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EVALUATION OF A VAPOR COMPRESSION DISTILLATION UNIT FOR LAUNDRY WASTEWATER REUSE

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A nominal 6 gallon per hour vapor compression distillation unit (VCDU) fabricated by Chemtric, Inc. of Rosemont, Illinois, was evaluated. The unit was designed to distill wastewater using less than 300 watt-hours of energy per gallon of recovered water. The object of the evaluation was to measure product water quality and energy use rates, and to monitor operation and maintenance over an extended run period. Operational time of 432 hours was accumulated on the VCDU over a 16-week period using laundry wastewater as the feed. →

Compared to tap water, product water quality from the laundry wastewater feed was lower in turbidity, total solids, and conductivity, but higher in total organic carbon and chemical oxygen demand. Energy use was very dependent on the operation of the storage tank heater. If all make up heat could be supplied solely by vapor compression, energy use was minimum. If it was necessary to add the storage tank heater, energy use was maximum. Actual operation used the storage tank heater part of the time and energy use averaged 655 watt-hours per gallon of water produced.

Energy use rates for the VCDU were high because of intermittent operation of the unit, lack of adequate operator controls, and maintenance problems. Maintenance problems proved to be a source of considerable difficulty and several modifications had to be made in order to get the VCDU to operate satisfactorily. Varying water levels and convection currents in the sump and storage tanks contributed to less than nominal heat transfer conditions which also affected energy use requirements.

Operation of the VCDU was terminated when foam from the concentrated wastewater began to carry-over into the product water, despite a foam entrainment control medium packed inside the processor tank. Product water quality deteriorated rapidly once foam carry-over became consistent.

ACKNOWLEDGMENT

Dr. William Cowen and Mr. Michael Smith performed all laboratory analyses on the many samples generated in this work. Their efforts and diligence are very much appreciated. The authors would also like to thank CPT Roy Miller for his advice and assistance over the length of this study.

TABLE OF CONTENTS

LIST OF FIGURES

[redacted]

LIST OF TABLES

INTRODUCTION

Vapor compression distillation is an attractive unit operation because it does not require the use of any expendable materials and is capable of recovering a high percentage of the influent applied to it. It is a potential alternative to treatment methods commonly associated with advanced wastewater treatment and wastewater reuse.

Under US Environmental Protection Agency (EPA) Contract No. 68-03-0346, Chemtric, Inc. of Rosemont, Illinois developed and tested a vapor compression distillation unit (VCDU) which utilized flash evaporation and vapor compression to recover usable hot water from contaminated wastewater. The project was conducted in cooperation with the National Aeronautics and Space Administration (NASA), the Department of Housing and Urban Development (HUD), the US Army Medical Research and Development Command, and the US Coast Guard.[1] Two nominal 6 gallons per hour (gph) vapor compression distillation units were fabricated. One unit was for the US Army Medical Research and Development Command and the other for NASA. The nature and time span of the contract, however, did not provide for extended testing of the VCDU.

The US Army and the US Coast Guard maintain an active interest in the vapor compression distillation operation and desired to subject the VCDU to further testing. In particular, it was desired to characterize the VCDU using laundry wastewater, a wastewater which could potentially be treated by a vapor compression distillation operation.

OBJECTIVE

The objective of this study was to characterize a vapor compression distillation unit using laundry wastewater.

PRINCIPLE OF OPERATION

Vapor compression distillation unit operation occurs at sub-atmospheric pressure which allows distillation to occur at relatively low (165°F) temperature. Using the vapor compressor and adequate insulation, it can transfer or recycle latent heat of condensation from the condensate to sensible heat in the incoming liquid to be evaporated. In this manner, much of the same energy that runs the vapor compressor also heats incoming water which is unlike conventional distillers where the required energy for evaporation is supplied wholly in the form of heat. Photographs of the VCDU are illustrated in Figure 1.

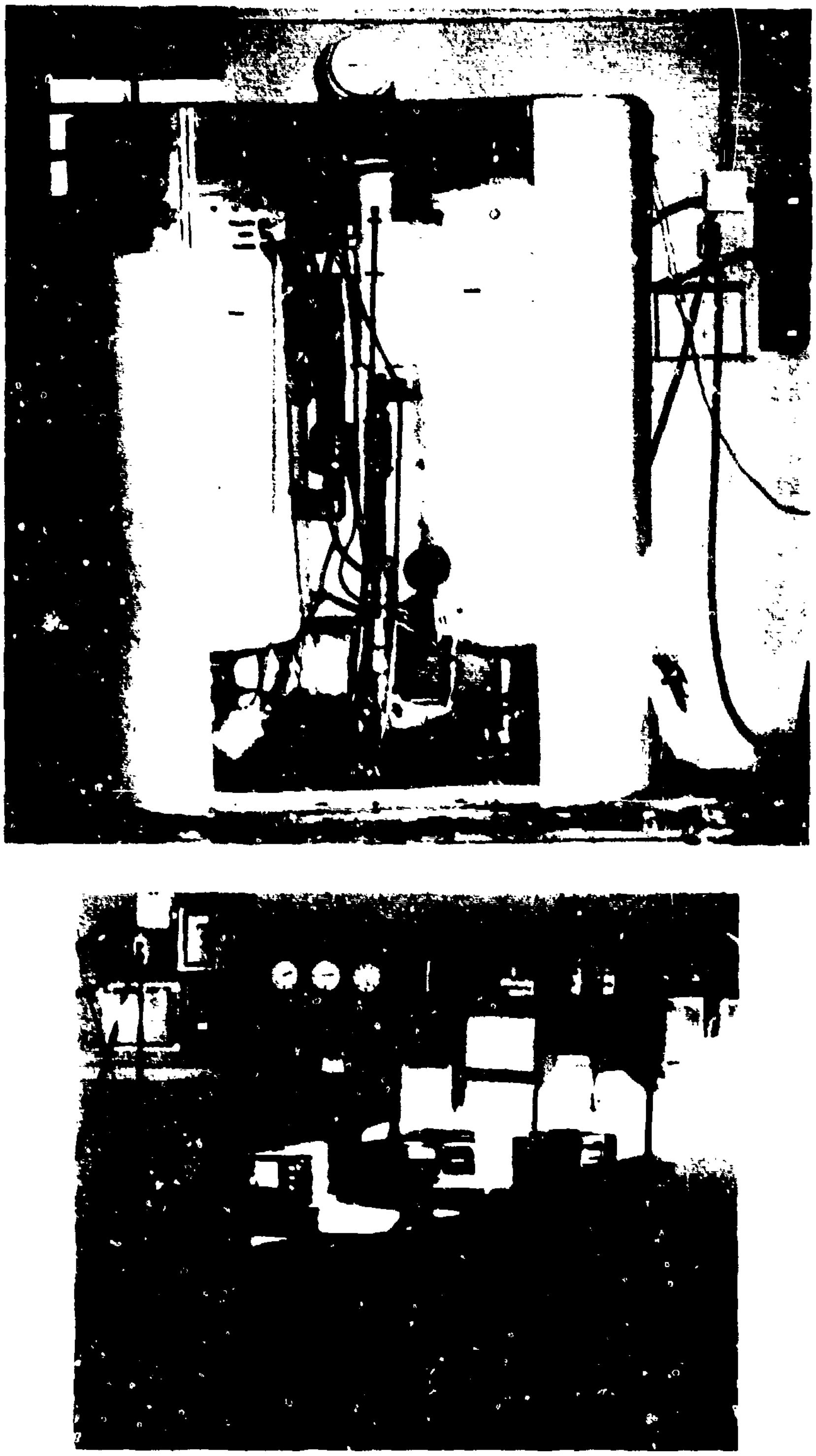

Figure 1. Vapor Compression Distillation Unit and Test Stand.

A detailed description of VCDU operation can be made with the aid of the schematic in Figure 2.[2] The process tank on the left is at sub-atmospheric pressure and can draw in feed water from the sump when the solenoid valve, activated by a liquid level switch inside the process tank, opens (1). The feed enters a liquor storage area (2) from which it is constantly pumped by a recycle pump to heat exchange coils (3). Condensing vapor outside the heat exchanger heats the liquid, a portion of which is flash evaporated by spraying it into the space above the liquor storage area of the process tank (4). The non-evaporated liquid portion falls back down into liquor while the water vapor is drawn up into a vapor compressor which compresses the vapor and also maintains a net vacuum in the process tank (5). A pressure switch regulates the on-off operation of the vapor compressor motor, shutting it off if the vacuum at the compressor becomes too small, thus protecting the motor against overloading and overheating. The vapor next passes below and up through the heat exchange coils (3) where it condenses. At this point the heat of condensation is transferred as sensible heat to the incoming recycle liquor. This section is referred to as the condenser section of the process tank. The condensate (6) becomes the product water of the process and is pumped to the storage tank (7). Any non-condensable volatile gases are also constantly pumped from the condensing area to preclude unwanted gas pressure buildup (8). An insulated shell covers the entire system.

Detailed thermodynamic design considerations about the VCDU can be found in the contract final report dated December 1976.[1] Basically, the unit is designed to produce distilled water at a rate of 6 gph and a condenser temperature of 165°F. Saturated vapor conditions are assumed for the process and thus the pressure of the vapor in the processing tank depends only upon its temperature. Efficiency of the recycle pump is assumed to be 50 percent.

The optimum design point for operation of the VCDU was found by computing the vapor compressor and recycle pump power requirements as a function of evaporator temperature. Vapor compressor and recycle pump power are in turn functions of several variables and conditions including those listed in the previous paragraph. Figure 3 is a copy of the graph resulting from design calculations by Chemtric, Inc. in which least power consumption was shown to occur at an evaporator temperature of 157°F. Optimum operating conditions are an evaporator temperature of 157°F and a condenser temperature of 165°F. This corresponds to 21 and 19 inches of mercury (inches Hg) vacuum, respectively under vapor saturation conditions.

Dimensions of the VCDU stand are 64 inches wide by 28 inches deep and 75 inches high. Storage tank volume is 100 gallons, recycle liquor volume is 33 gallons and sump volume is 29 gallons. Dry weight of the VCDU is 1100 pounds.

