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USE OF ELECTRIC FIELDS TO ENHANCE DRYING RATES
OF WATER-CONTAINING MATERIALS

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13. ABSTRACT *(Maximum 200 words)*

An important part of ERDEC defense research programs is the investigation of new technologies that could ameliorate specific problems in biological defense. A recent report (ERDEC-TR-258, June 1995) discussed the application of electric field technology to such problems. The present report is the second in a new series of documents which will seek novel applications of existing and emerging technology, including electric field and electrostatics technology, to biological defense scenarios. The present work demonstrates that typical drying times for water-containing or water-wetted materials such as fabrics and possibly biological matter can be decreased by factors of up to about 10 in electric fields ranging up to above 7 kV/cm. Measured electric currents over this range increase by 3-4 orders of magnitude. Recommendations are given for a limited series of simple experiments in which living organisms would be exposed to electric fields of varying strength in air, and the results analyzed. Such measurements have never been done before.

14. SUBJECT TERMS

Spores	DC voltages	Electric fields
Liquids	Drying rates	Electric charge
Bacteria	Electrostatics	(Continued on page 2)

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Biological defense
Enhanced evaporation

PREFACE

The work described in this report was authorized under Project No. 10162622A553, Chemical Biological Defense and General Investigation. This work was started in November 1994 and completed in August 1995.

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USE OF ELECTRIC FIELDS TO ENHANCE DRYING RATES

OF WATER-CONTAINING MATERIALS

1. INTRODUCTION

For many decades it has been known that liquid water is extensively structured due to hydrogen bonding. The bonds hold together molecular aggregates or "clusters" which comprise the liquid (Ref.1). Luck (Ref.2) has deduced that at 25 C, for example, 85% of liquid water is clustered at any instant of time. Water exhibits a rate of evaporation five to six orders of magnitude smaller than would be expected from kinetic theory; yet this theory works very well for unassociated substances like mercury (Ref.3). The heat of vaporization and surface tension of water are much larger than those of other substances. All of this behavior is consistent with the extensive clustering due to hydrogen bonding in the liquid, and thus it is generally explained on these grounds.

This unusual liquid comprises about two-thirds of the physical masses of our human bodies, and its unique properties accomodate the processes of life itself. For example, hydrogen bonding allows water molecules to serve as constituents of strands of DNA, and to be displaced by other constituents as required. Similarly, water is fundamental to the existence of all biological species and the living matter comprising them. The smallest things that can sustain life are comprised largely of water. Thus, if new scientific insights are gained into ways to greatly modify the expected physical properties of water, they might also greatly affect the properties of biological matter. That, in turn, might be important in problems of biological defense, and is the justification for this experimental study.

The liquid phase of water is balanced in nature by its vapor phase, which has almost universally been assumed to consist entirely of single water molecules (monomers) and perhaps small traces of Boltzmann-distributed dimers, trimers, etc. Our present views of homogeneous nucleation theory (Ref.4) are based upon this interpretation. But work over the past three decades has cast very serious doubts upon this view (Ref.5), and we now recognize that water vapor can contain huge populations of electrically neutral clusters of water molecules and much smaller numbers of their dissociative ions. These clusters greatly affect interactions between water's phases, and are responsible for many of its unusual physical properties.

The interface between the phases is the liquid water surface, be it flat as in the case of lakes or reservoirs, or sharply curved, as for tiny water aerosol droplets. It is not surprising that the physical interface between liquid water and its vapor, through which must pass the cluster species that determine such fundamental properties of water as saturation vapor pressure and surface tension, is poorly understood.

DeBoer (Ref.3) has stated that if this surface behavior were as expected from classical theory many lakes and seas would evaporate in a few hours, and the oceans would be dry in a few days. Croxton (Ref.6) devotes a short chapter to the subject, after stating in a prologue that any statistical mechanical theoretical treatment of the water surface presents particularly formidable problems and, indeed, that such a discussion of these interfacial properties might well be "premature."

The research discussed in this report began in 1986-1987 when one of the authors (HRC) performed a U.S. Secretary of the Army Research Fellowship at the University of Manchester (England) Institute of Science and Technology (UMIST), in the Department of Pure and Applied Physics of which the other author (JL) was Head. Results were entered into four laboratory notebooks (Ref.7). Some further results subsequently were published in the open literature (Refs.8-10), but only recently has electric field technology been reexamined seriously for possible adaptations to specific problems in biological defense (Ref.11). The present report considers direct current (DC) electric fields and their enhancement of drying rates (evaporation) from water-containing materials, for the purpose of investigating the feasibility of experimentation with biological materials.

