AN ABSTRACT OF THE THESIS OF

John H. Knutson for the degree of Master of Science in Bioresource Engineering presented on September 14, 1993.

Title: Design of Capillary Wick Pore-Water Samplers and Their Effects on Solute Travel Time and Dispersion

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John S. Selker

Passive Capillary Samplers (PCAPS) use the capillary potential of moist fiberglass wicks to draw pore-water samples from unsaturated soils. It is important that a sampling wick is cleaned and its hydraulic conductivity, scaled by the area of soil sampled, is matched to the conductivity of the soil in which the PCAPS will be installed. When properly matched the top of a wick will have the same pore-water pressure as the soil over a range of fluxes so no disruption of the native soil water flux occurs and representative samples are obtained. Currently, there is no formal proceedure for designing PCAPS. It is the goal of this research to provide a theoretically based systematic method of designing PCAPS for use in particular soils, and characterize their effects on the solutes being sampled.

To determine the most effective method of cleaning the wicks the porous properties of wicks were measured for: no

treatment; detergent water washed; acetone washed; and combusted conditions. The best method of removing contaminants from the wick material was determined to be combustion, which showed that some wicks had up to 3.6% by mass of impurities on them.

Conductivity tests were conducted using 15 wicks from three manufacturers. Unsaturated hydraulic conductivity was measured as a function of matric potential. These data were fit by regression to an exponential conductivity function with R^2 ranging from 0.79 to 0.99. Estimates of saturated conductivity ranged from 220 to 1380 cm/hr with lower conductivities observed in denser wicks.

Saturated conductivities were compared to values predicted by a capillary tube model parameterized by wick porosity, tortuosity, glass filament radius, and cross-sectional area. Model conductivities reproduced the observed trends in measured values (R^2 of 0.85) but tended to underestimate $K_{sat.}$

Wetting and draining volumetric moisture contents were measured in wicks for known pressures. Hysteresis between wetting and draining miosture contents was observed. The draining curves were used to predict unsaturated hydraulic conductivity, K{h}, using van Genuchtens equation (VG equation) coupled with Mualem's conductivity model. The draining moisture content data fit the VG equation very well ($R^2 > 0.953$) but tended to underestimate saturated water contents. Fit saturated water contents ranged from 0.49 to

0.573 while measured porosities ranged from 0.73 to 0.90. This underestimation occurred because the VG equation predicts an air entry region which did not exist in wicks. The VG equation parameters were used to predict hydraulic conductivity versus pressure using the Mualem model. Mualem's predicted K(h)-h values did not match well with measured data.

An exact solution of Richards equation for unsaturated flow is used to calculate matric potential in wicks given the flux and length. The calculated values were close to those measured during the conductivity tests with predicted matric potentials within 25 % of measured values across a wide range of wick lengths and fluxes. The predicted matric potentials tended to be within 5 % of the measured values for low fluxes (between 1.6 and 16.0 cm/hr). A systematic procedure for matching the pressure versus flux curve of a wick to that of a soil is presented to aid in the design of PCAPS for application at particular sites.

Tracer tests were conducted in order to determine a sampling wicks effects to solute travel time and dispersion. Resulting dispersivity values for the wicks ranged from 0.59 to 4.3 cm. Finite difference equations were used to simulate the additional solute dispersion and travel time a wick would cause when installed in the field. The simulations showed that dispersion by wicks is negligble and that additional travel times are 0.5 hr in a sand and 5 hr in a silt, which are also negligible.

Design of Capillary Wick Pore-Water Samplers and Their Effects on Solute Travel Time and Dispersion

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Redacted for Privacy

Head of department of Bioresource Engineering

Redacted for Privacy

Dean of Graduate School

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CHAPTER 1

FIBERGLASS WICK PREPARATION FOR USE IN PASSIVE CAPILLARY WICK SOIL PORE-WATER SAMPLERS

John H. Knutson, S.B. Lee, W.Q. Zhang, J.S. Selker

ABSTRACT

Passive Capillary Samplers (PCAPS) use the capillary potential generated by hanging fiberglass wicks to exert a sampling suction on soil water. Impurities on the fiberglass affect the capillary properties of the wick, and the chemical properties of the samples collected. To determine the need, and a method, for cleaning the wicks, capillary rise and moisture contents were measured using four preparations: uncleaned, detergent washed, acetone extracted, and combusted. Wicks were made with fibers produced by PPG Industries and Manville Company. Results showed that wicks made from PPG fibers lost up to 3.4% of original mass during combustion while Manville fiber wicks lost less than 0.6%. These losses are assumed to have been due to combustion of organic compounds applied by the manufacturers. All cleaning methods had higher capillary rise then obtained with uncleaned wicks. Combustion at 400°C for 4 hours was the best cleaning method, removing 98 to 100% of impurities.

INTRODUCTION

The Passive Capillary Sampler (PCAPS) is a new device being used to obtain pore-water and solute samples from unsaturated soils in groundwater quality monitoring (Holder et al. 1991; Boll et al. 1992; Boll et al. 1991; Poletika et al. 1992). PCAPS are installed in situ and passively use the natural capillary tension developed by moist hanging wicks, rather than applied potentials, to draw representative pore-water samples from soils. The capillary properties of the glass fibers are affected by the degree of contamination of their surfaces. In addition, chemical adsorption to organic contaminants on the glass could be a source of sampling error when measuring trace pollutants with the PCAPS system.

The objectives of the research were: first, to determine if cleaning the wicks is necessary, and second, to determine the efficiency of several methods for removing contaminants from the wick material. Fiberglass wick manufacturers indicated that there are three sources of impurities on the wicks: fiber binders, yarn oversprays, and lubricants from the braiding machines. Fiber binders hold the individual glass fibers together to increase the mechanical strength of the woven products. Oversprays, typically acrylic or starch oil based, are used to make fiberglass yarn braid more easily with less fiber loss.

Oversprays and binders are applied by the fiberglass yarn producers as specified by the braiding companies.

TEST METHODS

To quantify the effect of a cleaning method on wick performance, two measurements were evaluated: the wetting and draining moisture characteristic curves and the maximum capillary rise of water. The moisture characteristic curves were obtained by using two 150 cm lengths of each wick sample. Both lengths receiving the same treatment were oriented vertically and placed inside plastic tubes to eliminate evaporative losses. One length was allowed to wet by placing its bottom end in a beaker of dyed water. The other length was allowed to drain from saturation. Tests were conducted for 42-48 hours to ensure that equilibrium moisture conditions were obtained. The height of dye was measured to get an indication of capillary rise, then the wicks were cut into 5 cm segments. Each segment was weighed, dried and reweighed. The gravimetric moisture content was calculated by dividing the mass of water lost during drying by the dry mass of the segment.

These tests were carried out using fiberglass wicks from three braiding companies; Mid-Mountain Materials (Redmond, WA), Amatex (Norristown, PA), and Pepperell Braiding (Pepperell, MA). Amatex and Mid-Mountain wicks were made using fiberglass yarn produced by PPG Co. (Pittsburg, PA), while Pepperell wicks were made with yarn produced by Manville Co. (Manville, OH). Wicks were tested in four

treatment conditions: uncleaned, detergent water washed, acetone extracted, and combusted. Fifteen wick types were tested in the unwashed, washed and combusted conditions: three from Pepperell, six from Mid-Mountain, and six from Amatex. Representative results are presented. Two Mid-Mountain wicks were used in the acetone treatment tests and results for both are given. ("Matrix" and "knit" are product descriptions used by Mid-Mountain; "low," "medium," and "high" are wick descriptions used by Amatex; and "1/4 inch" and "3/8 inch" are the wick diameters listed by all three braiding companies.)

Unwashed wicks were cut directly from the spool and tested. Washed wicks were cleaned using a two-hour washing and rinsing procedure, after which they were allowed to dry completely. The washing procedure consisted of adding 7-10 CC of Alconox brand laboratory detergent to approximately 30 liters of hot tap water. The wicks were placed into a wire rack and immersed. The wicks were soaked for 20 minutes, agitated for five minutes, soaked an additional 10 minutes and agitated for another five minutes. The wicks were then drained and soaked in hot clean tap water followed by another five minutes of agitation. The wicks were drained in a 35 cm diameter spinning basket at approximately 700 RPM to remove as much water as possible without damaging the material. This rinsing and spinning process was repeated two more times using clean hot tap water. Finally, the

wicks were given two rinse/spin cycles with distilled water followed by oven-drying at 100°C.

Acetone extraction was carried out by soaking each 1.5 meter length of wick in 500 ml of laboratory grade acetone for 48 hours, draining, air drying for one day, then drying for 8 hours at 100°C. Combusted wicks were prepared by placing the unwashed wicks in a muffle oven for 3-4 hours at 400°C, well below the fiber softening temperature of 800°C (PPG, Manville, Personal Comm.).

An additional test was conducted to determine the temperature at which impurities were removed. The test involved placing segments of uncleaned wicks into precombusted and preweighed crucibles. The crucibles with wicks were weighed, then put into a muffle oven. After 1.5 hours the crucibles were removed from the oven, cooled, and reweighed. The percent of mass lost during combustion was calculated by dividing the mass lost by the original mass of the wick. The process was repeated for temperatures of 250 to 550°C, yielding a curve of mass loss versus combustion temperature.

RESULTS

Figure (1a) shows the measured wetting curves for the 1/4 inch diameter knit braided wick from Mid-Mountain Materials (Customary units retained as product designation). All cleaning methods (detergent water washing, acetone treatment, and combustion) resulted in a higher gravimetric moisture content at each elevation (matric potential) than was obtained with uncleaned wicks. Higher moisture content for the same matric potential results in a larger unsaturated conductivity. The results were similar for the Amatex and Pepperell wicks, with combustion being the most effective cleaning method.

Combustion results in a much higher capillary rise than other cleaning methods (Tbl. 1a). Higher capillary rise indicates that the maximum attainable pore-water tension of the wick is larger, so larger sampling suctions can be generated by designing PCAPS with longer wicks. Although cleaning is needed for the Pepperell 1/4 inch diameter wicks, washing in detergent water is nearly as efficient as combustion (Fig. 1b). This may be due to lesser amounts or different kinds of impurities on Pepperell wicks, as discussed below.

From Fig. (1c) it can be seen that almost all (>98% calculated as % mass lost at 400°C divided by % lost at 550

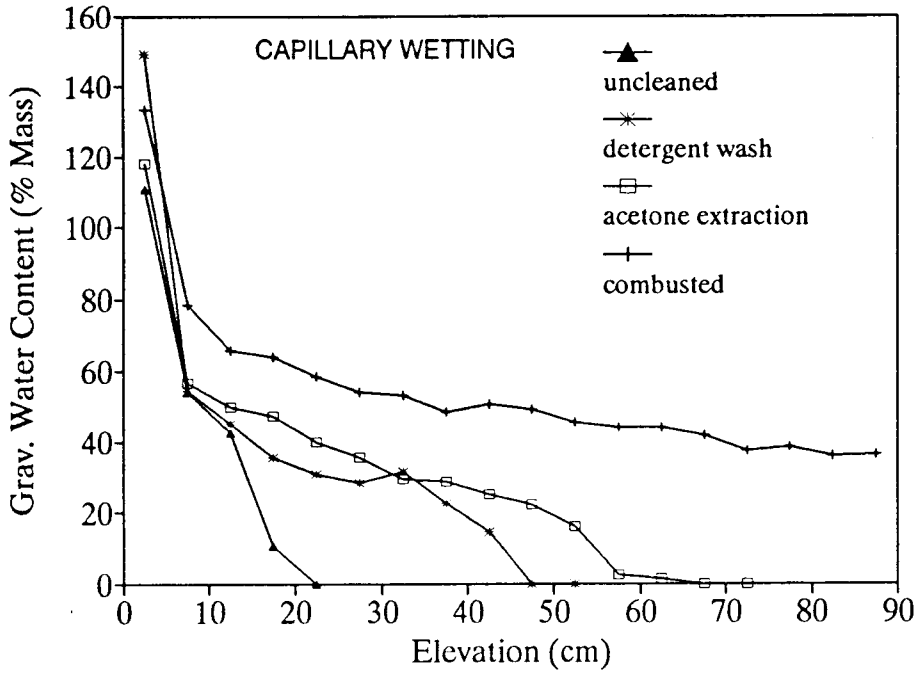

Figure 1a. Comparison of cleaning methods for Mid-Mountains 1/4" knit wick.

Table 1a. Capillary rise for the cleaning treatment methods.

WICK	TREATMENT	CAPILLARY RISE (cm)
1/4" KNIT	UNCLEANED	22
	DETERGENT WATER WASHED	47
	ACETONE WASHED	65
	COMBUSTED	93
1/4" MATRIX	UNCLEANED	67
	DETERGENT WATER WASHED	67
	ACETONE WASHED	72
	COMBUSTED	>150

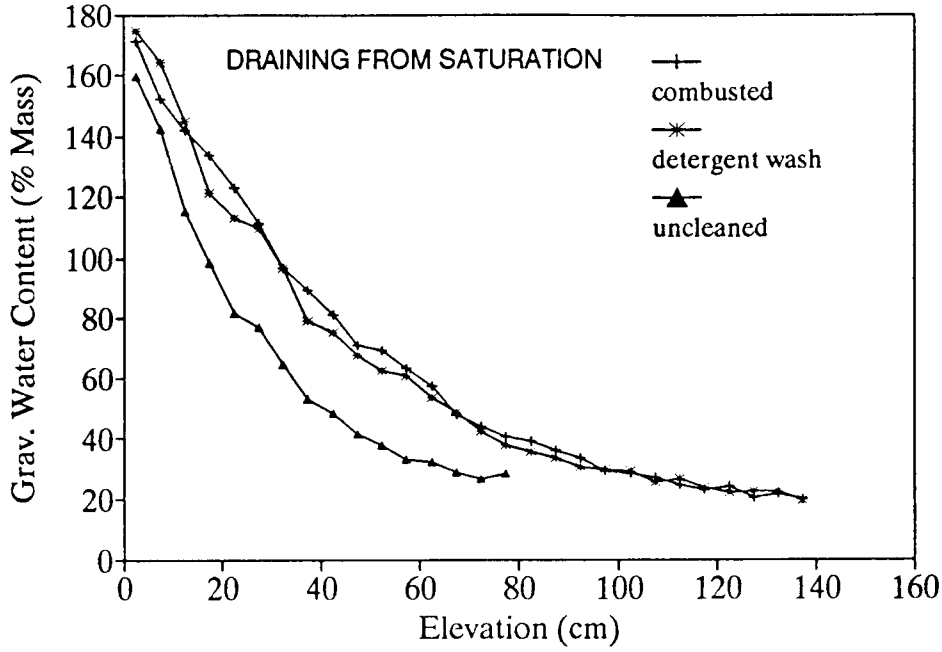

Figure 1b. Comparison of cleaning methods for the Pepperell 1/4" wick.

