that shown in Fig. 2 can be considered as a simulation. The simulation under consideration involves only 17 particles. Two dendrites are formed, the upper one having five particles and the lower one having six particles. Column 4 in Table 1 gives the matrix which represents the size of the two dendrites in the order of their formation. The distribution of dendrites is asymmetrical over the fiber. For an accurate simulation the entire front surface of the fiber should be considered.

One of the important parameters in filtration theory is the collection efficiency of single fibers, defined as the ratio $2y_{oc}/d_f$, where y_{oc} is the initial y coordinate of the particle which just moves past the collector. The trajectory of such a particle, called the limiting trajectory, moves farther away from the collector surface whenever a newly deposited particle protrudes in the cross-stream direction beyond the old surfaces. This can be seen in Fig. 2. The clean fiber has a y_{oc} of 0.13 d_f. After the first particle deposits, y_{oc} increases to 0.28 d_f. The change in collection efficiency is shown in column 5 of Table 1 for the simulation under consideration.

Repeated simulations with different sets of random numbers would generate an ensemble of dendrites resembling those actually formed on a piece of fiber shown in Fig. 3. The number of particles used in each simulation is determined by the particle concentration, the filtration time, and the height used in the simulation. The only requirement in selecting the height is that it should be greater than the final value of y_{oc} when the simulation is stopped. For simplicity, the simulation is carried out on a single cross section. A more realistic construction can be made by taking into account the randomness of the location of individual particles along the fiber length.

The above discussion explains how the interplay of the finite size of particles and the stochastic nature of the location of individual particles leads to the formation and growth of chainlike particle deposits. Other important parameters such as the Stokes number and the ratio of the particle size to the collector diameter would also influence the shape of the dendrites. Long dendrites tend to form near the front of the cylinder at high Stokes numbers, whereas they tend to form near the sides at low Stokes numbers. Conceivably, the deposit would become increasingly smoother as the size ratio decreases. An artifact of the simulation is that the shape of dendrites also depends on the size of the intervals Δy_o used. In the simulation discussed above, Δy_o is equal to $0.05\, d_p$. The form of the dendrites would become more realistic as the size of intervals is further reduced.

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1. C. E. Billings, thesis, California Institute of Technology (1966). This thesis includes a thorough review of earlier studies.
2. See the review by C. N. Davies [*Air Filtration* (Academic Press, New York, 1973)] and the new theory proposed by A. C. Payatakes and C. Tien [*J. Aerosol Sci.* 7, 85 (1976)].
3. The photograph in Fig. 3 was taken by C. E. Billings. We thank him for providing the negative.

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Pyroelectricity and Induced Pyroelectric Polarization in Leaves of the Palmlike Plant *Encephalartos villosus*

Abstract. *Quantitative pyroelectric measurements were made on the leaves of the palmlike plant* Encephalartos. *A pyroelectric response almost 50 times higher than the normal one could be induced by a small bias electric field, offering a means for highly increasing the efficiency of conversion of thermal to electrical energy. No evidence of ferroelectricity was found.*

Qualitative observations of the pyroelectric effect in the epidermis of the leaves of the palmlike gymnosperm plant *Encephalartos villosus* (family Cycadaceae) were first made by Athenstaedt (*1*). He observed that the orientation of the pyroelectric vector was such that the outer surfaces of the leaves became positive on heating. In the research we report here, the earlier observations were confirmed, proof was found that the effects observed are thermally induced and not photoinduced, and quantitative values were measured. Most important, we found that a pyroelectric polarization almost 50 times higher than the normal response could be induced by a small bias electric field. This effect, to our knowledge not previously observed in any other materials, offers a highly increased efficiency of conversion of thermal to electrical energy. No evidence of ferroelectricity was observed in the material.

The pyroelectric effect was measured by exposing thin samples of material to short rectangular pulses of light from a xenon lamp. The electric charges released were measured by a charge amplifier, the output of which was displayed on an oscilloscope. The intensity of the illumination was determined by calibration with tourmaline, and voltage-time curves were analyzed according to the method of Simhony and Shaulov (*2*). A sample was prepared from a fresh leaf by scraping away material from one surface with a scalpel until the thickness of the other epidermis was in the range 0.06 to 0.12 mm. A piece about 0.5 to 1.0 cm^2 in cross-sectional area was cut out. The sample was air-dried for 5 to 10 minutes and then attached to a copper electrode with silver paste. The free surface was also coated with silver paste, and electrical contact was made by means of a copper spring. The electrical resistance of the materials was of the order of 10^{11} ohms after preparation and did not change significantly over several days, indicating that the samples were dry at all times. Temperature variation of the sample from $-20°$ to 45°C was possible.