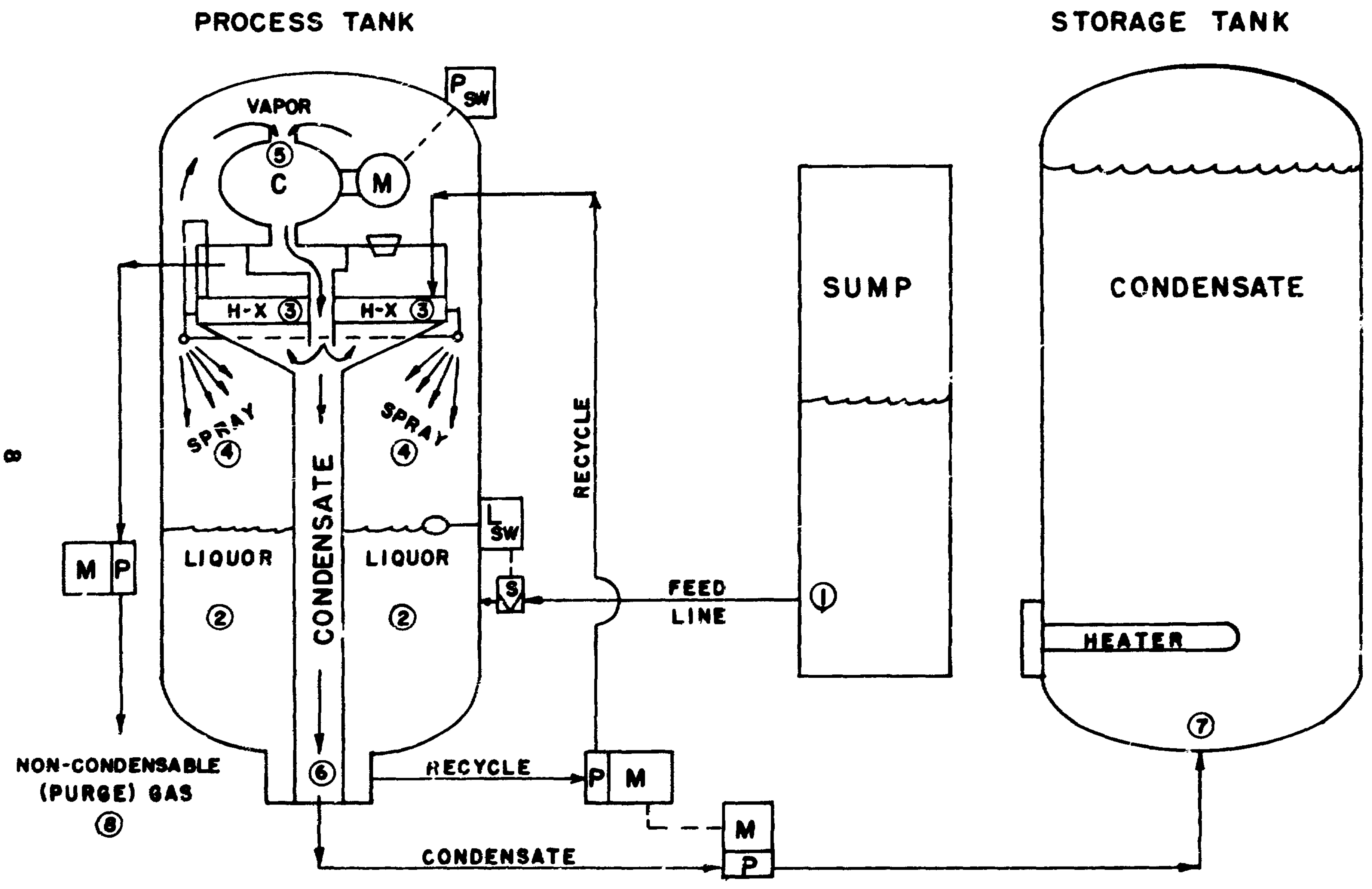

Figure 2. Vapor Compression Distillation Unit Schematic.

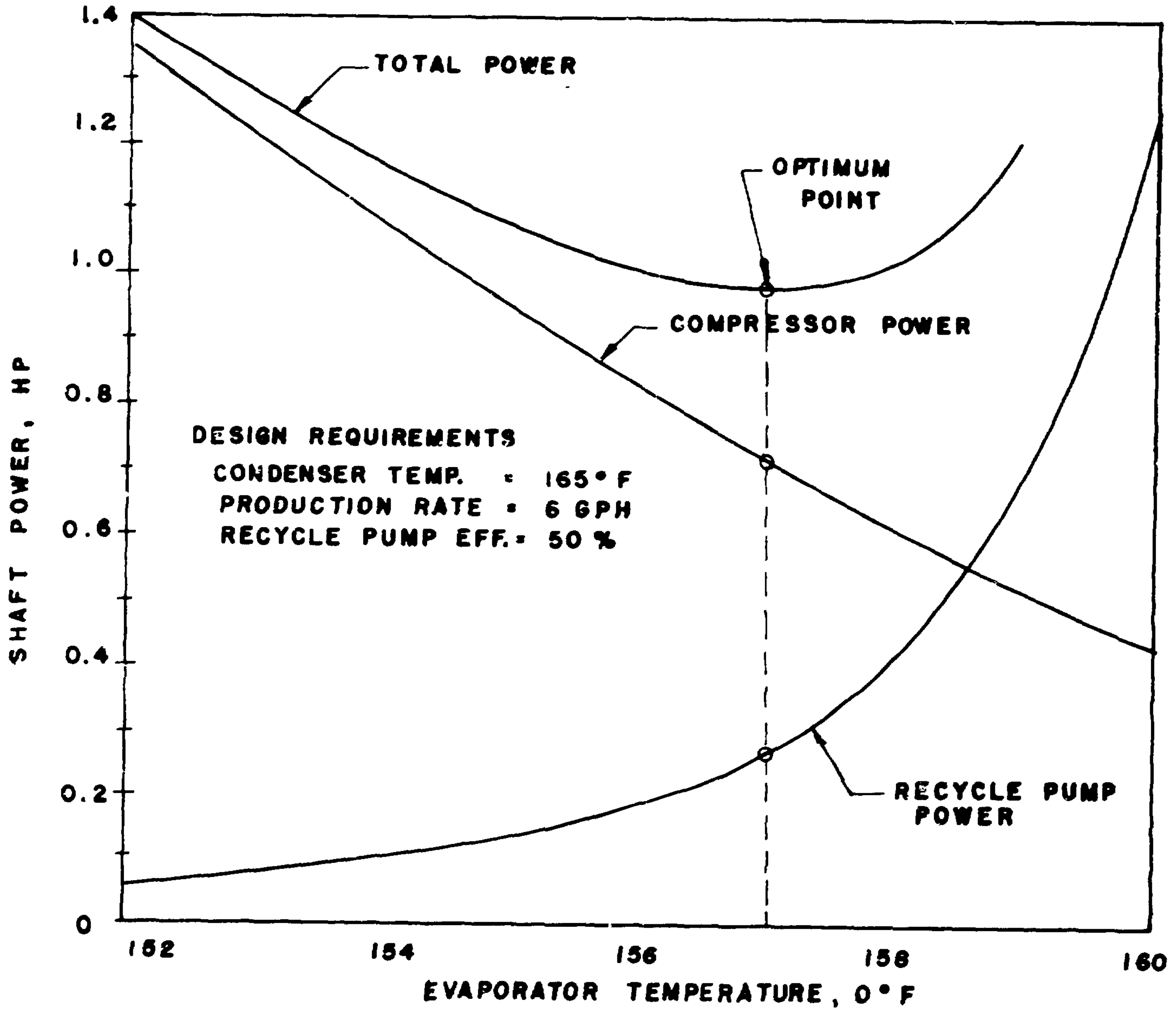

Figure 3. Optimum Evaporator Temperature as a Result of Design Calculations.

WATER PROCESSING

Distilled Water Processing

Initial operation of the Vapor Compression Distillation Unit used distilled water. The distilled water had a turbidity $\leq$ 3 nephelometric turbidity units (NTU), conductivity $\leq$ 10 micromhos per centimeter (µmho/cm) and a pH averaging 6.0. To begin, the distilled water was obtained from a glass still. Soon, when data showed that the VCDU produced equally good condensate, its product water was used as the next days influent. This mode of operation solved considerable logistical problems concerning producing 30 to 40 gallons of distilled water elsewhere daily and transferring it to the location of the VCDU.

In addition to demonstrating that the VCDU produced acceptable water, important objectives of initial operation were to become familiar with its operation, with its control, to observe trends of the measured parameters and their interrelationships, and to correlate these parameters to water production and quality.

Baseline operation was carried out over a period of 3 weeks and a total of 53.8 hours of operation. Activity during this period included considerable time and effort spent contending with operational idiosyncrasies of the distiller and significant mechanical failures and/or difficulties. General mechanical and operational considerations about the VCDU are detailed in a later section. Production rate, operational parameters, and product water quality are discussed below.

Table 1 lists the equipment used to measure VCDU parameters on site. Table 2 summarizes operational and water quality parameters for each run. Because of considerable mechanical and operational difficulties, the objective of initial baseline operation became to keep the unit running and gather some significant amount of operational data. The data in Table 2 then is not an example of "steady-state" operation but rather an approach to it, production efficiency rising in the latter runs (measured as lower energy usage), and the key operating parameter, evaporator vacuum, approaching 21 inches of mercury. Product water quality remained the same whether the unit was run efficiently or not. Conductivity and turbidity of the water was somewhat higher for the first two runs because the vessel was dirty. After this, product water quality mirrored that of the influent water. Water quality measurements reported in Table 2 are from samples of the total daily composite production taken after the runs end and not averaged discrete samples taken during the run. They represent actual water quality production of the unit.

Production rate, averaging 3.4 gph was less than expected and considerably less than the nominal 6 gph design. It increased with time during the baseline operation phase to a maximum of 4.5 gph as familiarity

TABLE 1. EQUIPMENT USED TO MEASURE VCDU PARAMETERS ON SITE

Instrument and Source	Parameter
Two element electrodynamic AC recording watt meter with appropriate transformers. Esterline Angus Model #A601C-DW1-2-5	Power, watts
Pressure/vacuum gauges: 0-30 inches Hg; 0-15 psig; 0-60 psig. US Gauge Model 5801, 4¼ inch dial	Pressure, psig or vacuum, inches of mercury
Analog temperature indicator and supplementary strip chart recorder for use with Type T thermocouple, 0-400°F. Love Model 100 temperature indicator and Model 103 temperature recorder	Temperature, °F
Mercury activated dial thermometer 30-180°F DURO Series 310	Temperature, °F
Conductivity meter, 0.01 to 1×10^6 μmho/cm range and ±½% accuracy; 3 range selection Lectro conductivity meter with k=0.1	Conductivity, μmho/cm
Turbidimeter, direct reading, formazin calibration standard, Nephelometric Turbidity Units, 0-1000 NTU, 5 range selection, sensitive to 0.004 NTU Hach Model 2100A turbidimeter	Turbidity, NTU
pH recorder, 2-12 pH, 0.2 pH intervals with strip chart. Analytical Measurements, Model 30DC	pH

with unit operation was gained. Table 2 demonstrates that production rate is associated closely with evaporator vacuum and was maximum when the vacuum was at 21 inches of mercury, as per design.

Energy use rate of the water was obtained by dividing watt-hours of energy used by gallons of water produced. Because each days effluent was used as influent for the next day's run, it was found best to heat a fixed amount of water in the storage tank and route the effluent to a separate tank which served as pump feed. Thus thermodynamically, heat from the hot effluent distillate was lost. Energy required for each gallon of water produced averaged 892 watt-hours. This included a 1500 watt heater needed to keep storage tank water hot. When effluent

TABLE 2. OPERATIONAL AND EFFLUENT WATER QUALITY PARAMETERS TREATING DISTILLED WATER INFLUENT

Run Time, hr	Production Rate, gal/hr	Energy Use Rate, watt-hr/gal	Evaporator Vacuum, inches Hg	Condenser Vacuum, inches Hg	ΔP, inches Hg	Superheat, °F	Storage Tank Temperature, °F	Conductivity, μmho/cm	Turbidity, NTU	pH
5.5	2.6	1,131	24.2	21.7	2.5	190	160	12.8	-	6.0
2.5	2.5	1,458	24.8	22.4	2.4	193	157	21.0	4.0	6.1
7.0	3.2	867	24.1	21.2	2.9	198	158	9.1	2.9	5.9
7.0	3.2	848	23.6	20.2	3.4	200	163	7.3	2.5	5.9
6.5	3.3	826	23.5	20.4	3.1	199	163	5.9	2.3	5.9
3.0	3.4	801	24.2	20.3	3.9	199	160	11.2	3.0	6.0
7.8	4.2	648	22.2	18.6	3.6	221	165	7.0	3.5	5.9
7.5	3.6	790	22.9	19.4	3.5	222	161	7.3	3.3	6.1
7.0	4.5	658	21.4	17.1	4.3	228	170	6.7	2.9	6.1
53.8										
Average:	3.4	892	23.4	20.1	3.3	206	162	9.8	3.0	6.0

is routed into the storage tank, need for the heater is theoretically none (at steady-state), all make up heat being provided by the vapor compressor. In such a case, without storage tank heater draw, energy for producing water would average 451 watt-hours per gallon. The unit is designed to produce water requiring approximately 300 watt-hours per gallon.

