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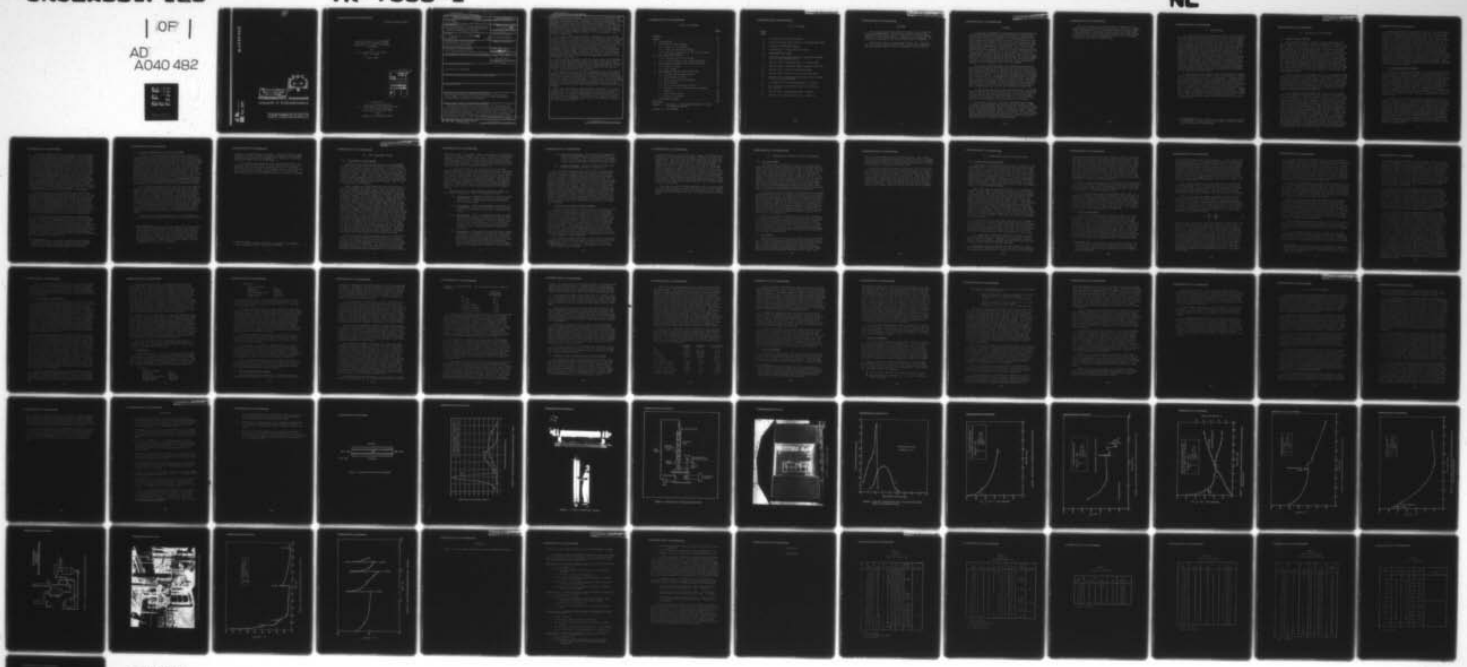

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HYDRONAUTICS, INCORPORATED

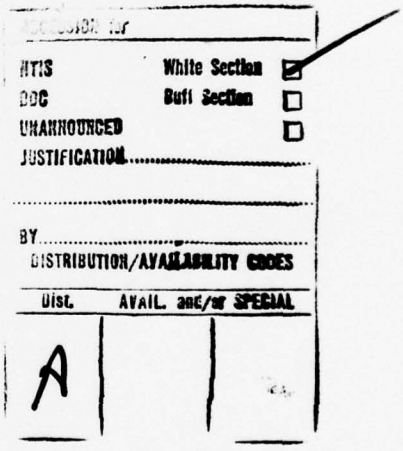
TECHNICAL REPORT 7658-1

THE DEVELOPMENT OF A HYDROPERM™ MICROFILTRATION SYSTEM FOR THE TREATMENT OF DOMESTIC WASTEWATER EFFLUENTS

by

T. R. Sundaram, J. E. Santo
and J. A. Brown

January 1977



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Laboratory experiments to investigate the feasibility of further concentrating the already concentrated (containing approximately one to two percent total solids) human wastes of the type encountered onboard U. S. Army watercraft or at field troop installations are described. The additional concentration is performed by cross-flow microfiltration utilizing unique microporous plastic tubes called HYDROPERM™, ~~(manufactured by~~

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~~HYDRONAUTICS, Incorporated~~). It is shown that a significant degree of dewatering of the concentrate can be achieved while producing a relatively clear, suspended-solids-free permeate. Fluidization of the sludge by the addition of a light oil (~~EXXON's Isopar~~), combined with the ability of HYDROPERM to separate oil-water emulsions, enables the attainment of even greater degrees of dewatering (up to ninety-eight percent). It is also demonstrated that the oil-based sludge residue can be further treated using the Carver-Greenfield Process, so as to produce a dry, sterile residue.

In a small scale demonstration, conducted as a part of the present study, it was shown that in the HYDROPERM step, 162 liters of water from an original 165 liters of black water were removed by filtration, leaving the original solids suspended in an emulsion of 15 liters of Isopar and approximately 3.1 liters of water. In the Carver-Greenfield step, the emulsion residue from the HYDROPERM step is dehydrated by evaporation in the presence of additional Isopar to give completely anhydrous solids suitable for direct incineration. Actually, the emulsion, containing a large percentage of hydrocarbon oil as it did, could have been incinerated directly without final dehydration; and that is the recommended operation.

On the relatively small scale of concern here, the HYDROPERM Process is far less expensive than the Carver-Greenfield Process, which only becomes economical on a scale of tens of hundreds of tons of dry weight per day; and the HYDROPERM Process is recommended alone for black water, with incineration of the concentrate and discharge of the filtrate.

The capital cost of a 110 ℓ/day HYDROPERM plant using Isopar and not treating the filtrate is approximately $2800 to $5600, depending upon the characteristics of the particular black water used; and as shown in Section V, paragraph 8, the labor, material and power costs are entirely minor. Conventional Carver-Greenfield plants cost hundreds of thousands of dollars for hundreds of tons treated per day; miniature Carver-Greenfield units are being studied, but they have not been demonstrated or estimated at this writing.

The only conventional waste disposal technique at all competitive with oil-assisted dewatering on this scale appears to be trucking away to a conventional sewage treatment plant somewhere nearby. Trucking is estimated to cost about $100 to $150 per 7600 liters—per week at 1100 liters per day—for a break-even time with a HYDROPERM plant of 20 to 40 weeks, assuming no filtrate polishing costs.

TABLE OF CONTENTS

LIST OF FIGURES

FOREWORD

The present report describes the results of a study conducted by HYDRONAUTICS, Incorporated under a contract (No. DAAG53-76-C-0129) from the U. S. Army Mobility Equipment Research and Development Command. Technical monitoring for the program was provided by Mr. Maurice Pressman of MERADCOM.

The authors wish to acknowledge the key role played in the study by Mr. Ronald Watson (their laboratory technician) who actually performed the tests described in this report.

SUMMARY

Laboratory experiments to investigate the feasibility of further concentrating the already concentrated (containing approximately one to two percent total solids) human wastes of the type encountered onboard U. S. Army watercraft or at field troop installations are described. The additional concentration is performed by cross-flow microfiltration utilizing unique microporous plastic tubes called HYDROPERM™ (manufactured by HYDRONAUTICS, Incorporated). It is shown that a significant degree of dewatering of the concentrate can be achieved while producing a relatively clear, suspended-solids-free permeate. Fluidization of the sludge by the addition of a light oil (EXXON's Isopar), combined with the ability of HYDROPERM to separate oil-water emulsions, enables the attainment of even greater degrees of dewatering (up to ninety-eight percent). It is also demonstrated that the oil-based sludge residue can be further treated using the Carver-Greenfield Process, so as to produce a dry, sterile residue.

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I. INTRODUCTION

As a result of the rapid deterioration of the quality of the environment in the United States in recent years, legislation has been enacted which severely restricts the discharge of waste effluents into the water, air or soil. The United States Army is not excluded from the responsibility of pollution abatement, and is concerned with the control of pollutants generated not only within logistical, manufacturing and troop installations, but also aboard Army vessels and by troops in the field in areas outside the range of permanent domestic wastewater treatment facilities (Reference 1). Indeed, the Sanitary Sciences Division of MERADCOM of Fort Belvoir, Virginia is presently carrying out investigations in the area of human waste treatment to develop the appropriate control technologies. The present report describes the results of a study that was carried out by HYDRONAUTICS, Incorporated, under the support of MERADCOM, to assess the feasibility of using cross-flow microfiltration (utilizing proprietary porous plastic tubes, called HYDROPERM™, developed by HYDRONAUTICS, Incorporated) as a principal unit operation in the treatment of human wastes.

A discussion of the nature of the waste-disposal problem that is addressed in the present study is contained in Section II of this report. Section II also contains a concise statement of the objectives of the present study. A description of the principal features of the HYDROPERM System are given in Section III, while a description of the experimental apparatus as well as the test procedures used in the present study are given in Section IV. The experimental results themselves as well as their implications are discussed in Section V. Though the present investigation is a preliminary feasibility study, some engineering economic estimates* on actual systems as they may be used in practice are also included in Section V. Finally, some concluding remarks and recommendations are given in Section VI.

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* These estimates were carried out, under a subcontract with HYDRONAUTICS, Incorporated, by Dr. John A. Brown of John Brown Associates, Incorporated.

II. DISCUSSION OF THE PROBLEM

II.1 Nature of the Problem

As already mentioned in Section I, Army operations require human-waste treatment under a variety of scenarios, aboard Army vessels and in field installations, to give merely two examples. To ameliorate the water pollution arising from the discharge of shipboard wastes into the coastal zone and inland waterways of the United States, several governmental agencies such as the Environmental Protection Agency, the Coast Guard and the Navy have supported the development of Marine Sanitation Devices (MSDs). As an alternative to these MSDs, many of which are still in various stages of development, the U. S. Navy has chosen a simple Collection, Holding and Transfer (CHT) System composed of state-of-the-art components. In the CHT concept (Reference 2, for example), the human wastes are simply collected and held in a holding tank while the ship is in restricted waters, with the collected wastes being eventually pumped out to a shoreside treatment facility when the ship enters a port.

The CHT concept is especially suited to Army requirements since most of the Army watercraft are relatively small in size (typically with 5- to 14-man crews). The concept is even more attractive if the required holding capacity can be increased by utilizing recirculating chemical toilets or reduced-volume flush commodes. Such concepts are also attractive for application in Army field installations, where the amount of human wastes generated in field latrines can be significantly reduced by using recirculating toilets.

When reduced-volume systems such as the ones mentioned above are utilized for collecting and holding human wastes, it is necessary to develop new methods for handling and treating these wastes. It is relevant to emphasize here that these concentrated wastes, which typically contain one or more percent of solids, are neither like the relatively less concentrated wastes encountered in municipal sewage treatment practice, nor of the consistency of sludge resulting from biological digestion of raw wastes. Thus the sludge dewatering and disposal techniques developed for municipal sewage are not directly applicable in the present context, at least not without further intermediate treatment steps. It should also be noted that any treatment methodology that is developed needs to be flexible and versatile, since it may be required to treat shipboard wastes in situ, treat wastes collected from several ships at a shorside facility, or treat wastes from field latrines. The objective of the present study was to investigate the feasibility of using the HYDROPERM system as a principal unit operation in the treatment methodology.

Water management and wastewater treatment are required in Army operations in other contexts as well. In areas of limited water availability, the best system for field application is one which emphasizes water recycle and reuse. Such a system may be required to treat the combined wastes from laundries, galleys, showers, and other sources, with options for the recycle, reuse or discharge of the treated wastewaters. The MUST system, currently under development for use in Army field hospitals, is a good example of such a system (Reference 3). In all these systems efficient removal of suspended and colloidal solids from the waste streams is a necessary prerequisite before further treatment. For example, advanced treatment processes such as reverse osmosis or carbon adsorption do not function successfully in the presence of fine solids, since, under these conditions, the RO membranes and the carbon columns experience severe clogging and attendant flux decline. The HYDROPERM system is ideally suited for the pretreatment of wastewaters prior to the use of advanced tertiary treatment methods of the type mentioned above.

II.2 Available Treatment Systems

There are three general classes of treatment systems which are available for treating the types of wastewaters under consideration here, namely, biological, chemical and physical. While biological treatment methods such as the activated sludge process, trickling filtration and storage oxidation lagoons have been used extensively in municipal sewage treatment, they are unsuitable for handling the relatively small volumes of concentrated sewage of concern here. Also, the biological systems are inherently neither compact nor portable, which are necessary requirements for field or shipboard application. Chemical treatment methods such as coagulation and flocculation often produce hydrous sludges which are difficult to dispose of and are also unsuited for the relatively concentrated wastes of concern here.

A third class of treatment system, one which utilizes a physical principle such as filtration, centrifugation or vacuum drying, is better able to fulfill the requirements of compactness, portability and flexibility. For example, the MUST water renovation system already mentioned above (Reference 3), utilizes many physical-treatment unit operations such as ultrafiltration and reverse osmosis. Several authors have also investigated the feasibility of utilizing membrane filtration processes, such as ultrafiltration (Reference 4) and reverse osmosis (Reference 5), for the treatment of raw municipal sewage effluents. Thus, it is logical to investiage the feasibility of utilizing physical filtration, either alone or together with other physical processes, for the treatment of the wastes of concern here.

Filtration processes can be grouped into two broad categories: normal-flow; and cross-flow types. In the former, the flow of the wastewater is normal to the filter surface, so that the separated solids continuously accumulate on it, cause a steady decline in filtration rate when the pressure differential across the filter medium is held constant and necessitate regular backwashing. Activated carbon and multimedia filters belong to this category, and they operate efficiently only when the suspended-solid content of the wastewater to be treated is quite low. However, it has recently been demonstrated (Reference 1) that a variation of the conventional vacuum drum filter technique can be used to successfully treat concentrated wastes of the type of concern here. In this technique, a fairly thick (2.5 to 13 cm) precaot of diatomaceous earth is depoisted on the rotating drum of a conventional vacuum filter prior to the start of the filtration, and a knife edge driven by a micrometer drive is utilized to continuously scrape off the precoat and the solids accumulating on it as filtration proceeds. Of course, every technique requires the eventual disposal of the sludge.

In cross-flow filtration (Figure 1), the flow of the wastewater is parallel to the filter surface, so that the continuous accumulation of the filtered solids on it can be prevented by the hydrodynamic shear exerted by the wastewaters as they flow past the filter surface. Thus, as filtration proceeds, the concentration of solids in the feed will continuously increase, and filtration can be continued until a sludge of a desired concentration if formed. In other words, cross-flow filtration affords, at least in principle*, the possibility of quasi-steady state operation with a nearly constant filtrate flux when the driving pressure differential across the filter surface is held constant (Reference 6).

The HYDROPERM filtration tubes belong to the general class of filters which can be grouped under cross-flow microfilters. However, the HYDROPERM tubes possess the important feature that their physical characteristics (such as tube diameter, wall thickness, porosity and pore-size distribution) can be controlled closely during the manufacturing process. With HYDROPERM, the pore-size distribution of the tubes can be selected for the size and the nature of the particulates in a given feed stream, so as to obtain optimum filtration performance. A detailed description of the features of HYDROPERM will be deferred until Section III.

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* In actual practice, a relatively slow flux decline will nevertheless occur, requiring "cleaning" of the filter surface over relatively longer intervals, say, of the order of once every one-hundred hours of operation.