In the absence of electric forces, the evaporation rates of liquids comply with well-established quantitatively defined laws. They depend on the ambient temperature, the ambient vapor pressure, the ventilation coefficient, the curvature of the evaporating surface, and other parameters. Thus, the drying rate of a sheet of material soaked in (or moistened with) some volatile liquid can be predicted with a considerable degree of precision.

However, some simple laboratory experiments (Refs.10,12) have indicated that in the presence of substantial- but readily producable- electric fields, the evaporation rates (and thus the drying rates) of wetted materials may be enhanced by a substantial amount. The enhancement factors measured in these two studies- which involved totally distinct experimental arrangements- were significantly different, and thus it was considered desirable to conduct some further, more detailed studies, in an attempt to resolve this discrepancy. In the present report, the liquid used was water and the materials were paper toweling and cotton cloth.

2. EXPERIMENTAL APPARATUS

The experiments, which yielded highly reproduceable results, were carried out using the apparatus shown in <u>Figure 1</u>. Two carefully smoothed circular copper electrodes (D) of diameter 6 cm with adjustable 0-10 cm spacing (G) were situated 2 cm apart, the line through their centers being vertical. They were supported by metal rods (R). One electrode was grounded and the other was connected to a variable direct current (DC) high-voltage supply through a heavily-insulated wire (W).

A disc of the test substrate material (S), of diameter 6 cm, was positioned on the grounded (bottom) electrode, and thus could be subjected to an electric field of chosen value. A small fan produced a gentle breeze across the substrate, in order to ensure that when it was moistened the air adjacent to it was reasonably characteristic of that in the laboratory. The apparatus was supported by a polystyrene insulator (I). Electrical heater wires (H) were wrapped around two columns formed between cutouts in the shaped insulator. These heater wires kept the polystyrene surfaces beneath them at a temperature near 100 C, thus preventing the formation of surface water layers on the insulator that might otherwise have provided leakage paths for electric currents between the two disc electrodes and their supporting rods.

A schematic representation of the experimental apparatus is shown in <u>Figure 2</u>. The two carefully smoothed circular copper electrodes (E), as discussed earlier, were 6 cm in diameter and had adjustable spacing which was set to 2 cm here. The grounded bottom electrode had the test substrate (S) placed upon it. The variable DC high-voltage power supply (V) was connected to the top electrode. This simple circuit was completed through the system ground.

3. EXPERIMENTAL PROCEDURE

The air temperature T was maintained close to 25 C, and the relative humidity H was typically around 50%, but by the use of drying and moistening agents values of H around 10% and 80% were also produced for selected studies. The range of values of the electric field E employed was from 0 to 7 kV/cm.

The basic experimental procedure was to place the substrate on the bottom electrode, moisten it with water, switch on the aspirating fan, select and apply the voltage V required to produce a chosen electric field E, and to make frequent readings of the mass M of the moistened substrate. Thus for each set of conditions the rate of mean loss of water from the substrate, dM/dt, was found to be reasonably constant, until the substrate started to dry; the information presented below was obtained when dM/dt was constant, in all cases.

