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THE DEVELOPMENT OF A HYDROPERM™ MICROFILTRATION SYSTEM FOR THE TREATMENT OF "MUST" HOSPITAL WASTEWATER EFFLUENTS

FINAL REPORT

By

T. R. SUNDARAM
and
J. E. SANTO

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The results of a laboratory study to investigate the feasibility of utilizing Hydroperm™ filtration to treat the waste from the MUST hospital complex are presented. Hydroperm filtration utilizes rugged, thick-walled thermoplastic tubes of controlled microporosity to achieve almost total removal of suspended solids and significant removal of dissolved solids from waste streams even at relatively low filtration pressures (typically 5 psi or 0.35 kg/cm²).

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20. Abstract (continued)

A unique feature of the tubes is that their pore structure can be matched to the size and nature of the suspended solids in different waste streams so as to obtain optimum filtration performance under a variety of test conditions. This optimization procedure is illustrated in the present study for MUST wastes by performing controlled laboratory tests with tubes of different pore structures. It is shown that Hydroperm filtration yields very good results even at extreme conditions of feed pH (down to 2.0) and temperature (down to 4.4°C), without experiencing fouling or clogging; such extreme feed-waste conditions are likely to be encountered during the operation of the MUST hospital complex. The results are compared, where possible, with available results from earlier tests on MUST wastes using ultrafiltration membranes. It is shown that the flux levels and rejection characteristics of Hydroperm tubes are superior to those of ultrafiltration membranes under comparable operating conditions.

FOREWORD

The present study was conducted by HYDRONAUTICS, Incorporated under a contract from the U. S. Army Medical Bioengineering Research and Development Laboratory. Technical monitoring for the program was provided by Capt. Walter Lambert and Capt. Barry Peterman of MBRDL.

The authors express thanks to their colleague, Mr. Ronald E. Watson, who conducted the tests described in the present paper, and meticulously recorded the results.

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I. SUMMARY

The results of a laboratory study to investigate the feasibility of utilizing Hydroperm filtration to treat the waste from the MUST hospital complex are presented. Hydroperm filtration utilizes rugged, thick-walled thermoplastic tubes of controlled microporosity to achieve almost total removal of suspended solids and significant removal of dissolved solids from waste streams even at relatively low filtration pressures (typically 5 psi or 0.35 kg/cm^2). A unique feature of the tubes is that their pore structure can be matched to the size and nature of the suspended solids in different waste streams so as to obtain optimum filtration performance under a variety of test conditions. This optimization procedure is illustrated in the present study for MUST wastes by performing controlled laboratory tests with tubes of different pore structures. It is shown that Hydroperm filtration yields very good results even at extreme conditions of feed pH (down to 2.0) and temperature (down to 4.4°C), without experiencing fouling or clogging; such extreme feed-waste conditions are likely to be encountered during the operation of the MUST hospital complex. The results are compared, where possible, with available results from earlier tests on MUST wastes using ultrafiltration membranes. It is shown that the flux levels and rejection characteristics of Hydroperm tubes are superior to those of ultrafiltration membranes under comparable operating conditions.

II. INTRODUCTION

The U. S. Army's mobile MUST medical complex, which is presently under development, is designed for rapid establishment and disestablishment. An integral part of the MUST system is a Water and Wastewater Management Subsystem (WWMS), which is required to treat all the wastewater (including toxic and contaminated wastes) that is generated within the complex, with the treatment being of sufficient quality for either discharge or water reuse. Several treatment unit operations have already been studied extensively[1] in terms of their ability, in various combinations, to treat wastewaters from operating rooms, x-ray labs, laundries, showers, kitchen and various other sources. Ultrafiltration was one of the unit operations originally considered (in part, as a pretreatment step for Reverse Osmosis). The present report contains the results of a study conducted by HYDRONAUTICS, Incorporated, under the sponsorship of the U. S. Army Medical Bioengineering Research and Development Laboratory, to examine the feasibility of using HYDROPERM™ microfiltration* as an alternative to ultrafiltration.

The detailed objectives of the study are set forth in Section III of the report. A brief description of the features of Hydroperm filtration is given in Section IV, including a discussion of the similarities and differences between the present technique and membrane ultrafiltration. The test results are given in Section V, including an analysis of the results. Some performance and economic comparisons with ultrafiltration are also given in this section. Finally, some concluding remarks and recommendations are given in Section VI.

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*HYDROPERM™ is the proprietary name applied to plastic filtration tubes that have been developed by HYDRONAUTICS, Incorporated.

III. OBJECTIVES OF THE STUDY

The novel method of filtration described in the present report is based on cross-flow filtration with thick-walled, porous plastic tubes, called Hydroperm (see Figure 1 for a schematic of the process). These tubes, which can be made from a wide variety of extrudable thermoplastics by a proprietary process, have several unique characteristics such as controlled microporosity and ruggedness. The characteristics of the tubes will be described in detail in Section IV; suffice it to state here that the tubes had previously been tested extensively with a variety of wastes, including laundry wastes[2,3]. Typical filtrate flux results from two prior tests are shown in Figures 2 and 3, with the former being for a test at a high circulating-flow temperature, namely, 70°C. It can be seen from the figures that, over the nearly six-hundred hours of the test duration, average filtrate fluxes as high as 70 and 100 gallons/ft^2-day (2856 and 4080 liters/m^2-day), respectively, were maintained at the two feed temperatures. The high flux levels are maintained by cleaning the tubes after every approximately one-hundred hours of continuous operation by circulating through them, for ten minutes, a mild phosphoric acid solution. Analysis of the feed and permeate revealed one-hundred percent rejection of suspended solids and eighty-five percent rejection of COD.

The present study was undertaken as a result of a proposal made, on the strength of the results mentioned above, to investigate the feasibility of utilizing Hydroperm filtration in the MUST system in place of ultrafiltration. Several advantages were perceived for the present filtration technique compared to ultrafiltration.

Since the thermoplastic tubes are rugged and inert, they are not susceptible to fouling or clogging; moreover, they can withstand, without any loss in performance, a wide range of variations in circulating flow pH, and temperature. In contrast, ultrafiltration membranes are more susceptible to damage by pH extremes, and nonionic surfactants have been identified as "bad actors" in causing membrane fouling[1]. Also the Hydroperm filtration technique is quite compact and requires considerably less power to operate than UF.

Thus the specific objective of the present study was not merely to test the MUST wastes with the tubes, but to do so under rather extreme conditions of circulating feed pH and temperature. The composite test fluid was also chosen, based on the recommendation of the Bioengineering Laboratory, not only

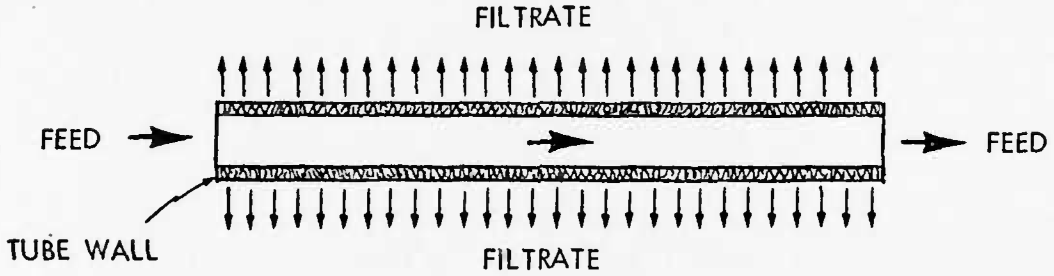

FIGURE 1 - CROSSFLOW FILTRATION SCHEMATIC

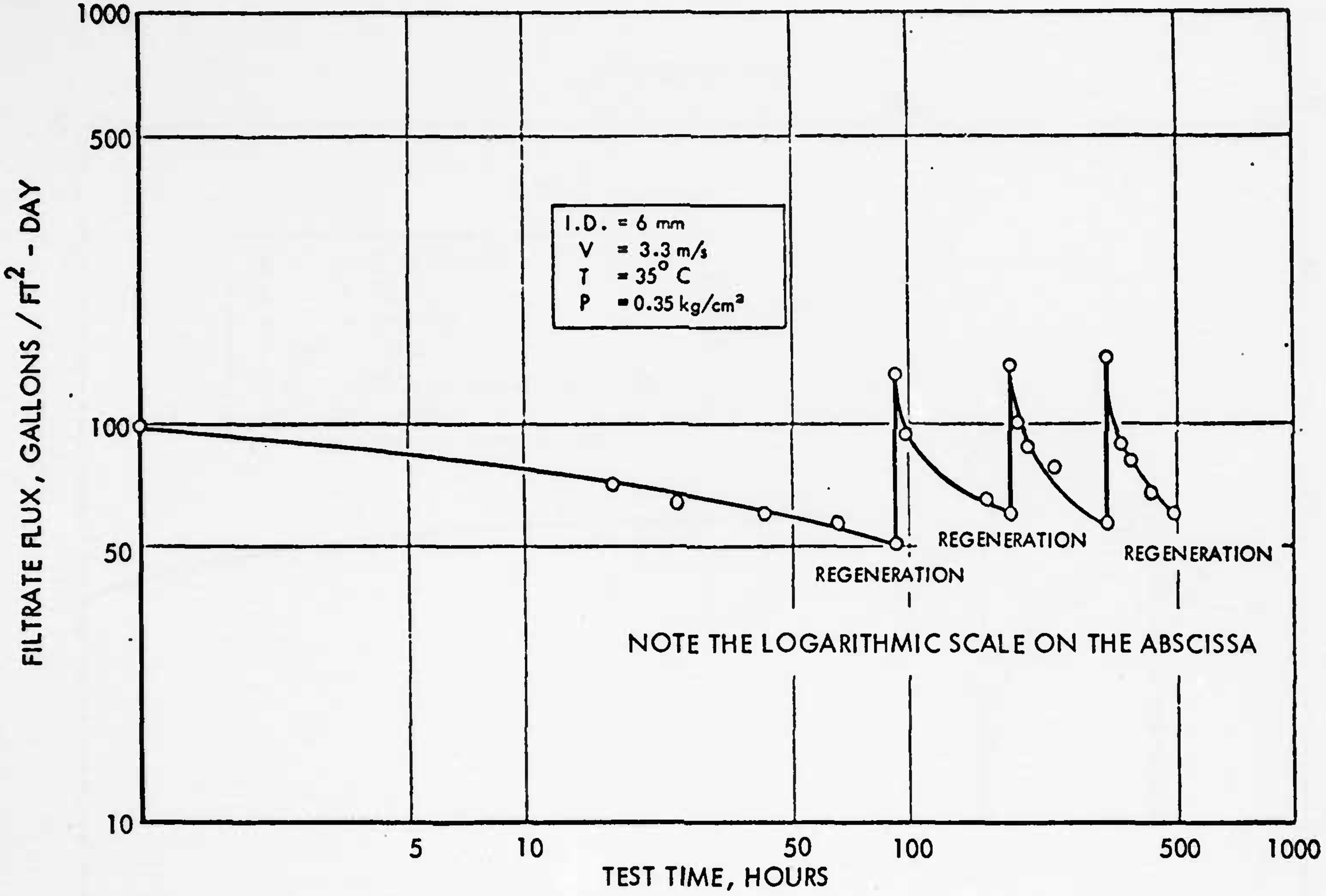

FIGURE 2 - TREATMENT OF LAUNDRY WASTES - CONTINUOUS MODE OPERATION (WASTES FROM THE NAVAL ACADEMY LAUNDRY, ANNAPOLIS, MD.)

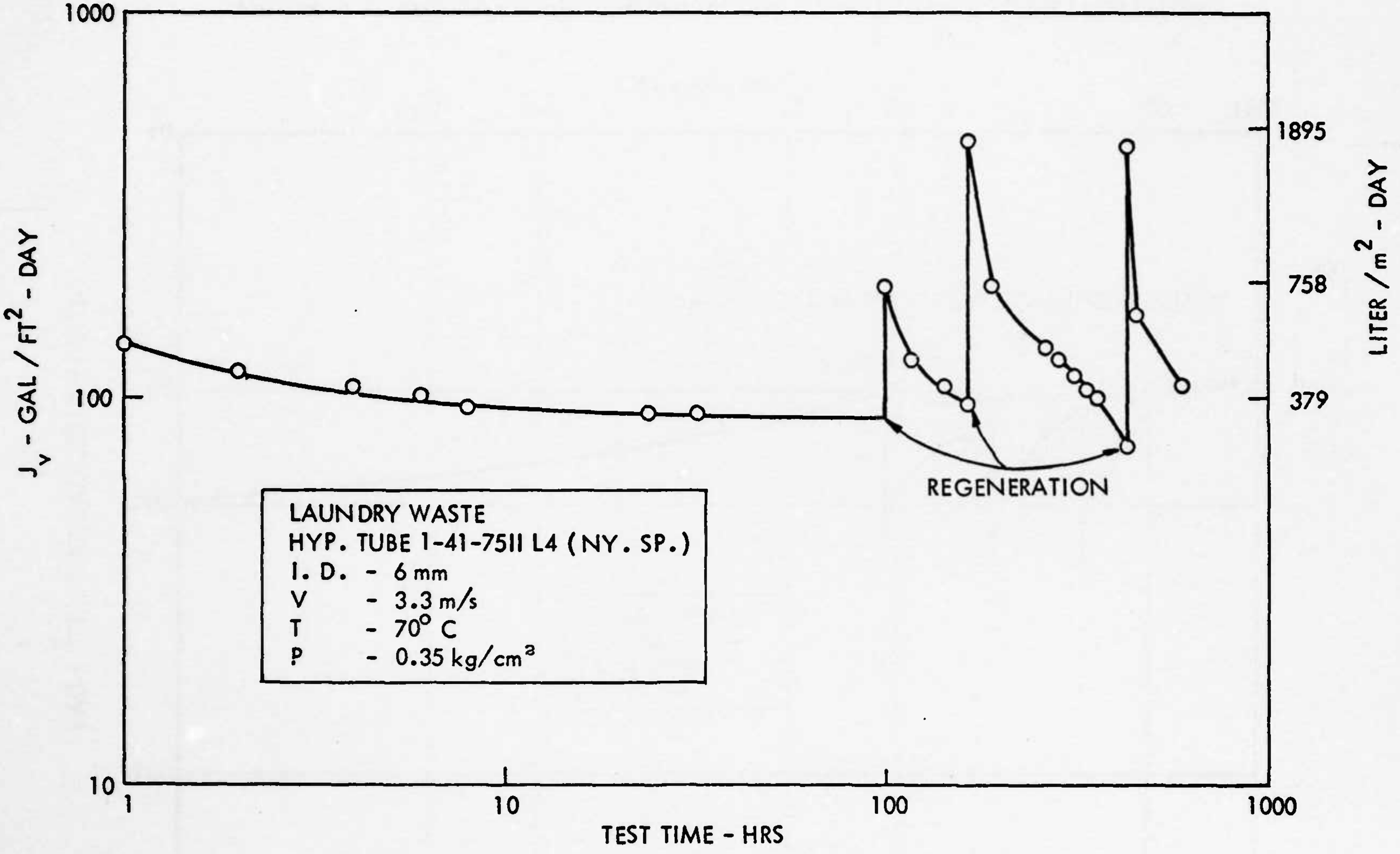

FIGURE 3 - HIGH TEMPERATURE LAUNDRY WASTE (U. S. NAVAL ACADEMY, ANNAPOLIS, MD.) FILTRATION TEST

for the purpose of employing a typical representative sample, but also from the point of view of emphasizing those constituents which cause fouling of UF membranes. The actual "recipe" used is shown in Table 1, and is analogous to that used in Reference 1 (p. 262) for the prior tests on MUST composite wastes using ultrafiltration membranes.

The test program consisted of initial tests with relatively short (~45 cm long), single Hydroperm tubes at two (extreme) values of temperature and pH. Tubes of two different pore structures were used in the tests since, as will be described in Section IV, the structure of the tubes can be optimized with respect to any specific wastewater under consideration. Flux decline and cleaning procedures for flux restoration were investigated during these tests, which were each approximately 50 hours in duration. After the initial tests, longer term tests were undertaken with a small filtration module.

The final objective of the program was to fabricate, and deliver to the Army, filtration modules that could be used for on-site testing in the MUST pilot plant.