II.3 Specific Objectives of the Present Study

In light of the background discussions given above, it is now possible to view the specific objectives of the present study in their proper perspective. The principal objective of the study was to examine the feasibility of utilizing HYDROPERM filtration to further reduce the volume of the wastewaters from recirculating or portable chemical toilets. The filtrate was required to satisfy either directly or after minimal further treatment (such as ozonation or chlorination) the following requirements: less than 150 mg/ℓ of suspended solids and 1000 fecal coliform bacteria per 100 mℓ of the permeate. The filtrate is also required to be of sufficient quality that it can be successfully treated for water renovation by advanced tertiary methods like reverse osmosis. The concentrate produced by the HYDROPERM unit operation is required to be sufficiently thick so as to afford further treatment by sludge-thickening and handling processes such as the Carver-Greenfield Process*.

The specific objectives of the present study were then to conduct a preliminary optimization study in terms of "selecting" the HYDROPERM System for the given effluent under consideration by choosing the appropriate pore structure of the tubes as well as the test conditions. An important objective was to assess the degree to which the already concentrated wastes can be concentrated further using HYDROPERM filtration, before utilizing a sludge dewatering process. In this regard, it should be emphasized that the basic limitation in achieving a high concentration of solids in the feed is not the inability of the HYDROPERM tubes to handle such wastes, but rather was associated with the difficulty of pumping thick sewage slurries. It should be noted that sewage slurries with even three to four percent of solids can be quite thixotropic in nature.

To make the study comprehensive, one of the objectives was to process the concentrate produced by the HYDROPERM System

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* The Carver-Greenfield Process (Reference 7) is an oil-based evaporative-drying technique which produces dry, sterile solids from sewage sludge. In the process, the sludge to be treated is fluidized by addition of a special oil and the mixture is evaporated under a controlled temperature. Since the water evaporates at a lower temperature than the oil, the water in the mixture can be driven off without the loss of oil. The solids are then removed by centrifugation and the oil is recycled.

using the Carver-Greenfield Process*. Since the ultimate feasibility of such a sewage treatment system may be as strongly influenced by economic considerations as others, a brief economic assessment was also undertaken.

It should be emphasized that the present study was a preliminary, feasibility study; as such, many aspects which are important for a final-system design (such as the long-term flux behavior of the tubes over hundreds of hours of operation) were not addressed in the present study. It is hoped that these aspects can be investigated in future follow-on programs.

* The tests were carried out under a subcontract by Dehydro-Tech Corporation, East Hanover, New Jersey.

III. THE HYDROPERM™ SYSTEM

III.1 Description of the System

The "heart" of the HYDROPERM System is the HYDROPERM microfiltration tube which is manufactured by HYDRONAUTICS, Incorporated using a proprietary process. As mentioned earlier, the important feature of these tubes is that their pore structure can be varied over a wide range during the manufacturing process. Three typical pore size distributions are shown in Figure 2. 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 2, 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 and, to date, tubes of Polyethylene, Nylon, PVC and Noryl have been produced. Tubes I and II in Figure 2 are made from Polyethylene, while Tube III is made from Nylon. 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 fairly simple model for the filtration process. 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, whose walls act as "in-depth" filters, particulates which are larger than the largest pore of the tubes will be retained on the inside walls of the tubes, while particles which are of smaller size will gradually penetrate into the wall matrix. Clearly, the filtration performance of the tubes (both as to flux rates and permeate quality) will depend upon the manner in which the smaller particles are retained within the filter matrix and upon the properties of the "cake" that may be formed by the larger particles retained at the tube walls. Continuous buildup of the cake is of course prevented by the shear exerted by the circulating feed flow within the tubes.

From the simple model described above, it is clear that there is a close relationship between the size of the particles in the feed and the size of the pores in the tubes, and that, for optimum performance, the tubes will have to be selected for a given effluent. The important feature of the HYDROPERM tubes is indeed that they afford such "selection" and laboratory tests with a wide variety of effluents have conclusively demonstrated (References 8 and 11) the practical

utility of such a selection. Before undertaking comprehensive tests with any new effluent, it is our practice to conduct preliminary "screening" tests with tubes of different pore-size distributions to determine which are the best suited to the specific effluent under consideration; more detailed tests are then done with the tube. Examples which illustrate the selection procedure will be given in Section IV.

In actual application, the tubes are used in bundles secured together at their ends by suitable fittings, and these "modules" constitute the basic "building blocks" of a filtration system. The modules can be arranged in any manner desired, and the waste waters are circulated, under pressure (usually 0.35 - 3.5 kg/cm^2), through the modules. The filtrate which permeates through the tubes is collected using appropriately designed equipment. A "typical" module is shown in Figure 3. This module has 242 tubes, each approximately 1.5 meters long, and has a total filtration area of 7.4 square meters.

When compared with other systems, HYDROPERM offers several unique advantages. These are summarized below:

(i) Compactness: HYDROPERM filtration systems, unlike biological and chemical systems, do not require large areas. Indeed, they can be engineered to fit available space.

(ii) Flexibility: Since the HYDROPERM systems can be produced in a wide range of sizes, and since construction is modular, no scale-up problems are involved.

(iii) Versatility: Since the HYDROPERM System is excellent for the removal of suspended solids and oils, the permeate can be either directly recycled in cases where the presence of dissolved solids does not bar such water reuse, or it can be treated further with tertiary systems where high quality product water is required either for reuse or discharge.

(iv) Ruggedness: Since they are made from inert thermoplastics, the performance of HYDROPERM tubes does not depend, in general, on changes in influent pH. Moreover, due to their rugged structure and low operating pressure, HYDROPERM modules are not subject to the fouling and leaking problems that have plagued some membrane systems; nor are they subject to clogging in the presence of oily wastes.

(v) Ease of Maintenance: Because of their ruggedness and modular construction, HYDROPERM systems are easy to maintain. They can be engineered in such a way that a failure in a given module causes only a small part of the total system to be shut down.

(vi) Product Recovery: Since no chemical changes are involved, product recovery is possible.

The virtually total absence of suspended solids in the permeate from the HYDROPERM tubes makes the permeate ideally suited for further treatment for the removal of dissolved solids by optimal existing reverse osmosis membrane systems, so as to produce a completely reusable product water. It should be noted that commercially available cost-effective RO membrane systems perform rather poorly in the presence of fine suspended solids, due to the formation of deposits and clogging at the membrane surface. Thus, there is, in general, a rapid decline of the product-water flux to unacceptably low values. However, when the membrane modules are supplied with the high quality permeate from the HYDROPERM system, no such difficulties should arise, because of the virtually total absence of suspended solids in the permeate. Therefore, the unique combination of the proprietary HYDROPERM system and a reverse osmosis membrane system should be capable of producing reusable product water from numerous inudstrial or domestic effluents.

III.2 Previous Tests with Sewage Effluents

Numerous laboratory and field tests have been carried out with HYDROPERM filtration of a variety of waste effluents. Since these tests have been described fully elsewhere (References 8-11), they will not be discussed here. However, it is relevant to review here previous tests on HYDROPERM filtration of sewage effluents. Tests have been conducted* with both dilute untreated sewage effluents and concentrated digested municipal sludge. In both types of tests, HYDROPERM tubes demonstrated the ability for almost total removal of suspended solids. The untreated raw wastes tested had a total-solids content of about 750 mg/ℓ of which about 120 mg/ℓ was suspended solids. The filtrate was almost free of suspended solids and BOD rejection was about 90%. Feed coliform bacteria was reduced from about 1,100/100 mℓ in the feed to about 3/100 mℓ in the permeate.

The digested sludge tested had a total solids content of 18,000 mg/ℓ of which the suspended solids accounted for about 16,000 mg/ℓ. The BOD of the feed was 2,600 mg/ℓ and the

* These tests were conducted at HYDRONAUTICS, Incorporated by J. Ricklis and A. Gollan.

coliform count was over one million. Again, the filtrate was nearly free of suspended solids even at these high feed concentrations. BOD reduction was again about 90% and there was almost total removal of the fecal coliform bacteria with the values in the feed and the permeate being respectively, 1,100,000/100 mℓ and 11/100 mℓ. One interesting result of these tests that is worth emphasizing is that the HYDROPERM tubes displayed, in spite of their micron-sized pores, significant removal capability for total nitrogen and phosphates. In the sludge tests the total nitrogen concentrations of the feed and permeate were, respectively, 1,390 mg/ℓ and 200 mg/ℓ, while the corresponding values for phosphates were 340 mg/ℓ and 62 mg/ℓ. These rather surprising results have to be viewed in terms of the in-depth filtration characteristics of the HYDROPERM tubes and the "dynamic membrane" that probably forms on their inner walls.

One other feature of HYDROPERM tubes that is worth noting in the present context is their ability to separate oil-water emulsions (References 8 and 9). As will be seen in Section V, this feature of the tubes was used to advantage in the present study.

IV. EXPERIMENTAL APPARATUS AND TEST PROCEDURES

IV.1 The Test Loops

The laboratory 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 were either 6 mm or 9mm, 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 4. As indicated on the figure, the loops contain a feed reservoir (~ 11 liters capacity), a circulating pump, a flow meter, pressure gauges to measure pressure deops over the length of the tubing being tested and appropriate valving. To ensure proper hygenic conditions, the tests were conducted in a small, self-contained shed; see Figure 5.

Basically, two different modes of operation are used when carrying out the tests. In the first, which is the one most often used in the tests and simulates "continuous-mode" field operation, the permeate is remixed into the feed reservoir, so that (except for evaporation losses) the volume of the circulating feed, as well as its suspended-solids concentration, remain constant. The feed in the reservoir is replaced at appropriate intervals to eliminate changes in characteristics due to biological activity and/or constant recirculation. Provision is also made to compensate automatically with additional feed for any loss in circulating-fluid volume due to evaporation (see Figure 4).

In the second mode of laboratory tests, which simulates a batchwise process in a field prototype system, the permeate is collected in a separate reservoir, so that the volume of the circulating feed continuously decreases while its suspended solids concentration continuously increases. In this mode of operation, the tests are continued until specified feed concentration is reached or until the volume of the feed becomes so low that adequate pump suction from the reservoir can no longer be maintained.

IV.2 The Wastes

The wastes tested in the present study were obtained from the operators of portable, construction-site toilets, since these wastes were considered to be most representative of the type of wastes generated at Army field installations. In general, these wastes contained various additives such as preservatives (usually formaldehyde), coloring agents (blue-green dyes) and odor-masking compounds (such as pine oil).

They also had rather unusual characteristics. For example, total solids determination was made difficult by the apparently significant amount of volatile solids present in the wastes. Controlled evaporation at 55°C under vacuum indicated a total solids content of between 1.23% and 1.6%.

The wastes were also quite thixotropic, and could not be filtered with standard filter paper; no permeation at all occurred under gravity when the wastes were allowed to stand over a filter paper in a funnel. Similar results were obtained with standard glass filters under vacuum. Thus the suspended solids content of the wastes were estimated using centrifugation. Centrifuging of the wastes for three hours at 3,000 rpm yielded a value for suspended solids content of about 4,300 mg/ℓ. However, because of the reasons already outlined, the above figure has to be regarded as an estimate.

V. EXPERIMENTAL RESULTS AND DISCUSSION

V.1 Preliminary Screening Tests

As mentioned in Section II, the important feature of the HYDROPERM tubes is indeed that they can be selected for any given effluent, in the sense that their essential characteristics (such as pore-size distribution) and operating conditions can be varied to obtain the best possible performance with the specific feed under consideration. The selection is accomplished by performing a series of screening tests, each usually only a few hours in duration, on several HYDROPERM tubes (with a wide range of characteristics) over a range of operating conditions (such as circulation velocity and pressure). The present study began with several such "screening" tests on various HYDROPERM tubes.

The first test was done with a 9 mm I.D., Polyethylene HYDROPERM tube with a porosity of 65% and a wall thickness of 1 mm. The pore-size distribution of the tube used is shown in Figure 6(a). The test conditions were 0.35 kg/cm^2 filtration pressure and an internal circulation velocity of 1.8 m/sec. The initial flux from this tube was 559 ℓ/m^2-day, while the permeate was relatively clear, with a light blue-green color, and free of any suspended solids. After one hour of continuous filtration at a constant-concentration mode (that is, with the permeate being remixed into the holding reservoir), the flux dropped to 387 ℓ/m^2-day, and after five hours to 175 ℓ/m^2-day. In view of the relatively thick and difficult nature of the waste, the above results were in themselves not unsatisfactory; however, it was believed that better results were possible. Thus, this test was discontinued after five hours.

In the second test, the wastes were first put through a 10-mesh sieve to see what effect this might have on filtration performance; all other conditions were identical to those in the first test. Sieving did seem to improve the initial flux, which was now 991 ℓ/m^2-day. However, after three hours of operation, the flux was essentially the same as in the first test. Again, the test was discontinued at this point.

In a third test, again the same tube was used but with the test conditions now being changed to 3.3 m/sec velocity and 0.7 kg/cm^2 pressure. However, the performance did not change markedly, with the initial flux being 604 ℓ/m^2-day and the flux after 3 hours being 163 ℓ/m^2-day.

Screening tests were also done with a number of other tube types with varying results. All of these tests need not be described in detail here. Suffice it to say that the best

results were obtained with three different types of tubes and that these were chosen for further more detailed tests. All three of these tubes had relatively high initial fluxes (more than 816 ℓ/m^2-day) and relatively small flux declines. Also, all three of the tubes were of 9 mm inside diameter and 1 mm wall thickness, though two of the tubes were made from Nylon and the third from Polyethylene. The two Nylon tubes had a porosity of 65%, with one having a pore structure identical to that shown in Figure 2 (Tube III); the other had a pore-size distribution which was somewhat less peaked and had the maximum number of pores at a somewhat larger pore size. The Polyethylene tube had a porosity of 80% and its pore-size distribution is shown in Figure 2 (Tube II).

Since the two Nylon tubes had very similar pore structures and had very similar performance, no specific distinction will be made between them in the discussions given below with both being referred to simply as Nylon tubes; the third tube will be referred to as the Polyethylene tube*.

It was also learned from the screening tests that, in general, a smaller filtration pressure is to be preferred over a larger one since, even though the higher pressures yield higher initial fluxes, they also lead to much larger flux declines. For example, at a filtration pressure of 0.2 kg/cm^2 and a circulating velocity of 3.3 m/sec the Nylon tube yielded an initial flux of 1,195 ℓ/m^2-day and after twenty hours of continuous operation a flux of 596 ℓ/m^2-day. The detailed results from this test are shown in Figure 7.

V.2 Concentration Tests

All of the "screening" tests described above were conducted in the constant-concentration mode in which the permeate from the tubes is continuously remixed into the feed reservoir. Thus, both the total volume of the feed being processed as well as its concentration always remain constant during the tests. While this mode of operation is desirable for the rapid screening of different tubes, the ultimate application of the tubes requires that they treat a waste which is of increasingly higher concentrations; that is, they are required to produce concentrated sludge and clear permeate from the initial wastes. Thus tests were also conducted with the selected Nylon and Polyethylene tubes in "concentration modes." There were two different types of experiments that

* Of course, this terminology is for convenience only. The actual material used in the construction of the tubes is of secondary importance in determining the performance; pore structure and pore-size distribution are the fundamental parameters.

were conducted under this classification. In the first, which can be termed the "batch-concentration mode," the permeate is continuously withdrawn from the system (which is started with an initial fixed volume of feed wastes), so that the concentration of the circulating wastes continuously increases and the total volume of the circulating wastes continuously decreases. In the second, which can be termed the "constant-volume mode," fresh feed is added continuously to the waste holding reservoir at the same rate that the permeate is produced, so that the volume of the circulating fluid always remains constant; the concentration of the feed, of course, continuously increases.