To demonstrate that the electrical response to the light pulses was truly a pyroelectric effect and not a photoeffect, the light was partially absorbed by a series of optical filters. Measurements were made with the epidermis samples as well as with a copper-constantan thermocouple, tourmaline, and bovine tendon. The pyroelectric properties of tourmaline have been known since antiquity (*3*), and tendon was previously shown to be pyroelectric by Lang (*4*), using a heating and cooling technique. All of the materials examined were painted with the same silver paste. Figure 1 shows the electrical response (relative to that with unfiltered light) for each material plotted against the 50 percent transmission points of the filters. For comparison with a typical photosensitive material, a similar curve for a silicon photodiode was recorded. The response of the epidermis is clearly due to a change in temperature, and thus the effect is a pyroelectric one.

The measurement method used gives the ratio of the pyroelectric coefficient to the product of the density and the heat capacity, $p/\rho c$ (in coulomb cm $joule^{-1}$). Precise values of the density and the heat capacity have not yet been determined, but estimates of 0.9 g cm^{-3} and 1.4 joule g^{-1} $°C^{-1}$, respectively, are used here. The pyroelectric coefficient of the epidermis of *Encephalartos* showed typical biological scatter, having a value (mean $\pm$ standard deviation) of $1.3 \pm 0.4 \times$

10^{-12} coulomb cm^{-2} °C^{-1} at 25°C, measured on seven samples from three different plants. The polarity of the outer surface was always positive on heating. The temperature dependence of the effect showed no significant anomalies, increasing at a rate of approximately 0.5 percent °C^{-1}.

Experiments to see if the epidermis was ferroelectric produced the most surprising results. Direct-current voltages of −30 to +30 volts from dry cells were imposed across samples and the pyroelectric response was measured while the bias was applied. A typical result is shown in Fig. 2. Without bias, a pyroelectric signal of 85 mv was observed. The signal increased linearly to 720 mv with a positive bias field of 2.7 kv cm^{-1} and decreased to −595 mv with a negative bias of 2.7 kv cm^{-1}. In all cases, the bias could be removed and the pyroelectric response immediately returned to its original value. The magnitudes of the induced pyroelectric responses were quite variable from sample to sample, but the same polarity behavior was always observed. Several samples gave induced pyroelectric responses as large as 8.8 volts with a bias of 2.7 kv cm^{-1}, and corresponding values with negative bias fields (compared to 175 mv without a bias field). Measurements at temperatures of 10°, 25°, and 45°C all gave similar results. The optical filters were used to verify the thermal (pyroelectric) nature of the responses, and results similar to that for the epidermis sample in Fig. 1 were invariably obtained. Bias fields as large as 18.2 kv cm^{-1} were imposed for 1 minute with a high-voltage source. Although it was not possible to measure the pyroelectric response while these large fields were applied, the response immediately after the field was removed was the same as that before. Because fields of this magnitude can easily reverse the polarity of domains of most ferroelectric materials at temperatures well removed from the Curie point (*5*), it can be concluded that the epidermis of *Encephalartos* is not ferroelectric. The results of Fig. 2 suggest that the pyroelectric response with bias is the algebraic sum of the response without bias and an induced effect that varies linearly with electric field. When the light pulses were allowed to strike the inner (scraped) surfaces of the samples, the responses with the bias field were much smaller than those obtained when the light impinged on the external surfaces. This indicates that the induced response may have originated in the wax or lipid layer at the outer surface of the epidermis. The measured dielectric constant of the material was approximately 100. Pyroelectric responses can be induced with bias fields in ferroelectrics such as $BaTiO_3$ or triglycine sulfate at temperatures above their Curie points (*5*), but very high polarizabilities (that is, high dielectric constants) are required. The epidermis of *Encephalartos* is certainly not uniform in composition and may contain a layer with an extremely high dielectric constant. More detailed structural determinations are definitely required to clarify the origin of the effects. Because pyroelectricity is a common property of many plant and animal materials (*6*), the physiological implications of these observations may be very significant.