	Constituent	Conc. (mg/l unless otherwise stated)
1.	Detergent Type I* (FSN 7930-634-3935)	221.0
2.	Sparklene (Fisher Chem.)	202.0
3.	Haema-Sol Detergent (nonsudsing)	197.0
4.	Hair	114.0
5.	Shower/Laboratory Cleaner Formula SBS-52**	50.5
6.	Hand Soap (Lava)	34.8
7.	Scouring Powder	22.1
8.	Talc	10.1
9.	Soil (kaolinite)	9.6
10.	Silver Chloride	7.2
11.	Hair oil	75.8
12.	Hair gel	18.7
13.	Vegetable oil	17.6
14.	Grease (Lard)	11.7
15.	Toothpaste	18.7
16.	Hair Shampoo	2.5
17.	Suspended Solids (Dog Food)	140.0
18.	Blood (Animal)	183 µl/l
19.	1½% Agar	70 µl/l
20.	Betadine	189.0
21.	Wescodyne	35.6

Table 1

MUST Hospital Composite Waste—Substances Expected to Foul UF or RO Membranes†

* Available from GSA Sources as a Stock Item.

** Available from Carey Machinery and Supply, Baltimore, Md.

† "Recipe" provided by Dr. W. Cowen and Capt. W. Lambert of the U. S. Army Medical Bioengineering Research and Development Laboratory.

IV. FEATURES OF HYDROPERM FILTRATION

Since detailed descriptions of Hydroperm tubes have been given elsewhere[2-6], they need not be repeated here; rather, only a brief summary will be given. The filtration characteristics of the tubes combine both the "in-depth" filtration aspects of multimedia filters and the "thin-skinned" aspects of membrane ultrafilters. For example, while the removal of micron-sized particles and colloids is often impossible with conventional through-flow filters, these tubes are capable of removing such particles. On the other hand, in a manner similar to multimedia filters, the tubes will allow the smaller particles and colloids in the waste streams to actually penetrate into their wall matrix. It should be noted that the pore structure of the tubes differs from those of membrane ultrafilters in that the pore sizes of the former are of the order of several microns with the "length" of the pores being many times their diameters. A schematic view of cross-flow filtration through the tubes is shown in Figure 1. The feed flow is through the inside of the tubes at relatively low pressure (2 to 10 psi*) and the filtrate permeation occurs through the relatively thick (~1 mm) tube walls.

Pore size distributions of three typical tubes are shown in Figure 4. Tube I has a rather "flat" distribution with the pores ranging in size from 2 microns to 10 microns. On the other hand, Tube III has a "peaked" distribution, with most of the pores being in the 2-micron range. Tube II has an intermediate distribution. Other properties of the tubes can also be varied in a controlled manner. For example, in Figure 4 Tubes I and III have a porosity of 65%, while Tube II has an 80% porosity. The tubes can also be made from many thermoplastics such as Polyethylene, Nylon, PVC and Noryl. Tubes I and II in Figure 4 are made from Polyethylene, while Tube III is made from Nylon.

Two views of the pore structure of a typical Hydroperm tube are shown in Figure 5. These photographs were taken with the aid of a Scanning Electron Microscope and are of a transverse section of the tubes; the view in (a) has a magnification factor of two hundred, while that in (b) has a magnification factor of one thousand. The open-cell, reticulated nature of the pore structure can be appreciated from these photographs. These features are of crucial importance in determining the performance of a given tube when it is used with a specific effluent, as can be seen by considering a relatively simple model for the filtration process.

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* 1 psi = 0.07031 kg/cm^2

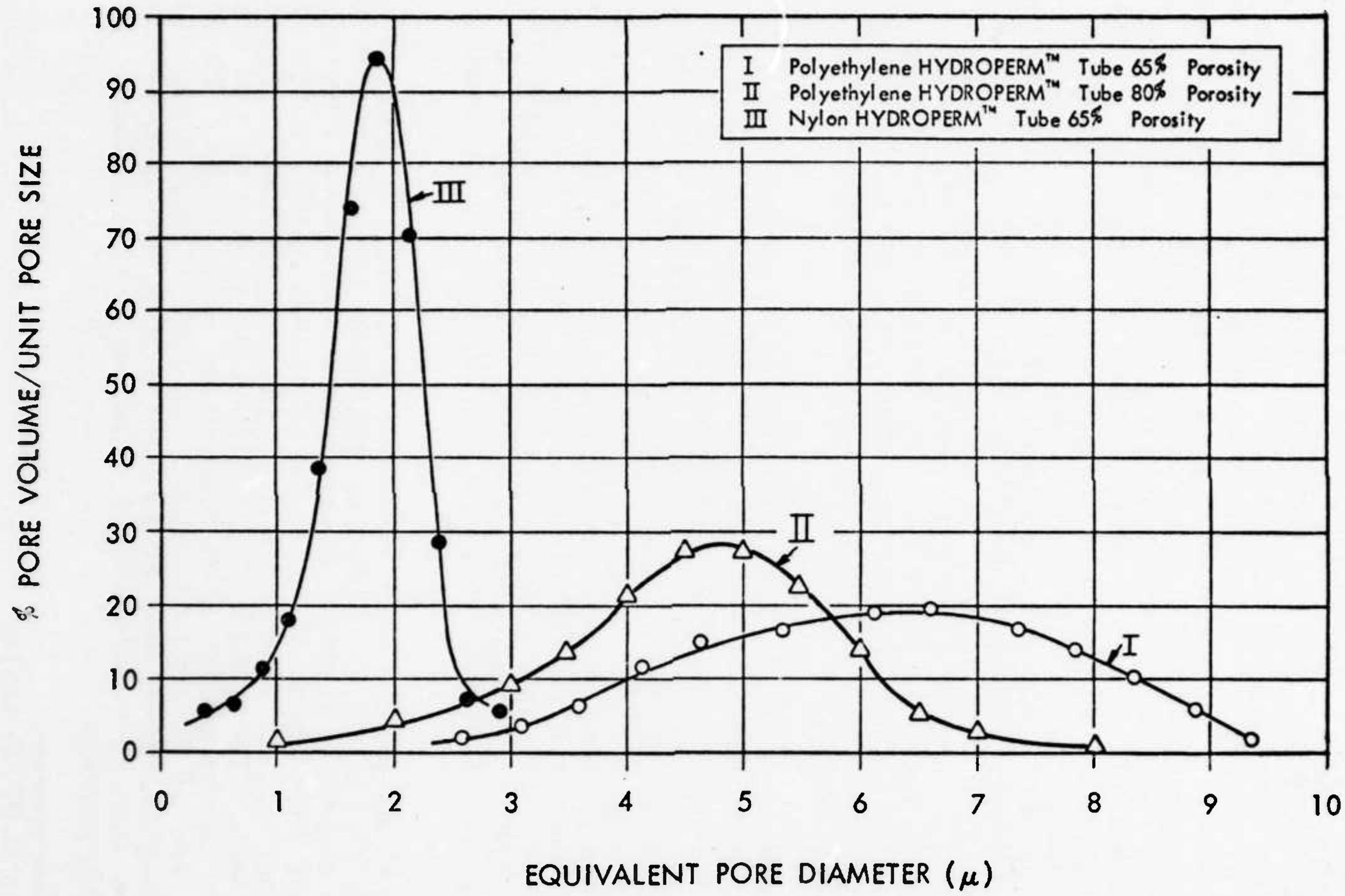
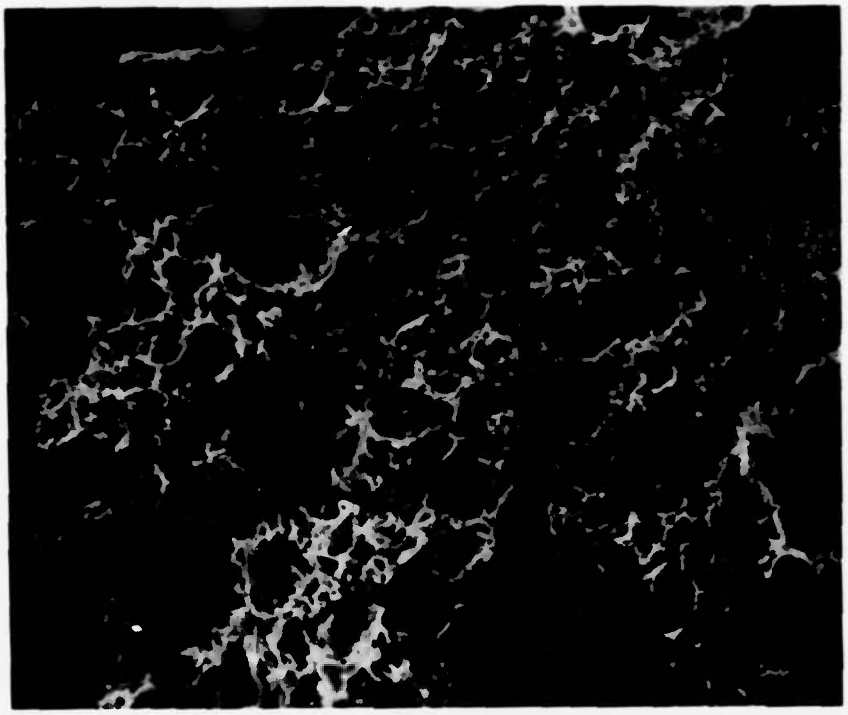
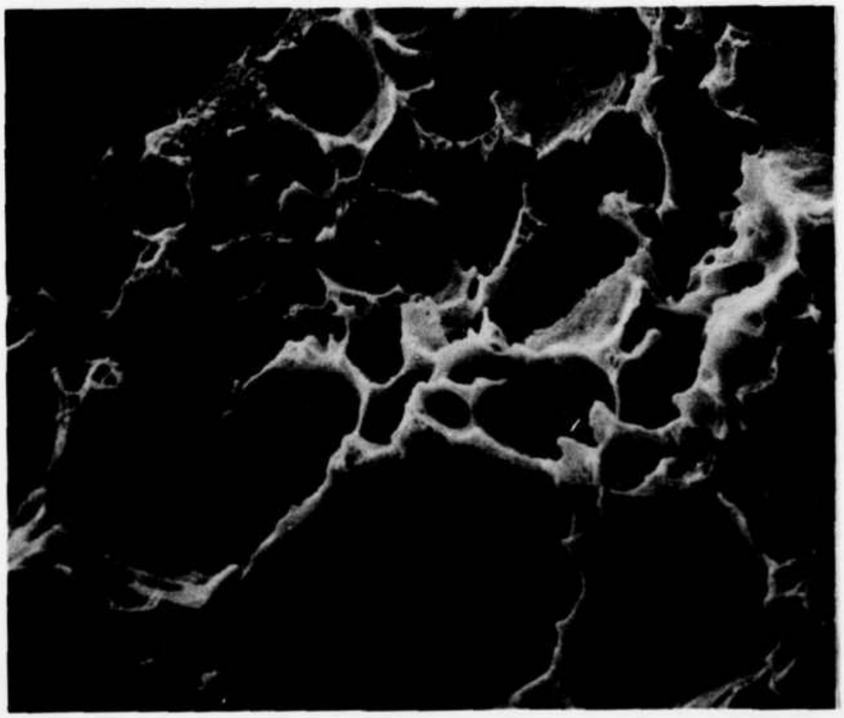


FIGURE 4 - TYPICAL PORE SIZE DISTRIBUTION OF HYDROPERM™ TUBES



a) S.E.M. 200X



b) S.E.M. 1000X

FIGURE 5 - ELECTRON MICROPHOTOGRAPHS OF HYDROPERM TUBE PORE STRUCTURE - TRANSVERSE SECTION

In general, any effluent from which suspended solids removal is desired will contain a wide range of particulates, ranging in diameter from several microns to colloidal dimensions. When such effluents are circulated through the inside of a tubular filter such as Hydroperm, the solids particles will be slowly driven, with the permeating flow, toward the wall. Thus, the concentration of the particles in regions close to the wall will steadily increase, this tendency being delimited only by the turbulent diffusion of the particles from regions of high concentration to those of lower concentration (that is, away from the walls toward the center of the tube).

The turbulent diffusion (which tends to decrease the particle concentration near the wall) is dependent on the shear stress that is exerted on the walls by the cross-flow circulation, and, hence, its velocity. On the other hand, the permeation rate (which tends to increase the particle concentration near the wall) depends on the pressure differential across the filter surface (Poiseuille's law) as well as the pore structure of the tubes (Darcy's law)[7]. A quasi-steady state profile of the concentration of the particles will be established near the wall, when the two opposing tendencies mentioned above exactly balance each other. The resulting "particle polarization" in this case is entirely analogous[8] to the "concentration polarization" of solutes that occurs close to walls of ultrafiltration and reverse-osmosis membranes.

Because of the in-depth filtration characteristics of the tubes, other factors also come into play. Specifically, particles which are smaller than the largest pore size of the tubes can actually enter the wall matrix, while particles which are larger than all of the pores in the tubes will be retained at the walls. This feature is illustrated schematically in Figure 6 which shows the particle-size distribution in the feed plotted on the same scale as the pore-size distribution of the filtration tubes. The shaded region represents the particles which are smaller than the largest pore size and can thus enter the wall matrix. These particles will ultimately become entrapped within the wall of the tube because of the irregular and tortuous nature of the pores. Thus as filtration proceeds, the pore structure of the tube as well as its permeability will undergo a gradual change due to the clogging of some of the pores by the intruder particles. However, the tendency of new particles to enter the tube matrix will decrease as a filter cake forms on the walls due to the particle polarization described earlier. Clearly, both the change in the pore structure and the properties of the filter cake will be strongly influenced by the shaded overlap region in Figure 6 and, consequently, so will be the filtration performance.

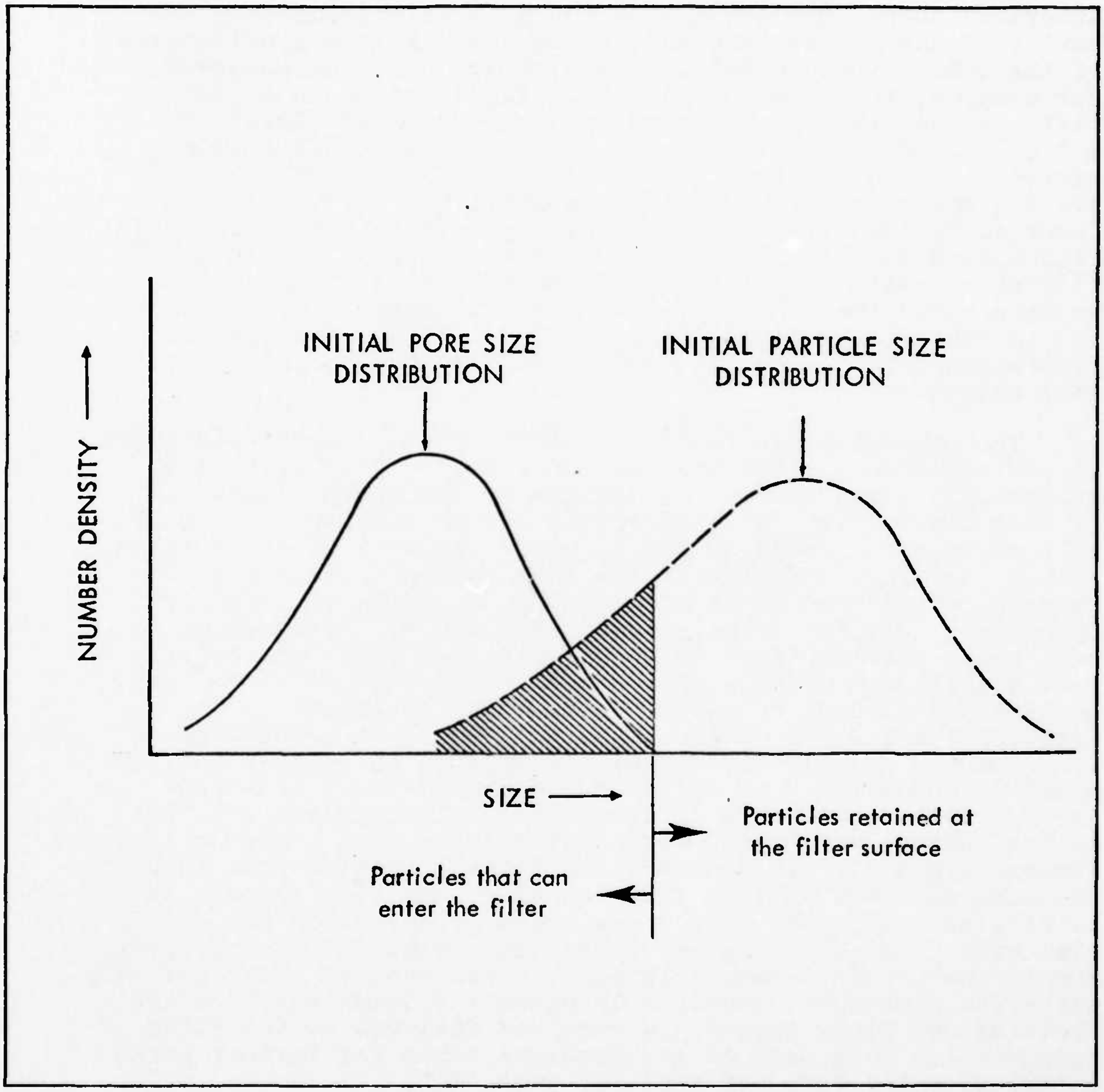


FIGURE 6 - SCHEMATIC OF THE FILTER CLOGGING PHENOMENA

Because of the hybrid nature of the filtration process described above, involving both the ultrafiltration-like behavior of the filter cake and the in-depth filtration features of the tubes, some surprising results are often encountered. For example, the tubes display a fairly large (as high as sixty percent in some applications) rejection of dissolved solids, a rather surprising result in view of their initial, micron-sized pore structure. While this feature of the filtration may be attributed to the formation of a dynamic "membrane", the effect has to be viewed not in terms of a thin film formed in situ, but in terms of a change in the in-depth filtration characteristics of the tubes. In many applications we have noted that the filtration characteristics of the tubes can be improved by impregnating various filter aids such as diatomaceous earth, kaolite, and activated carbon into their wall matrix.

