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ELECTRICAL CONDUCTIVITY OF SINGLE WOOD PULP FIBERS

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ABSTRACT

The dc electrical conductivity of single wood pulp fibers has been measured as a function of field strength, relative humidity, and time of application of the electric field. Over a range of field strengths from zero to 5 kv/cm, the fibers behave ohmically. The conductivity, σ , of single fibers varies exponentially with relative humidity (RH) according to

$$\sigma = \sigma_0 \exp (A \cdot RH).$$

For holopulped fibers of loblolly pine, the constants σ_0 and A are 2.9×10^{-10} mho/cm and 0.135, respectively. No differences were observed between earlywood and latewood fibers. The conductivity data from the latewood fibers were compared to in-plane conductivity data obtained on small paper samples cut from a handsheet made from unbeaten loblolly pine latewood fibers. The fiber conductivities are 50 to 100 times greater than the paper conductivity. The handsheet was also used to obtain a moisture content-relative humidity curve which permitted examining the data as a function of moisture content.

This paper has been submitted for publication in Tappi.

Introduction

Electrical conduction in single wood pulp fibers is of interest from several viewpoints. It is assumed that a more thorough understanding of the process at the fiber level is a prerequisite to understanding conduction in the fiber mat as a whole. Smith (1) demonstrated that the specific conductivity in the plane of a sheet could be correlated with the relative bonded area. The objectives of the present work were to develop suitable methods for making measurements of conductivity on individual wood pulp fibers, to compare fiber and sheet conductivities, and to ascertain if conductivity measurements on single fiber-to-fiber bonds could be used to monitor the change in bonded area as the joint is stressed to failure.

This paper is concerned only with the measurement of conductivity of single latewood or earlywood fibers of holopulped loblolly pine. The experimental apparatus is described, and the results are presented. The fiber data are compared to some preliminary in-plane conductivity data obtained on small paper samples prepared from the same fiber. There does not appear to be any other data published on the electrical properties of single wood pulp fibers, although Smith (2) did study parallel combinations of single fibers.

Results and discussion

Currents were measured as a function of time, electric field strength, and relative humidity (moisture content). Figure 1 depicts the current as a function of time upon application of a steady electric field of about 2 kv/cm. The conduction current remains nearly constant for a period of 8 to 10 minutes and then decays with time, eventually reaching

an equilibrium value after 5 to 6 hours. The final value is about one-fifth of the starting value. If the electric field is maintained for much longer times, say 50 to 100 hours, the loblolly pine fibers appear to suffer irreversible damage in that they become insensitive to changing relative humidity.

[Fig. 1 here]

Studies of the conduction current as a function of applied electric field strength gave a linear relationship (ohmic behavior) at all relative humidities. One set of data for a latewood fiber is shown in Fig. 2. If the conduction process in paper is ionic (the current carriers are ions), one expects the relationship between current, I , and applied field strength, E , to vary as:

$$I = C \sinh (DE),$$

where C and D are constants (3). Such a dependence has been observed for paper (4,5) and regenerated cellulose films (5). In the case of low E , such as here, the hyperbolic sine function may be approximated by its argument (DE), and a linear (ohmic) behavior is expected.

[Fig. 2 here]

It was not possible to determine the moisture content of the individual fibers, so the fiber conductivity is shown as a function of the ambient relative humidity in Fig. 3. Data were recorded two minutes after the application of the electric field (see Fig. 1). Each latewood data point shown on Fig. 3 is an average of measurements on four separate fibers, and each earlywood point is an average of measurements on six or seven separate fibers. The results for earlywood and latewood are similar. The data can be expressed by an equation of the form

$$\sigma = \sigma_0 \exp (A \cdot RH).$$

For the data in Fig. 3 the constants σ_0 and A have the values 2.9×10^{-10} mho/cm and 0.135, respectively, with a correlation coefficient of 0.98.