The ΔP in Table 2 represents the difference between the evaporator and condenser vacuums in inches of mercury, where evaporator vacuum is always larger than condenser vacuum. It was learned early in the operation that although 21 and 19 inches of vacuum are optimum operation points for evaporator and condenser vacuums, they cannot be maintained at the same time. Thus, the 21 inches for evaporator vacuum was chosen as the set point with resulting condenser vacuum "observed" indirectly as ΔP. It was felt that ΔP was a potential operational aid, perhaps giving warning of changes in system operation or correlating with other trends.

Superheat is the amount of heat above that of the saturated vapor for the particular vacuum existing in the condenser. For the purposes of the evaluation, heat and temperature were taken as equivalent. Superheat was measured just as the vapor exited the vapor compressor and before subsequent expansion (and loss of heat) in the main body of condenser. For example, in the first run, the condenser vacuum averaged 21.7 inches which corresponds to 154°F for saturated vapor conditions. Temperature measured at the vapor compressor exit was 190°F. Superheat is then 190-154 = 36°F. For ease of operation, and in order to be consistent with the first VCDU report,[1] the temperature measured was termed superheat and not the difference. Superheat is reported in this manner throughout the report.

The superheat measurement, as defined, has proved to be an important operational aid. When it is high, water production can be expected to be high. Changes in it will precede changes in evaporator vacuum, which in turn signals changes from the "norm" for one reason or another. Operation of the unit is not static or constant, and there are continual temperature and vacuum fluctuations. A detailed discussion about operation is in a later section.

Salt Water Processing

Table 3 summarizes average operational and water quality data for nine runs in three phases. Each phase consisted of three runs totaling 18 hours running time and had a different salt water content.

Four, 10, and 20 grams of salt per liter of water were added to the VCDU influent in each successive phase. Tap water was used as the baseline water instead of distilled water. (General characteristics of the tap water are listed in Table 5.)

TABLE 3. OPERATIONAL AND EFFLUENT WATER QUALITY PARAMETERS TREATING VARIOUS SALT WATER INFLUENTS

Run Time, hr	Production Rate, gal/hr	Energy Use Rate, watt-hr/gal	Evaporator Vacuum, inches Hg	Condenser Vacuum, inches Hg	ΔP, inches Hg	Superheat, °F	Storage Tank Temperature, °F	Conductivity, μmho/cm	Turbidity, NTU	pH
4,000 mg/l NaCl influent:										
6	3.4	867	22.0	18.3	3.7	236	160	7	3.5	6.2
6	4.3	651	21.7	17.5	4.2	223	167	10	3.0	6.0
6	4.2	692	21.6	17.5	4.1	222	167	13	3.2	6.4
18										
Average	4.0	737	21.8	17.8	4.0	227	165	10	3.2	6.2
10,000 mg/l NaCl influent:										
6	3.5	804	23.5	20.0	3.5	208	157	34	2.6	6.2
6	3.7	757	23.8	20.4	3.4	205	159	10	2.5	6.4
6	3.3	888	23.1	18.4	4.7	227	162	10	3.4	6.8
18										
Average	3.5	816	23.5	19.6	3.9	213	159	18	2.8	6.5
20,000 mg/l NaCl influent:										
6	2.9	960	23.5	19.3	4.2	223	155	8	2.0	6.4
6	3.8	747	23.2	18.9	4.3	211	161	13	1.8	6.4
6	3.5	800	23.6	20.4	3.2	213	160	24	2.8	6.8
18										
Average	3.4	836	23.4	19.5	3.9	216	159	15	2.2	6.5

Superheat averaged about 10 to 20°C higher for the salt water runs than for the distilled water baseline runs. No significant trends in average superheat temperatures among phases were noted for this limited series of runs. Superheat, though relatively high, fluctuated quite a bit from run to run.

Production rate remained nearly the same as with distilled water influent. Energy requirements, however, went down, ostensibly because of the better heat transfer properties of the salt water. As with the distilled water runs, effluent was routed to a separate tank because it was desirable to have a daily composite for water quality measurement. Thus, the heat energy of the effluent was lost and the heater worked continuously. With this configuration, energy to produce the water was 737, 816, and 836 watt-hours per gallon for phases 1, 2, and 3 respectively. Had the 1500 watt heater been off, energy requirements could have dropped to 362, 387, and 395 watt-hours per gallon for phases 1, 2, and 3.

Operational parameters were not as good for this series of runs as was desirable. Evaporator vacuum averaged 1 to 2 inches of mercury above the set point of 21 inches. Storage tank temperature averaged about 5° below the desired 165°F. One of the reasons was that there had been considerable maintenance difficulty with the vapor compressor motor and it was decided to operate at a higher vacuum (lower pressure) so as not to overload the motor. In addition, the lower temperatures and higher vacuums encountered at start up and through the early run times are reflected in the average figures.

Quality of the effluent water was quite stable. Water quality measurements were made from daily composite samples. Conductivity was only slightly higher during this series of runs (14 versus 10 μmho/cm) than the previous distilled water influent tests. The pH averaged 6.4 compared to 6.0. In both series of runs water quality remained essentially the same regardless of input to the VCDU.

Laundry Wastewater Processing

Initial Operation. Composition and concentration of the synthetic laundry wastewater was, with one exception, identical to that expected from Army field hospitals.[3] The current housing, equipment, and power supply support for Army field hospitals is termed MUST: Medical Unit, Self-Contained, Transportable. The particular brand or source for each constituent followed the recipe used by the Walden Research Division of Abcor, Inc. in their breadboard studies of the MUST Water Processing Element.[4] Table 4 lists the composition of the synthetic laundry wastewater. Blood was not included in the composition because of difficulty involved in obtaining and storing whole blood.

TABLE 4. COMPOSITION OF THE SYNTHETIC LAUNDRY WASTEWATER

Constituent	Concentration
Soap, laundry, neutral, Type I (FSN 7930-634-3935)	650 mg/l
Alkalinity (as sodium carbonate - Fisher Scientific, Inc.)	500 mg/l
Oil & grease (Wesson vegetable oil)	200 mg/l
Kaolinite clay (Fisher Scientific, Inc.)	150 mg/l
Sour and blue (FSN 7930-205-288)	116 mg/l
Urea (Fisher Scientific, Inc.)	20 mg/l
N,N-Diethyl-m-toluamide (Fisher Scientific, Inc.)	874 ml/l

Synthetic laundry components were mixed with tap water in 50 gallon batches. General characteristics of the tap water and resulting synthetic laundry wastewater are listed in Table 5. Ranges for the several samples analyzed are shown as applicable. Values for the chemical oxygen demand (COD) and total organic carbon (TOC) of the wastewater feed are estimates. The feed was a soapy, clumpy, non-homogeneous mixture containing considerable suspended solids and not conducive to accurate TOC or COD measurement. The instruments used to measure turbidity, pH, and conductivity are described in Table 1. Total solids followed the procedure described in the 14th edition of "Standard Methods."[5] TOC was measured in the laboratory using either a Beckman, Inc. Model 915 Infrared TOC Analyzer or a Phase Separations, Ltd. TOCSIN Total Organic Carbon Analyser. COD was measured after the method of Jirka and Carter.[6]

Several changes were made in VCDU operation within the first week of operation. A 2,000 watt heater arrived and replaced the 1,500 watt storage tank heater which had been used to date. (Earlier, upon initial arrival at Fort Detrick, the VCDU had an inoperative 2,000 watt heater and the 1500 watt heater was the most powerful readily obtainable unit.) Effluent condensate was routed to the storage tank to minimize heat losses and operate the VCDU as designed. The storage tank was calibrated and a sampling valve was installed in the condensate line. Finally, a third head was added to the peristaltic pump to pump laundry wastewater from the feed tank into the VCDU sump without taking the front insulating cover off.

TABLE 5. GENERAL CHARACTERISTIC PARAMETERS OF THE TAP WATER MAKE-UP AND SYNTHETIC LAUNDRY WASTEWATER FEED

	Total Solids, mg/l	Turbidity, NTU	pH	Conductivity, μmho/cm	COD, mg/l	TOC, mg/l
Tap water	140-160	<3	7.4-7.6	230-280	≤6	≤3
Synthetic laundry wastewater	1,900-2,000	800-925	9.2-9.4	866-949	800[a]	66[a]

a. Estimates.

Since the product water (condensate) was now entering the storage tank, a schedule of storage tank water removal had to be established to make room for the continuous product water flow. As it turned out, the frequency of water removal, amount, and level of water in the storage tank (and the sump) all affected heat transfer within the VCDU and, therefore, water production rates. This particular aspect of VCDU operation is discussed in detail in the section on operation.

Transfer of product water to the storage tank brought with it new realities. Shortly into the run it was noticed that while draining the tank, temperature of the water (measured near the bottom at the entrance of the product water condensate to the storage tank) increased as much as 30°F. It became "obvious" that there was a water temperature gradient along the height of the storage tank. Thus, storage tank temperature, depending on where you measured it, could not be considered an 'absolute value,' and therefore, was of less value for operational control.

Draining the tank resulted in temperature gage readings over 180°F as hot top water was drained out the bottom of the storage tank past the temperature probe. The heater thermostat was set at approximately 165°F and it was felt that the extra heat could not be attributed solely to that added by the vapor-compressor. It was reasoned that the 180°F+ readings were either correct and the heater thermostat was out of order, or the 180°F+ readings were false and the temperature probe needed calibrating. The latter instance proved to be the case. The mercury activated dial thermometer had been reading 18°F too high. Constant vibration of the VCDU had apparently caused the dial indicator to gradually slip out of phase. The dial thermometer was recalibrated and mounted beside and off of the VCDU. Previous temperature measurements were adjusted 18° accordingly.

With the storage tank temperature now measuring lower than had first been suspected, the initial procedure was to set the heater thermostat higher. It was soon noticed that the heater cycled on and off very frequently - approximately every 2 minutes - as hot water rose and cooler condensate water entered the storage tank. Furthermore, when such rapid cycling occurred, the desired 21 inches of evaporator vacuum was not reached any faster than at the lower heater temperature settings. Considering this and the fact that there was a temperature gradient from the bottom to the top of the tank, temperatures as measured at the storage tank condensate inlet generally remained between 140 and 150°F and were given secondary importance to attaining 21 inches Hg of evaporator vacuum as rapidly as possible.

Although the temperature probe did not indicate the average temperature in the storage tank, it is felt it did indicate temperature of the incoming product water condensate to the storage tank. Average storage tank temperature during the laundry wastewater run was 145°F. Average condenser vacuum during the run was 19.9 inches of mercury, which in a saturated atmosphere translates into 162°F. Assuming temperatures and pressures measured were correct, this indicates a 17°F drop in condensate temperature as it traveled from the condenser section of the processor to the entrance of the storage tank.

Operational Characteristics and Product Quality. The laundry wastewater processing run was scheduled similarly to the distilled and salt water runs. The VCDU was operated 6 to 7 hours each working day, then put in standby at night and on weekends: heat on, but pumps and compressor still. During this idle period, evaporator vacuum would increase 3 to 5 inches of mercury because of inactivity in the processor and, as a result, a portion of the next day's run was spent getting back up to 21 inches Hg of evaporator vacuum. The result of non-steady state operation was non-optimum performance. Being out of design conditions did allow trends to be plotted and evaluated as the various operational parameters changed and the 21 inches Hg evaporator vacuum was reached. Such trends are demonstrated and discussed later in this section.

Processing of synthetic laundry wastewater ran for 431 hours during which time solids were allowed to build up in the recycle liquor. Total solids in the liquor reached 5.3 percent before operation was terminated because of excessive solids carry over into the condensate from foaming in the liquor.