The practical manifestation of the factors mentioned above is reflected in the behavior of the filtrate flux with time. In general, a characteristic feature of Hydroperm filtration is that the filtrate flux decreases within the first few hours of operation to a value which is about one-half of the initial value. However, thenceforth the flux remains essentially unchanged, often even after several tens of hours of continuous operation; see, for example, Figures 2 and 3. Although in most cases the "plateau" values of the fluxes are themselves well within economically acceptable limits, the situation can be improved further by cleaning the tubes periodically by flushing the insides of the tubes with a cleaning solution. The cleaning solution is circulated through the tubes, for ten minutes, under the same operating conditions that are used during filtration*. This procedure not only restores the flux to the initial value, but also restores the flux behavior (see Figures 2 and 3). In contrast, in ultrafiltration even though cleaning restores initial flux behavior, the flux rapidly declines, so that after only a few hours of operation the beneficial effects of cleaning are lost. The relative ease of cleaning in the present example is also in contrast to the relatively elaborate procedures required in ultrafiltration where several cleaning and rinse cycles are required followed by insertion of sponge balls into each of the membrane tubes for further mechanical cleaning (see Reference 1, page 283).

From the discussion given above, it is clear that the filtration performance is influenced not only by such factors as the filtration pressure, circulating flow velocity, temperature (which changes the fluid viscosity, and, hence, by Darcy's[7] law, the permeation rate), but also by the pore-size distribution,

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*Based on our previous experiences, after the suitable cleaner has been selected, only about 10 minutes cleaning is necessary to restore the flux near to its initial value.

pore structure and the particle-size distribution in the wastes. The particle polarization that occurs near the walls of the tube is found to be beneficial for filtration performance provided that it is controlled by a proper choice of the operating pressure and circulating-flow velocity.

As mentioned earlier, the unique feature of the tubes is that their pore characteristics can be "tailored" (that is, controlled in a systematic manner) to suite the characteristics of a given waste effluent; this "tailoring" or optimization procedure has been illustrated in References 2, 5 and 6.

In the test results given in the next section, it will be seen that when two tubes of different pore structures are used to filter MUST wastewaters, they yield significantly different results even when they are tested under identical flow conditions.

V. TEST RESULTS AND ANALYSES

The experiments described in the present report consisted of tests with mostly single Hydroperm tubes, though tests with small modules containing a "bundle" of several tubes have also been performed. The inside diameters of the single tubes tested were either 6 mm or 9 mm, and they had a length of about 46 cm so that their filtration-surface area ranged from about 86 cm^2 (13 in.^{2}) to 130 cm^2 (20 in.^{2}). A schematic view of a typical single-tube test loop is shown in Figure 7. As indicated on the figure, the loops contain a feed reservoir (~3 gallons, 11.4ℓ capacity), a circulating pump, a flow meter, pressure gauges to measure pressure drops over the length of the tubing being tested and appropriate valving. Provision also exists for controlling the circulating fluid temperature.

Tube Optimization Tests

As mentioned earlier, one of the principal objectives of the present study was to test Hydroperm tubes with MUST wastes under extreme conditions of pH and temperature, and to optimize the pore structure of the tubes for maximum performance. The optimization is carried out through laboratory tests (each usually of 50 hours duration) on single tubes. In the first test series tubes of two different materials (Nylon and Polyethylene) and two different internal diameters were used. The test matrix was also composed of two values of the pH (nominally 2 and 8) and two values of the operating temperature (nominally 4°C and 50°C. In all of the tests, the average filtration pressure was 5 psi and the circulating feed velocity was 2.1m/sec (7ft/sec). The composition of the synthetic waste used is shown in Table 1.

The results from the low temperature, high pH test are shown in Figure 8. The 6 mm-internal diameter, Nylon tube tested had the pore-size distribution shown as III in Figure 4. The initial flux of the tube was about 60 gallons/ft^2-day (2,450 liters/m^2-day) and the flux declined to about 12 gallons/ft^2-day (480 liters/m^2-day) after fifty hours of continuous operation. The characteristic shape of the flux-time curve, alluded to earlier, can be seen; namely, the initial relatively-rapid decline, followed by a nearly-constant plateau.

After fifty hours of operation, the tube was cleaned by circulating through it, for ten minutes, a weak solution of phosphoric acid (available under the commercial name of Servac). It can be seen from the figure that the cleaning restored the flux to about 30 gallons/ft^2-day (1,200 liters/m^2-day); more importantly, after another seventy hours of operation, the flux again had leveled off at about 12 gallons/ft^2-day (489 ℓ/m^2-day).

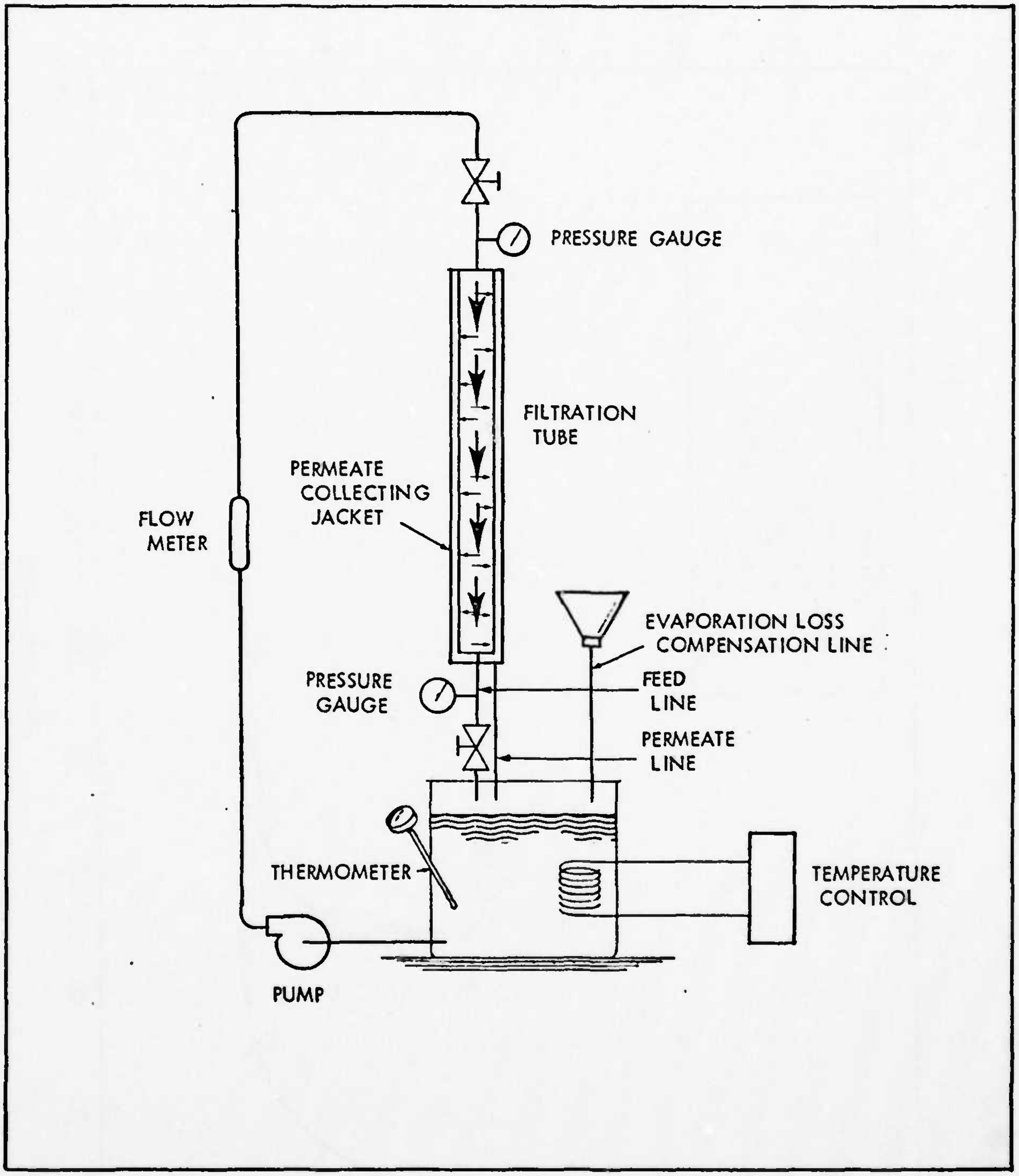

FIGURE 7 - SCHEMATIC OF A HYDROPERM FILTRATION TEST LOOP

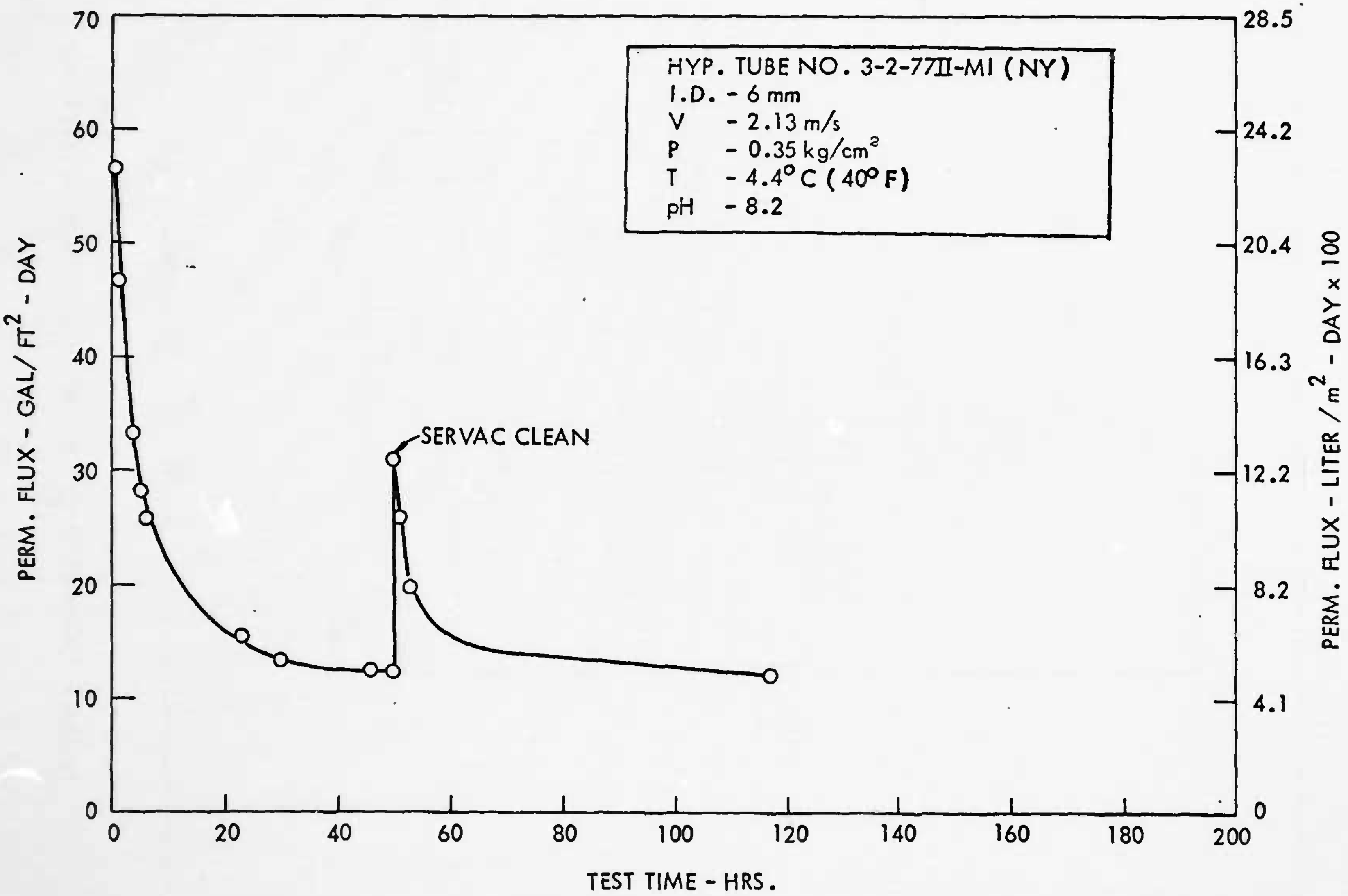

FIGURE 8 - OPTIMIZATION TEST AT LOW TEMPERATURE AND MODERATE pH - TEST NO. 1

Thus, this experiment demonstrates that a fairly simple cleaning procedure can be effective in maintaining significant flux levels.

Figure 9 shows the results of a test conducted under temperature, pH and operating conditions identical to those for the test described above, but with a different tube having a somewhat tighter pore structure and an internal diameter of 9 mm. It can be seen that the fluxes for this tube are generally lower. This test reveals that cleaning, for ten minutes, with a hypochlorite solution is as effective as cleaning with Servac.

Figure 10 shows the results of a test with a 9 mm Nylon tube, but with essentially the same pore structure as that in Test 1. It can be seen that the flux levels in this test were comparable to those in Test 1. In this case, cleaning with a hypochlorite solution, after twenty-six hours of continuous operation, did restore the initial flux; however, the flux decline immediately following cleaning was fairly rapid, so that the beneficial effects of cleaning were lost after about three hours.

The next series of tests were done at a temperature of about 49°C (120°F) and a pH of about 8. Results of a test with a 6-mm I.D. tube with the pore structure III shown in Figure 4 are given in Figure 11. It can be seen from the figure that after fifty hours of operation, the "plateau" value of the flux was about 800 liters/m^2-day (20 gallons/ft^2-day). Cleaning with Servac again restored the flux; however, the subsequent plateau value of the flux (after nearly seventy hours of unattended operation during a long weekend) was found to be more than double the value before cleaning. It was conjectured that this effect may be due to waste degradation caused by constant recirculation in the relatively small test loop, and, hence, the circulating feed was replaced by a fresh batch. While the flux did decline after feed replacement, the value was still nearly equal to 1600 liters/m^2-day (40 gallons/ft^2-day) after twenty-two hours of further operation. Indeed Servac cleaning at this point increased the average flux to about 2000 liters/m^2-day (50 gallons/ft^2-day). Further cycles of feed change and cleaning are also depicted in the figure. In all, after 210 hours of operation, the flux was 1200 liters/m^2-day (30 gallons/ft^2-day).

A replication of the test shown in Figure 11 is given in Figure 12. These two tests, though for nearly identical test conditions and with tubes of identical pore structure, were conducted several days apart and with different batches of wastes as well as tubes. The objective of the second test was to assess the degree of repeatability that can be achieved during the optimization tests in a relatively small test loop. It can be seen that in spite of the slight difference in pH, the flux behavior in the two tests is quite similar.