[Fig. 3 here]

The above equation also describes the conductivity data obtained for the paper made from unbeaten latewood fibers. The values of σ_0 and A for the paper are 2.0×10^{-12} mho/cm and 0.154, respectively, with a correlation coefficient of 0.99. The fiber conductivity is about 50 to 100 times greater than the paper conductivity. A similar result was reported by Smith (2).

If it is assumed that the fiber moisture content is the same as the moisture content of the paper, the conductivity results for the fibers and paper can also be plotted and compared as functions of moisture content. The data were plotted according to Murphy's expression (6), relating σ and moisture content M , given by $\sigma = \sigma_s \left(\frac{M}{M_s}\right)^{\underline{n}}$. Here M_s is the moisture content and σ_s the conductivity at saturation. Murphy believed that \underline{n} was fundamentally related to the cellulose structure (in particular, the number of water absorption sites between ion generating sites). Barker and Thomas (7) proposed a modification to Murphy's expression in which \underline{n} was believed to be correlated with the hydration numbers of the ions present.

The value of \underline{n} for the (holopulped latewood fiber) paper was 8.9, in agreement with Murphy's results on cotton thread, where $\underline{n} = 9.3$. For the single fibers, however, \underline{n} was found to be 7.7, suggesting that perhaps different factors are important in fiber conductivity, compared to paper conductivity. Clearly more work is needed before this can be resolved.

Experimental

Loblolly pine fibers were used in the study. These had been characterized for another study and were readily available. The original wood was pulped using a two step process of acid chlorite lignin modifications and repeated caustic extraction (holopulping).

For the electrical measurements, individual fibers were mounted between two stainless steel pin electrodes which in turn were mounted in an electrically shielded Fiber Test Mount (FTM). The fibers were attached to the pins using a starch adhesive. Other adhesives were investigated, including a conductive paste, but there were no significant differences in the measured electrical conductivity. The starch was chosen because it was easy to use and provided good mechanical strength. Using a special clamp, we could remove the pin electrodes from the FTM for mounting (or conditioning) of the fibers. All electrical connections inside the FTM and electrical standoffs were insulated with Teflon.

The FTM was located inside a controlled humidity chamber which used saturated salt solutions to provide a range of relative humidities from 11 to 84%. (At 50% RH no salt solution was required since the working environment was controlled to this value.) A schematic of the experimental apparatus is shown in Fig. 4. The usual precautions were taken for making measurements on any high resistance material. The interconnections between components were made with Teflon-insulated coaxial cables, rigidly mounted to prevent any motion. The entire experimental apparatus was positioned inside a grounded wire mesh cavity in order to prevent any extraneous electrical interference.

[Fig. 4 here]

The leakage current of the empty FTM was less than 10^{-14} amps at all relative humidities less than 50% and was about 5×10^{-14} amps at 84% RH. When compared to the measured currents in the single fiber investigations, these leakage currents are negligible at all relative humidities, except the lowest (11%), where the leakage is about 1% of the measured current.

After a fiber was mounted between the pin electrodes, it was allowed to equilibrate with the test environment for six hours before it was mounted in the FTM, where it was conditioned for another hour before testing. The transfer from the conditioning chamber took approximately one minute, during which time the fiber was exposed to a 50% RH environment. Separate studies revealed, however, that the same results were obtained if the fiber was conditioned for the full time in the test chamber.

The conductivity, σ , is calculated according to the equation:

$$\sigma = IL/VA,$$

where V is the applied voltage (volts), I is the measured current (amps), L is the fiber length between pins (cm), and A is the fiber cross-sectional area (cm^2). The length of the fiber was taken as the pin-to-pin distance along the longitudinal axis of the fiber, as determined with an Olympus microscope. Cross-sectional areas were determined using the Compacted Fiber Dimension Apparatus at The Institute of Paper Chemistry (8). Average cross-sectional areas were $5.6 \times 10^{-4} \text{ mm}^2$ and $4.6 \times 10^{-4} \text{ mm}^2$ for the earlywood and latewood fibers, respectively. Pin-to-pin distances were typically 2 to 3 mm. An applied potential of 500 volts was used in all conductivity measurements.