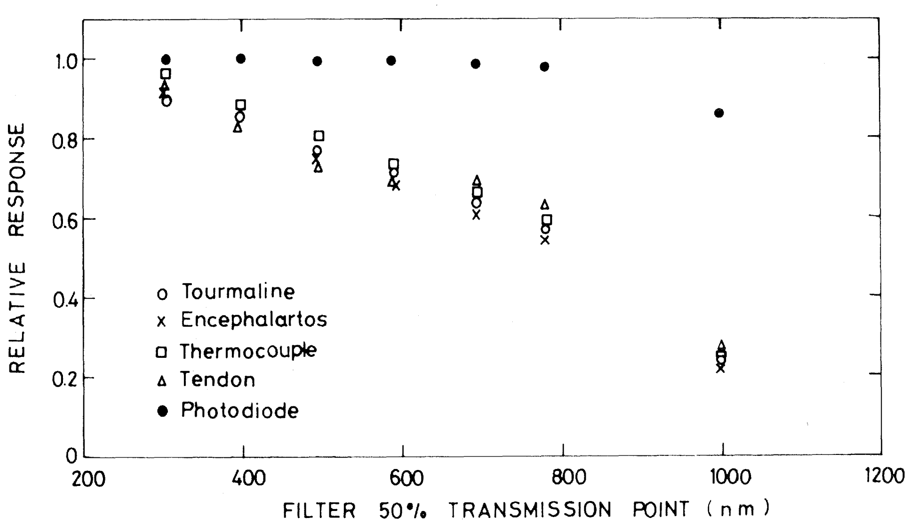

Fig. 1. Effect of optically absorbing the shorter wavelengths of light on pyroelectric and photoelectric materials.

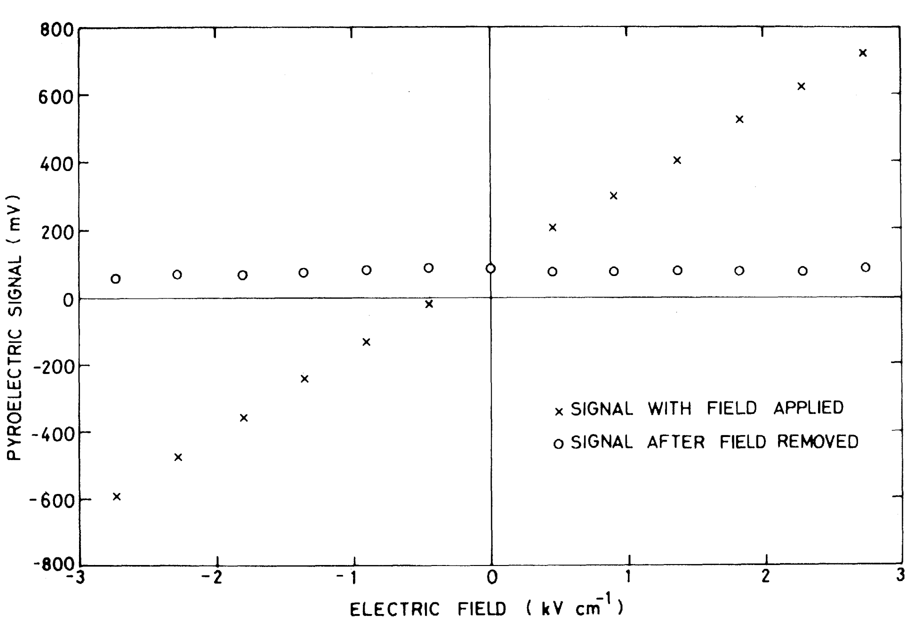

Fig. 2. Dependence of pyroelectric response on applied electric field.

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7. Appreciation is expressed to the Staatinstitut für Botanik der Universität Hamburg for donation of the plant material. This work was carried out at the Institut für Molekular-Physikalische Physiologie in Kiel with the generous support of the Deutsche Forschungsgemeinschaft and the Deutscher Akademischer Austauschdienst, who are thanked by the authors.

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