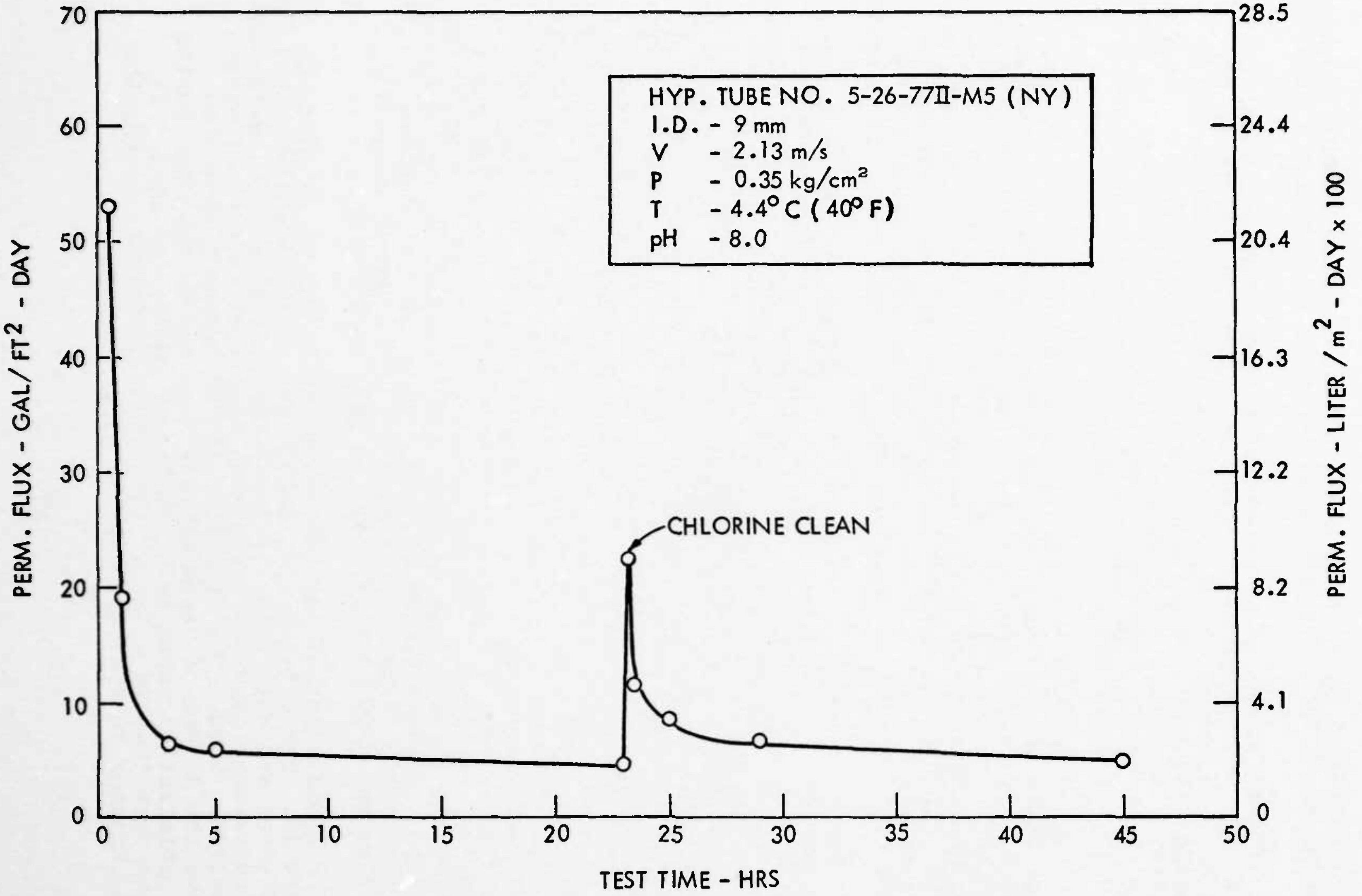

FIGURE 9 - OPTIMIZATION TEST AT LOW TEMPERATURE AND MODERATE pH - TEST NO. 2

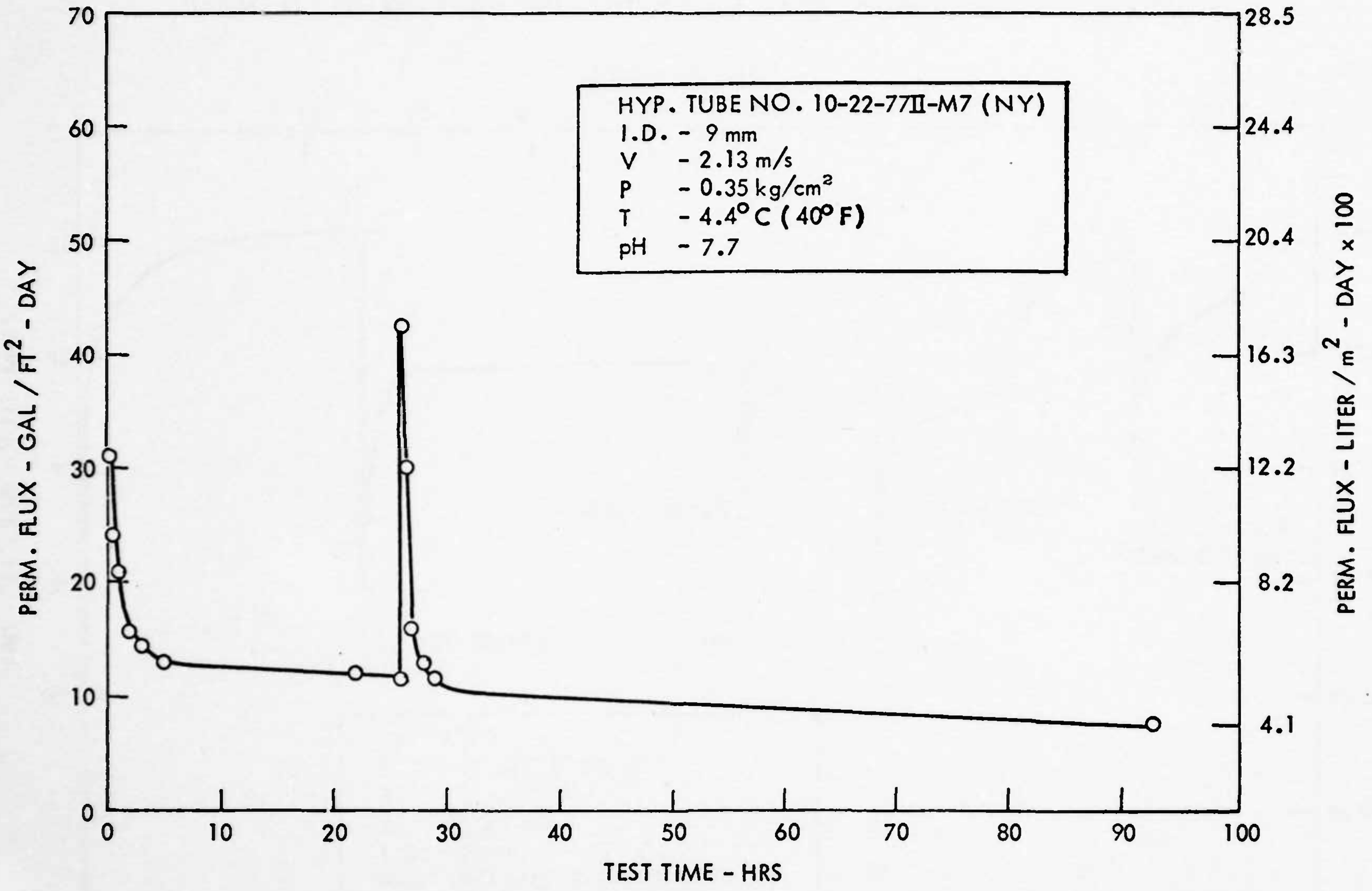

FIGURE 10 - OPTIMIZATION TEST AT LOW TEMPERATURE AND MODERATE pH - TEST NO. 3

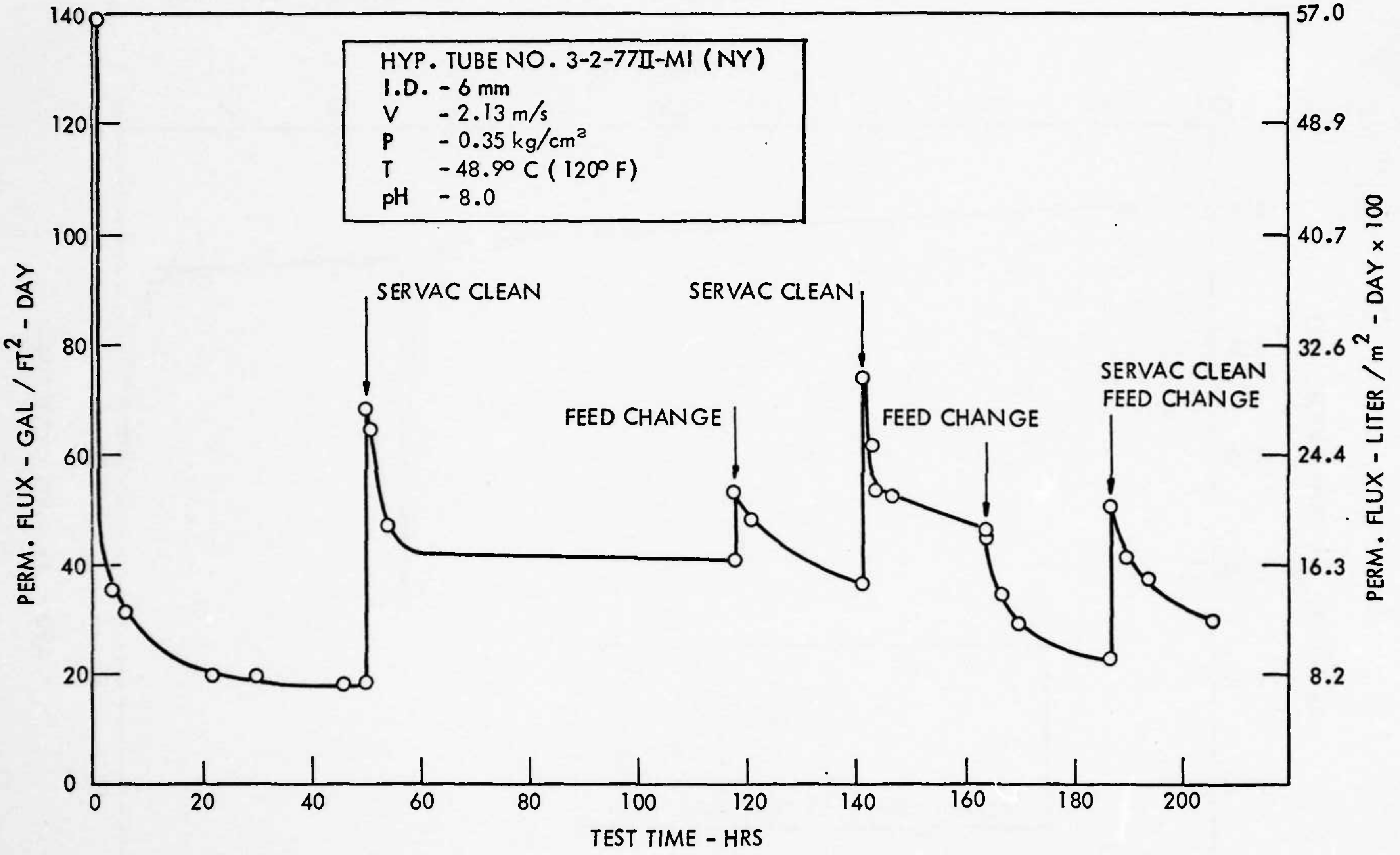

FIGURE 11 - OPTIMIZATION TEST AT HIGH TEMPERATURE AND MODERATE pH - TEST NO. 4

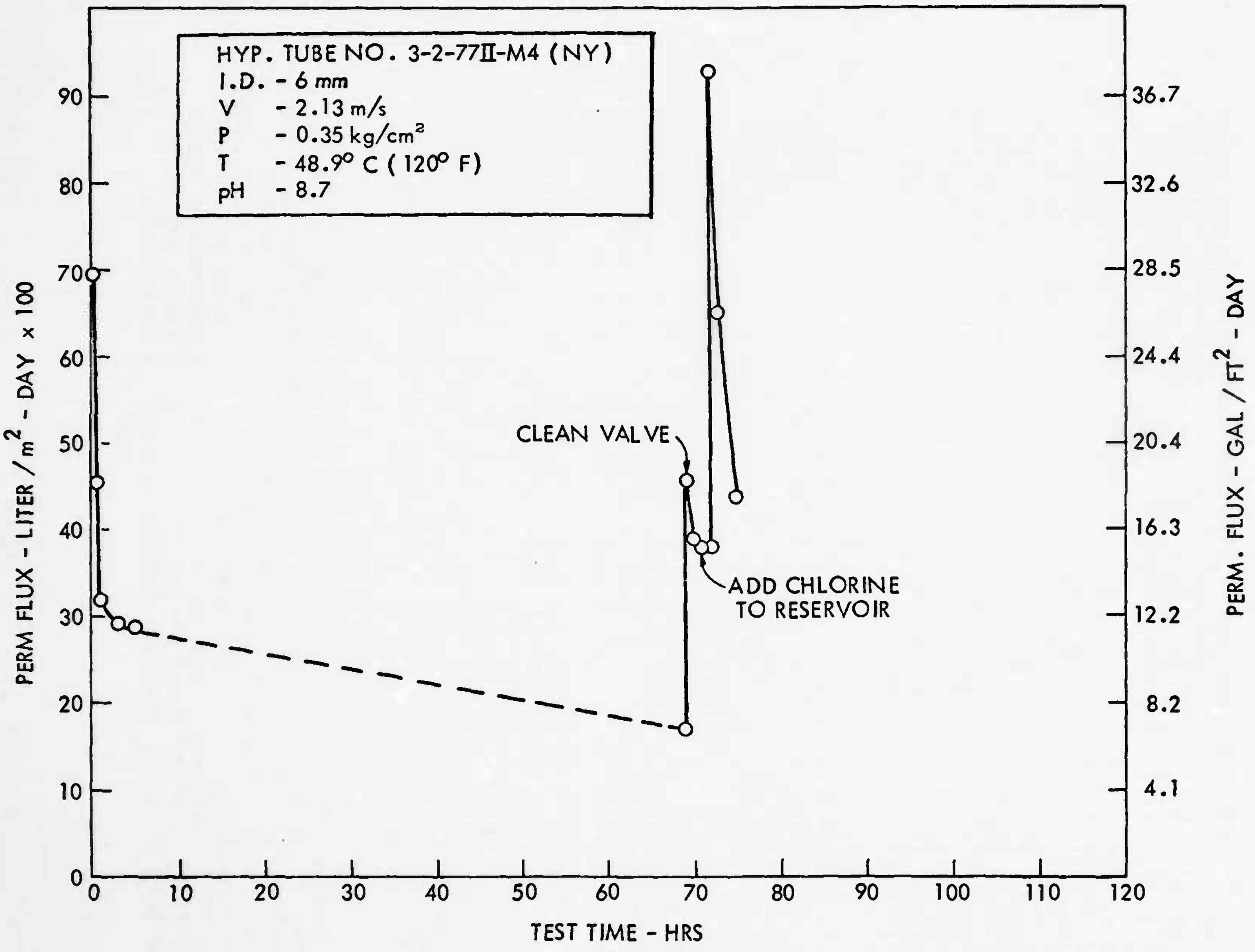

FIGURE 12 - OPTIMIZATION TEST AT HIGH TEMPERATURE AND MODERATE pH - TEST 5

Two other points are worthy of note regarding the data shown in Figure 12. During a period of unattended operation, a small valve in the test loop was partially clogged by the hair present in the composite waste, leading to a reduction in filtration pressure and consequent reduction in flux. However, unclogging of the valve immediately led to a restoration of the flux, indicating that the tubes were not irreversibly affected by the valve failure. A second feature of interest to note in Figure 12 is the effect of the addition of a small amount of hypochlorite to the feed tank. The tube was not cleaned prior to the addition of 1 mℓ /liter of a hypochlorite solution to the feed; yet, the filtrate flux increased almost immediately to nearly 400 liters/m^2-day (100 gallons/ft^2-day), thereby indicating the great influence of changes in feed character on the flux.