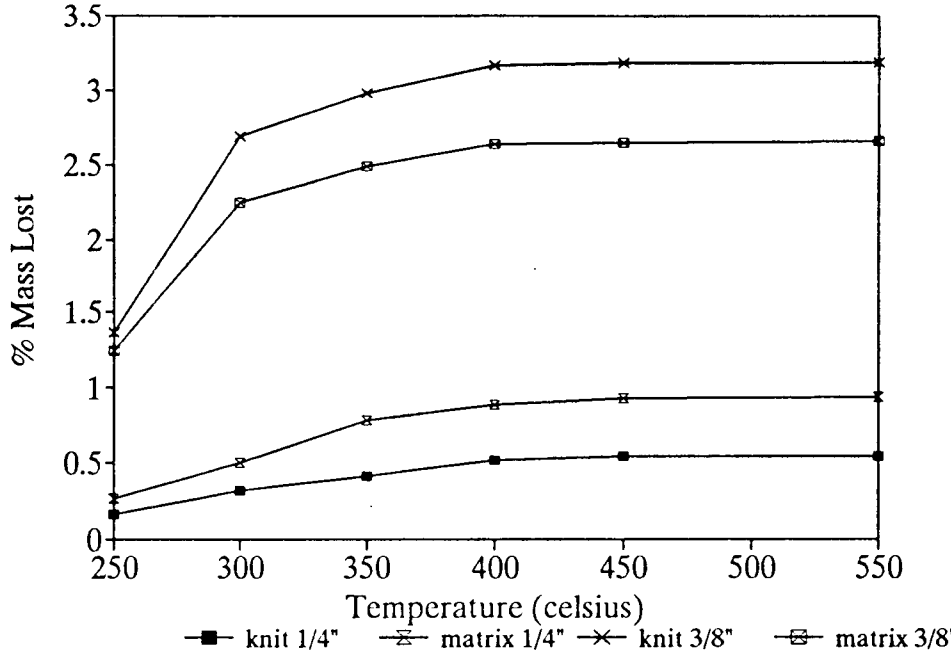

Figure 1c. Mass lost versus combustion temperature for the Mid-Mountain Wicks.

°C) of the total removable mass is lost by combusting wicks at 400°C. The Amatex and Pepperell wicks exhibited similar behavior with Pepperell wicks losing a smaller percent of total mass. Pepperell wicks' lesser loss of mass indicates that they have less total impurities perhaps, explaining the small difference between the detergent water washed and combusted characteristic curves (Fig. (1b)).

Fibers from different companies can vary in their chemical composition as well as in the types of oversprays and binders (impurities) applied. This leads to variations in temperature response and in the amount of impurities between wicks which are similar in size and density, but which are manufactured by different companies. For the samples tested, wicks composed of fibers from PPG (Mid-Mountain, Amatex) lost up to 3.4% of their total uncombusted mass (assumed to be organic impurities) during combustion, while wicks made with Manville fibers (Pepperell) lost only up to 0.6%.

CONCLUSIONS

Cleaning to remove impurities is essential in order to obtain optimum performance when using fiberglass wicks in PCAPS. Combustion of the wicks at 400°C removes >98% of the impurities within three hours. All of the wicks tested showed considerable improvements in capillary properties after cleaning. Wicks from different braiding companies may have different cleaning needs, suggesting that appropriate cleaning methods should be verified and employed for a particular wick prior to its use in soil pore-water sampling. It should be noted that wick manufacturers may change the source of their fibers or the types of binders and oversprays used without changing the wick product names, indicating that combustion is the only reliable cleaning method tested. All fibers may not have the same softening point. Wicks from Pepperell showed fiber changes at temperatures below 800°C. It should also be noted that manufacturers might change the amount of oversprays used. The preceding results are for wicks with a maximum of 3.6% by mass of impurities. Wicks with greater amounts of impurities could require combustion for longer periods, or at higher temperatures, in order to achieve the desired level of cleanliness.

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CHAPTER 2

HYDRAULIC PROPERTIES AND SELECTION OF FIBERGLASS WICKS FOR USE IN PASSIVE CAPILLARY WICK SOIL PORE-WATER SAMPLERS

John H. Knutson, J.S. Selker

ABSTRACT

Passive Capillary Samplers (PCAPS) use the capillary tension of moist fiberglass wicks to draw pore-water samples from unsaturated soils. It is important that a sampling wick's hydraulic conductivity, scaled by the area of soil sampled, is matched to the conductivity of the soil in which the PCAPS will be installed. Currently, there is no formal procedure for matching PCAPS to soils, and in order to develop one, more must be known about the conductivity-pressure relationships in wicks. As is shown, when properly matched, the top of a wick will have close to the same pore-water tension as the soil over a range of fluxes, so minimal disruption of the native soil water flux occurs and representative samples are obtained.

Conductivity test results are reported for 15 wicks from three manufacturers. Unsaturated hydraulic conductivity was measured as a function of matric potential. These data were fit by regression to an exponential conductivity function with R^2 ranging from 0.79 to 0.99. Estimates of saturated conductivity from regressing the exponential equation on data from the wicks ranged from 220

to 1380 cm/hr with lower conductivities observed in denser wicks. Saturated conductivities were compared to values predicted by a capillary tube model parameterized by porosity, tortuosity, glass filament radius, and cross-sectional wick area. Model conductivities reproduced the observed trends in measured values (R^2 of 0.85) but tended to underestimate $K_{sat.}$

Wetting and draining volumetric moisture contents were measured in wicks for known pressures. Hysteresis was observed. The draining curves were used to predict hydraulic conductivity versus pressure, K(h)-h, using van Genuchtens equation (VG equation) coupled with the Mualem conductivity model. The measured draining moisture content data fit the VG equation very well (R^2 > 0.953) but tended to underestimate saturated water contents. Fit saturated water contents ranged from 0.49 to 0.573 while measured porosities ranged from 0.73 to 0.90. K(h)-h values predicted using the Mualem model with the VG equation parameters did not match well with measured data, indicating that it may be limited as a predictive method for wicks.

An exact solution for unsaturated flow under constant infiltration is used to calculate matric potential in wicks given flux and length. The calculated values were close to those measured during the conductivity tests, with predicted matric potentials within 25 % of measured values across a

wide range of wick lengths and fluxes. The predicted matric potentials tended to be within 5 % of the measured values for fluxes between 1.6 and 16.0 cm/hr. A systematic procedure for matching the pressure versus flux curve of a wick to that of a soil is presented to aid in the design of PCAPS for application at particular sites.

INTRODUCTION

Many studies of vadose zone processes require pore-water samples which are representative of the time dependent net percolation. A new sampler for use in the unsaturated zone is the Passive Capillary Sampler (PCAPS) (Holder and Brown, 1991; Boll et al., 1991, Boll et al., 1992; Poletika et al., 1992). PCAPS use hanging fiberglass wicks which develop capillary tension to draw pore-water samples from soils (Fig. 2a). During flow, the pore-water at the bottom of a wick is at atmospheric pressure while the matric potential at the top is a function of flux. This sampling method has several advantages over other sampling techniques. First, it does not require vacuum pumps or other vacuum equipment because PCAPS use the natural capillary tension of porous wicks to passively draw water from the unsaturated soil matrix over a range of pressures. PCAPS also intercept flow from a known area of soil, accurately collecting both macropore (Steenhuis et al., 1993) and matrix flow.

Wicks used in PCAPS must be cleaned (Knutson et al., In Press 1993) and matched to the soil in which it will be used. The conductivity-pressure relationship of a wick determines the tension applied to the soil water for a given wick flux and length. Adequate soil conductivity data is typically available, but there has been very little study

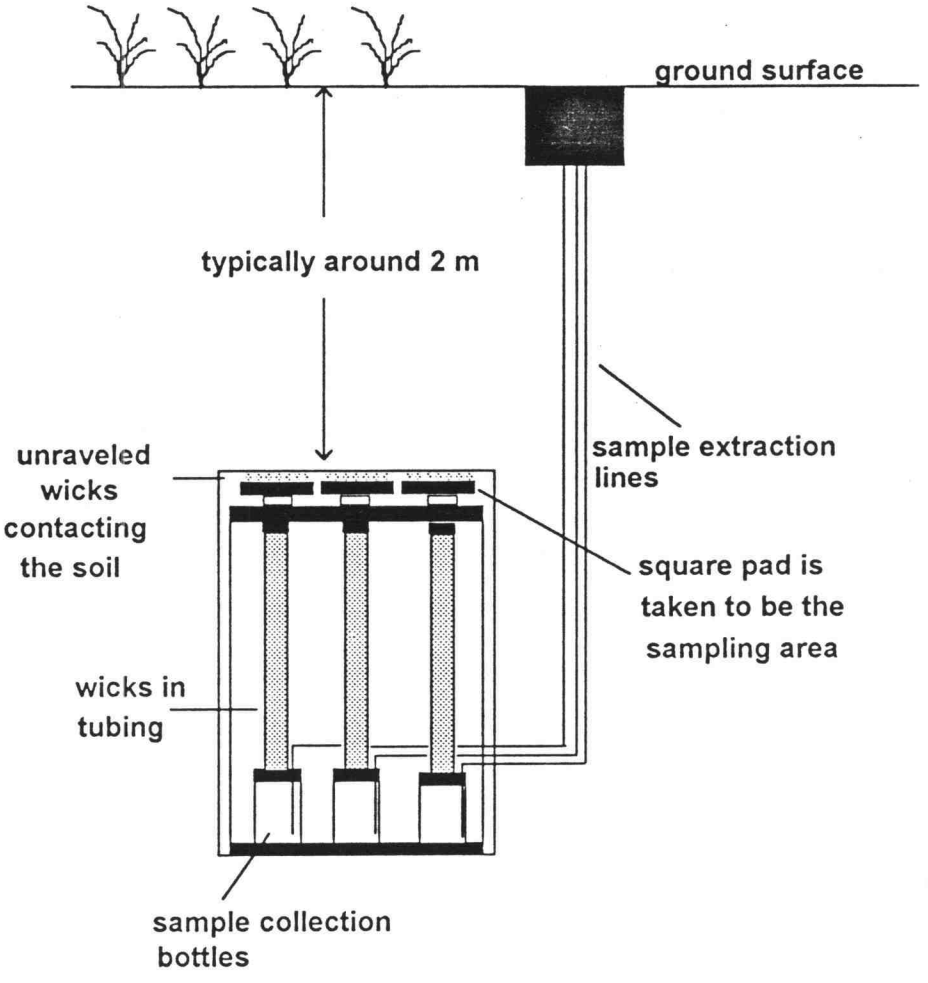

Figure 2a. Side view of a PCAPS installed in the field.

about the conductivity of fiberglass wicks.

Boll et al. [1992] presented conductivity data for a 9.5 mm diameter wick produced by Pepperell Braiding Co. (Pepperell MA). From this data, Boll et al. [1992] derived Eq. (1) to estimate matric potential at the top of a wick given the specific soil water flux (q_{soil}):

$$h=-56.35\left[\frac{q_{soil}A_{sample}}{A_{wick}}\right]^{-0.2577} \quad (-50<h<0) \qquad (1)$$

where h is matric potential (cm H_2O) at the top of a 50 cm wick, A_{sample} is the wick sampling area, and A_{wick} is the wick cross-sectional area. The bracketed quantity is the flux through the wick. While the relationship is appealing from a PCAPS design perspective there are some conceptual problems. For instance, as the flux goes to zero the matric potential at the top of a moist wick should equal its length but Eq. (1) predicts an infinite tension. In addition, if the flux through a wick is equal to its saturated conductivity then the pressure should be zero at all locations, but this relationship only approaches zero as the flux goes to infinity. Finally, it is implied that wicks with other cross sectional areas can be described by this relationship. As shown below, different braid patterns, densities, porosities, tortuosities, and glass filament diameters give rise to a range of conductivity-pressure

relationships in wicks from Pepperell as well as those from other manufacturers.

OBJECTIVES

The goal of this paper is to aid in the selection of wicks for use in PCAPS by accomplishing five objectives: (1) determine conductivity-pressure (K-h) relationships in a selection of commercially available wicks; (2) derive a relationship which allows estimation of saturated conductivity based on easily measurable wick properties; (3) compare measured K-h data to values predicted from wick draining curves using available models; (4) use the conductivity-pressure relationship to derive an equation relating wick flux and length to applied matric potential, and finally; (5) present a formal procedure to aid in wick selection given the soil type and water fluxes.

MATERIALS AND METHODS

Unsaturated Conductivity and Air Entry Tests

Laboratory tests were conducted on 15 fiberglass wicks (Tbl. 2a) to determine the conductivity versus pressure (K-h) relationships. Three of the wicks were obtained from Pepperell Braiding Co., six from Mid-Mountain Materials Co. (Redmond, WA.), and six from Amatex Co. (Norristown, PA.). The numbers 1, 1/2, 3/8, and 1/4 are the wick diameters in inches as reported by the manufacturers and are used here for product designation. The terms Knit and Matrix refer to braid types produced by Mid-Mountain Materials Co. High, Medium and Low are density designations used by Amatex Co.

Impurities were removed from the wicks by bringing them to 400 degrees celsius in the presence of ample oxygen following Knutson et al. [In Press 1993]. One clean 1 m sample of each wick was placed inside of a transparent plastic tube and oriented vertically. A Masterflex speed controllable positive displacement pump (Cole-Parmer Instr. Co., Chicago, IL) was used to supply water to the top of the wicks. The initial flow exceeded the wick's saturated conductivity. The pump speed was incrementally reduced to a minimum flow of 7 ml/hr. When pressure equilibrium was achieved for each flow rate, tensiometers installed at 13, 33, 53, 73, and 100 cm above the bottom of the wicks were

Table 2a. Wicks used in capillary tests.

COMPANY WICK NAME	WICK DESIGNATION
PEPPERELL 1/4 # 1286	PEP 1/4
PEPPERELL 1/2 # 1381	PEP 1/2
PEPPERELL 3/8 # 1380	PEP 3/8
MID-MOUNTAIN 1/2 MATRIX BRAID	MM 1/2 MAT
MID-MOUNTAIN 1/2 KNIT BRAID	MM 1/2 KNT
MID-MOUNTAIN 3/8 MATRIX BRAID	MM 3/8 MAT
MID-MOUNTAIN 3/8 KNIT BRAID	MM 3/8 KNT
MID-MOUNTAIN 1/4 MATRIX BRAID	MM 1/4 MAT
MID-MOUNTAIN 1/4 KNIT BRAID	MM 1/4 KNT
AMATEX 3/8 HI-DEN. # 10-864KR-02	AM 3/8 HI
AMATEX 3/8 MED-DEN. # 10-863KR-02	AM 3/8 MD
AMATEX 3/8 LOW-DEN. # 10-862KT-02	AM 3/8 LO
AMATEX 1/4 MED-DEN. # 10-863KR-01	AM 1/4 MD
AMATEX 1/4 LOW-DEN. # 10-862KT-01	AM 1/4 LO
AMATEX 1 MED-DEN. # 10-863KR-08	AM 1

used to measure pore-water tensions (Fig. 2b). The larger Amatex 1 inch wick required a larger plastic tube which had tensiometers installed at 10, 36, 56, 76, and 100 cm above the bottom. Tensiometers were constructed using Motorola (Phoenix, AZ) MPX 2010DP pressure transducers, Mott Metallurgical Co. (Farmington, CT) porous stainless steel disks and hollow brass bodies after Selker et al. [1992] (Fig. 2c). Conductivities were calculated from the flux and pressure data (Jury et al. 1991, p. 100-102).