Figure 4 is a plot of inches of mercury of evaporator vacuum versus production in gallons per hour. It illustrates a ragged but definite trend of increasing production with vacuum decrease as would be expected according to the design of the unit. Average production realized over an inch of vacuum is also plotted, which smooths out the trend. It shows a gradual, fairly constant trend of increasing production approximately 0.3 to 0.4 gallons per hour with each inch of vacuum decrease. It was

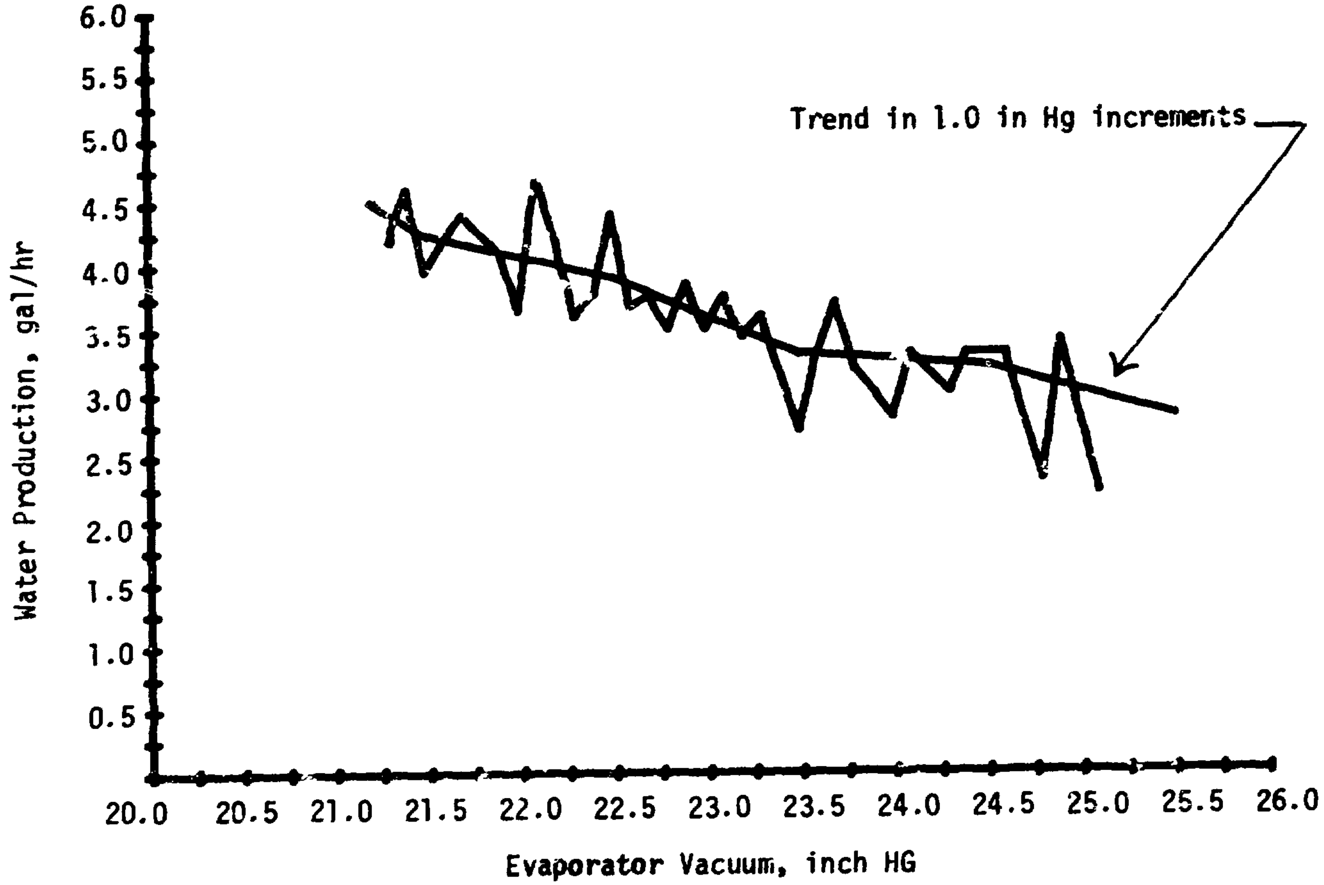

Figure 4. Evaporator Vacuum Versus Water Production.

felt that higher production could have been obtained at lower vacuums, however the compressor motor is not designed to bear the higher pressure load and would have been shut off by its high pressure switch.

Figure 5 is a plot of ΔP in inches of mercury versus production in gallons per hour. The ΔP was defined earlier as the difference between evaporator and condenser vacuums with the latter always smaller than the former. Figure 5 also shows a gradual trend, in this case, of increasing production with increasing ΔP. Design of the VCDU is predicated on 2 inches of mercury difference, but during the operation 3 to 4 inches were experienced.

Figure 6 complements Figure 5. It is a plot of the average daily condenser and evaporator vacuums as the run progressed. The condenser and evaporator vacuums follow one anothers high and low average daily values closely. Further scrutiny of the figure and further analyses of the data show that their difference (ΔP) is greatest when the vacuum values are low, compared to when both condenser and evaporator vacuums are high. VCDU operation reached steady state and experienced best production at the "low" 21 inches mercury of evaporator vacuum.

Average daily production was found for each 5°F increment of superheat. A running average spanning 15°F and moving up in 5°F increments was then plotted versus production (Fig. 7). Significant in the figure is the dramatic increase in production rate after 205°F. During operation of the VCDU, the superheat was observed to fluctuate first and give the earliest indication of operational changes. It functioned in a passive role, a result of VCDU operation, rather than in an active role as was the evaporator vacuum.

Total solids were monitored daily in the product condensate and recycle liquor. One of the main objectives of VCDU operation was to find out at what maximum solids content the unit could recycle laundry wastewater. As it turned out, the limiting factor was foaming and not solids content despite the entrainment control medium consisting of fibrous pellets.

The first indication of atypical operation occurred approximately 275 hours into the run at a recycle liquor solids content of 4.7 percent. There was a sudden drop in the superheat. Samples of the product water taken when superheat was low showed a definite increase in total solids. Time periods of low superheat processing with the accompanying decrease in product water quality became more and more frequent until 349 hours into the run when solids carry-over from the recycle liquor into the product condensate became so frequent that the liquor total solids content began to decrease.

Figure 8 is a plot of product water and recycle liquor total solids content. Total solids in the latter reached 5.3 percent before they

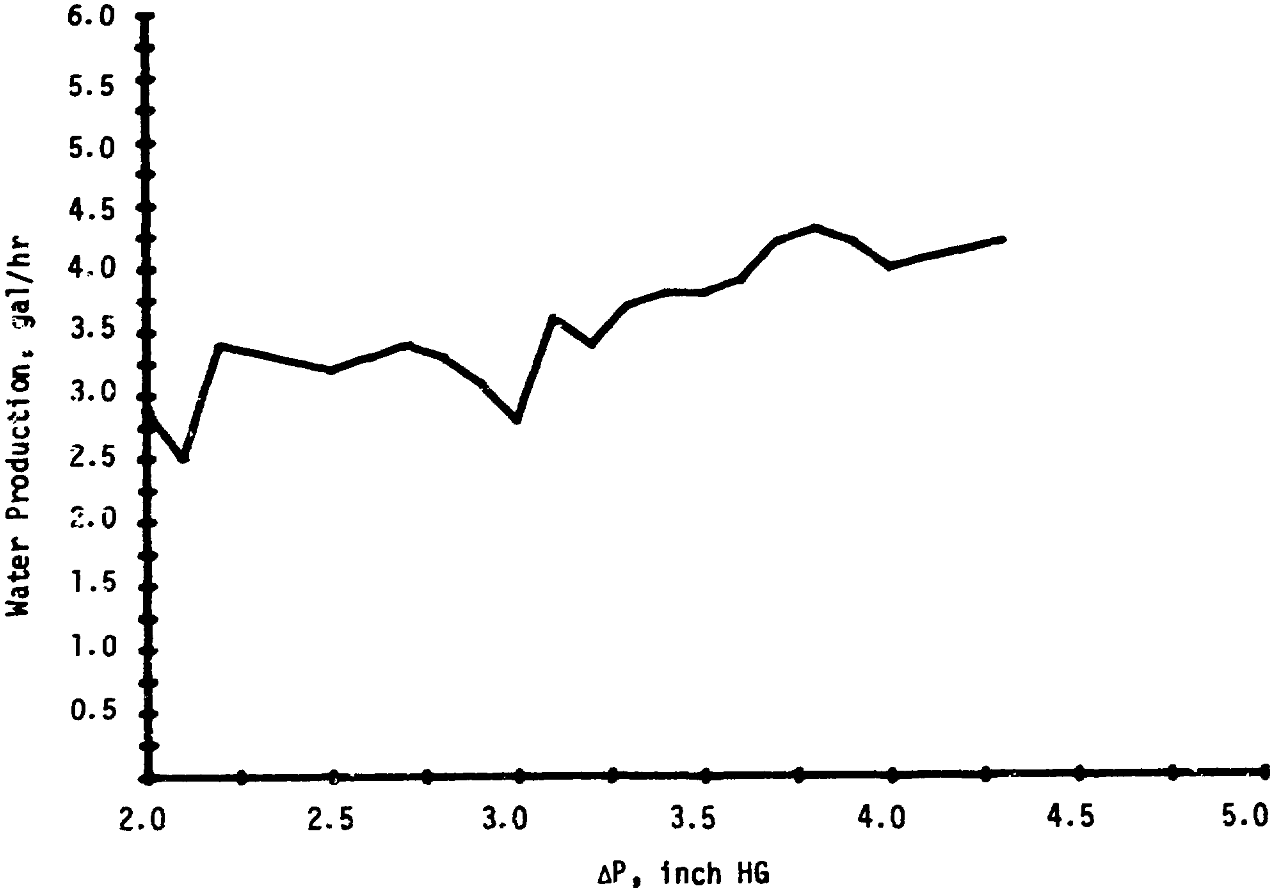

Figure 5. Difference Between Condenser and Evaporator Vacuums (ΔP) Versus Water Production.