The constant-volume tests were done with the Nylon tube described earlier (pore structure analogous to that of Tube III in Figure 2). The test pressure was 0.14 kg/cm^2 and the test temperature was about 25°C. The circulating velocity through the tube (which had an I.D. of 9mm) was 3.3 m/sec. The volume of the wastes used in the test was about 7.6 liters.

The test results are shown in detail in Figure 8. The initial permeate flux was about 1,020 ℓ/m^2-day, and after a little more than one hour, the flux had decreased to about 489 ℓ/m^2-day. However, thenceforth, the flux remained nearly constant at the latter value (see Figure 8) despite the fact that the concentration was increasing steadily. Note that for a constant-volume mode, the concentration must increase linearly with the amount of permeate produced, with the actual functional relationship being

$$C = \left(1 + \frac{V_p}{V_i}\right) C_i \qquad [1]$$

where C_i and C are respectively the initial concentration and the concentration at any subsequent time, V_p is the total volume of the permeate produced up to the time under consideration and V_i is the initial feed volume (equal to the volume of the circulating flow). In the derivation of Equation [1], we have assumed that all of the suspended solids are retained within the system by the tubes and that there is a conservation (with time) of these solids within the test setup. The former assumption is justified by the fact that the permeate produced in the tests is almost totally free of suspended solids; more will be said about the latter assumption in Section V.6. Based on the amount of permeate that was collected, it is estimated from Equation [1] that the concentration of solids in the circulating fluid at the end of 20 hours was about one and one-half times that at the start of the test.

It has already been pointed out that the concentrated sewage wastes used in the present study were quite thixotropic and difficult to pump. A direct manifestation of this fact was frequent pump failures and the clogging of valves in the test loops during the experiments, especially as the wastes were further concentrated*. Thus, twenty hours into the constant-volume concentration test, there was a pump failure and the test had to be interrupted. When the pump was repaired and the test was resumed with the same feed after an elapsed time of seventy-two hours, the initial flux was 640 ℓ/m^2-day, but this quickly dropped to the range of values (~ 490 ℓ/m^2-day) before the interruption (see Figure 8).

The test was continued for twenty-four more hours (for a total of forty-four hours) when it had to be interrupted again due to the clogging of a valve in the test loop. The flux at the time of interruption was 473 ℓ/m^2-day. However, it should be noted that the thixotropic nature of the wastes also frequently caused significant uncontrolled reductions in internal pressure (and hence, also the flux), especially when the tests were continued unattended during the night.

After resumption of testing, the constant-volume-mode operation was continued for twenty-three more hours (for a total of sixty-seven hours from the start), with frequent interruptions due to pump failure and valve clogging. As can be seen from Figure 8, the average permeate flux during this period was about 226 ℓ/m^2-day. From this point, the test was carried out in a "batch-concentration mode"; that is, the permeate was withdrawn from the system with no feed being added to it. The flux results for this part of the test are also shown in Figure 8, the average flux being about 245 ℓ/m^2-day despite the increasing concentration.

The conclusion which can be drawn from the test described above is that HYDROPERM tubes are capable of producing essentially suspended-solids-free permeate at the indicated flux levels even from relatively concentrated, thixotropic sewage wastes.

A second concentration test was carried out using the Polyethylene tube of eighty percent porosity (see Figure 2, Tube II for its pore-size distribution). The major drawback of this tube is that, because of the large void volume in its wall matrix, it is relatively weak and, therefore, susceptible

* These results demonstrate that in the design of pilot-scale or prototype plants to handle such thixotropic sludges, great care should be taken in selecting the proper types of pumps and valving.

to failure, especially when used with certain types of effluents. Nevertheless, it was decided to carry out some detailed studies with this tube since it displayed large values for the permeate flux during the screening tests. For example, at a filtration pressure of 0.35 kg/cm^2 and circulating-flow velocity of 1.8 m/sec, its initial permeate flux was over 3,060 ℓ/m^2-day! When tested in a constant-concentration mode, the flux gradually decreased and after four hours of operation, was 2,280 ℓ/m^2-day. Later, however, there was a physical failure of the tube and the test had to be discontinued. To ensure that the failure was not an anamolous one due to a random imperfection in the tube, the test was repeated under identical conditions with a new tube. Again, tube failure occurred after six hours of testing.

Failure of the type described above in high porosity, thin-walled tubes is due to material fatigue and has been studied extensively at HYDRONAUTICS, Incorporated in a different context. The fatigue failure of the tubes is strongly dependent on the internal pressure and test temperature, and can be prevented either by suitably controlling these parameters or by taking appropriate measures to strengthen the tubes. The latter course of action involves using larger wall thicknesses, stronger tube materials (such as Nylon instead of Polyethylene), incorporation of various strengthening agents within the tube matrix and mechanical strengthening of the tubes by the use of external supporting jackets.

Thus the failure of the eighty-percent porosity Polyethylene tubes during the screening tests was not in itself considered to be a fatal flaw at this early stage of investigation and it was decided to undertake concentration tests at a lower filtration pressure. If these preliminary results were successful, then means of increasing the strength of the tubes (while maintaining the pore structure and the pore-size distribution) will clearly be worth investigating at a later date. The results of the test are shown in Figure 9. The test was conducted in a batch-concentration mode at a filtration pressure by 0.14 kg/cm^2 and a feed velocity of 3.3 m/sec. As indicated in Figure 9, the initial flux at the start of the concentration was 983 ℓ/m^2-day. The initial volume of the waste was about 7.6 liters, and the right-hand scale in Figure 9 indicates the volume reduction as concentration proceeded. After some thirty-five hours of intermittent operation (the tests were halted at night), eighty percent of the initial volume had been removed from the system as a relatively clear permeate free of any suspended solids. The corresponding flux levels are also indicated in Figure 9 and it can be seen that these are quite reasonable. The total volume of permeate collected at the end of thirty-five hours was 6,151 milliliters and this value is in excellent agreement with that obtained by integrating the area under the flux curve in Figure 9. The volume of concentrated sludge remaining was 1,490 milliliters.

In addition to the test described above, the same tube was also operated intermittently in the constant-concentration mode. The tube did ultimately fail after forty-four hours of operation. Thus, in summary, if the Polyethylene tube can be adequately strengthened, it offers the potential for yielding relatively high fluxes while operating in a concentration mode.

V.3 Tests Using Oil Fluidization

As mentioned earlier, the principal difficulty in treating the relatively concentrated wastes of the type of concern here is not that the HYDROPERM tubes are unable to handle such wastes, but, rather, that these wastes are extremely thixotropic, difficult to pump and cause frequent clogging of valves and other constrictions in the test loops. To overcome this difficulty, a new method of fluidization had been tried earlier at HYDRONAUTICS, Incorporated. In this method a fluid which is immiscible with the wastes and does not permeate through the HYDROPERM tubes is added to the sludge before it is circulated through the tubes. Since the added fluid does not permeate through the tubes, it maintains the sludge in a fluid state while continuous dewatering is accomplished. This technique had been employed earlier with municipal sewage sludge by using oil as fluidizing medium, since HYDROPERM tubes have the ability to separate oil-water mixtures (References 8 and 9).

In the present study, initial exploratory tests on the oil-fluidization technique were conducted by slowly adding, during a test, specific amounts of Isopar (which is a highly refined, white petroleum oil) to the circulating fluid. All of the oil-fluidization experiments were conducted with Nylon tubes (with the pore characteristics described earlier) and the test pressure and velocity were respectively 0.35 kg/cm^2 and 1.8 m/sec. The first test was started with the wastes alone and was run in a constant-concentration mode. The initial permeate flux was 1,277 ℓ/m^2-day. Within one-half hour the flux had dropped to 995 ℓ/m^2-day. At this point one liter of Isopar was added to the feed tank, which contained about seven liters (2 gallons) of waste. Relatively clear effluent continued to permeate through the tubes. The bulk of the oil was retained within the circulating flow and the very slight trace of oil that appeared in the permeate separated out easily on standing. The test was continued for a total of six hours with frequent addition of oil. The final flux was about 489 ℓ/m^2-day.

After the initial test, a more comprehensive test was undertaken in the constant-concentration mode. The test was begun with a mixture of equal parts of the waste and Isopar. The test continued smoothly and in an uninterrupted fashion for forty-seven hours. The final permeate flux was 237 ℓ/m^2-day.

Concentration tests were also carried out in the oil-fluidized mode. These tests were carried out on 6 mm I.D. Nylon tubes with a pore structure similar to that of 9 mm I.D. tubes. The results of one of the tests is shown in Figure 10. The test was begun with a mixture of 3.8 liters of waste and 3.8 liters of Isopar. As shown in Figure 10, the initial flux was 1,179 ℓ/m^2-day. For the first twenty hours the test was carried out in a constant-concentration mode; that is, the permeate was remixed into the feed reservoir. Thenceforth, the test continued in a batch-concentration mode; that is, the permeate was collected separately. After twenty-six hours of continuous operation, 1,540 milliliters of permeate had been collected and the flux was 224 ℓ/m^2-day. At this point the test was discontinued. Since the volume of the waste at the start of the test was about 3.8 liters, the degree of dewatering achieved was about forty percent.

Another test was conducted in a slightly different operational mode. This mode is similar to the constant-volume mode described earlier, but here oil is added continuously to the circulating fluid to replace the permeate that is withdrawn. Thus, the volume of wastes in the circulating fluid continuously decreases (and its concentration increases) even though the total volume of the circulating fluid remains constant. The results of this test are shown in Figure 11. The test was begun with a mixture of 3.8 liters each of the waste and the oil. After forty-two hours of operation, 3,280 milliliters of permeate had been removed from the system. Thus, the degree of dewatering was eighty-seven percent! Details of the flux concentration histories are shown in Figure 11.

The tests described above demonstrate that the oil-fluidization, when combined with HYDROPERM filtration, is a powerful technique for dewatering the difficult thixotropic sludges of the type of concern here.

V.4 Module Tests

As mentioned earlier, one of the objectives of the present study was to produce a concentrated sludge using HYDROPERM tubes and to assess the feasibility of further dewatering of this sludge using the Carver-Greenfield Process. For this purpose, preexisting HYDROPERM modules were used to concentrate the remainder of the 208 liter drum of waste feed that had been obtained from the portable-toilet operator.

Module I

Number of tubes:	7
Tube I.D.:	0.9 cm
Material:	Nylon
Active Surface area:	736.3 cm^2
Module length:	45.72 cm
Module OD:	6.03 cm

Module II

Number of tubes:	7
Tube I.D.:	0.9 cm
Material:	Nylon
Active surface area:	2288 cm^2
Module length:	121.92 cm
Module OD:	6.03 cm

As pointed out earlier, these wastes contained about 1.5% solids in water to which a proprietary preservative containing pine oil and formaldehyde had been added. It also contained a green dye.

The test was conducted in constant-volume mode and began with a mixture of equal volumes of the waste and Isopar (about 15 liters each). Clear water permeated out through the HYDROPERM tube wall, and the operator added more of the wastes to the reservoir from time to time so as to keep the reservoir volume (and oil/water ratio) constant. This operation was continued until the entire drum had been added and an equivalent amount of filtered water collected, leaving about 30 liters of the oil-sludge mixture in the holding reservoir. Beyond this point the filtration was continued in a batch-concentration mode. However, as the filtration proceeded and the reservoir level began to fall, the mixture gelled rather abruptly into an unpumpable residue!

The gelled residue was scraped out of the reservoir, jugged in a polyethylene carboy, and shipped to the Dehydro-Tech Corporation for analysis and final dewatering by the Carver-Greenfield Process. That phase of this work is described in Section V.5 below.

The permeate was retained at HYDRONAUTICS, Incorporated for analysis, and a smaple was forwarded to Dehydro-Tech Corporation for their analysis and for comparison with the original wastewater. The Dehydro-Tech findings are discussed in Section V.6 along with the other analyses. A sample of the original wastewater was also forwarded to Dehydro-Tech for analysis and comparison with the other two samples.

While a detailed analysis of the results will be deferred till later, it is relevant to note here that the total volume of waste treated was 165 liters. The volume of permeate removed was 162 liters. Thus, the degree of dewatering achieved by HYDROPERM alone was 98.1%.

V.5 The Carver-Greenfield Process

The Carver-Greenfield Process is a technique for the highly efficient removal of water by evaporation without the

problems of thickening and scaling that are often encountered in simpler techniques. A metered quantity of fluidizing oil is added to the feed solution, slurry or sludge; and the mixture is passed through a series of multiple-effect, falling-film evaporators where the water is evaporated, leaving the solids suspended in the oil as a fluid slurry. The oil is then separated from the dry solids in a centrifuge and returned to the feed tank for reuse.

One of the banes of most direct contact and heated surface evaporators is the fouling of interior surfaces by the precipitation and caking of separating and/or decomposing solutes; and one of the major limitations of any concentration or filtration process is the thickening—often to the point of gellation—of the feed stream that occurs as the fluidizing liquid is removed and the concentration of suspended solids rises. It is not unusual for organic slurries such as sewage sludges to become too thick to pump at solid loadings of 3% and to become quasi-solids at loadings of 6%. Such colloidal systems can be further dewatered only with great difficulty in devices such as centrifuges or pressure or vacuum filters.

In the Carver-Greenfield Process, the added fluidizing oil captures the precipitating solids and keeps them in freely-circulating suspension. It even fluidizes such intractable systems as the normally-unpumpable quasi-gels formed by activated sludge solids and water, and activated sludge is readily dewatered all the way to dryness in a Carver-Greenfield unit. Unlike the aqueous case, the oil-solids slurries are readily separated by simple filtration or centrifugation to give dry, recovered solids and clean fluids.

The HYDROPERM residue, consisting of a stiff oil-water emulsion, was first analyzed in a glassware unit simulative of a full-scale Carver-Greenfield unit. In this analytical procedure, a sample of the raw feed is mixed with toluene in a distillation flask; and a mixture of water and toluene is distilled off and condensed until no more water comes over. More toluene is added from time to time if necessary. The toluene remaining in the flask is then separated from the solids remaining the the flask, and the toluene is evaporated to dryness. All amounts are weighed. This gives the amount of evaporable water in the feed, the amount of oil-soluble residue (usually called "fats and oils"), and the amount of oil-insoluble residue (usually called "nonfat solids"). In the case of domestic sewages, the "nonfat solids" are largely cellulose fibers from disintegrated paper; and the "fats and oils" are a complex mixture of involatile natural liquids such as esters and low molecular weight fats.

The HYDROPERM residue contained a major amount of Isopar since Isopar was added in the filtration step, and the Isopar

content was also measured. The resulting analyses were as follows:

	HYDROPERM Concentrate
pH	8.1
% water	31.0
% Isopar	66.7
% total solids	2.34
% "nonfat solids"	1.69
% "fats and oils"	0.65

A test on the HYDROPERM residue was also conducted in the Carver-Greenfield pilot plant in East Hanover, New Jersey, which is a single-stage, vertical, falling-film evaporator with associated feed and mixing tanks, circulating pumps, vapor chamber, collection vessels, centrifuge and the like. It is illustrated in the schematic flow diagram shown in Figure 12 and the general photo shown in Figure 13. It has a capacity of approximately 6.8 - 15.9 kg of water evaporated per hour depending upon the characteristics of the feed. It is not designed for high efficiencies or throughput; but rather for demonstrations of feasibility, screening for unexpected difficulties and the gathering of engineering data such as yields, heat transfer rates, and the like.