Additional tests were conducted on six representative wick samples to estimate the air-entry suction. One meter long wick samples were drained from saturation for 48 hours while protected from evaporation (Fig. 2d). Each wick was cut into 5 cm segments which were weighed, dried, and reweighed. Another test was done with 20 cm long wick samples using 1 cm segment lengths for the first 10 cm above saturated conditions in order to obtain higher resolution for changes in moisture content at low tensions. The data from the two tests were combined. The gravimetric water content for each segment was calculated by dividing the mass of water lost by drying in an oven at 100 degrees celsius for 48 hr by the dry mass of the wick. The air entry suction was estimated by the height of constant moisture content above the bottom end of a wick in centimeters of water after Jury et al. [1991].

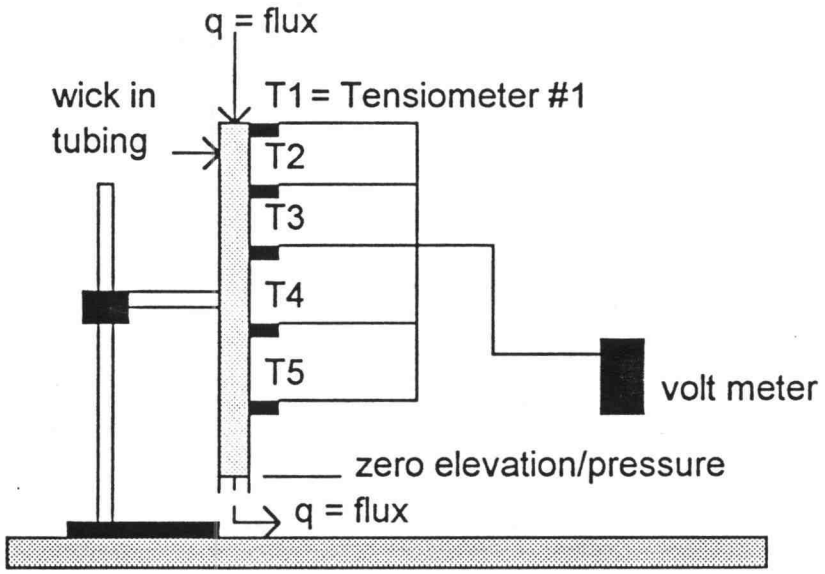

Figure 2b. Conductivity experimental design.

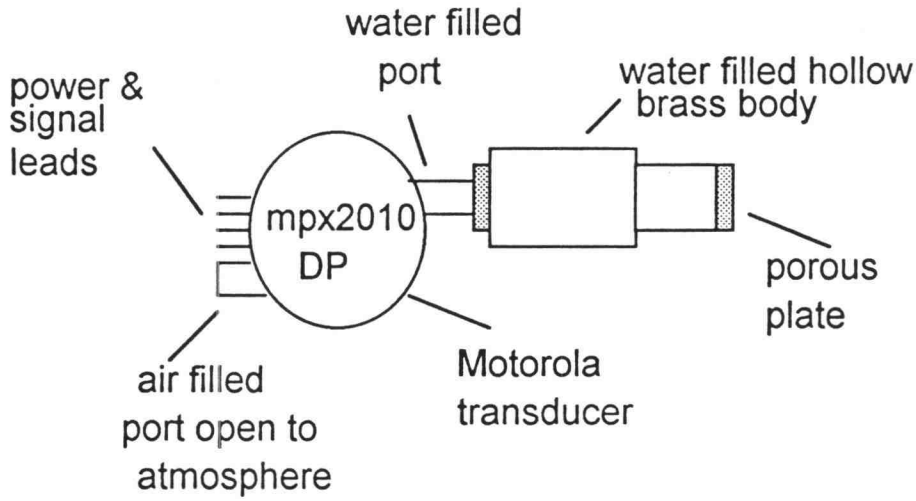

Figure 2c. Tensiometer Design

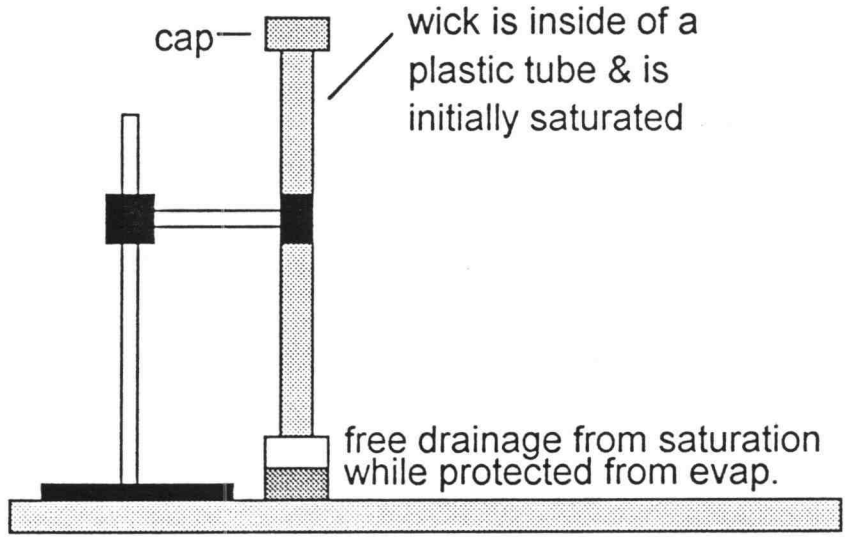

Figure 2d. Air-Entry Pressure experimental design.

Moisture Characteristic Curves Tests

Impurities were again removed from the wicks by combustion at 400 degrees celsius following Knutson et al. Moisture characteristic tests were carried out on twelve differrent wicks using two 1.5 m samples of each type. The Mid-Mountain 1/4 inch knit wick and Amatex 1/4 inch wicks were ommited due to their limited applicability in PCAPS sampling. Each of the two samples was placed inside of a transparent plastic tube and oriented vertically. One sample was allowed to wet by placing it's bottom end in a reservoir of dye water while the other sample was saturated by filling the tube with distilled water, then allowed to drain (Fig. 2e). Both samples were protected from evaporation by covering the top of the tubes and the reservoirs with wax film. The tests were conducted for 42-48 hours to ensure that equilibrium was achieved, then each 1.5 m length was cut into 5 cm segments starting at the bottom. Each segment was weighed wet, dried at 100°C for 24 hours, and reweighed. Volumetric moisture contents were calculated for the mid-point elevation of each segment. The volume of water lost by a segment was calculated by dividing the mass lost during drying by the density of water (0.998 gm/cm^3, 20°C). The volume of each segment was calculated by multiplying it's length and cross sectional area. The wetting moisture content versus pressure data were compared to the draining data to demonstrate hysteresis between the

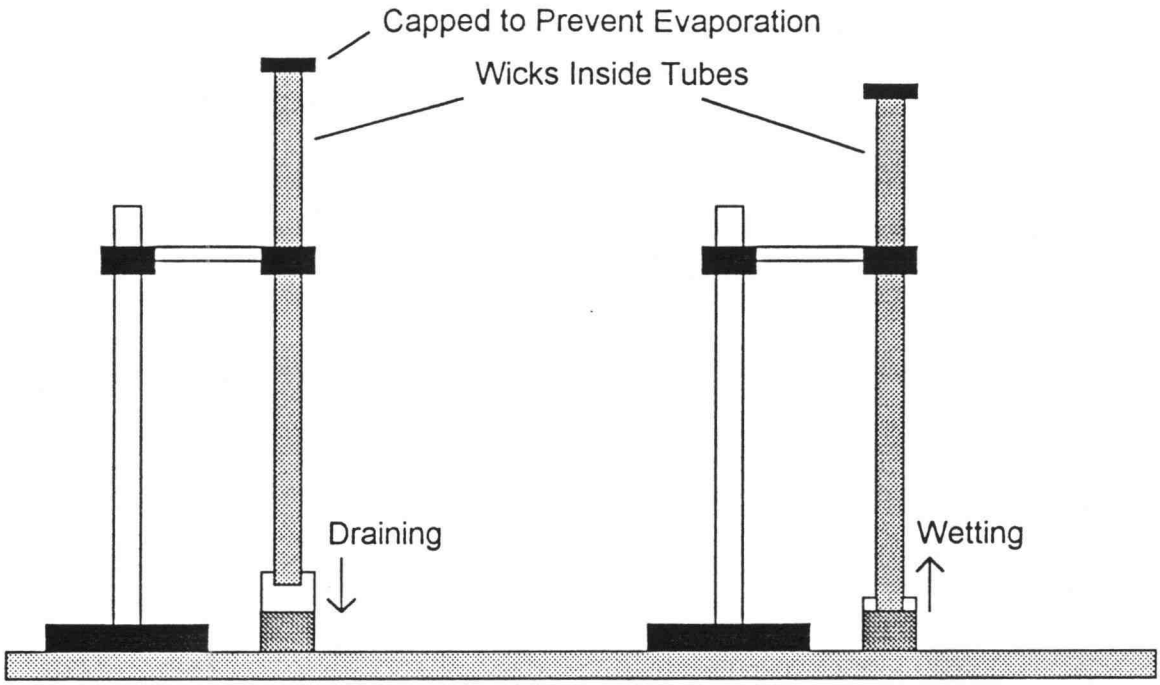

Figure 2e. Moisture characteristic curves experimental design.

processes. Draining curves were analyzed using the RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils (U.S. Salinity Lab. USDA, Riverside, CA, 1991) to determine function parameters and estimate hydraulic conductivity versus pressure.

RESULTS AND ANALYSIS

Conductivity Tests Results

The air entry test results indicated that there is no classic soil-water type air entry pressure. This can be seen in Fig. (2f) which shows moisture content versus elevation above zero pressure for the 1/2 inch Mid-Mountain wicks and is typical of the wicks tested. If an air entry pressure exists there would be a region of constant moisture content for small elevations, but in this case the moisture content drops rapidly with slight increases in elevation (i.e. pore-water tension). This performance is not unexpected considering the structure of wicks. The outer strands of the wicks are loosely woven forming an open matrix of large pores which will drain under minimal suction, resulting in negligible air entry pressure.

If the unsaturated conductivity, K(h), data of wicks exhibit exponential behavior with respect to pressure, h, then a graph of the ln(k(h)) versus pore-water pressure should be linear. Typical ln(K(h)) versus pressure data are shown in Fig. (2g). The data are well described by a linear relationship supporting the use of the modified exponential equation introduced by Rijtema [1965]:

$$K(h) = K_{sat}\exp[a(h + h_e)] \qquad (2)$$

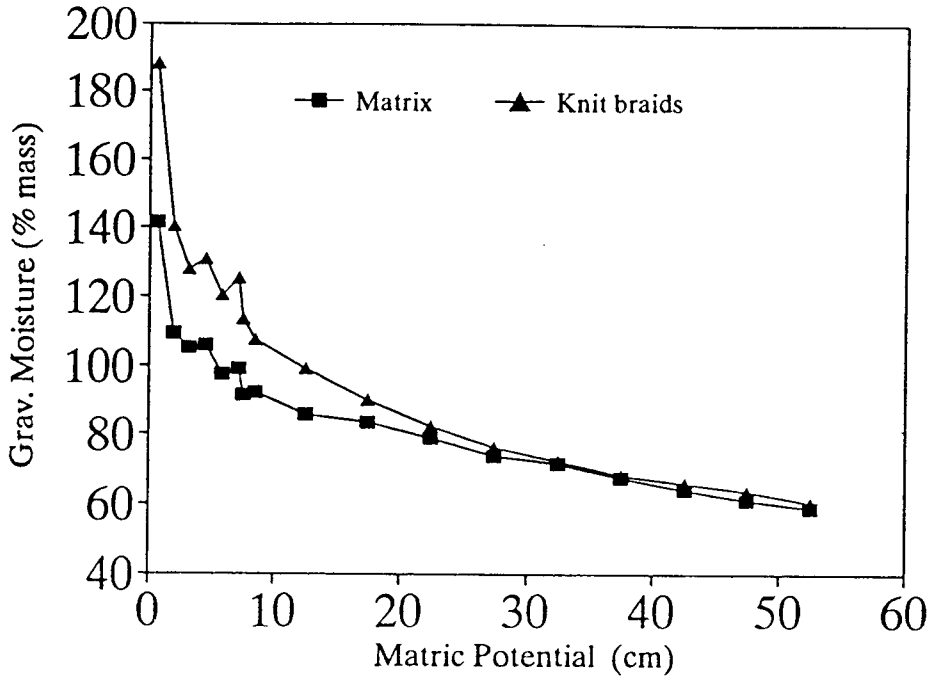

Figure 2f. Results of the air-entry tests for the Mid-Mountain 1/2" wicks.

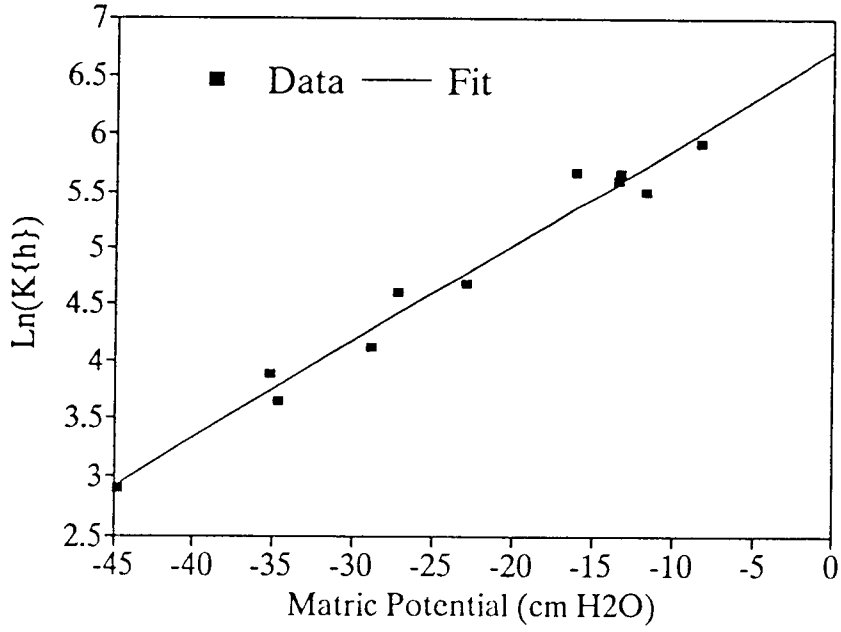

Figure 2g. Natural log of K{h} data for the Pepperell 1/2" wick.

where K_{sat} is saturated conductivity, h is matric potential, h_e is effective air entry suction, K(h) is unsaturated conductivity, "a" is a constant related to the medium. Since air entry suction h_e is negligible Eq. (2) may be written as:

$$\ln(K(h)) = \ln(K_{sat}) + ah \qquad (3)$$

which is the familiar exponential conductivity relationship introduced by Gardner [1958]. The K(h)-h data for each wick were fit by linear regression ($0.79 \leq R^2 \leq .99$) to Eq. (3) resulting in estimates of K_{sat} and "a" (Tbl. 2b). The typical fit of Eq. (3) to the data is illustrated for the Pepperell 3/8 inch wick (Fig. 2h). The regression analysis used data for tensions of -2 cm of water or larger. Data obtained at lower tensions were considered unreliable due to the possibility of water flowing outside of the wick fabric. Also, data otained with the tensiometer placed at 100 cm were left out of the calculations for high flows because the readings were influenced by pulses of water from the inlet tube. In general, Eq. (3) fit the experimental data very well with some tendency to underestimate K(h) at low tensions. K_{sat} estimates obtained from the regressions ranged from 220 to 1380 cm/hr. Highest conductivities were obtained for wicks with lower densities (Tbl. 2c). The values of "a" ranged from 0.047 to 0.136 cm^{-1} with the exception of Mid-Mountains 1/4 knit which had a value of

Table 2b. Estimates of saturated conductivity, constant "a", and R ^ 2 from the regressions.