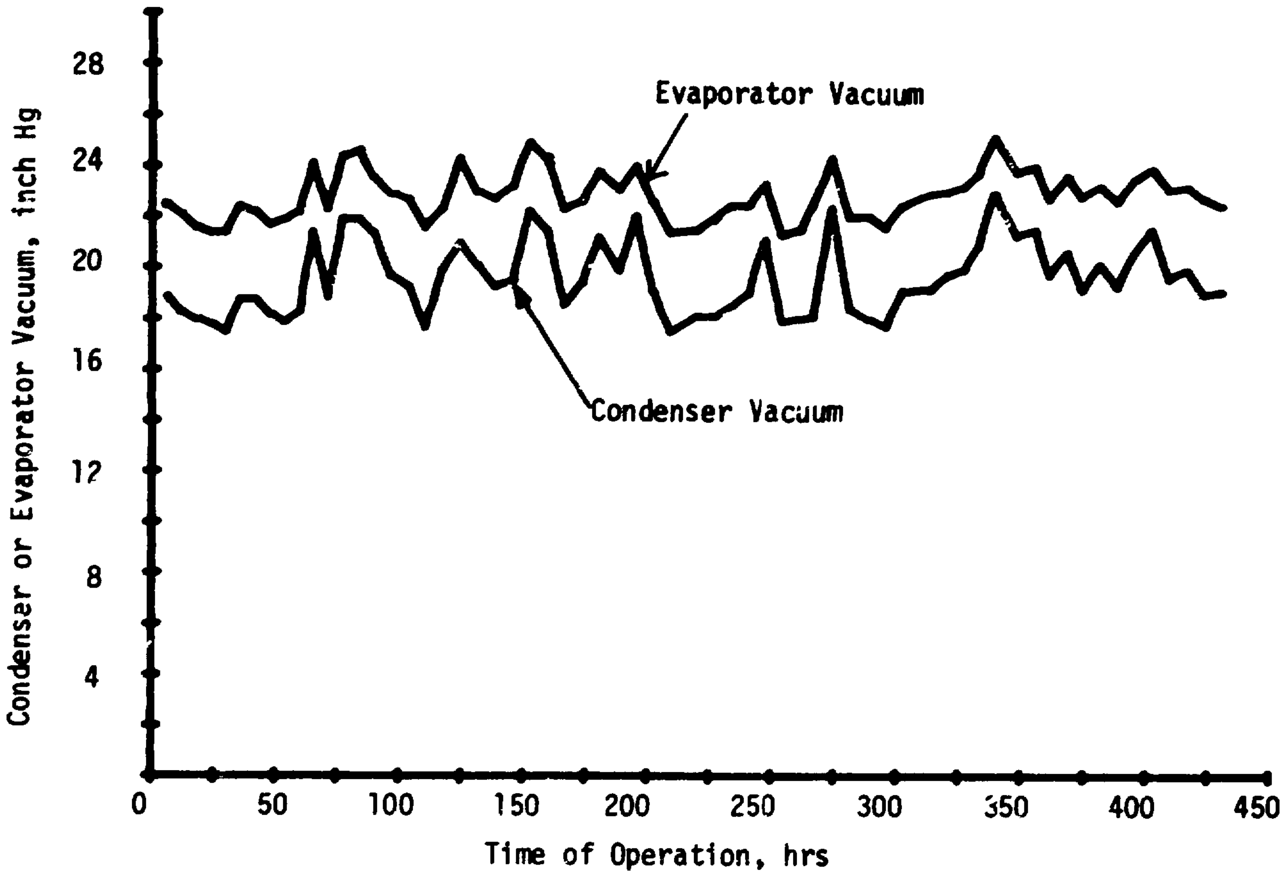

Figure 6. Condenser and Evaporator Vacuums Versus Time of Operation.

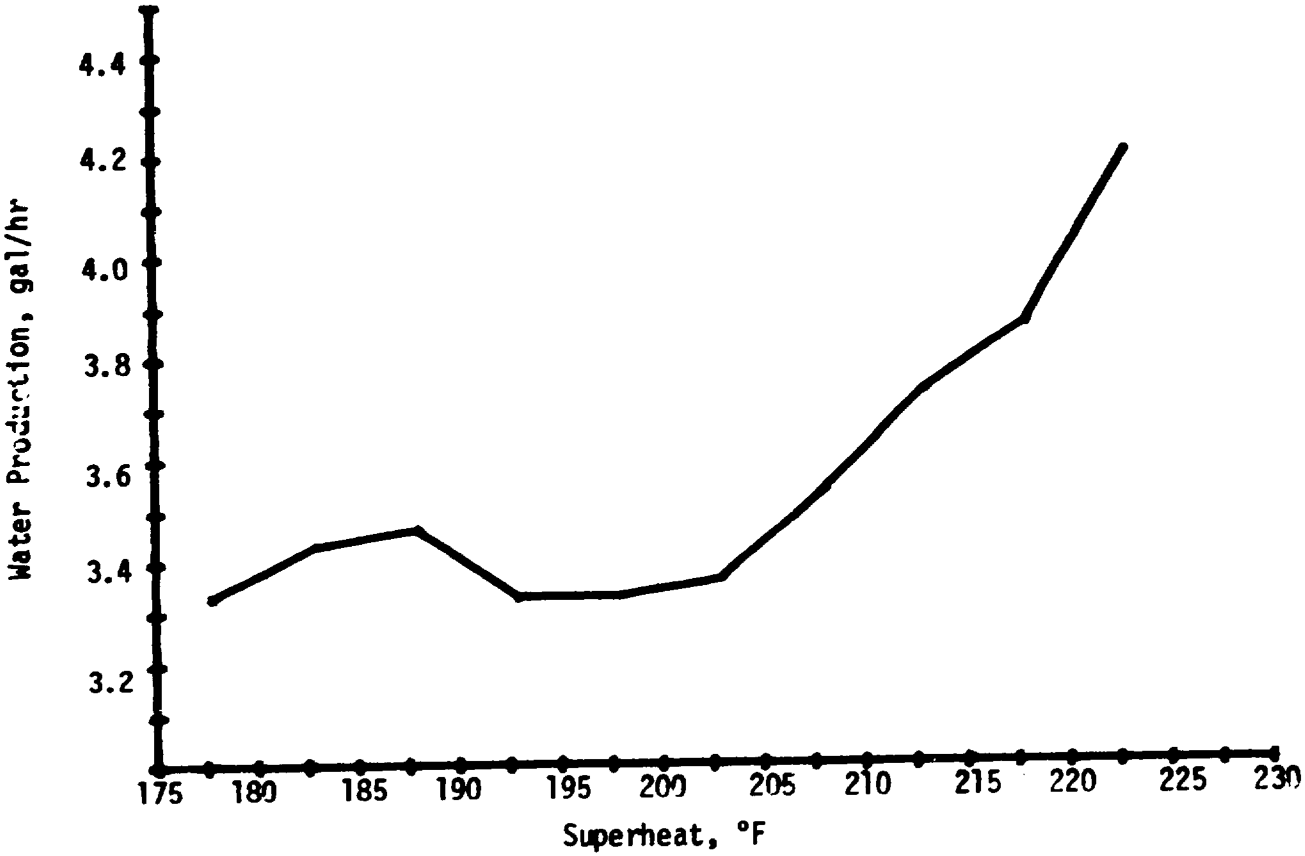

Figure 7. Superheat Versus Water Production

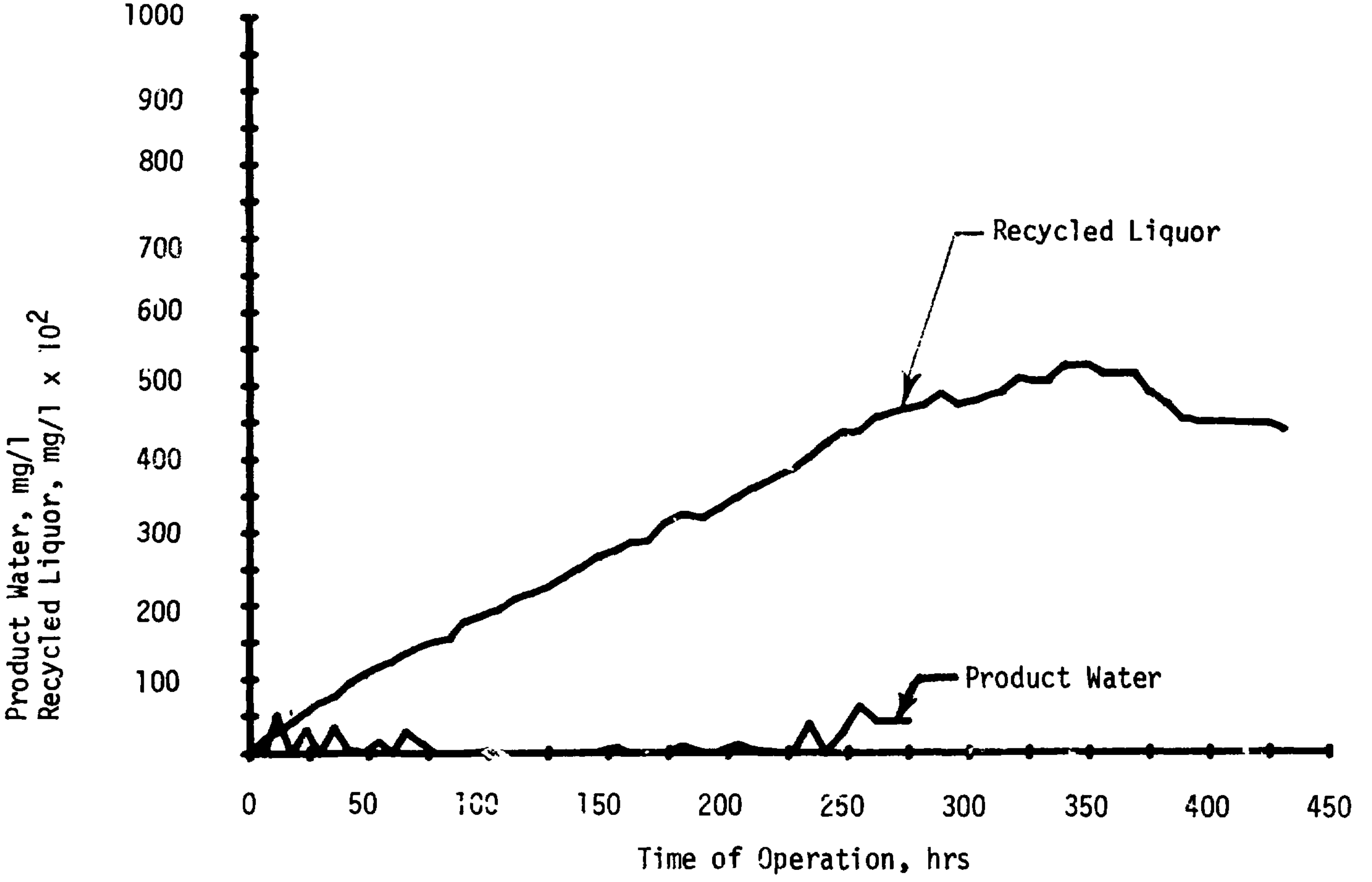

Figure 8. Recycled Liquor and Product Water Total Solids Versus Time of Operation.

began to decrease. VCDU processing continued to 432 hours to verify the trend. Prior to 275 hours into the run, daily product water solids content normally ranged from 0 to 15 mg/l with random exceptions measuring as high as 63 mg/l. After 275 hours the quality of the product water depended on whether one sampled when the superheat was low or high. Defining superheat to be low when it was < 180°F, (hourly measurements recorded as low as 150°F), total solids measurements ranged from 491 to 2,167 mg/l and averaged 1,301 mg/l. During "high" superheat sampling, solids measurements of the product water ranged from 78 to 470 mg/l and averaged 193 mg/l - poor compared to the solids content experienced prior to 275 hours of operation. Conductivity of the product water was also measured and followed total solid trends. Measurements made after 275 hours are not plotted in Figure 8 because of the subsequent irratic values.

Figure 9 is a plot of recycled liquor total solids and turbidity as the run progressed. The turbidity values decrease even as total solids increase. This was a surprising trend and it indirectly characterizes the nature of the liquor. The fact that soap will readily combine with ions in solution including iron from the VCDU and tend to precipitate out was considered, but rejected as not the case. The recycle line is near the bottom of the processor and the sample port is in the recycle line. Contents of the samples were well mixed. Rather, it is the nature of the floc, which, although opaque to the eye, exhibited diminishing light scattering characteristics over time, ostensibly because of the constant mixing through the centrifugal recirculation pump and even though total solids were increasing. Interestingly, turbidity of the recycle liquor began to increase after 349 hours of operation, at the same time the total solids began to decrease. A line is drawn through this time to accentuate the trend. It is not known whether this trend is a coincidental or a characteristic relationship between the total solids and turbidity. Measurement of suspended solids would be desirable for future study.

The data gathered over the laundry wastewater processing run were plotted to note any trends with respect to storage tank temperature and production. Below about 140°F, the production rate was less, but other than this "turning point" no trends were noted. Plotted data was random and scattered. It should be pointed out again that the storage tank temperature was measured near the bottom and below the heater. There was an increasing temperature gradient throughout the tank so that average tank temperature was higher than measured.

The data were also compared to discover any relationship between energy use rate and production rate. The data showed that energy usage was not a function of production, but rather how long the storage tank heater was on. The role of the storage tank heater is discussed in detail in the Operation and Maintenance section.