The wastewater concentrate removed from the HYDROPERM unit and shipped to Dehydro-Tech Corporation weighed 10 kg (approximately four gallons) and contained 6.6 kg of Isopar which had been added in the HYDROPERM step, leaving only 3.32 kg of actual sample. This is much too small a sample for proper operation of the Hanover pilot plant; consequently, the results obtained are general rather than detailed. The situation is rescued, however, by the fact that the wastewater residue is so similar to other residues which have been processed in large amounts that comparisons and extrapolations are quite valid.

A total of 0.18 kg of nonvolatiles was recovered from the pilot plant run, as compared to 0.23 kg predicted from the analytical data (0.17 kg of nonfat solids and 0.06 kg of fats-and-oils). In view of the inadequate size of the sample, this is good agreement. The pilot plant normally leaves a trace of Isopar in the recovered solids for dust control, and this can easily account for the extra 0.05 kg. None of the predicted 0.06 kg of fats-and-oils was recovered because the very small amount—only about 65 ml!—was simply lost on the internal surfaces of the pilot plant and in the volume of circulating

Isopar. As noted above, much larger samples are required for operations in good yields. Nevertheless, the essentially quantitative recovery of the nonfat solids, coupled with the familiarity of the sample type and the demonstrated lack of unexpected problems, makes this test run a satisfactory one.

The recovered nonfat solids consisted of a fluffy, fibrous, light-gray mass with very little odor. It was apparently essentially cellulose fibers from disintegrated paper, and would be expected to have a fuel value on the order of 1,990 Kcal, based on extensive experience with other, similar residues.

With the sole reservation that the sample size was too small to give good recovery of "fats-and-oils" in the pilot plant, this was an entirely satisfactory demonstration. No operational problems were encountered, and the recovered nonfat solids were in good agreement with analytical predictions. Although this process could technically operate in the field without difficulty, the economics of the system size prohibit its application.

Assuming a typical, multiple-effect Carver-Greenfield plant and recovery of the Isopar, the dehydration process would be energetically self-sustaining. Self-sustainment requires a feed solids content of approximately 6 Wt-% of which 70% is 5,550 Kcal/kg fuel value material, for a net fuel content of 233 Kcal/kg as compared to a net fuel content of this wastewater residue (ex Isopar) of 330 Kcal/kg. As a practical matter, however, one would never consider building a multiple-effect Carver-Greenfield plant for such a small waste stream (given as 1,061 liters of wastewater per day); the capital investment would be too large.

Of course, the resultant HYDROPERM residue emulsion containing a large fraction of oil is directly burnable without any further processing or dehydration; and that would be the recommended disposal method.

V.6 Analyses of the Concentrate and Permeate Samples

As already mentioned, the permeate in all of the tests conducted during the present study were found to be totally free of suspended solids. The total solids in the permeate (in this case, also equal to the dissolved solids) ranged from 0.37 to 0.65 percent. Since the total solids of the initial feed ranged from 1.23 to 1.6 percent (of which about 0.43 percent was suspended solids), the above results would appear to indicate that the HYDROPERM tubes also displayed a significant rejection for the dissolved solids!

However, a puzzling aspect of the results was also that the total solids in the concentrates did not increase in the expected manner. For example, in the test shown in Figure 9, eighty percent dewatering of the original feed was achieved, so that a five-fold increase in the suspended solids alone would be expected (or 5 x 0.43 = 2.15 percent). However, an analysis of the total solids in the final concentrate yielded only 1.81 permeate! Such material imbalances and the "disappearance" of solids were a rule in the present tests. Because of the in-depth nature of HYDROPERM filtration and also because of the filter cake that forms along the tube walls, it can be postulated that some of the solids are "lost" either into the wall structure or into the filter cake. However, this postulate alone is insufficient to explain away the significant imbalances noted in the tests, so that some additional explanation in necessary. It can be speculated that the missing solids were volatilized and/or oxidized during the prolonged aeration and agitation that takes place in the test loops. It should be noted that typically, depending on the circulating velocity, the entire volume of wastes in the test-loop reservoirs used in the present study are circulated through the HYDROPERM tubes once every one to three minutes.

Similar mass imbalances were also found in the detailed analyses that were carried out by Dehydro-Tech Corporation on the HYDROPERM concentrate from the module runs. The following detailed analyses and inspections were obtained on the raw feed, the HYDROPERM permeate and the HYDROPERM concentrate. Measured or observed values are shown in bold face type, assumed values are shown in parentheses, and calculated values are shown in quotation marks.

	Raw Feed	Permeate	Concentrate
pH	6.00	—	8.1
Liters	165.09	(161.98)	15.16
Kilograms	"164.73"	"161.63"	9.98
Wt-% water	"98.62"	"99.43"	31.0
Wt-% Isopar	0	0	66.7
Wt-% Total Solids	1.38	0.57	2.34
Wt-% Nonfat Solids	0.93	—	1.69
Wt-% Fats-and-Oils	0.45	—	0.65
Kilograms Solids Calc.	"2.27"	"0.91"	"0.23"
Kilograms Recovered	—	—	0.17

Again, the most significant feature of the above data is that approximately 1.13 kg of the initial 2.27 kg of dissolved and suspended solids appear to have disappeared during the filtration process. The exact amount is unknown because not all of the concentrate was recovered and weighed: there had to be some appreciable amount held up inside the HYDROPERM module and in the piping (because of the rather abrupt gelling described in Section V.4). But no conceivable amount of holdup could account for the observed approximately 50% loss, so there has to be a major disappearance mechanism. It can only be speculated that the missing material was volatilized—perhaps with oxidation—during the prolonged, intensive aeration associated with circulation through the HYDROPERM module*.

It might be pointed out that the 0.17 kg of solids recovered from the concentrate is actually in good agreement with the 0.24 kg predicted from analytical studies. The 0.23 kg consists of 0.16 kg of insoluble solids plus 0.06 kg of Isopar-soluble oily materials. The recovered material inherently consists of the insoluble solids with perhaps a trace of Isopar and/or soluble oils left on them, and 0.16 plus-a-little is in good agreement with 0.17.

In view of the fact that several different tests at two independent laboratories have yielded essentially the same results, it seems highly unlikely that there could be any errors in the analyses. Thus the "disappearance" of the solids has to be accepted at face value, with volatilization due to aeration and agitation being the tentative explanation. We cannot resist pointing out that no dismay should be felt at the disappearance of half of this feedstock. The object of this entire exercise is to get rid of this feedstock, and its voluntary disappearance is to be accepted with pleasure!

V.7 Flux Regeneration

It was pointed out earlier that unlike through-flow filtration, cross-flow filtration provides an ability to operate in an essentially quasi-steady state fashion. Nevertheless, there is, in general, a slow flux decline due to the buildup of a thin cake layer next to the tube walls. Moreover, since

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* The exact amount of volatilization that can occur in an actual pilot or prototype plant will presumably depend on the relative magnitudes of the holding-tank volume-rate of pumping of the wastes through the HYDROPERM modules, that is, on the average residence time of a particle within the holding tank before being recirculated.

HYDROPERM includes some aspects of in-depth filters, the effective pore structure of the tubes may gradually change with time due to the intrusion of particles in the feedstock into the tube matrix. In a typical HYDROPERM test in a constant-concentration mode, the flux usually declines in two stages. In the first stage, the flux declines rapidly from the initial value to about fifty to sixty percent of that value within an hour or two. In the second stage the flux gradually decreases over a period of several tens of hours to values which are only a few percent lower than the value at the end of the first stage. In the tests, it is usual practice to "restore" the flux to its initial value after a period of about one-hundred hours operation by "cleaning" the tubes for about ten laundry wastes, it has been found (Reference 11) that the flux can be restored (after each one-hundred hours of operation) to its initial value by circulating through the tubes for ten minutes a mild solution containing phosphoric acid. Similarly, when treating turbid waters it has been found that the flux can be restored by using a weak solution of sodium hypochlorite. Backwashing of the tubes is also possible.

In the present study, only a very preliminary investigation of cleaning was carried out. It has been found that, for the present wastes, a commercially-available bleach holds considerable promise. A more systematic and detailed investigation of the cleaning procedure should certainly be a necessary part of any follow-on studies.

V.8 Economic Estimates

As a part of the present study, a brief economic analysis of the proposed system was also undertaken. At the outset, it should be pointed out that the volumes of wastes involved in the present context are considerably smaller than ones for which we have experience in estimating costs. At 7.6 liters per day per man of concentrated waste, the total volume of wastes to be treated per day for a 14-man watercraft is only 106 liters! The cost of a HYDROPERM plant, like that of any other plant, is a function of scale, with large plants being much more economical on a per-gallon basis than small plants.

Thus, in these preliminary estimates, we have confined our attention to a shore-based facility that can treat the wastes from a group of watercraft. For small plants, on the order of 1,061 liters per day as contemplated in this study, the following generalities apply:

- Module cost = 538 per square meter of filter area.
- Associated pumps, piping, etc. = $5.00 to $10.00 per 3.79 liter/day.

- Filter area required = Daily load in liters/attainable flux in liter/meter^2-day.

  * Typical attainable flux in dewatering a 1.5-2% solids feed by approximately eighty percent .....409 ℓ/m^2-day.

  * Typical attainable flux in dewatering a 1.5-2% solids feed by more than eighty percent .....204 ℓ/m^2-day.

Assuming a requirement of 1,061 liters of wastewater per day (ten 14-man watercarft and 7.58 liters of wastewater per man per day; for 1,059 kg per day water and 13.6 kg per day solids), a HYDROPERM plant would consist of one HYDROPERM module and a pump and associated piping. At 409 ℓ/m^2-day and \$0.758/ℓ/day, the capital cost would be \$2,800. At 405 ℓ/m^2-day and \$0.379/ℓ/day, the cost would be \$5,600. Labor costs would be negligible, particularly if GI-operated, since very little operator attention is required, and material costs (principally for Isopar, \$0.29/ℓ) would also be negligible. Power costs to drive the circulating pump would be small and are not taken into account. The normal industrial costs of taxes and insurance are also not considered here. It should go without saying that the above numbers are first-cut estimates only, good for perspective and order of magnitude planning. Any serious cost estimate should be based on extended term pilot plant runs and should itemize all capital and operating costs in as much detail as possible for the specific application.

This study was focused on the removal of wastewater solids only; but in a complete installation, there would be additional operations required. The wastewater concentrate would have to be disposed of at some additional cost, and the filtrate may need polishing at some additional cost before discharge to receiving waters. The concentrate should pose no problem. At 67% Isopar it is flammable and could be disposed of in almost any available incinerator or burner. The filtrate water is beyond the scope of this study, although some preliminary thoughts are offered later in this section.

The Carver-Greenfield Process, which is economical on a large scale, would have a prohibitively high capital cost on the tiny scale of 1,061 liters per day. Some figures which apply to larger scales are contained in Appendix A.

It is appropriate at this point to compare the costs of HYDROPERM treatment with other methods. The technique of rotary vacuum precoat filtration (RVPF) dewatering of black water and other similar sludges was investigated by Johns-Manville for MERDC on Contract DAAG53-75-C-0276, and a

detailed summary of the work is available in the Final Report from that contract dated January 26, 1976. Briefly, the technique consists of applying a fairly thick (one to four inches) diatomaceous earth precoat onto a rotary vacuum filter and then filtering macerated black water through it to give a solids-free filtrate and a filter cake. The filter coat blinds rather quickly, and a rotary knife is used to shave the dewatered cake down to fresh filter aid after each pass through the feed reservoir. The discharged filter cake runs around 45% solids, about 6 to 12% volatile solids; and the filtrate is high enough in BOD and TOC that further treatment, as with carbon, is suggested.

Using a commercially-available 0.91 m diameter by 0.30 m face rotary precoat filter and HYFLO filter aid with appropriate tankage, piping and vacuum and transfer pumps, Johns-Manville estimated an equipment cost of $35,400 for a 758 ℓ/day untreated human waste treatment system, exclusive of filter cake incineration or filtrate polishing systems. They estimated a total weight, on two skids, of 1,362 kg empty; and they estimated a materials (filter aid) cost of $14.60 per 3,790 ℓiters filtered and a power cost of 151 Kwhr per 3,790 liters filtered.

Assuming the service is available at the site, hauling the black water away by a septic tank cleaning contractor is the cheapest solution in the short run. The trucks carry 7,580 litters typically, which means a 7,580 liter holding tank could be filled and then trucked away roughly once a week. Costs vary, but a typical hauling charge is $100 to $150 per truckload. At $125/load, $5000 would provide 41 weeks of disposal service (at 1,061 ℓ/day) with no additional costs of solids incineration or filtrate polishing. Over some longer periods of time, depending on the costs of solids, incineration and filtrate polishing, on-site treatment by HYDROPERM becomes more economical.

Most boat and trailer pump-out stations (in the New York - New Jersey area at least) either haul their wastes to a sludge dumping area or send them to a large, conventional, sewage treatment plant where they are mixed with a much larger volume of municipal sewage and disappear from sight. No example was found of a pump-out station that treated its own waste.

There are of course, a number of incinerating toilet systems on the market and/or under development. With incinerators, these systems run tens of thousands of dollars. They will not be discussed further here.

Finally, a few words on the need for "polishing" the HYDROPERM filtrate are in order. the data herein show a total solids content of 0.57% for the filtrate, which translates to 21.56 kg per thousand gallons or 4,700 mg/ℓ of dissolved burden. Some of that may be alkalinity and dissolved inorganic salts; but a considerable fraction of it is probably BOD and malodorous materials, and the filtrate will probably need some kind of polishing treatment.

Carbon column treatment is commonly suggested for such effluents. It is almost universally applicable, and capital and operating cost studies are available in MERADCOM files. It does present a new disposal problem: that of the spent carbon.

An alternative which should be considered is the new ozone-UV oxidation process which offers any (including limited) degree of polishing and imposes no logistic or disposal burdens except its electric power requirements. One embodiment of the ozone-UV process (Westgate's ULTROX) offers skid-mounted pilot units of appropriate size and cites power costs of $0.30 per 3,790 liters for treating 379,000 liters per day of secondary effluent of 16 mg/l TOC. Smaller units and heavier TOC loadings would cost more per 3,790 liters but less per day.

VI. CONCLUDING REMARKS

The present study was concerned with a preliminary feasibility investiagtion of the use of HYDROPERM filtration to concentrate the already concentrated human-waste effluents that are encountered onboard Army watercraft or at Army field latrine facilities. Laboratory tests with single tubes and with small modules have demonstrated that HYDROPERM is capable of achieving high degrees of dewatering of these concentrated sludges, especially when fluidized by the addition of an appropriate oil. Preliminary economic estimates also demonstrate that HYDROPERM can be quite cost effective.

While this preliminary study has satisfactorily answered many of the important questions relevant to actual system application, others remain. For example, the present study did not include an investigation of the long-term (several hundred hours) flux behavior of the tubes; nor did it include a systematic investigation of the periodic "cleaning" of the tubes to restore the flux levels to the initial high levels. These aspects should certainly be investigated as necessary prerequisites to the design and demonstration of a pilot plant.

Another aspect of the present study which warrants further investigation is the apparent total-solids loss encountered during the filtration process. If as postulated volatilization is the mechanism by which the solids disappear, then a sampling and analysis of the resulting gases and vapors is necessary to ensure that they are not hazardous to health, either by themselves or by acting as carriers for undesirable bacteria.

The results of the present study are sufficiently promising to warrant proceeding to the next logical step of the design and demonstration of a pilot plant. The volumes of he wastes involved in the present study are such that the "pilot" plant can be essentially of full-scale size, say, capable of processing about 1,061 liters of waste per day. The pilot plant can include oil fluidization and a means of further treatment of the permeate either by carbon adsorption or by UV-ozonation. It is recommended that a pilot plant be designed, fabricated and laboratory tested, followed by an actual demonstration (operating for a period of not less than two weeks) at a site specified by MERADCOM.