Figure 13 shows the results of a test with a 9-mm I.D. tube of the same type as that used in the test shown in Figure 9. It can be seen that after about five hours of operation the flux reaches a nearly constant value of 600 liters/m^2-day (15 gallons/ft^2-day) and that chlorine cleaning effectively restores the flux to the initial value. The increase in the flux after about thirty hours of operation may be due to feed degradation. A replication of this test is shown in Figure 14, though these two tests were done several days apart with different batches of the composite wastes. Note also the slight difference in the values of the pH in the two tests.

Figures 15 and 16, respectively, show the results of tests with the 6-mm and 9-mm I.D. tubes at low values of both the pH and temperature. The trends in the results are essentially the same as for the previous cases, with the 6-mm tube giving somewhat higher fluxes than the larger tube. The only new noteworthy feature in these tests is that cleaning the tubes with an enzyme detergent is equally as effective as cleaning with chlorine or Servac.

One test of particular interest is that shown in Figure 17 for the case of a low pH and a high temperature. In this case, after about twenty-five hours of operation, the feed began decomposing rapidly, and separated into a precipitate and a clear fluid. The flux levels also increased dramatically after the decomposition. This chemical change in the character of the fluid may be of importance in the actual MUST pilot plant operation. After the feed was replaced by a fresh batch and the tube cleaned, the flux behavior returned to normal.