Table 6 is a summary of the daily operational parameters over the laundry wastewater processing run. Operational parameters were recorded

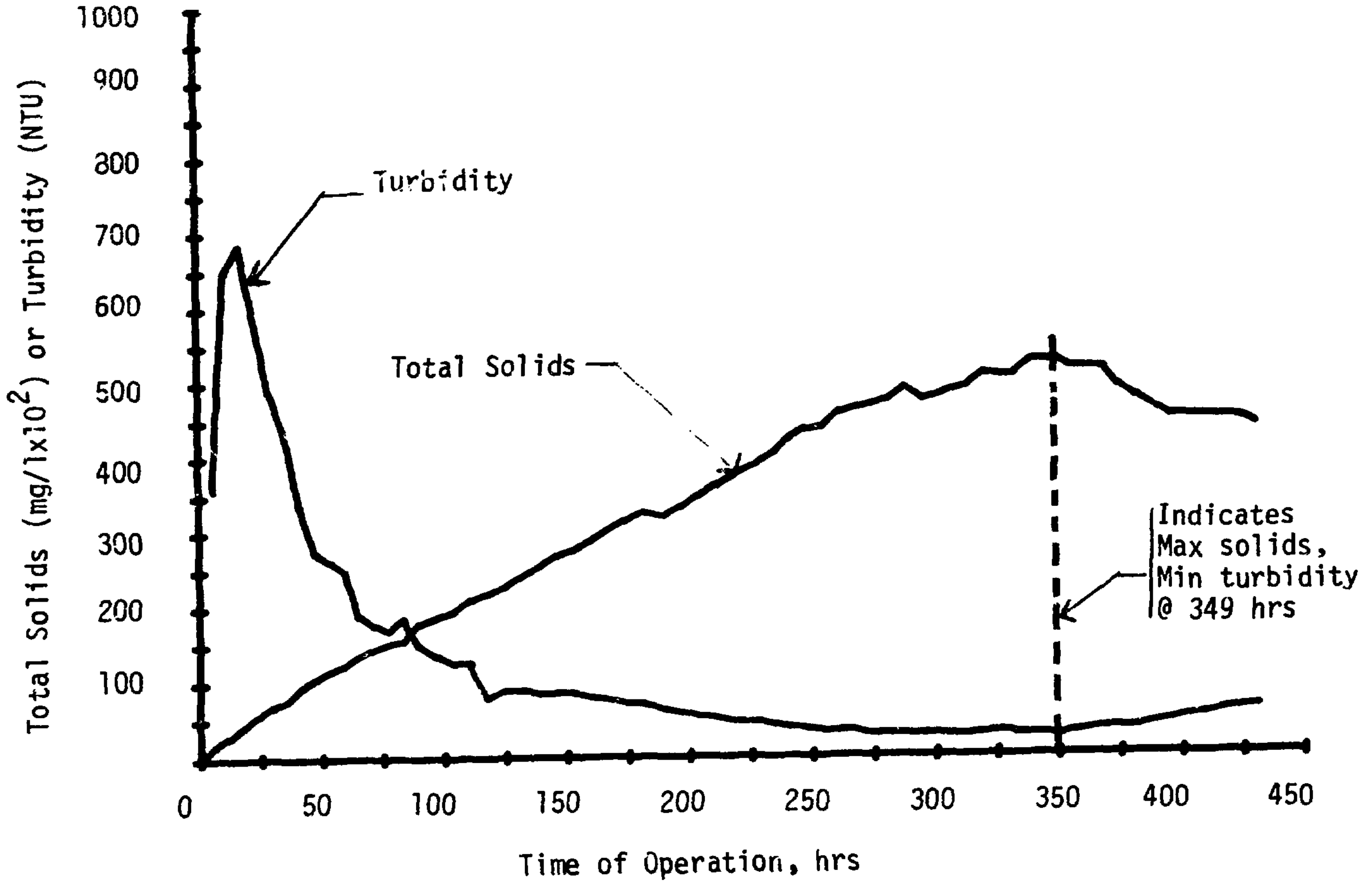

Figure 9. Recycled Liquor Total Solids and Turbidity Versus Time of Operation.

TABLE 6. AVERAGE DAILY OPERATIONAL PARAMETERS FOR THE LAUNDRY WASTEWATER PROCESSING STUDY

Operational Parameter	Over Entire Study		During Maximum Production	
	Average	Range	Average	Range
Evaporator vacuum, inches Hg	23.0	21.4-25.1	21.6	21.4-22.1
Condenser vacuum, inches Hg	19.9	17.7-22.9	17.9	17.5-18.3
ΔP, inches Hg	3.1	2.1-4.0	3.8	3.7-3.9
Recycle pressure, psig	17.9	13.4-19.9	19.2	19.0-19.7
Power, KW	2.4	1.4-3.7	3.1	3.0-3.1
Production, gph	3.6	2.0-4.7	4.7	-
Storage tank temperature, °F	145	126-155	150	149-151
Superheat, °F	216[a]	186-229[a]	222	214-226
Energy use rate, watt-hr/gal	667	--	660	-

a. Through 275 hours of running time.

hourly, then averaged for the day. Average values (of the daily averages) and ranges for each parameter are given for the entire run and for 3 days where daily production averaged a maximum 4.7 gph. The maximum production experienced in any 1 hour was 5.3 gph. Superheat ranges are shown only through 275 hours and not the entire 431 hours. When foam carry-over began at 275 hours, superheat fluctuated and this considerably affected its daily average. The other operational parameters were not so affected and any "turning point" was not apparent.

Table 6 allows comparison of average parameter values over the entire run and during the most productive run. Production was maximum near the design 21 inches of evaporator vacuum, but ΔP approached 4 inches rather than 2, as per design. Power required to operate at maximum production was more, but the increased yield resulted in a similar energy processing requirement of 660-667 watt-hours per gallon. Finally, storage tank temperature and superheat were both higher than average during maximum production which suggests that a larger heater and/or better control of heat addition is desirable.

Average daily product water quality parameters are listed in Table 7. Product water samples were taken twice daily at approximately 2 and 6 hours into the run. After about 200 hours of cumulative operating time, sampling was reduced to once daily at 6 hours into the run when the rate of production was normally maximum. These grab samples provided product water to make total solids, TOC, and COD measurements. Grab samples for on-site measurements of turbidity, pH, and conductivity normally were taken at least three times during a run and averaged for the day.

TABLE 7. AVERAGE DAILY PRODUCT WATER QUALITY PARAMETERS FOR THE LAUNDRY WASTEWATER PROCESSING STUDY[a]

Water Quality Parameter	Average	Range
Turbidity, NTU	1.9	0.7-3.1
pH	6.6	5.8-7.8
Conductivity, μmho/cm	65	52-110
Total solids, mg/l	11	0-63
Chemical oxygen demand, mg/l	49	34-67
Total organic carbon, mg/l	9.4	5.9-13.6

a. Through 275 hours of operating time.

Average product water quality parameters are reported only through 275 hours. Foam carry-over with its accompanying solids entrainment affected water quality greatly. Measurements made after this point depended on whether foam carry-over was occurring during the sample time. For example, COD ranged as high as 200 mg/l, TOC as high as 165 mg/l, and total solids measured over 8,800 mg/l during such times.

With the obvious exception of foam carry-over, product water quality was independent of VCDU operation or production rate. Ranges of the various parameters were normally narrow. Table 7 is somewhat misleading in that the few high or low "exceptions" which widen the range span are duly listed.

Post-Operation Inspection. When laundry wastewater processing operations ceased, the VCDU was cooled and inspection of the unit began. After removing the processor head, the foam entrainment material consisting of fibrous pellets was removed. It was sandwiched between a wire mesh and placed around the annulus formed by the evaporator shell inner diameter and condenser shell outer diameter.

Next, bolts along the periphery of the vapor compressor - compressor motor mounting plate were unscrewed to allow removal of an assembly consisting of compressor, motor, mounting plate, spray ring with piping and nozzles, and heat exchange coils. Removal of the assembly from the body of the VCDU and its various protrusions was awkward and cumbersome. There were no attachments in the mounting plate for hoisting the assembly.

A powdery creme colored residue covered the compressor and motor indicating the foam had reached the vapor compressor, as had been suspected. The residue was obviously a soapy substance. After cleaning off the residue from the compressor and motor, it was noted that the motor was unpainted. Apparently, the paint had blistered off from high motor heat.

The spray ring has provisions for six nozzles. Water enters opposite sides of the ring. Each water feed supplies three nozzles and is independent of its opposite feed since the two feeds are separated by two walls in the spray ring pipe 180 degrees apart around the periphery. Three nozzles supplied by one feed were completely clogged. Two nozzles supplied by the other feed were partially clogged and the third connection had no nozzle, but was completely open. Most of the water flow had obviously been going unsprayed through this open three-quarter inch pipe, much like a water faucet. In retrospect, it was somewhat surprising that the average 3.6 gph production realized was as high as it was.

Figure 10 shows photographs of the detached compressor assembly. The compressor motor is in the top foreground and the vapor compressor with its open vapor entry port on top is in the background. Below the compressor-motor platform are the heat exchange coils where condensing vapor outside heated the incoming wastewater inside. Figure 10 also shows the five clogged or partially clogged spray nozzles detached from the spray ring. The spray ring would normally be located just below and coincentric to the heat exchange coils. For other photographs of the unit, including one showing the compressor assembly in place, the reader is referred to reference 1.

There was close inspection of the materials clogging the nozzle and nozzle pipes. In the side where all three nozzles were clogged, the material was dark, apparently a combination of rust, soap, dirt, and some obvious pellet fiber material. Pellets had fallen into the liquor, had passed through the recirculation pump and piping and gotten lodged in the spray ring. On the other side, the two existing nozzles were partially blocked with the light creme colored soapy material. The spray annulus was slowly being coated and becoming smaller: one nozzle was about three-quarters full diameter, the other about one-half full diameter.

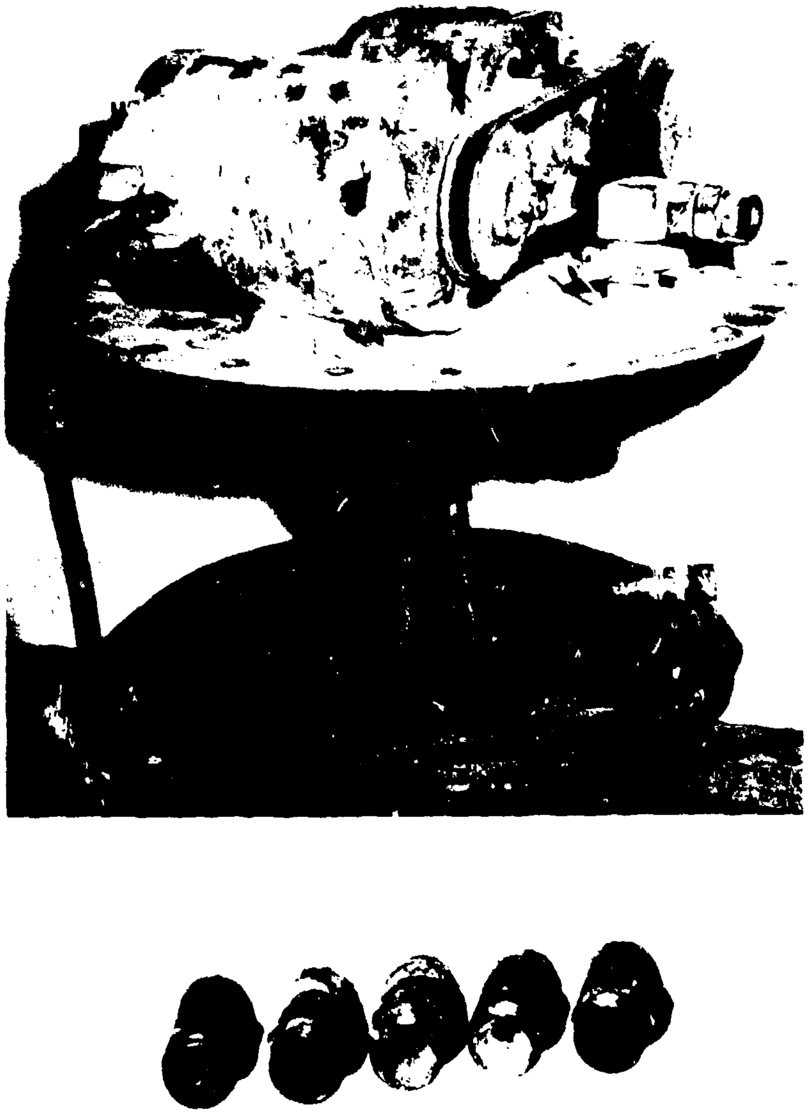

Figure 10. Compressor Assembly and Spray Nozzles after 431 Hours of Operation.

