform bacteria in the recovered water were negative. Analysis of the water output per U.S. Public Health standards showed it to be of good quality.

SECTION II

SYSTEM REQUIREMENTS

Two kinds of requirements were imposed upon the design and development program. First, the performance criteria were established by the procuring activity. The General American Research Division (GARD) undertook to advance water recovery technology by developing the waste water recycle loop and integrating it into the distillation system. All performance criteria were met or surpassed. By eliminating the periodic cleaning of the equipment required to remove the solids present in urine and other waste waters, the recycle loop demonstrated that aerospace water recovery can be a continuous process.

Performance Criteria

The specific performance requirements and comments on the system's conformance with each requirement are listed below. (The entire test program is explained in detail in Section IV of this report).

Recovery Rate

Requirement: Minimum of 30 pounds of potable water per 24 hours.

This parameter fixed system sizing. The compressor pumping rate, heat transfer areas, liquid pump sizing and filter capacity were calculated to produce the required water output rate without being excessively large and wasteful of power weight and volume. The average recovery rate over the 14-day acceptance test was 33 pounds per 24-hours - a 10-percent margin over the minimum requirement.

Energy

Requirement: Maximum of 1500 watt-hours/per 24 hours, with a goal of 1,000 watt-hours per 24 hours.

This requirement severely penalized an oversized system and increased the significance of accurate system sizing. During the 14-day acceptance test the average energy demand was 1474 watt-hours per 24 hours, which is slightly under the maximum allowed including the 10 percent margin on recovery rate.

On the basis of energy per pound of potable water recovered, which more accurately depicts the system characteristics, the energy demand limit becomes 50 watt-hours per pound with a goal of 33.3 watt-hours per pound. Throughout the 14-day test, a demand of 45.5 watt-hours per pound was measured.

Yield

Requirement: Minimum of 85 percent.

This requirement established the volume of input liquid which must be recovered and set a limit on the amount of recycle liquid which could be rejected to remove the solids. A low rejection rate would improve the yield, at the expense of recovery rate and energy demand. Conversely, a high rejection rate would improve recovery rate and energy demand at the expense of yield efficiency. During the same 14-day test in which the minimum recovery rate and maximum power demand requirements were met, a yield efficiency of 86.0 percent was attained.

Maintenance

Requirement: None for minimum of 14 days.

This requirement indicates that no corrective measures were to be applied to the operating system during the acceptance test run. It does, however, permit batch operation with daily removal of solids. During long-term runs, the system requires lubrication of two seals, through externally mounted fittings, at 3-day intervals. It does not require the daily routine maintenance necessary with batch-type systems.

Mode of Operation

Requirement: Automatic with manual override.

All normal functions of the system are automatically controlled, also the maintenance of a clean evaporator surface is automatically accomplished by the recycle loop. A manual override on the feed flow rate can effectively compensate for malfunctions in the process cycle.

Operating Pressure

Requirement: Capable of operation in 5 to 15 psia atmosphere.

The entire distillation unit is operated at the saturation pressure of water at the local ambient temperature. It is isolated from its environment; therefore, it will operate normally at any ambient pressure up to the structural limit. (Operation above this limit will cause buckling of the outer shell.)

Operating Temperature

Requirement: Urine input, 15.6 to 37.8 C(60 to 100 F); potable water output, 15.6 to 48.9 C(60 to 120 F).

Development testing was performed at urine input temperature as specified. Input urine was neither heated nor cooled; it was maintained at laboratory temperature. Mid-afternoon temperatures in August and early-morning temperatures in December exceeded the range specified. The system showed a higher recovery rate at lower ambient temperatures because the vapor being pumped from the evaporator to the condensor at a constant volumetric flow rate was of a higher density. The recovery rate at the highest temperature, however, was above the minimum required.

Potable water is neither heated nor cooled by the process and emerges at the ambient temperature.

G-Forces

Requirement: Operating, 0 - 1 g; nonoperating, 0 - 6 g's in any direction.

All tests were performed in a 1-gravity field, but theoretical zero-g capability was built into the system by rotating the entire distillation unit. The centrifugal force so generated will maintain the liquid-gas interface in the absence of natural gravity.

Volume
Requirement: Maximum of 2.5 cubic feet.

The volume of the system was 2.38 cubic feet.

Power
Several power source choices were available.

A 208-volt, 3-phase, 400-cps source was selected to maximize electrical efficiency and minimize weight.

Air Consumption
Requirement: Maximum of 0.50 pounds oxygen per 24 hours.

The foregoing requirement established the maximum allowable leakage rate from the ambient into the evacuated distillation unit. With the dynamic seals properly installed and lubricated, the leakage rate was well below the maximum.

Test Requirements
Requirement: One 3-day shakedown, and one 14-day operative run.

The shakedown test was run with tap-water input for the purpose of final system adjustments and test crew familiarization. The 14-day operative run was made with urine input, that test was extended to 17 consecutive days to evaluate system operation beyond design conditions.

Water Quality
Requirement: Complete chemical analysis and tests per Public Health Service - Drinking Water Standards, 1961.

Daily tests of a few indicative requirements of water quality were performed. Complete analysis and tests were performed by an outside laboratory. The water was of generally good quality. All test results are included in Section IV.

Cycle Time
Requirement: None specified, but prefer continuous.

A batch-type system would have been acceptable but a continuous-process system was desired. GARD undertook the development of the recycle loop and thereby expanded the program scope.

Recycle Loop Requirements
To make any water recovery process continuous, the periodic task of manually removing the solids left in the evaporator by the evaporated water must be eliminated. The recycle loop removes the solids automatically and continuously by dilution. That is, the solids which enter the evaporator with the waste water leave the evaporator with the liquid being recycled. The most important requirement, therefore, is to maintain the recycle-liquid solids concentration below the level at which

excessive boiling point elevation occurs. That requirement may be met by (1) maintaining the feed-to-evaporation-flow-rate-ratio higher than a minimum value and (2) extracting a quantity of concentrated recycle liquid from the loop periodically to remove the dissolved solids and establish an upper limit on evaporator-input-liquid concentration. The minimum feed-to-evaporation ratio was established at 4 to 1 by weight. The solids input to the system is approximately 1 pound per day (36 lb urine per day input x .03 solids in urine). The recycle rate was set at 4 pounds per day to remove 1 pound of solids in a 25% concentrated solution, thereby maintaining the solids balance and limiting solids concentration.

In addition, it is desirable to maintain the evaporator liquid level without the use of electrical level sensors and controls. In the vacuum distillation system, waste-liquid feed and recycle-liquid removal are maintained constant and interdependent by separate but synchronized pumps. To hold the flow rates constantly proportional, both pumps are driven by a common shaft.

SECTION III

MODEL DESCRIPTION

The Water Recovery System generates potable water from human urine and other waste waters by a three-step process: (1) chemical pretreatment, (2) vacuum distillation, and (3) adsorption filtration of the condensate. The system is designed to operated in either a weightless or normal gravitational state and is considered a prototype model of a flight-qualified system.

A vapor compressor is located between the evaporator and condenser to minimize the energy required for distillation. Compression of the water vapor generated in the evaporator causes the condenser temperature to be higher than the evaporator temperature because the saturation (boiling) temperature increases with pressure. The latent heat of condensation is transferred back to the evaporator through a highly conductive common wall, and the energy required to drive the distillation process is only that required to drive the vapor compressor. This unique method reduces the heating/cooling equivalent energy to one-sixth of that needed to drive the distillation process by electric, waste or nuclear heat, and space radiators.

Another unique feature of this system is the recycling of waste water by feeding the water at a higher rate than the distillation rate and removing the excess liquid from the evaporator. This feature prevents the accumulation of solids in the evaporator; thus permits continuous operation for an indefinite period without the need for cleaning the evaporator surfaces. The recycle liquid is pumped to the recycle tank before it is filtered and returned to the evaporator (Figure 1). Fresh urine and/or wash water is added to the system in the recycle tank to dilute the recycle liquid.

