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REFURBISHMENT & TESTING OF THE INTEGRATED WASTE MANAGEMENT SYSTEM

CONTRACT NAS 9-9014

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FOREWORD

This report describes the work performed by the AMGLO Corporation, 4333 North Ravenswood Avenue, Chicago, Illinois, under Contract NAS 9-9014 - for refurbishment and testing of the NASA/MSC Integrated Waste Management System. This program was sponsored by and performed for the Crew Systems Division of the NASA Manned Spacecraft Center. Mr. M. L. Owen (EC3) was the designated Technical Monitor of this program.

The work reported herein was started in December 1968 and completed in August 1969. Robert A. Bambenek (Program Manager), Phillip P. Nuccio (Project Engineer), Thomas L. Hurley (Biochemical Specialist) and Frank Chybik, Jr. (Electronic Specialist) submitted the draft copy of this report on 29 September 1969. Other personnel who worked on this program are: Walter J. Jasionowski (Chemical Engineer), Peter W. Glocker (Drafting Technician) and Andrew L. Murman (Electronic Technician). The authors are indebted to these individuals - and Dean Thompson, Richard Sauer and Charles Verostko of NASA/MSC - and Charles E. Hansen (consultant), who provided part of the background information required to perform this program.

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SECTION 1

INTRODUCTION & SUMMARY

Previous studies have shown that manned spacecraft designed for missions longer than several months duration should include a system for recoverying water from metabolic wastes, to circumvent the large weight and volume requirements associated with carrying stored water. To assure the availability of a flight-qualifiable water recovery system for these missions, the NASA Manned Spacecraft Center has supported the development of an Integrated Waste Management System (IWMS). This system includes compression distillation units for recoverying water from urine, humidity condensate, concentrated wash water and slurried feces.

The initial MSC funded efforts on IWMS development were conducted with the Marquardt Corporation. They developed a compression distillation unit under NAS 9-1680, and a prototype model of an IWMS under NAS 9-5119. These efforts resulted in the development of hardware that has the desired operational potential; however, subsequent tests indicated the need for additional work to confirm the suitability of this design for long term missions.

The additional development work was conducted with the AMGLO Corporation. The specific objectives of this program, as delineated in Exhibit A of Contract NAS 9-9014, are summarized as follows.

1. Receive, disassemble, clean, inspect, repair and/or replace components, and automate the IWMS.

2. Reassemble and checkout system, using distilled water, to establish performance characteristics.

3. Conduct a 30-day simulated mission test, using urine and feces.

4. Recalibrate system, using distilled water.

5. Analyze test results, to determine consumption of expendables.

6. Prepare and submit a final report which (1) summarizes the test results, (2) discusses the functional utility of this system, and (3) describes the modifications recommended to improve system performance.

The system as received from NASA/MSC was reasonably clean and in good condition, except for a broken support on the fecal collector. The system was disassembled, cleaned and inspected - before it was concluded that the following repairs and/or modifications should be made.

A. Arrangement

1. Replace the solenoid-operated shut-off valves, located between the waste collectors and storage tanks, with hand-operated ball valves; the solenoid valves failed due to excessive cycling.

2. Install an inventory control subsystem to avoid overfeeding the distillation units.

3. Disconnect the condensate coolers, which are unnecessary with the new inventory control system.

4. Replace the cabinet temperature control system with a light bulb and an exhaust fan - to reduce the complexity of the system.

B. Post-Treatment

1. Locate the conductivity sensors and diverter valves upstream of charcoal filters, instead of downstream - to shorten response time and avoid unnecessary contamination of the filters.

2. Install biological filters upstream of charcoal filters - to prolong their useful life.

3. Install additional sampling ports, and use improved septums.

4. Reduce the volume and L/D ratio of the charcoal filters - to maximize loading efficiency.

C. Distillation Units

1. Replace the solenoid-operated condenser purge valve with a calibrated needle valve - to improve reliability and performance.

2. Move the purge point from the vapor-inlet end to the opposite end of the condenser - to minimize the partial pressure of non-condensibles over the entire surface of the condenser.

3. Plug the purge openings at the top of the condensate reflux columns - to minimize "flashing" on the suction side of the diaphragm-type condensate pumps.

4. Install peristaltic-type pumps between the diaphragm pumps and the condensate accumulators - to fill the condensate accumulators without excessive pressures in the dynamic seals.

5. Redesign the dynamic seal pack - to provide larger faces on the carbon seals.

6. Refurbish the vapor compressors - which had some damaged parts.

7. Remove the internal, solenoid-operated feed valves - which served no obvious purpose.

8. Replace the rotational drive gears and DC motors with gear boxes and AC motors - to avoid variations in rotational speed.

9. Refurbish the evaporator wiper systems - which had worn bearings and weak clutches.

D. Instrumentation & Controls

1. Replace the still feed control system with a new system that utilizes signals from the condensate accumulators.

2. Replace the urine and fecal collector control systems with new systems that use mechanical instead of solid-state timers.

3. Repair one of the four conductivity meters.

4. Discard the pH meter - which was inoperable and served no control function.

5. Design and fabricate a test panel for automatic counting of waste feed and condensate dump cycles, and varying the frequency of evaporator wipes.

Figures 1 and 2 presented on the next page show two views of the refurbished IWMS, after the 30-day test. Figure 1 shows the location of the urinal, fecal collector, the still drive motors and the test panel. Figure 2 shows the post-treatment systems, and one of the stills in the insulating cabinet.

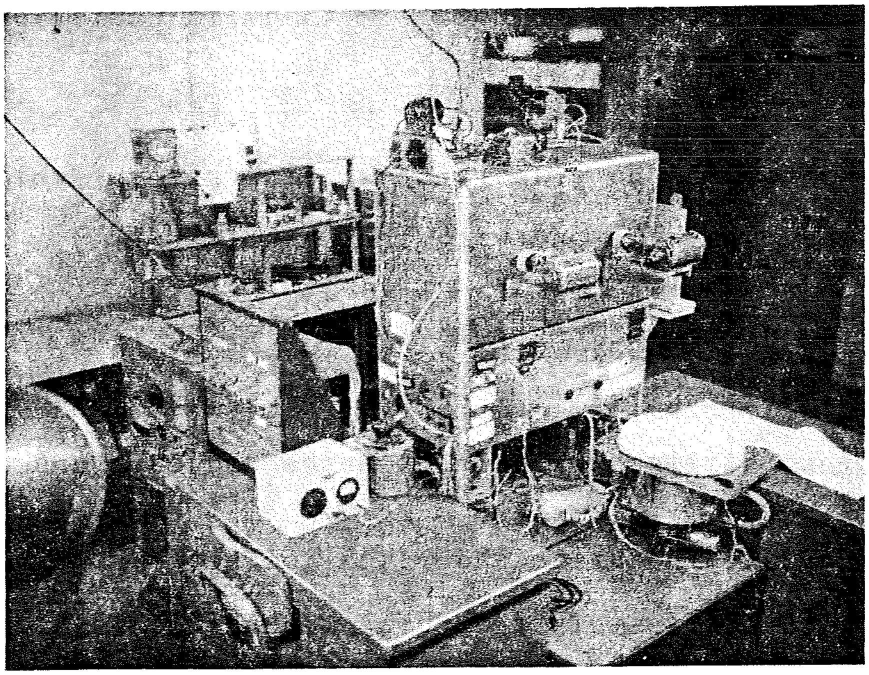


FIGURE 1, TEST SET-UP

Front & Right-Side View

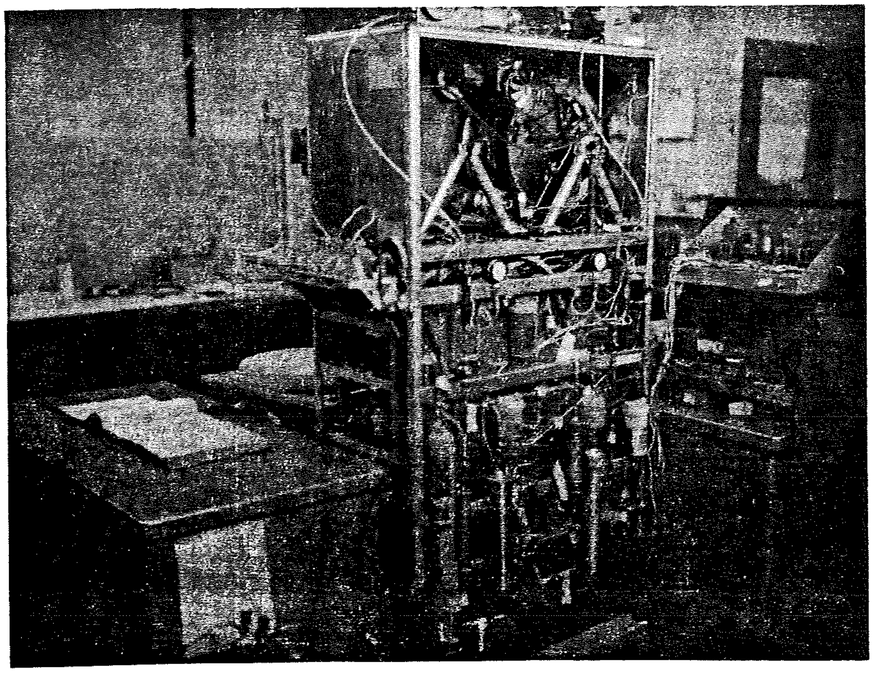


FIGURE 2, TEST SET-UP

Rear & Left-Side View

Nineteen tests were performed with distilled water to calibrate the refurbished IWMS. The duration of each test ranged from 2.25 to 34.42 hours, depending upon the objectives of each test and the occurrence of operational problems. The total run time accumulated on the urine and fecal stills was 324 and 382 hours, respectively. This was more test time than anticipated - because the recovery rate and yield data obtained indicated that the performance of the stills was substantially below the design performance, and parameters were varied to find the optimum combination.

The calibration tests were terminated when it was concluded that the low recovery rate (up to 188 ml/hr instead of 454 ml/hr) was primarily due to low volumetric efficiency of the compressor, and the low yield (up to 82% instead of 98%) was due to an excessive amount of inboard air leakage. These tests also indicated that the IWMS still design cannot dry concentrated waste water because of poor thermal design; water vaporized in the evaporator and/or dryer condenses on the flat end plates, from where it is centrifuged back into the dryer. Correction of this thermal deficiency would have required a major redesign. Since this deficiency did not preclude determining the quality of the recovered water and other important program objectives, the 30-day test was initiated without any design changes.

The 30-day simulated mission test was performed on an around-the-clock basis for seven days each week. During this period the urine and fecal loops were operated for 343 and 337½ hours, respectively; frequent breakdowns, especially with the urine still, prevented the accumulation of more running time. A major difficulty encountered with the fecal loop was plugging of the feed passage in the still's dynamic seal. After 19 days of operation the fecal loop was shut-down because the evaporator surface was fouled with solids. The fecal still was then connected to the urine loop, because the urine still had become inoperable, and urine condensate was needed to complete the evaluation of the urine loop post-treatment subsystem.

The water quality analyses performed during the 30-day test indicate that silver-dosed flush water is not capable of maintaining sterile conditions in the waste collection and storage subsystems. Also, the use of high evaporator temperatures (ca. 120°F) without acid pretreatment, causes the raw condensate to have an excessively high COD and ammonia concentration. However, the test results do indicate that even with this relatively bad condensate (1) filtration and silver dosing produce water that is sterile and chemically acceptable, and (2) use of a biological filter upstream of the charcoal filter, extends the useful life of this filter to at least ten days. In addition, the water produced by passing the filtered and silver-dosed condensate through a mixed bed of ion exchange resin exceeds all current standards for potability, and contains no coliform bacteria. The deionized water was not sterile (MPN/ml=5.4) but identification of the microorganism present indicates that it was a soil-type bacteria that could be anticipated in ion-exchange resins.

The results obtained during this program indicate that an improved IWMS should:

1. Use a chemical disinfectant in the flush water.
2. Filter-out suspended solids before feeding fecal slurry into a still.
3. Use a still that (1) operates at saturation temperatures near cabin temperature (65 to 75°F), (2) contains no more than one dynamic seal, and (3) pumps concentrated waste water to an external dryer.
4. Utilize pasteurization temperatures to sterilize the ion-exchange resin, and/or stored potable water.

The preliminary design of an upgraded IWMS that includes these recommendations, and a reverse osmosis type of wash water loop, is presented in Section 6 of this report.

SECTION 2

SYSTEM DESCRIPTION & MODIFICATIONS

The NASA/MSC Integrated Waste Management System built under Contract NAS 9-5119 was delivered to AMGLO at the beginning of this program. The system included water-flushed urine and fecal collectors manufactured by General Electric Company; water distillation units, liquid handling and post-treatment loops, and control circuitry built by the Marquardt Corporation; and some water-quality-assessment instrumentation from the Myron L. Company. The system had been operated for five days in a simulated mission. The results and data from that test were useful in establishing the course of action for the refurbishment program reported herein.

2.1 Arrangement

Briefly, operation of the system is as follows: Waste materials are collected in appropriate receptacles, transferred to the waste side of bladder-type, holding tanks and fed, in batches, to the distillation units. Condensate received from the distillation process is filtered and sterilized by the post-treatment cells before it is delivered to the flush-water side of the same holding tanks. From there it is either used to flush the waste collectors or, in the urine loop, deionized for use as potable drinking water. If either loop accumulates an excessive amount of water, it is automatically dumped through relief valves.

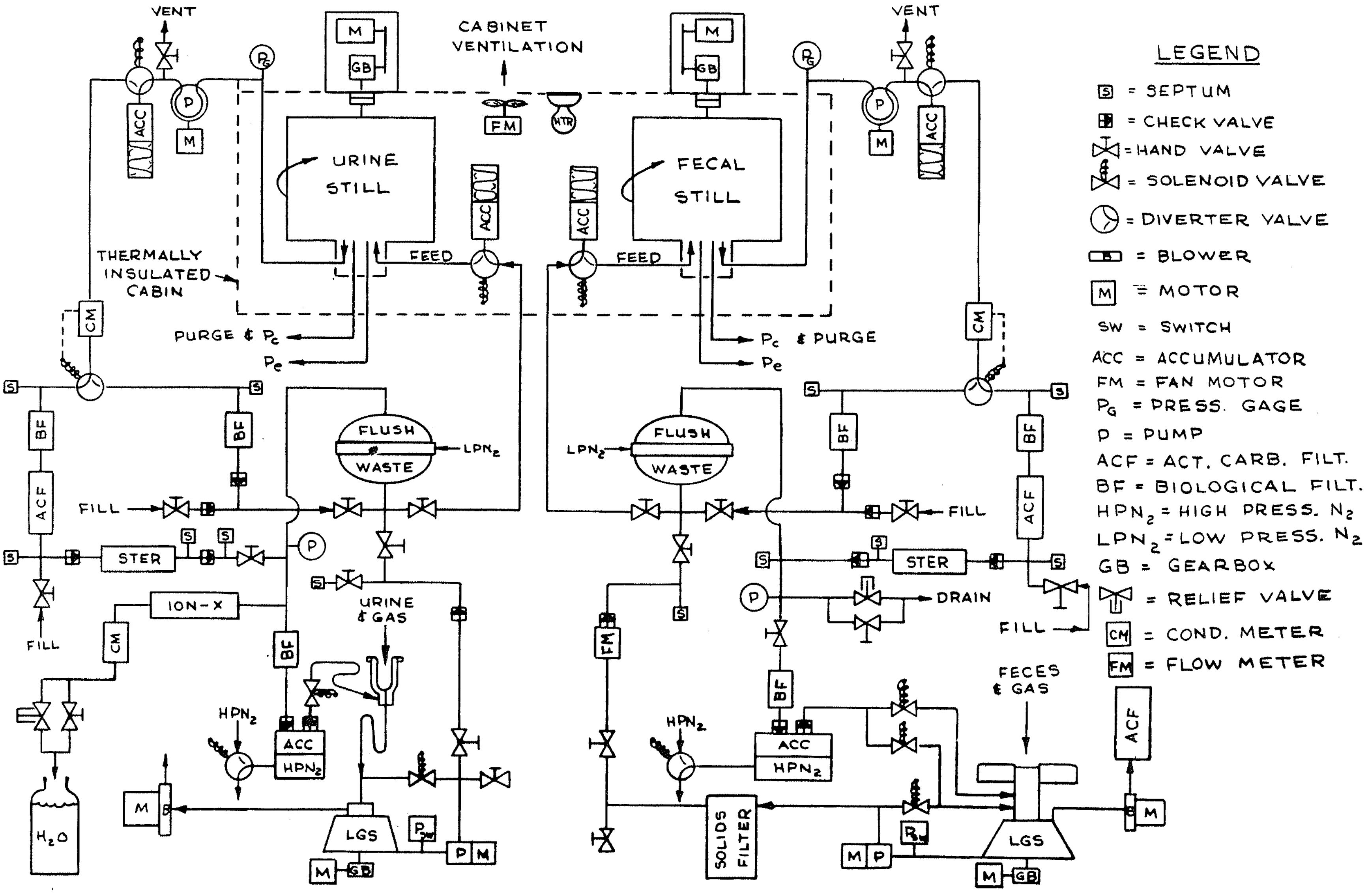
The system was intended to serve a 3-man crew for a 30-day period. Neither the general arrangement nor the sizing was changed in this effort; however, certain detail modifications were made. The refurbished system is shown schematically as figure 3, which is laid out to show the approximate physical location of the components within the packaged assembly.

The most significant modifications were made to the post-treatment scheme, distillation units, and controls and instrumentation circuitry. These changes are discussed later in this section. Modifications of the interconnecting components and support devices are discussed below.

2.1.1 Waste Transfer Valves

Solenoid operated ball valves were used between the collectors and the waste-storage tanks. They were opened when the waste transfer pumps developed enough head to close a pressure switch, and closed when the pumps were stopped (to prevent back flow from the pressurized tanks to the collectors). The valves in both the urine and fecal loops were inoperative when received; they were returned to the manufacturer for repairs, but both failed again during calibration testing. The cause of failure was excessive cycling, which overheated their rotary solenoids. Excessive cycling was experienced because the pressure switches had too wide of a dead-band for the variation in pressure between no-flow and full-flow conditions. Hand-operated ball valves were substituted and manually operated by the test personnel to duplicate the automatic operation of the original electric valves.