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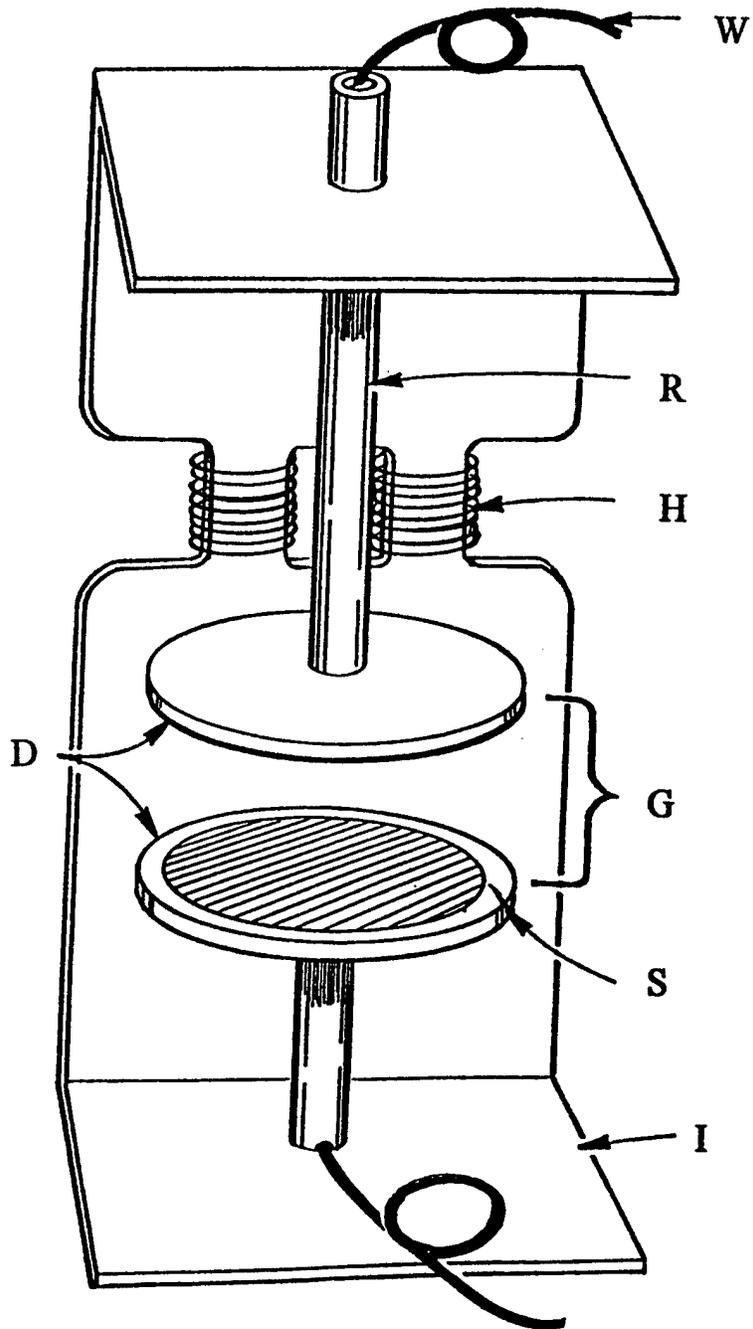
Figure 1. Apparatus for the Measurement of Currents Associated with Drying in Electric Fields.
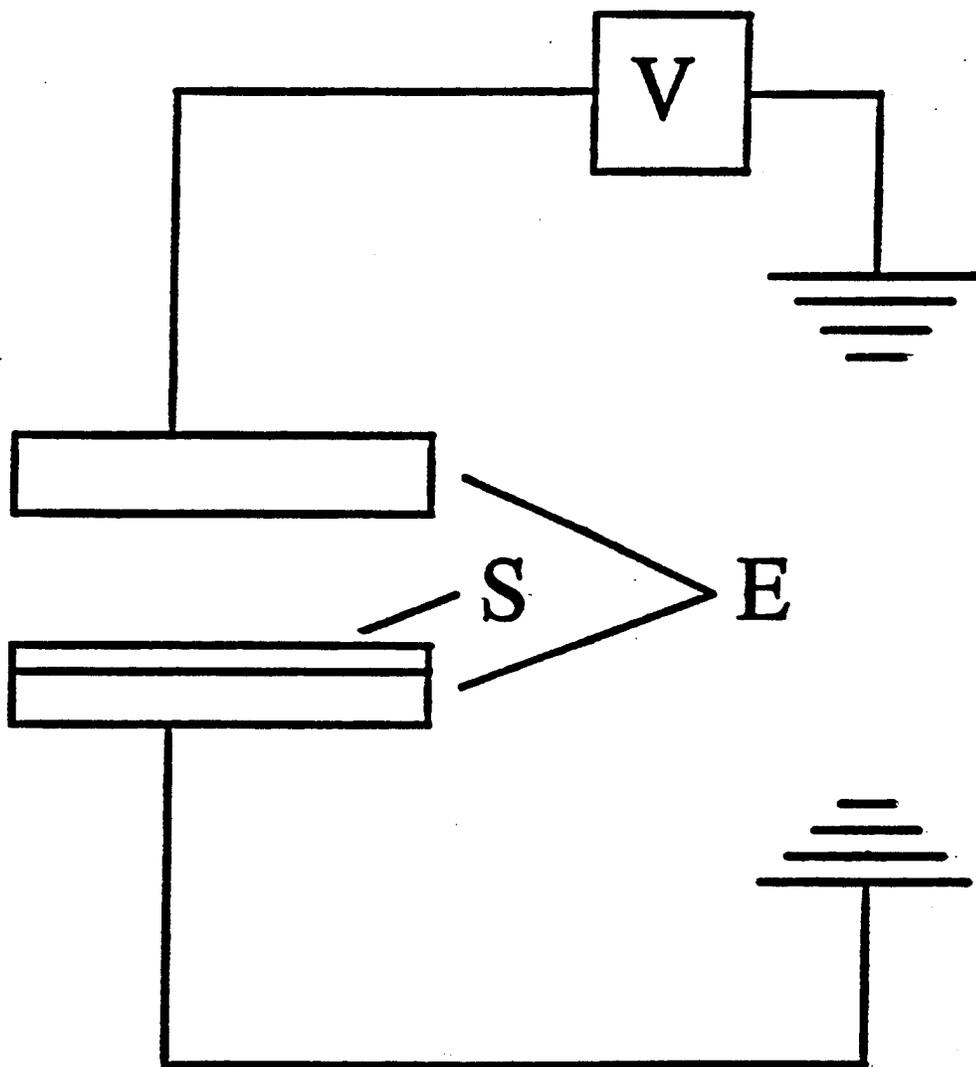
Figure 2. Schematic of Apparatus in Figure 1; V, Variable High-Voltage Supply; E, Electrodes; S, Substrate.