WICK	Ksat (cm/hr)	"a" (cm ^ -1)	R ^ 2
PEP 1/4	622	0.075	0.91
PEP 1/2	1168	0.098	0.98
PEP 3/8	829	0.085	0.97
MM 1/2 MAT	220	0.064	0.99
MM 1/2 KNT	328	0.091	0.90
MM 3/8 MAT	323	0.062	0.94
MM 3/8 KNT	528	0.129	0.86
MM 1/4 MAT	288	0.089	0.93
AM 3/8 HI	273	0.047	0.91
AM 3/8 MD	460	0.066	0.93
AM 3/8 LO	607	0.083	0.88
AM 1/4 MD	291	0.077	0.79
AM 1/4 LO	411	0.136	0.87
AM 1	618	0.074	0.98
MM 1/4 KNT	1380	0.319	0.95

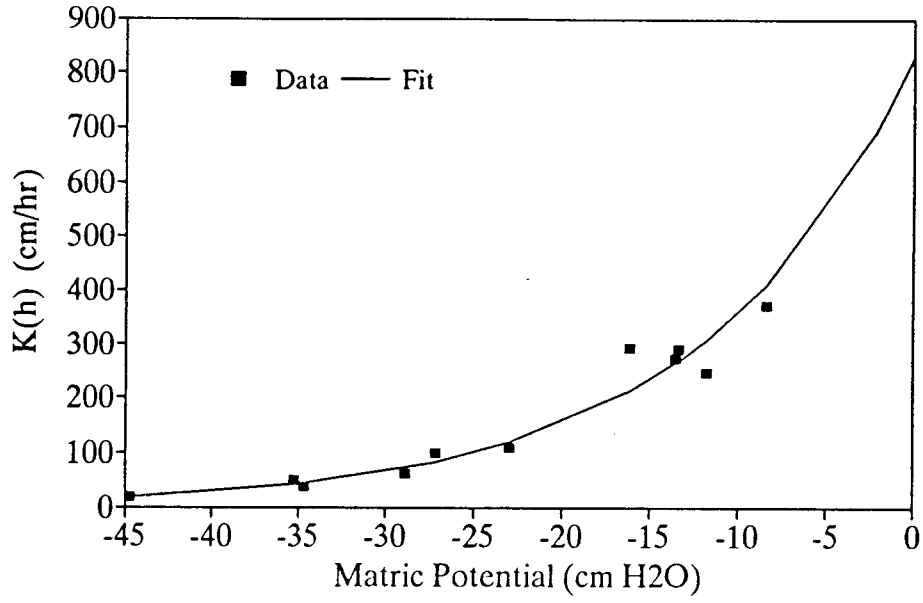

Figure 2h. Fit of the exponential equation to the Pepperell 1/2" K{h} data.

0.319. This particular wick's properties were unique; it was very elastic in length, was loosely woven, and had a high tortuosity. Due it's excessive elongation when wet and low maximum capillary suction (less than 10% of the other wicks), this wick was determined to be unsuitable for application in PCAPS and is excluded from subsequent analysis.

A quantitative description of wick physical properties would be useful to sampler designers. To characterize the properties of the wicks, the diameter, bulk density, porosity, apparent (or strand) tortuosity, and glass filament radius were measured (Tbl. 2c). Diameters are the average of 5 measurements made with dial calipers. Bulk density was calculated by dividing the mass of a known length of wick by its volume. Porosity was calculated as one minus the ratio of wick bulk density to glass density. Glass density was assumed to be 2.6 gm/cm^3 (PPG Data Sheet) for all wicks. Apparent (or strand) tortuosity was estimated by unravelling a known length of wick. Since not all unraveled strands were the same length, a mass averaged value was calculated. This was done by summing the products of the individual strand lengths times their masses and dividing by the total mass. The mass averaged unraveled strand length divided into the braided segment length is taken as the apparent tortuosity. Average glass filament diameters were obtained from the manufacturers and are 7

Table 2c. Wick physical properties.

WICKS	DIAMETER (cm)	BULK DENSITY (gm/cm^3)	POROSITY	FILAMENT TORTOUS.	FIBER RADIUS (mm)
PEP 1/4	0.64	0.45	0.83	0.78	0.0035
PEP 1/2	1.45	0.25	0.90	0.79	0.0035
PEP 3/8	0.87	0.33	0.87	0.86	0.0035
MM 1/2 MAT	1.26	0.70	0.73	0.19	0.0045
MM 1/2 KNT	1.34	0.55	0.79	0.15	0.0045
MM 3/8 MAT	1.02	0.67	0.74	0.19	0.0045
MM 3/8 KNT	0.94	0.35	0.87	0.19	0.0045
MM 1/4 MAT	0.85	0.66	0.75	0.19	0.0045
AM 3/8 HI	1.06	0.64	0.75	0.36	0.0045
AM 3/8 MED	0.97	0.47	0.82	0.26	0.0045
AM 3/8 LO	1.12	0.31	0.88	0.19	0.0045
AM 1/4 MED	0.65	0.56	0.78	0.29	0.0045
AM 1/4 LO	0.72	0.39	0.85	0.19	0.0045
AM 1	2.93	0.36	0.86	0.37	0.0045
MM 1/4 KNT	0.64	0.48	0.82	0.19	0.0045

microns for the Pepperell, and 9 microns for the Mid-Mountain and Amatex wicks (Personal Comm., 1992). The porosities (p) of the wicks are large compared to naturally occurring porous media, with all wicks having $p > 0.73$. Apparent tortuosities ranged from 0.154 to 0.862.

Predicting Wick Saturated Conductivity

It would be convenient if a wick's conductivity could be calculated from the easily measurable properties given in Tbl. (2c). This would allow parameter estimation for new wicks without extensive laboratory experiments. Using the assumptions of square filament packing, a single effective pore radius, and continuous fibers, a capillary tube model was derived (See Appendix A) to estimate saturated conductivities by:

$$K_{sat} = C_3 \left[\frac{D_w g}{4v} T^2 \pi r^2 \left(\frac{p}{1-p} \right) \right] \quad (m/s) \qquad (4)$$

where p is porosity, T is the actual tortuosity, r is fiber diameter (m), D_w is the density of water, g is gravitational acceleration, v is the dynamic viscosity of the fluid, and C_3 is a unitless constant related to pore geometry. As discussed above the fiber radius can be obtained from manufacturers, while porosity and apparent tortuosity is easily measured. The apparent tortuosity measured is

greater than the actual tortuosity because wick pores are not isolated capillaries but exhibit significant connectivity. To account for this connectivity, and maximize the relationship between modeled K_{sat} and measured K_{sat}, a relationship between the actual tortuosity and the measured values is needed. It was found that estimating the actual tortuosity to be equal to the square root of the measured values resulted in the maximum fit between the K_{sat} values in Tbl. (2b) and modeled K_{sat}. The quantity in brackets was calculated for the wicks and regressed against the K_{sat} values in Tbl. (2b) to estimate C_3 equal to 4.85. Calculated conductivities from the capillary tube model explain the variation observed in wicks reasonably well (R^2 = 0.85) (Fig. 2i).

Moisture Characteristic Tests Results

The moisture test results showed the expected hysteresis between wetting and draining water contents as demonstrated by Boll et al. [1992]. Hysteresis is shown for the Mid-Mountain 1/2 Knit wick (Fig. 2j) and is typical of wick behavior. This was true in all wicks with draining moisture contents as much as 15% higher than wetting values. The draining curves were fit by the RETC code to the equation supplied by van Genuchten [1980] (VG equation):

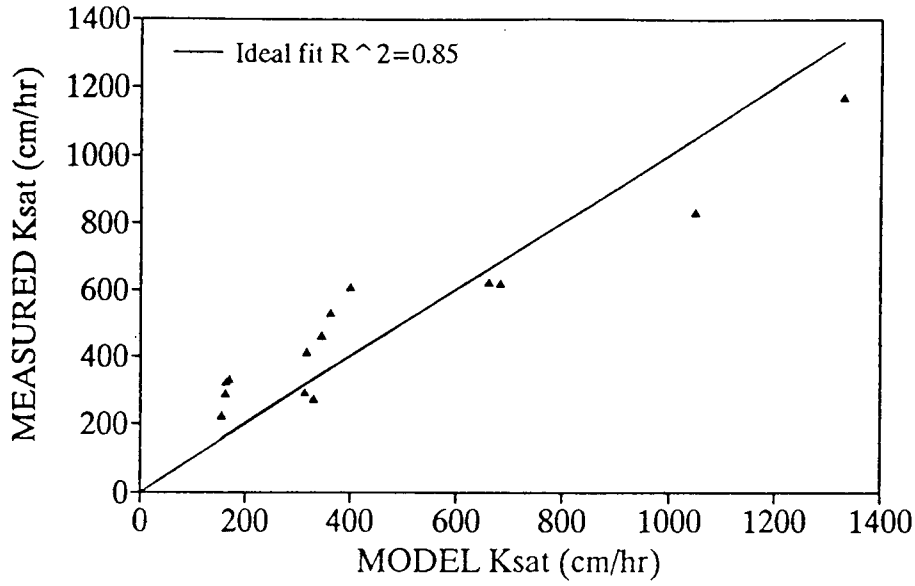

Figure 2i. Capillary tube model of Ksat versus the estimates in Tbl. (2b).

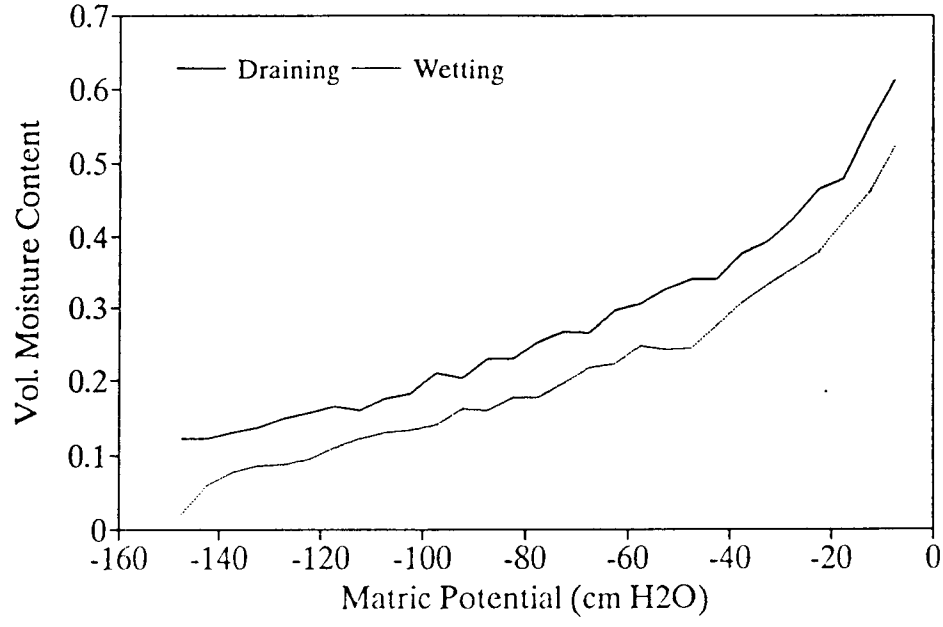

Figure 2j. Moisture content hysteresis observed in the Mid-Mountain 1/2" knit wick.

$$S_e = \frac{1}{[1+(\alpha h)^n]^m} \qquad (5)$$

where S_e is the effective degree of saturation, and h (units of positive length) is the capillary suction. The constants α (positive units of 1/length), n (dimensionless), and m (dimensionless) are empirical values affecting the shape of the moisture retention curve. The effective degree of saturation is defined as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (6)$$

where θ is the moisture content at some pressure, θ_r is the residual moisture content, and θ_s is the saturated moisture content (zero pressure). The values of θ_r, θ_s, α, n, and m were fit by the RETC code to data from the draining tests. The VG equation (Eq. 5) fit the data very well ($R^2 \geq 0.953$) except for a tendency to predict an air entry region thus underestimating θ_s. Fit values of θ_s ranged from 0.49 to 0.79 (measured porosities ranged from 0.73 to 0.90 (Tbl. 2c)) and residual moisture contents ranged from zero to 0.21. Values of n ranged from 1.005 to 3.611, m ranged from 0.395 to 6.67, and α ranged from 0.0041 to 0.055 cm^{-1} (Tbl. 2d). A typical fit of Eq. (5) to the data is shown for the Mid-Mountain 3/8 inch Knit wick (Fig. 2k).

Table 2d. van Genuchten parameters and R ^ 2 values obtained by regressing the V.G. equation on the draining moisture content data.

Wick	Theta sat	Theta res	Alpha(1/cm)	n	m	R^2
AM3/8HI	0.573	0	0.0134	2.307	0.765	0.992
AM3/8MD	0.672	0	0.024	2.76	0.51	0.995
AM3/8LO	0.573	0	0.0245	2.025	0.832	0.995
AM1	0.79	0	0.0237	1.44	1.25	0.998
MM1/4MAT	0.49	0.1565	0.0061	1.732	3.228	0.953
MM3/8MAT	0.711	0.21	0.0046	1.454	6.667	0.959
MM3/8KNT	0.49	0.021	0.0172	1.961	1.139	0.996
MM1/2MAT	0.69	0	0.0055	1.124	2.229	0.988
MM1/2KNT	0.65	0	0.0041	1.005	3.58	0.978
PEP3/8	0.77	0.04	0.02816	2.72	0.971	0.994
PEP1/2	0.63	0	0.055	3.611	0.395	0.965
PEP1/4	0.7	0	0.0259	2.172	0.682	0.971

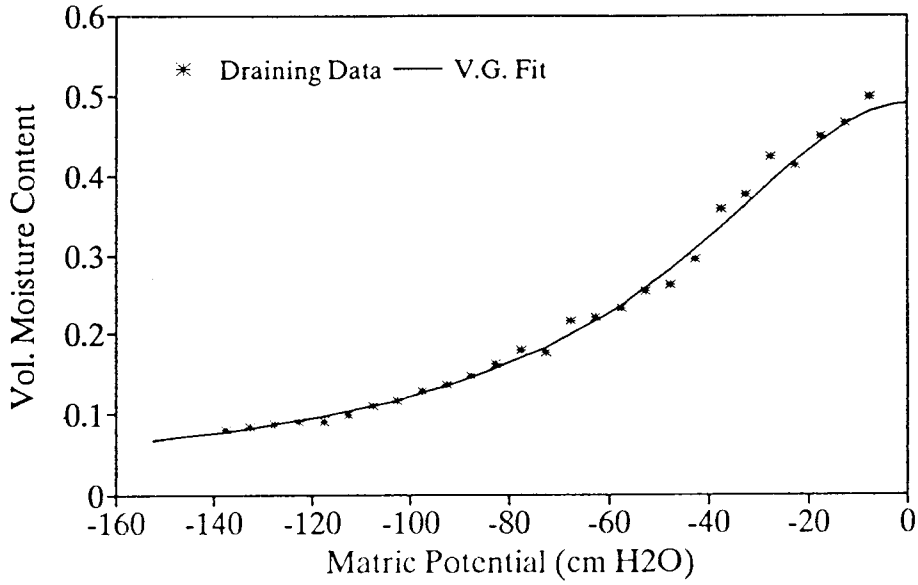

Figure 2k. van Genuchten fit to the draining moisture content data of the Mid-Mountain 3/8" knit wick.