FIGURE 3, SCHEMATIC OF REFURBISHED IWMS



2.1.2 Still Inventory Control

Originally, the system included two spring-loaded, roll-diaphragm accumulators and two solenoid-operated diverter valves for batch feeding waste liquids into the urine and fecal stills. Two feed control schemes had been tried previously. First attempts to avoid overfeeding the stills involved injecting waste materials whenever the delta P sensed by two strain-gage pressure transducers, that rotated with each still, indicated that the evaporators were nearly dry. Unfortunately, the pressure signals had to be transmitted to the control circuit through slip rings, which distorted the signals and caused erratic feed operation. Finally, feeding on a fixed-time basis was tried, which obviously works only if the system recovery rate is higher than the feed rate.

Ideally, a distillation unit that operates on a batch cycle should feed waste into the evaporator whenever the unit has produced a batch of condensate - irrespective of the other operating parameters. This control assures that the distillation process will continue uninterrupted during periods of high water production rates, and will not become flooded when its water output is slow or the evaporator pressure reading is changed by some irrelevant cause. Under this contract two additional accumulators were built to measure water output (see figure 3); they were electrically interlocked to the feed accumulators to maintain the balance between input and output. The location of the "full" switch on the condensate accumulator was made adjustable to control output yield as a percentage of input.

2.1.3 Condensate Cooler

Air-cooled heat exchangers were originally used between the distillation units and the post-treatment circuit; their purpose was to extract the sensible heat gained by the water during the distillation process. Under conditions of maximum water recovery rate and maximum distillation temperature, the heat gained ranged up to 50 btu per hour - which could be adequately rejected through the inventory-control accumulators and interconnecting lines. The heat exchanges, therefore, were bypassed - and some pumping power was eliminated.

2.1.4 Distillation Temperature Control

The distillation units are contained within a thermally insulated chamber which was fitted with two electric heaters, a blower, dampers operated by rotary solenoids, two thermostats, solid-state logic circuitry, and appropriate air baffles and ducting. To improve reliability during the test these components were removed and replaced by a light bulb located inside the chamber for heating,and a fan to move air through the chamber for cooling. Variacs controlled power to the heater and fan to maintain close control over any distillation temperature within a broad range.

2.2 Post-Treatment

Post-treatment (PT)is a combination of purification processes which are used to eliminate entrained and/or co-distilled matter from the raw condensate exiting the stills.

The PT processes used in both the original and refurbished IWMS are: (1) 0.35 micron absolute filtration, (2) adsorption by activated charcoal, (3) silver ion dosing with a silver chloride column, and (4) deionization by ion-exchange resins. The PT processes in both systems were monitored by in-line conductivity sensors; these sensors also controlled the function of 3-way solenoid valves which, when energized by the sensor unit, diverted low grade water to the waste tank.

The approaches to post-treatment pursued in the original and refurbished systems were similar; that is, both systems treated the raw condensate from each still in separate loops consisting of identical and interchangeable components. The urine and fecal loops in both systems differed in only one respect; that is, the inclusion of a deionizer column in the urine loop; this deionizer treated the water intended for crew consumption, but not water used for flushing.

Many components in the original PT loops were simply cleaned, checked-out and reinstalled. However, changes were made in the arrangement and design of some components. The following sections describe these changes along with a description of the major components in the PT loops.

2.2.1 Arrangement

In the original system, low grade condensate was shunted to the waste tank (on the basis of conductivity) after charcoal treatment. Also, biological contamination of the charcoal column was neglected; biological contamination and subsequent proliferation is the major cause of shortened charcoal column life. Since the charcoal columns constitute a major expendable item, changes conducive to lengthening of column life were warranted.

The conductivity sensor and 3-way valve formerly located at the charcoal column outlet were moved to the inlet side of the column; this change permitted monitoring of the raw condensate and rejection of low quality condensate prior to treatment in column, thereby eliminating an unnecessary load on the column. The 0.35 micron filter formerly located at the silver chloride column outlet was placed between the charcoal column inlet and the 3-way valve; this pre-sterilized filter was aseptically joined to the redesigned charcoal column (see Section 2.2.2), forming a sterile assembly which was replaced as a unit when necessary. The estimated life of the filter-charcoal column assembly was 9-10 days based primarily on retardation of microbial proliferation.

The remaining changes in the arrangement of the loops of the original system are presented in the following.

1. The ECS water treatment loop, which interfaced with urine PT loop, was eliminated because a realistic ECS water simulant could not be obtained. The original simulant was distilled water which would have made further treatment unnecessary and would have confused the assessment of water quality.

2. Connecting lines and valves, which permitted transfer of treated water between the urine and fecal PT loops, were eliminated; these lines were not consistent with keeping the two loops separate and increased, unnecessarily, the probability of water balance errors.

3. The water pressure relief valves for each loop were provided with separate drain lines.

4. The existing sample ports were modified to accept the Hamilton multiple-layer silicone rubber septum. Three additional sample ports were also installed in each loop.

5. The 3-way valve located downstream from the deionizer effluent conductivity sensor was eliminated; shunting of low-grade deionizer effluent to the waste tank would have hindered water quality assessment.

2.2.2 Component Description

Activated Charcoal Column The original columns provided a 2.5" x 10" long cylindrical bed requiring 1.7 lbs. of 10 x 50 mesh charcoal. These columns provided much more charcoal than could be effectively used before microbial proliferation necessitated replacement. Also, the 4 to 1 length to diameter ratio provided by the columns is far from the optimum of the 8 to 1 ratio necessary for minimizing channeling.

The columns designed and fabricated by AMGLO used 0.64 lbs. of charcoal in a 1.5" x 12" long cylindrical bed. The incorporation of a 0.35 micron filter to reduce microbial contamination extended the estimated life of the column to 9-10 days. The new column design was based on (1) the nominal 10-day life, (2) the daily maximum condensate output of 16.26 lbs., (3) an assumed organic loading in the raw condensate equivalent to 300 PPM COD, and (4) an absorption capacity of 9% of charcoal weight.

Barnebey-Cheney type 365, 20 x 50 mesh activated charcoal was used in the new column. The charcoal was treated with dilute hydrocloric acid and boiled twice in two volumes of deionized water; it was then packed into columns and flushed with deionized water until the effluent gave a pH of 6.0 and a specific resistance greater than 200,000 ohms. The column ports were plugged with cotton and the column autoclaved ($250^{\circ}F$, 30 psia) for 1 hour. A presterilized filter was aseptically connected to inlet; the assembly was then filled with sterile deionized water and installed in the system.

Biological Filters Two configurations of the Pall Ultipor filter (0.35 micron) were used in both the original and refurbished systems. One configuration consisted of a presterilized housing and element cartridge (Pall #MBY2001URA) which was used to filter raw condensate in the refurbished system and the silver chloride column effluent in the original system. The second configuration consisted of a housing (Pall #ACP4463) with a replaceable element (Pall #MCS1201UW); these filters served as barriers to microbial migration in locations where treated water lines interfaced with waste lines or components likely to be contaminated with waste.

Silver Chloride Column These columns contained a 1.0" x 8.0" long cylindrical bed containing 0.80 lbs. of a mixture of silver chloride granules and 0.4 mm glass beads. The columns were cleaned and repacked with a freshly prepared silver chloride-glass bead mixture before reinstallation. Preparation of the silver chloride involved grinding reagent grade material with mortar and pestile in semi-darkness until a 10 x 50 mesh product was obtained. The glass beads (0.45 lbs.) and silver chloride particles (0.35 lbs.) were manually blended and packed into the columns which were flushed with deionized water and installed in the system.

Ion-Exchange Column This column was identical with the activated charcoal column and provided a capacity of approximately 800 ml of wet resin. Although this column design was not the optimum for effective resin performance, it was retained in the refurbished system because of the low pressure drop it afforded. Pressure drop was an important consideration since potable water had to be available at a reasonable flow rate. The column was packed with 550 ml of a mixed, strong acid-strong base exchange resin (Rexyn I-300, Fisher Scientific) and 250 ml of a strong acid, cation exchange resin (Rexyn 101, Fisher Scientific). The strong acid, cation exchanger layer was at the inlet end of the column.

The two ion exchange columns used were prepared differently. The first column was saturated with 37% formaldehyde solution for 24 hours; the column was flushed with sterile deionized water until a negligible COD was obtained on the effluent flushing water. The second column was washed in the same manner but with deionized water only.

2.3 Distillation Units

The distillation units were designed to operate according to the classic Vapor Compression Vacuum Distillation Cycle in which water vapor is collected from the evaporator and driven by a compressor to the condenser operating at a higher temperature and pressure than the evaporator. Latent heat is transferred, therefore, from the condenser to the evaporator through a common metallic wall. These units included, in addition, a dryer section within the evaporator space, a mechanical wiper to load the dryer section and an electric heater to supply latent heat for the drying process. The entire unit is rotated to maintain liquid/gas interfaces in the absence of gravity. A schematic drawing, in section, of a distillation unit is shown as figure 4 on the next page. No change to the basic operating cycle was made under this contract; some of the details and components were modified however, and are discussed below.

2.3.1 Condenser Purge

Originally, non-condensible gases were to be purged from the condenser intermittently by opening an electric solenoid valve located inside the rotating distillation unit. The condenser volume and an intermittent purge would cause large gradients in non-condensible concentration in the condenser, between valve openings. The valve was removed and replaced with a micrometer-type valve in the purge line, to purge the condenser continuously and improve operational reliability.

The original condenser purge hole was located at the same end of the condenser which received the vapor and non-condensibles from the compressor. The other end of the condenser was dead-ended. Non-condensibles would accumulate at the dead end while the purge hole would preferentially draw vapor from the adjacent vapor inlet hole. This vapor short circuit would result in high water loss to the purge, and low recovery rate by insulating a

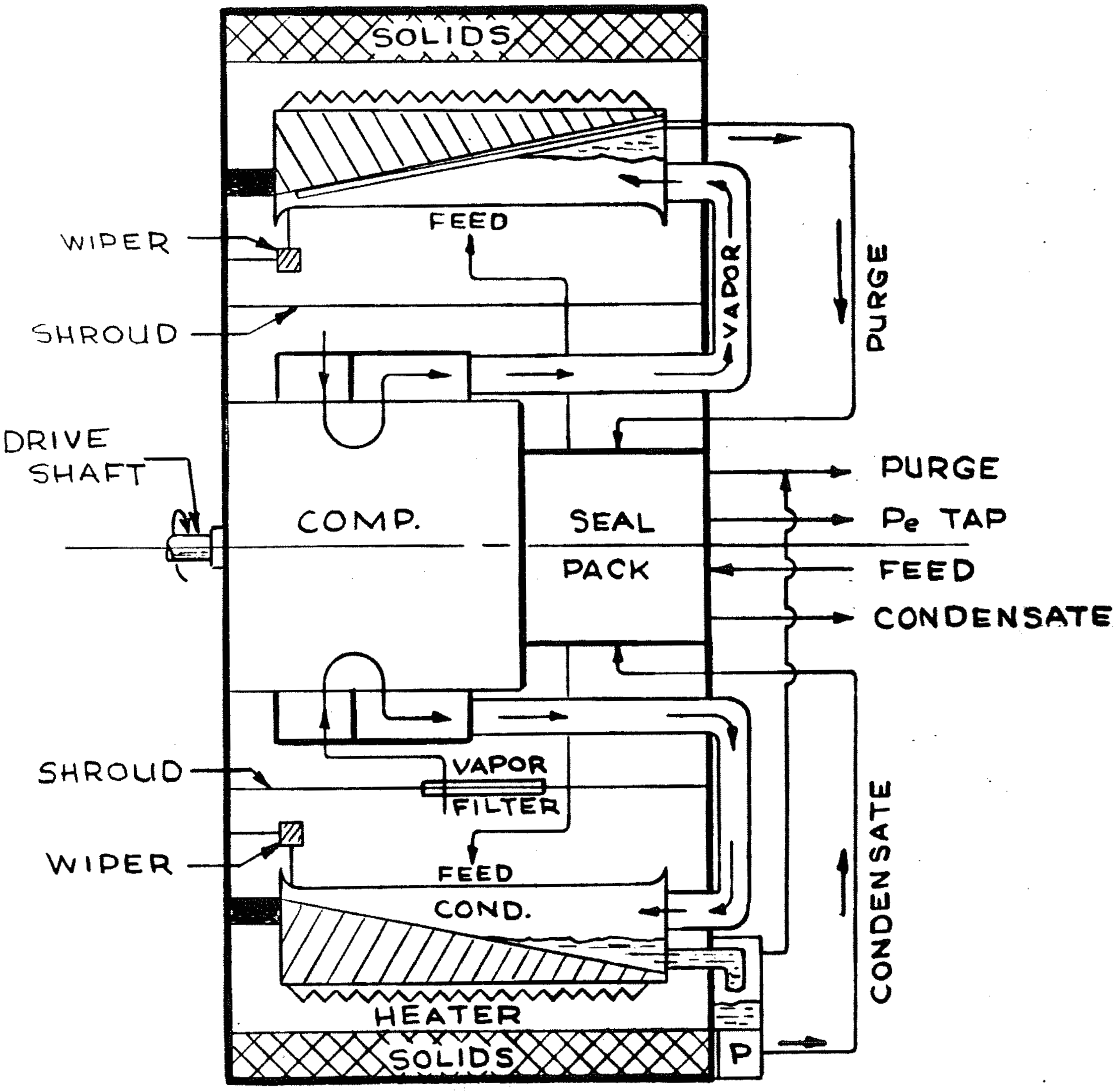


FIGURE 4 - SCHEMATIC CROSS-SECTION OF STILL

portion of the condenser surface with non-condensible gases and rendering it inactive for latent heat transfer. To remedy the condition, a small-diameter tube was inserted into the condenser through the purge hole to the dead end. The purge opening therefore, was located at a point far removed from the vapor inlet. The compressor-outlet gases were forced to traverse the entire condenser to reach the purge opening which increased the vapor's exposure to the condensing surface and minimized the partial pressure of non-condensibles.

The original purge circuit in the distillation units withdrew gas from a reflux column located at the condensate pump inlet as well as from the condenser. The two purge paths were in parallel - slightly biased to favor purge through the reflux column. That bias, and the addition of the long, small-diameter purge tube in the condenser, caused the point of lowest pressure to occur at the condensate pump inlet rather than at the dead-end of the condenser. Flashing of the condensate at the pump inlet resulted, and the pump became vapor bound until the centrifugal head on the water leaving the condenser was large enough to overcome the loss in pressure caused by the purge. Flow from the pump therefore, was intermittent, occuring in slugs of 100 ml or greater, then ceasing until the water head redeveloped. During the period of water accumulation, of course, the water which flashed was lost to the purge. The effectiveness of the reflux column in separating co-distilled ammonia was in serious doubt even before this effort began; the parallel purge line to the column, therefore, was plugged. The slug size was reduced to less than 20 ml each, less water was lost to purge and, with only the condenser purge open, better control over non-condensible gases was maintained.

2.3.2 Condensate Pumps

Product water was removed from the condensers by reciprocating diaphragm and check valve pumps mounted on the rotating distillation units. The condensate was passed between dynamic sealing faces and the post-treatment circuit in the original layout. The addition of the water-inventory-control accumulator requires (1) a higher pump-discharge pressure, and (2) a more constant flow rate than the original pump could produce. Peristaltic booster pumps were added to the condensate lines between the distillation units and the accumulators to help correct both deficiencies. The booster pumps were individually driven by adjustable-speed motors and could apply the necessary discharge pressure; they also generated a low suction pressure and thereby reduced the discharge head against which the original diaphragm pumps operated. That lower discharge head requirement improved the pump's ability to clear itself of gas by letting the pump outlet valve open at lower pressures. The gas, therefore, could pass through the discharge valve. In the original pump a gas bleed hole was located in parallel with the inlet check valve to return the gas to the condenser; that bleed hole was plugged when tests showed that vapor locking could be effectively controlled by adjusting the booster pump suction pressure. With the bleed hole plugged, the effective clearance volume in the pump head was reduced, vapor lock was virtually eliminated and slugging was reduced to a level tolerable by the Still Inventory Accumulator.

Another advantage gained by adding the booster pump is that with the low suction pressure condensate passes within the dynamic seal assembly at a lower absolute pressure. Its effect in unbalancing the seal, therefore, is minimal and the leak potential is much lower.

2.3.3 Dynamic Seal Assembly

Three fluid lines pass into the rotating distillation units; they are: feed liquid in, purge gas out, and condensate out. In addition, a seal must be made between those parts and the still evaporator space, and another seal to exclude the ambient gas. These five chambers were separated by four dynamic carbon-on-steel interfaces. In the original design however, the interfaces were too narrow and were rapidly worn by the abrasive solids contained in waste materials. Upon disassembly of the original seal assembly it was noted that the carbon surfaces had become locked into one position by solids deposits and were unable to conform to their wobbling mating surfaces. A new seal assembly was designed to alleviate both the wear and wobble problems, without changing the fluid flow patterns, and to reduce the number of sealing surfaces required. The new seal was built (1) with greater contact area at the interfaces to prolong life, and (2) without cavities where movement for wobble compensation is necessary.

Wear of the new seal was not measurable after nearly 1000 hours of operation. Wobble compensation of the seal installed in the fecal still was adequate. In the urine still, however, the new assembly did not maintain good sealing of the ambient air which resulted in high leak rate to the urine evaporator. The required wobble in that still was greater than that necessary in the fecal still and sometimes exceeded the seal's capacity to conform. The resulting leakage of ambient-pressure gas upset the balance of forces within the seal assembly and applied a tightening load. On several occasions that load was great enough to cause still seizure. Efforts to reduce the required wobble in the urine still yielded only temporary success. The seal's capacity for wobble was increased too, but could not compensate consistantly for the changing alignment of the adjacent structure. To reduce the wobble requirement in the urine still, the original structure had to be either re-made to eliminate the dimensional differences between the two stills or redesigned to reduce deformations which affect seal alignment. When this difference between the still assemblies was detected there was insufficient time remaining in the program to undertake either of the alternatives. Instead, it was decided during the long-term test to run the good still first as a fecal still then as a urine still.