Dissolved solids in the recycle liquid elevate the boiling temperature in the evaporator and reduce the distillation rate. Thus, the recovery rate attainable will decrease as the solids concentration increases, unless a portion of the recycle liquid is periodically removed from the system. If the recycle liquid is never removed, the solids concentration will increase and water recovery will cease, leaving a heavy sludge in the evaporator. Therefore, to achieve continuous operation without cleaning the evaporator it is necessary to dump part of the recycle liquid each day and maintain a solids concentration of 25% or less.

Configuration and Design

All parts of the system are fabricated of light-weight aluminum alloy with protective coatings or stainless steel to prevent the corrosive action normally encountered during the storage and handling of urine. Accessibility of components was also assigned a high priority so the various subassemblies could be easily removed and inspected.

In its final configuration, the distillation unit is a horizontally-oriented cylinder consisting of two major sections (Figure 2): a bowl assembly and a compressor drive assembly. In addition, the system

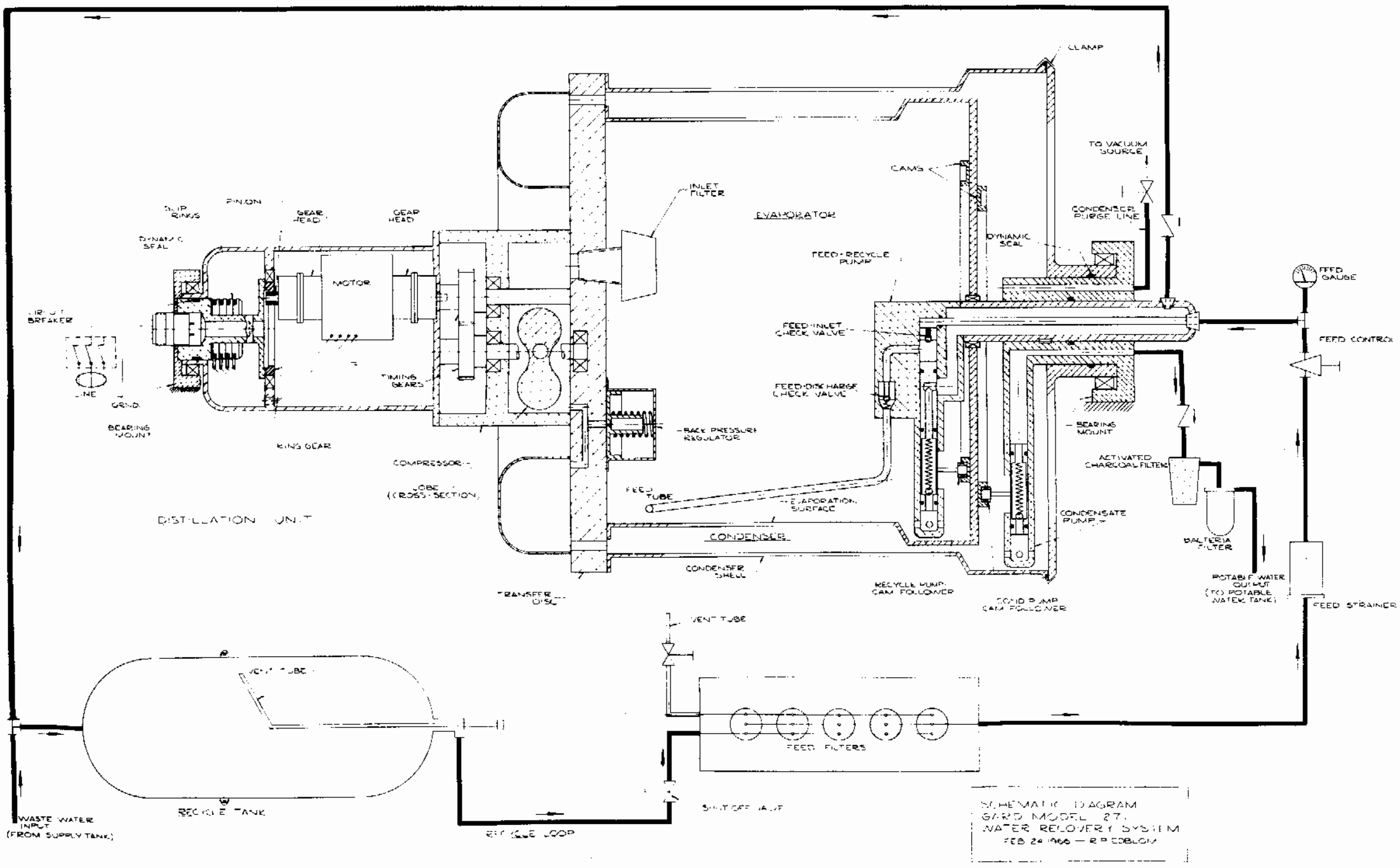

Figure 1 GARD MODEL 1271 WATER RECOVERY SYSTEM SCHEMATIC FLOW DIAGRAM

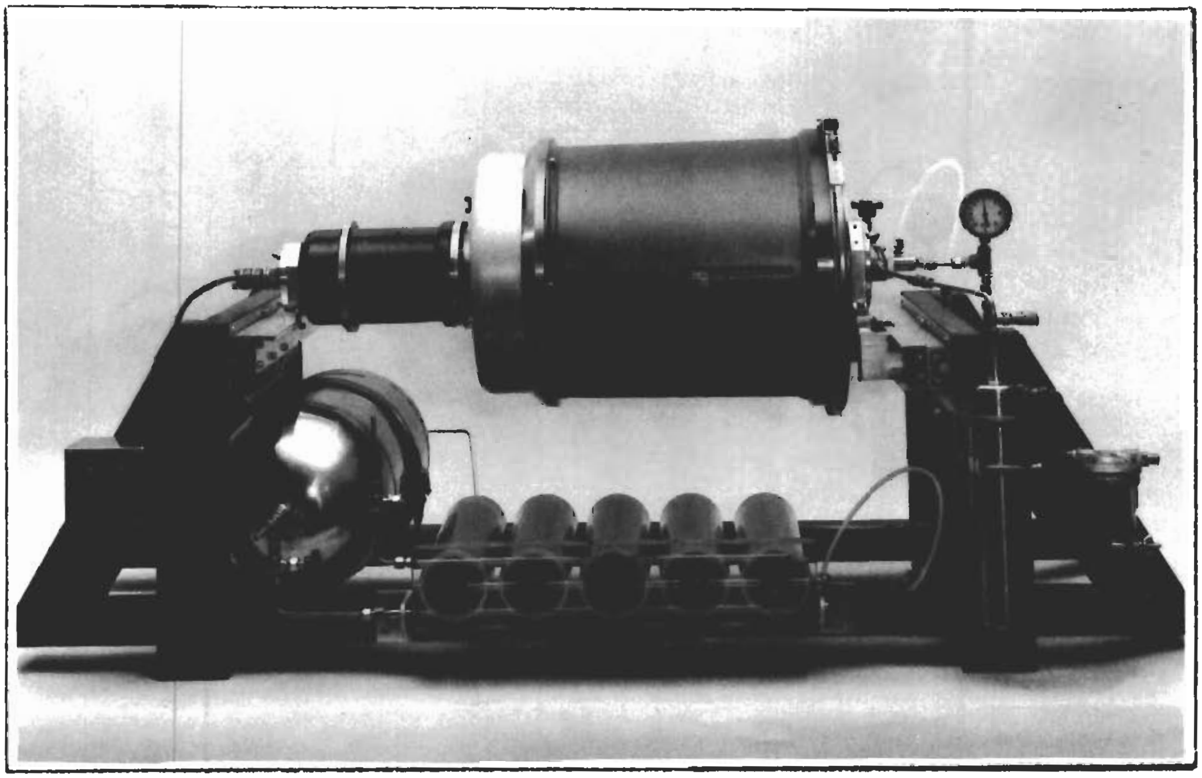

Figure 2 GARD MODEL 1271 WATER RECOVERY UNIT

contains three supplemental components including (1) the waste water recycle tank and input filters, (2) the condensate filters, and (3) the support assembly. The supplemental components are packaged below the rotating section and interconnected by tubing.