The RETC code was also used to estimate relative conductivity versus pressure for the wicks using the Mualem [1976b] Hydraulic Conductivity Model for the case of independent n and m. The solution for this case is:

$$\frac{K(h)}{K_s} = \frac{n^2}{[(mn+1)\beta(p,q)]^2(\alpha h)^{2+mn(l+2)}} \qquad (7)$$

where K(h) is the conductivity at capillary suction h. K_s is the saturated conductivity, α, n, and m are the VG Equation constants, and l is a pore connectivity factor assumed to be 0.5. The constants p and q are calculated from n and m:

$$p = m + \frac{1}{n} \quad ; \quad q = 1 - \frac{1}{n} \qquad (8;9)$$

$\beta(p,q)$ refers to the complete Beta function. The values of saturated conductivity used are those listed in Tbl. (2b). The Mualem conductivity function did not fit the exponential values well, as is shown for three different wicks (Fig. 21), but tended to randomly over or under-estimate K(h).

Predicting Wick Matric Potential as a Function of Flux

To achieve the fourth objective, it is necessary to predict pore-water pressure at the top of a wick as a

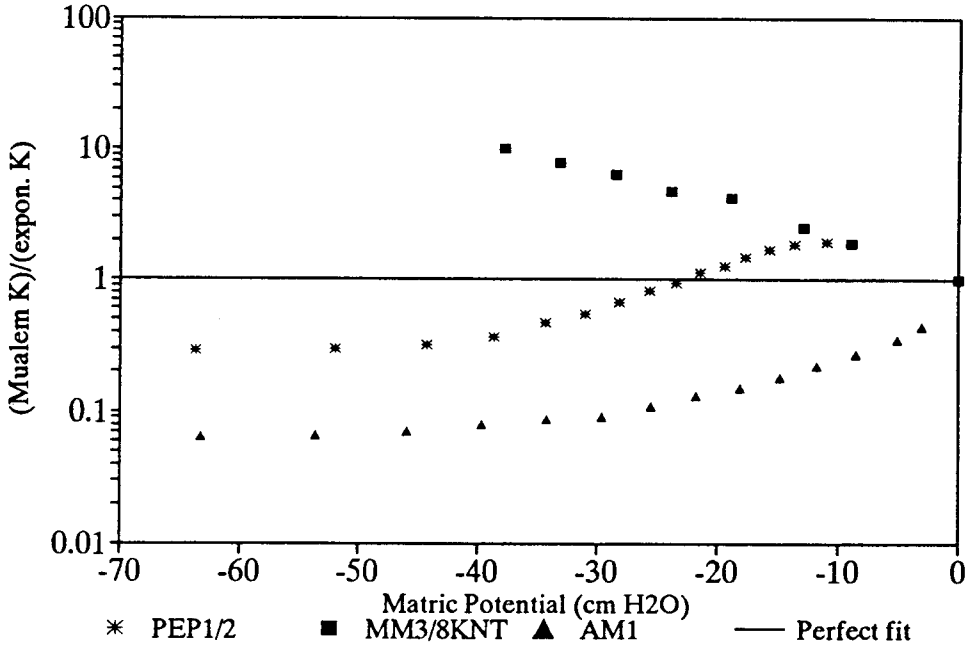

Figure 21. Mualems predicted K{h} divided by the exponential K{h} values versus matric potential.

function of flux, length, and conductivity-pressure relationship. Gardner [1958] used the exponential K(h)-h relationship of Eq. (3) to solve the Richards equation for steady state evaporative flux from a water table resulting in:

$$h = \left(\frac{1}{a}\right) \ln\left[\exp(az)\left(\frac{q}{K_{sat}} + 1\right) - \frac{q}{K_{sat}}\right] \qquad (10)$$

where h is matric potential at elevation z above the water table (negative upward), q is flux (positive upward), K_{sat} is the saturated conductivity, and "a" is the exponential constant of Eq. (3) seen earlier. This solution is suited to wicks used in PCAPS since they are well described by an exponential K(h)-h relationship. The sign of the flux, q, becomes negative since constant infiltration is being considered rather than evaporation and z is now the length of the wick. The analogy between soil and wick systems is shown in Fig. (2m). Calculated wick pore-water tensions are compared to measured values at four different elevations in the 1/2 inch Mid-Mountain knit wick, which had a below average fit to Eq. (3) (R^2 = 0.90 compared to average R^2 = 0.93 and median R^2 = 0.93), and for the 1 inch diameter Amatex wick which had an above average fit (R^2 = 0.98) for four different fluxes (Tbl. 2e). Predicted pressures are all very close to the measured values verifying that Eq. (10) can be used to estimate matric potentials in wicks for

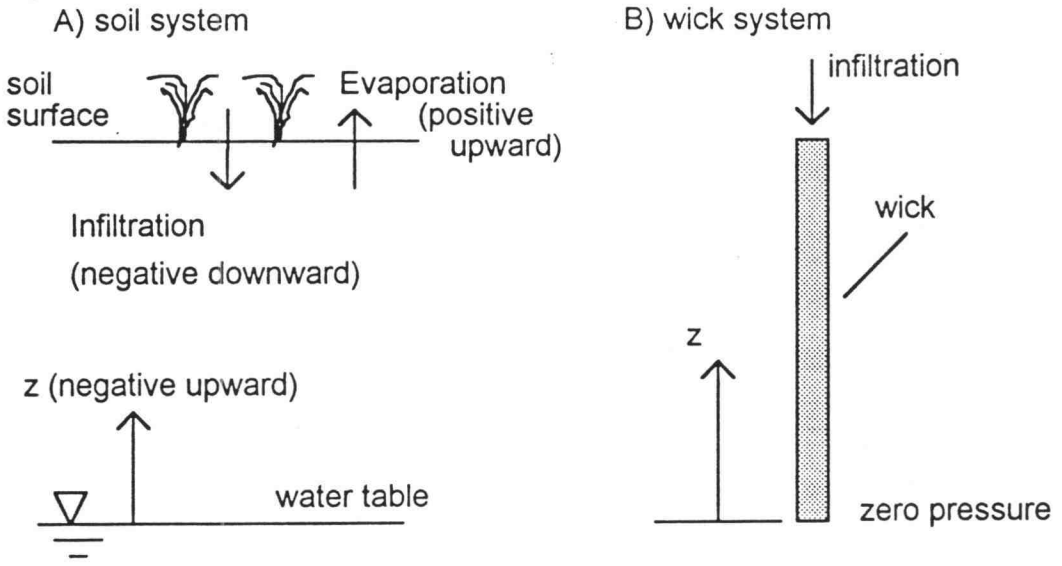

Figure 2m. Analogy between soil and wick systems.

Table 2e. Measured matric potentials compared to calculated values for four different fluxes.

VERTICAL FLUX (cm/hr)	ELEVATION ABOVE 0 (cm)	MEASURED PRESSURE (cm H2O)	PREDICTED PRESSURE (cm H2O)	RATIO
Mid-Mountain 1/2 Inch Knit				
-95	73	-10.0	-13.6	0.74
	53	-10.8	-13.4	0.81
	33	-10.3	-12.4	0.83
	13	-7.1	-7.5	0.95
-32	73	-20.9	-25.4	0.82
	53	-21.5	-24.8	0.87
	33	-18.5	-21.4	0.86
	13	-8.9	-10.8	0.82
-16	73	-31.4	-32.9	0.95
	53	-30.0	-31.6	0.95
	33	-23.2	-25.8	0.90
	13	-9.6	-11.8	0.81
-5	73	-48.8	-45.1	1.08
	53	-41.0	-41.4	0.99
	33	-27.9	-30.2	0.92
	13	-9.8	-12.6	0.78
Amatex 1"				
-22	76	-43.6	-43.8	1.00
	56	-40.9	-40.2	1.02
	36	-30.5	-30.7	0.99
	10	-7.9	-9.5	0.83
-7	76	-58.1	-56.8	1.02
	56	-49.0	-48.8	1.00
	36	-34.2	-34.1	1.00
	10	-7.3	-9.8	0.74
-3	76	-65.0	-64.5	1.01
	56	-51.7	-52.4	0.99
	36	-34.9	-35.2	0.99
	10	-7.3	-9.9	0.74
-1.3	76	-70.6	-69.8	1.01
	56	-53.6	-54.3	0.99
	36	-35.4	-35.6	0.99
	10	-7.3	-10.0	0.73

given fluxes. The results are similar for the other wicks. Equation (10) appears to be superior to Eq. (1) given earlier; when q = 0, h = wick length, and when q = K_{sat}, h = 0 as should be expected.

Matching Wick Samplers to Specific Sites

The fifth objective was to develop a simple method to select wicks for use in a given soil. One simple case would be to match wicks to a soil having an exponential K(h)-h relationship. The design goal is to have pore-water tensions at the top of a wick be the same as in the native soil profile over a range of percolation rates. The flux through a wick is calculated by multiplying the soil pore-water flux by the area of soil sampled (sampling area) then dividing by the wick's cross-sectional area. If the water table is considered to be far below the sampler (z large) then Eq. (10) reduces to:

$$h_{soil} = \frac{1}{a_{soil}} \ln\left[-\frac{q_s}{K'_{sat}}\right] \qquad (11)$$

where h_{soil} is the pore-water pressure in the soil for flux q_s (negative downward), a_{soil} is the exponential constant for the soil and K'_{sat} is the soils saturated conductivity. It should be noted that Gardner also provided solutions to

calculate h_{soil} for additional conductivity functions, and these solutions can be used in place of Eq. (10) or (11) where soils are not described well by the exponential function. The pressure versus flux for a wick is:

$$h_{wick} = \frac{1}{a_w} \ln\left[\exp(a_w z_w)\left(q_s \frac{A_s}{A_w K_{sat}} + 1\right) - \left(q_s \frac{A_s}{A_w K_{sat}}\right)\right] \qquad (12)$$

where h_{wick} is the pore-water pressure at the top of a wick with length z_w (negative), A_s is the area of soil sampled by the wick, A_w is the wick cross-sectional area, K_{sat} is the saturated conductivity of the wick, a_w is the wicks exponential constant, and q_s (negative downward) is the soil water flux. Subtracting Eq. (11) from Eq. (12) will give the difference, or residual, in pore-water pressure between the top of a wick and the soil for any flux, sampling area and wick length. If the residual is negative then the top of the wick has a higher water tension and over-sampling would be predicted and, alternately, positive residuals indicate under-sampling.

Soil matric potential versus conductivity data taken from Mualem [1976a] for Ida Silt Loam and Rehovot sand are shown in Fig.s (2n) and (2o). The figures also show the fit of Eq. (3) to the data in order to estimate the exponential constants (a_{soil}) which were 0.067 cm^{-1} for the Ida silt loam

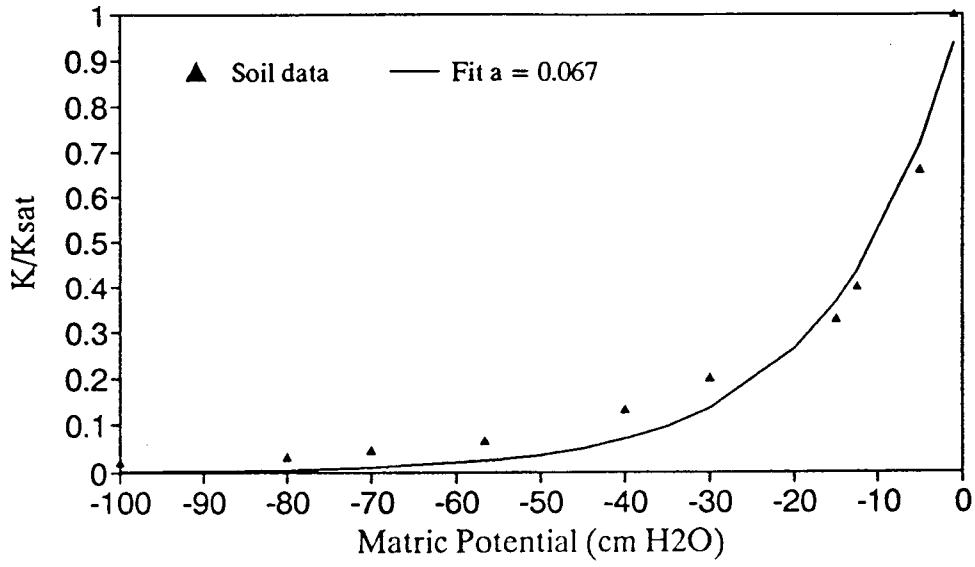

Figure 2n. Estimating "a" for the Ia silt loam soil.

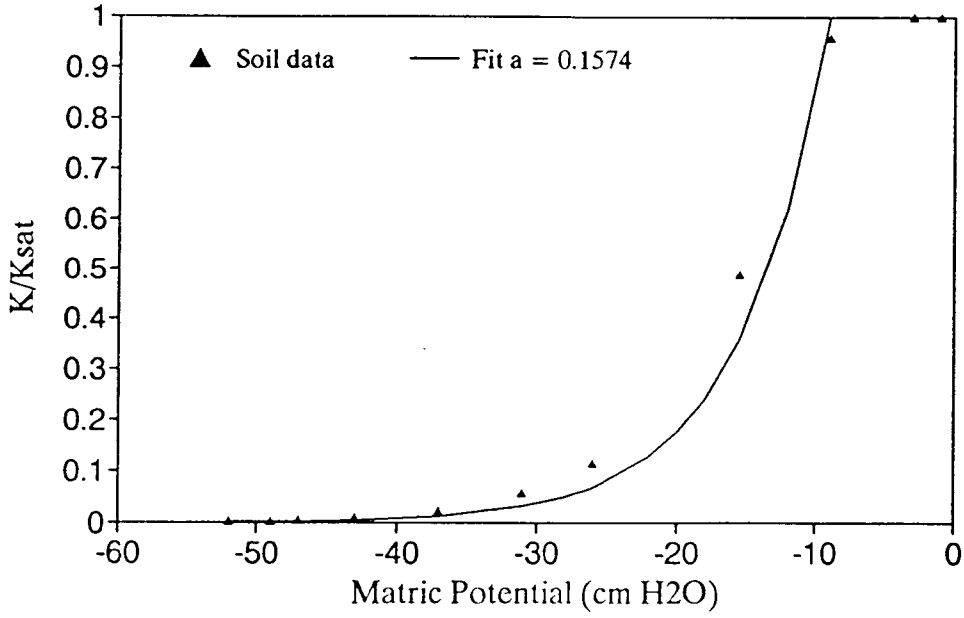

Figure 2o. Estmating "a" for the Rehovot sand soil.

and 0.157 cm^{-1} for the Rehovot sand. An air entry pressure of -9.5 cm H_2O was used for the sand. Saturated conductivities were given by Mualem to be 1.5 cm/hr for the silt loam and 27.5 cm/hr for the sand.