It has already been pointed out that HYDROPERM is quite versatile and that it can be used for water revonvation and reuse in a wide variety of scenarios. For example, HYDROPERM would be ideally suited for use as a principal unit operation

for the combined treatment of kitchen, laundry, shower and sewage wastes, including various water-reuse options. This possibility could be, and should be, further pursued.

The versatility of the HYDROPERM system for processing shipboard wastes can be seen by considering the following two alternative scenarios. In the first, the toilets are replaced by reduced-volume flush systems or recirculating chemical systems and the wastes are collected in a holding tank. At 7.58 liters per man per day of this concentrated waste, the minimum holding capacity (practical considerations dictate that the holding tank be oversized with a reasonable margin of safety) required in a 14-man Army watercraft will be 106 ℓ/day. In this scenario no shipboard treatment of the wastes is required, and the collected wastes can be discharged into a shoreside treatment facility. This is the option considered in the present study, with the wastes being treated by the HYDROPERM process (in combination with other unit operations) so as to produce a dischargeable permeate and a concentrated sludge. This option is more attractive for new watercarft than for old ones, since in the latter case extensive backfitting may be required.

In the other scenario, the conventional toilets are retained and the wastes are collected in a central holding tank. This is the option embodied in the Navy's Collection, Holding and Transfer (CHT) System. However, at 75.8 liters per day per man the holding capacity required for this dilute waste will be excessive, especially since Army watercraft may be required to operate away from shore for periods of two or three days at a time. On the other hand, this option will become viable if the holding tank is equipped with a "service module", which continuously reduces the volume of the holding tank by producing a dischargeable effluent and a more concentrated waste. A ninety-percent volume reduction will reduce the required holding capacity to the same as that for a reduced-volume flush system. This option may be the preferred one for existing watercraft, since minimum backfitting will be required.

While the present study was concerned only with the filtration of concentrated wastes, previous studies have demonstrated that HYDROPERM is also ideally suited for concentrating dilute wastes. Thus a service module consisting of HYDROPERM and a polishing step would be capable of achieving volume reductions of any desired degree. Such a system can be relatively simple and automated, with level sensors in the holding tanks turning "on" the service module when the liquid level reaches a specified high point and turning it "off" when the level reaches a specified low point. It should be noted that this shipboard concentration may be carried out either to a limited extent, with further concentration taking place in a

in a shoreside facility, or to a more complete extent onboard the watercraft itself. The former may be the preferred option if a "mix" of both of the scenarios mentioned above is used, and if shoreside facilities are constructed. The holding requirements can also be reudced if shipboard water-reuse options (in kitchen, shower, laundry and toilets) are utilized.

In summary, we believe that HYDROPERM filtration is a versatile process which has the potential for successful application in a wide variety of Army wastewater treatment scenarios. A comprehensive technical and economic trade-off study of these scenarios, including the water treatment options that are provided by HYDROPERM, would in itself be quite worthwhile.

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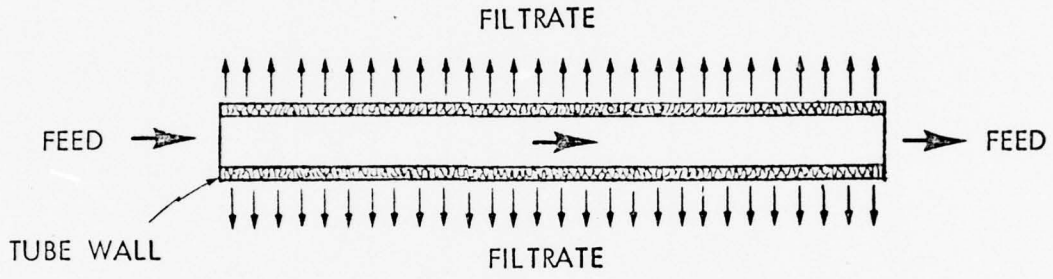