The stationary shaft (through which was ducted the fluid lines to the dynamic seal assembly) originally protruded through the opposite end of the distillation unit. At that end a bearing and the fifth dynamic seal were located. This seal was eliminated by placing a cover over the stationary shaft and sealing the cover to the rotating still with a static seal. The rotating cover then was carried in a bearing external to the distillation unit.

2.3.4 Vapor Compressor

Reciprocating diaphragm compressors were designed into the distillation units before this program began. Their performance was satisfactory but previous testing caused some permanent deformations and cracking in the main reciprocating parts (shuttles), which were made of a polycarbonate resin. Also, some of the Mylar valves were partially delaminated. The compressors were returned to the original manufacturer, Myron L Company, for refurbishment; most of the dynamic parts were either rebuilt or replaced. The plastic shuttles were replaced with aluminum assemblies manufactured under Contract NAS 9-5119, in anticipation of weaknesses in the original parts. New stainless steal valve disks were made to replace the mylar parts, and the design of the teflon diaphragms was altered slightly to reduce wrinkling and improve life. The reworked compressors were also performance tested and calibrated by the vendor.

2.3.5 Internal Feed Valve

Solenoid-operated valves were located inside the rotating distillation units to open and close the feed-liquid line in syncronization with the external feed valves. The intent was to avoid vaporization of the feed liquid located between the two valves by isolating it from the evaporator chamber and thereby, achieve positive control over each batch size. It was reasoned however, that waste liquid vaporization within the feed line would have no adverse effects because the next batch of feed would redesolve any residue in the line which was originally in solution. Also, the volume of the feed line between the two valves was insignificant, relative to either the evaporator capacity or the feed-batch volume - and that positive control over feed-liquid quantity would be achieved by the still inventory control device. The internal feed valves, therefore, were removed. Operational reliability was improved without the valves and their related circuitry.

2.3.6 Rotation Drive

The distillation units must be rotated to maintain liquid/gas interfaces in a weightless state. That rotation was used, in conjunction with a cam-roller mechanism, to drive the internally-mounted compressors. Originally, the stills were driven through a large diameter ring gear mounted on the perifery. The ring gear meshed with a pinion driven by a DC motor located on the still support structure. The pinion was sized to produce the necessary speed reduction. Excessive tooth wear and breakage occured during previous testing because the gear center distance could not be maintained. Too much structure and too many parts had to be dimensionally stable to hold the center distance necessary for rolling contact between the meshing teeth; that stability was not possible when the operating thermal and dynamic stresses were applied.

The drive motors were undersized for the application. They ran too hot and eventually were fitted with water-cooled jackets. The varying torque requirements of the distillation units, combined with the poor speed regulation of the DC motors, caused wide variations in still speed - including some seizures.

A new drive was designed which incorporated an AC motor for better speed control and a speed reducer in which the gear center distance was small and maintained by a single casing. The output shaft of the speed reducer was direct-coupled to the still. No effort was made to maximize either thermal or mechanical efficiency of the new drive, because the still it was driving was not representative of the low power consumption attainable with the vapor compression cycle. Instead, a "work horse" drive was designed for trouble-free, constant-speed operation at low cost.

2.3.7 Solids Wipers

Mechanically operated evaporator wipers were incorporated into the distillation units originally. A circular rubber lip, held by a steel ring, was made to traverse the evaporator surface by the syncronized rotation of three lead screws. The screws were driven through electric clutches and by the unit's rotation. A chain running on sprockets attached to each lead screw maintained the required syncronized movement, and magnetically operated limit switches inside the units signalled the completion of each wiper stroke. The residue wiped from the evaporator was pushed to the dryer section of the stills located at the outermost diameter.

During the refurbishment effort the clutches were rebuilt and adjusted for holding torque. Several small bearings which run continuously in the clutches had failed and were apparently overloaded in this application. The dynamic seal and bearing for each lead screw was replaced, and the syncronization checked. Two limit switches were broken and were replaced with identical switches.

During the testing program the clutch bearings failed several times. The most probable cause is that in this application the entire clutch assembly rotates on a center several inches removed from its own center; the bearings, therefore, carry a centrifugal load in addition to the normal shaft load. A major redesign of the clutches or the wiper drive line is necessary to correct this deficiency. Also, during testing, one of the magnets which operates the travel-limit switches lost flux; switch operation was erratic and on one occasion the wiper ring overtraveled and caused clutch slippage. That failure had no adverse effect upon the clutch because the magnetic particle clutch can run stalled, rather it drove the ring against some electrical wires and crushed them.

The most serious limitation of the wiper mechanism is the need for three dynamic seals (one for each lead screw where it penetrates the still envelope). Leakage in this dynamic vacuum system is a major limitation to good performance. While most of the in-leakage occured through the main shaft seal throughout the testing phase, the wiper screw leakage became increasingly severe.

2.4 Instrumentation and Control

The original concept for control of the stills was based on sensing the evaporator and compressor ΔP. When the ΔP would be high the feed valve, discharge valve and/or wiper mechanism would function. The wipe when enabled would inhibit the feed until completion of the wipe cycle.

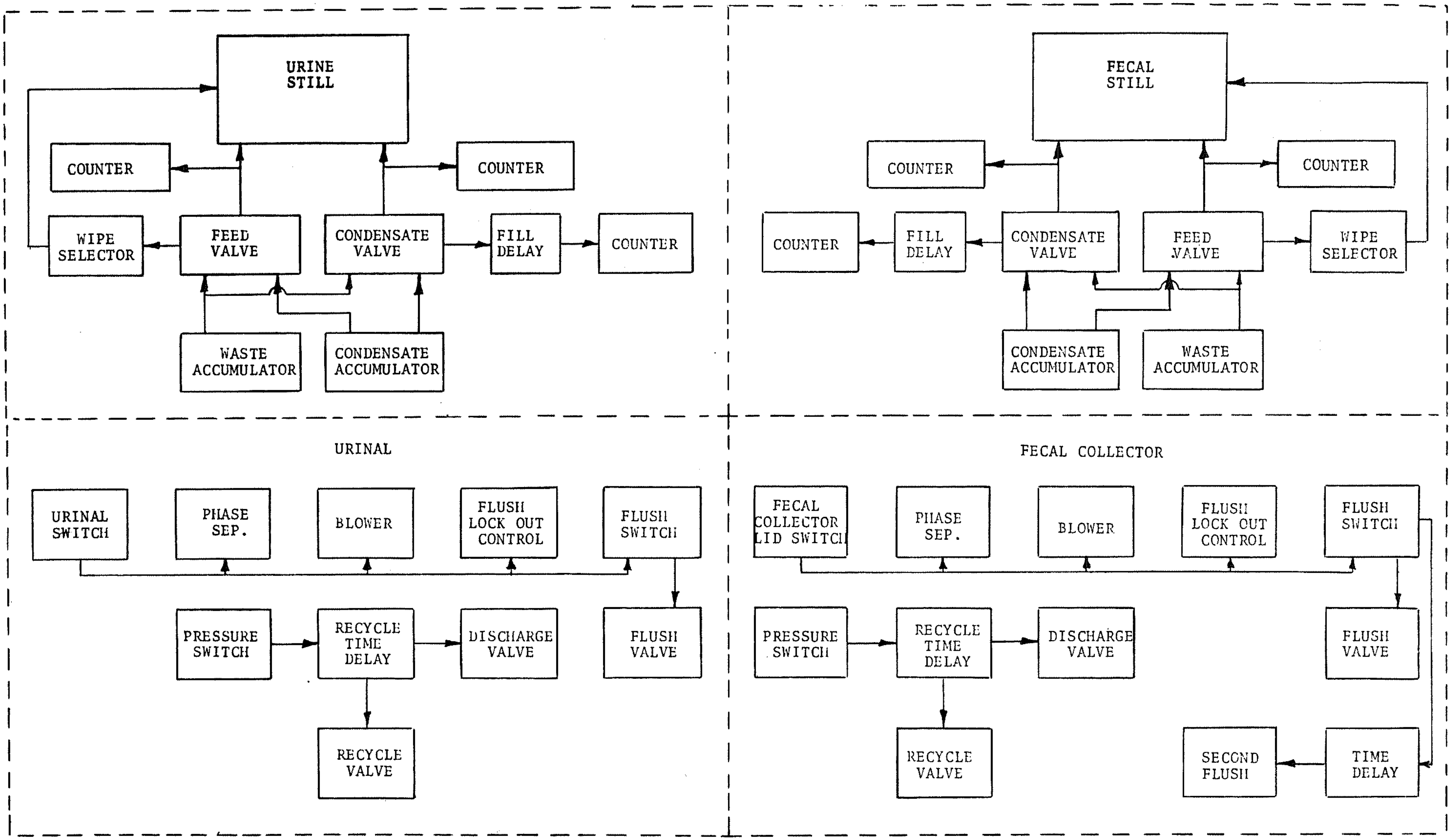
The control of the waste collectors was based on sensing the pressure developed in the phase separators, when waste was introduced into the system. Flush was accomplished by the manipulation of a push button switch. The discharge of the waste into the waste storage tanks was inhibited by a recycle timer. This allowed the waste to be recycled through the phase separator for a predetermined length of time before being discharged into the waste storage tank.

Conductivity detectors were provided for determining water quality in both the fecal and urine loops. The detectors have an adjustable set point, provisions for visual readout and a control function for operating a solenoid valve. If at any time the conductivity of the water flowing through the conductivity detectors cell would exceed the pre-set limit, the water would be automatically diverted back to the waste tank for reprocessing. Four conductivity detectors were provided; one in the fecal loop, two in the urine loop and one in the drink water. If reprocessing was required, the water would remain diverted to the waste storage tank even if the conductivity returned to an acceptable level until manipulation of a manual reset. A pH meter was used on the drink water outlet for a final check on water quality.

AMGLO modified the controls to take advantage of more positive functions for control signals. A simplified block diagram of the improved control system is shown in figure 5.

Control of the still feed cycle is based on output volume. Condensate from the stills is constantly pumped into an accumulator. When the accumulator is filled to a predetermined volume, a plunger attached to the accumulator diaphragm, a limit switch is actuated. This operates a solenoid valve allowing the conden-

FIGURE 5. BLOCK DIAGRAM OF CONTROL CIRCUIT



sate to be discharged through a conductivity detector to either good water storage or reprocess, depending on quality as determined by the conductivity detector. Upon complete discharge of the condensate accumulator the plunger activates a second limit switch. This switch, depending on the preselected program, will either enable the feed valve solenoid or the wiper. Any time the wiper is enabled, the feed is inhibited until completion of the wipe cycle. Counters to count the number of feed and discharge cycles were provided, on the control panel, to assist in making water balance calculations.

The functions of the waste collectors remained the same as the original concept, but new control circuitry was constructed because the original circuitry was not functional when received at AMGLO. Components were obviously missing and many loose wires were found. An attempt was made at using the existing circuitry but the drawings supplied with the equipment did not match the circuits. The most expedient alternative was to design and construct new circuitry. The phase separators and blowers are enabled whenever the collectors are put in service - when the urinal is removed from it's holder and/or when the lid is raised on the fecal collector. The phase separators and blowers remain operating until the end of the waste discharge cycle. Flush is accomplished by the manipulation of a manual switch. Only one switch is required and operating the switch will only flush the collector in use. If both collectors are in use, both will flush.

The flush cycle can only be enabled once during a collection cycle. A second flush is provided on the fecal collector, to clean the bowl. This flush is enabled by a time delay which is enabled by the manual flush switch.

After the phase separator has built up a pressure head on the waste, sufficient to operate a pressure switch, the pressure switch enables a solenoid valve through a timer. This valve and timer allow the waste to be recycled through the phase separator for a predetermined length of time. When the timer times out, the recycle valve is inhibited and the discharge solenoid valve is enabled, allowing the waste to be pumped to the waste storage tank. The discharge pump continues to operate until the pressure head on the pressure switch drops, indicating all of the waste has been pumped into the waste storage tank. The waste is now ready for processing and the waste collectors are ready for the next collection cycle.

Three conductivity detectors were used - one for urine condensate, one for fecal condensate, and the other on the drink water outlet. If the conductivity of the water exceeded a predetermined level, a solenoid valve would be enabled and the water would be diverted for reprocessing. A visual indicator was provided to show conductivity detector condition. The water would remain diverted even if the conductivity became acceptable until the solenoid valve is reset. Reset can only be accomplished if the conductivity is acceptable.

During initial checkout of the conductivity detectors one of the sensing cells was found defective. The defective cell was returned to the original manufacturer for repair. The defect was determined to be an open resistor; repair was accomplished and the cell returned to AMGLO.

SECTION 3

TEST PROCEDURE

3.1 Calibration Tests

The initial tests of the fully assembled system were run to verify that the machine operated as an integrated system,and that further testing could proceed as planned. Instrumentation was checked and calibrated; the still inventory control device was adjusted volumetrically; automatic transport of liquid throughout the urine and fecal loops was verified; and a data sheet was drawn up to record all pertinent information in subsequent tests.

All calibration runs were made using distilled water as input liquid. The input was measured volumetrically to maintain balances, then manually poured into the collectors. The separators and pumps delivered the simulated loads to the waste side of the pressurized storage tanks, from which batches of feed were measured and delivered to the distillation units by the automatic inventory control device. Output water from the stills was measured by the inventory control device, and then delivered in batches to graduated cylinders external to the system. The post-treatment cells and the good-water storage tanks therefore, were not used during calibration testing, and the collectors were not flushed after loading. Omission of the flush cycles and bypassing the condensate-handling components permitted rapid accumulation and analysis of performance data by eliminating lag times and variable retention volumes. A chart, in addition to the data sheet, was maintained during each run by the test engineer; he plotted input water quantity and the cumulative total of condensate batch volume received in the graduated cylinders. Samples of the charts, for calibration run No. 12, are shown on the next two pages. Changes in recovery rates were immediately detectable by changes in the output-curve slope and a cursory running water balance was always available. Very fine calibration of the feed and condensate batch sizes were made by knowing the number of batches processed through the distillation units and the total volume of water transferred. At the end of each run, dryer retention quantity, trap loss and output yield were readily calculated from the charted data.

Each calibration test was run until equilibrium performance was achieved and maintained for several hours. The data was then analyzed to determine which independent variables should be changed for the next run. When those changes could be made without stopping the distillation units the run was continued until equilibrium was again achieved under the new conditions. Some reduction in start-up time was realized by that procedure, and it reduced the number of calendar days spent on calibration testing because the system was often run 24 hours per day by three 2-man test teams.