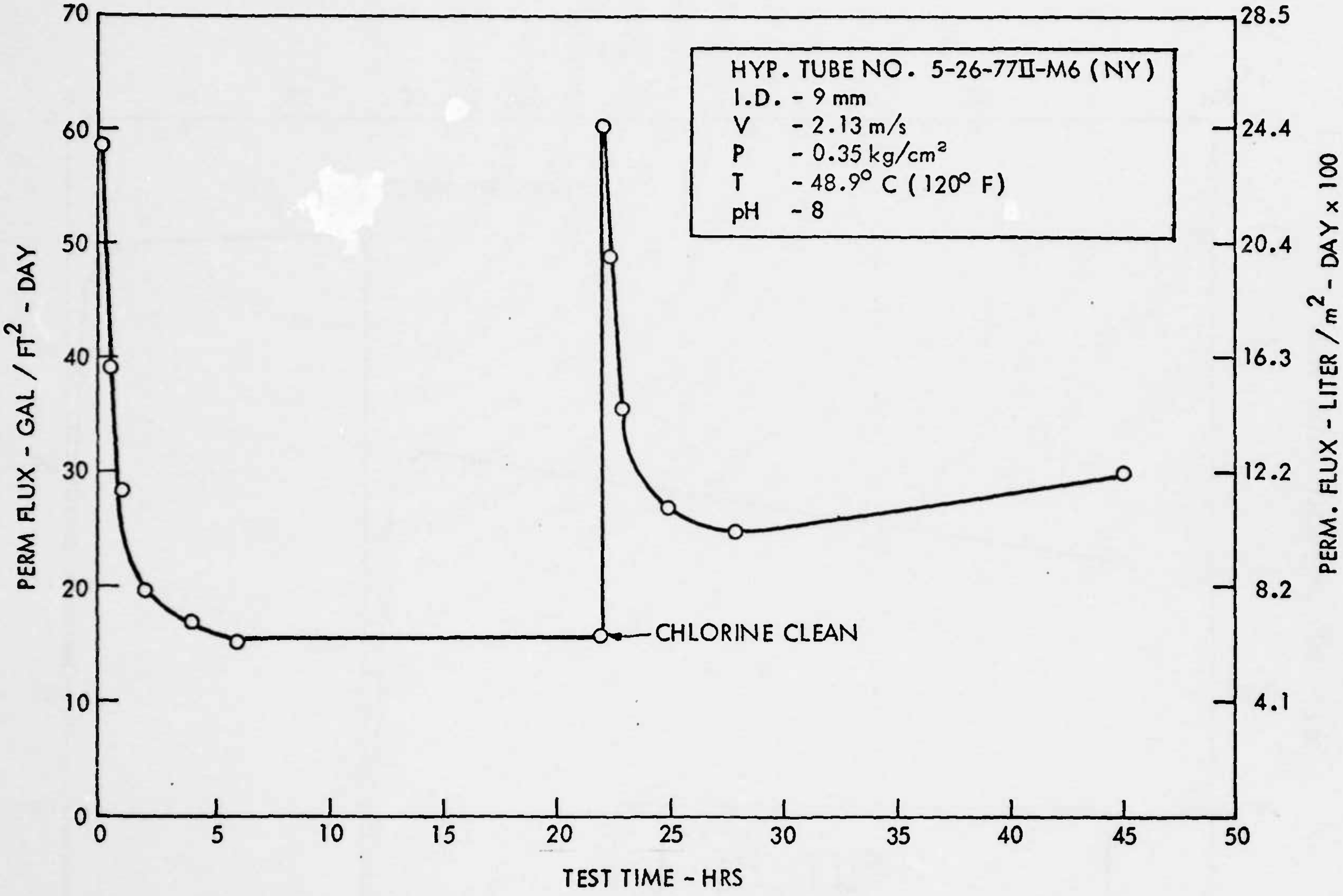

FIGURE 13 - OPTIMIZATION TEST AT HIGH TEMPERATURE AND MODERATE pH - TEST NO. 6

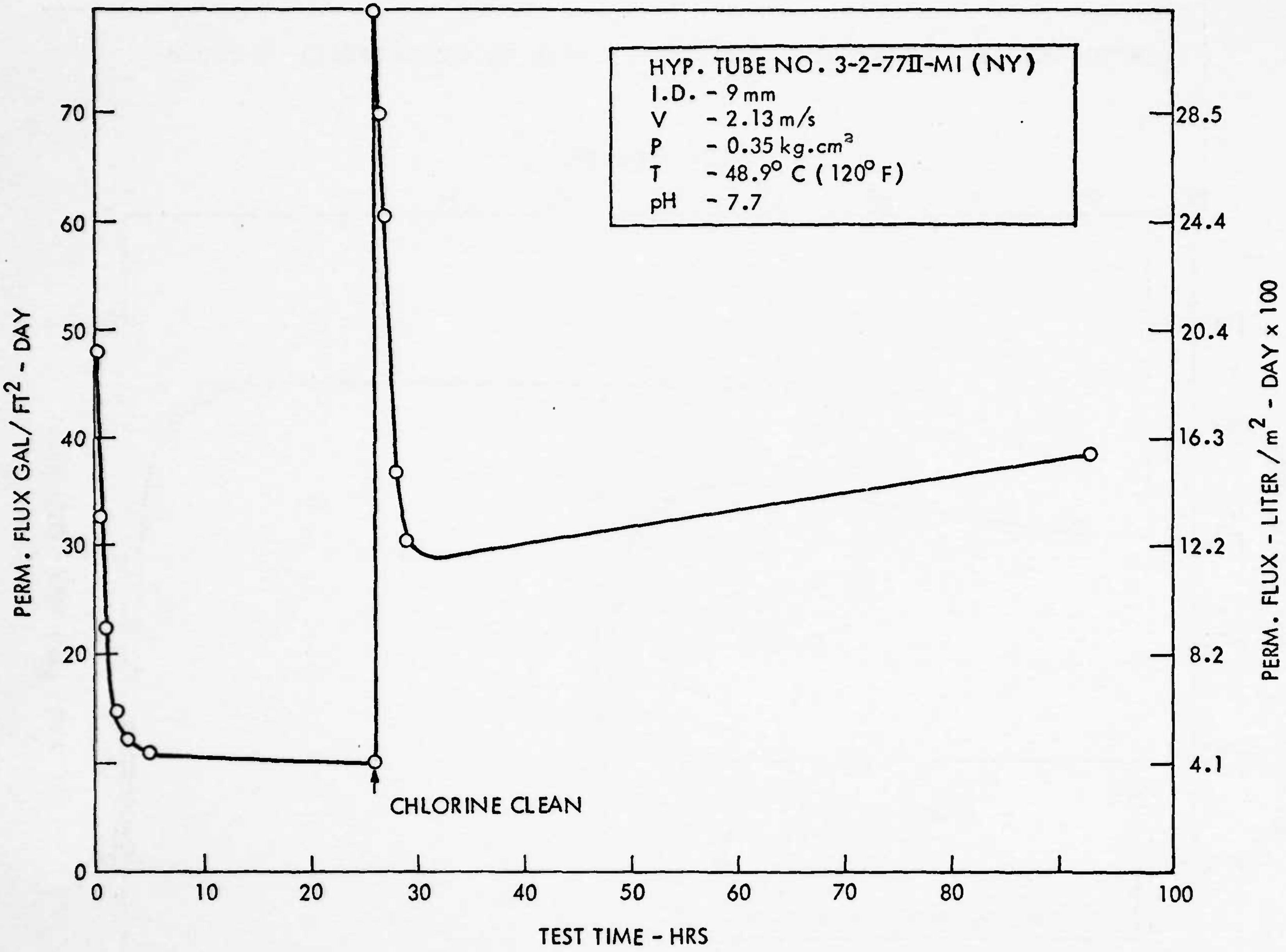

FIGURE 14 - OPTIMIZATION TEST AT HIGH TEMPERATURE AND MODERATE pH - TEST NO. 7

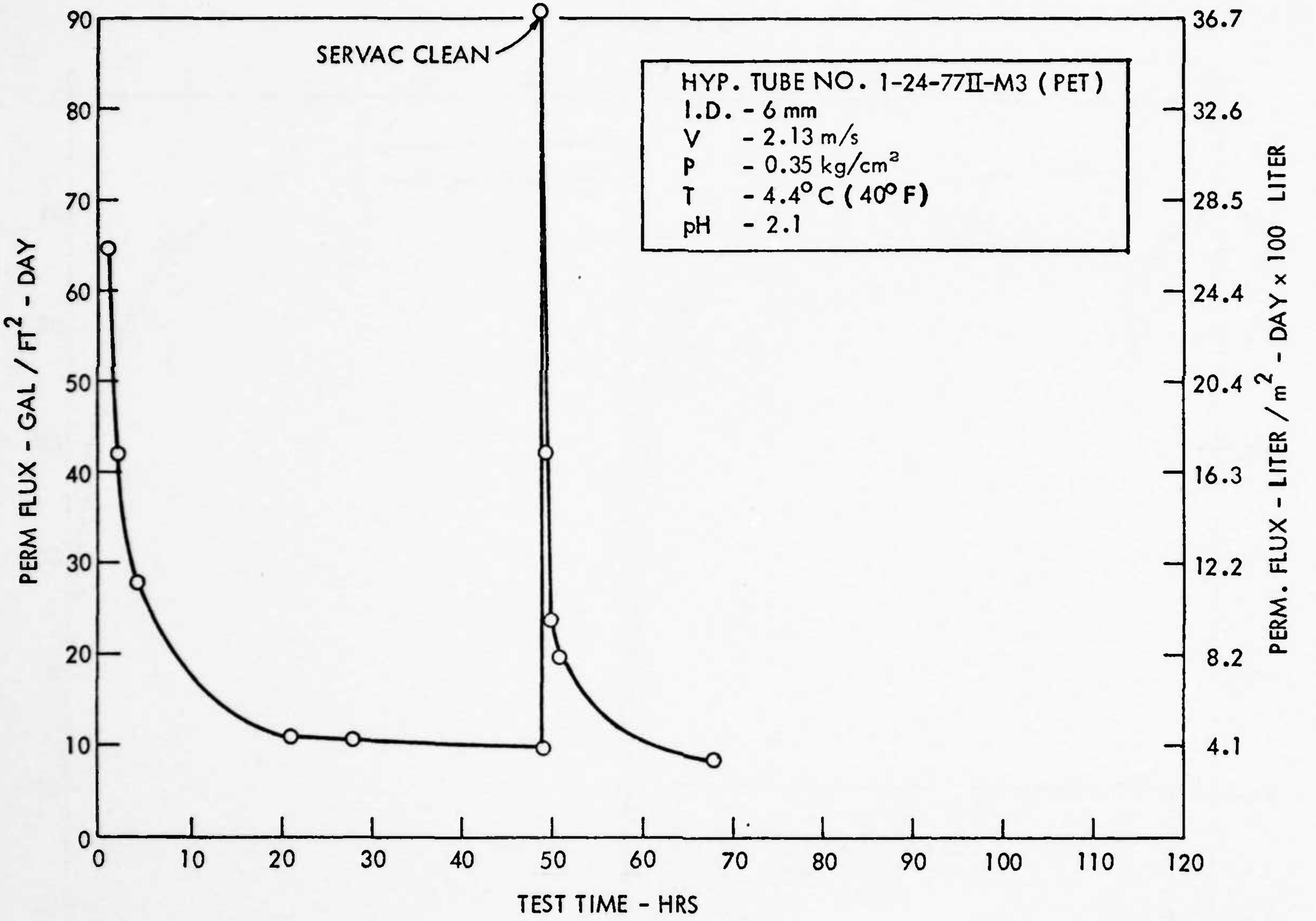

FIGURE 15 - OPTIMIZATION TEST AT LOW TEMPERATURE AND LOW pH - TEST NO. 8

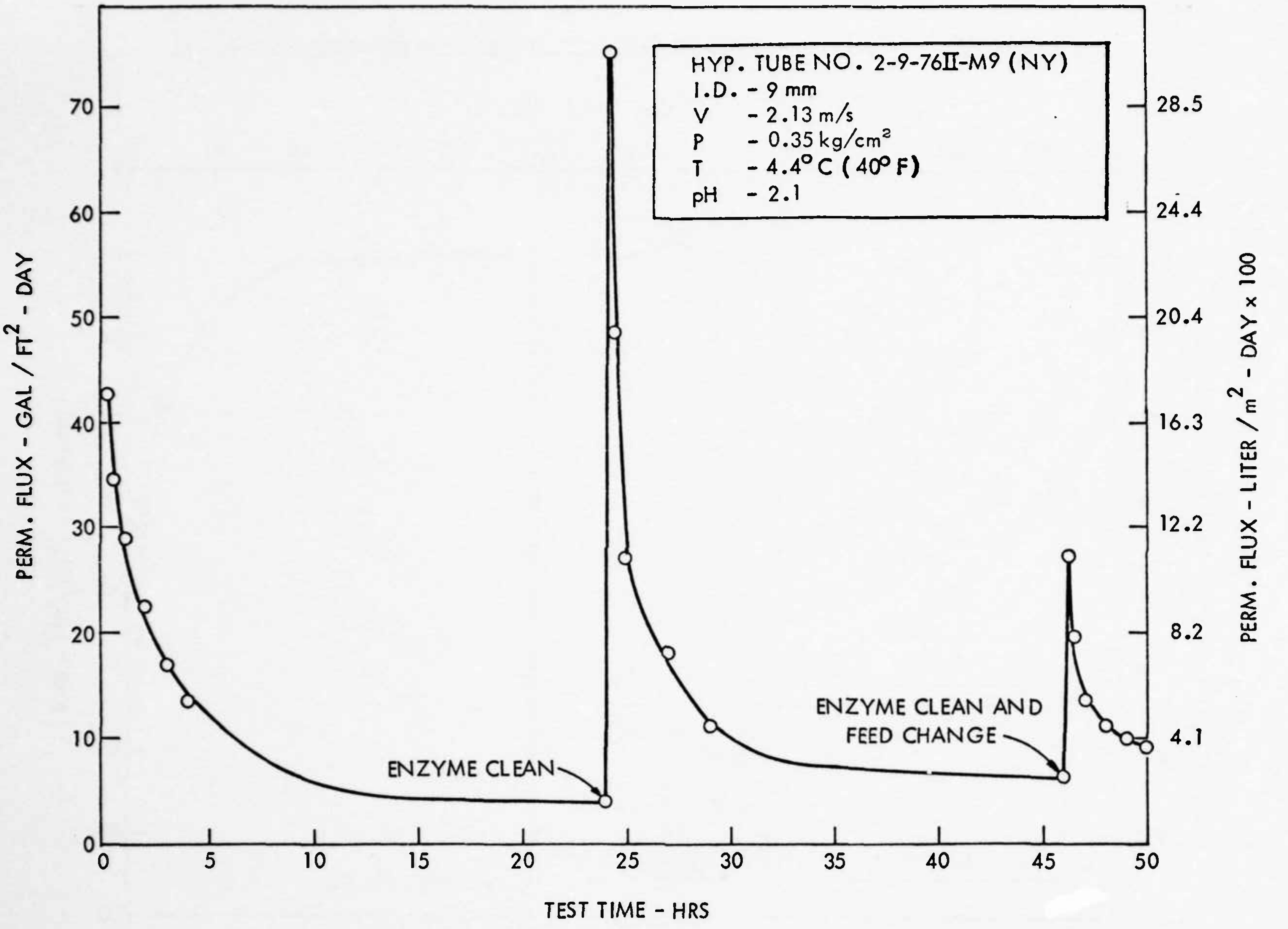

FIGURE 16 - OPTIMIZATION TEST AT LOW TEMPERATURE AND LOW pH - TEST NO. 9

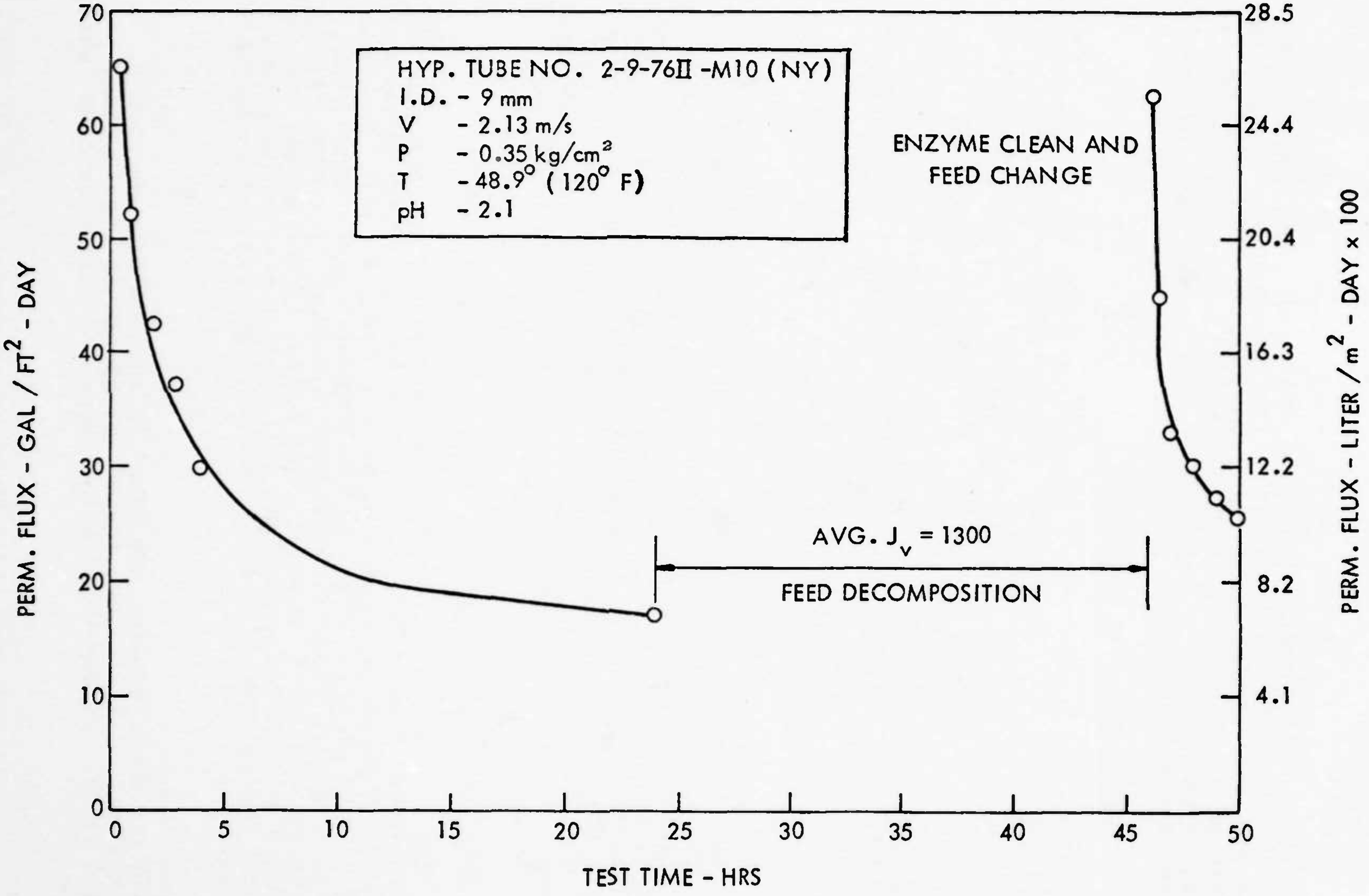

FIGURE 17 - OPTIMIZATION TEST AT HIGH TEMPERATURE AND LOW pH - TEST NO. 10

Based on the results outlined above, the recommended tube for use in a module for the MUST pilot plant is the 6 mm, Nylon tube with the pore structure corresponding to that shown as III in Figure 4. The recommended operating conditions are 5 psi pressure and a circulating velocity of 7 ft/sec (or approximately 1 gpm of circulating flow per tube).

Tests on Long-Term Flux Behavior

After the initial tube-optimization tests and the selection of the appropriate tube for use with the MUST wastes, a test of several-hundred-hours duration was conducted to determine the long-term flux behavior of the selected tube. The results of the test are shown in Figure 18. The test was conducted at room temperature, that is, at approximately 25°C; however, in Figure 18 the flux data themselves as well as those corrected* to a temperature of 48.9°C are shown, so as to afford direct comparison with the results shown in Figure 11. It can be seen from the figure that after 328 hours of continuous operation, the nature of the flux behavior is essentially the same as that during the first few hours of operation.

Comparison of Figures 18 and 11 show, as expected, considerable similarities in flux behavior. The comparison also reveals that the spuriously high value of the "plateau" flux noted after the first cleaning in Figure 11 can be attributed, at least partially, to the change in feed characteristics due to repeated recirculation at a high temperature. The long-term tests also reveal that best results in flux restoration are achieved when the tubes are first cleaned for ten minutes with a hypochlorite solution, followed by cleaning for ten minutes with a Servac solution.

Tests in Concentration Mode

All of the tests described thus far were done in a constant-concentration recirculation mode; that is, the filtrate was continuously remixed into the feed holding tank, so as to keep the feed conditions as nearly constant as possible throughout the tests. However, separate tests were also done on concentrating, to various degrees, a given initial volume of the waste; that is, in these tests the filtrate was collected in a separate reservoir and the solids concentration in the feed was allowed to increase continuously.

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*The corrections applied are those to account for the change, according to Darcy's law, due to the change in circulating fluid viscosity; see Table 2 for values of the correction factors used.

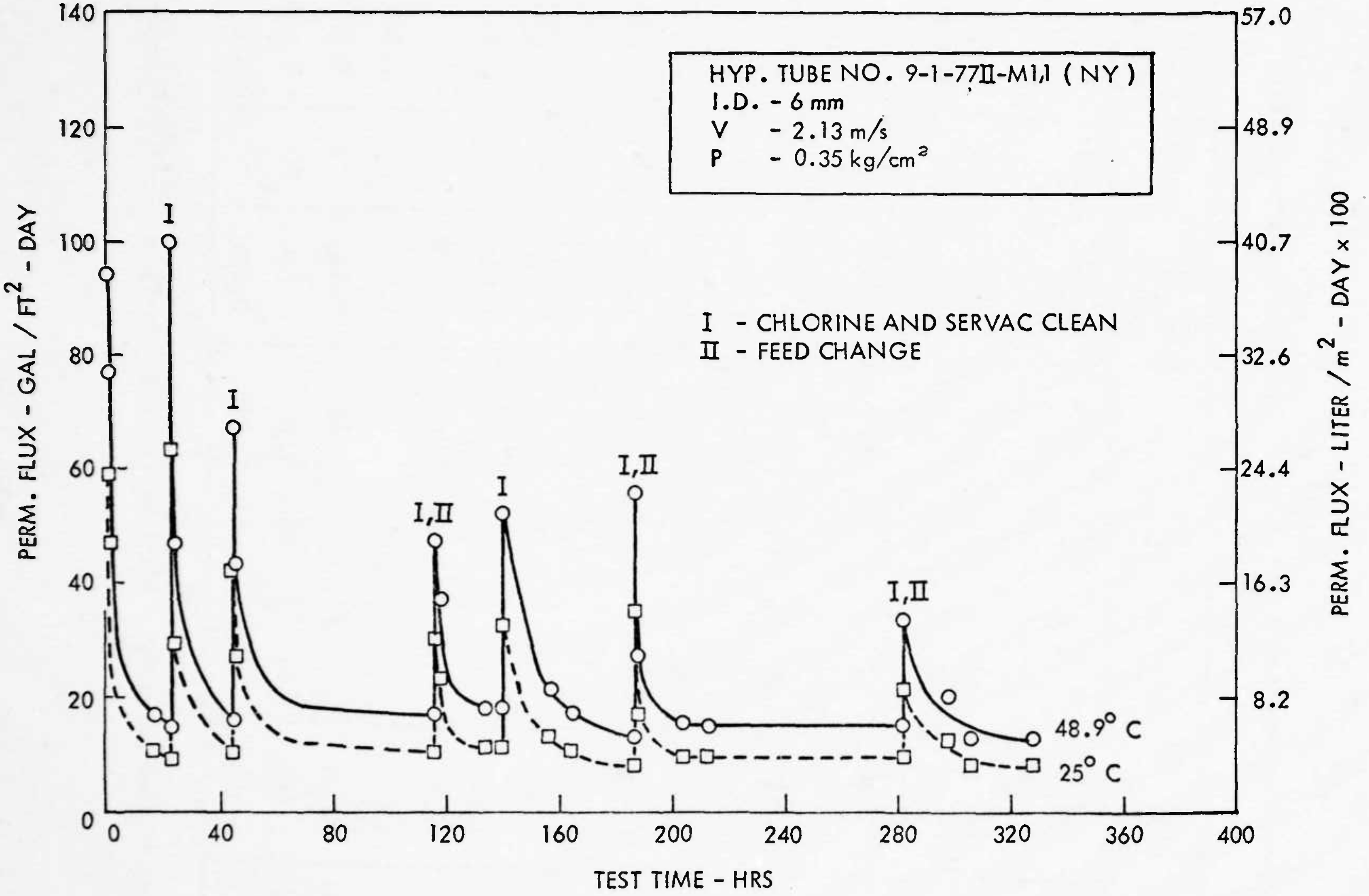

FIGURE 18 - TESTS ON LONG-TERM FLUX BEHAVIOR

Table 2
Correction Factors for the Effect of Temperature on Flux (normalized to 35°C)

Temp. °C	Correction Factor	Temp. °C	Correction Factor	Temp °C	Correction Factor	Temp. °C	Correction Factor
10	1.810	28	1.157	46	0.814	64	0.612
11	1.760	29	1.132	47	0.800	65	0.603
12	1.711	30	1.108	48	0.787	66	0.594
13	1.665	31	1.085	49	0.773	67	0.586
14	1.621	32	1.063	50	0.760	68	0.578
15	1.578	33	1.041	51	0.748	69	0.570
16	1.538	34	1.020	52	0.736	70	0.562
17	1.499	35	1.000	53	0.724	71	0.555
18	1.462	36	0.981	54	0.712	72	0.547
19	1.426	37	0.962	55	0.701	73	0.540
20	1.391	38	0.943	56	0.690	74	0.533
21	1.358	39	0.925	57	0.679	75	0.526
22	1.326	40	0.908	58	0.669	76	0.519
23	1.295	41	0.891	59	0.659	77	0.512
24	1.265	42	0.875	60	0.649	78	0.506
25	1.237	43	0.859	61	0.639	79	0.500
26	1.209	44	0.844	62	0.630	80	0.493
27	1.183	45	0.829	63	0.621		

$$\text{Flux at Temperature } T_1 = \text{Flux at Temperature } T_2 \times \frac{\text{Corr.Factor at } T_2}{\text{Corr.Factor at } T_1}$$

Results from the concentration mode test using a single tube of 6-mm I.D. and 38.5-cm length (Filtration Surface Area = 72.6 cm^2) are shown in Figure 19. These tests were conducted at a pH of about 8 and at a temperature of about 4.4°C, so that they complement the results shown in Figure 8. As in the constant-concentration mode of testing, the initial flux over the first few minutes of operation was about 60 gallons/ft^2-day (2400 liters/m^2-day); and after four hours of uninterrupted operation, the flux had declined to about 23.5 gallons/ft^2-day (950 liters/m^2-day), a value which is slightly lower than the value at the corresponding time in Figure 8. During this time, about 0.56 gallons (2.12 liters) had been removed as a clear, colorless permeate from the initial 2 gallons (7.56 liters) of feed, for a volume reduction of 28%. The volume reductions are indicated in Figure 19 by crosses and the corresponding values are shown in the right-hand scale.

After four hours of operation, the test was stopped overnight. However, at the resumption of testing the following morning, the fluxes were essentially the same, indicating that the stagnant conditions did not adversely affect filtration performance. After twenty hours of operation, eighty percent of the initial volume of the feed had been removed as permeate. It can be seen from the figure that the flux after twenty hours is only slightly lower than the corresponding value in Figure 8, in spite of the fivefold increase in concentration in the present case. Since 1.61 gallons (6.09 liters) were removed in 20 hours, and since the filtration area of the tube was 0.078 ft^2 (72.6 cm^2), the average flux during this period was 24.8 gallons/ft^2-day (1,000 liters/m^2-day).

A second concentration-mode test was conducted at room temperature (~25°C) using a small module which had a total of 2143 cm^2 (2.31 ft^2) of filtration area. The results of this test are shown in Figure 20(a), both in terms of the flux and the degree of volume reduction. The values of the flux adjusted to 48.9°C are also shown in the figure, so as to afford comparison with the results shown in Figure 11.

The initial volume of feed in the reservoir was 10 gallons (37.85 liters) and, as the concentration proceeded, fresh batches of feed were added to the reservoir, so that at the end of 3½ hours of operation the total volume of feed processed was 25 gallons (94.64 liters). During this period 24 gallons (90.85 liters) of filtrate were collected as a clear, colorless fluid, so that the volume reduction achieved was 96%. Since 24 gallons (90,85 liters) of permeate were collected during 3.5 hours, using a filter area of 2.31 ft^2 (2143 cm^2), the average flux during the concentration process was 71.24 gallons/ft^2-day (2907 liters/m^2-day).