FIGURE 1 - CROSSFLOW FILTRATION SCHEMATIC

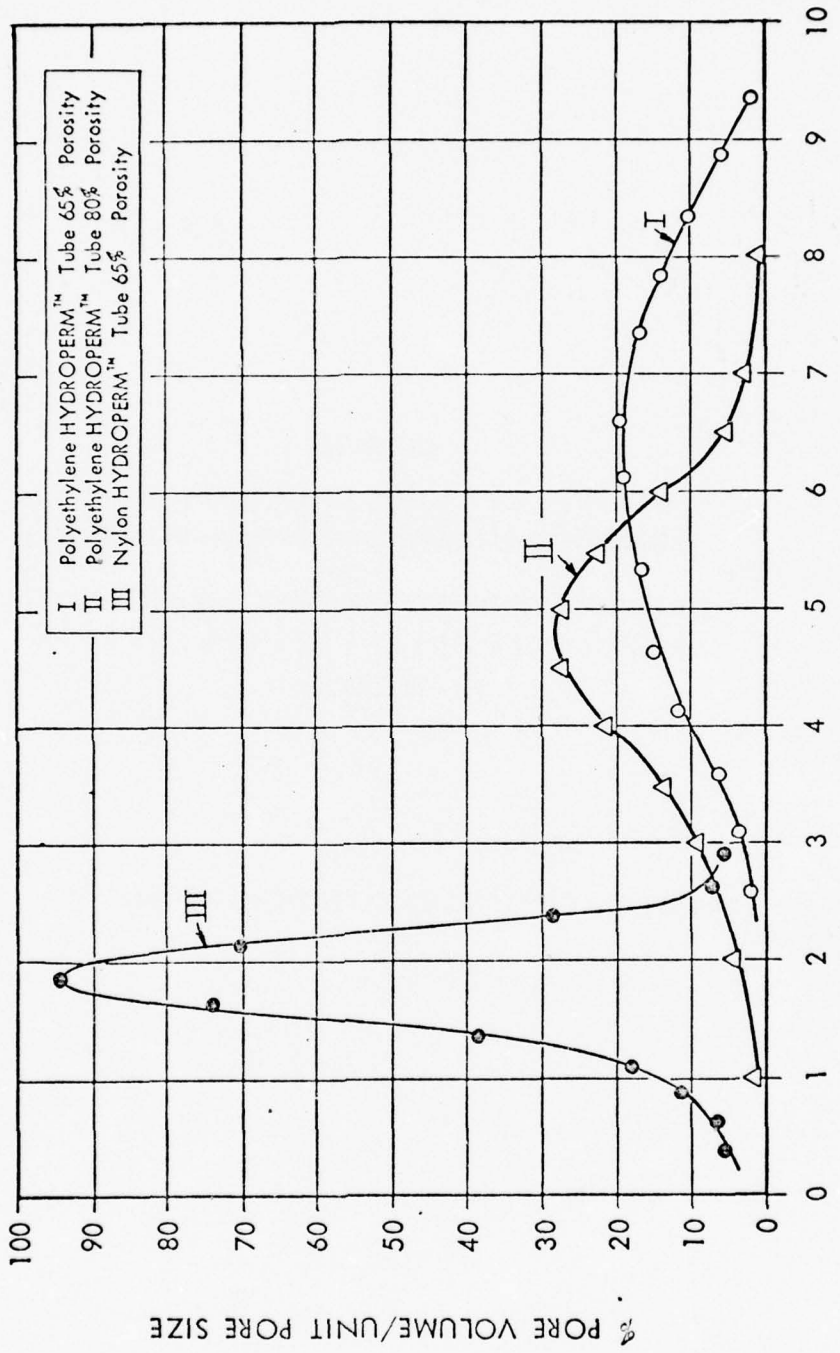

FIGURE 2 - TYPICAL PORE SIZE DISTRIBUTION OF HYDROPERM™ TUBES

FIGURE 3 - A TYPICAL HYDROPERM™ MODULE

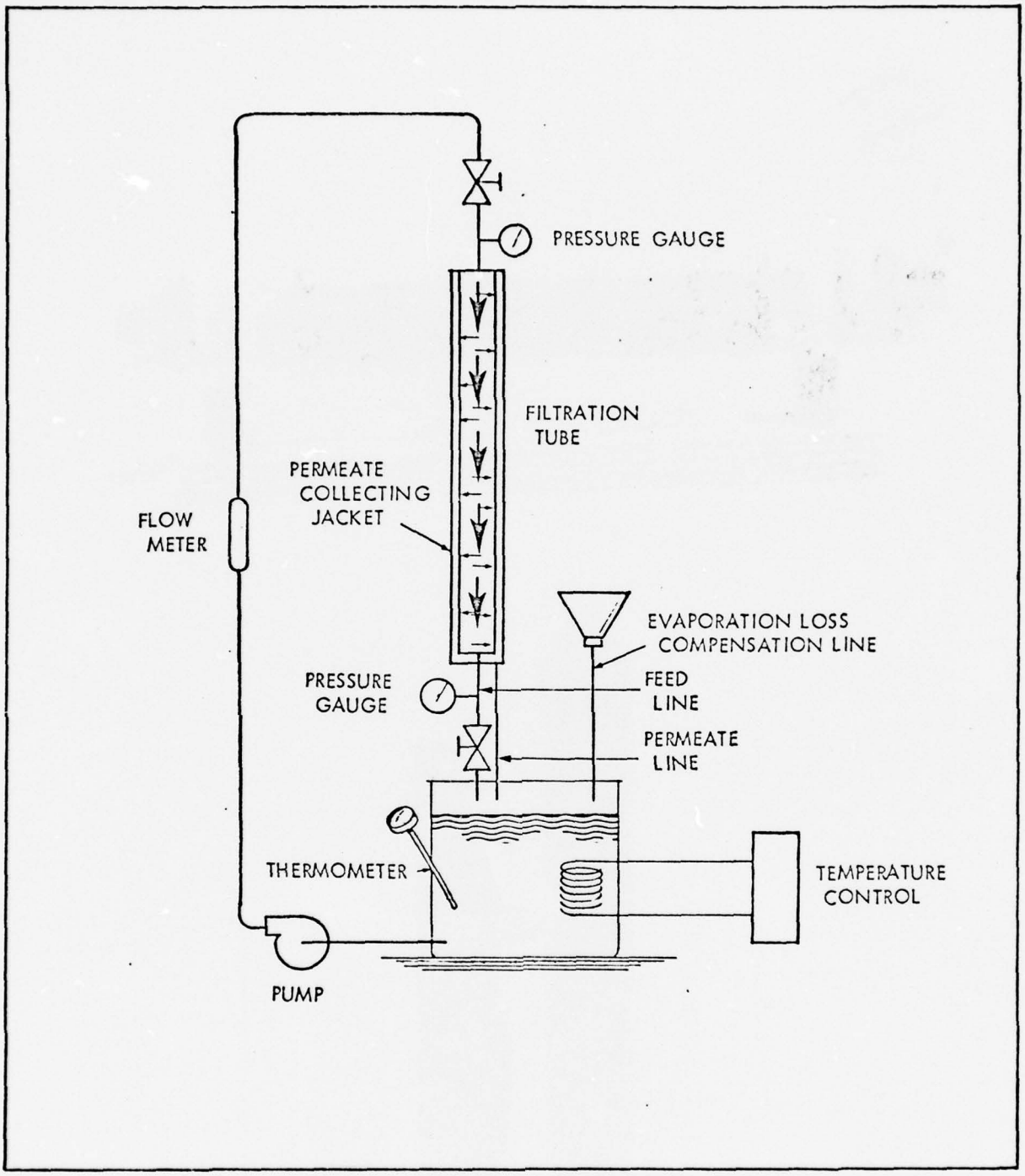

FIGURE 4 - SCHEMATIC OF A SINGLE TUBE TEST LOOP

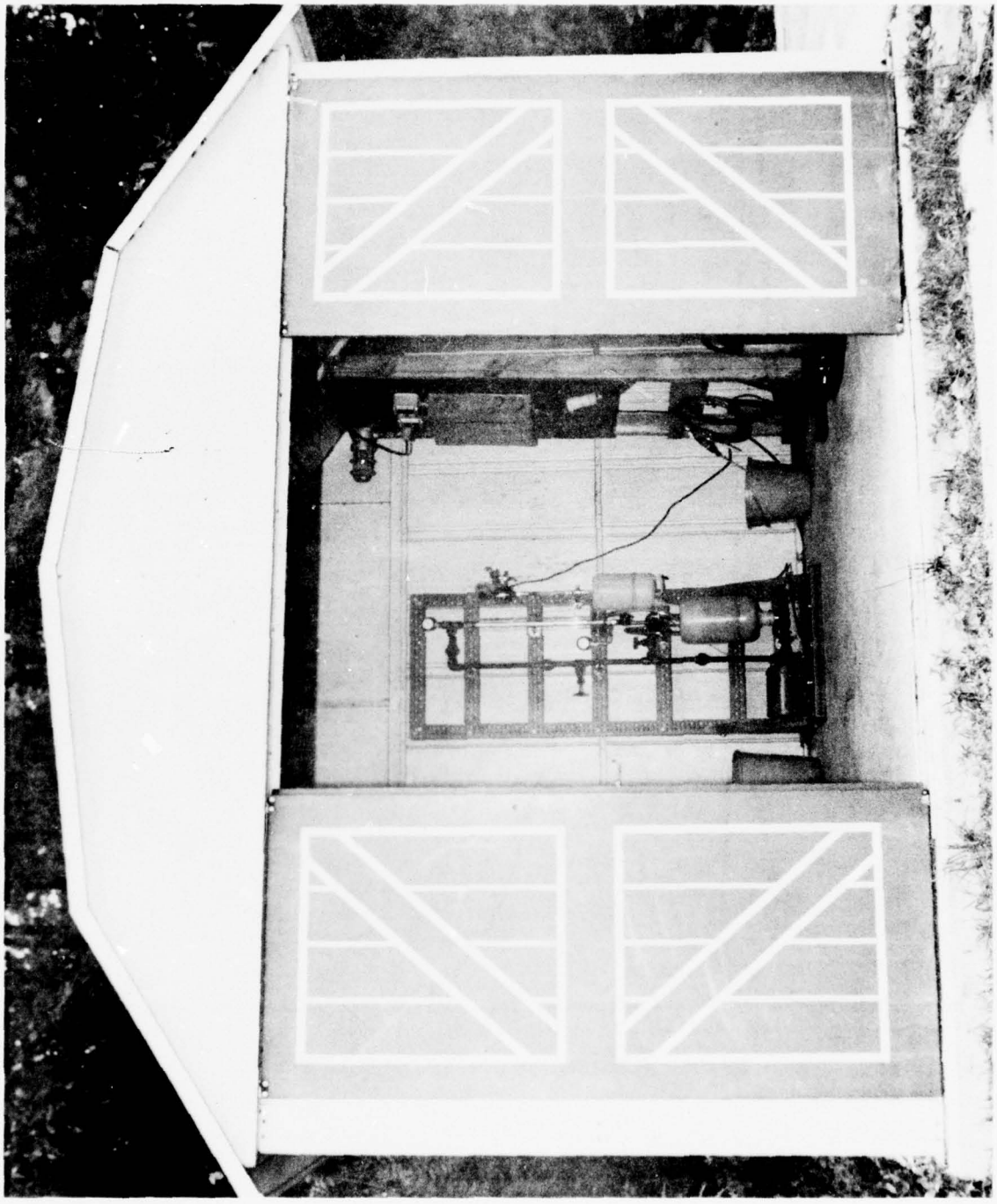

FIGURE 5 - HYDROPERM TEST SHED

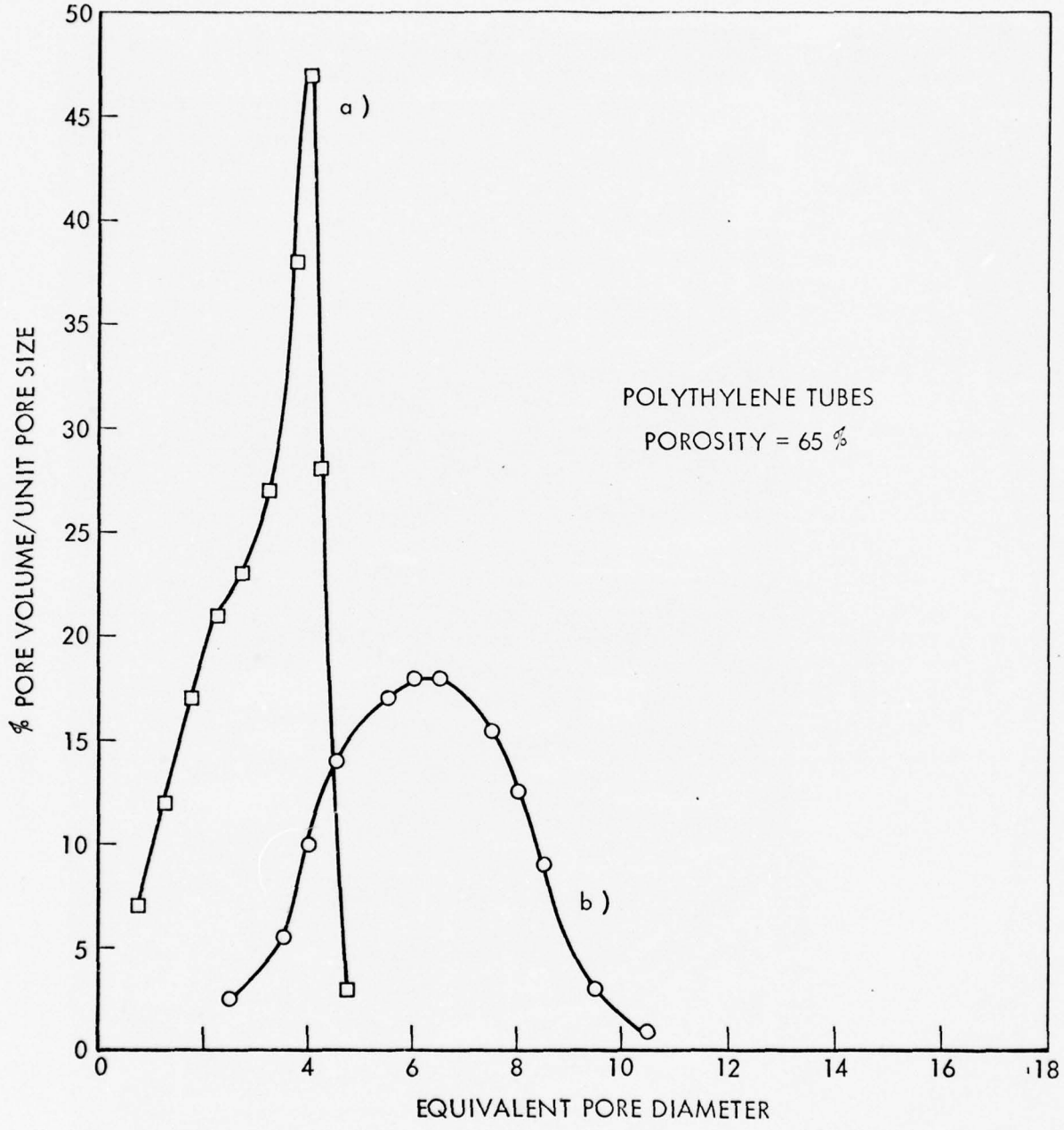

FIGURE 6 - PORE-SIZE DISTRIBUTIONS OF TWO POLYETHYLENE TUBES USED IN THE SCREENING TESTS

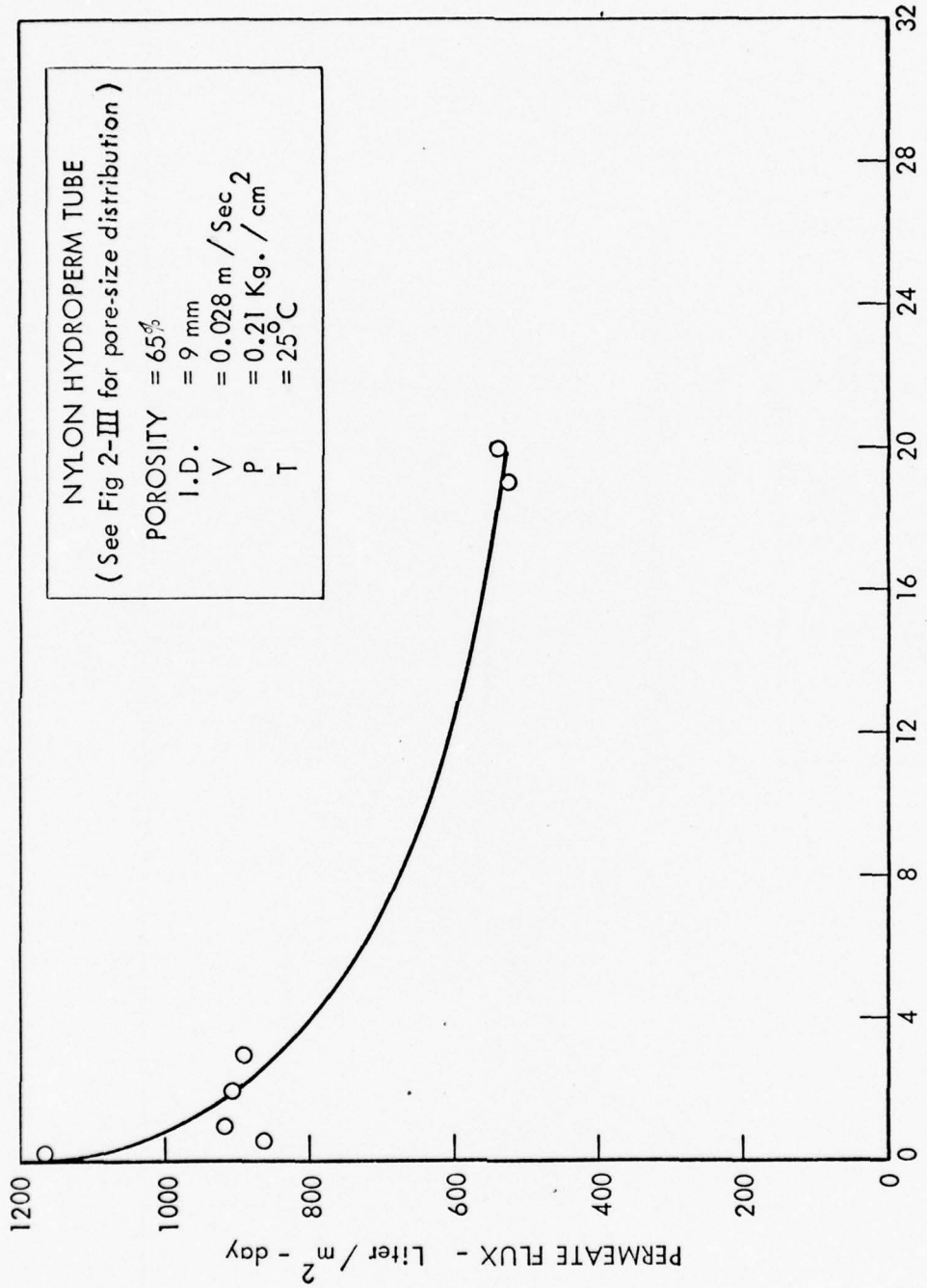

FIGURE 7 - RESULTS FROM A SCREENING TEST ON A NYLON TUBE

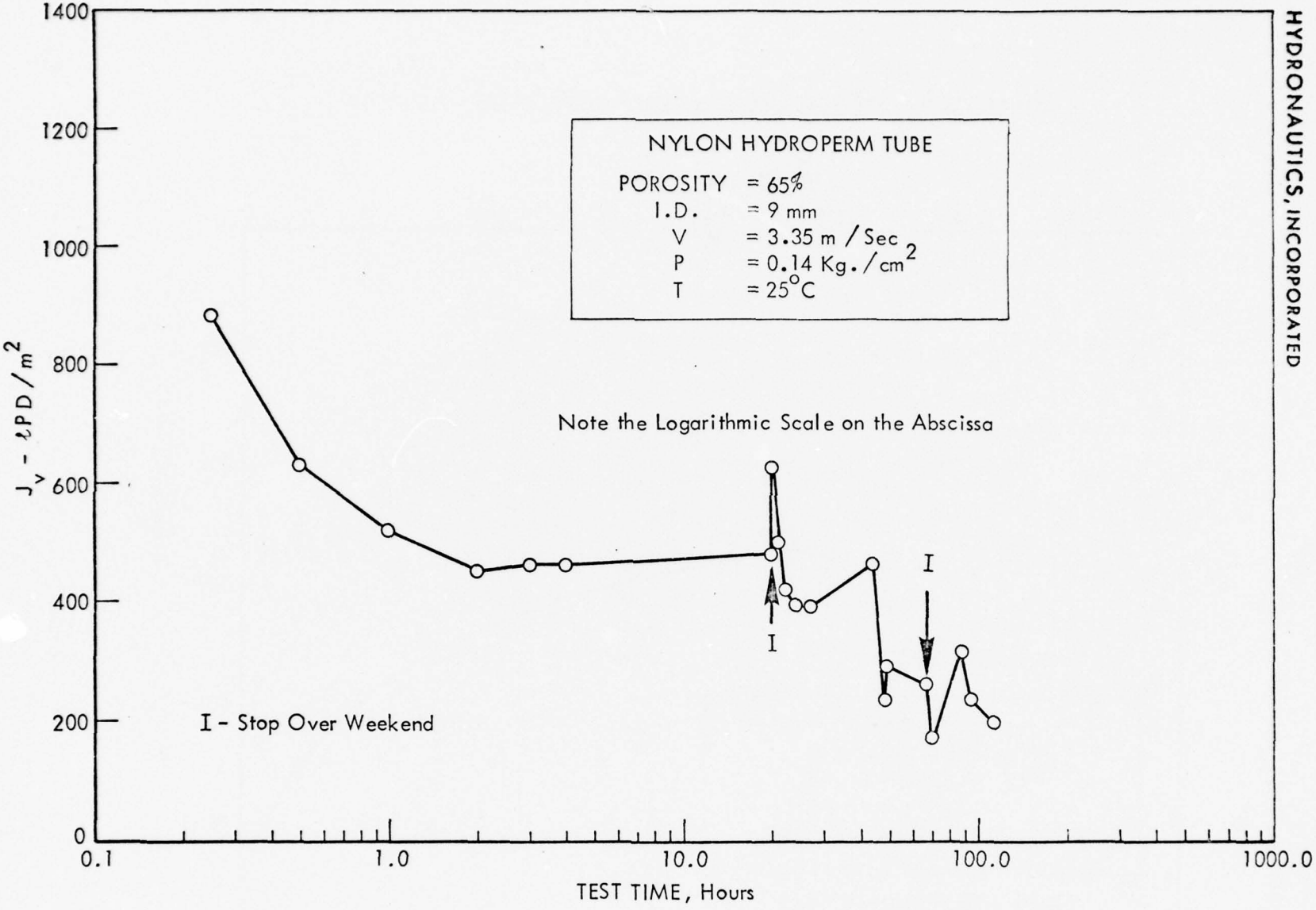

FIGURE 8 - RESULTS FROM A CONSTANT-VOLUME CONCENTRATION TEST

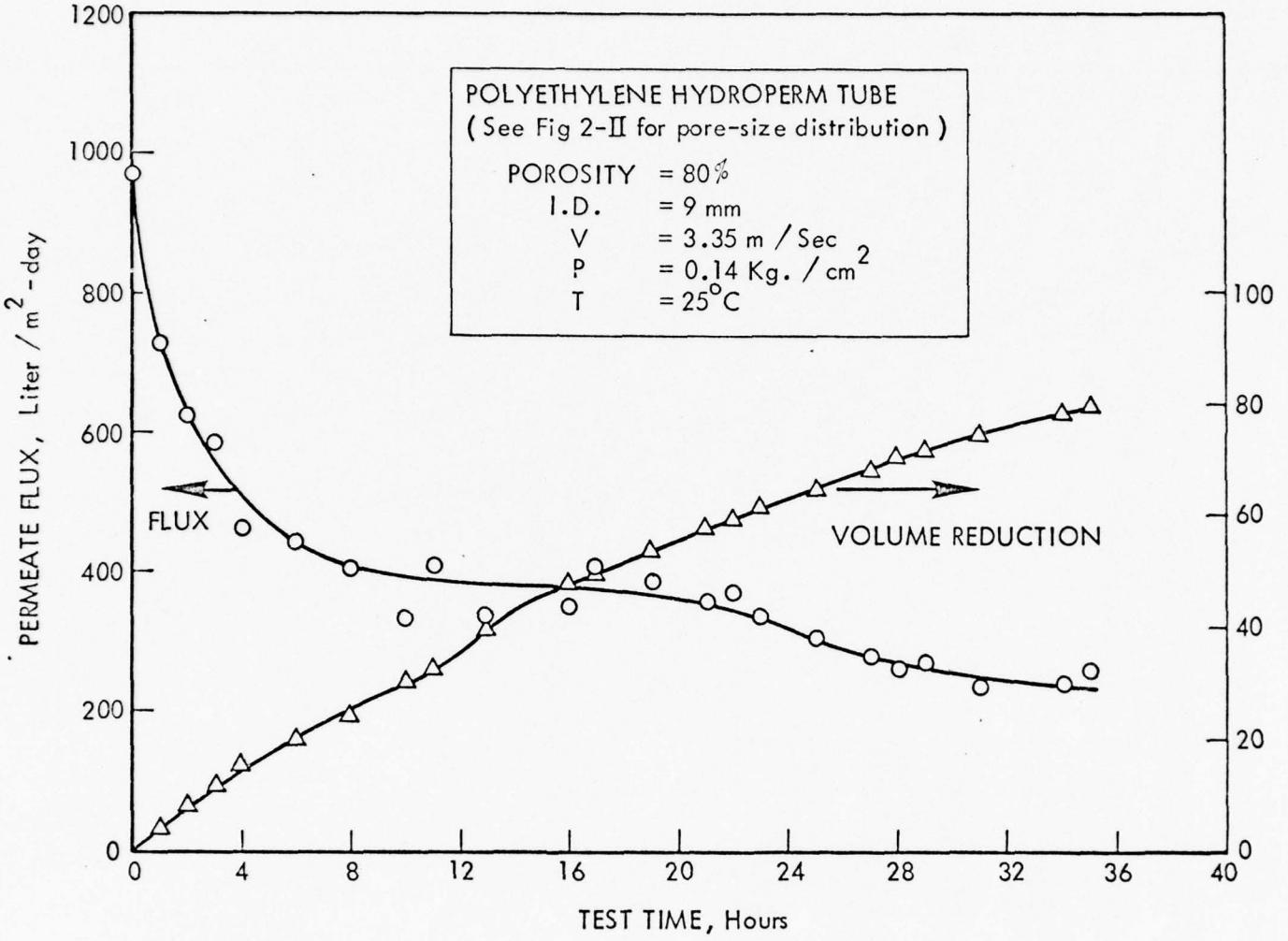

FIGURE 9 - RESULTS FROM A BATCH-CONCENTRATION TEST ON CONCENTRATED SEWAGE WASTES

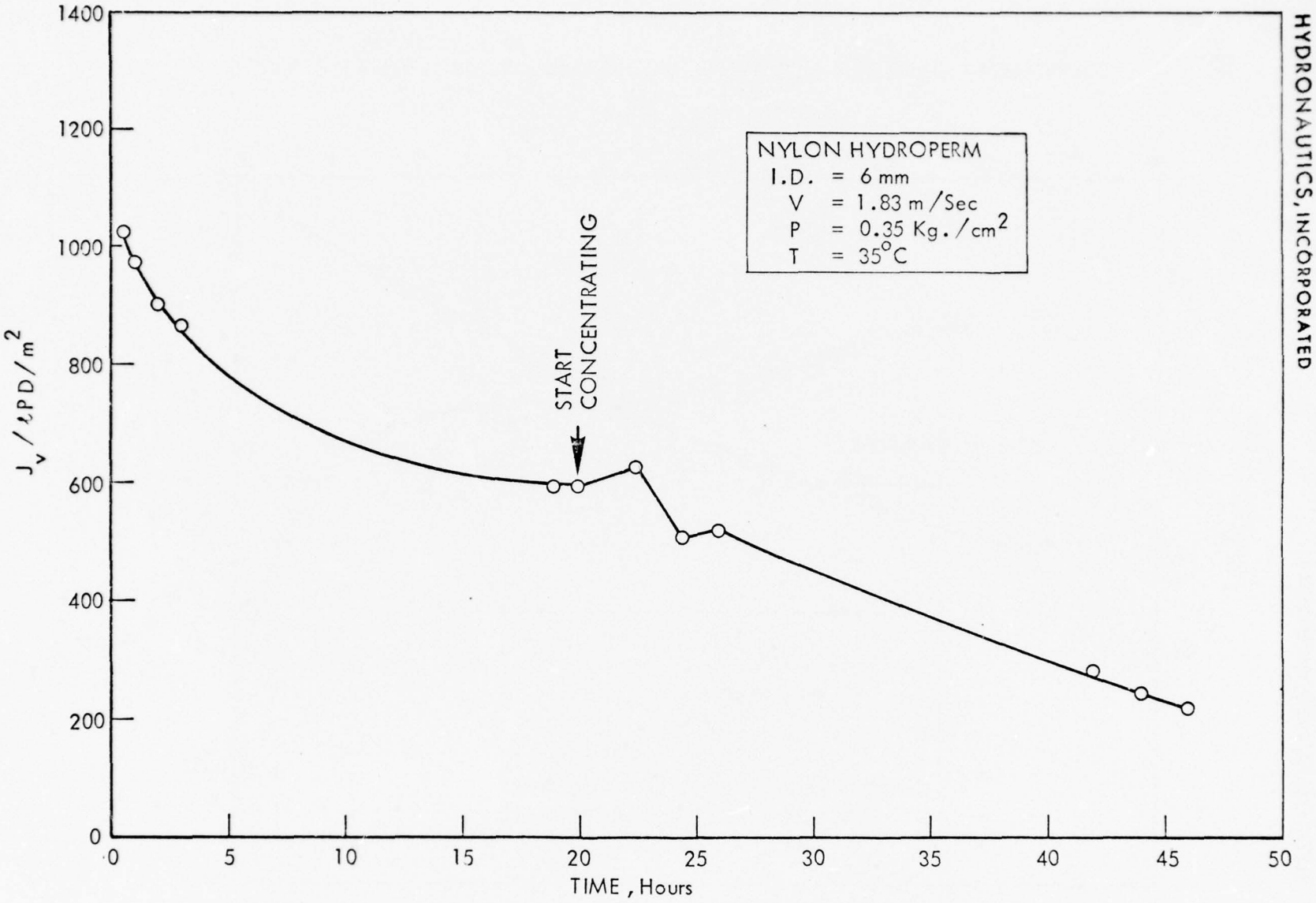

FIGURE 10 - RESULTS FROM A TEST IN AN OIL-FLUIDIZED MODE

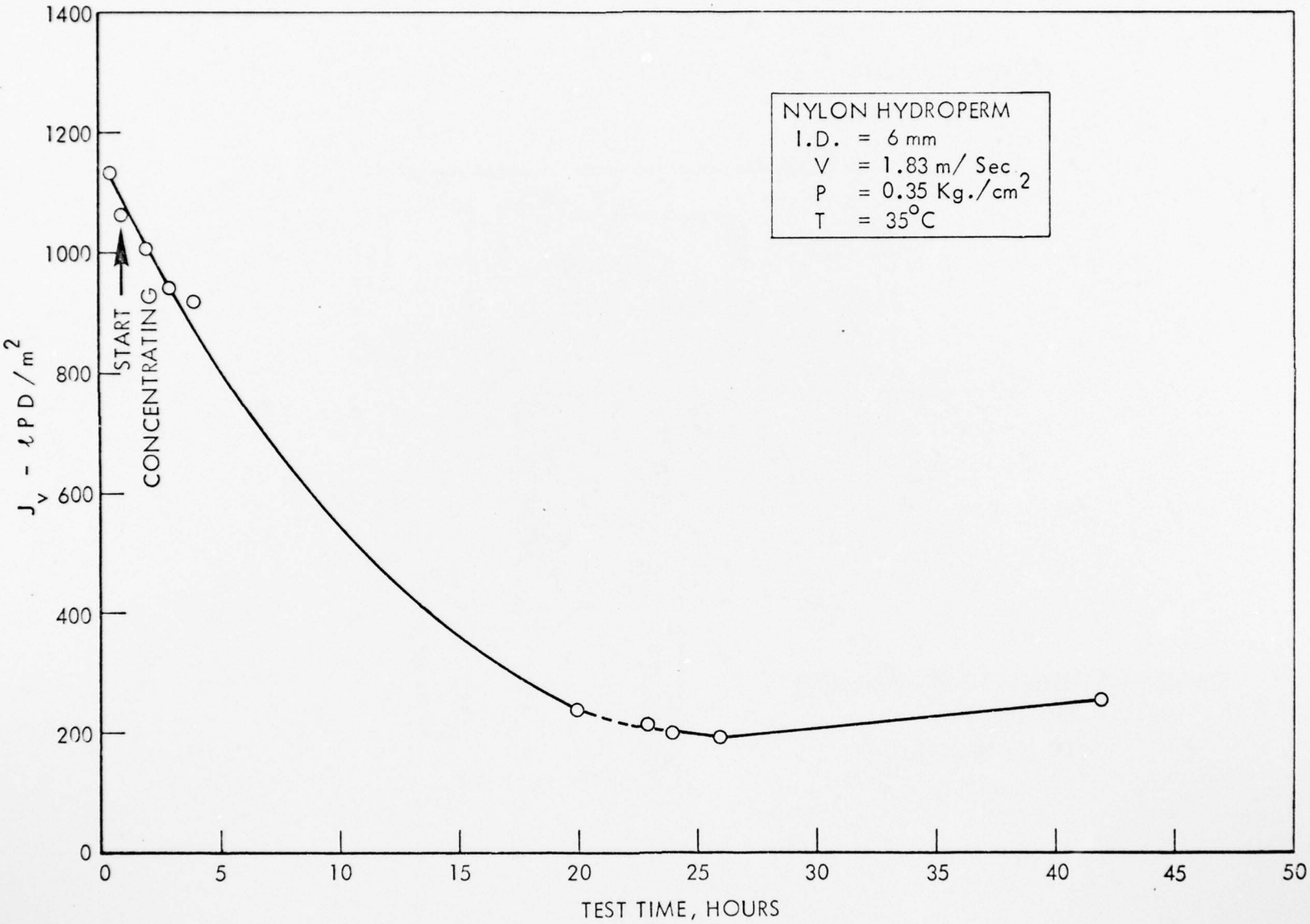

FIGURE 11 - RESULTS FROM A CONSTANT-VOLUME CONCENTRATION TEST IN AN OIL-FLUIDIZED MODE

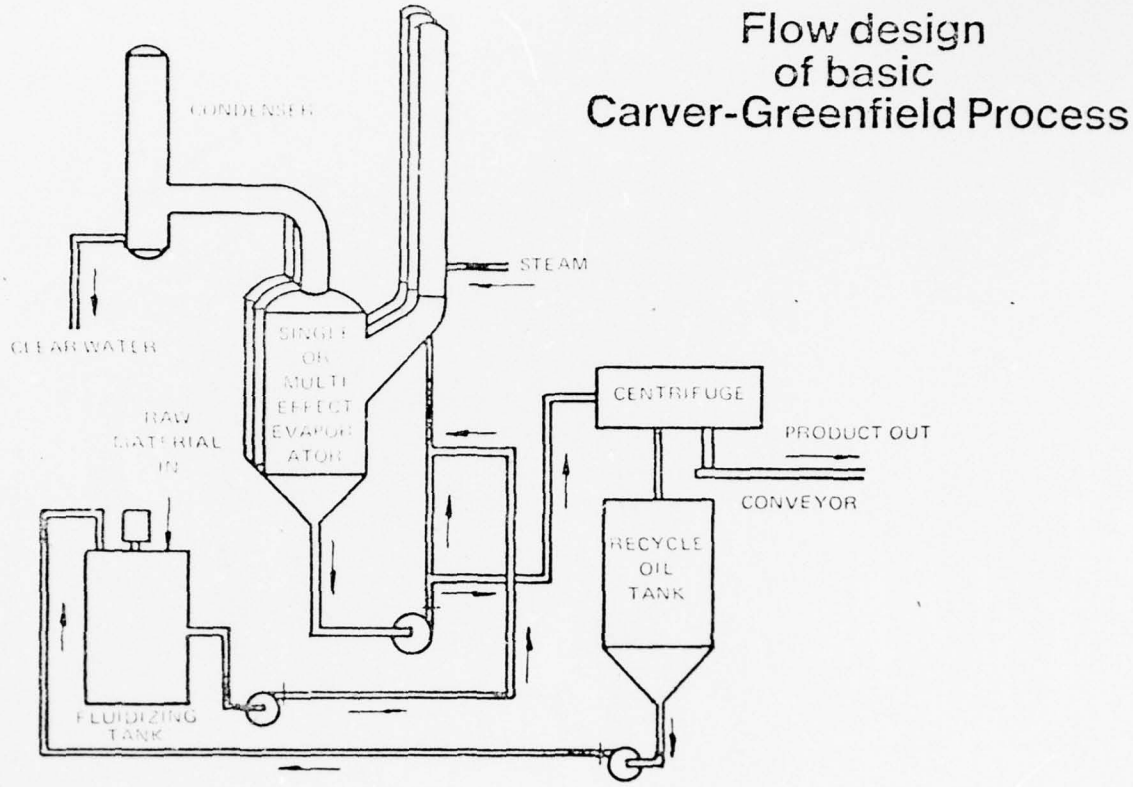

FIGURE 12 - A SCHEMATIC OF THE CARVER-GREENFIELD PROCESS

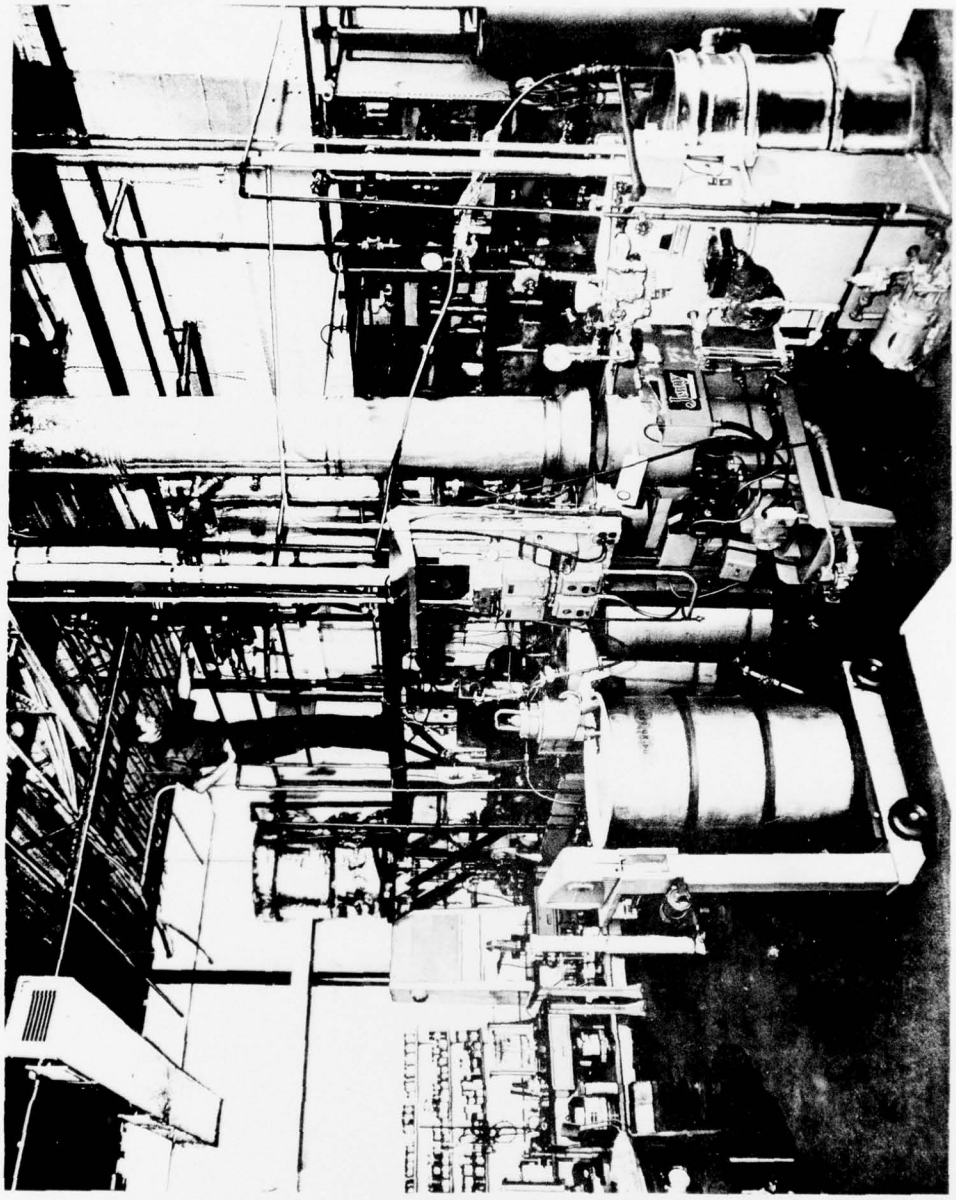

FIGURE 13 - THE CARVER-GREENFILED PILOT PLANT AT HANOVER, NEW JERSEY

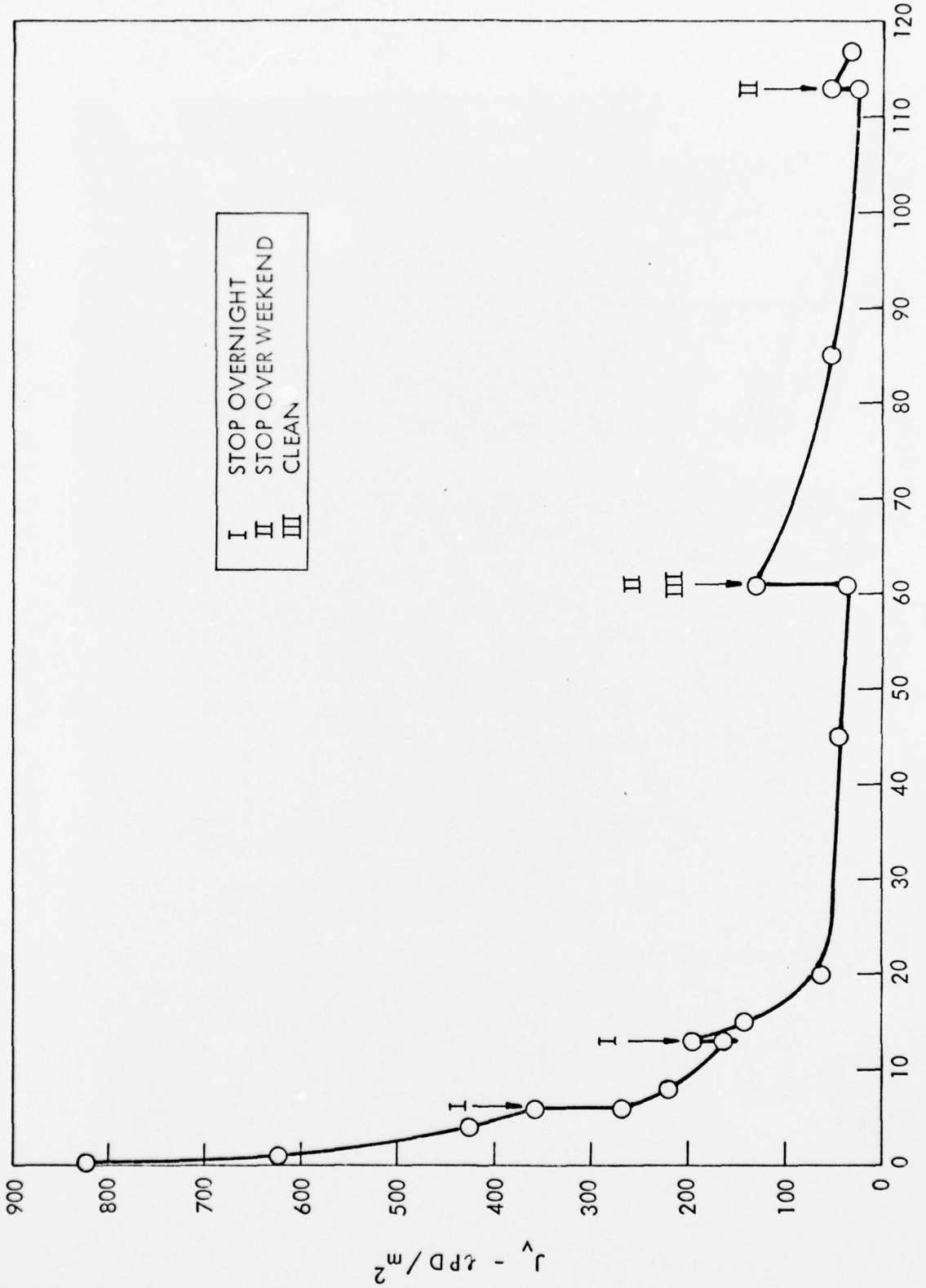

FIGURE 14 - RESULTS FROM CONCENTRATION TEST - MODULE I

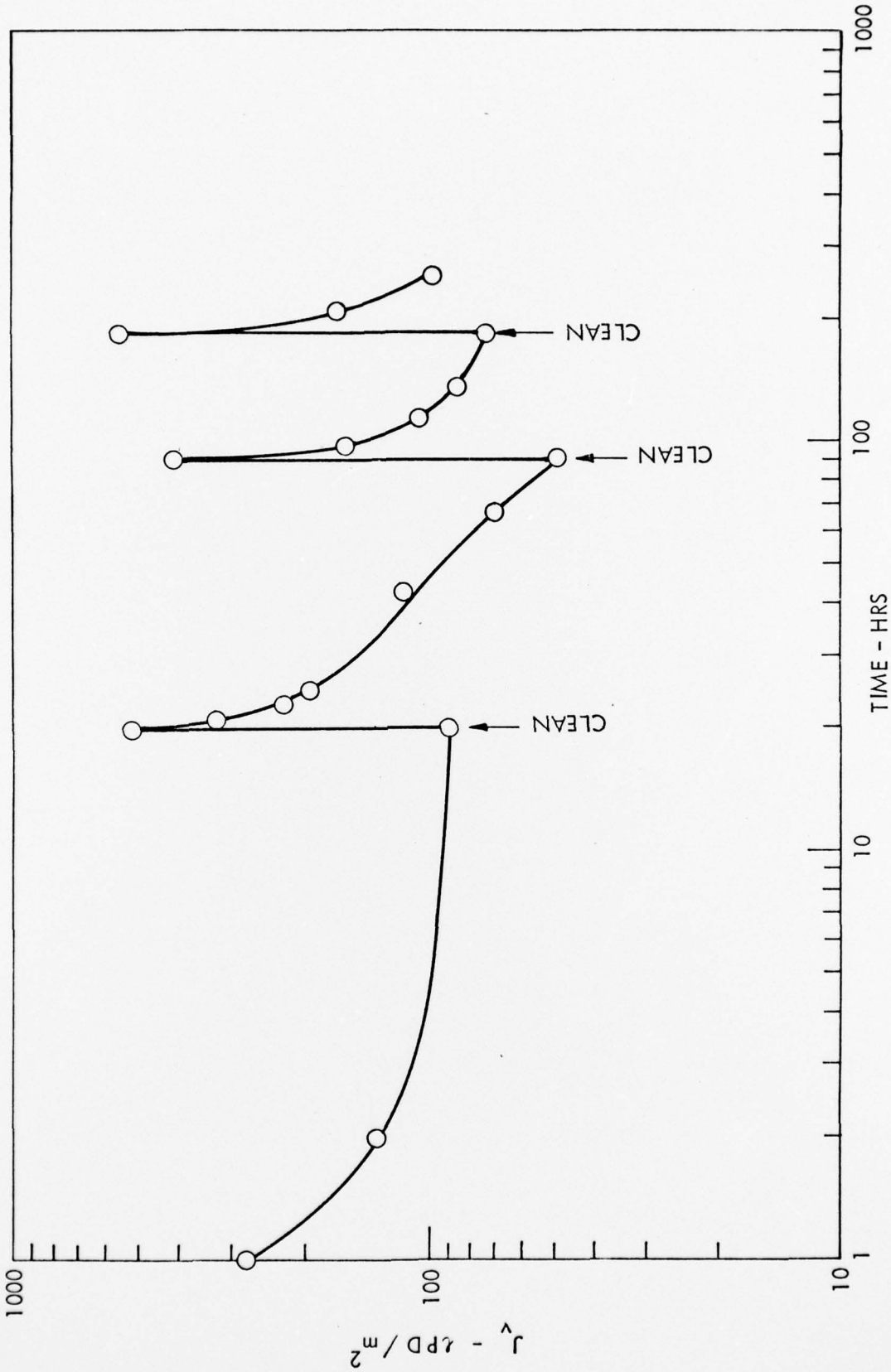

FIGURE 15 - RESULTS FROM CONCENTRATION TEST - MODULE II

APPENDIX A

ECONOMICS OF THE CARVER-GREENFIELD SOLIDS DEHYDRATION PROCESS

ECONOMICS OF THE CARVER-GREENFIELD SOLIDS DEHYDRATION PROCESS

Conventional Carver-Greenfield plants are vastly too large for this 1,061 liter/day application. They become economical only at the level of tons or hundreds of tons per day. The following examples are illustrative:

Example No. 1 - Municipal Sewage Sludge (Engineering Estimate)

- o New York City area.
- o 227 tons/day (dry basis) of pressed or centrifuged sludge.
- o Sale of surplus fuel as electricity.
- * Worst case: 12.5% solids digested sludge = $19.07/ metric ton net cost.
- * Median case: 20% solids undigested sludge = $27.20/ metric ton net profit.
- * Best case: 40% solids undigested sludge = $27.44/ metric ton net profit.

Example No. 2 - Municipal Sewage Sludge (Engineering Estimate)

- o Washington, D. C. area.
- o 173 tons/day (dry basis) of 20% solids filter cake from mixed primary and secondary sludge.
- o Surplus fuel sold as pellets.
- * Net capital and operating cost - $19.73/dry metric ton.

Example No. 3 - Wastewater from Instant Coffee Plant (actual case history)

- o New Jersey area.
- o 30,418 kg of water evaporated per hour.
- * Net cost per liter, without fuel recovery = 0.31¢/ liter.
- * Net cost per liter, with fuel recovery - 0.21¢/liter.