A handsheet was prepared from the unbeaten latewood fibers and wet pressed at 50 psi. The relative bonded area was estimated directly from electron micrographs of the paper cross sections to be 14.8%.

Several small rectangles of paper were also cut from the handsheet for conductivity measurements, and the balance of the handsheet was used to determine a moisture content-relative humidity curve. The conductivity and weight measurements were made in a variable condition room, allowing ample time after a change in relative humidity for the paper specimens to equilibrate with the new environment. In the conductivity measurements the rectangular samples were mounted between two parallel vertical pins using a conductive paste, Electrodag +502*. The conductivity was measured in the plane of the paper. Duplicate specimens were used, with an average cross-sectional area of 1.07 mm² at an average electrode separation distance of 4.8 mm. The applied potential was 500 volts.

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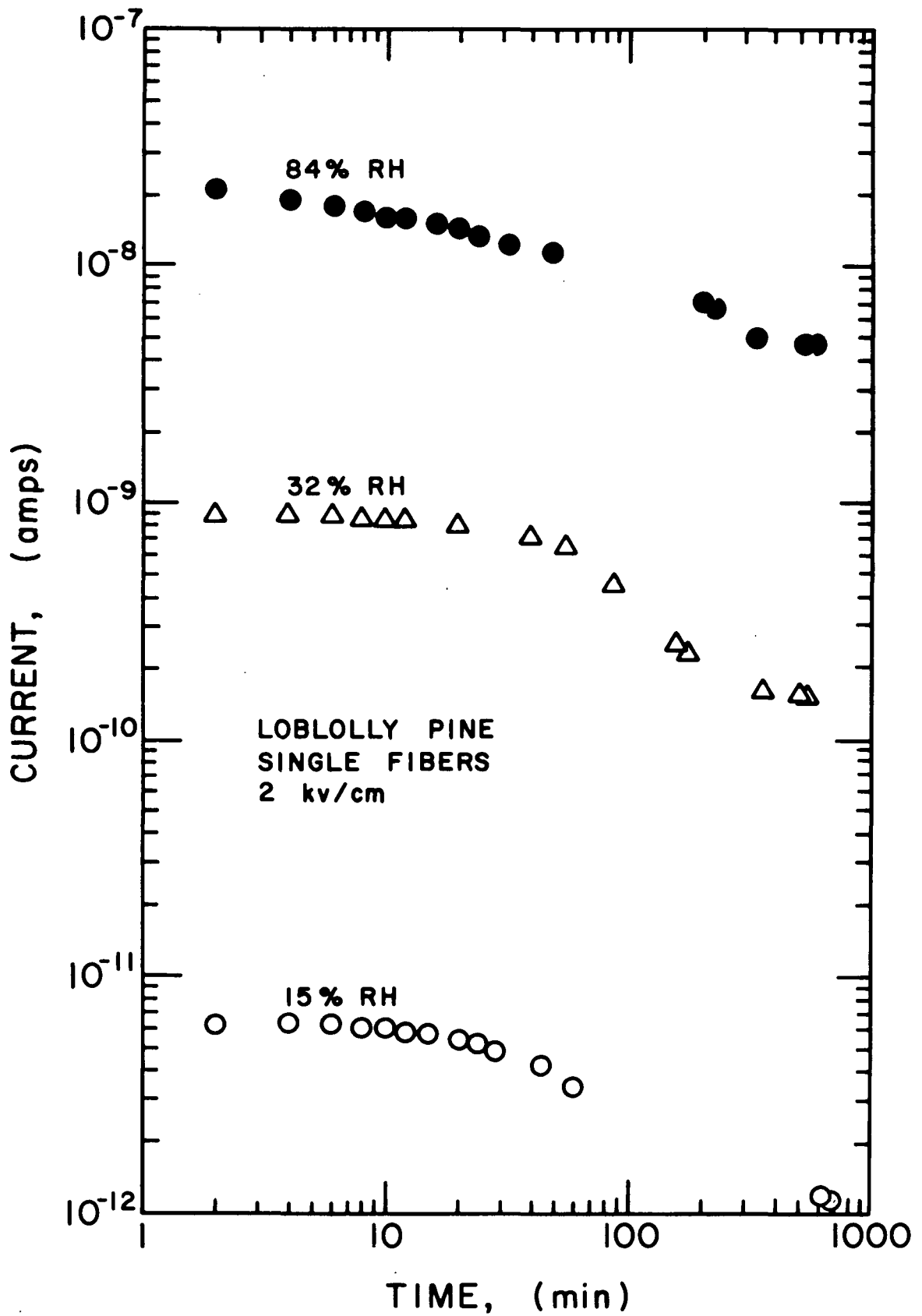