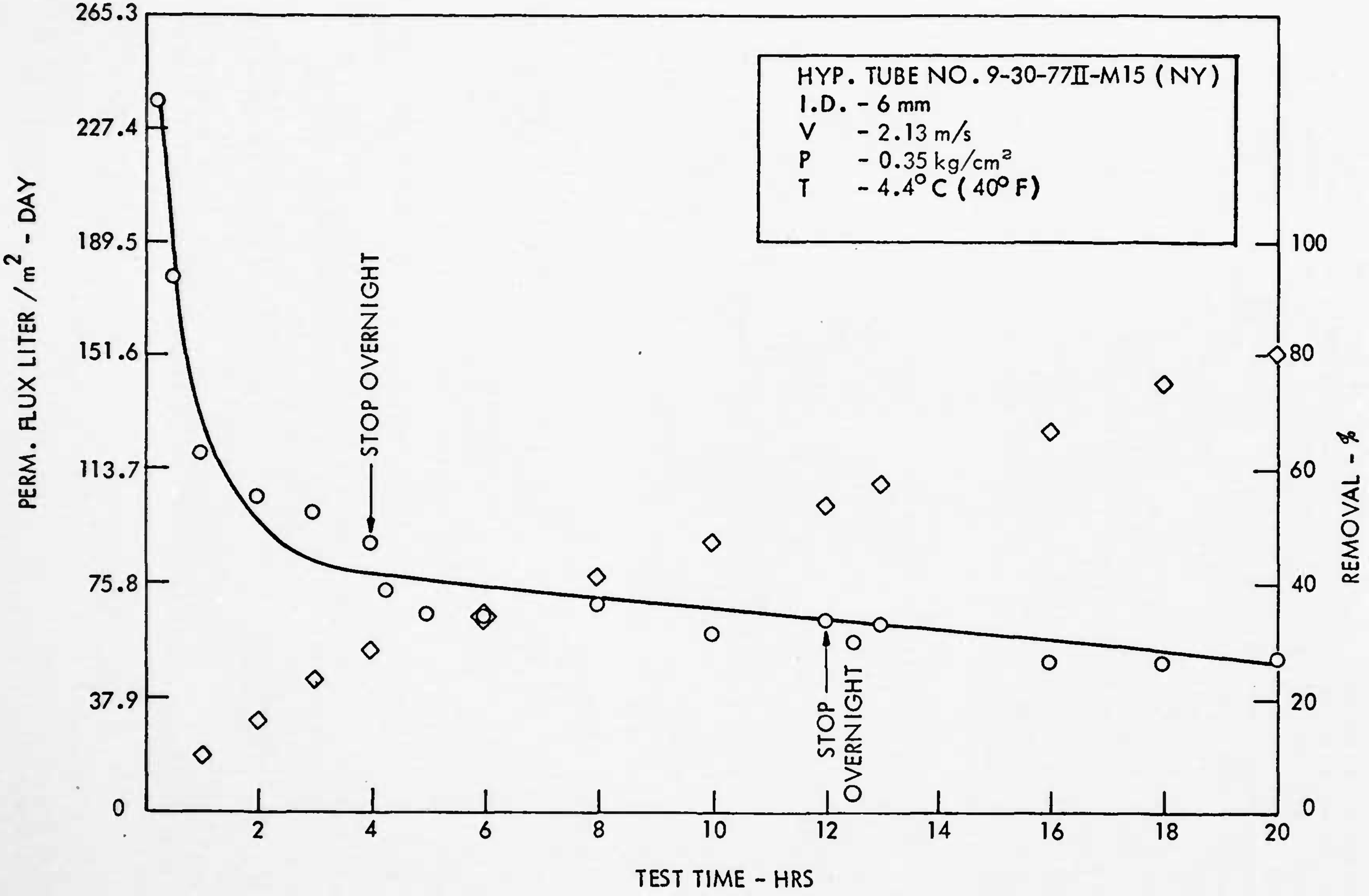

FIGURE 19 - CONCENTRATION TEST AT LOW TEMPERATURE

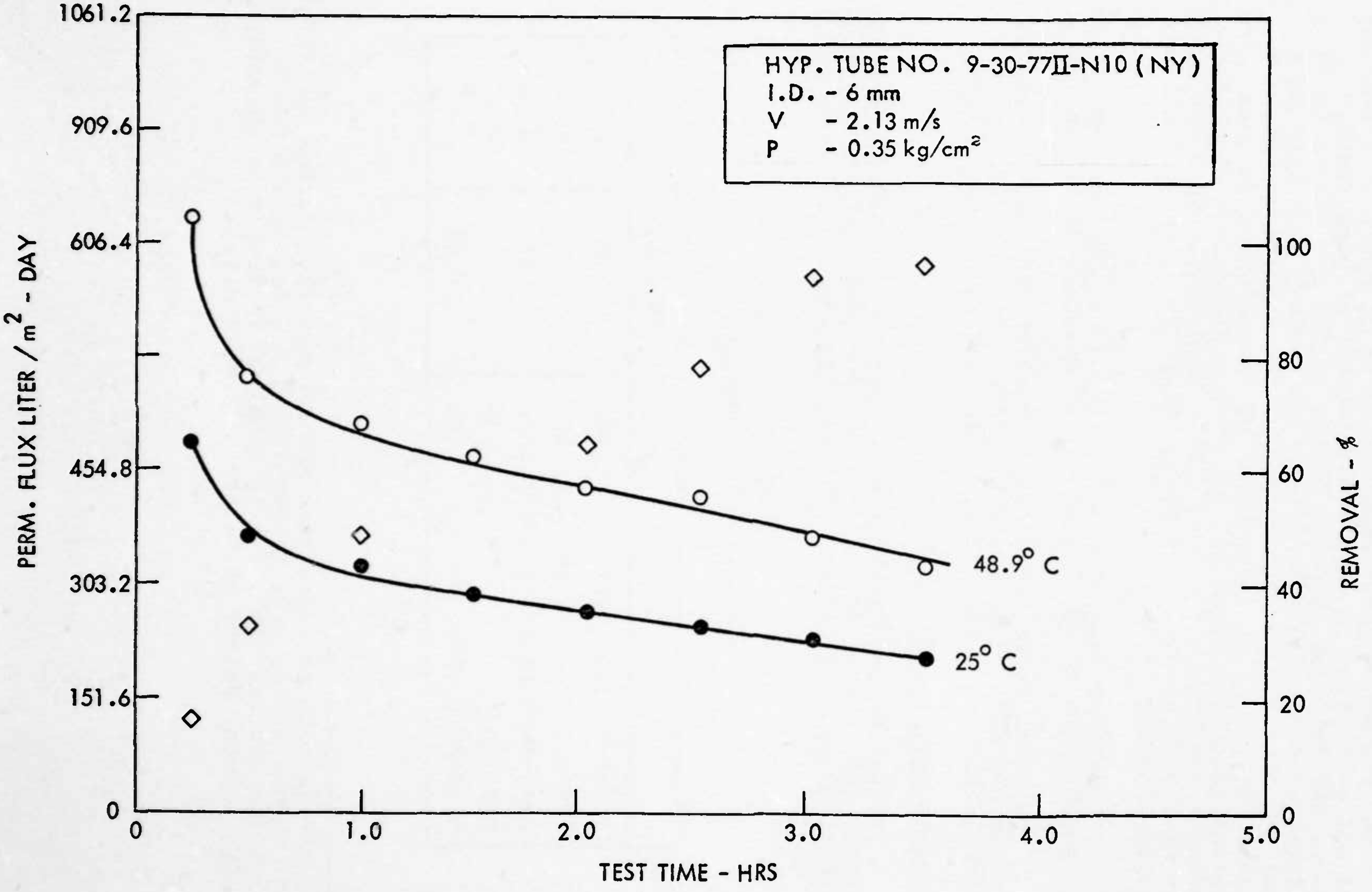

FIGURE 20 a - CONCENTRATION TEST AT ROOM TEMPERATURE - MODULE

The volume of feed remaining after 3½ hours of operation was not sufficient to enable maintenance of pump suction; hence, the test was stopped. However, the one gallon (3.79 liters) of concentrate remaining was further processed in a smaller, single-tube test loop, and the results are shown in Figure 20(b). After seven hours of operation, a further 0.66 gallons (2.5 liters) of filtrate were collected using a tube having a surface area of 0.078 ft^2 (72.6 cm^2). Thus the average flux during this phase of the test was 29 gallons/ft^2-day (11.79/m^2-day).

The average flux over the entire concentration period can be computed* to be 68.52 gallons/ft^2-day (2790 liters/m^2-day).

The tests described above demonstrate that Hydroperm filtration can achieve large volume reductions (nearly seventy-fivefold concentration) at significantly high flux levels.

Permeate Quality Analysis

During the constant-concentration tests, permeate and feed samples were collected and analyzed for total solids, suspended solids, BOD and turbidity. The results are listed in Table 3:

Table 3

Analysis of MUST Waste

	Feed	Permeate	% Removal
Total Solids (mg/ℓ)	1,200	490	59.2
Suspended Solids (mg/ℓ)	190	0	100.0
Dissolved Solids (mg/ℓ)	1,010	490	51.5
BOD (mg/ℓ)	135	20	85.2
Turbidity, JTU	98	0.24	-

---

*If the filtration area, time and average flux during the first and second phases are, respectively, A_1, t_1, q_1 and A_2, t_2, q_2, then the average flux, $\overline{q}$, is equal to $(A_1 t_1 q_1 + A_2 t_2 q_2)/(A_1 t_1 + A_2 t_2)$ = Total Volume of Filtrate/$(A_1 t_1 + A_2 t_2)$.

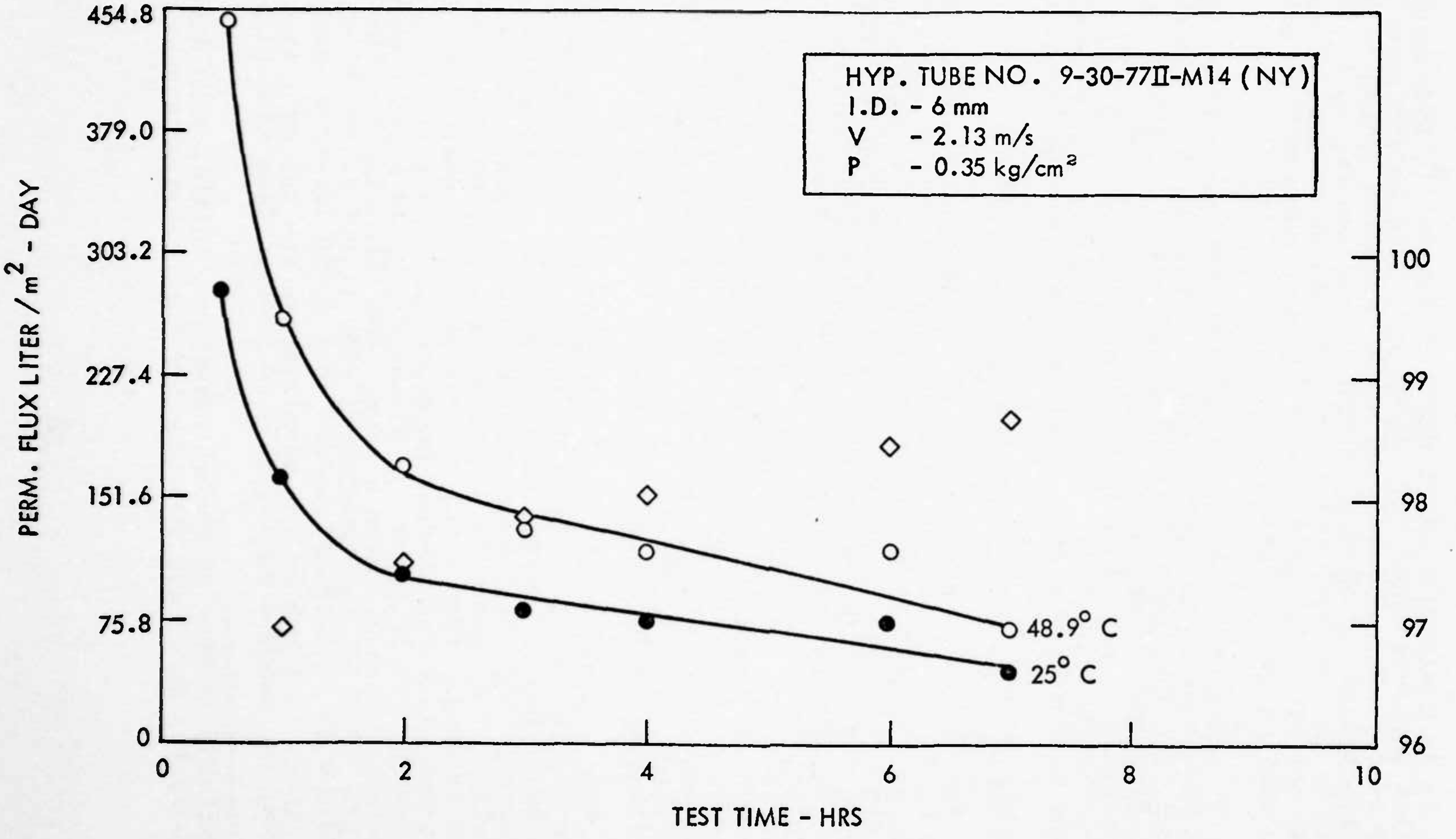

FIGURE 20 b - CONCENTRATION TEST AT ROOM TEMPERATURE - SINGLE TUBE

As in tests with other waste effluents[2-6], Hydroperm filtration achieves total removal of suspended solids from the MUST waste. The surprisingly high* dissolved solids rejection is also typical of Hydroperm filtration, and has to be attributed to the in-depth nature of the filtration process as well as to the likely formation of a "dynamic membrane" on the inside surface of the tube[2,3].

It can also be seen from Table 3 that there is a significant reduction in BOD and an almost total removal of turbidity. Indeed, the turbidity of the permeate was often indistinguishable from that of the control sample of distilled water. It is relevant to note that the near-total removal of turbidity and suspended solids was maintained even when concentrated feed wastes were filtered (during the concentration mode of testing).

Analysis of the Results and Comparison with UF

The laboratory test results described above demonstrate that Hydroperm tubes are capable of effectively filtering MUST waste even under extreme conditions of pH and temperature without either fouling or clogging. The flux-time curves for all of the test conditions exhibit a characteristic behavior in which the initial flux declines within the first few hours of operation to a nearly-constant, "plateau" value. The flux is restored to the initial value when a fairly simple cleaning procedure is used. Under this procedure a weak hypochlorite solution is first circulated through the tubes (at the same conditions of pressure, temperature and flow velocity as in the filtration operation) for ten minutes, followed by a similar treatment with a Servac solution.

From the continuous-mode (constant-concentration mode) tests shown in Figures 8, 11 (or 12), 15 and 17, it can be seen that even under rather extreme conditions of pH and (low) temperature, Hydroperm yields time-averaged fluxes over twenty-four hours of operation of at least 22.5 gallons/ft^2-day (900 liters/m^2-day). In other words, this level of flux can be maintained by cleaning the tubes every twenty-four hours or so. The tests in a concentration mode (Figures 19, 20 and 21) yield average values of the fluxes which are even higher. Specifically, the time-averaged flux at 4.4°C is 24.8 gallons/ft^2-day (1,000 liters/m^2-day), while at 48.9°C it is 68.5 gallons/ft^2-day (2790 liters/m^2-day).

Thus, in terms of the requirements for the MUST treatment system, two-hundred square feet of tube-surface area will provide

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*Surprising in view of the micron-sized, initial pore distribution of the tubes and the very low filtration pressure.

the 4,500 gallons (17,000 liters) of filtrate that are needed per day. A "standard" Hydroperm module provides one-hundred square feet (9.29 m^2) of filtration area, and consists of approximately 250, 6 mm I.D. tubes, each with an active length of about two meters (6.5 foot). Hence, two standard modules are sufficient to provide the required volume of permeate per day, even under extreme conditions of feed pH and temperature. Under normal operating conditions, even one module is more than adequate to provide the required volumes.

Permeate flux is only one of the important quantities which governs the economic viability of a filtration system. Another parameter which is of considerable importance[5] for a cross-flow filtration system is what can be called the "production efficiency" or "production ratio", defined as the permeate production per "pass" of the circulating feed through the filtration system. This quantity is of interest since it directly determines the circulating flow that is required* and, hence, the sizes of the pumps and the flow conduits.

In general, in most cross-flow filtration systems the production ratio is quite low, unlike through-flow systems for which the value is near unity. It is relevant to compare the production ratio of a Hydroperm module with that of the ultrafiltration module described by Gollan, et al.[1] The circulating flow required (to maintain a cross-flow velocity of 7 ft/sec) per Hydroperm tube is about 1 gpm, for a total of 250 gpm (950 ℓpm) per module. On the other hand, the tubular membranes described in Reference 1 have an internal diameter of one inch (2.54 cm) and require 30 gpm (114 ℓpm) per tube in order to maintain the proper cross-flow velocity.

Now, the average flux yielded by Hydroperm during a seventy-fivefold concentration cycle, at 25°C and at the natural p^H of the wastes, was 68.5 gallons/ft^2-day (2790 liters/m^2-day). The value given in Reference 1 (Table 6, page 69) for the average flux yielded by UF during a tenfold concentration cycle at 100°F (38°C) is 82.4 gallons/ft^2-day (3360 liters/m^2-day). If the Hydroperm flux is also corrected to 100°F, the corresponding value is 89.9 gallons/ft^2-day (3670 liters/m^2-day).**

From the values of the circulation rate and flux given above, the production ratio for a single Hydroperm module can be calculated to be 1/40; that is, during each "pass" of the circulating fluid through the module, 1/40th of it is removed as permeate. If the two modules recommended for the MUST system (to provide satisfactory operation even under extreme conditions of PH and temperature) are operated in series, the production

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*Circulating flow = permeate production required per unit time/ Production Ratio.

**All comparisons given below between Hydroperm and UF are for the batch concentration mode of operation at the natural pH of the MUST wastes and at 100°F, since this is the only case for which directly comparable data are available.

ratio of the system will be 1/20, when operated at 100°F and at the natural pH of the wastes. Under these conditions the system will produce 750 gallons (2840 liters) of permeate per hour, so that the 4500 gallons (17,000 liters) of permeate required per day will be produced within six hours of operation of the system. On the other hand, when the system is operated under extreme conditions of pH and temperature, as in a continuous mode of operation, the permeate flux is about 22.5 gallons/ft^2-day (900 liters/m^2-day), and the production ratio for a two-module system operated in series will be 1/80. The rate of permeate production for this case is 187.5 gallons (710 liters) per hour.