Component Description

A description of each primary component in the two major subsections of the distillation unit (bowl assembly and compressor drive assembly) plus the aforementioned three supplemental components follows:

Bowl Assembly

The bowl assembly contains the transfer disk assembly, the condenser shell, the evaporator bowl, the condensate pump, and the feed/recycle pump. The bowls are flanged at one end for attachment to the central shaft which supports that end of the bowl assembly.

The transfer disk, Figure 3, is machined from aluminum alloy with mounting bosses for (1) the inlet filter, (2) the compressor relief valve, and (3) four holes for transporting vapor to the condenser. Grooves with "O"-ring seals are also machined into the face for attachment and sealing of both the condenser shell and the evaporator bowl. The inlet filter is a commercial filter housing with a screen brazed in-place inside the gas passageway. An 80-mesh screen was provided to prevent the introduction of droplets into the vapor transfer tubes and ultimately into the compressor. The compressor relief valve (Figure 4) is machined from aluminum alloy with a stainless steel spring. An O-ring on the relief valve stem seals the stem against the machined surface of the transfer disk when the valve is in its normal (closed) position. The relief valve is set to open at 0.27 psi Δp.

The condenser shell is a two-component assembly consisting of a rolled and welded sleeve and a removable head. The two-piece design, (Figure 5) was selected to permit ready access to the condensate pump by simply unclamping the head. The sleeve is machined at one end for cap-screw attachment to the transfer disk. This end also incorporates a machined ring which bears against an O-ring in the transfer disk producing a leak-proof seal at this seam. The opposite end of the sleeve includes an O-ring groove to form the leakproof head-bowl junction. A stainless steel V-band clamp secures the head to the sleeve.

The evaporator bowl is a one-piece assembly made from a rolled and welded cylinder, a cast end plate, and a machined flange. After final welding, the bowl was precision machined to form a ring at the open end which bears on an O-ring in the transfer disk producing a leakproof seam. The head (or closed end) is finish-machined for installation of the cam rings which drive the pumps. The internal eccentric ring (Figure 6) operates the feed/recycle pump, and the external ring (Figure 7) drives the condensate pump.

The condensate pump, (Figure 8) consists of an aluminum alloy housing, which includes the mounting boss, and a stainless steel cylinder plus a precision piston that operates inside the cylinder. Sealing of the piston in the cylinder is accomplished by a combination of O-rings and a Teflon® slipper seal. Low sliding friction is achieved