- * Cost to haul away to dump, untreated = 1.31¢/liter.

Example No. 4 - Spent Brewery Mash (actual case history)

- o Rock Mountain area.
- o 13.62 metric tons/day (dry basis) capacity of 4% solids waste activated sludge from brewing wastewaters.

- o Sale of pelletized dried product for animal feed contemplated.
- * Total capital and operating cost = $174/metric ton.
- * Product value as animal feed = $330-440/metric ton.

As a very rough rule of thumb, Carver-Greenfield plants have usually turned out to cost about one-half as much to build and operate as equivalent spray-drying or incineration plants, mainly due to the energy and fuel economies of multiple-effect heat utilization. When the dried solids have fuel value, there is a further cost saving in that their combustion can often provide all the energy needed to operate all the evaporation stages; and the plant has zero energy consumption: if the product is to be burned and if the raw feed contains more than 4.2% of nonvolatiles with fuel value of 5,550 kcal/kg, the Carver-Greenfield plant becomes a net energy producer.

Construction costs are subject to all the usual geographic, inflationary and option selection effects; but the following examples using mid-1976 prices are illustrative:

- o One-stage, pilot-scale plant. All stainless steel. 34 kg of water evaporated per hour. $110,000.
- o Three-stage, industrial-scale plant. Carbon steel. 681-908 kg of water evaporated per hour. $250,000.
- o Four-stage, commercial-scale plant. Carbon steel. 4,540 kg of water evaporated per hour. $750,000 to $1,000,000.

Miniature Carver-Greenfield plants designed to handle 947-1,895 liters of wastewater per day are under study at this writing (January 1977); but they have not yet been designed or cost estimated. It is anticipated that they will be single-stage units with simplified heat recovery and oil recycle systems, sacrificing some of their usual energy efficiency in favor of compactness and low cost. They will retain all the advantages of oil fluidization, and their output streams will still be distilled water and anhydrous solids. It is anticipated that they will be skid or truck mounted and will fit into approximately an 0.2 meter cube.

APPENDIX B

DATA TABLES

Table 1
Module I
(Data for Figure 14)

Time Hrs.	P Kq/cm²	V m/sec	T °C	J* v ℓpd/m²	Perm. Coll. Liter	Remarks
0.25	0.35	1.83	25	289.3		
1.00			24	273.0		I
2.00			25	134.5		
20.00		1.83	22	89.6	4.052	II
20.25		3.35	15	517.5		
21.00			24	321.9		
23.00			29	224.1		
25.00			25	191.5		
43.00			23	114.1	6.827	
67.00			21	69.3	5.397	
91.00			24	48.9	4.282	II
91.25			17	407.5		
98.00			24	158.9	3.087	
115.00			24	105.9	4.867	
138.00			25	85.6	6.067	
162.00			27	81.5	5.727	
186.00			25	73.3	4.869	II
186.25	0.35		12	550.1	3.672	
210.00	0.21		26	167.1	7.752	