The ultrafiltration module described in Reference 1 contains eight (1" diameter) tubes, each ten feet long, so that the filtration area per module is 17.6 ft^2 (1.64 m^2). The eight tubes in each module are connected in series so that the circulating flow required per module is only 30 gpm (114 ℓpm). Thus when the module is used to filter the MUST wastes at their natural pH and at a temperature of 100°F, 37.8°C (that is, at a flux of 82.4 gallons/ft^2-day), the production ratio is 30. No data are available about the performance of the UF modules under extreme conditions of pH and temperature.

The power requirement for operating a cross-flow system of a given capacity depends on the production ratio as well as on the pressure drop through the system. The pressure drop through a single Hydroperm module is 3 psi, (0.21 kg/cm^2 when operated at an internal velocity of 7 ft/sec (2.1 m/sec). Thus for a two-module system, the power requirement (regardless of whether the modules are operated in parallel or in series) is 0.87 HP (0.65 kw). It is again relevant to emphasize that at the stated values of the power requirement and the filtration area, the Hydroperm system will be capable of producing sufficient permeate even at extreme conditions of pH and temperature.

If, on the other hand, the system is to be operated only at the natural pH of the wastes and at a temperature of 100°F, the required filtration area is only 50 ft^2 (4.65 m^2) and the power requirement is 0.22 HP (0.18 kw). The corresponding values for the UF system are (Reference 1, Table 12, page 84) 61.5 ft^2 (5.7 m^2) and 1.5 HP. A detailed comparison between UF and Hydroperm is given in Table 4.

A similar comparison can be made between the quality of the UF and Hydroperm filtrates, and this is shown in Table 5.

It can be seen from the comparisons given in Tables 4 and 5 that Hydroperm has several significant advantages over ultrafiltration. In addition to being made of rugged thermoplastic

Table 4

Comparison of the Filter-Surface Area
and Power Requirements for UF and Hydroperm
for a MUST System

	UF*	Hydroperm
1) Average Flux** at 100°F and natural pH of Waste, gallons/ft^2-day (liters/m^2-day)	82.4 (3360)	89.9 (3670)
2) Filter-surface area, ft^2 (m^2)	61.5 (5.71)	50.0 (4.65)
3) Feed circulation rate, gpm (ℓpm)	12.0 (456)	12.5 (460)
4) Power Requirement, HP (kw)	1.5 (1.1)	0.22 (0.16)
5) Operating Pressure, psi (kg/cm^2)	50.0 (3.5)	5.0 (0.35)

*Data from Table 12 (p. 84) and Figure 28 (p. 81) of Reference 1.
**In "concentration" mode.

Table 5

Comparison of the Permeate Qualities of
UF and Hydroperm
(MUST Hospital Composite Waste)

	Ultrafiltration*		Hydroperm Filtration	
	Feed Concentration	% Removal	Feed Concentration	% Removal
Total Solids	1,240 mg/ℓ	56.5	1,200 mg/ℓ	59.2
Suspended Solids	185 mg/ℓ	92.5	190 mg/ℓ	100.0
Dissolved Solids	1,060 mg/ℓ	50.1	1,010 mg/ℓ	51.5
Turbidity	210 NTU	93.3	98 JTU	99.8
COD	1,270 mg/ℓ	63.1	-	-
BOD	-	-	135 mg/ℓ	85.2

*Data from Table E5 (page 309) of Reference 1.

material, Hydroperm tubes are also extremely compact. For example, the 50 ft^2 of filtration area required for operation at 100°F and at normal pH is provided by a single small module of about 6 inches diameter and seven feet long. In comparison, ultrafiltration requires four modules, each of which contains eight one-inch diameter tubes, ten feet long.

VI. CONCLUDING REMARKS

The present report has described the results of a laboratory study undertaken to examine the feasibility of utilizing Hydroperm filtration to treat MUST hospital wastes. The results show that Hydroperm filtration yields excellent flux and rejection even at extremes of operating pH (down to 2) and temperature (down to 4.4°C). The performance characteristics of Hydroperm at comparable operating conditions are better than those of ultrafiltration, in spite of the initially micron-sized pore structure of the Hydroperm tubes. This feature is attributed to the in-depth character of the Hydroperm filtration process and to the formation of a dynamic membrane on the inside surface of the tubes.

A natural follow-up to the present laboratory study is the testing of Hydroperm modules in a MUST waste treatment pilot plant. Indeed, as a part of the requirements of the contract under which the present study was conducted, Hydroperm modules are being delivered to the U. S. Army Medical Bioengineering Research and Development Laboratory and will be tested by them in a pilot plant.

The present study was of limited scope and some questions remain unanswered. Specifically, the ability of the pore structure of the Hydroperm tubes to be "tailored" or optimized to a given effluent was exploited only to a limited extent in the present study. This feature of the tubes is especially important when filtering special wastes as those from the X-ray laboratories or from operating rooms. It will be appropriate to study this aspect further if the pilot plant operation confirms the expected versatility of Hydroperm filtration for treating a variety of MUST wastes.

REFERENCES

1. Gollan, Arye Z., et al., "Evaluation of Membrane Separation Processes, Carbon Adsorption, and Ozonation for Treatment of MUST Hospital Wastes," U. S. Army Medical Research and Development Command Report AD A030057/4 WP., Washington, D. C. 20314, August 1976.

2. Sundaram, T. R., and Santo, J. E., "Microfiltration of Military Waste Effluents," Seventh Annual Symposium on Environmental Research - Meeting Report (Ed: J. A. Brown), American Defense Preparedness Association, Washington, D. C., September 1976.

3. Sundaram, T. R., and Santo, J. E., "Removal of Suspended and Colloidal Solids from Waste Streams by the Use of Cross-Flow Microfiltration." ASME Publication No. 77-ENAS-51, July 1977.

4. Duncan, J. D., Sundaram, T. R., Fruman, D. H., and Santo, J. E., "A Unique Microfiltration System for Treating Industrial Effluents." Paper presented at the Second International Congress on Industrial Waste Water and Wastes, Stockholm, Sweden, February 1975. See also, Progress in Water Technology, Vol. 8, Nos. 2/3, pp. 181-189, Pergaman Press, 1976.

5. Sundaram, T. R., and Santo, J. E., "Removal of Turbidity from Natural Streams by the Use of Microfiltration," HYDRONAUTICS, Incorporated Technical Report 7662-1, June 1976.

6. Sundaram, T. R., and Santo, J. E., "The Development of a HYDROPERM Microfiltration System for the Treatment of Domestic Waste Water Effluents," HYDRONAUTICS, Incorporated Technical Report 7658-1, January 1977.

7. Bear, J., Dynamics of Fluids in Porous Media, American Elsavier Co., 1972.

8. Henry, J. D., Jr., "Cross Flow Filtration," Recent Developments in Separation Science, Volume 2, CRC Press, pp. 205-225, 1972.

APPENDIX A

DATA FOR FIGURES 8 THROUGH 14

Table 1
Data for Figure 8

Time, hrs.	P kg/cm^2	V m/sec	T °C	Permeate Flux* ℓpd/m^2
0.5	0.35	2.1	12	2310.3
1.0	↓	↓	12	1911.0
3.5			12	1356.8
5.0			11	1149.0
6.0			11	1051.2
23.0			11	623.4
30.0			12	541.9
46.0			12	509.3
50.0			12	509.3
50.25			9	1271.3
51.0			12	1063.5
53.0			13	806.8
117.0	0.35	2.1	13	497.1

*Corr. to 4.4°C

Table 2
Data for Figure 9

Time, hrs.	P kg/cm^2	V m/sec	T °C	Permeate Flux* ℓpd/m^2
0.5	0.35	2.1	12	2163.6
1.0	↓	↓	12	778.2
3.0			12	264.8
5.0			12	281.1
23.0			13	183.4
23.25			9	920.9
23.5			12	468.6
25.0			13	346.3
29.0			13	273.0
45.0	0.35	2.1	13	200.0

*Corr. to 4.4°C

Table 3

Data for Figure 10

Time, hrs.	P kg/cm^2	V m/sec	T °C	Permeate Flux* ℓpd/m^2
0.25	0.35	2.1	12	1271.3
0.50			12	986.1
1.00			12	847.5
2.00			12	639.7
3.00			13	586.7
5.00			13	529.7
22.00			13	497.1
26.00			13	476.7
26.25			10	1739.9
26.50			12	1222.4
27.00			13	684.5
28.00			13	529.7
29.00	↓	↓	13	476.7
93.00	0.35	2.1	13	309.7

*Corr. to 4.4°C

Table 4

Data for Figure 11

Time hrs.	P kg/cm^2	V m/sec	T °C	Permeate Flux* ℓpd/m^2
0.5	0.35	2.1	39	5671.8
3.5	↓	↓	46	1442.4
6.0			49	1275.3
22.0			49	802.7
30.0			47	794.5
46.0			51	741.6
50.0			50	753.8
50.25			46	2787.0
51.0			51	2644.4
54.0			51	1939.5
118.0			54	1678.7
118.25			44	2188.1
121.0			49	1972.1
141.5			43	1499.5
141.75			45	3031.5
142.5			45	2542.6
144.0			46	2188.1
147.0			50	2151.4
164.0			52	1906.9
164.25			41	1849.9
167.0			46	1422.0
170.0			49	1206.1
187.0			52	937.2
187.25			44	2069.9
190.0			50	1686.9
194.0			53	1536.1
210.0	0.35	2.1	54	1210.2

*Corr. to 48.9°C

Table 5
Data for Figure 12

Time hrs.	P kg/cm^2	V m/sec	T °C	Permeate Flux* ℓpd/m^2
0.25	0.35	2.1	43	2835.9
0.50	↓	↓	46	1845.8
1.00			50	1291.6
3.00			50	1181.6
5.00			47	1169.4
69.00			49	692.7
69.25			42	1858.0
70.00			50	1576.9
71.00			54	1544.3
72.00			54	1544.3
72.25			54	3781.2
73.00			49	2644.4
75.00	0.35	2.1	46	1768.4

*Corr. to 48.9°C

Table 6
Data for Figure 13

Time hrs.	P kg/cm^2	V m/sec	T °C	Permeate Flux* ℓpd/m^2
0.25	0.35	2.1	47	2387.7
0.50	↓	↓	49	1593.2
1.00			51	1149.0
2.00			52	794.5
4.00			49	680.5
6.00			49	615.3
22.00			51	635.6
22.25			40	2452.9
23.00			46	1446.5
25.00			52	1087.9
28.00			52	1002.4
45.00	0.35	2.1	54	1214.2

*Corr. to 48.9°C

Table 7

Data for Figure 14

Time hrs.	P kg/cm^2	V m/sec	T °C	Permeate Flux* ℓpd/m^2
0.25	0.35	2.1	43	1951.7
0.50	↓	↓	46	1332.4
1.00			47	908.6
2.00			49	594.9
3.00			48	493.0
5.00			49	440.1
26.00			49	415.6
26.25			40	3288.2
26.50			43	2807.4
27.00			50	2053.6
28.00			47	1499.5
29.00			45	1246.8
93.00	0.35	2.1	46	1572.8

*Corr. to 48.9°C

Table 8
Data for Figure 15

Time hrs.	P kg/cm^2	V m/sec	T °C	Permeate Flux* ℓpd/m^2
1.00	0.35	2.1	12	2632.2
2.00	↓	↓	13	1707.3
4.00	↓	↓	12	1116.4
21.00	↓	↓	13	436.0
28.00	↓	↓	12	436.0
49.00	↓	↓	12	383.0
49.25	↓	↓	10	3707.9
49.50	↓	↓	11	1723.6
50.00	↓	↓	12	1169.4
51.00	↓	↓	12	798.6
68.00	0.35	2.1	13	342.3

*Corr. to 4.4°C

Table 9
Data for Figure 16

Time, hrs.	P kg/cm^2	V m/sec	T °C	Permeate Flux* ℓpd/m^2
0.25	0.35	2.1	12	1739.9
0.50	↓	↓	12	1409.8
1.00			12	1177.6
1.50			13	1051.2
2.00			13	916.8
3.00			13	684.5
4.00			13	550.1
24.00			13	163.0
24.25			10	3084.5
24.50			12	1976.2
25.00			13	1100.1
27.00			13	733.4
29.00			13	456.4
46.00			13	256.7
46.25			11	1112.4
46.50			12	798.6
47.00			13	550.1
48.00			13	456.4
49.00			13	403.4
50.00	0.35	2.1	13	366.7

*Corr. to 4.4°C

Table 10
Data for Figure 17

Time, hrs.	P kg/cm^2	V m/sec	T °C	Permeate Flux* ℓpd/m^2
0.25	0.35	2.1	41	3292.3
0.50	↓	↓	45	2648.5
1.00			51	2126.9
2.00			50	1727.6
3.00			50	1511.7
4.00			49	1210.2
24.00			46	692.7
46.25			42	2546.6
46.50			45	1825.4
47.00			58	1340.5
48.00			50	1230.5
49.00			52	1108.3
50.00	0.35	2.1	52	1043.1

*Corr. to 48.9°C

Table 11

Data for Figure 18

Time, hrs.	P kg/cm^2	V m/sec	T $^\circ$C	Permeate Flux* ℓpd/m^2
0.5	0.35	2.1	21	3842.3
1.0	↓	↓	21	3145.6
17.0	↓	↓	21	700.8
23.0	↓	↓	22	615.2
23.25	↓	↓	22	4095.0
24.0	↓	↓	22	1911.0
45.0	↓	↓	23	668.2
45.25	↓	↓	22	2730.0
46.0	↓	↓	22	1772.5
116.0	↓	↓	25	700.8
116.25	↓	↓	22	1931.4
118.0	↓	↓	24	1519.8
134.0	↓	↓	23	733.4
140.0	↓	↓	26	745.7
140.25	↓	↓	24	2114.7
157.0	↓	↓	23	867.9
165.0	↓	↓	25	700.8
187.0	↓	↓	24	521.5
187.25	↓	↓	24	2277.7
188.0	↓	↓	23	1112.4
204.0	↓	↓	21	627.5
213.0	↓	↓	22	615.3
282.0	↓	↓	22	615.3
282.25	↓	↓	22	1365.0
298.0	↓	↓	22	819.0
306.0	↓	↓	24	521.5
328.0	0.35	2.1	24	521.5

*Corr. to 48.9°C

Table 12
Data for Figure 19

Time, hrs.	P kg/cm^2	V m/sec	T °C	J_V* ℓpd/m^2	Permeate Collected mℓ
0.25	0.35	2.1	12	2550.7	-
0.50	↓	↓	12	1911.0	-
1.00			12	1267.2	760
2.00			12	1116.4	450
3.00			12	1063.5	400
4.00			12	957.5	390
4.25			10	786.4	-
5.00			12	700.8	-
6.00			12	700.8	460
8.00			12	733.4	540
10.00			12	635.6	460
12.00			13	680.5	475
12.50			14	603.0	-
13.00			14	664.2	260
16.00			19	529.7	720
18.00			21	529.7	660
20.00	0.35	2.1	22	541.9	410

*Corr. to 4.4°C

Table 13
Data for Figure 20(a)

Time, Hrs.	P kg/cm^2	V m/sec	T °C	J_V* $\ell pd/m^2$	Permeate Collected $m\ell$
0.25	0.35	2.1	21	5256.2	15140.0
0.50	↓	↓	22	7986.2	15140.0
1.00			23	3504.2	15140.0
1.50			23	3096.7	-
2.00			24	2770.7	15140.0
2.50			24	2648.5	13247.5
3.00			27	2485.5	15140.0
3.50	0.35	2.1	27	2200.3	1892.5

*Corr. to 25°C

Table 14

Data for Figure 20(b)

Time, Hrs.	P kg/cm^2	V m/sec	T °C	J_V* ℓpd/m^2	Permeate Collected mℓ
0.5	0.35	2.1	29	3015.2	-
1.0	↓	↓	31	1752.1	880
2.0	↓	↓	30	1120.5	500
3.0	↓	↓	31	876.0	335
4.0	↓	↓	31	814.9	230
6.0	↓	↓	31	814.9	390
7.0	0.35	2.1	31	489.0	190

*Corr. to 25°C

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