Having obtained an accurate value of dM/dt for one set of conditions- this usually involved a measurement period of several minutes- a change was made in E or H and the procedure was repeated. In this way, a full set of data points was obtained.

4.   EFFECTS OF RELATIVE HUMIDITY AND TEMPERATURE
      UPON ENHANCED OR ACCELERATED DRYING

For fixed conditions of E, H and T, dM/dt was found to be reasonably constant, until the substrate started to become dry. The information presented below was obtained when dM/dt was constant in all cases. Having obtained an accurate value of dM/dt for one set of conditions over a measurement period of several minutes, a change was made to E, T or H and the procedure was repeated.

Figure 3 (with T = 20 C, H = 50%) shows that dM/dt increases monotonically with E, the slope of the curve being linear for E greater than 2 kV/cm, and somewhat smaller for values of E between 0 and 2 kV/cm. The figure indicates the uncertainties attached to the individual values of dM/dt for each of the eight values of E employed in creating this curve.

Figure 4 (with T = 30 C, H = 50%) reveals a (dM/dt)/E relationship similar in form to that illustrated in Figure 3, but with the drying rates substantially increased, presumably because of the higher vapor deficits (and resulting evaporation rates) associated with higher temperatures.

Figure 5 shows the results of an experiment in which dM/dt was measured as the electric field E was changed several times. The results are basically consistent with those of Figures 3 and 4 and indicate (by comparing the first phase of this experiment with the final one, for both of which E = 0) that there is a slight tendency for dM/dt to diminish with time.

Figure 6 shows that at all values of the electric field E the rate of mass loss dM/dt increases as the relative humidity H decreases (i.e., as the vapor deficit in the air washing over the substrate increases). The three curves shown (for H = 10, 50, 80%) are roughly parallel, the difference between them in the field-free situation (E = 0) being essentially maintained as E increases from zero to the maximum value employed (7 kV/cm).