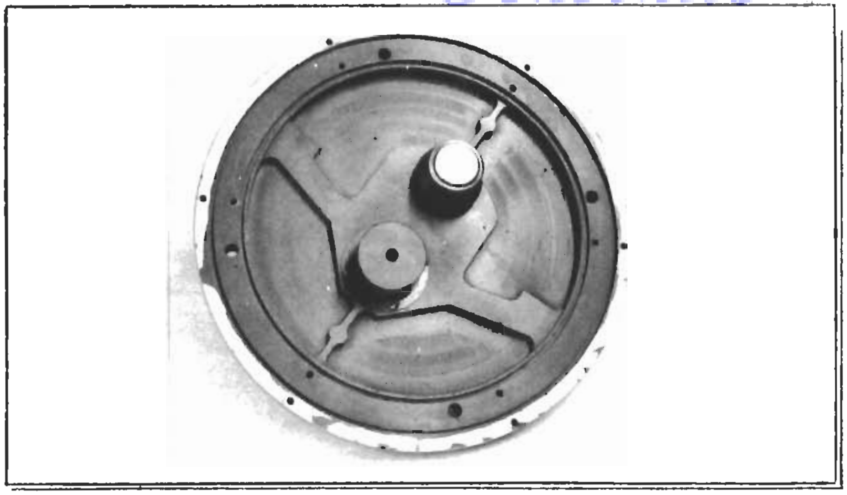

Figure 3 TRANSFER DISK ASSEMBLY

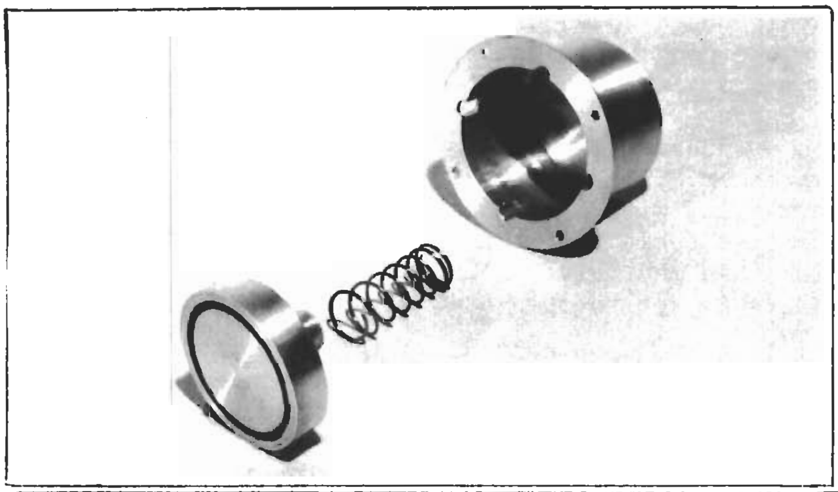

Figure 4 COMPRESSOR RELIEF VALVE

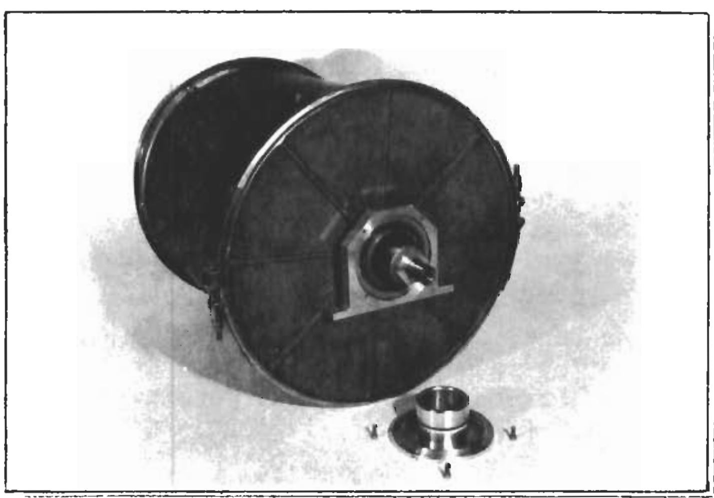

Figure 5 CONDENSER SHELL ASSEMBLED

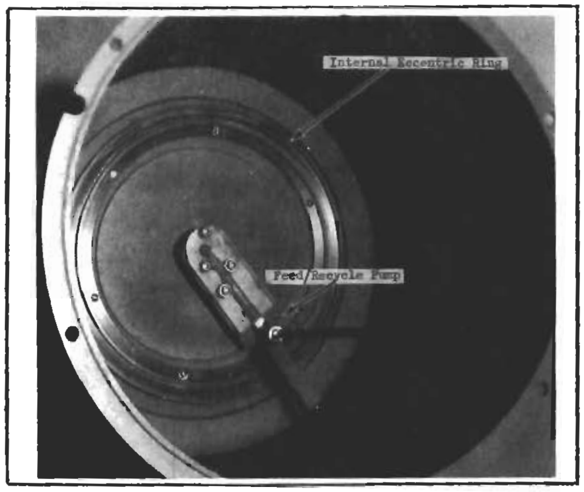

Figure 6 INTERIOR VIEW OF EVAPORATOR BOWL

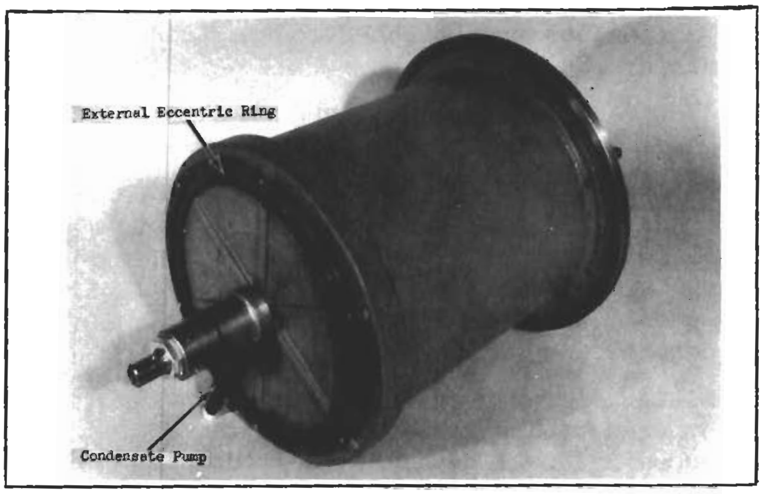

Figure 7 EXTERIOR VIEW OF EVAPORATOR BOWL

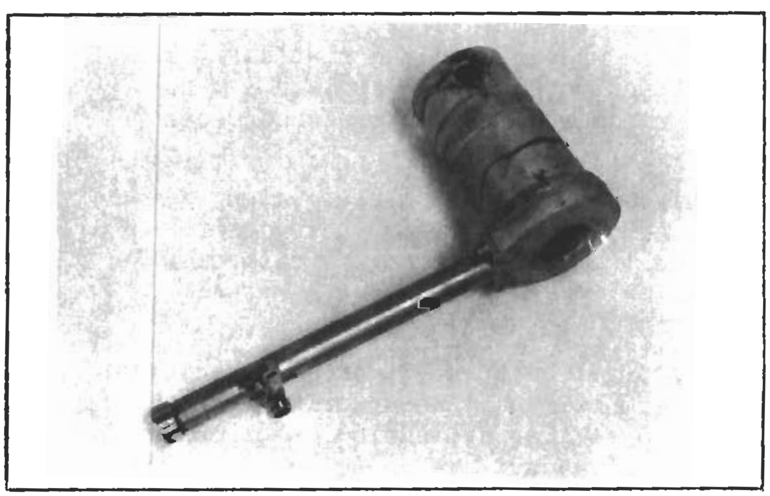

Figure 8 CONDENSATE PUMP ASSEMBLY

by the Teflon slipper seal operating on the honed stainless steel cylinder bore. Two ball bearings running in the eccentric grooves, drive the piston in a reciprocating motion.

The feed/recycle pump (Figure 9) is a dual-purpose unit that meters urine into the evaporator bowl and removes concentrated liquid from the evaporator bowl. The two-pump assembly is built upon an acrylic plastic body with valves and a reciprocating piston integrated into a compact unit. The two valves on the feed metering pump are standard commercial parts, while the check valve in the recycle pump is custom-designed for the specific application. The piston, which reciprocates in a honed stainless steel cylinder, is sealed by a combination of O-rings and a Teflon slipper seal. This piston, however, is equipped with three Teflon riders to carry the radial forces between the piston and the cylinder wall. Two ball bearings on a stud-mounted carriage drive the piston from the rotating eccentric groove.

Compressor-Drive Assembly

The compressor-drive assembly contains the compressor assembly, the timing gear housing, the motor housing, the drive motor, and the commutator/connector assembly. These components are attached to the transfer disk on the opposite side of the bowl assembly.

The compressor assembly is a custom-designed rotary-lobe unit fabricated of aluminum alloy to reduce weight. The compressor displaces 0.0105 cubic feet per revolution and is driven at 3150 rpm through a gear box, by the motor.

The timing gear housing (Figure 10), is machined from aluminum alloy and fitted to the lobe housing. It contains stainless steel ball bearings as well as the anodized aluminum and the nickel-plated aluminum timing gears which maintain proper meshing of the compressor lobes.

The motor housing is mounted to the timing gear housing and becomes a vacuum-tight enclosure for the motor and the brush assembly. The cast aluminum housing is machined for the radial seal gland at the electrical connector end. The sealing surface is lined with stainless steel and polished to minimize wear on the O-ring seal.

The drive motor is a 400-cycle, 3-phase, 208-volt unit with nominal power consumption of 60 watts. A gearhead at one end reduces the motor nominal speed of 12,000 rpm to 391 rpm at the main-drive output shaft. This shaft is fitted with a pinion which meshes with the stationary ring gear to produce the normal bowl rotational speed of 54 rpm. A square shaft at the opposite end of the drive motor matches a broached recess in the compressor shaft to drive the compressor at 3150 rpm.

The commutator/connector assembly is a non-moving part which (1) holds the pump end dynamic seal, (2) holds the stationary ring gear, and (3) forms the portion of the electrical circuit between the connector and the commutator.

Waste-Water Recycle Tank

This two-piece, stainless steel, 5-gallon tank (Figure 11) recieves concentrated liquid from the evaporator bowl and make-up urine from the supply tank. It is fabricated from two similar cylindrical sections with hemispheric heads. The sections are coupled by a V-band clamp, an arrangement which also simplifies disassembly for cleaning between missions.

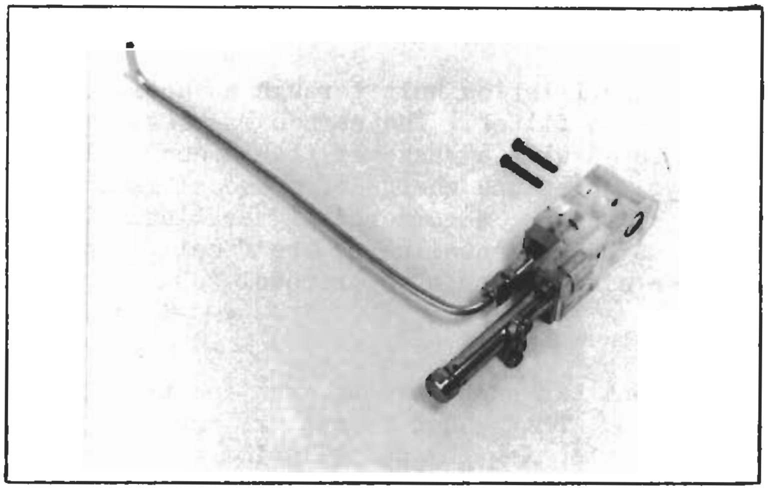

Figure 9 FEED/RECYCLE PUMP ASSEMBLY

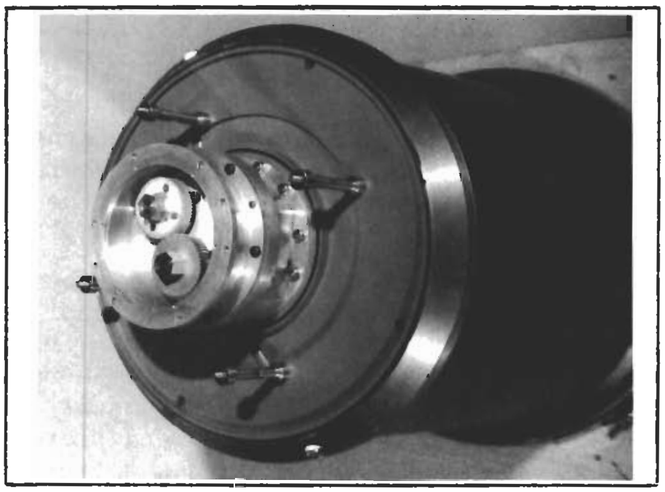

Figure 10 COMPRESSOR - END VIEW OF DISTILLATION UNIT (DRIVE REMOVED)