FIGURE 6, CONDENSATE OUTPUT VS. TIME - URINE LOOP
CALIBRATION RUN NO. 12
MEAN PE: 50 TORR

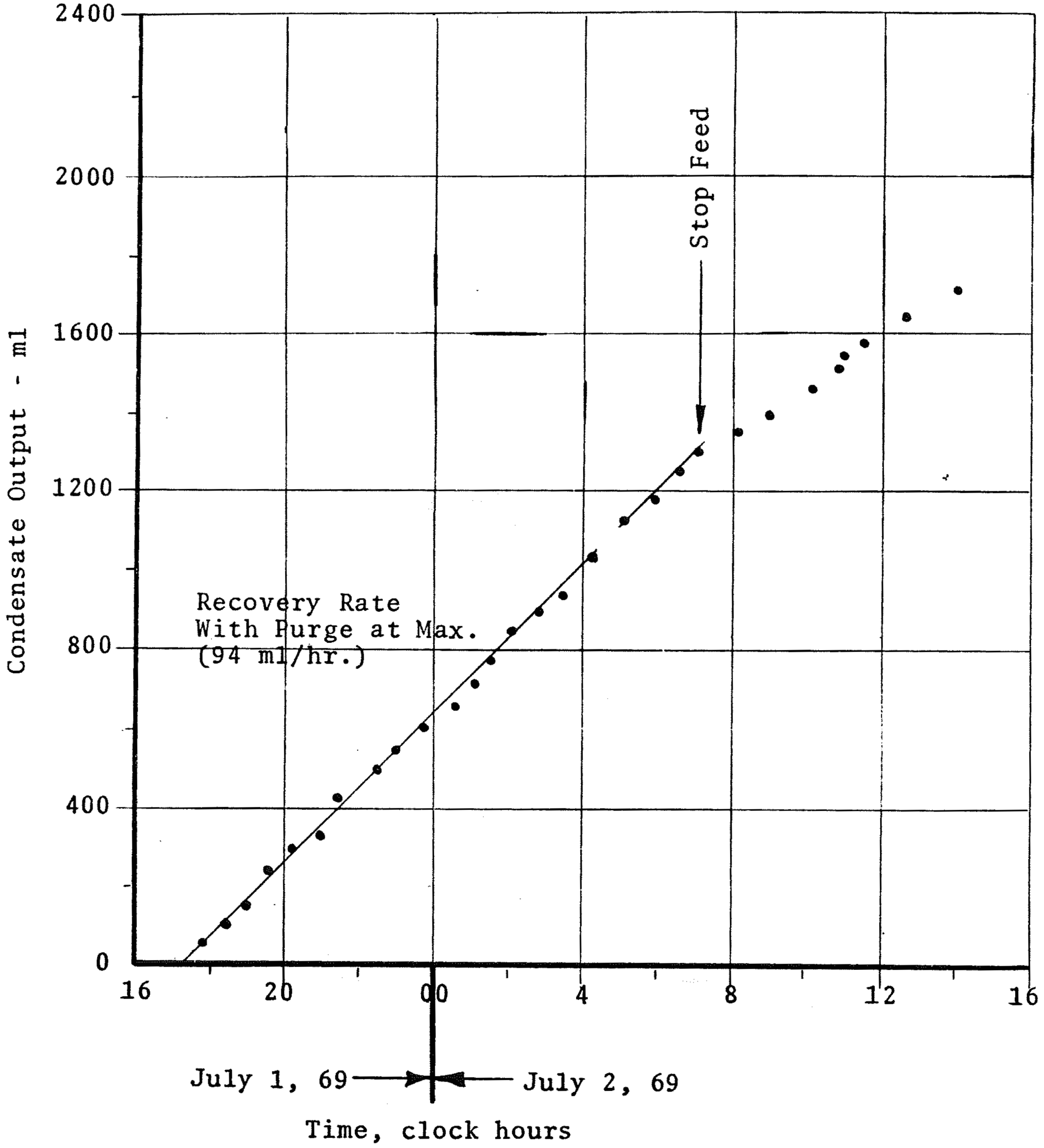
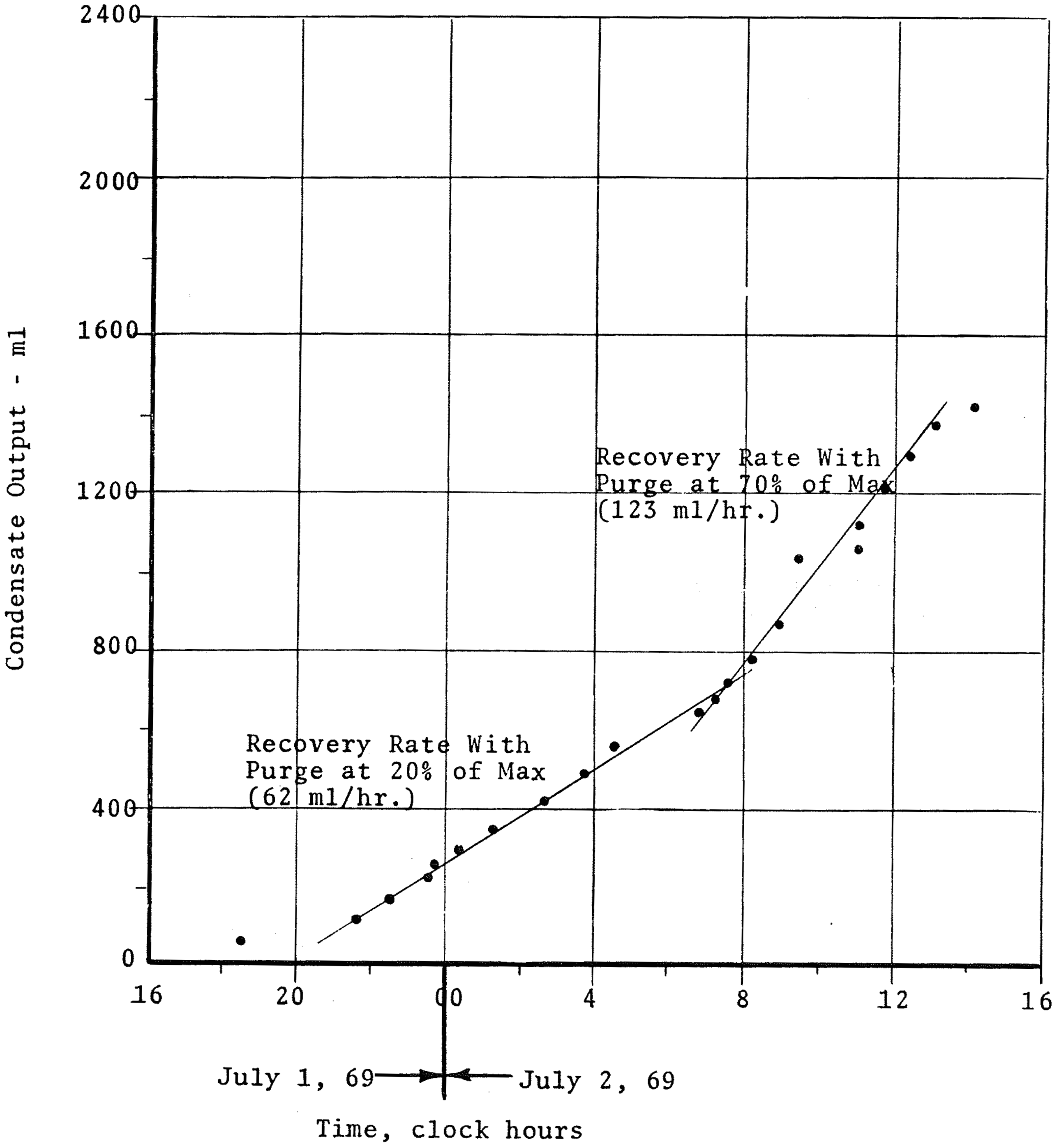


FIGURE 7, CONDENSATE OUTPUT VS. TIME - FECAL LOOP
CALIBRATION RUN NO. 12
MEAN PE: 45 & 40 TORR

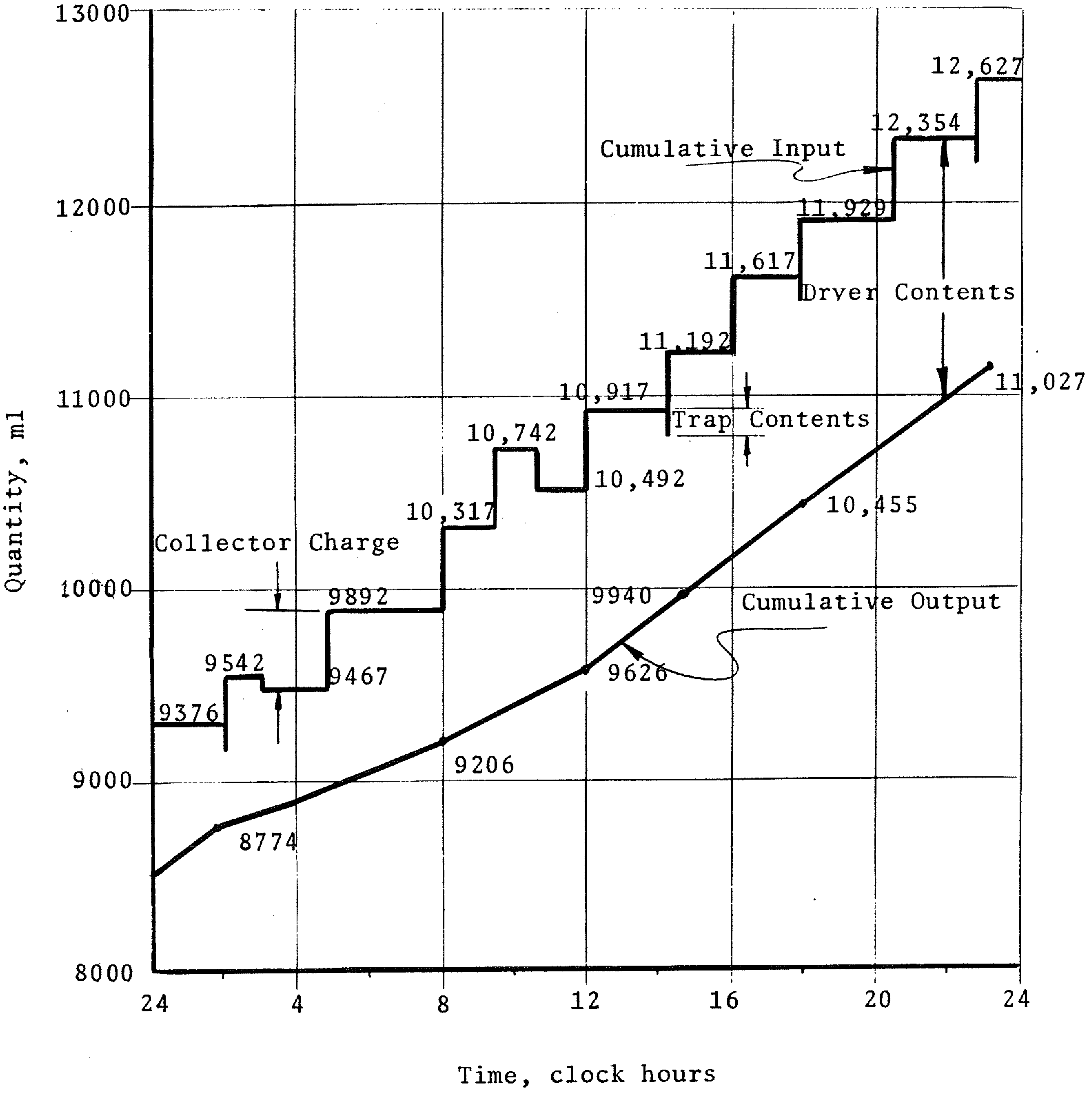


3.2 Thirty-Day Test

During the simulated mission test the testing procedure was modified only slightly from the calibration runs. Live wastes collected from test personnel, rather than distilled water, became the input materials. A measured load of waste was manually poured into the appropriate collector whenever the waste side of a storage tank emptied. Condensate was delivered to the post-treatment cells then to the good-water storage tanks. Both collectors were flushed with water from those tanks after each loading. After a flush cycle the water remaining in the good-water storage tanks was drained to maintain the system's water balance and establish a point on the charts. Chemical and biological evaluations were performed on the output water and on samples of condensate at various points in the post-treatment circuit.

Purge losses were measured and plotted on daily charts together with total input to the collectors and total condensate drained from the system. Those charts were used to maintain a complete-system water balance and determine the dryer retention quantity in each still. With the flush loops operating, however, the total condensate drained from the system does not represent the true recovery rate. Instead, the total of water removed, plus condensate samples taken from the post-treatment circuit, and flush water recycled through the collectors was plotted on the time-based charts to show the true recovery rates of the distillation units. One of the daily charts is shown on the next page.

FIGURE 8, DAILY BALANCE CHART, DAY NO. 23 URINE LOOP
AUGUST 2, 1969



Throughout the 30-day test, emphasis was placed upon keeping the system running at it's maximum recovery rate. Other primary objectives were to minimize vapor losses through the vacuum purge, maximize the water output as a percentage of input (yield), and evaluate the post-treatment cells in their effectiveness and life. Whenever an adjustment or repair was necessary to meet an objective, it was performed and the test continued without interruption. It was anticipated, therefore, that some of the independent variables would be different at the end of the test than at the outset. The testing technique, including instrumentation and data analysis, was set-up to indicate changes in performance as soon as a trend was established.

The test was conducted by a ten-man crew comprised of five engineers and five technicians. One engineer and one technician were present at all times throughout the test duration. A schedule was established which paired every engineer with every technician several times throughout the ninety 8-hour shifts to eliminate any procedural differences which might have occurred with isolated teams.

SECTION 4

TEST RESULTS

4.1 Calibration Tests

Nineteen runs were made to calibrate the urine and/or fecal stills. All runs were made with distilled water as the input liquid; the results are summarized on the next two pages. Test runs #1-12, 15 & 16 were performed with the still cabinet open, to determine recovery rate with low evaporator pressures. Run #9 was performed with the dryer heaters "off" to achieve even lower evaporator pressures. Runs #13, 14, 17, 18 & 19 were performed with the cabinet closed. Run #13 was performed with a 150-watt heat source (light bulb) in the cabinet with the stills, to achieve evaporator vapor pressures greater than 90 torr. An adjustable-speed exhaust fan was installed in the cabinet before run #18, to achieve evaporator pressures between 80 and 50 torr.

At the conclusion of calibration testing, the urine loop and still had accumulated 324 test hours, while the fecal loop and still had been run 382 hours.

The tables show the start and finish time of each run, its duration and water balance information in the first eight columns.

The steady recovery rate listed in the next column is the rate of output measured while condensate was flowing.

TABLE 1

SUMMARY

CALIBRATION RUNS - URINE LOOP

Run No.	Year/Month/Date/Time (End - Start)	Duration (hr:min)	Total Feed (ml)	Total Condensate (ml)	Trap Loss (ml)	Dryer Retention (ml)	Steady Rec. Rate (ml/hr)	Average Rec. Rate (ml/hr)	Yield (%)	Ambient Temp. (°C)	Heater Current (amp)	Mean Pe (torr)	Mean Δp (torr)	Purge Valve Setting
1	69/6/12/2425 - 12/2005	(Urine Loop Not Operated During This Run)												
2	14/1728 - 14/1245	4:43	750+	0	97	---	(Condensate Returned to Flush)			24	0.8	50	--	NA
3	16/2337 - 16/1330	10:07	1200	800	331	---	---	80	--	25	0.8	55	--	NA
	17/2400 - 17/1120	12:40	---	385	585	---	---	30	--	25	0.8	45	40+	NA
4	19/0045 - 18/1030	14:15	755	0	307	150	---	0	0	25	0.8	45	3	NA
5	20/2100 - 19/1535	29:25	1980	1031	467	563	79	35	52	25	0.8	45	10	NA
6	21/1715 - 21/1500	2:15	(Sprung Gas Leak During Feed and Seized)											
7	23/1900 - 23/1130	(Urine Loop Not Operated During This Run)												
8	26/1417 - 26/1100	3:17	(Sprung Gas Leak During Feed and Seized)											
9	28/0824 - 27/2310	9:24	500	148	---	---	31	16	30	27	0.0	40	10	7x - 8x
10	29/0010 - 28/1200	12:10	500	0	---	---	0	0	0	28	0.8	50	5	100
			(Discovered Leak in Compressor Discharge)											
11	69/7/ 1/1440 - 30/0315	34:25	3965	3062	542	280	115	88	76	27	0.8	50	40+	100
12	2/1415 - 1/1615	22:00	2500	1766	234	520	94	80	71	27	0.8	50	40+	10x
13	3/1410 - 2/1715	10:55	995	174	810	0	ERRATIC	16	18	50-42	0.8	80-40	50+	6x - 100
14	5/0009 - 4/1030	13:39	822	404	201	54	34-64	30	49	35-40	0.8-0.0	30-60	40-60	6x - 5x
15	5/0810 - 5/0250	5:20	401	134	81	164	ERRATIC	31	33	27	0.0	(Run Too Short)		
16	6/1115 - 5/2100	14:15	1065	924	256	63	133-33	65	75	24	0.8	45	10	3x
17	6/1910 - 6/1205	7:05	665	464	179	0	96	66	70	35-40	0.8	70	20	3x - 2x
18	7/1120 - 6/2005	15:15	1301	908	330	21	108-80-68	60	70	40-40-35	0.8	75-55-55	15-25-30	2x
19	8/0046 - 7/1238	12:08	1500	1170	158	173	135	98	78	41	0.8	80	10	2x

TABLE 2

SUMMARY
CALIBRATION RUNS - FECAL LOOP

Run No.	Year/Month/Date/Time (End - Start)	Duration (hours)	Total Feed (ml)	Total Condensate (ml)	Trap Loss (ml)	Dryer Retention (ml)	Steady Rec. Rate (ml/hr)	Average Rec. Rate (ml/hr)	Yield (%)	Ambient Temp. (°C)	Heater Current (amp)	Mean Pe (torr)	Mean ΔP (torr)	Purge Valve Setting
1	69/6/12/2425 - 12/2005	4:20	750	610	122	---	---	141	81	27	0.8	40	Varied	NA
2	14/1728 - 14/1245	4:43	1500+	0	103	---	(Condensate Returned to Flush)			24	0.8	50	NR	NA
3	16/2337 - 16/1330	10:07	1500	1060+	235	---	ERRATIC	106	--	25	0.8	40	--	NA
	17/2400 - 17/1120	12:40	0	675	450	---	DRY-OUT	53	--	25	0.8	40	20	NA
4	19/0045 - 18/1030	14:15	1300	897	390	170	132	63	69	25	0.8	40	10	NA
5	20/2100 - 19/1535	29:25	3410	2427	558	395	129	83	71	25	0.8	40	10	NA
6	21/2100 - 21/1500	6:00	730	369	102	(below) 700	79	61	50	24	0.8	35	40	NA
7	23/1900 - 23/1130	7:30	985	618	55	(above)	125	82	63	24	0.8	35	20	NA
8	26/1645 - 26/1100	5:45	955	557			188	102	58	27	0.8	50	8	NA
9	28/0824 - 27/2310	9:24	1000	523			TRANSIENT	57	52	27	0.0	40	Varied	4x - 8x
10	29/0010 - 28/1200	12:10	700	223			36	18	32	28	0.8	80	50+	100
11	69/7/ 1/1440 - 30/0315	34:25	4350	3334	483	250	136	96	76	27	0.8	50	10	10x - 6x
12	2/1415 - 1/1615	22:00	2000	1463	164	340	123	67	73	27	0.8	45-40	40-10	2x - 7x
13	3/1410 - 2/1715	10:55	910	170	741	0	27	15	19	50-42	0.8	90-40	50+	3x - 10x
14	5/0009 - 3/1030	13:39	763	x	238	6	79	x	x	35-40	0.8-0	60	35	10x
15	5/0810 - 5/0250	5:20	594	71	30	403	15	13	12	27	0.0	(Run Too Short)		
16	6/1110 - 5/2100	14:10	852	310	143	363	52-22	22	38	24	0.8	60-70	35-50+	10x - 4x
17	6/1910 - 6/1205	7:05	1000	817	175	0	185	117	82	35-40	0.8	70	20	6x
18	7/1120 - 6/2005	15:15	2210	1512	331	408	153-88	99	69	40-35	0.8	85-75	45-45	6x - 8x
19	8/0046 - 7/1238	12:08	1500	697	358	205	---	58	55	41	0.8	(Excessive Gas Leak)		

The average recovery rate relates the total condensate received and the entire test duration; it includes, therefore, the start-up time and other transients characteristic to the design as tested.

The column headed "Yield" shows a simple volumetric percentage of output condensate to input water.

Ambient temperature is that measured inside the enclosure containing the stills; it is not room temperature.

Heater current is that flowing through the dryer heater located inside each distillation unit. The power level corresponding to 0.8 amperes is 40 watts.

Mean Pe is the pressure measured in the evaporator at the mid-time between batch injections of input water, in millimeters of mercury absolute (torr). With batch feedings, evaporator pressure varies slightly throughout the batch, but there exists a nearly level plateau for the middle 3/4 of the batch time; that plateau is recorded as mean Pe. Evaporator pressure is the sum of the saturation pressure of water vapor at its local temperature plus the partial pressure of non-condensible gases contained within the evaporator.