5.   MEASUREMENTS OF CURRENTS ASSOCIATED
      WITH DRYING IN ELECTRIC FIELDS

In these experiments, which yielded highly reproducible results, the apparatus used was again that shown in Figure 1. In this work, moistened substrates were placed on one or both electrodes (one above the other), where they adhered to the disc
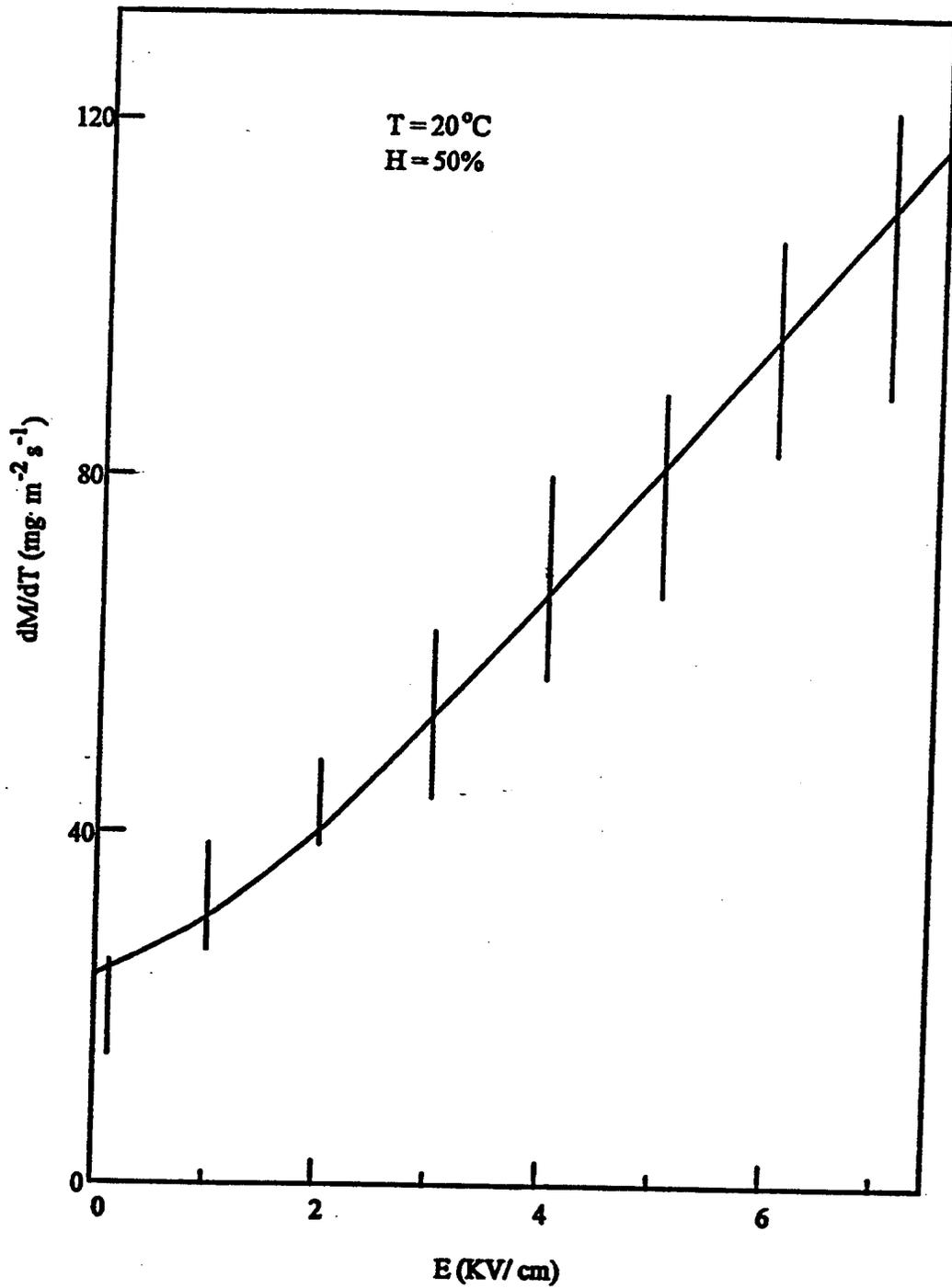
Figure 3. Drying Rate dM/dt (mg/sq m sec) as a Function of
           Applied Electric Field E (kV/cm) for Paper
           Toweling; T = 20 C, H = 50%.