Material clogging nozzles on each side was of different composition giving the impression that clogging of the nozzles had occurred at different times on opposite sides.

Inspection of the nozzle connection having no nozzle showed that connector threads were covered with the soapy material and were not stripped. There was considerable surprise at the missing nozzle considering that the others could only be removed with a wrench. Attempts were made, without success, to obtain the nozzle at the bottom of the processor (by flushing the liquor area with water) or to locate it by feeling with a probe pushed down from the top. Because of the configuration of the VCDU, it was never ascertained whether the missing nozzle was at the bottom or not. It is felt that it was not in the spray ring during evaluation of the VCDU. Production rates averaged 3.4, 3.6, and 3.6 gph for the distilled, salt, and laundry wastewater runs, respectively. Recirculation pressures averaged 12.5, 12.3 and 17.9 psig, respectively.

OPERATION

Operation of the Vapor Compression Distillation Unit required significant attention to monitoring processor parameters and was influenced by several interrelated variables. The philosophy over a period of operating time evolved into two parts. First, the goal of reaching and maintaining 1 inches of mercury for the evaporator vacuum as soon as practicable remained constant. Second, the desire to operate the VCDU with minimum power and/or maximum production justified some operational experimentation. Thus, the nominal storage tank temperature set point of 165°F was not considered inviolate and some short term investigations were made to determine if other storage temperatures were more efficient in conserving energy or increasing production during the laundry water processing phase. Measured storage tank temperatures were, in fact, lower than 165°F due to the location of the temperature probe and temperature gradient in the tank.

Daily runs with the VCDU normally spanned 6 to 7 hours of the working day. The remaining time was taken for wastewater preparation, sample measurement and routine maintenance of the unit. After work the unit was put on standby: pressure and temperature maintained overnight or the weekend, pumps and compressor still.

Confidence in the VCDU was never gained to the point where it was felt it could be left running unattended. Lack of confidence in the integrity of the mechanical components, including tubing, and constant pressure and temperature (rate) changes, made operator attention and rapid response necessary to prevent possible major component failures requiring significant and repeated amounts of downtime. During the laundry wastewater processing run the peristaltic tubing failed six times, two of which were overnight during standby. In the first case, the condensate effluent tube failed and emptied the storage tank, burning up the heater. In the second case, the purge line failed, destroying vacuum and shutting down operation until the next day. The flexible tubing to transfer the liquids or gases may be desirable for a bench scale operation, but not for a full-scale operation such as the VCDU. In general, it was felt the chance of failure during unattended operation was too great to ignore.

Barring other difficulties, 21 inches of evaporator vacuum was normally achieved sometime after 3 running hours, when temperatures lost on standby were regained. Constant water production was rarely reached, varying about one-half gallon per hour or more throughout the run after the first hour or so. The rate would normally increase until 21 inches of evaporator vacuum was reached then vascillate about that operational point.

Temperature fluctuations from external sources affected a run. Overnight temperatures in the building where the VCDU stood determined the starting point (evaporator and condenser vacuums, storage tank temperature) for a days run, and, therefore, indirectly the time to reach steady state. Although the unit is insulated, it was still affected. It took less time to reach desired operating conditions in summer than in winter.

Influent wastewater temperature, its rate and time of addition to the sump, affected a run. Influent wastewater was always cooler than the process water within the unit. Experience showed that the VCDU experienced least shock when wastewater was added to the sump in small increments towards the end of the run (for subsequent heating overnight). This approach was limited however, and competed for the time slot with other activities such as wastewater makeup, sample preparation, and sample measurement. Furthermore, adding the influent slowly (normally over a half-hour period or more) - routing the water from the makeup tank into the "closed" VCDU processor - created logistical and control problems. In practice, there was fresh, relatively cold influent water being added to the sump at least once sometime during the run.

Operating conditions within the VCDU affected a run. Water level in the processor was set; levels in the sump and storage tank varied according to rate of feed, removal, and production. Generally speaking, heat transfer to the processor from the heated storage tank was most efficient when all water levels were the same, since heat transfer through the air was poor. On the other hand, allowing water levels to remain at the process tank level limited the useful volumes of the sump and storage tanks. Furthermore, controlling water levels to this degree was practically impossible. Influent addition to the sump and effluent removal from the storage tank was manually controlled. Water production varied and was a function of VCDU operation.

The water temperature gradient within the storage tank affected a run. The storage tank heater is located towards the bottom of the tank. The temperature measuring probe is just below it and about 40° to the side at the processor tank effluent level. Depending on the water level, temperature of the water varied 20-30°F from bottom to top. Estimating the "average" temperature of the storage tank water was difficult.

Rising hot water caused the heater to cycle on and off frequently, especially if the thermostat was set high. The result was that close control of the heater and accurate measurement of water temperature in the storage tank was not possible. Furthermore, when water in the storage tank was removed to allow room for condensate from the processor to enter, the colder bottom water left first, the hotter top water stayed, the storage tank average temperature increased and the VCDU was thrown off steady state: vacuum and temperatures went out of phase. [illegible] a short time vacuums decreased and the vacuum compressor motor load increased, introducing a possible overload situation and shut-down. Shut-down was an extreme situation and only occurred a couple of times, but nevertheless, had to be considered.

Changes in temperature, whether for external or internal reasons, had a sequential effect on operation. For the most common case, temperature decrease was followed by evaporator and condenser vacuum increase, a recycle pressure decrease, and superheat decrease. The net effect was a drop in production and variance from desired operational conditions.

Heat was added to the VCDU via the storage tank heater and/or the vapor compressor. During evaluation of the VCDU there was considerable preoccupation and testing to determine optimum heater operation since it was the single largest power user. In retrospect, it is felt that the heater needed to be on during start up only until a "reasonable" water production rate was attained. After this point it is felt that the compressor could supply adequate heat to reach the optimum 21 inches evaporator vacuum and maximum production in the minimum time. Having the heater on during this interval did not seem to result in reaching the 21 inches any sooner and in fact, often put the VCDU temperature and pressure rates of change out of phase.

Operator control of VCDU operation then consisted of adding heat by turning on the heater or removing heat by taking off the front cover. This latter operation was necessary because at 21 inches of evaporator vacuum the VCDU would still continue to gain heat from the motor compressor unless the cover was removed.

Considering that VCDU operation was a dynamic process, these were primitive controls for the operator. It was felt that addition of a heater in the processor and a fan or some type of heat exchanger in the VCDU should be investigated. They are necessary for more control of the operation and as a start towards the desirable goal of less operator attention. A heater in the storage tank would still be needed if significant standby periods were anticipated.

No attempts were made to stop foaming. Rather, operation was monitored to record at which point foaming began and how subsequent solids carry-over affected condensate quality. Potential measures which could be investigated to alleviate the foaming problem include use of a low suds detergent, antifoaming agents, and a demister in the evaporator head. The reticulated fibrous pellets used no doubt retarded foam carry-over. A disadvantage of the pellets was that they could drop into the liquor and potentially ruin the recirculation pump or clog the spray ring. The pellets and their supporting wire mesh also impeded flow of vapor up towards the vapor compressor and possibly acted as premature condensing surfaces.

Table 8 gives a breakdown of average power requirements of the VCDU. With the exception of the storage tank heater, the power draw of the pumps and motors did vary with operating conditions, but it is felt that the data in Table 8 represents normal operating power requirements.

Table 8 allows for some interesting observations. If a nominal 6 gallons per hour is produced, the energy use rate becomes 583 watt-hours per gallon when the heater is always on or 250 watt-hours per gallon if the storage tank heater is always off. For 5 gallons per hour this is 700 and 300 watt-hours per gallon, respectively. Actual operation saw closer to 3.6 gallons per hour which gives potential energy use rates of 972 and 417 watt-hours per gallon, respectively. During this time, the heater was on part of the time and actual energy usage was about 665 watt-hours per gallon. Energy usage for water production will not drop to the nominal 300 watt-hours per gallon unless production rates exceed 5 gallons per hour and the water heater is off for most of the time.

TABLE 8. AVERAGE POWER REQUIREMENTS OF THE VAPOR COMPRESSION DISTILLATION UNIT

Item		Watts
Storage tank heater (2000 W)		2000
Condensate transfer and volatile gas purge pump (peristaltic pump)		150
Liquor recirculation pump (centrifugal pump)		750
Vapor compressor motor		600
	TOTAL	3500

MAINTENANCE

Tables 9 and 10 list maintenance difficulties and, for some cases, what was done to overcome them. Table 9 is listed in order of degree of difficulty or nuisance, with the first item the worst case.

Access to the processor head was complicated by the VCDU's outer insulation shell which made it difficult to get to the 36 bolts attaching the processor head to its body. The wrench to remove the bolts was hard to get in place between the insulation and processor body and required considerable contortions. Access to the bolts was made considerably easier by the addition of a hinged access panel containing the upper portion of the processor insulation.

Once access to the processor tank was acquired, the job of getting inside the processor for maintenance or repairs began. The processor head to the VCDU contains 36 bolts around its periphery, which attach it to the processor body. Holes through the head and body which are bridged by the bolts had to be mated exactly. Slight warping of the head-body contact surface allowed outside pressure to enter the processor

TABLE 9. MAINTENANCE PROBLEMS ENCOUNTERED ON THE VAPOR COMPRESSION DISTILLATION UNIT

Difficulty of access into the processor head and limited working space inside
Burn-out and failure of the vapor compressor motor
Sample contamination and liquid level line plugging with rust particles
Failure of the storage heater temperature switch
Evaporation of feed water from the sump
Loss of vacuum from the processor
Slippage and excess wearing of the vapor compressor drive belt
Partial collapse of the recirculation hose
Wearing of transfer tubing
Loosening of electrical terminals in the recirculation pump

TABLE 10. MODIFICATIONS AND/OR CHANGES MADE TO THE VAPOR COMPRESSION DISTILLATION UNIT

Addition of a hinged access door to the process tank for easier access

Addition of copper coils containing cooling water around the vapor compression motor (later removed)

Exchanging the vapor compressor drive pulley with one of smaller diameter (and later re-exchanging with the original)

Removal and rewiring of starter switch externally from vapor compressor motor

Replacement of rubber gasket between processor body and head with 1/8-inch TFE fluorocarbon gasket material

Replacement of vapor compressor V-belt drive with notch-belt drive to motor

Addition of reinforcing wire around the flexible recirculation hose to prevent collapse

Addition of new electrical terminal lugs in the recirculation pump which resisted vibration and subsequent disconnect

Installation of recycle sample and drain valves

Addition of a peristaltic pump to add feed to the sump tank

Addition of eye bolts to the compressor-motor mounting plate

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if top and bottom holes were not perfectly matched. Furthermore, bolts had to be torqued evenly and adequately around the circumference if processor vacuum was to be maintained. Access into and subsequent successful replacement of the processor head was a time consuming, arduous task.