Mean ΔP, in the next column, is the pressure difference between the evaporator and the condenser, measured in torr. It is also the total head rise required of the compressor including friction and valve losses. Relief valves on the discharge side of the compressors were set to open at 50-60 torr pressure difference to protect the compressor diaphragms and check valves from excessively high loading.

Purge valve setting, in the last column, shows on a relative scale, the size of a critical orifice in the vacuum purge line. The numbers are the reading of a micrometer-handle valve which has a nearly linear flow-to-opening relationship. The symbol X after a reading indicates that purge bypass valve was closed, and the symbol O indicates that it was open. All flow through the purge valve was passed through a freeze-out trap to isolate the water from the non-condensible purge gas.

4.2 Thirty-Day Test

A thirty-day test of the entire system was begun when the performance of both loops had been established under calibration test conditions, predictable responses to changes in operating parameters were shown by both distillation units, and the testing procedure became routine.

Recorded results of the simulated 30-day mission test are summarized on the next several pages. A separate table is presented for each of the two loops which shows daily totals of

TABLE 5

TEST SUMMARY - URINE LOOP

		Input				Output		Losses		
Day	Time (hrs)	Urine (ml)	Water (ml)	Flush (ml)	Total (ml)	Condensate (ml)	Yield (%)	Purge (ml)	Other* (ml)	Remarks
1	25½	0	1925	1050	2975	1932	65	625	418	Started at 2230 hours on 10 July 69
2	18	0	978	534	1512	907	60	853	-248	Stopped at 1800 to drain dryer, restarted at 2000
2	3	275	0	150	425	95	--	111	219	Still seized at 2300
3	2	275	0	95	370	--	--	--	370	Restarted at 2200
4	12½	550	0	195	745	195	26	635	-85	Still seized at 0330 and 1230, shut-down at 1230 for repairs
5	9	275	0	150	425	--	--	247	178	Restarted at 1015, periodic seizures until shut-down at 1915
6	--	--	--	--	--	--	--	--	--	Urine still removed from system for repairs
12	--	--	--	--	--	--	--	--	--	Urine still replaced in system
13	12½	0	975	225	1200	409	34	444	347	Restarted at 1130, high leak developed at 1600
14	15	0	725	0	725	390	54	473	-138	Shut-down to repair dryer heater
15	--	--	--	--	--	--	--	--	--	Urine still down for heater repair
16	7	550	0	300	850	25	--	--	825	Periodic seizures, shut-down to inspect & replace drive motor
17	21½	1650	0	900	2550	1396	55	939	215	Installed Marquardt seal pack, condensate leaked to trap
18	23½	1100	0	600	1700	1206	71	1272	-778	Feed plugged, shut-down at 2330 to reinstall AMGLO seal pack
19	4½	0	0	0	0	0	--	--	--	Periodic high leak, stopped to remove still
19	3	0	375	0	375	--	--	--	375	Connected fecal still to urine loop & started at 2100
20	24	0	0	4250	4250	2554	60	426	1270	Fed silver-dosed water to clean out system
21	24	1300	0	1675	2975	1992	67	639	344	Started feeding raw urine
22	19	1925	0	1050	2975	989	33	542	1444	Stopped to drain dryer, heater shorted, installed external heater
23	24	2650	0	1950	4600	2865	62	663	1072	Increased heater current from 0.8 to 1.2A, started anti-foam
24	24	1845	0	1575	3420	2684	78	518	218	Started acid pretreatment
25	6½	725	0	400	1125	524	46	532	69	Still seized at 0630, feed seal badly pitted
26	10	0	0	0	0	0	--	--	--	Restarted with bad leak, stopped to repair seal pack
27	11	275	0	150	425	0	--	230	195	Restarted with bad leak, stopped to repair seal pack
28	13	0		425	425	580	--	258	-413	Restarted with bad leak, stopped to straighten shaft
29	18½	1625	0	1100	2725	667	25	177	1881	Restarted at 0530, delta P too low
30	12	550	0	300	850	475	56	300	75	Shaft moved and caused large leak, stopped test at 1200 hours.
	343	15570	4978	17074	37622	19885	53	9884	7853	

TABLE 4

TEST SUMMARY - FECAL LOOP

		Input				Output		Losses		
Day	Time (hrs)	Feces (gms)	Water (ml)	Flush (ml)	Total (ml)	Condensate (ml)	Yield (%)	Purge (ml)	Other* (ml)	Remarks
1	23½	0	2200	2100	4300	3303	77	609	388	Started feeding water at 0030 hours, 11 July 69
2	17½	0	2100	2100	4200	3547	84	790	-137	Stopped at 1730 to drain dryer, restarted at 2030
2	2½	0	700	670	1370	(Added to day #4)		120	1250	Shut-down at 2330 to remove & repair urine still
3	2	0	--	--	--	--	--	--	--	Restarted at 2200 when urine still was reinstalled
4	16½	0	1650	1345	2995	3217	75	144	-366	Shut-down at 1630 hours to remove & repair urine still
5	10½	0	825	675	1500	955	64	146	399	Restarted at 1020 hours, shut-down at 1910, restarted at 2220
6	23½	300	2475	2075	4550	3196	70	510	844	Feed plugged for one hour, stopped at 2350 to remove urine still
7	23	150	1650	1350	3000	1356	**	431	1213	Feed plugged for eight hours, stopped for one hour
8	24	150	825	675	1500	1397	61	254	-151	Feed plugged for two hours, installed 50 micron solids filter
9	24	150	1325	1695	3020	2195	73	743	82	Feed plugged for five hours
10	10½	0	0	0	0	675	--	65	-740	Feed plugged for five hours - stopped to unplug, drain & repair heater
11	22½	0	1650	975	2625	975	63	294	1356	Restarted at 0130 hours, fed Alconox Solution to clean out seal pack
12	20½	0	825	675	1500	748	50	381	371	Stopped for 3½ hours to repair leak on wiper shaft seal
13	23	0	1650	1350	3000	2288	76	522	190	Stopped for 1 hour to drain dryer
14	18	300	1300	1300	2600	988	38	555	1057	Still seized at 1800 hours - drained dryer & bladder tank
15	19	300	1650	1350	3000	692	23	354	1954	Changed feed filter, restarted, experienced leaking & plugging, drained
16	20½	102	715	1015	1730	278	16	515	937	Started feeding solid feces, stopped to drain dryer
17	11½	0	0	0	0	0	--	--	--	Feed plugged for 7 hours, stopped to replace wiper seals
18	7½	0	0	750	750	0	--	--	750	Repaired compressor, restarted, stopped to grease wiper seals & restarted
19	17½	0	0	0	0	13	--	237	-250	Shut-down fecal loop at 1730 when it was concluded that solids on evaporator had reduced recovery rate.
	337½	1452			41640	25823	62	6670	9147	

** Not applicable because condensate drained following day.

* Water lost to feed filters, flushing bladder tank, dryer & leakage from flush accumulator.

FIGURE 9

INPUT/OUTPUT SUMMARY - URINE LOOP

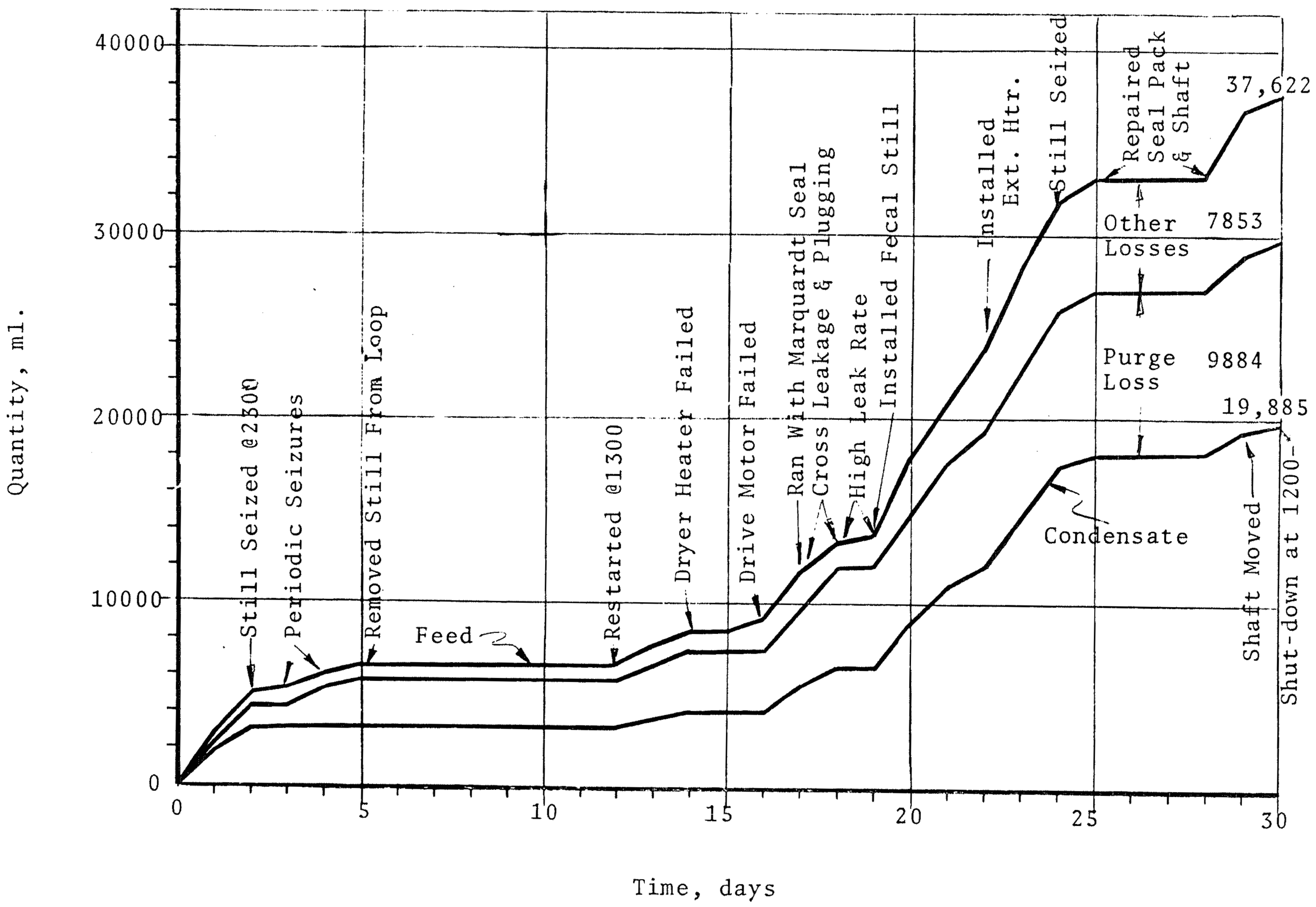
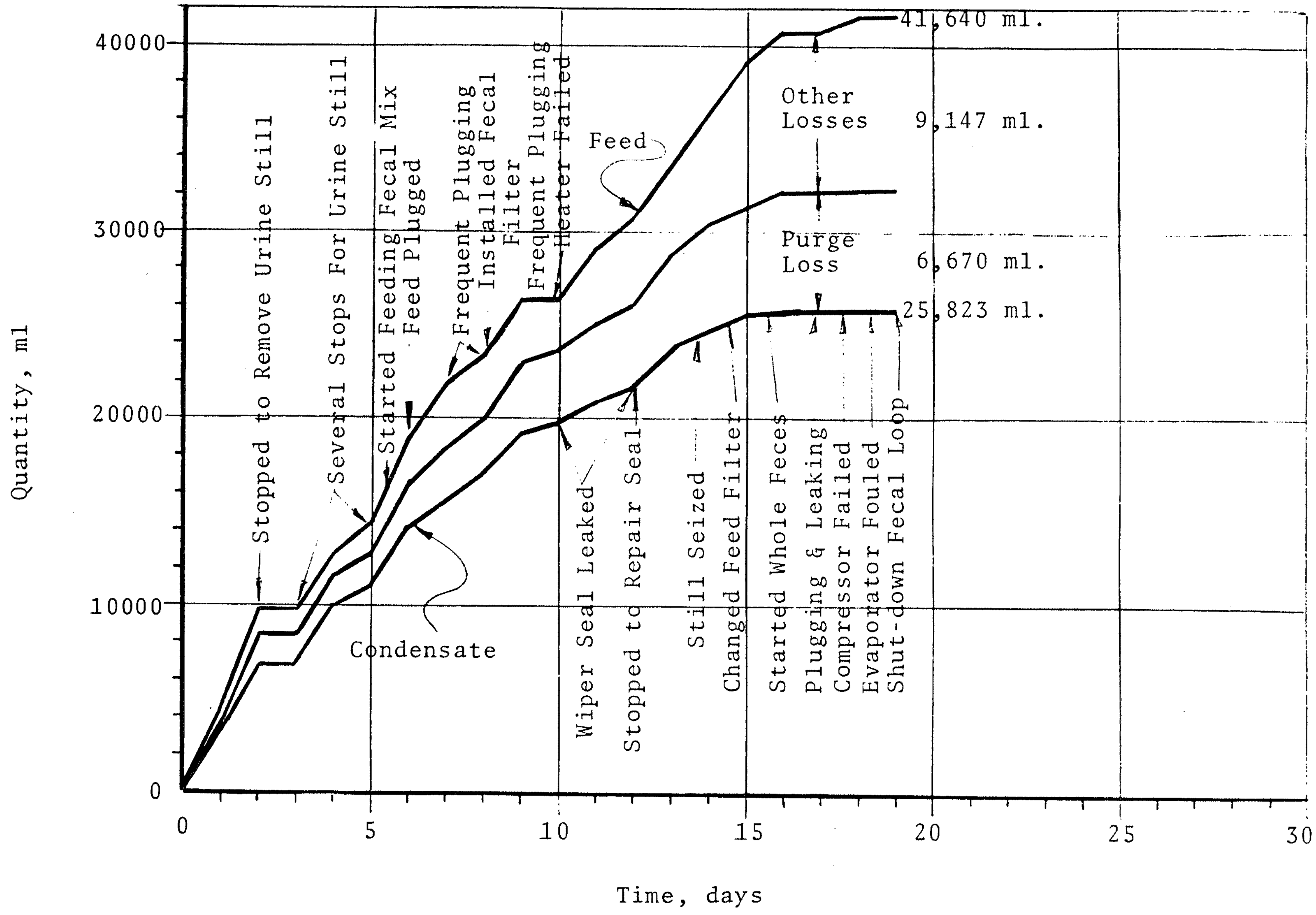


FIGURE 10

INPUT/OUTPUT SUMMARY - FECAL LOOP



input liquids, output condensate, yield, losses and remarks. Following the tables are graphs showing cumulative totals of the daily balances covering the entire test duration.

4.2.1 Urine Loop

Testing of the urine loop was run according to the Test Plan except when failures forced departures - as described below. The urine still seized shortly after receiving its first batch of urine - after accumulating 324 hours of operation with tap water input. Through the first 19 days that unit accumulated another 154 test hours between several repair periods. The most frequent cause for shutdown was seizure, 5 times. Other down-time was caused by a heater failure, wiper-drive clutch failures (twice), a compressor failure, once to install the original Marquardt seal assembly, and once again to remove it when leakage of condensate to purge was detected. On the 19th day the urine still was removed from the system and the fecal still moved from the fecal loop to the urine loop. The test results, therefore, were obtained by operating the urine collector and its transport and post-treatment circuit in conjunction with the urine still for the first 19 days, and with the fecal still for the last 11 days.

Performance of the fecal still while operating in the urine loop was diminished by high leak rates through the main seal and the wiper seals late in the test. The main seal was severely pitted on the 15th day shortly after starting acid pretreatment of the input urine. Subsequently, intermittent high leak rates were attributed to mechanical misalignment, most probably caused by a bent main shaft.

During 343 hours of testing, the urine loop recovered 19,885 ml of condensate for a yeild efficiency of 53 percent.

4.2.2 Fecal Loop

Testing of the fecal loop ran according to the Test Plan except for the following problems. Shortly after injecting the first load of feces into the fecal collector the waste line entering the fecal distillation unit became plugged by suspended solids. The passage was opened by applying a vacuum on the plugged line and testing was resumed. The problem was recurrent, however, and a filter was placed between the fecal collector and the waste storage tank.

Excessive leaking through the wiper screw seals forced a temporary shut-down on the 12th day and again on the 17th day. Other failures encountered were: the wiper-drive clutch bearings which prevented automatic wiper operation and required that the distillation unit be stopped to turn the wiper-drive screws manually, a dryer heater failure, and a worn and disintegrated compressor drive cam - one piece of which became lodged under a compressor relief valve.

Testing of the fecal still in the fecal loop was terminated on the 19th day when solids accumulation on the evaporator surface reduced its recovery rate to less than 1 ml/hr. At that time the fecal still was fed silver-dosed water to restore its evaporator surface and placed in the urine loop.

During the 337½ hours of test time the fecal loop recovered 25,832 ml of condensate, which is a yield of 62% of the input volume.

4.2.3 Water Quality

A group of 10 key analyses were employed for water quality assessment; the daily assessment routine included in-process as well as product water. The daily analyses were augmented by qualitative biological tests which identified the predominating organisms in the various water samples. Detailed chemical analysis of the product waters was performed by NASA personnel at MSC; these analyses were performed as often as water output permitted.

Low condensate output in combination with operating difficulties limited the number and volume of water samples taken for analysis. The average daily output of urine and fecal condensate amounted to 920 and 1,410 ml respectively. The quantitative biological analyses required 60 ml while the chemical/physical tests (excluding total solids tests) consumed 80 ml for a total sample volume of 140 ml. Sampling, the raw condensate, filtered water, and silver-dosed water would have removed a significant quantity (420 ml or 30-45% of the average daily output) of the water from the respective loop; the net effect of the sampling is a significant reduction in the process load handled by the components in the post-treatment loop; consequently, complete analyses of in-process water were conducted on a limited schedule.