The plot shows data with label "T = 30°C" and "H = 50%". The y-axis is labeled dM/dT (mg·m^{-2}·s^{-1}) with gridlines at 100 and 200. The x-axis is labeled E (KV/cm) with marks at 0, 2, 4, 6.
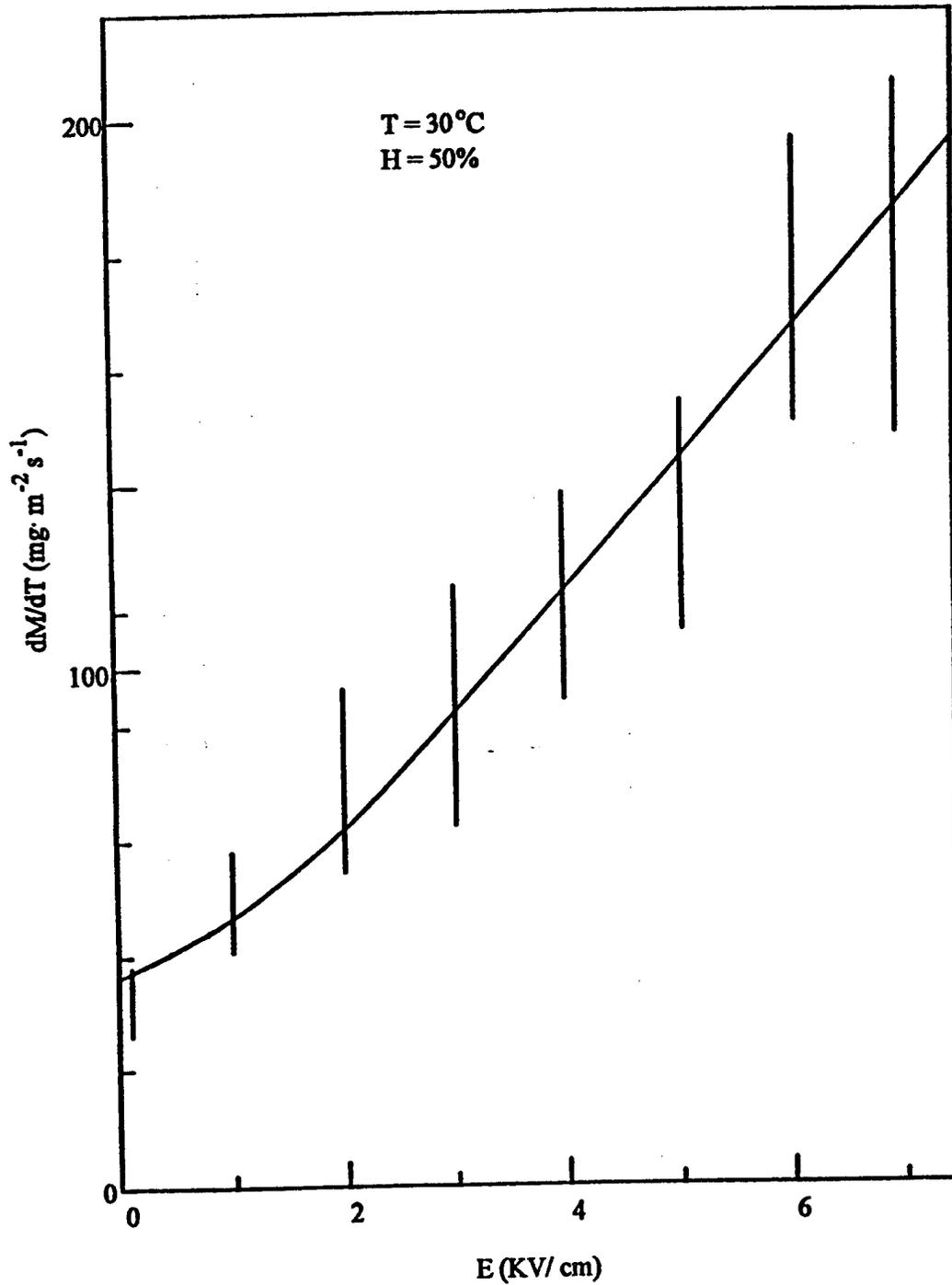
Figure 4. Drying Rate dM/dt (mg/sq m sec) as a Function of Applied Electric Field E (kV/cm) for Paper Toweling; T = 30 C, H = 50%.
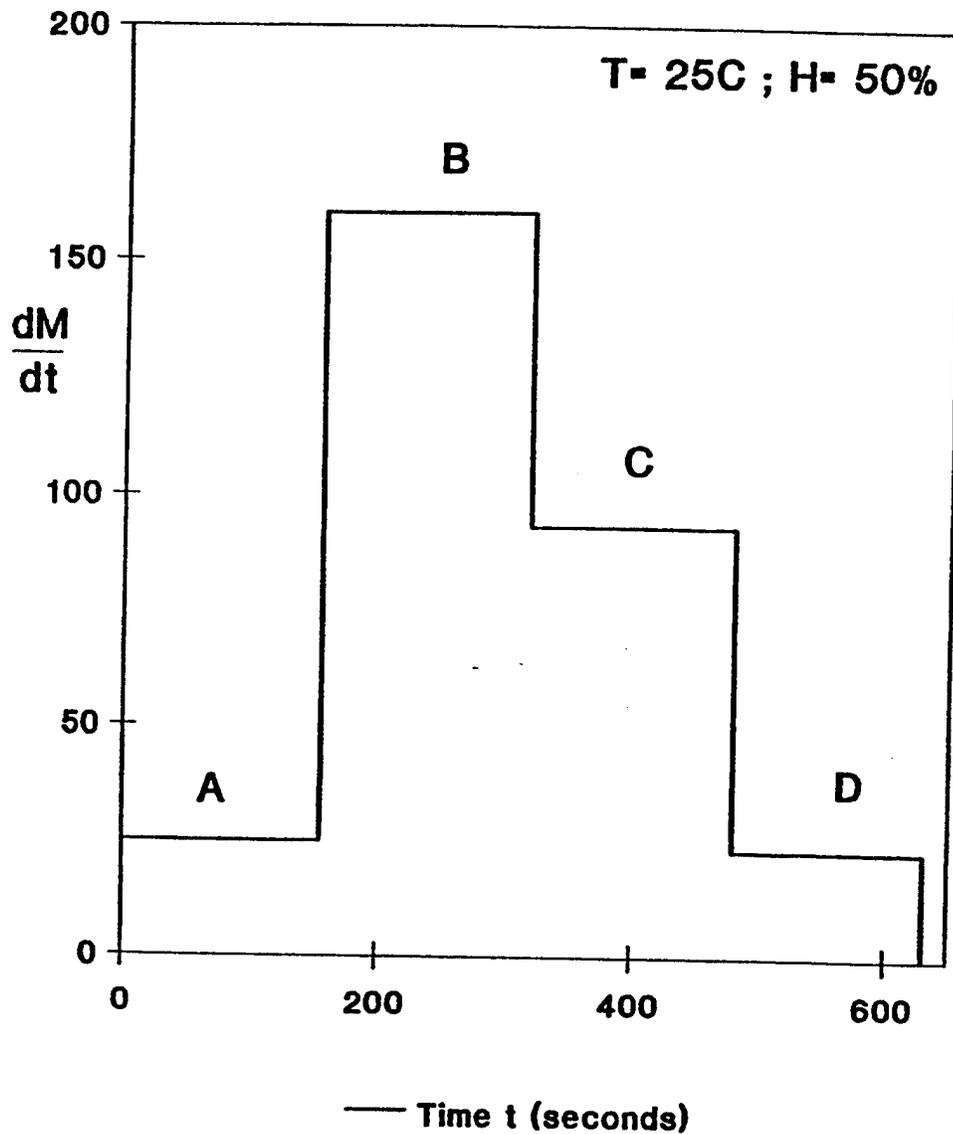