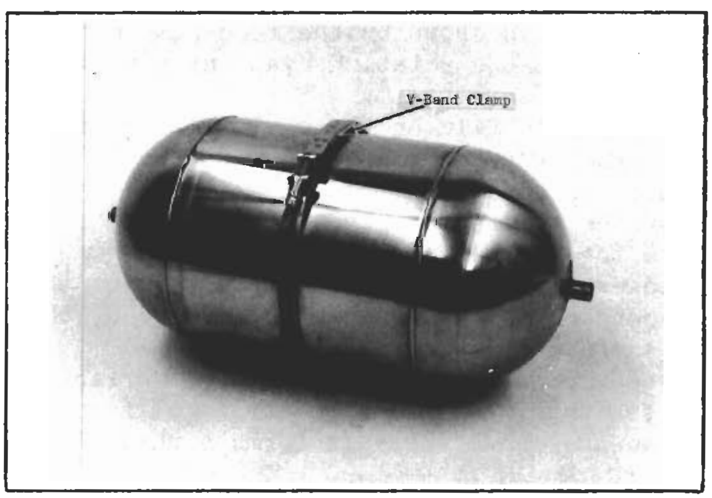

Figure 11 WASTE WATER RECYCLE TANK

Condensate Filters

Condensate flows from the distillation unit through an activated carbon bed, then through a bacteria filter. The carbon is contained in a stainless steel cylinder equipped with a gasketed-flange and a clamp for easy removal and servicing. A 1-pound charge of charcoal is sufficient to post-treat 100 pounds of water. A commercially available filter enclosed in a clear plastic housing is installed as the final condensate filter. The replaceable filter element has a 98% removal capacity for particles of 0.15 micron size.

Support Assembly

The rotating distillation unit is supported at each end by ball bearings mounted in pillow blocks. Both end supports are mounted on 18-inch linear slides which permit extending the distillation unit outward 17 inches from its stowed location for ready access. Locks on each slide positively restrain both the extended and the retracted positions. The supporting bearings and the moving parts of the slide mechanisms are serviced for long-term use and require no periodic maintenance or lubrication. For laboratory tests, the unit was mounted on a temporary wooden frame. If the unit is mounted inside an environmental chamber, the 37-inch dimension between the two slide-mounting faces should be maintained.

Operating Principle

Start-up of the recovery system requires reduction of the internal pressure to 50 torr or less. In a spacecraft installation, this would be accomplished by venting the distillation unit through the wall of the vehicle. For laboratory operation, a vacuum pump is required.

When the 50-torr internal pressure is reached, the system may be put into operation by closing the electrical switch. As the power is applied, the drive motor begins to rotate and the following events occur:

(1) The distillation unit begins to rotate, stabilizing at 54 rpm.

(2) As the bowl assembly rotates, (a) the feed/recycle pump is given a reciprocating motion by the eccentric grooves in the end plate of the evaporator bowl (b) the condensate pump is also given a reciprocating motion as its follower tracks in the cam grooves mounted on the outer surface of the evaporator bowl, and (c) the compressor rotates.

With the mechanical components operating, a flow of liquids and gases commences as follows:

(1) Urine from the recycle tank is drawn by the feed-pump side of the feed/recycle pump and metered into the rotating evaporator bowl, impinging on the walls.

(2) The fluid forms a thin liquid film on the bowl walls during exposure to the low pressure in the evaporator section. As the fluid adsorbs heat from the bowl, water is vaporized.

(3) Vapor is drawn off by the compressor, leaving the urine solids in the liquid to be returned to the recycle tank by the recycle pump.

(4) The compressor increases the pressure and temperature of the vapor, and delivers it to the condenser annulus which is formed by the condenser shell and the outer surface of the evaporator bowl.

(5) As the pressurized vapor contacts the cooler outer surface of the evaporator bowl, it condenses and is thrown by centrifugal force onto the inner surface of the condenser bowl where it forms a thin liquid

film. Meanwhile the heat of condensation extracted from the condensing vapors is transferred through the evaporator-condensor wall to continue the vaporization process within the evaporator.

(6) The condensate pump draws the liquid from the sump in the conical condenser shell and passes it through the condensate filters for post-treatment, then into a potable water storage tank.

SECTION IV

DEVELOPMENT PROGRAM

The successful development of this system, the first built with a recycle loop, required the solution of unique problems in concentrated urine transport and storage, long-term maintenance-free operation, and the effects of constantly changing solids content in the liquid being evaporated. Some components required minor modifications; others were completely redesigned when the critical operating parameters became known. Significantly, no changes in the recycle loop concept were warranted.

Materials Compatibility Tests

A comparison was made of the corrosion resistance of candidate materials in contact with the recycle liquor. A bath was prepared to represent the corrosive medium. It contained partially evaporated urine, iodine, and hydrochloric acid in concentrations typical of the recycle liquor. Samples of the candidate materials were dried, weighed, partially submerged in the bath for 14 days, then redried and reweighed. The liquid was also analyzed to detect changes in its composition caused by the test materials. Lightweight materials which showed the best corrosion resistance were Kanigen® plated aluminum and Teflon® coated aluminum. Table I includes the results compiled for the test samples.

Another objective of the compatibility test was to check the efficacy of iodine and HCl to control biological growth and fix the ammonia (to control pH) in the presence of the test materials. The additives proved satisfactory; no biological growth, change in pH, precipitation, change in viscosity, or other deleterious change was detected throughout the 14-day test.

Other materials deemed satisfactory on the basis of a literature survey included 18-8 stainless steel and most plastics. The system was designed and built using only the acceptable materials.

Tests

The complete system was assembled and operated with tap water as the input liquid, as a shakedown and familiarization run. Next a series of tests were run to determine which elements of the original configuration required modification. Altogether 19 development test runs were made. Some were intended to be full-duration acceptance tests but were terminated by failures of critical components. Table II is a compilation of the results of the development and acceptance tests.

Acceptance Test

When test run no. 20 was begun, it was believed the system was capable of passing the required acceptance test - - three days with tap water input, followed by 14 days with urine input. By that time, however, more than 700 hours running time had been accumulated on the entire system and more than 1,000 hours on some components. Certain operating components were reaching the end of their useful life. The 3-day test was completed without a failure (run no. 20), but after 10-1/2 days of the 14-day test (run no. 21), a compressor bearing failed, terminating that attempt at a full-duration run. Repairs were made and a successful acceptance test (run no. 22) was completed.

Table I

PASSIVE MATERIALS COMPATIBILITY TEST RESULTS

14-Day Continuous, One-half Submergence in Liquid

Sample No.	Description of Aluminum Finish	Weight Change, One-Half Submerged*	Visual Observations
1	Bare-untreated	-0.58%	Very severe corrosion, deep crevices in surface.
2	Clear Anodized	-0.17%	Deep pitting along liquid line.
3	0.0015 inch Teflon coat	-0.01%	No detectible corrosion, slight darkening.
4	0.002 Kanigen® coat	+0.03%	No detectible corrosion, or color change.
5	Heavy chromate treat without post rinse	-1.5%	No chromate color, deep crevices some performations.
6	Heavy chromate treat with post rinse	-1.03%	No chromate color, deep crevices, some perforations.
7	Light chromate without post rinse	-0.47%	No chromate color, some crevices, and deep pitting.
8	Light chromate with post rinse	-0.26%	No chromate color, some crevices and some pitting.
9	0.0015 inch hardcoat	-0.05%	Light corrosion, moderate discoloration.
10	0.0010 inch hardcoat	-0.17%	Moderate corrosion, white powder on surface.
11	0.0006 inch hardcoat	-0.22%	Severe corrosion, white powder on surface.