The results of the daily quality tests of urine and fecal loop water are presented in tables 5 and 6, respectively. The tables show the analyses performed and the results obtained for each test day and sample type. The samples analyzed are representative portions of water at various stages in the recovery sequence. The analyses performed are, for the most part, adequately described by table headings; COD and MPN do warrant further description which is presented in the following paragraphs.

COD or chemical oxygen demand analysis is based on the oxidation of organic matter by chromic-acid and the concomitant reduction of hexavalent chromium to trivalent chromium. The number of equivalents involved in the oxidation-reduction is determined titremetrically. The weight of organic material oxidized is expressed as equivalent weights of oxygen; consequently, COD values do not indicate, directly, the actual concentration of an organic species but only the weight of oxygen necessary for oxidation of the carbonaceous matter present. The COD analysis is similar to TOC (total organic carbon) and TOD (total

TABLE 5

WATER QUALITY - URINE LOOP

Day	Type of Sample	Specific Resistance (ohms)	pH	COD (ppm)	Ammonia (ppm)	Silver (ppm)	Total Solids (ppm)	Color	Odor	Turbidity	MPN Bac/ml.	Remarks
17	Ag Dosed	8,600	6.5	32	0.64	1.1	70	none	none	none	--	Installed Marquardt seal
18	Ag Dosed	7,000	6.2	38	1.0	1.1	38	none	none	none	--	Removed Marquardt seal
19	Deionized	50,000	6.2	44	0.5	0.01	42	none	none	none	--	Urine fed to condenser
20	Deionized	60,000	6.4	62	0.5	0.01	39	none	amine	cloudy	--	Replaced post-treatment beds
21	Raw Cond.	8,000	9.2	76	--	--	--	none	some	some	--	Resumed feeding urine
	Filtered	8,200	6.8	88	0.5	--	--	none	none	none	--	Fresh filters
	Deionized	340,000	6.0	6	0.5	0.01	--	none	none	none	--	Fresh sterilizer & deionizer
22	Raw Cond.	1,400	9.2	94	170	--	--	none	some	none	--	
	Filtered	15,000	8.7	38	9.2	--	--	none	none	none	--	
	Deionized	360,000	5.5	30	0.5	0.36	25	none	none	none	--	
23	Feed Tank	--	--	--	--	--	--	--	--	--	16	
	Raw Cond.	1,400	9.0	148	27	--	--	none	some	some	24	
	Filtered	2,000	6.6	40	0.9	--	--	none	none	none	--	
	Ag Dosed	1,800	6.1	38	0.9	--	--	none	none	none	--	
	Deionized	810,000	6.8	26	0.5	0.01	70	none	none	none	5.4	
24	Raw Cond.	2,000	8.8	--	--	--	--	none	some	some	--	
	Filtered	8,000	7.2	--	--	--	--	none	none	none	--	
	Ag Dosed	--	--	--	0.5	--	--	none	none	none	--	
	Deionized	440,000	6.8	56	0.5	0.01	66	none	none	none	--	
25	Raw Cond.	2,400	9.4	134	105	--	--	none	some	some	42.6	
	Filtered	4,000	8.9	78	105	--	--	none	some	none	.02	
	Ag Dosed	--	--	78	105	--	--	none	some	none	0	
	Deionized	510,000	6.8	34	0.5	0.01	53	none	none	none	5.4	
26	--	--	--	--	--	--	--	--	--	--	--	No condensate available
27	--	--	--	--	--	--	--	--	--	--	--	No condensate available
28	--	--	--	--	--	--	--	--	--	--	--	No condensate available
29	Deionized	220,000	6.2	82	0.5	0.01	89	none	some	none	.49	
30	Feed Tank	--	--	--	--	--	--	--	--	--	34.8	
	Raw Cond.	150	7.9	1770	397	--	--	some	some	some	10^6	
	Filtered	--	8.0	138	154	--	--	some	some	none	0.23	
	Ag Dosed	1,200	8.0	108	154	--	--	some	some	none	0	
	Deionized	130,000	5.8	98	0.5	0.01	134	none	none	none	54.2	

TABLE 6

WATER QUALITY - FECAL LOOP

Day	Type of Sample	Specific Resistance (ohms)	pH	COD (ppm)	Ammonia (ppm)	Silver (ppm)	Total Solids (ppm)	Color	Odor	Turbidity	MPN Bac/ml.	Remarks
6	Ag Dosed	24,000	6.5	14	3.6	1.1	2	none	none	none	--	First fecal feed
7	Ag Dosed	10,000	6.0	14	7.0	1.2	125	none	none	none	--	
8	Ag Dosed	7,000	6.4	25	19.0	0.25	186	none	none	none	--	
9	Ag Dosed	5,300	6.5	22	27.4	--	--	none	none	none	--	
10	--	--	--	--	--	--	--	--	--	--	--	Fed water to system
11	--	--	--	--	--	--	--	--	--	--	--	Fed ALCONOX solution
12	Raw Cond.	3,000	8.8	204	135.0	--	--	none	some	none	0.02	Fed water to system
13	Ag Dosed	8,000	6.8	76	14.8	0.25	140	--	--	--	--	Fed water to system
14	Ag Dosed	7,000	7.0	54	15.1	0.44	96	none	some	some	--	Resumed feeding feces
15	Ag Dosed	7,100	7.1	92	24.4	1.20	198	none	none	none	--	
16	Ag Dosed	6,900	6.8	32	12.1	0.44	64	none	none	some	--	Last fecal feed
17	--	--	--	--	--	--	--	--	--	--	--	Feed plugged
18	--	--	--	--	--	--	--	--	--	--	--	Compressor failed
19	--	--	--	--	--	--	--	--	--	--	--	Shut-down to use still in urine loop

oxygen demand) analyses in that all of these analyses do not identify the species of contaminant. COD values are, very generally, 3 times greater than TOC values when determined from identical solutions. Significant differences are to be expected between TOD and COD values because TOD analysis measures oxidizable nitrogen and sulfur while the COD does not.

The standard MPN or most probable number analysis* was changed to permit estimation of the total number of bacteria present. The change consisted of substituting thioglycolate broth for the customary lactose broth. Thioglycolate broth was used because it supports the growth of a very broad spectrum of microorganisms including aerobic and anaerobic bacteria. The MPN performed on IWMS water entailed inoculation of five thioglycolate tubes for each aliquot volume; the aliquots were decimal volumes from 10 to .0001 mil. The five 10 ml aliquots of each water type were inoculated in 200 ml thioglycolate broth; the remaining aliquots (1.0 ml or 1.0 ml of a serial dilution) were inoculated into 20 ml of thioglycolate.

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* Standard Methods For The Examination Of Water And Waste Water, 12th ed. American Public Health Assn., 1965. pp 604-605.

The results of the detailed analyses of the urine and fecal loop product water are presented in table 7. The urine loop deionized water is intended for crew consumption while the fecal loop water is intended for flushing the collector. With exception of the barium value on day 30, the concentrations of the non-organic substances in each urine loop sample was lower than the minimum detectable concentration of the analysis employed; the minimum detectable concentration for each of these analyses, save lead, exceeds all applicable requirements; the organic matter present in the urine loop samples is well below the NASA/NRC recommended limit. The fecal loop samples differ from the urine loop mainly in manganese, nickel and silver concentrations and are sufficiently pure for flushing purposes.

The qualitative biological tests sought to identify the major or predominating types of microorganisms occuring in the water samples submitted to MPN analysis. The tests entailed subculturing from the positive MPN tubes onto blood agar and trypticase soy agar which were incubated aerobically and anaerobically. Distinct colonies were picked for gram staining, microscopic examinations, and further culturing on one or more of the following media: (1) Endo agar, (2) Seller's agar, (3) rose bengal-malt extract agar, (4) azide-blood agar, (5) phenylethyl alcohol-blood agar, and (6) tryptophane broth.

TABLE 7

DETAILED PRODUCT WATER ANALYSIS - URINE & FECAL LOOPS*

TYPE OF ANALYSIS**	FECAL LOOP Ag Dosed		URINE LOOP Deionized			
	Day 7	Day 14	Day 21	Day 22	Day 29	Day 30
BARIUM	1.7	<0.5	<0.5	<0.5	<0.5	2.5
CADMIUM	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
COPPER	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
IRON	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
LEAD	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
MANGANESE	0.84	<0.05	<0.05	<0.05	<0.05	<0.05
NICKEL	0.74	0.12	<0.05	<0.05	<0.05	<0.05
NITRATE	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2
SILVER	0.17	0.47	<0.05	<0.05	<0.05	<0.05
ZINC	0.04	<0.01	<0.01	<0.01	<0.01	<0.01
TOTAL ORGANIC CARBON	5.0	37.0	2.0	2.0	5.0	--
TOTAL OXYGEN DEMAND	15.5	127.5	18.0	--	23.5	18.0

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* Data compiled by C. E. Verostko, NASA/MSC

** All values are mg/liter

The tentative identifications arrived at on the basis of the above are as follows:

1. The fecal condensate on day 12 contained, exclusively, a species of pseudomonas.
2. The predominant organism in the urine waste was a species of proteus. The sample on day 23 did contain species of coliforms, pseudomonas and micrococci, but the sample on day 30 was almost pure proteus.
3. The urine condensate samples contained chiefly a species of proteus on day 23 and 25, although coliforms and micrococci were present. The sample on day 30 was virtually pure proteus.
4. The silver-dosed water, being sterile, did not require qualitative tests.
5. The deionized or potable water contained very consistently only one type of organism, that is, a species of arthrobacter.

The biological quality of the residual water and waste water in the IWMS was assayed 48 days after test termination. Samples were aseptically taken from the fecal filter, fecal storage tank and the flush water side of both urine and fecal storage tanks; the urine waste storage tank did not contain sufficient waste water for analysis. Aerobic plate counts via the membrane filter technique and standard sterility tests were conducted on each sample. The flush water samples were sterile as evidenced by the lack of growth on the agar plate, and in the sterility test media; the aerobic count of the fecal filter sample exceeded 10,000 per ml while the storage tank sample yielded a count of 610 per ml.

SECTION 5

DISCUSSION OF TEST RESULTS

5.1 Calibration Tests

With a fixed-displacement compressor, driven at constant speed, the recovery rate of the vapor compression units tested should be linear with evaporator saturation pressure. Within the narrow range of pressures tested, departures from that linearity are very small. The recovery may be calculated by the expression

$$\overline{R} = \frac{D}{\text{Sp.Vol.}} \times \text{Vol.Eff.} \times 453.6$$

where:

$\overline{R}$ = recovery rate, ml/hr

D = compressor displacement, ft^3/hr

Sp.Vol. = specific volume of vapor at saturation pressure, ft^3/lb

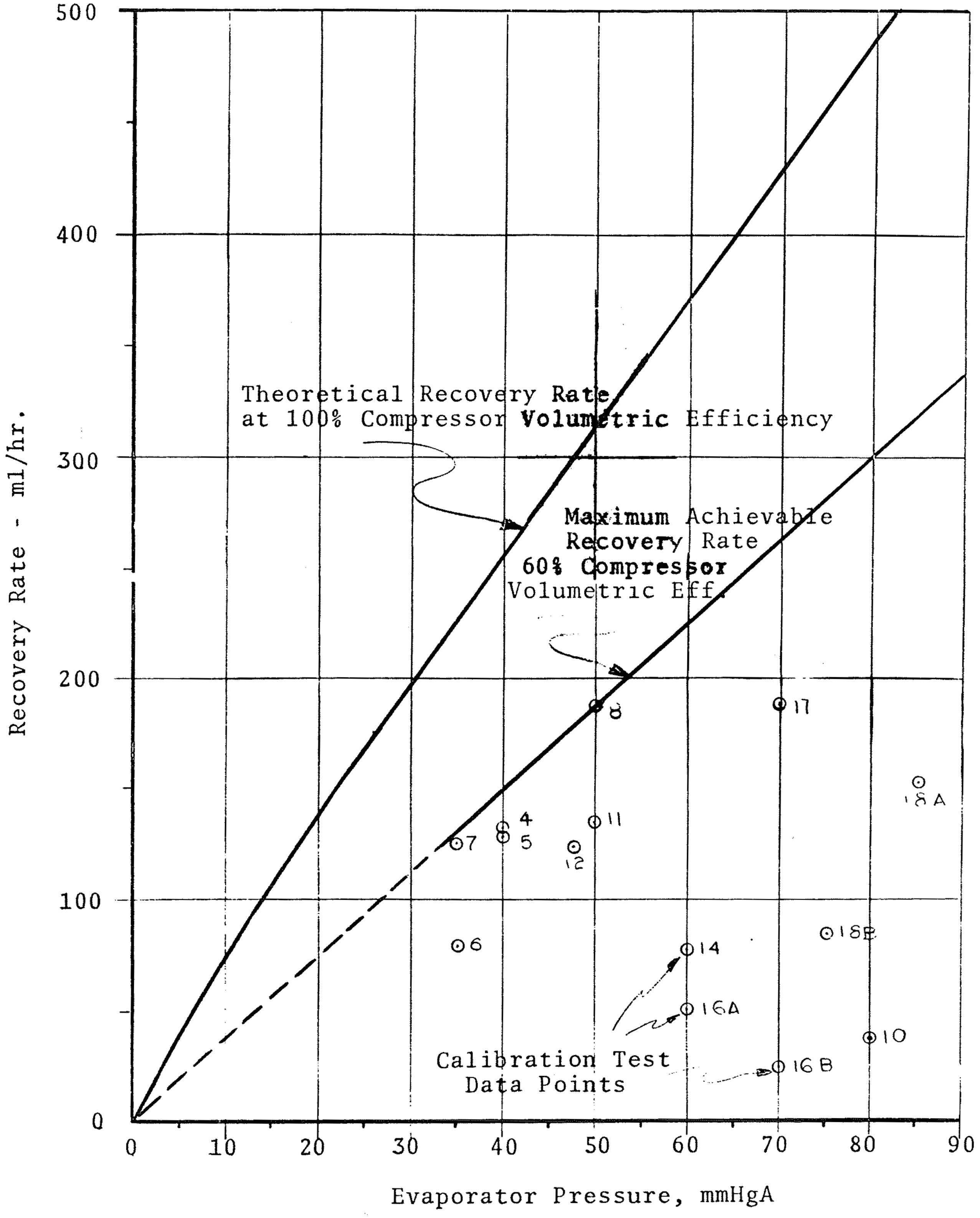
Vol.Eff.= compressor volumetric efficiency, % x 100, and

453.6 = a constant, ml/lb.

From the compressor's physical dimensions and driven speed its displacement was calculated to be 236 ft^3/hr.

The recovery rate for 100 percent compressor volumetric efficiency as it varies with saturation pressure is plotted on the graph on the next page. Also plotted are the steady recovery rates achieved during the calibration tests of the fecal loop. A similar graph for the urine loop is shown on page 5-6.

FIGURE 11, RECOVERY RATE VS. EVAPORATOR PRESSURE
CALIBRATION TESTS, FECAL STILL DISTILLATION UNIT



Recovery rates near the 100% curve are difficult to achieve with a real compressor. Tuned passages to utilize vapor inertia, carefully timed valve closures and other delicate adjustments are necessary to overcome friction and pressure losses and raise volumetric efficiency of a reciprocating compressor. These efforts were not made for the compressors built for these units; also, some differences in valve-opening delta P's between the two compressors were apparent. The calibration test results showed maximum recovery rates lower than the 100% curve due mainly to the real compressor's lower volumetric efficiency. The best recovery rate achieved with the fecal unit lies on a line representing 60 percent volumetric efficiency for that compressor, while the other unit achieved only 51 percent effective volumetric efficiency. That difference is due in part to a persistantly higher gas leak rate into the urine still which partially insulated the heat transfer surfaces and increased the pressure rise required across the compressor. Significatly, these units were designed with the condenser located within the evaporator so that inleakage entered the evaporator - then was transported by the compressor, along with the vapor, to the condenser. That gas occupied a portion of the compressor's displacement and further reduced its effective vapor pumping rate. If the inleakage had occurred into the condenser it would have been removed by the purge without passing through the compressor. Also, the inleakage would have had a lesser effect on compressor head rise because it would not have been present in the evaporator to mask the heat transfer surface.

5.1.1 Fecal Unit

As shown in figure 11 and table 2 (page 4-3), the best recovery rate achieved by the fecal unit was during run No. 8. During that run the measured compressor delta P was low (8 torr) which is evidence of a low inleakage rate. Similarly, runs No. 4, 5 and 7 showed recovery rates near the 60% volumetric efficiency line and low-to-moderate delta P's. These four runs represent the best low-temperature performance achievable with these distillation units. A low delta P prevailed during runs No. 11 and 12 also, but in an effort to improve yield from each batch of feed water, the time-based recovery rate was diminished. High delta P's during runs No. 6, 10, 14 and 16 all correspond to low recovery rates and probable high leak rates. Noteworthy is the effect of decreasing the purge rate, by 60 percent, during run No. 16. The required compressor delta P was increased from 35 torr to more than 50 torr; at that pressure rise the compressor relief valves were partially open which decreased the vapor flow rate to the condenser. The evaporator pressure increased from 60 to 70 torr indicating a greater concentration of non-condensible gases in the evaporator. The combined effect of lower vapor flow and heat transfer rates decreased recovery rate from 52 to 22 ml/hr.

Tests No. 17 & 18 were run at elevated temperature and high evaporator pressure. Their recovery rates fall below the 60 percent volumetric efficiency line mainly because of air leakage into the evaporator. Another phenomenon exists however, which predicts some degradation in performance at elevated evaporator temperatures. At higher saturation temperature, and with the same compressor pressure rise the temperature difference of water vapor is smaller. Considering that vapor temperature difference is the driving force for latent heat transfer from condenser to evaporator, and that available area is constant, heat is transferred at a slower rate when operating at high temperature. Therefore, water is vaporized at a slower rate. It is known that the recovery rates measured for tests 17 & 18 were not limited only by the lower temperature difference because during the simulated mission test higher recovery rates were observed while operating in the same temperature region (288 ml/hr at 85 torr).