Figure 5. Drying Rate dM/dt (mg/sq m sec) for Paper Toweling as a Function of Time t (sec) for Various Values of Electric Field Strength E (kV/cm); for (A) and (D), E = 0; for (B), E = 7; for (C), E = 4; T = 25 C, H = 50%.
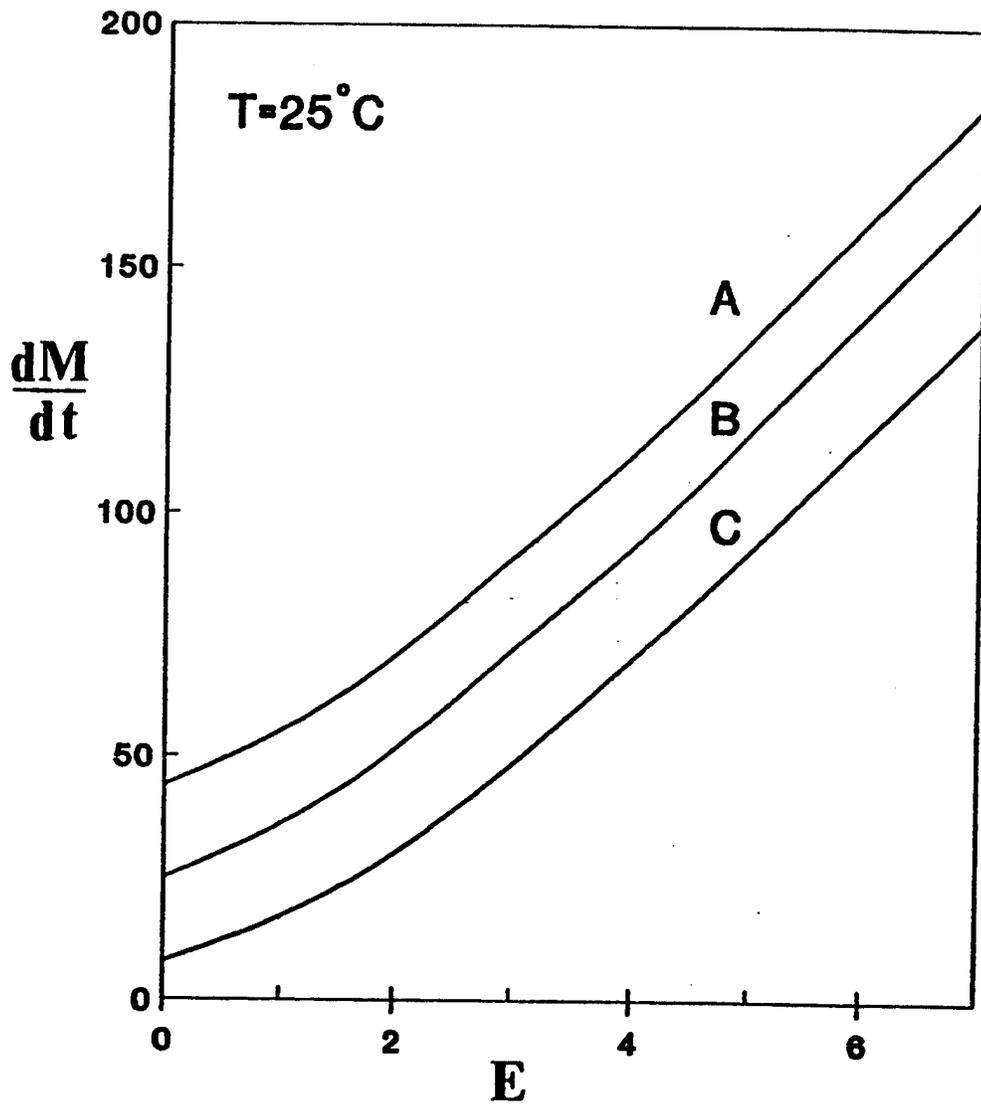
Figure 6.
Drying Rate dM/dt (mg/sq m sec) for Paper Toweling as a Function of Applied Electric Field E (kV/cm) for Three Values of Relative Humidity H (%); (A) H = 10%; (B) H = 50%; (C) H = 80%.