Figure 1. Current versus time for single fibers of loblolly pine

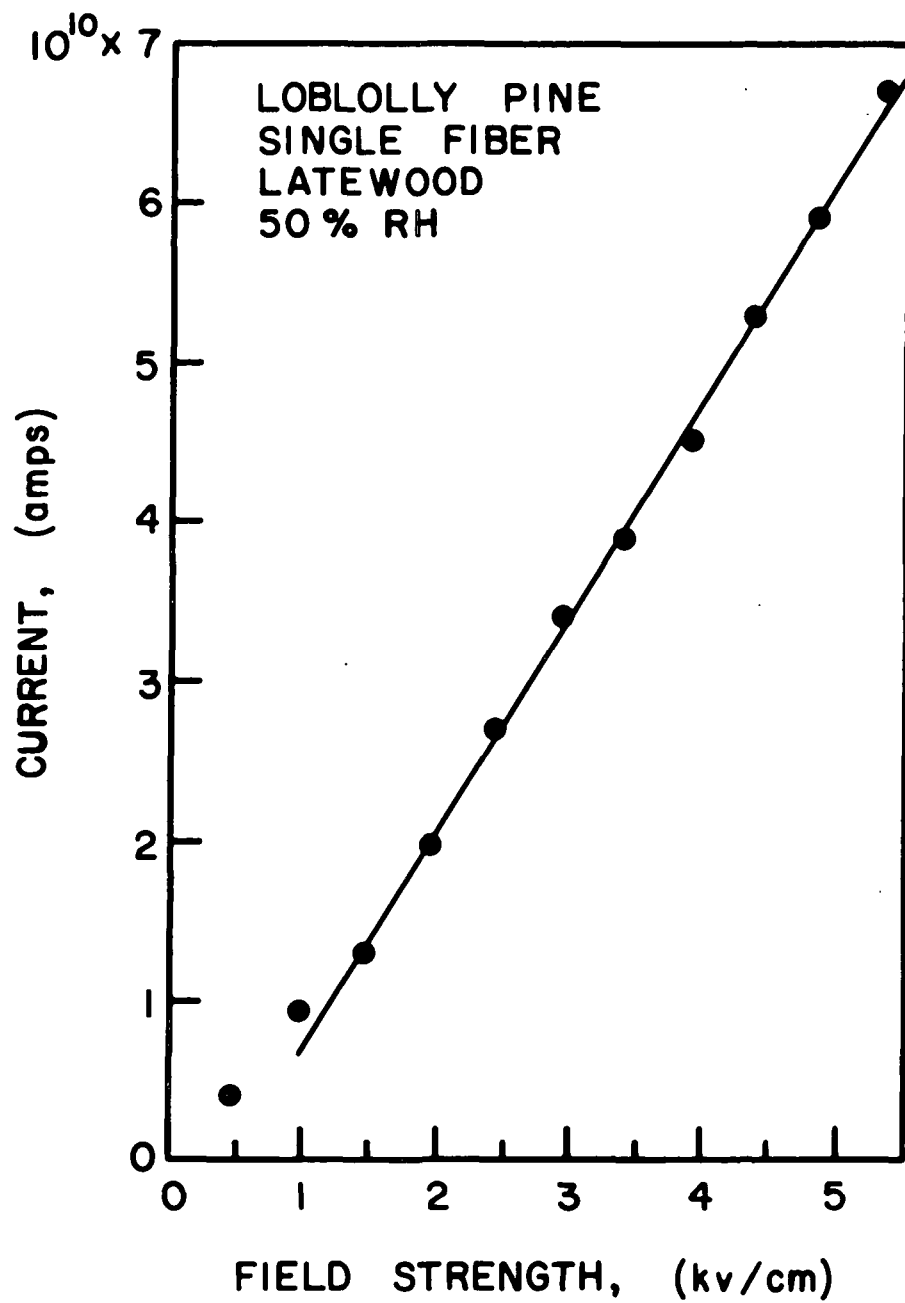


Figure 2. Current versus field