*One-half submergence was representative of most applications, i.e., the evaporator bowl, in which only the inner surface is exposed to recycle liquor. Other components, however, are completely submerged - but they all have a lower surface-to-volume ratio than the evaporator.

Table II

COMPILATION OF RESULTS OF DEVELOPMENT AND ACCEPTANCE TESTS RUN AT GARD ON MODEL 1271 AUTOMATIC WATER RECOVERY SYSTEM

Test Run Number	Starting Date	Duration, Hours	Test Results or Failures and Corrective Action
1	1/18/66	26	Lubricant failure in compressor-drive speed reducer. Loose seat in condenate-pump check valve. Replaced failed parts.
2	1/22/66	5	Low speed drive-gear failure. Replaced gear box.
3	1/23/66	2	Feed pump failure, which flooded evaporator and bound compressor. Repaired feed pump.
4	1/24/66	11	Residue in compressor, high torque load opened circuit breaker. Cleaned, relubricated and re-assembled compressor.
5	1/25/66	39	Binding compressor lobes, residue still present. Replaced compressor inlet filter.
6A	2/2/66	6	Solid particles between compressor lobes. Installed screen in inlet filter.
6B	2/3/66	42	Compressor gear box failure, caused by high loading in previous tests. Replaced gear box.
7	2/17/66	39	Recycle pump check-valve spring corroded. Evaporator flooded and liquid slugged through compressor. Gear box failure. Rebuilt recycle pump.
8	3/9/66	23	Drive-gear failure. Bearing alignment had changed. Realigned drive.
9	3/16/66	4	Drive-gear failure. Bearing and shaft reworked.
10	3/21/66	1/2	Recycle pump drive-bearing failure. Replaced with wider bearing.
11A	3/22/66	1	Loose seat in condensate pump. Replaced seat.
11B	3/22/66	84	Bowl-drive gear failure. Changed gear material.
12	4/5/66	84	Recycle pump middle seal failure. Bowl-drive gear worn. Replaced seal and changed gear material.
13	4/13/66	16	Corrosion in recycle pump cylinder bore. Rebuilt recycle pump piston.
14A	5/13/66	60	Condensate pump drive-gear failure. Corrosion in recycle pump bore. Rebuilt recycle pump cylinder.
14B	5/16/66	72	Bowl drive-gear failure. Slip ring wear detected. Changed gear material.
15	6/2/66	48	Condensate pump drive bearing failure. Bowl drive-gear wear. Replaced bearing and changed gear material.

Table II (Cont'd)

Test Run Number	Starting Date	Duration, Hours,	Test Results or Failures and Corrective Action
16	6/29/66	72	Low-speed drive bearing misaligned, which caused bowl-drive-gear failure. Aligned bearing and replaced gear.
17	7/6/66	24	Compressor timing changed. Loose seat in condensate pump check valve. Rebuilt compressor.
18	9/25/66	48	High-speed gear box failure. Change to petroleum grease. Feed pump failed to open. Redesigned feed/recycle pump using purchased valves.
19	9/29/66	16	Dynamic seal failure. High purge rate. Sleeved seal surface with 18-8 stainless steel. Installed sharp-edged seat in recycle and condensate pump valves and redesigned bowl drive using internal-tooth gear.
20	9/30/66	72	3-day water test.
21	10/7/66	252	Compressor bearing failure after 10-1/2 days of intended 14-day test. Replaced special bearings with standard size stainless steel bearings. Pump drive bearings worn, replaced with 2-bearing carriage.
22	11/11/66	408	17-day test. System delivered to AMRL.

The technical results of test no. 22 run are presented graphically in Figure 12. The graph shows that the water recovery rate decreases as the solids concentration in the feed liquid increases. This interaction is caused by the higher enthalpy rise required to vaporize concentrated solutions of this type. Limiting the concentration, therefore, maintains the recovery rate above a corresponding level. The permissible concentration of recycle liquor was thus established at 25%. That concentration was maintained by draining recycle liquor from the recycle loop at the rate of 4 lb per day.

Solids equilibrium through a long-term run will be self-stabilizing whenever the mass extracted daily exceeds the mass of solids input daily. The concentration of solids in the liquor can be controlled by setting the ratio of total mass extracted-to-mass of solids input. In the case reported herein, the daily solids input was approximately 1 pound (36 pounds of urine with 3% solids concentration), and the extraction rate of 4 pounds per day limited the concentration to 25% (1 pound of solids, equaling the input rate, and 3 pounds of water). Figure 12 also shows an increase in energy required to maintain the constant daily production of potable water. This increase is a direct reflection of the lower recovery rate; a longer running time, at the same power level, is required per day. Similarly, the energy required can be controlled by establishing the recycle-liquor extraction rate.

High extraction rates, as noted, improve recovery rate and energy required, but decrease yield efficiency, the portion of the input liquid which is converted to potable water. Therefore, a tradeoff study, which weighs water recovery system size, input energy, and time against make-up water tankage volume and weight, will establish the most advantageous recycle liquor extraction rate. During the 14-day test the yield efficiency was maintained at 86% while the other parameters also remained within the allowable limits.

Output water was analyzed daily in GARD's chemistry laboratory. Composite samples of several days'production were analyzed by two impartial outside laboratories. Water of generally good quality was produced throughout the acceptance test run. All tests for coliform bacteria were negative. By the 12th, 13th, and 14th days, however, the characteristics of long-term recycle loop performance could be seen, after operation adjustments were made, the water quality was excellent. The excellent quality achieved late in the test should be attainable throughout subsequent tests with the recycle loop operated in accordance with developed procedures. Table III summarizes the results of the analysis of water recovered during the acceptance tests (run no. 22). Table IV shows the results of analysis made by the Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio, of water produced by the system while being operated by laboratory personnel at the Aerospace Medical Research Laboratories.

Taft's report included the following statement:

"The vapor compression samples, GARD, were of good mineral quality. In particular, this run appeared to have removed both the ammonia and urea."