Once inside the processor head, the vapor compressor and vapor compressor motor were exposed. The compressor motor and compressor are united by a drive belt. There were several times when the processor head had to be opened for maintenance and inspection; replacement of a compressor motor, or replacement or tightening of the drive belt. Such instances meant turning the motor tie-down bolts or tightening the belt around the pulley. For both cases a special tool had to be fashioned because of lack of space in the head to torque a bolt or, in the case of belt tightening, operate a lever. Mounting the compressor motor on rails or over elongated slots would have allowed more lattitude in adjusting the motor and torquing the belt.

The vapor compressor motor was the mechanical component giving the most trouble. Difficulty with the motor was not entirely unexpected since the unit had a previous history of compressor motor overheating. At the recommendation of Chemtric, Inc., and before beginning operation at Fort Detrick, copper tubing containing cooling (recirculating) water had been wrapped around the motor in an effort to keep it cooler. Upon the first motor failure it became obvious that the cooling coils were insufficient. The motor was sent back to the shop, rewound, Class H insulation added, and seals and bearings were checked and replaced as necessary.

Before beginning operation with the overhauled motor, a slightly smaller pulley (30 instead of 31 inch diameter) was attached to its shaft to reduce torque and subsequent load to the motor. Subsequent operation with the overhauled motor, its cooling coils and smaller pulley, was very cautious, and the motor amperage load now monitored frequently. The efforts proved largely unsuccessful. Load to the motor did not seem less and measurements varied. Distilled water production fell significantly because the revolutions per minute of the compressor fell due to the smaller pulley diameter. Drive belt slippage was also experienced. After about 30 hours of operation the motor again failed because of excess heat which melted the insulation and destroyed the windings.

After analysis of motor amperage readings and with the benefit of hindsight, it was finally deduced that the starter, unprotected from the surrounding environment as well as the motor, got moist. The centrifugal switch contacts in the starter wouldn't open or opened sluggishly causing the motor to continue to operate slowly with starter windings. Subsequent overloading of the starter and overheating of the motor occurred, melting the insulation and leaving the motor exposed to heat damage.

A recently acquired spare motor was then used in place of the burned out one. This time the centrifugal starter was replaced by an external relay wired to the motor. The cooling coils were removed and the original pulley attached. Subsequent operation at nominal experimental conditions showed a load averaging 6 amperes on the motor, significantly less than its 8.4 amperes motor rating.

Recurring contamination of the produced water occurred from oxidation of the low carbon steel used to build the processor. Rusting was apparent especially in the sump where feed water was quiescent, and to a lesser degree, in the storage tank. Rust particles built up in the liquid level lines attached to them requiring periodic cleaning. During the early operating period, rust particles were evident in the condensate coming from the processor. Later into the testing program and especially as laundry wastewater solids increased, rust particles in condensate samples were not noticed.

The storage tank is actually a continuous flow chamber with process water entering and water for reuse being drawn off. In the previous section about VCDU operation, it was noted that there existed a temperature gradient from bottom of the storage tank to the top, with hot water rising. Such convection currents within the storage tank caused frequent on-off operation of the storage tank heater. Relatively cold condensate entered the bottom of the tank and the heater came on to make up for heat losses. The condensate was quickly heated in the immediate vicinity of the heater and the heater went off according to the thermostat setting. Soon it was replaced with another slug of relatively cold condensate and the heater came on again. The on-off cycling of the heater sometimes as frequent as once per minute, caused premature failure of its temperature switch and it had to be repaired.

More importantly, VCDU operation suffered because operation became more conservative to prevent more such repeated instances. Removal and replacement of a heater requires at least 3 days downtime: about 1 day for storage tank water to cool enough to remove the heater and replace it with a new one; 2 days to fill the storage tank and bring temperature up to operating conditions. This is minimum. If a spare is not available, time for repair or procurement must be added. When the spare is used, a new one must be procured and operation continues knowing there is no backup part. For this case in point and for others such as the compressor motor, lack of reliable or properly designed mechanical components affected operational technique, effectiveness, and control.

The amount of evaporation from the feed tank was surprising. Water balances around the VCDU showed that on the average about 2 gallons of water evaporated over a 6 hour run. Assuming, for discussion, that the VCDU produces its nominal 36 gallons in 6 hours, there is a 95 percent recovery of the available wastewater feed - close to the 96 percent recovery predicted by the fabricator. When production is less, the percent recovery is proportionately less since evaporation remains fairly constant. About 4 gallons evaporated overnight when the VCDU was on standby, and about 16 gallons evaporated during the weekend. Although not a maintenance problem *per se*, water losses from evaporation required additional feed water which in turn affected operation as described in a previous section.

The flat rubber gasket between the processor head and body was found to be unwieldy. It covered the entire body-head contact surface area and holes in it had to match the bolt hole openings. Replacing it successfully on to the contact area was difficult. Pressure leaks would occur once a vacuum was pulled because of some irregularity in the gasket. A one-eighth inch TFE fluorocarbon rubber gasket which molded well into processor body-head contact area proved successful and much easier to install.

Early in the testing program, one reason for erratic production was traced to drive belt slippage between the vapor compressor and motor. After several unsuccessful attempts at tightening the belt and two or three different belt substitutions, the original V-belt drive was replaced with the correct notch-belt drive designed for the compressor motor pulley.

Another problem encountered during early VCDU testing was collapse of the recirculation hose during standby at nights or weekends because of vacuum conditions in the processor. It was difficult to pop the heavy duty hose back to its round form, yet if left in the collapsed, relatively flat configuration, liquor recirculation flow was restricted and condensate production was reduced. Wrapping some reinforcing wire around the hose gave it enough strength and form to maintain its round shape under vacuum conditions.

Purging of volatile gases and transfer of the condensate to the storage tank was accomplished with a peristaltic type tube pump. A regular maintenance task was to regularly pull the tubing through the pump so as to expose different sections of tubing to the pump peristaltic action with time. Despite precautions, wearing of the tubing did occur and holes in the tubing at the pump head resulted in loss of water or vacuum in the processor depending on the tubing affected. Such occurrences were infrequent and with two exceptions, were caught before extensive damage could occur. Nevertheless, the irratic history of tube failure with its potential for causing shut-down and possible heater burn-out or compressor motor overload was a major reason for putting the VCDU in standby status overnight and not continuing wastewater processing unattended. The constant temperature and pressure (rate) changes requiring operator attention was the other reason.

Vibration of the VCDU caused some problem with recirculation pump failure. The pump would stop, but if kicked would start up again. At first it was thought the centrifugal impellers were worn or jammed, but later was traced to electrical terminals that periodically came loose. After two separate instances of such failure, the electrical terminals were replaced with lugs which did not vibrate loose.

Other modifications made for ease of operation and evaluation include addition of recycle sample and drain valves. A drain valve at the bottom of the storage tank was not added but would be desirable as a replacement for the existing pipe to tube connection. A third head on the peristaltic head was added to transfer feed to the sump without opening the VCDU cover. Finally, eye bolts were added to the compressor-motor mounting plate for ease of removal of the entire processing/spray ring assembly.

CONCLUSIONS AND RECOMMENDATIONS

The Vapor Compression Distillation Unit as designed and fabricated is mechanically unsound.

The Vapor Compression Distillation Unit lacks adequate controls for unattended operation. A means for better control of heat addition and removal is desirable. Adding a heater in the process liquor and a fan to the insulation shell are possible areas for further testing. Liquid level controls in the sump and storage tank are also needed.

The Vapor Compression Distillation Unit, like similar operations involving high temperatures and liquid to gas phase changes, is subject to fouling, scaling, volatilization, corroding, and foaming problems. The first three items are functions of wastewater organic content and water hardness. Less corrosion would be experienced with the VCDU if it used high carbon steel for construction of its tanks. Possible antifoaming measures include using a low sudsing detergent similar to the one used in dishwashers, placing a demister in the top portion of the processing tank, using an antifoaming agent with the detergent, or installing baffles in the evaporator portion of the processing tank.

Precluding foaming problems, the Vapor Compression Distillation Unit can produce a laundry water distillate containing a total solids content averaging ≤ 15 mg/l, a chemical oxygen demand averaging ≤ 50 mg/l, and a total organic carbon content averaging ≤ 10 mg/l when the recycle liquor solids content is as high as 5 percent.

The Vapor Compression Distillation Unit can average distillate production of 3.5 gallons per hour. It is felt higher production was not attained because of clogged and missing spray nozzles.

Energy used by the Vapor Compression Distillation Unit to produce a gallon of distillate averaged 667 watt-hours or about 2 cents a gallon at a typical domestic energy cost of 3 cents per kilowatt-hour. This energy figure includes energy used by the 2000 watt heater a portion of the time to bring the unit each day to steady-state, nominal operating conditions. Subtracting the energy required by the heater, the figure becomes 417 watt-hours per gallon or about 1.2 cents cost per gallon at the 3.5 gallon per hour production rate.

A reliable and adequate compressor motor is necessary for successful, continuous operation of the Vapor Compression Distillation Unit. Placement of the compressor motor outside the processor where it is readily accessible and subject to less harsh environmental conditions is highly desirable.

Integration of the condensate transfer and purge line pump motors into the body of the Vapor Compression Distillation Unit is desirable. A lint filter or similar type filter should also be installed in the feed line. Tables 9 and 10 list other mechanical considerations.

Long term evaluation of laundry wastewater treatment was terminated earlier than scheduled because of solids carry-over due to foaming. The reticulated fibrous pellets used to inhibit foaming are unsatisfactory.

It is felt that the Vapor Compression Distillation Unit has the potential of reliably treating laundry wastewater within the quality constraints listed above if its mechanical and material deficiencies are corrected and adequate controls installed. Operation of the VCDU will be ultimately limited from excessive carry-over into the distillate due to foaming and/or large impurities built up as solids or volatile solutes.

LITERATURE CITED

1. Guarino, V.J. and R.A. Bambenek, "Development and Testing of a Wastewater Recycler and Heater," EPA Environmental Protection Technology Series 600/2-76-289 (December 1976).

2. Guarino, V.J. and R.A. Bambenek, "Development and Testing of a Wastewater Recycler and Heater," Interim Report NASA Brief, EPA Contract No. 68-03-0346 (1975).

3. "Water Quality Engineering Special Study No. 99-003-71: Evaluation of the Water Processing Element, Medical Unit, Self-Contained, Transportable (MUST)," US Army Environmental Hygiene Agency, Aberdeen, MD (September 1970-February 1971).

4. Gollan, A.Z., K.J. McNulty, R.L. Goldsmith, M.H. Kleper and D.C. Grant, "Evaluation of Membrane Separation Processes, Carbon Adsorption, and Ozonation for Treatment of MUST Hospital Wastes," Final Report Contract No. DAMD 17-74-C-4066, US Army Medical Research and Development Command (August 1976).

5. "Standard Methods for the Examination of Water and Wastewater," Fourteenth Edition, American Public Health Association, NY (1975).

6. Kirka, A.M. and M.J. Carter, "Micro Semi-Automated Analysis of Surface Waters and Wastewaters for Chemical Oxygen Demand," Anal. Chem., 47(8):1397-1402 (July 1975).

LIST OF ABBREVIATIONS

COD	chemical oxygen demand
°F	degrees Fahrenheit
gal	gallons
gph	gallons per hour
hr	hour
inches Hg	inches of mercury
MUST	Medical Unit, Self Contained, Transportable
mg/l	milligrams per liter
NTU	nephelometric turbidity units
psig	pounds per square inch, gage
TOC	total organic carbon
VCDU	vapor compression distillation unit
μmho/cm	micromhos per centimeter

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