strength for single loblolly pine fiber

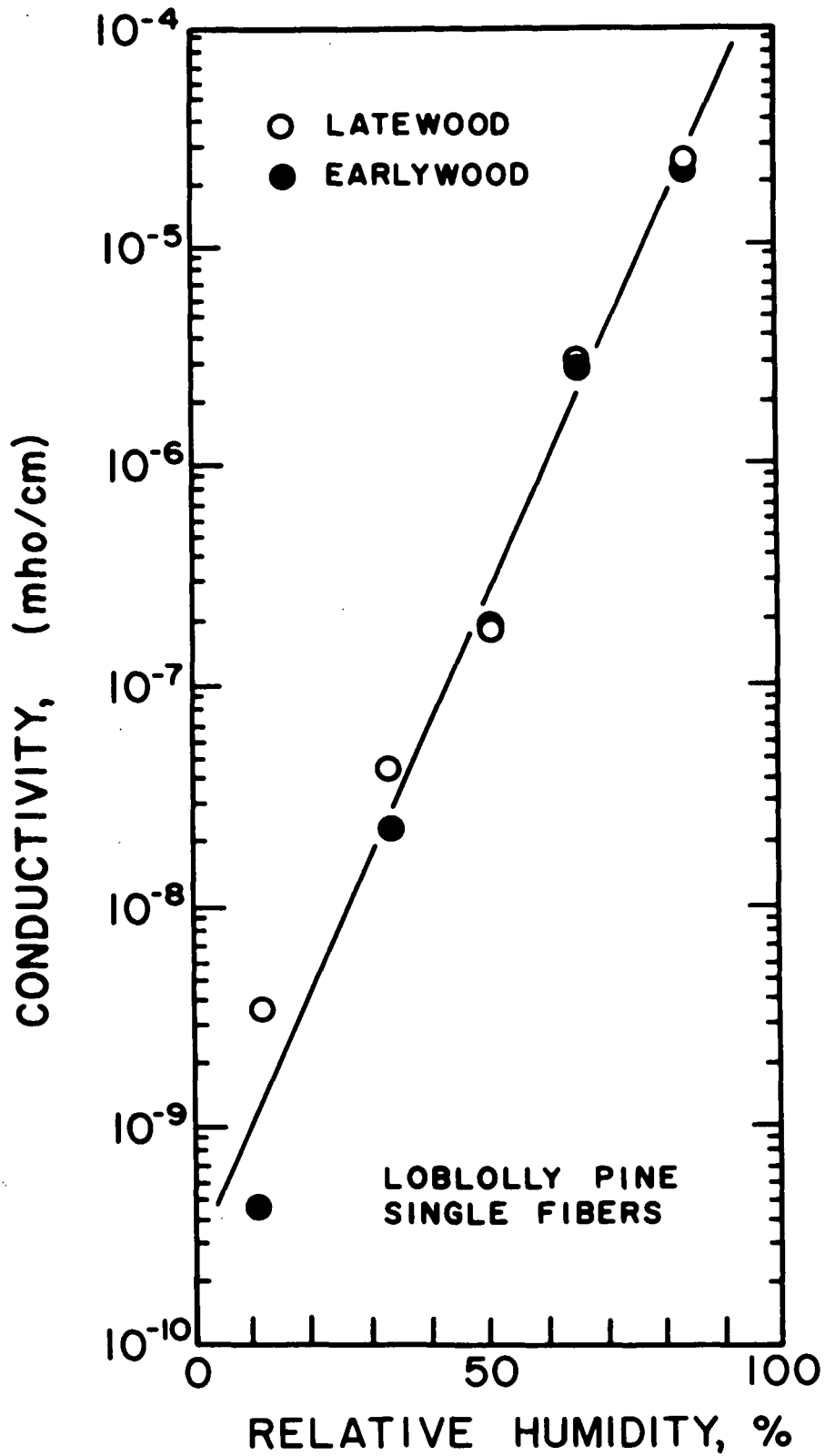


Figure 3. Conductivity versus relative humidity for latewood