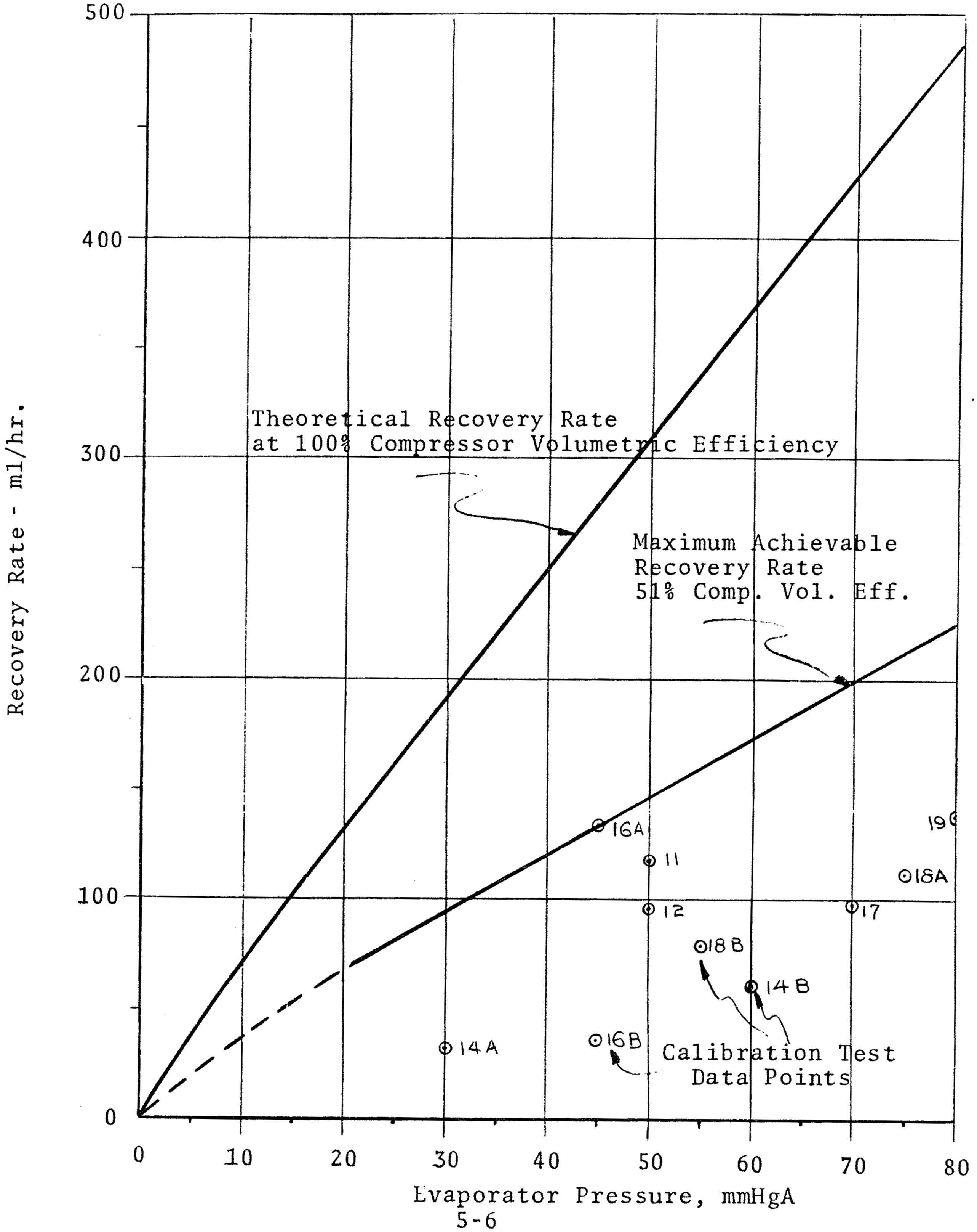
It might have been possible to investigate in detail the effect of high temperature and pressure on recovery rate, but that determination would shift when the evaporator contained fecal waste instead of distilled water.

5.1.2 Urine Unit

A similar graph was drawn for the urine distillation unit, figure 12. The same compressor displacement and operating speed prevailed, therefore, the recovery rate at 100% compressor volumetric efficiency is a duplicate of that determined for the fecal unit. The measured performance of the urine still, however, was significantly lower and less reproducible. Results of the first ten runs must be discounted because they were run with one

FIGURE 12, RECOVERY RATE VS. EVAPORATOR PRESSURE

CALIBRATION TESTS, URINE DISTILLATION UNIT



of the two vapor tubes between the compressor and condenser leaking vapor to the evaporator. (It was discovered after run No. 10 that one of the original tubes was approximately 5/16-inch too short to reach its socket in the vapor duct. Part of the compressor output, therefore, was dumped to the evaporator. It must also be assumed that vapor driven to the condenser via the other tube was leaking back to the evaporator).

The best performance by the urine distillation unit was achieved during run No. 16-A when the compressor head rise was low (10 torr) and the purge rate was low (30 percent of maximum). The steady recovery rate for that run lies on the 51 percent volumetric efficiency line. Runs No. 11 and 12 show the effect of high inleakage rates. The vapor compression cycle was forced to operate by extracting the non-condensible gases; those gases were transported through the compressor, which diminished its vapor-handling capacity and lowered the recovery rate. Similarly, during run No. 14, high inleakage was experienced, but the purge rate was decreased to reduce trap losses. Higher concentration of non-condensibles in the condenser raised the pressure-rise requirement upon the compressor and forced the relief valves open. The lower net vapor flow to the condenser is reflected in lower recovery rates than measured in runs 11 and 12.

Good high-temperature performance was achieved during run No. 19, the last calibration test. The inleakage was low as evidenced by the low pressure rise (10 torr) and low purge rate (20 percent of maximum). Relatively high yield (78%) and low trap losses (approximately 13 ml/hr) were also measured for run No. 19. A lower temperature difference prevailed between the condenser and evaporator than was present during run No. 16-A, which was run at the same pressure difference. The lower temperature difference diminished heat transfer rate and lowered the recovery rate to a level below that attainable with a compressor operating at 51% volumetric efficiency.

5.2 Thirty-Day Test

5.2.1 Performance

Test results show that the IWMS as tested can produce good water over a long time; it falls short, however in the areas of reliability, recovery rate and yield. It has been demonstrated during this test that the system can collect and store waste products, but that biological growth was present in the storage tanks. Fully automatic operation of the retention and transport machinery was achieved. Throughout the tests, there was no occurrence of evaporator flooding nor was there a trend to indicate that flooding would eventually occur within the planned duration. Post-treatment of the condensate was effective in eliminating all dangerous contaminants from the drink-water stream.

The major limitation of the system is over-complexity of the distillation units. The units as tested contained seven dynamic seals (three on the wiper screws and four on the main shaft). Leakage past these seals seriously dimished recovery rate and forced high purge rates which lowered yield to 62 percent in the fecal loop and 53 percent in the urine loop. Seal failures were also the major limitation on system reliability and caused other failures, such as seizures. The inclusion of mechanical wipers in the still design added great complexity and unreliability to the distillation units. The wiper design requires that electrical and magnetic dynamic interfaces be maintained in addition to the mechanical seals. Failures in the wiper limit switches, drive clutches and seals occurred several times during the 30-day test; finally, wiper operation was abandoned.

The fecal loop was operated for 337½ hours of a possible 456 hours, or 74 percent of the test duration. Part of its downtime was to facilitate safe removal of the urine still from the common cabinet. Sixteen percent of the input volume was lost with the purge gas. That high loss is accountable to two main causes: (1) a high purge rate was necessary to maintain a reasonably low partial pressure of non-condensibles in the evaporator, and (2) the purge gas extracted from the condenser probably carried entrained condensate. The condenser is a 3/8-inch wide annular space six inches long, which is a poor configuration for phase separation. It is not possible therefore, to put the purge opening at a location which assures that no liquid will be drawn off with the purge gas.

The urine loop was operated for only 343 hours of a possible 720 hours, or a little over 47 percent of test duration. Most of its down-time was caused by seal failures and seizures. Approximately 26 percent of the input liquid to the urine loop was lost to the purge. A small part of that was leakage from the condensate line to the purge line when the unit was operated with the Marquardt seal. But, most of the loss is attributed to high purge rates necessary to overcome gas leakage, and poor phase separation within the condenser.

The performance and failures of the compression distillation units tested during this simulated mission, cannot be considered representative of the compression distillation cycle. Solutions to its short comings - reliability, recovery rate and yield - are known and have been tested. The significant parameter, power consumption, was not measured during this test because the power consumed by the many seals would have obscured the true power necessary to make the cycle operate.

5.2.2 Water Quality

The quality of the water produced by the IWMS is the sum of contributions made by the distillation process and the ancillary purification processes in the post-treatment loop. The quality of the water after treatment by each process measures the performance of that process and identifies the nature of its contribution to product water quality.

A discussion of the quality of water at each major stage of the recovery process is presented in the following sections.

5.2.2.1 Raw Condensate Quality

Raw condensate quality is an important measure of still performance; its contaminant load also dictates the performance requirement of the post-treatment loop.

The quality of the condensates obtained from the urine and fecal CD units were generally similar. Ammonia concentrations of 25 to 175 ppm, COD values of 75 to 205 ppm, and pH values of 8.8 to 9.4 were typical of both condensate types. Each condensate type had a slight to moderate odor characteristic of the waste from which it was distilled. Both types were generally colorless and clear to slightly turbid. The total bacteria content of the raw condensate did not exceed 45 bacteria per ml of condensate. The specific resistance (SR) of both urine and fecal condensate varied between 1,400 to 8,000 ohm/cm^2. The mineral content, inferred from the compositional changes effected by the biological and charcoal filters, probably did not exceed 100 ppm in most instances; by similar inferrance, the mineral content of the fecal condensate showed little day to day variance and was generally lower than the urine condensate. The raw condensate on day 30 was extensively contaminated by waste and is regarded as a special case; the contamination occurred as a result of the badly degraded seal pack performance noted on day 30.

The lack of striking differences in the quality of the raw condensate, despite the obvious differences between urine and fecal waste, are due to (1) the collection regimens followed for each waste, (2) some inherent similarities, and (3) similar underlying causes for condensate contamination. The above considerations are discussed further in the following paragraphs.

The collection regimens for urine and feces differed significantly. The waste to silver-dosed water (flush water) ratio is 20 times greater in the fecal collector effluent than in the urine collector effluent; the differing ratios tend to (1) reduce the concentration of volatile organics in the fecal slurry to a level near that of diluted urine, and (2) reduce the massive fecal bacteria density by dilution and by providing a higher waste slurry silver concentration. The main effect, then, of the differing collection regimens is the minimization of quantitative compositional differences.

Both raw wastes contain similar ammonia concentrations. More importantly, however, is the fact that the ammonia concentration in each waste can be increased by one or two orders of magnitude through the metabolic activity of bacteria normally found in the waste - the ammonia bearing substrate, the metabolic pathway and type bacteria involved are different but the net effect is the same, that is, liberation of ammonia. Another point of similarity is that urine often contains microorganisms common to feces.

The main causes of condensate contamination, characterized by unsatisfactory COD, ammonia, and bacteria concentrations, are (1) ineffective waste pretreatment, (2) the low foam-head volume in the evaporator, and (3) high (110-120°F) evaporator temperatures. The silver dose provided was ineffectual in controlling waste bacteria; lack of bacterial control resulted in higher than normal ammonia concentrations. The space between the evaporator surface and the compressor in-take filter was not large enough to provide a foam free vapor path; the result is entrainment of raw waste droplets which are carried by the vapor stream into the condenser. Evaporator temperature controls the partial pressure of the volatile waste solids right along with the partial pressure of water vapor for any given waste composition; consequently, increasing evaporator temperature increases the concentration of undesirable volatiles in the vapor.

5.2.2.2 Flush Water Quality

Flush water is raw condensate that has been processed through the biological filter, activated charcoal column, and silver chloride column. The raw condensate processed by the above was characterized by significantly reduced COD and ammonia values, by slightly acid to neutral pH values, and by the absence of viable bacteria.

The biological charcoal filter assembly was responsible for all of the improvements in the chemical quality of the condensate. The filter assembly maintained the COD of the flush water at approximately 100 ppm throughout the 10-day life of the column; this effluent COD represented a change of an order of magnitude or more in the COD of the raw condensate on several days. The filter assembly maintained the ammonia concentration at 30 ppm or less for 11 days in the fecal loop and 6 days in the urine loop; the reduction in ammonia concentration was generally by an order of magnitude or more; the differing ammonia capacities may be due to day to day variations in raw condensate composition. The combined effects of ammonia and organics removal was a more neutral pH and a higher specific resistance than was typical of the raw condensate. The biological purity of the filter effluent received limited evaluation; however, the evaluation performed on the filter assembly in the urine loop indicated that the number of viable bacteria in the filter effluent was very small (2 bacteria/100 ml on day 25 and 23 bacteria/100 ml on day 30). The filter assemblies demonstrated a useful life of at least 10 days; the fecal loop filter was on stream for 11 days and processed condensate for 9 of these days; the urine loop assembly was on stream for 10 days and processed condensate for 7 of these days; an assembly installed in the urine loop on day 17 was removed on day 20 because raw waste was fed into the condenser inadvertently.

The silver chloride column produced water that was sterile in each of the instances tested, and maintained the water in the storage tank sterile over a 48-day period. The silver content of the effluent is influenced by column temperature and the chemical purity of the column influent; at room temperature the silver concentration is from 1.0 to 1.5 ppm; chloride ion, because of the solubility produce constant, decreases the silver content; ammonia which forms a stable chelation complex with silver, tends to increase the silver concentration.

The detailed analyses of fecal loop flush water (table 7 on page 4-18) show that the trace metal content of flush water is in most instances less than would be required by the most stringent potability standards. Manganese and nickel, which undoubably are due to errosion within the nearly all stainless steel system, were the major metal contaminants. Barium which probably existed as the sulfate, was present in both urine and fecal flush water; the presence of this metal is not readily attributable to a definite source and may have been the result of stainless corrosion or carbon seal wear. Silver, of course, was deliberately added to provide a measure of waste pretreatment to provide residual bacterial control.

Lacking specifications for flush water quality, acceptability is difficult to demonstrate. In view of the intended external use, the water need not meet potable standards. The quality of the flush water produced in both loops is comparable if not superior to tap water encountered in many areas of the United States, and is of adequate purity for its intended use.

5.2.2.3 Potable Water

Potable water is produced only by the urine loop and is flush water which has been processed through the deionizer.

The deionizer in the urine loop serves to remove primarily the silver ions added for sterilization and waste treatment, and to remove other miscellaneous contaminants. The central problem with the deionizer is its sterilization before installation in the system. The first column prepared was treated with 37% formaldehyde (reagent grade) prior to use in the system; the result of this treatment was a sterile effluent and concomitantly, materially reduced exchanger performance. The second column used was not sterilized before use; the result was excellent exchanger performance, but with some bacterial contamination. The bacteria causing the contamination is believed to have been associated with the ion-exchange resin before installation because (1) the column influent (flush water) was sterile, and (2) the causative organism (a species of arthrobacter) was never recovered in the post-treatment loop upstream of the deionizer.

The chemical quality of the potable water meets or exceeds the standards set by the U. S. Public Health, the NASA/NRC ad hoc panel and MSC Specification C35 for the parameters measured. The biological quality exceeded the U. S. Public Health Service requirement for less than 2.2 coliform bacteria per 100 ml; however, the average bacterial density of 500/100 ml of water, despite the fact that the only organism found was a non-pathogenic soil bacteria, precludes conformity with most biological purity standards.

Two areas pertinent to chemical quality warrant further discussion. First, the lead content of the potable water was shown to be less than 0.25 ppm which was the minimum concentration detectable in the NASA/MSC laboratory; the acceptable level for lead ranges from 0.05 to 0.2 ppm so that strict conformity to the standards of the above mentioned agency could not be demonstrated. Secondly, the barium concentration on day 30 exceeds the standard set by all of the above; the probable cause of the evident failure of the deionizer is that species involved is probably barium sulfate which is a finely divided insoluable form of barium; this barium species would be capable of passage through the deionizer and probably incapable of absorbtion by the crew man since sulfate concentrations in the range of 2-10 ppm would be sufficient to prevent dissassociation of barium sulfate.

5.3 Conclusions

Seizure of the rotating assembly occurred after feeding waste liquids through the dynamic seals. These seizures occurred five times in the urine loop and once in the fecal loop, and were most probably caused by the presence of dissolved solids in the liquid which normally weeps through the dynamic seal. The cyclic operation of these seals (where a batch of waste is injected, some weeps across the dynamic interface, which runs warm and thereby evaporates the water and leaves the solids) is conducive to build-up of high viscosity, even abrasive materials between the rubbing surfaces. After each seizure the mating surfaces were washed and the test continued. The conclusion drawn from this experience is that waste liquid should be ducted through all stationary piping and should never contact a surface warmer than the evaporator. The feed manifold inside a still, therefore, should remain stationary, to avoid passing through a dynamic seal. Also, better distribution of the liquid upon the evaporator surface will result from relative motion between the stationary manifold and the rotating evaporator.

Excessive inleakage of ambient gas to both stills occurred several times throughout the testing program. The configuration and design of the transport passages requires that four dynamic seals be maintained between five chambers (evaporator, condensate passage, purge passage, feed passage and ambient). Further, the dynamic interfaces must move to compensate for alignment errors between the stationary and rotating members. The alignment apparently was changing continuously. Seizures and other forces applied to the light 1/2 inch diameter central shaft increased the required wobble requirement and prevented the original tight sealing (both stills leaked less than $1x10^{-3}$CFM at the start of the test, and both leaked approximately $2x10^{-2}$CFM when taken out of service). To reference the seal performance, the original seals supplied with the distillation units were installed. In the urine unit the original seal performed well for seven (7) hours then leaked condensate to the purge gas and ambient air to the evaporator. In the fecal unit the original seal leaked severely and did not permit evacuation below 13 psia. It must be concluded from this experience that the alignment of dynamic seals must not be dependent upon long flexible shafts or any other non-rigid structure; more importantly, however, dynamic seals should be eliminated whenever possible - if only to reduce power consumption.