Figures (2p) and (2q) show the soil water pressure as a function of downward flux for locations in the silt loam and sand where the water table is considered deep (Eq. 11). The water tensions range from 0 to -54 cm for the silt loam and 0 to -50 cm for the sand. These figures also show curves of pressure at the top of various wicks given the same soil fluxes (Eq. 12). The q-h curves for the wick and soil match well for the silt loam using an Amatex 3/8 inch Medium Density wick with a length of 80 cm and a sampling area of 225 cm^2. The fit is good for the sand as well using a Pepperell 1/2 inch wick with a length of 45 cm and a sampling area of 75 cm^2 but over-sampling at low fluxes is predicted. Over sampling is predicted for the sand because the calculated matric potentials are greater in the wick than in the soil. In order to get the curves to match well it is first necessary to choose a wick with the right saturated conductivity, exponential constant, and cross-sectional area, then to choose the right combination of wick length and sampling area. This can easily be done using a spreadsheet program.

To match wicks to a soil, first it must be recognized

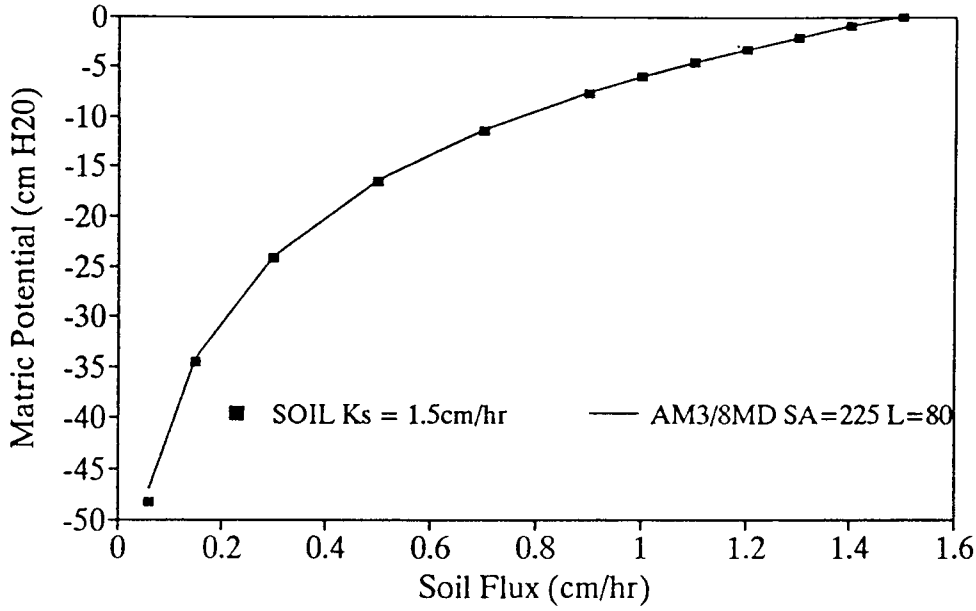

Figure 2p. Predicted matric potential match of the Ida silt loam and the top of a sampling wick. "SA" is the sampling area and "L" is the wick length.

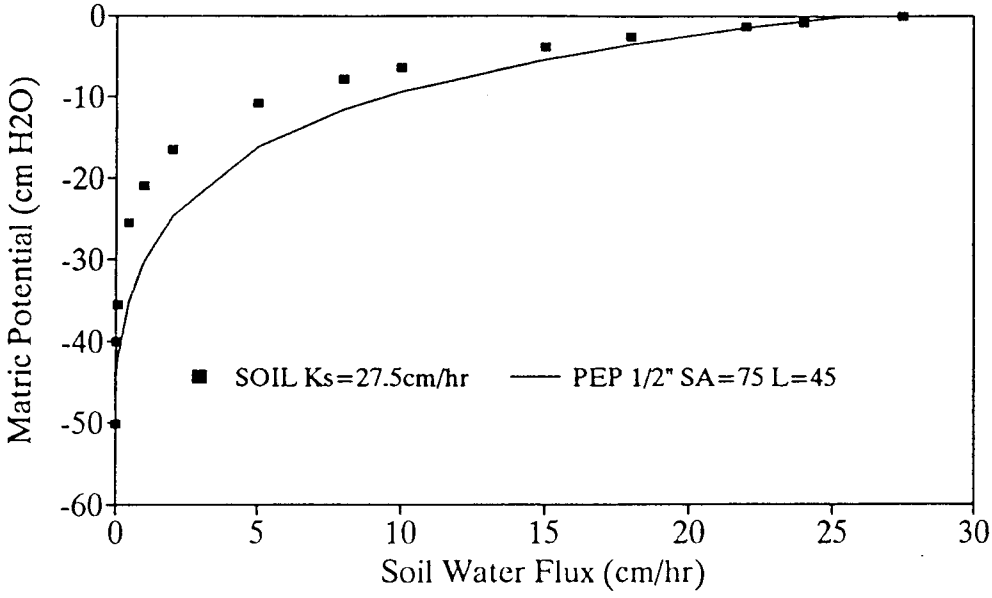

Figure 2q. Predicted matric potential match of the Rehovot sand and the top of a sampling wick. "SA" is the sampling area and "L" is the wick length.

that if significant fluxes are expected at soil water tensions more negative than -100 cm then the PCAPS sampling method may not be appropriate since this would require a wick length of at least 100 cm, resulting in an awkwardly large design. The soil conductivity function parameters (a_{soil}, K'_{sat}) must be obtained and Eq. (11) (or an alternate method) should be used to calculate soil pore-water pressures for the desired range of fluxes. Equation (12) is then used to calculate pressures at the top of a selected wick using the maximum length allowable for the PCAPS design (1 meter is suggested). A sampling area can be solved for by iteration (or by a non-linear optimizer common to spreadsheet programs) so the sum of the squared residuals is minimized. The wicks' pore-water pressures are insensitive to length except at very low fluxes, so the designer can determine if a wick's length may be shortened without sacrificing the level of fit. If the wick-soil fit is not acceptable then repeat the process using the parameters for a different wick. The above method provides a systematic way to select wicks when designing PCAPS. If a water table is present then Eq. (10) can be used to calculate soil water tensions instead of Eq. (11).

CONCLUSIONS

Conductivity-pressure relationships in fiberglass wicks were shown to be described well by an exponential function. The saturated conductivity of wicks can be estimated from easily measured parameters using a capillary tube model. From analysis of the moisture characteristic and air entry tests data it was determined that: there is no well definable air entry pressure; hysteresis occurs between the wetting and draining processes; the van Genuchten equation describes the draining moisture content versus pressure relationship well but tends to underestimate θ_s; and estimates of K(h) versus h obtained using Mualems conductivity model with van Genuchtens parameters do not correspond well to measured values. Gardner's solution of Richards equation for constant evaporative flux from a water table can be used to estimate matric potentials in wicks under constant infiltration. A systematic procedure is provided to aid in PCAPS design using these results.

There are several areas which merit further research. A comprehensive measurement of the variability in properties exhibited by single wick types would be useful. As stated earlier, wick producers may change the physical properties without changing the product designation, and this will be the cause of the greatest variability. It would also be useful to refine the relationship between a capillary tube

model of K_{sat} and measured values so better estimates of wick conductivities can be obtained. In particular, the relationship between the actual tortuosity and the strand tortuosity needs to be studied more. A systematic way to estimate the constant "a" for wicks would be helpful for calculating matric potentials as a function of flux. PCAPS designers can avoid some of these limitations by using the wicks which have been characterized in this paper, or by determining K_{sat} and "a" experimentally. It should also be noted that soil properties vary greatly over small regions and uncertainty in these properties must be considered when matching PCAPS to soils.

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CHAPTER 3

FIBERGLASS WICK EFFECTS TO SOLUTE TRAVEL TIME AND DISPERSION FOR APPLICATION IN MONITORING VADOSE ZONE CHEMICAL TRANSPORT

John H. Knutson, J.S. Selker

ABSTRACT

Fiberglass wick samplers are being evaluated by scientists to determine their effectivness as a soil pore-water sampler. Part of this evaluation requires knowing what effects the sampler itself has on the transport of the chemical being sampled.

Tracer (FD&C Blue Dye #1) tests were conducted to determine the effects which a wick has on the travel time and dispersion of a chemical moving vertically through soil to a wick sampler. The breakthrough data fit the convective-dispersive equation well ($R^2 > 0.981$) and resulting dispersivity estimates ranged from 0.59 to 4.3 cm. A finite difference program was used to show that additional travel time and dispersion caused by a sampling wick are negligible compared to the effects of solute travel through a soil. This result is expected because a single wick may sample up to 900 cm^2 of soil and typically has an area under 5 cm^2 thus the flux through a wick is much greater than in the soil.

INTRODUCTION

Studying contaminant transport in the vadose zone requires the ability to obtain soil pore-water samples which are representative of fluxes to the water table. In order to accomplish this, pressure continuity must exist between the soil pore-water and the sampling device and the area of soil sampled must be known. It is also important that the effects which the sampling device has on the transport and breakthrough of a chemical can be accounted for. A new sampler for use in the unsaturated zone is the Passive Capillary Sampler (PCAPS) (Holder and Brown, 1991; Boll et al. 1992; Poletika et al. 1992). PCAPS use hanging fiberglass wicks which develop capillary tension to draw pore-water samples from soils (Fig. 3a). Vacuum pumps and other suction equipment are not required to draw samples using PCAPS because the wicks naturally develop capillary tension to sample water in the vadose zone over a range of pressures. PCAPS intercept flow from a known area of soil (sampling area), accurately collecting both macropore (Steenhuis et al. In Press, 1993) and matrix flow. Also, it is possible to design samplers for use at particular sites by matching the pore-water pressure at the top of a wick to the matric potential in the soil profile over a range of fluxes (Knutson[b] et al. In Press 1993).

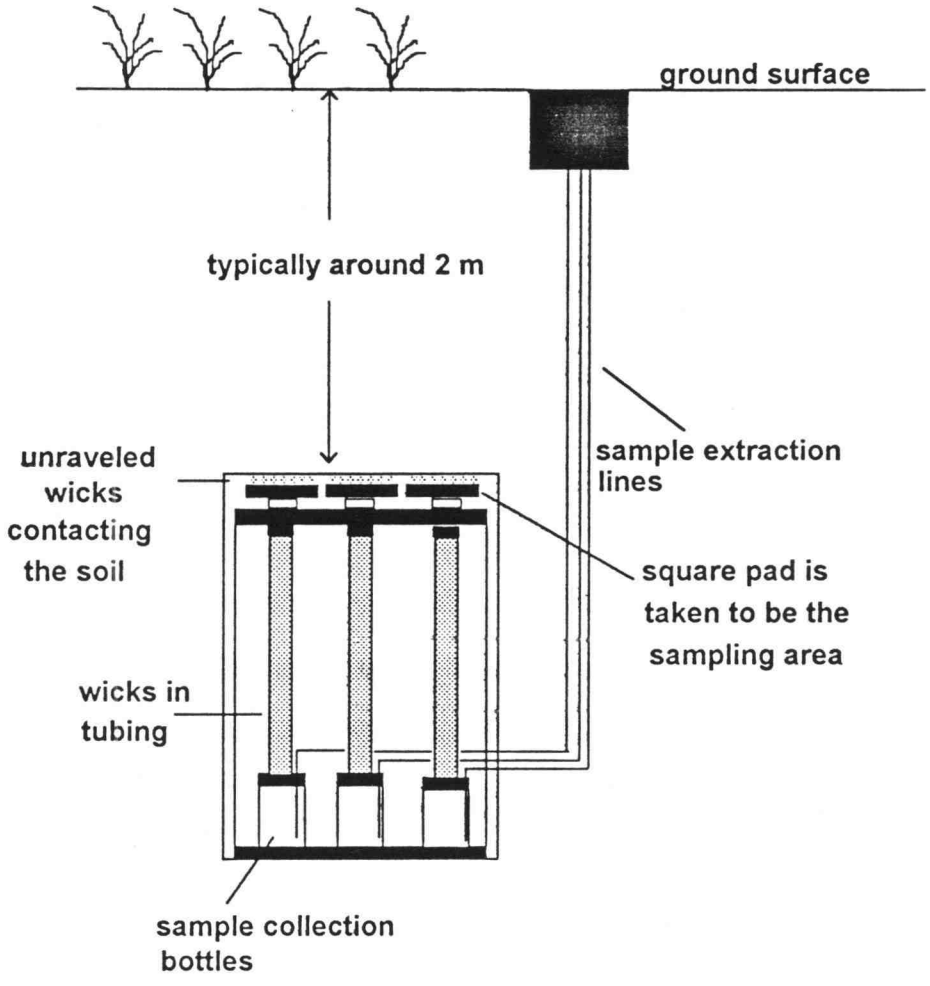

Figure 3a. Side view of PCAPS installed in the field.

OBJECTIVES

The work presented here is concerned with the effects which fiberglass wicks may have on the transport of chemicals and, if necessary, how to account for these effects.

Previous research has yielded promising results. Boll et al. [1992] reported a typical dispersivity of 1.03 cm and a retardation coefficient of 1.3 using FD&C Blue Dye #1 and a 50 cm length of 1.27 cm diameter wick produced by Pepperell Braiding Co. (Pepperell, MA). No chemical retardation was found by Brown et al. [1986] for a 1.27 cm diameter Pepperell wick. Poletika et al. [1992] found a typical dispersivity of 1.9 cm and retardation coefficients of 1.07 for Simazine and 1.04 for MS-2 Coliphage virus particles in a 9.5 mm diameter Pepperell wick. These dispersivities and retardation coefficients are all negligible when compared to typical values found in field soils. The small amounts of sorption reported by Boll et al. and Poletika et al. could be due to impurities on the wicks. Knutson et al. [In Press 1993a] demonstrated that wicks received from manufacturers have various types and amounts of organic chemical coatings which dramatically affect the porous media properties. These compounds could cause sorption of solutes. Knutson also presented data showing that combustion at 400°C effectively removes these

contaminants from the wick material.

MATERIALS AND METHODS

Woven and braided fiberglass wicks were purchased from three manufacturers. Three wicks from Pepperell Braiding Co. (Pepperell, MA), six wicks from Amatex Co. (Norristown, PA), and six from Mid-Mountain Materials Co. (Redmond, WA) (Tbl. 3a). In Tbl. (3a) the terms "High", Medium", and "Low" refer to density designations used by Amatex, "Knit" and "Matrix " refer to braid types used by Mid-Mountain, and the numbers "1", "1/2", "3/8", and "1/4" are used by all three manufacturers to identify wick diameters. These terms are retained and the product numbers are given for the Amatex and Pepperell wicks to aid interested parties in obtaining wicks. Impurities were removed from the wicks by combustion at 400 degrees celsius following Knutson et al. [In Press 1993a].

Dispersivity tests were carried out using 55 cm lengths of cleaned wicks. Each wick sample was placed inside of a vertical clear plastic tube. The top 5 cm of the wicks were frayed and wrapped over the top of the tube then capped. A 1 mm I.D. tube ran from a 500 mg/l FD&C Blue Dye #1 tracer source and a distilled water source to a valve then through a positive displacement pump and into the cap (Fig. 3b). The small I.D. tube was used to minimize any dispersion within the tracer delivery system. The wicks were saturated by plugging the bottom of the tube and allowing it to fill

Table 3a. Fiberglass wicks used in dispersion tests.