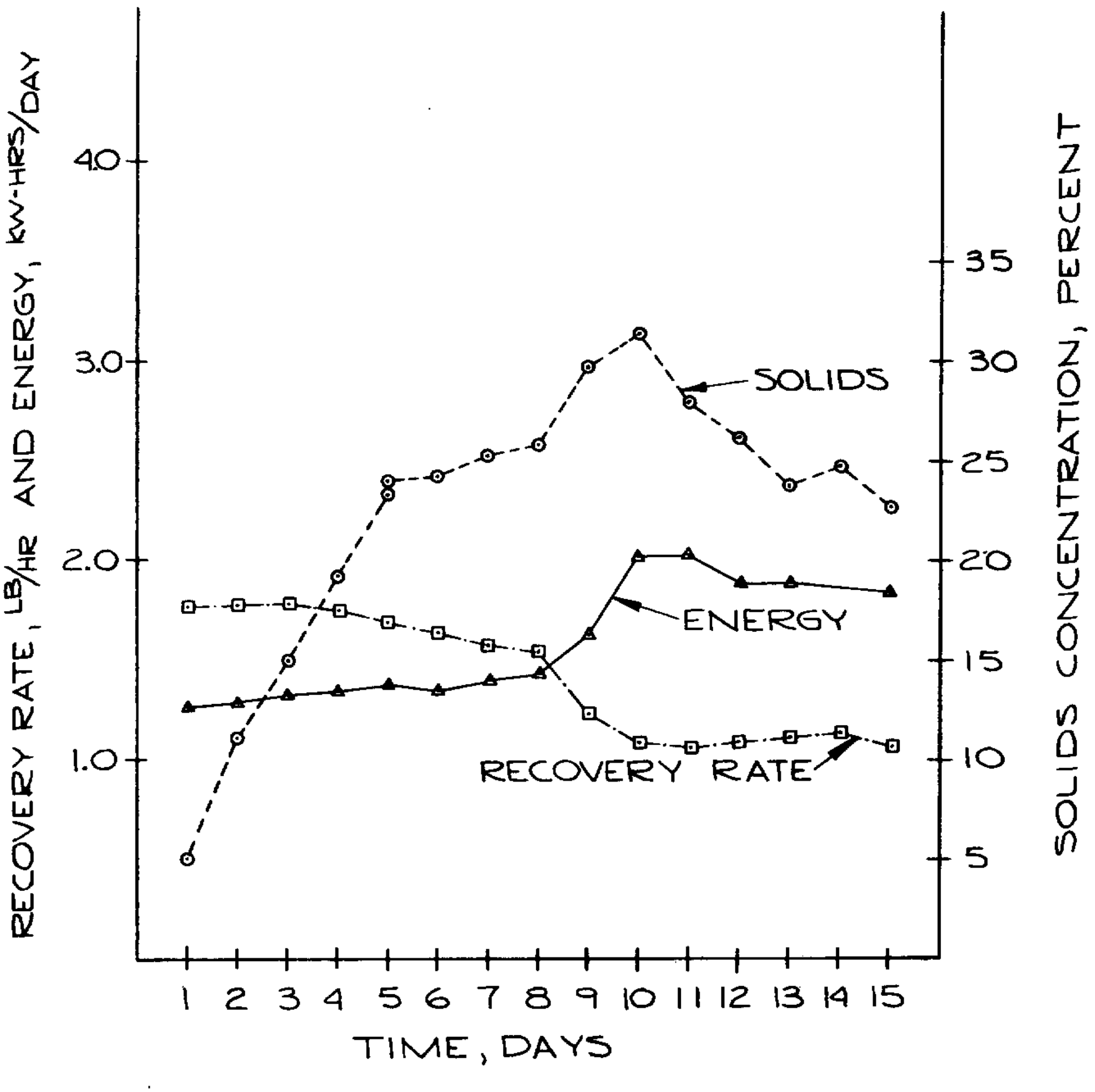

Figure 12 PERFORMANCE CURVES, RUN NO. 22
(ACCEPTANCE TEST)

Table III

SUMMARY OF WATER QUALITY TESTS, RUN NO. 22, (ACCEPTANCE TEST)

By GARD

Day No.	Quantity, (lbs)	Yield Efficiency, (%)	Electrical Resistance, (Ohms)	Coliform Density, (No/100 cc)	Total Carbon, (ppm)	pH
1	30.25	84	25,000	0	9.5	6.6
2	30.12	100.3	45,000	0	231.0	6.4
3	31.13	88.9	25,000	0	259.0	6.4
4	32.0	88.9	36,500	0	243.0	6.4
5	31.25	93.4	19,000	0	230.0	6.8
6	30.50	89.7	14,000	0	172.0	6.8
7	31.50	92.6	7,100	0	9.5	4.0
8	30.25	86.5	11,500	0	23.9	4.2
9	32.50	90.4	14,500	0	49.1	5.0
10	30.25	84.0	20,000	0	77.8	6.0
11	30.25	75.6	8,000	0	141.0	7.9
12	31.0	86.2	12,000	0	6.0	5.7
13	30.0	75.0	19,000	0	9.5	5.2
14	20.0	71.5	23,500	0	36.4	6.3
	421.0 (total)	86.0 (Average)				

Table III Continued

SUMMARY OF WATER QUALITY TESTS, RUN NO. 22, (ACCEPTANCE TEST)

Contaminants	Concentration, (Parts per Million) Day 1	Composite Days 2 to 6	Composite Days 7 to 14
Alkyl Benzene Sulfonate	Nil	Nil	0.00
Arsenic	.004	.002	.005
Chloride	19.0	5.0	18.0
Copper	28.5	22.6	1.5
Cyanide	Nil	Nil	0.00
Fluoride	.1	0.12	.08
Iron	1.8	1.6	1.6
Manganese	0.0	1.7	.01
Nitrate	.5	1.0	.25
Phenols	.012	.02	.06
Sulfate	20.0	40.0	10.0
Total Dissolved Solids	61.0	605.9	128.0
Zinc	.06	0.5	0.2
Barium	1.5	1.4	.05
Cadmium	0.0	0.0	.005
Chromium	0.0	0.0	.005
Lead	0.6	0.5	2.1
Selenium	.001	.002	.010
Silver	0.4	0.5	.015
Ammonia as Nitrogen	.28	0.4	0.75
Chemical Oxygen Demand	20.0	507.3	91.6
pH Value	6.2	6.2	5.2
Turbidity (Jackson Units)	5.0	10.0	28.0
Color (Chloro platinate)	2.0	4.0	10.0
Odor (Threshold No.) at 60°C	20.0	8.0	6.0

Table III Contined

SUMMARY OF WATER QUALITY TESTS, RUN NO. 22, (ACCEPTANCE TEST)

By Robert A. Taft Center, Cincinnati, Ohio

Composite Sample, Days 12, 13, & 14 Test Run No. 22

Contaminants	Mg/l	Contaminants	Mg/l
Calcium	6.4	Molybdenum	< 0.010
Sodium	< 1.0	Manganese	0.033
Potassium	0.2	Aluminum	< 0.010
Ammonia	12.5	Beryllium	< 0.0003
Sulfate	18.0	Copper	0.007
Total phosphate	0.02	Silver	0.0033
Boron	0.015	Cobalt	0.023
Phosphorus	0.045	Lead	< 0.010
Iron	0.014	Chromium	< 0.003
Zinc	0.130	Vanadium	< 0.010
Cadmium	0.060	Barium	0.012
Nickel	< 1.0*	Strontium	0.010

*By spectrographic analysis - not confirmed by wet chemistry;

Conductivity	77 μ MHOS
Total Alkalinity	< 1 mg/l
pH	4.8
Total Carbon	5.4 mg/l
Urea	< 0.1 mg/l

Table IV

SUMMARY OF WATER QUALITY TEST

By Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio on Water Collected from GARD Model 1271, Automatic Water Recovery System at AMRL, Operated by AMRL Personnel, January 14, 1967.

Contaminant	Mg/l	Contaminant	Mg/l
Calcium	18.0	Nickel	.450
Magnesium	6.3	Molybdenum	< .010
Sodium	< 1.0	Manganese	.015
Potassium	0.7	Aluminum	.030
Ammonia	0.3	Beryllium	< .00003
Sulfate	< 1.0	Copper	.005
Chloride	8.0	Silver	.0033
Total Phosphate	0.04	Cobalt	.013
Boron	.021	Lead	.015
Phosphorus	.055	Chromium	< .003
Iron	.005	Vanadium	< .010
Zinc	.035	Barium	.016
Cadmium	.015	Strontium	.049

Conductivity	144 μ MHOS
Total Hardness	70 mg/l
pH	6.5
Total Carbon	198
Urea	< 0.1 mg/l

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Development of the GARD Model 1271 vapor compression vacuum distillation water recovery system was delayed by component failures rather than the use of an unsound technical approach. The system can be improved substantially through design simplification. The most important conclusion reached during this program was that water recovery for aerospace applications can be a continuous process through an indefinitely long mission, without the need for cleaning the evaporator. Liquids can be continuously pumped to and from a system by synchronized pumps which automatically control flow rates and liquid levels without electrical sensors and controls. The solids left by the evaporation process will remain in solution and be pumped from the evaporator. The concentrated liquor can be diluted, filtered, and recycled back to the evaporator.