A related problem was plugging of the feed passages within the dynamic seal. This occurred seven times in the fecal loop, and once in the urine loop. The different character of fecal waste, which contains more solids in suspension and less in solution than urine waste, explains its tendency to cause plugging rather than seizure. Alternating pressure and vacuum was applied to the feed line to remove the stoppage whenever it occurred.

While larger passages would have prolonged the time between plugging failures, they would not have alleviated the problem. The ultimate solution is the elimination of fecal waste flow through a heated passage. To facilitate this test, filters were placed between the fecal collector and the storage tank to reduce the quantity of suspended solids transported through the seal passages.

Successful operation of the wipers was never achieved for more than several passes across the evaporator. Clutches which transmit the wiper driving torque failed frequently and in several ways, the magnetically operated limit switches inside the evaporators failed and their actuating magnet lost flux. Finally, the wiper-drive screws began leaking ambient air to the evaporator and it was decided to seal-up the screw entrance holes and abandon wiper operation. In future distillation units the evaporator surface should be flushed clean continuously rather than wiped clean occasionally.

Both compressors showed signs of wear in the bearings and drive cam. The cam in the fecal still compressor was replaced when pieces were torn away and one piece became lodged in a compressor valve. An internal screw in the urine still compressor came out and became lodged between the diaphragm and one of the heads. The diaphragm was destroyed and was replaced with a spare, the head was repaired and put back into service.

Generally, however, the reciprocating compressors performed better than anticipated, especially considering that they were a retrofit to an existing envelope and operating parameters. The selection of a reciprocating compressor for the volumetric flow rate and gas density prevailing in this application is a good one. They were sized, however, to transfer one pound of vapor per hour at design temperature of 115 to 120°F, which requires that they operate at 100 percent volumetric efficiency. In the real case losses in the vapor ducts and across the valves preclude that high efficiency. Test results showed a maximum volumetric efficiency of 60 percent.

Dryer heaters in both stills failed, once because the wiper ring crushed the wires against the casing when a wiper limit switch failed in the fecal still, and in the urine still when the heater became delaminated, highly conductive urine salts entered and an internal short developed. On both occasions the heaters were repaired and were functioning at the conclusion of the test. The complexity of a rotating electrical heater, however, should be avoidable because of the relative ease by which heat can be transferred by a stationary source. Brush alignment to carry heater power through the rotating interface was a constant concern and required periodic adjustment.

SECTION 6

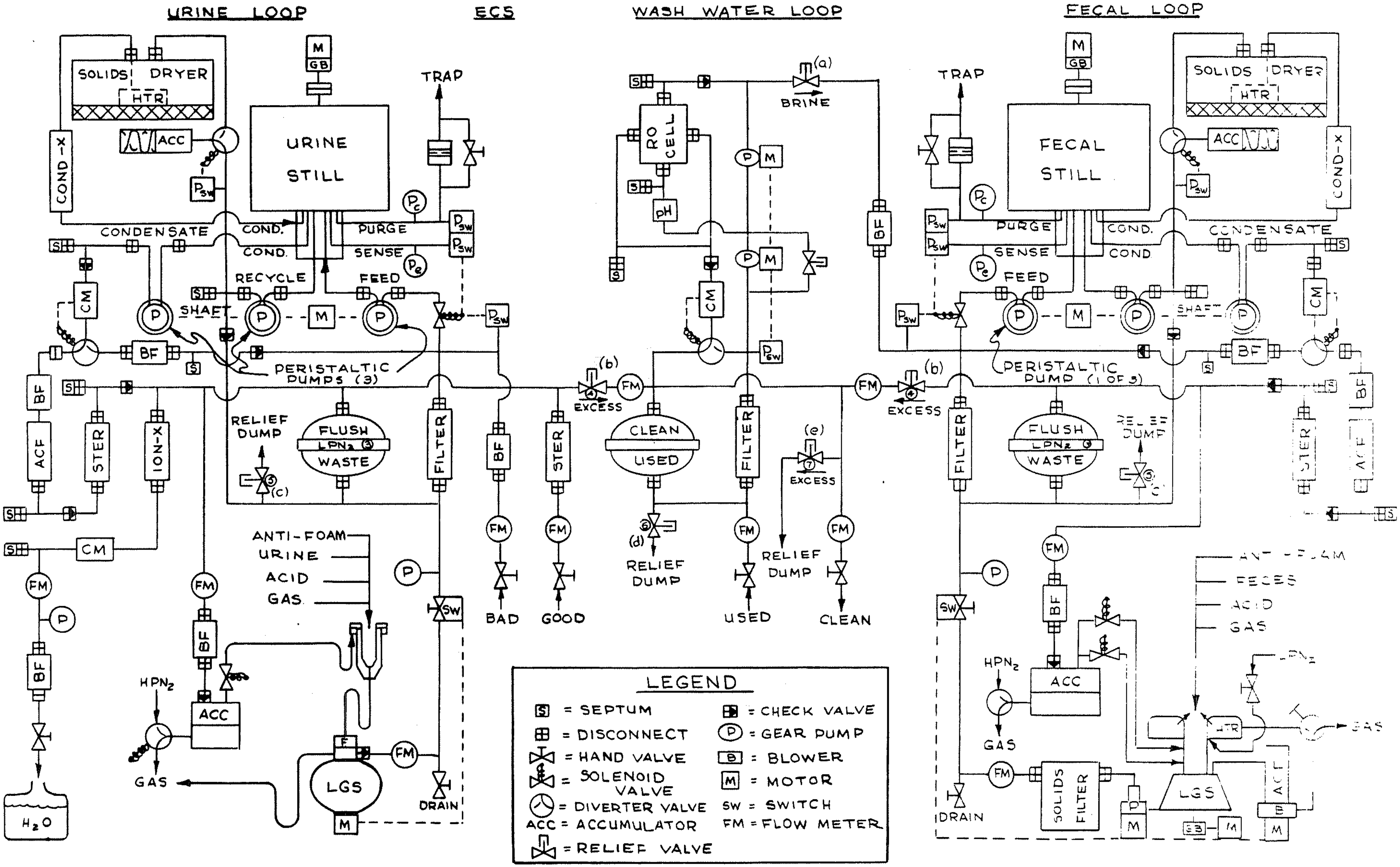
RECOMMENDATIONS

Long-term test experience and analysis of test results for the present system forms a basis to make rational recommendations for an improved IWMS. Generally, the present design posture is sound. The major limitation to the present system is over-complexity of the distillation units; a recommended design is presented in Section 6.3. Other modifications are more evolutionary than revolutionary and are discussed in detail below.

6.1 Arrangement

A Reverse Osmosis Wash Water Loop should be integrated into an upgraded IWMS to investigate its power saving potential and adaptability while operating simultaneously with the compression distillation loops. The recommended schematic flow diagram for that integration is shown as figure 13 on the next page. The diagram shows a pressure relief valve (marked a) to transport brine from the RO loop to fecal loop where it will be distilled for the final purification of wash water. Excess water will accumulate in the fecal loop because the brine input will exceed the sum of purge losses and dryer input rate. Similarly, excess water will accumulate in the urine loop because ECS condensate, in a large quantity, is delivered to that circuit; some of the ECS condensate will come from the wash water loop. The excess from both waste loops should be returned, in the form of flush water, to the "clean" side of the wash water loop (valves marked b).

FIGURE 13, PROPOSED SCHEMATIC FOR UPGRADED IWMS



In actual crew use the system's water inventory will increase by the accumulation of metabolic water. Relief dump valves should be located in the waste side of the urine and fecal loop storage tanks (valves marked c) to drain off the metabolic accumulation volume in the form of waste liquid. In the event that no waste is present in those tanks (tanks full of only flush water) a relief dump valve on the "used water" side of the wash water loop (marked d) opens to dump the excess volume - in the form of used wash water. Finally, if none of the tanks contain waste water it will be necessary to dump clean wash water (valve marked e); this is an unlikely condition, it might occur however, when the system serves fewer men than the design number. The dump sequence should be controlled by setting the opening pressure of each valve according to a corresponding pressure sequence.

Integrating flow meters should be located where shown on the schematic diagram for testing to maintain a water balance for the system and an always-current register of the flow profile. Other techniques are either more cumbersome or risk contaminating the stream if the lines are opened to make quantitative measurements.

6.2 Post-Treatment

The post-treatment loop in the refurbished IWMS as shown in the schematic in figure 3, performed more than adequately. The improved design of the CD units should result in better quality raw condensate and enhance the performance of the post-treatment loop. Consequently, significant changes in the post-treatment loop, both in the components and their arrangement, is not recommended.

However, some minor changes or additions could further improve post-treatment loop performance. A biological filter should be installed between the deionizer outlet and the drain or drink valve to prevent back migration of bacteria from sources external to the post-treatment loop. The deionizer should be sterilized prior to installation in the loop; the recommended method for column sterilization is long term (1-3 days) storage of the prepared column at pasteurization temperature (163°F).

6.3 Distillation Units

The recommended design of an improved compression distillation unit is shown on the next page. Some design features of the distillation units evaluated during this program proved to be improvements over previous methodology. The external location of the condensate pump, for example, improves its accessability and permits lubricating its drive to improve its reliability - but it requires another dynamic seal. The external pump rotates with the condenser, its output line, therefore must pass between dynamic interfaces to reach the stationary post-treatment circuit.

Considering that these tests were successfully run with the external condensate pump generating only the head necessary to preclude flashing in the line passing through the dynamic seal, it is recommended that the pump be replaced with a stationary

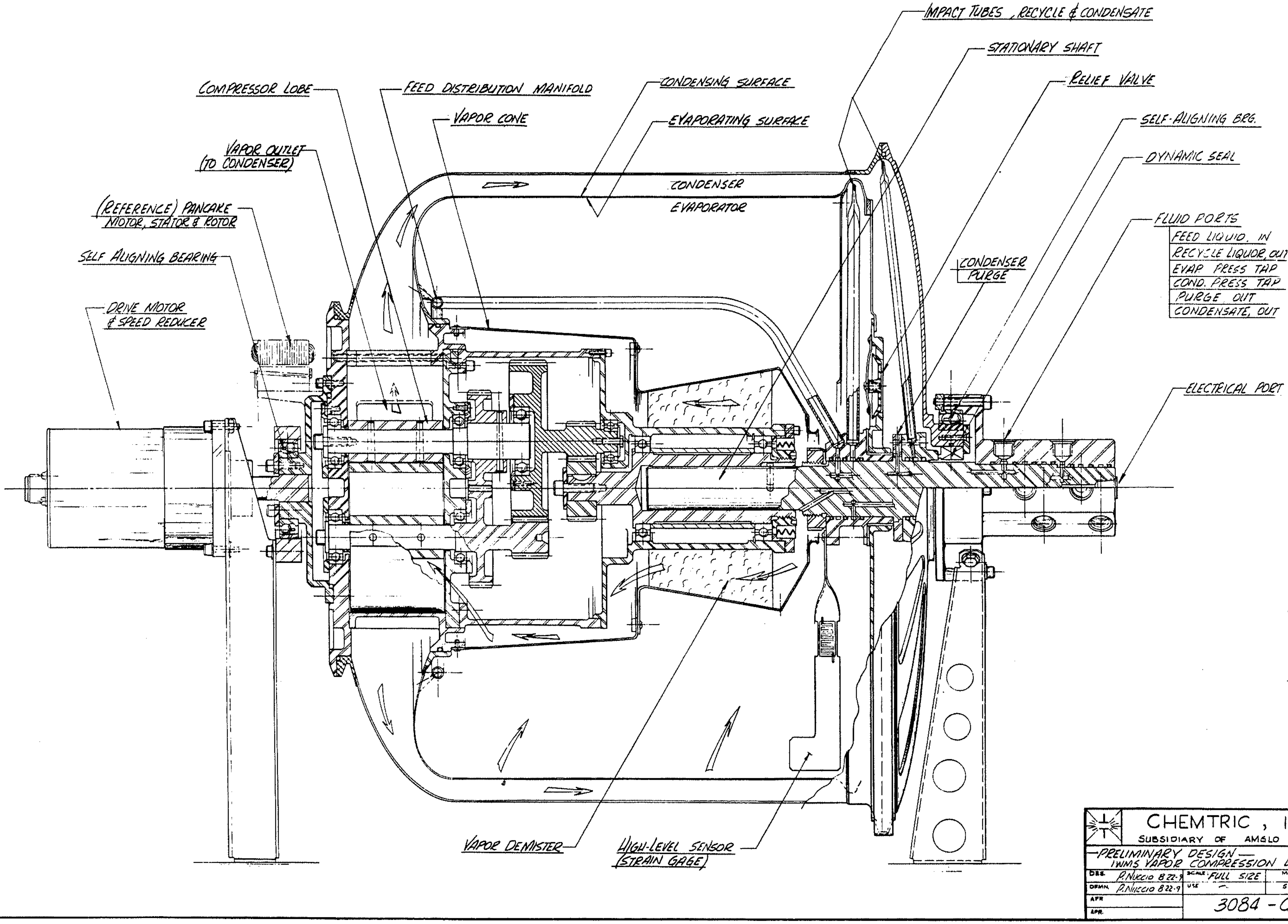


FIGURE 14, PRELIMINARY DESIGN OF DISTILLATION UNIT impact tube extending into a sump in the condenser. Flow through the stationary tube need not pass through a seal to reach the post-treatment circuit because all piping from the tube inlet to the circuit will be stationary. Velocity pressure of the water at the tube inlet will be sufficient to prevent flashing in the line up to the inlet of a perastaltic tubing pump, located external to the rotating assembly.

Future compression distillation units should be built with an external and separable solids-dryer section rather than with a dryer integrated into the evaporator section. An external dryer can be made to use drive motor heat or any other waste heat, thereby eliminating the electrical resistance heater used in the present stills. With a separable dryer the distillation units need not be opened to remove the accumulated solids after operating a fixed number of man days. Instead, a sealed dryer can be disconnected, put into storage and a fresh dryer put in its place. Thus a more efficient and asthetically acceptable system will result by physically separating the dryer and evaporator.

It is recommended that future compression distillation units be built with the evaporator contained within the condenser, as shown in the drawing,rather than reversed as the present units were designed. The thermodynamic cycle dictates that some heat be rejected (i.e., approximately the compressor work). When the evaporator is external, that heat is delivered with the vapor to the confined condenser. From there it is transferred to the vaporizing liquid in the evaporator and finally rejected through the evaporator walls as latent heat by condensing vapor. The droplets so formed are returned to the evaporator. Thus part of the condenser/evaporator interface is used for heat rejection. In the recommended configuration, with the condenser external, the heat to be rejected enters the condenser as superheat in the vapor and is dumped through the outer wall to ambient without requiring part of the heat transfer area. Both configurations are self-stabilizing and will operate at the same equilibrium temperatures in the same ambient, but with an external condenser less heat transfer area is required for the same compressor head rise and, therefore, power input.

Another advantage to the external condenser is that gas in-leakage enters the condenser rather than the evaporator. The purge, always located in the condenser, will remove the leakage gas without its passing through the compressor. While it is more advantageous to prevent leakage effectively than to process it properly, the external-condenser design is less affected by high leakage, should it ever occur.

Mechanical wipers should not be used to remove evaporation residue in a compression distillation system. Instead, the evaporator surface should be flushed clean by continuously feeding waste material to one end of the evaporator and at a rate several times the evaporation rate. The excess feed liquid, at a greater concentration of dissolved solids, should be removed from the opposite end of the evaporator, mixed with fresh waste and recycled through the evaporator. A portion of the concentrated stream leaving the evaporator should be diverted to the dryer. Evaporation within the unit will operate as a continuous process without gross changes in temperatures and pressures caused by a constantly varying boiling point of the waste liquor. Also, the possibility of fouling the heat transfer surface by dried solids is eliminated. Most important is the inherant simplicity and higher reliability of a continuous process over a batch process which must be started, sensed, stopped and restarted in sequence.

Finally, it is recommended that the distillation process be conducted at normal ambient temperature (65°F to 80°F) rather than at the higher temperature applied to the present units. Two advantages are readily apparent for the room-temperature system; (1) co-distillation of ammonia and other contaminants occurs at a much lower rate, which reduces the load placed on the post-treatment cells, and (2) the need for thermal insulation and temperature control is eliminated entirely, leaving instead, a reduction in weight and power required and an improvement in operational reliability. The volumetric flow rate through the compressor will be greater at lower saturation temperatures for the same mass flow rate. A rotary lobe compressor, therefore, is recommended for the room-temperature unit because it satisfies the specific speed requirement at the greater volumetric flow rate.*

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* ASME Paper, Water Reclamation Via Compression Distillation, J. F. Berninger, et.al. pp 2.

6.4 Fecal Collector

The present fecal collector is intended to macerate and liquify the waste to permit its processing as a liquid. The presence of solids in suspension, however, fouled the distillation unit's evaporator surface and plugged some seal passages during the test. The passages can be redesigned to alleviate the plugging problem, but to prevent surface fouling the suspended solids should be filtered out of the stream before the distillation process. No change in solids storage volume is indicated between the present system which stores the suspended solids after the distillation process, and the recommended method.

The recommended fecal collector need be only a self-cleaning transport device and a graded filter. The requirement for fine maceration is thereby removed.

6.5 Urine Collector

A simplified liquid/gas centrifugal separator is recommended for the urine collector. The present separator is the rotary vane type which develops a diminishing discharge pressure as its liquid contents are pumped out. (Liquid friction with the stationary wall becomes increasingly significant as the liquid quantity decreases and impeller submergence decreases). The present separator requires an additional pump located in the liquid line to compensate for the decreasing discharge head. The present unit also requires a blower to move gas through the separator.

Recommended is a rotary bowl type separator with a stationary impact tube. Discharge pressure will be nearly independent of quantity contained in the bowl; any pressure variation will be toward an increase as liquid friction with the stationary tube decreases. The recommended separator, therefore, will not require the present booster pump. Further, a gas blower can be integrated very conveniently into a rotating bowl separator to eliminate another component. The specific design recommended is an improved version of the liquid-gas separator developed for the NASA/LRC ILSS.