COMPANY WICK NAME	WICK DESIGNATION
PEPPERELL 1/4 # 1286	PEP 1/4
PEPPERELL 1/2 # 1381	PEP 1/2
PEPPERELL 3/8 # 1380	PEP 3/8
MID-MOUNTAIN 1/2 MATRIX BRAID	MM 1/2 MAT
MID-MOUNTAIN 1/2 KNIT BRAID	MM 1/2 KNT
MID-MOUNTAIN 3/8 MATRIX BRAID	MM 3/8 MAT
MID-MOUNTAIN 3/8 KNIT BRAID	MM 3/8 KNT
MID-MOUNTAIN 1/4 MATRIX BRAID	MM 1/4 MAT
MID-MOUNTAIN 1/4 KNIT BRAID	MM 1/4 KNT
AMATEX 3/8 HI-DEN. # 10-864KR-02	AM 3/8 HI
AMATEX 3/8 MED-DEN. # 10-863KR-02	AM 3/8 MD
AMATEX 3/8 LOW-DEN. # 10-862KT-02	AM 3/8 LO
AMATEX 1/4 MED-DEN. # 10-863KR-01	AM 1/4 MD
AMATEX 1/4 LOW-DEN. # 10-862KT-01	AM 1/4 LO
AMATEX 1 MED-DEN. # 10-863KR-08	AM 1

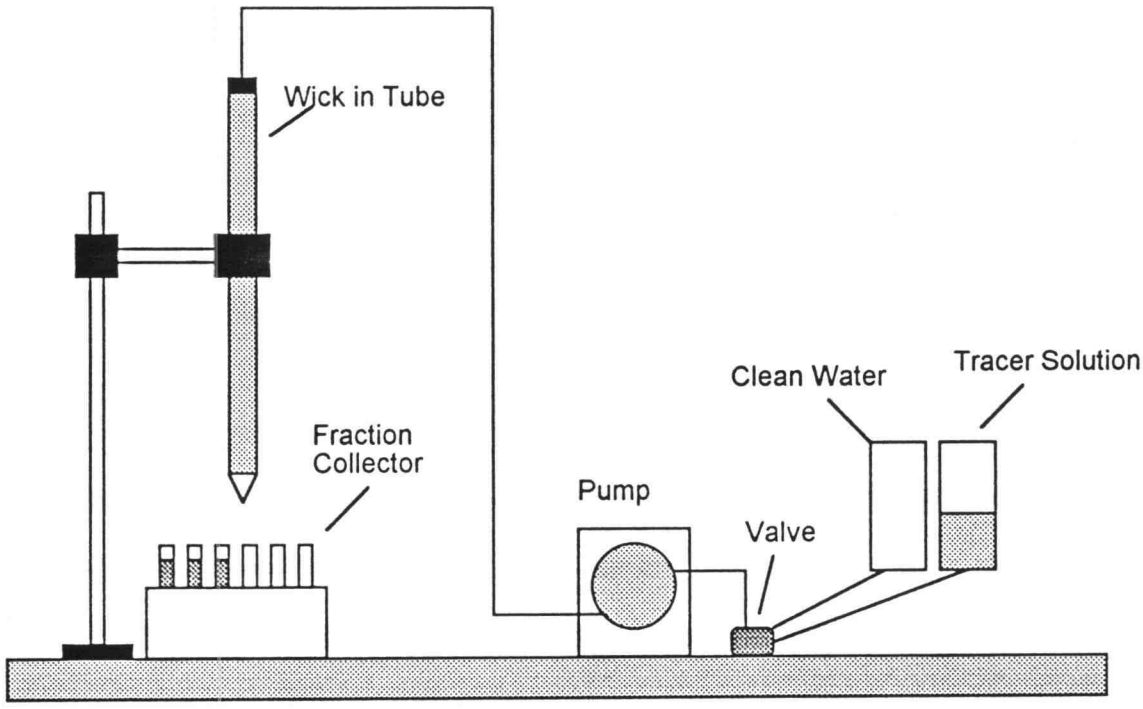

Figure 3b. tracer tests experimental design.

with distilled water, then drained under constant flows of 335 or 120 ml/hr. The flow of distilled water was maintained for 15-20 minutes allowing the moisture profile to come to equilibrium after which tracer flow was initiated. Tracer flow was continued until full breakthrough was approximated and then the valve was switched back to distilled water and the step down portion of the B.T.C. was obtained. A fraction collector was used to time and take samples which were analyzed using a spectrophotometer set at 430 nm wavelength. This wavelength was used due to the high tracer concentration. The resulting concentration versus time data were fit to the convective-dispersive equation (CDE) using the CXTFIT program (Parker et al. 1984) and estimates of dipersivity were obtained.

RESULTS AND ANALYSIS

Dispersivity Tests Results

Dispersivity values obtained by fitting the convective dispersive equation (CDE) to the BTC data ranged from 0.59 to 4.3 cm (Tbl. 3b). Typically the data fit the CDE very well ($R^2 \geq 0.981$). Fit pore water velocities were used to calculate the average moisture contents for the known fluxes. The ratio of the flux divided by the pore water velocity estimates the average moisture content. If the calculated moisture content exceeded the measured porosity then the results for that case were omitted due to the possibility of flow down the outside of the wick. The fit curves and data are shown for above average, average and below average fits to the CDE (Fig.s 3c, 3d, 3e). Relative concentrations are equal to 0.5 after one pore volume has moved through the wicks, as would be expected for an unadsorbed compound.

Wick Effects to Dispersion and Travel Time

A chemical being hydraulically transported downward in the soil would be intercepted by a PCAPS and then flow down a wick length to the collection vessel. Single wicks in PCAPS might intercept flow from 100 - 900 cm^2 of soil and typically has a cross-sectional area under 5 cm^2 so the flux

Table 3b. Dispersivity test flowrates, wick porosities, and values obtained with CXTFIT.

WICK NAME	Test Flowrate (ml/min)	CXTFIT Disp. (cm)	CXTFIT Pore Vel. (cm/min)	Theta Vmin/Vmax ratio	Measured Porosity	R^2
MM1/2KNT	5.600	1.290	5.900	0.671	0.790	0.995
MM1/2MAT	2.000	1.070	2.320	0.691	0.730	0.999
MM3/8KNT	5.600	0.750	9.400	0.856	0.870	0.999
MM1/4MAT	2.000	2.550	4.840	0.728	0.750	0.999
AM3/8HI	5.600	4.300	8.600	0.736	0.750	0.986
AM3/8LO	5.600	0.698	8.500	0.667	0.880	0.993
PEP1/2	5.600	0.590	5.300	0.638	0.900	0.991
PEP3/8	2.000	0.830	4.100	0.821	0.870	0.984

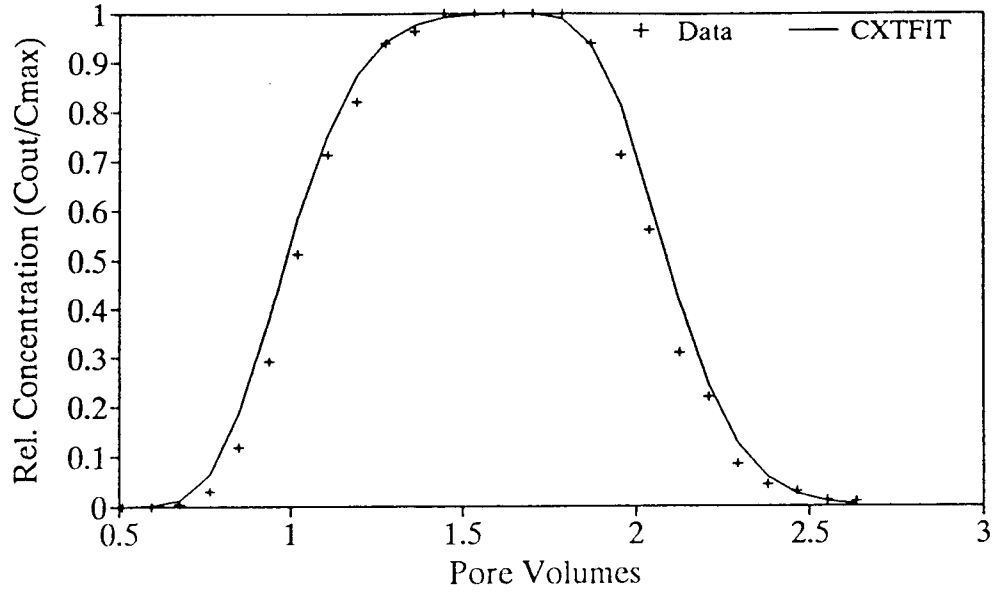

Figure 3c. B.T.C. from CXTFIT fot the Amatex low density 3/8" wick.

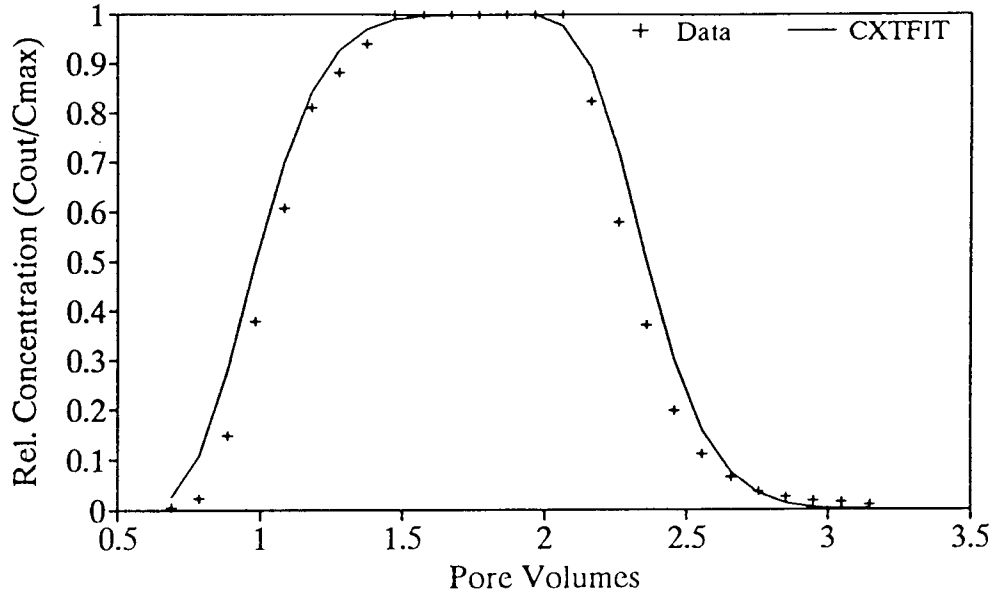

Figure 3d. B.T.C. from CXTFIT for the Pepperell 3/8" wick.

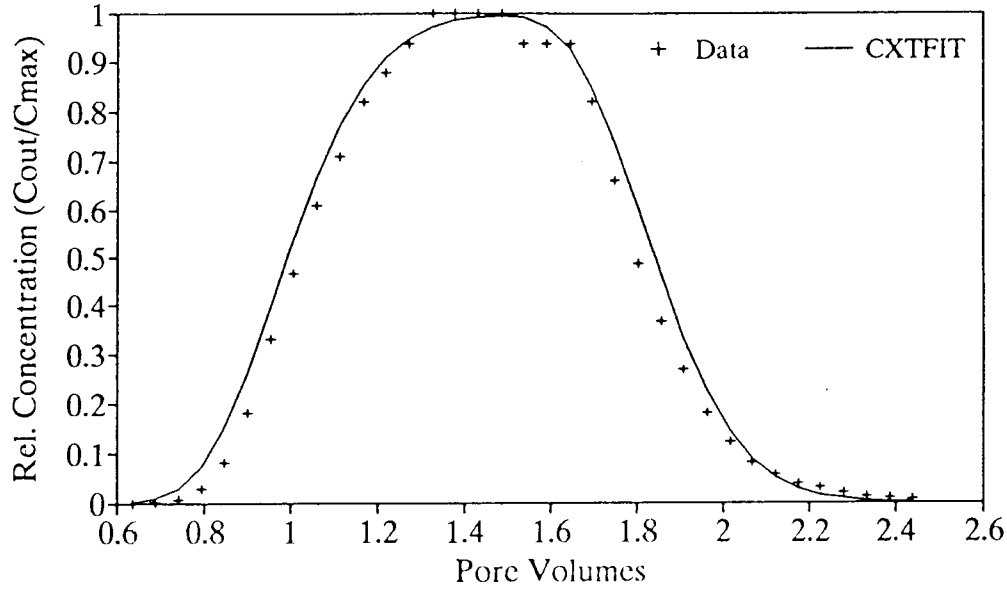

Figure 3c. B.T.C. from CXTFIT for the Pepperell 1/2" wick

in the wick will be much larger than in the soil but there would be some additional travel time. There will also be some additional dispersion due to traveling through a wick. Poletika et al. [1992] used statistical moments analysis to suggest that both travel time and dispersion are negligibly affected by the additional flow through a wick when compared to values for soils. The method used here to determine a wicks effect on travel time and dispersion is to use finite difference equations to model flow through a wick given time variable concentration input from a soil column (Fig. 3f).

The CDE is used to model vertical flow of a non-sorbing chemical through a soil column having typical properties of a sand or a silt (Tbl. 3c). The resulting concentration versus time values at the bottom of the soil column are time stepped through a wick having a large dispersivity value using a basic computer program (Appendix B). The concentration versus time estimates for the bottom of the wick are compared to the input values at the bottom of the soil column. From the simulation it was apparent that dispersion in wicks is negligible and travel times are only slightly increased, as expected (Fig.s 3g and 3h). Figures (3g) and (3h) show that the shape of the concentration versus time curves out the bottom of a wick are almost exactly the same as into the top of a wick, so dispersion by wicks is negligible. The concentrations are plotted versus time so that additional travel times (distance between

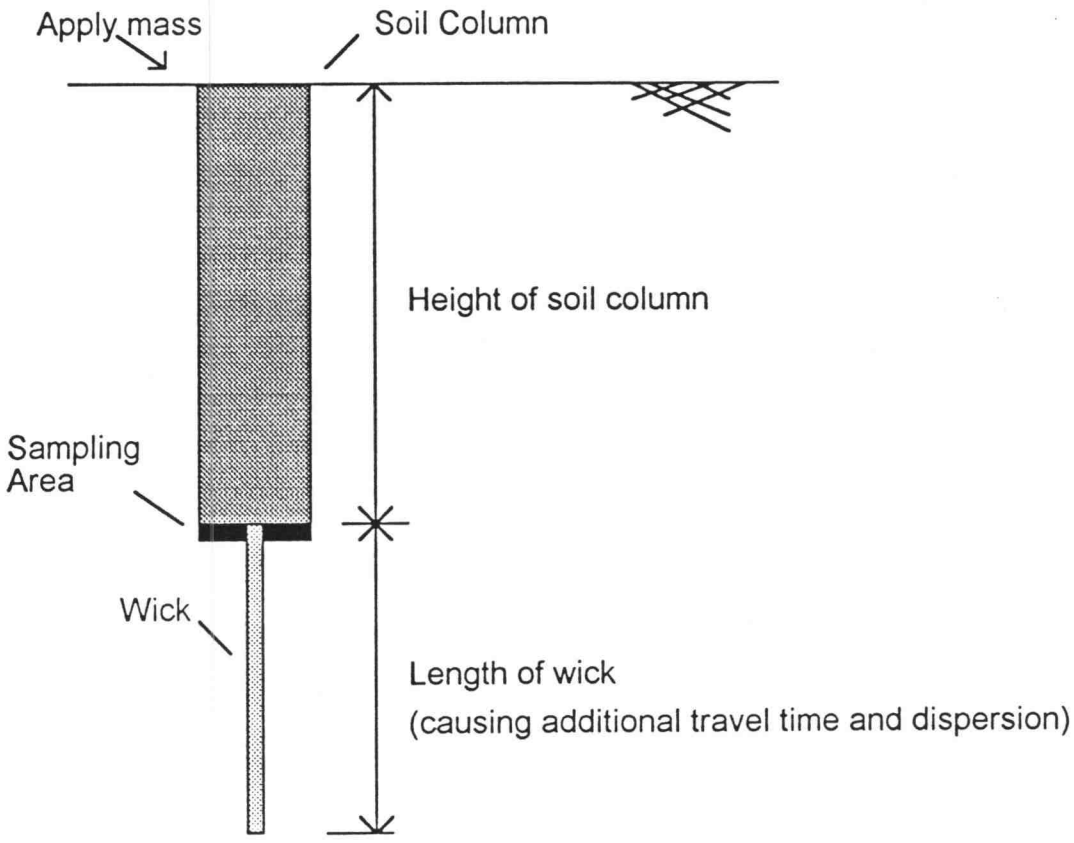

Figure 3f. Diagram of simulated flow in a soil column and a wick.