and earlywood single fibers of loblolly pine

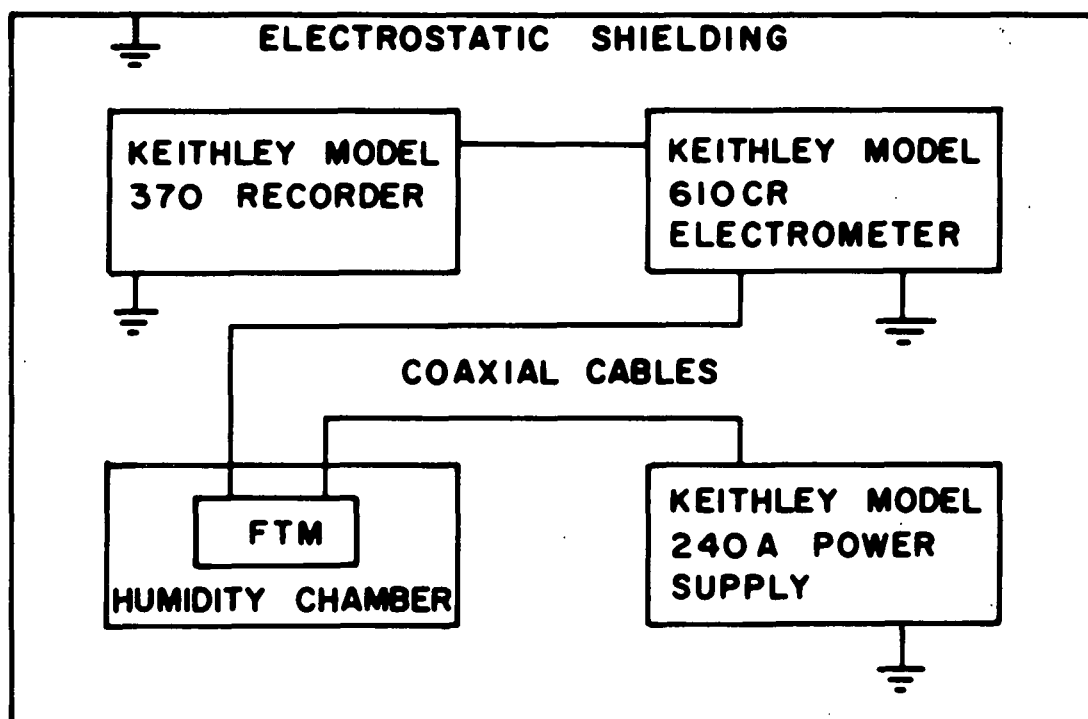


Figure 4. Schematic drawing of experimental apparatus