234.00	0.21		22	130.4	9.122	
258.00	0.21	3.35	21	97.8	7.472	

* Corr. to 35°C.
I - Start Concentration
II - Cleaning

Table 2

Module II
(Data for Figure 15)

Time Hrs.	P Kq/cm^2	V m/sec	T °C	J_v* ℓpd/m^2	Perm. Coll. Liter	Remarks
0.25	0.21	3.35	13	823.1		
1.00			20	623.4		I
4.00			25	427.8	14.992	
6.00			25	358.6	7.912	II
6.25			15	268.9		
8.00			23	220.0		
13.00			26	163.0	14.592	II
13.25			13	195.6		
15.00			24	142.6		
20.00			26	61.1	7.492	
45.00			22	44.8	11.612	
61.00			23	36.7	6.402	III, IV
61.25			14	130.4		
85.00			25	53.0	13.872	
113.00			27	24.4	8.182	IV
113.50	↓	↓	23	53.0		
117.00	0.21	3.35	26	32.6	3.502	

*Corr. to 25°C
I - Start Concentration
II - Stop Overnight
III - Cleaning
IV - Stop over Weekend

Table 3
(Data for Figure 7)

Time Hrs.	P Kg/cm²	V m/sec	T °C	J_v* ℓpd/m²
0.25	0.21	0.028	23	1193.9
0.50	↓	↓	26	880.1
1.00	↓	↓	28	937.2
2.00	↓	↓	30	929.0
3.00	↓	↓	30	945.3
19.00	↓	↓	27	533.8
20.00	0.21	0.028	30	594.9

*Corr. to 25°C

Table 4
(Data for Figure 8)

Time Hrs.	P Kg/cm^2	V m/sec	T °C	J_v* ℓpd/m^2
0.25	0.14	3.35	17	900.5
0.50	↓	↓	21	643.8
1.00			23	529.7
2.00			24	460.4
3.00			23	472.7
4.00			23	472.7
20.00			23	493.0 **
20.25			14	639.7
21.00			23	513.4
22.00			25	431.9
24.00			24	399.3
27.00			24	399.3
44.00			23	472.7
48.00			24	240.4
49.00			26	297.4 **
66.50			23	220.0
68.00			23	195.6
87.00			22	326.0
94.00	↓	↓	24	240.4
112.0	0.14	3.35	24	203.7

*Corr. to 25°C
**Stop Over Weekend

Table 5
(Data for Figure 9)
Starting Volume - 7641 ml.

Time Hrs.	P kg/cm²	V m/sec	T °C	J * v ℓpd/m²	Perm Coll. ml.
0.25	0.14	3.35	26	982.0	
1.00			23	737.5	330
2.00			27	635.6	310
3.00			27	599.0	300
4.00			25	468.6	210
6.00			25	448.2	360
8.00			26	415.6	430
10.00			24	338.2	404
11.00			23	419.7	180
13.00			26	342.3	540
16.00			27	358.6	576
17.00			18	415.6	185
19.00			20	395.2	300
21.00			21	362.6	310
22.00			22	374.9	160
23.00			24	338.2	120
25.00			24	313.7	265
27.00			25	281.1	280
28.00			24	264.8	151
29.00			24	277.1	115
31.00			24	240.4	215
34.00			23	244.5	290
35.00	0.14	3.35	29	268.9	120

* Corr. to 25°C.

Table 6

Data for Figure 10

Time Hrs.	P Kq/cm²	V m/sec	T °C	J_v^* ℓpd/m²	Remarks
0.25	0.35	1.83	27	1177.6	
0.50	↓	↓	26	1043.1	
1.00	↓	↓	29	990.1	
2.00	↓	↓	25	937.2	
3.00	↓	↓	25	884.2	
19.00	↓	↓	24	603.0	
20.00	↓	↓	24	603.0	Start Concentration
22.50	↓	↓	25	639.7	
24.50	↓	↓	25	517.5	
26.00	↓	↓	26	529.7	
42.00	↓	↓	26	289.3	
44.00	↓	↓	28	240.4	
46.00	0.35	1.83	29	224.1	

* Corr. to 35° C.

Table 7
(Data for Figure 11)

Time Hrs.	P Kg/cm^2	V m/sec	T ^{o}C	J_v^* $\ell pd/m^2$
0.25	0.35	1.83	23	1202.0
0.50	↓	↓	26	1153.1
1.00	↓	↓	25	1083.8 **
2.00	↓	↓	26	1026.8
3.00	↓	↓	26	961.6
4.00	↓	↓	25	937.2
20.00	↓	↓	23	244.5
23.00	↓	↓	28	122.2
24.00	↓	↓	26	203.7
26.00	↓	↓	25	195.6
42.00	0.35	1.83	31	260.8

*Corr. to $25^{o}C$
**Start Concentration