Table 3c. Simulation parameters for determining a wicks effects on the travel time and dispersion of a chemical being sampled.

Sand						
Mass Applied (g)	Applic. Area (cm ^ 2)	Column Length (cm)	Soil Disp. (cm)	Soil Flux (cm/hr)	Volum. Moisture (ratio)	Pore Velocity (cm/hr)
1	10000	100	5	3.75	0.25	15
Silt						
1	10000	100	5	0.45	0.3	1.5
Wick In Sand						
Sampling Area (cm ^ 2)	Wick Area (cm ^ 2)	Wick Length (cm)	Wick Disp. (cm)	Wick Flux (cm/hr)	Volum. Moisture (ratio)	Pore Velocity (cm/hr)
100	1.5	55	3	250	0.6	417
Wick In Silt						
100	1.5	55	3	30	0.4	75

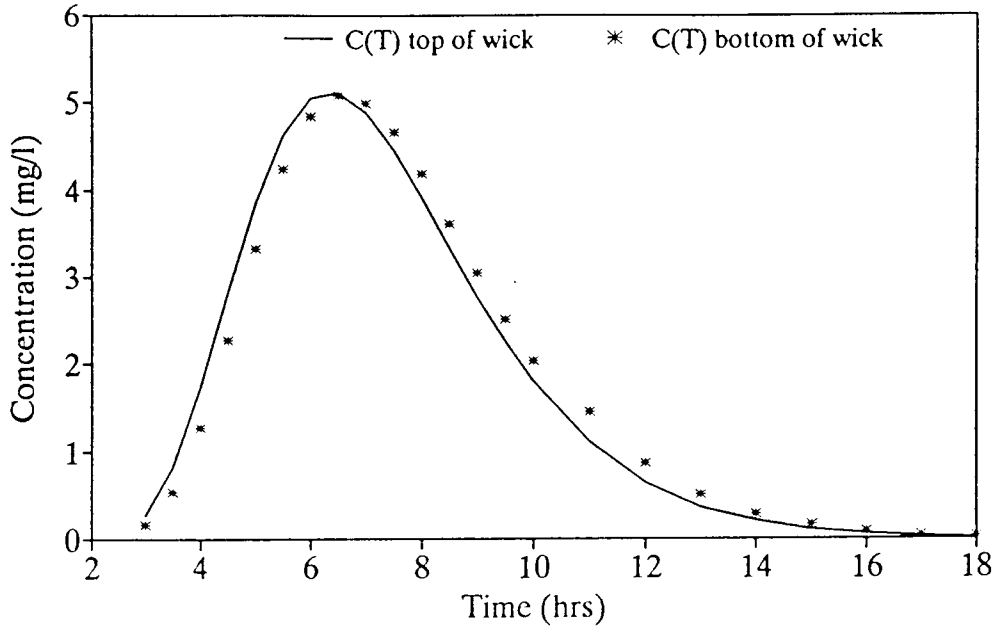

Figure 3g. PCAPS effects to B.T.C. of a chemical in sand.

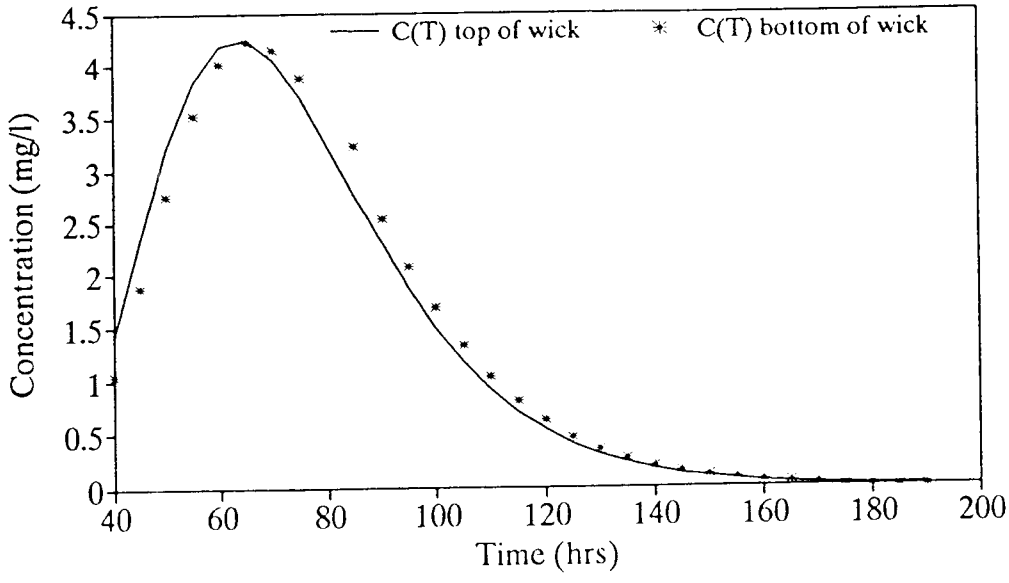

Figure 3h. PCAPS effects to B.T.C. of a chemical in silt.

peaks) can be seen. The additional travel times are approximately 0.5 hrs for the sand and 5 hrs for the silt.

CONCLUSIONS

From analyzing the dispersivity test data it was determined that the wicks effects to both travel time and dispersion are negligible when compared to typical soil values. Researchers may neglect wick effects when analyzing data obtained with PCAPS. This means that it can be assumed that concentration-time values from PCAPS sampling bottles are the same as the values at the vertical location of the top of the sampler. To obtain the soil flux of a chemical past the top of a PCAPS it is necessary to divide the volume collected by the sampling interval and sampling area.

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APPENDICES

APPENDIX A. CAPILLARY TUBE MODEL OF SATURATED CONDUCTIVITY

For a column of length L with N flow paths oriented vertically in the z direction it has been shown (Bear, 1972. pp. 162-164) that the flow rate through the column can be modeled by:

$$Q = C_1 N R^4 D_w g (1/v) (dH/dL_e) \qquad (A1)$$

where Q is flowrate, R is the representative pore radius, D_w is density of water, g is gravity, v is dynamic viscosity, H is head, L_e is actual length of flow paths, C_1 is a constant relating to pore geometry, and N is the number of flow paths. By definition the flux, q, is simply:

$$q = Q/A_t = Q/(A_v/p) = Qp/(NC_2R^2) \qquad (A2)$$

where A_t is the total cross-sectional area, A_v is the area of voids, p is the porosity, and C_2 is another constant relating to pore geometry. The actual length of the flow path and the component of flux in the z-direction is given by:

$$\text{Flow Length} \qquad L_e = L/T \qquad (A3)$$

$$\text{Flux Component} \qquad q_z = qT \qquad (A4)$$

where L is the column length, T is the tortuosity, and q_z is the flux in the z-direction. Combining Eq. (A1), (A2), (A3), and (A4) and solving for the z-component flux gives the relationship below:

$$q_z = C_3T^2R^2pD_wg(1/v)*dH/dL \qquad (A5)$$

Where C_3 is a constant resulting from combining C_1 and C_2. Equating Eq. (A5) with Darcy's law and solving for an expression for the saturated conductivity, K_{sat}, gives:

$$K_{sat} = C_3R^2T^2pD_wg(1/v) \qquad (A6)$$

Equation (A6) is an expression for conductivity based on pore geometry (C_3), pore radius (R), porosity (p), tortuosity (T), and fluid properties (D_w*g, v). It is necessary to estimate R. This can be done by assuming some geometric orientation of wick fibers. If square fiber packing is assumed the geometry of a representative elementary area (REA) has the geometry shown in Fig. (A1), where R is the pore radius and r is the fiber radius. A_t, the total area of the REA will be given by:

$$A_t = (2R)^2 \qquad (A7)$$

While the area of glass A_g is given by:

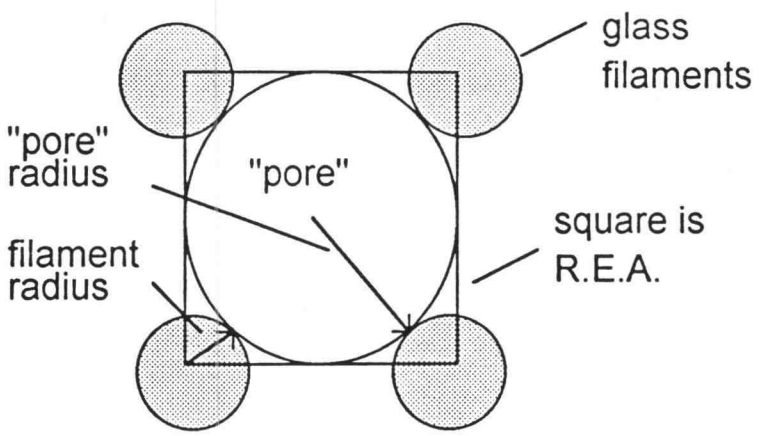

Figure A1. Geometry of square fiber packing.

$$A_g = \pi(r)^2 \qquad (A8)$$

The porosity of the system is given by:

$$p = 1 - A_g/A_t \qquad (A9)$$

or

$$p = 1 - \pi(r^2)/(4R^2) \qquad (A10)$$

Solving Eq. (A10) for R yields:

$$R = [(\pi r^2)/(4(1-p))]^{1/2} \qquad (A11)$$

Equation (A11) can then be substituted into Eq. (A6) to obtain a final expression for conductivity based on measurable properties:

$$K = C_3 [\frac{\pi r^2 T^2 D_w g}{4v} (\frac{p}{1-p})] \qquad (A12)$$

The quantity inside the brackets can be calculated for the wicks then regressed against saturated conductivity values to estimate the value of C_3.

APPENDIX B. PROGRAM FOR SIMULATING SOLUTE TRANSPORT THROUGH A LENGTH (L) OF WICK YEILDING C(L,TIME) VALUES FOR TIME VARIABLE INPUT CONCENTRATIONS TO THE TOP OF THE WICK.

Program Listing

```
REM Simulated advection and dispersion in a vertical
REM column with time dependent input concentration
REM ---------------------------------------------
DEFDBL C
DEFINT I,J,K,N,T
DEFSNG D,d,t
INPUT "enter Tin, C(Tin) DATA FILE NAME",FILEIN$
INPUT "enter NUMBER OF DATA POINTS",KURVIN
INPUT "enter COLUMN LENGTH (meters)",L
INPUT "enter DISPERSIVITY (cm)",disp
INPUT "enter COLUMN AREA, FLOW RATE (cm^2,cm^3/sec)",A,Q
INPUT "enter MOISTURE CONTENT (RATIO)",theta
REM ---------------------------------------------
REM calc. pore water vel,dispersion coef.
 dT = disp*(.21*A/Q)
 dX = disp*.775/theta
 V = Q/(A*theta)
 D = disp*V/theta
REM calc. apparent disp, disp. volume factor, # cells
 Dp = (V/2)*((dx)-(V*dT))
 STBL1 = (D-Dp)*dT/(dX^2)
PRINT DP,"DP"
```

```
PRINT D,"D"
PRINT dX,"dX"
PRINT dT,"dT"
PRINT STBL1 "STABILITY CRITERIA #1 < .5 ?"
INPUT "OK? yes = 1, no = 0",OK
IF OK = 0 THEN GOTO BYBY
REM ----------------------------------------
REM calc disp factor, # of cells
 W = (D-Dp)*dT/(dX^2)
 K = L*100/dX
 NUM = KURVIN-1
DIM C(K)
DIM CT(K)
REM ----------------------------------------
REM zeros in all cells, time averaged
   OPEN FILEIN$ FOR INPUT AS #2
   INPUT# 2, T1 ,Cin1
   INPUT# 2, T2 ,Cin2
   FOR N = 1 TO K
      IF N = 1 THEN C(N) = (Cin1+Cin2)/2 : CT(N) =
(Cin1+Cin2)/2_
      ELSE  C(N) = 0 : CT(N) = 0
   NEXT N
REM ----------------------------------------
REM main loop to iterate through cells
MAR:
    I = (T2-T1)*3600/dT
```

```
    FOR J = 1 TO I
     FOR N = 1 TO K
      IF N = 1  THEN  CT(N) = (Cin1+Cin2)/2_
    ELSE  IF N = K  THEN CT(N) =
C(N)*(1-(V*dT/dX)-W)+C(N-1)*(W+(V*dT/dX))_
    ELSE  CT(N) =
(C(N)*(1-(V*dT/dX)-2*W))+(C(N-1)*(W+(V*dT/dX)))+(C(N+1)*W)
     NEXT N
     FOR N = 1 TO K
      C(N) = CT(N)
     NEXT N
      IF J = I THEN GOTO CAR
     NEXT J
  REM ------------------------------------------------
  FAR:
      Cin1 = Cin2
      T1 = T2
      INPUT# 2, T2 ,Cin2
      GOTO MAR
  JAR:
  REM ------------------------------------------------
  REM print portion
      NUM = NUM-1
      OPEN "DISP.dta" FOR OUTPUT AS #1
      TD$ = "time(hours)"
      CC$ = "concent(mg/cm^3)"
      PRINT #1, TD$,CC$
```

```
                IF C(K) < 10^-10  THEN GOTO FAR
                PRINT #1, T2,C(K)
                GOTO FAR
  CAR:
      IF NUM = KURVIN-1 THEN GOTO JAR
      NUM = NUM-1
                IF NUM = 0 THEN GOTO PAR
                IF C(K) < 10^-10 THEN GOTO FAR
  PAR:
                PRINT #1, T2,C(K)
                IF NUM = 0 THEN GOTO BAR
                GOTO FAR
  BAR:
  REM ------------------------------------------------
  CLOSE# 1
  CLOSE# 2
  BEEP 2
BYBY:
  END
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