Increased solids concentration in the feed liquid decreases the water recovery rate but does not increase the peak power demand. Highly concentrated feed liquid will be transformed to potable water more slowly than fresh urine but will not require higher input power. The spacecraft power supply, therefore, can be sized to operate the water recovery system at a constant power level. Energy required per pound of water, of course, increases with solids concentration because the lower recovery rate requires additional running time to recover a pound of water. Effective and precise control over the interrelated solids concentration, recovery rate, and energy required per pound of potable water is achieved by establishing the recycle-liquor extraction rate. Recycle liquor extraction can be made an automatic process too. A diverter valve could be placed in the recycle output line to discharge a portion of recycle liquid.

There exists a tradeoff between yield efficiency and energy input. Higher extraction rates reduce yield but improve the energy requirement; oppositely, lower extraction rates increase both yield and the energy requirement. The best extraction rate, therefore, is dependent to some extent upon the power supply.

Recommendations

Two areas of potential refinement are apparent.

(1) The initial machine was designed to run continuously, assuming that waste water would always be available for processing. Substantial reductions in water inventory, and therefore takeoff weight, are possible if the system is able to produce water when waste is available and can idle at a lower power level when all the inventory is in the potable water tank. A larger system would be attractive because a substantial increase in capacity would be effected by a small increase in size. Further, larger systems operate at higher efficiency. The reduction in water inventory and the lower long-term energy demand should easily compensate for a small increase in machine size.

(2) Recycle liquor extracted from the loop at the rate of 4 pounds per day contained 75% water. This represents an appreciable loss of water

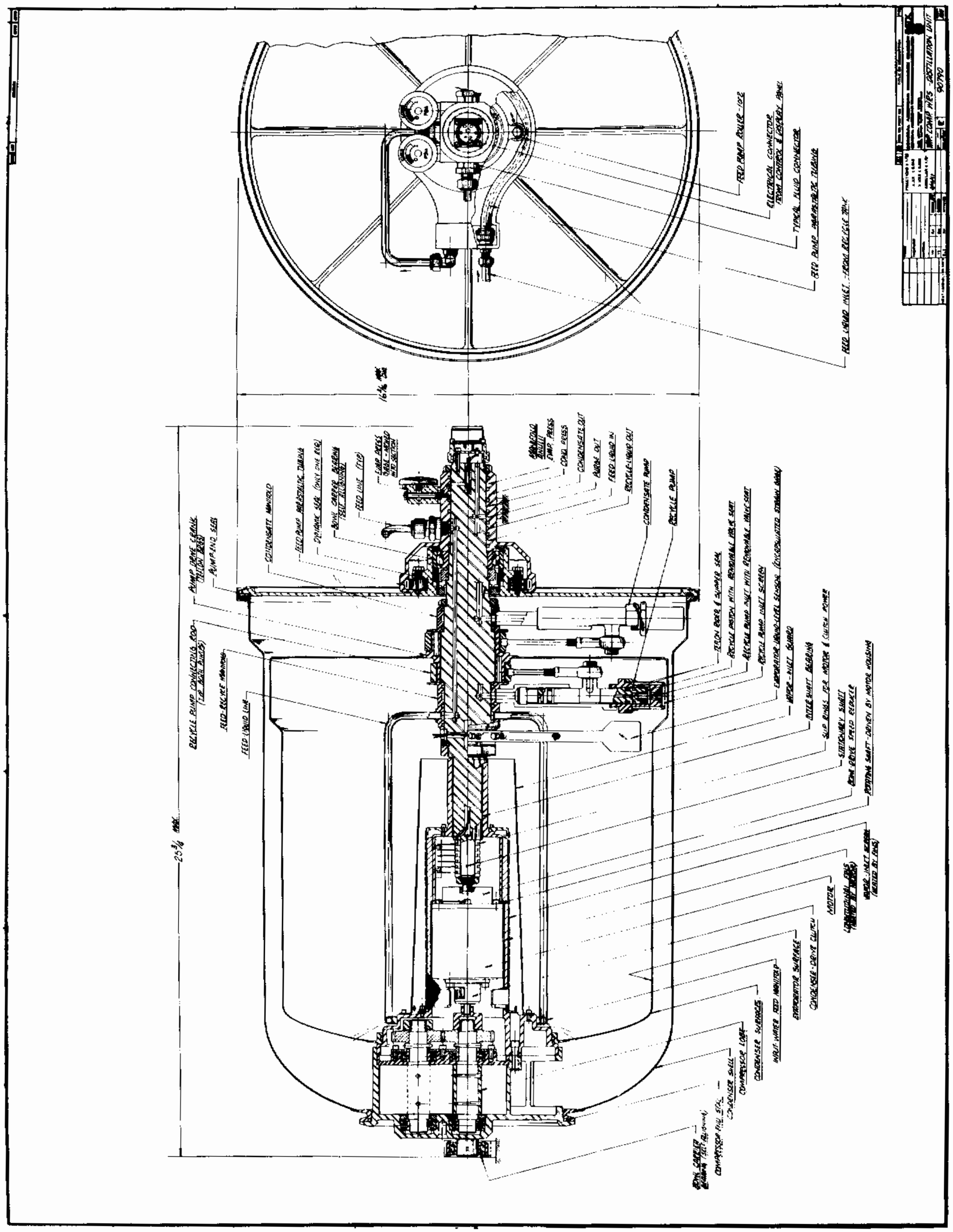

Figure 13 PRELIMINARY DESIGN, AUTOMATIC WATER RECOVERY SYSTEM

over a long-duration mission. The next logical step would be to recover the water in the extracted liquor, leaving solids separated for further processing.

It is recommended that these refinements be incorporated into a vapor compression, vacuum distillation water recovery system with recycle loop as soon as possible so that realistic operating guidelines will be available when a flight model of the system is required. A proposed design of a vapor compression system incorporating the refinement is presented as Figure 13. All problems encountered with the Model 1271 system were analyzed, their causes clearly isolated and defined, and appropriate solutions applied to the new configuration.

Briefly, the important characteristics of the new design are:

1. The compressor is driven directly by the motor, thus eliminating a gear box. A clutch is added to conserve power when water recovery is not required.
2. The feed pump does not require dynamic seals.
3. The drive line (motor, etc.) is packaged within the evaporator to minimize volume and improve efficiency.
4. The recycle and feed pumps are driven by a more positive crank mechanism and utilize better valves.
5. The number of static seals on the rotating unit has been reduced from 19 to 2 and the number of dynamic seals, from 2 to 1.
6. Maintainability, accessibility, and structural integrity are all markedly improved in the new design.

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13. ABSTRACT

A water recovery system for reclaiming potable water from urine and other waste waters was designed, fabricated and tested. The system operates on the vacuum distillation principle with vapor compression for the recovery of latent heat. Chemical pretreatment of the waste liquid is employed and the condensate is post-treated by absorption and filtration. A unique waste-liquid recycle technique was developed. The technique maintains clean evaporator surfaces (thus eliminating the need for periodic cleaning), and permits continuous automatic operation for an indefinite period. The system is designated GARD Model 1271 Automatic Water Recovery System. The materials, finishes, and built-in artificial gravity required for a flight qualifiable system were incorporated into the model which weighs 98 pounds and occupies less than 2.5 cubic feet. Electrical energy consumption varied according to the solids concentration of the feed liquid, and ranged from 34.6 watt-hours per pound of potable water recovered from low-solids urine to 55.4 watt-hours per pound when processing urine concentrated to 32 percent solids. During a 14-day acceptance test performed on the model, 421 pounds of potable water were recovered from 490 pounds of urine for a yield efficiency of 86 percent.

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Life Support						
Water Renovation						
Water Recovery						
Recycle						
Closed-Loop Water Recovery						
Vapor Compression						
Vacuum Distillation						
Water and Waste Management						
Artificial Gravity						
Urine						
Urine Solids						
Water Treatment						
Continuous Operation						
Automatic Operation						

Security Classification