surfaces until they dried out. The substrates were moistened with water and weighed before, during, and after each trial. The most commonly used test substrates were circular discs of the same diameter as the disc electrodes, cut from ordinary thin cotton handkerchief fabric or common brown paper toweling. Other materials that were investigated included laboratory filter papers, brown paper from bags, dimpled white paper toweling, thin plastic sponges, and thin plastic meshes (Ref.7).

The experimental procedure was as follows. The disc electrodes were adjusted to a given spacing (usually 10 cm in this work, as compared to 2 cm in work discussed earlier). The insulated high-voltage wires were connected in series with a current-indicating meter and a variable 60 kV DC high-voltage power supply (Gamma Model RR-60-1R/VOL), with a line and load regulation of 0.005%, ripple of 0.02%, and a separate current regulating loop providing current regulation of better than 100 uA from short circuit to rated voltage.

The current-indicating meter was connected between the low-voltage electrode and ground to minimize pickup. A sensitive current meter (Keithley Model 610C electrometer) was used in preliminary checkout measurements but, because a mishap could destroy this expensive instrument, an inexpensive vacuum-tube voltmeter (VTVM) was used instead to measure conduction currents between the disc electrodes. The VTVM had a constant input resistance of 10 megohms regardless of the voltage range selected. Thus for any given VTVM range the conduction current, I, in Amperes, was always equal to $Ev/10^7$, where Ev (volts) was the VTVM reading. When the electric heater- mentioned earlier- was switched on, the leakage currents across the insulators with the discs removed were always below the sensitivity threshold of the electrometer; detectable currents were measured only when the disc electrodes were in place.

The two disc electrode faces were wiped with a dry cloth, and measurements were first made of I vs. E for the dry electrodes as E was gradually increased from about 1 to 10 kV/cm. After readings with the dry electrodes were completed, the substrates to be tested were weighed and moistened with water, then weighed again. They were then pressed smoothly onto the faces of one or both disc electrodes, and E was either fixed at a given value (for drying time experiments) or gradually increased over a short time span (to measure I vs. E for a given substrate and time in the drying cycle). When dry, the substrate masses ranged from 0.4 to 0.6 g; when thoroughly wetted, they ranged from 2.1 g for brown paper toweling to 2.9 g for a thin cotton handkerchief fabric.

Figure 7 presents measured values of I and E when cotton substrates were wetted with water and placed on either one or both of the disc electrodes. it also shows the I/E relationship

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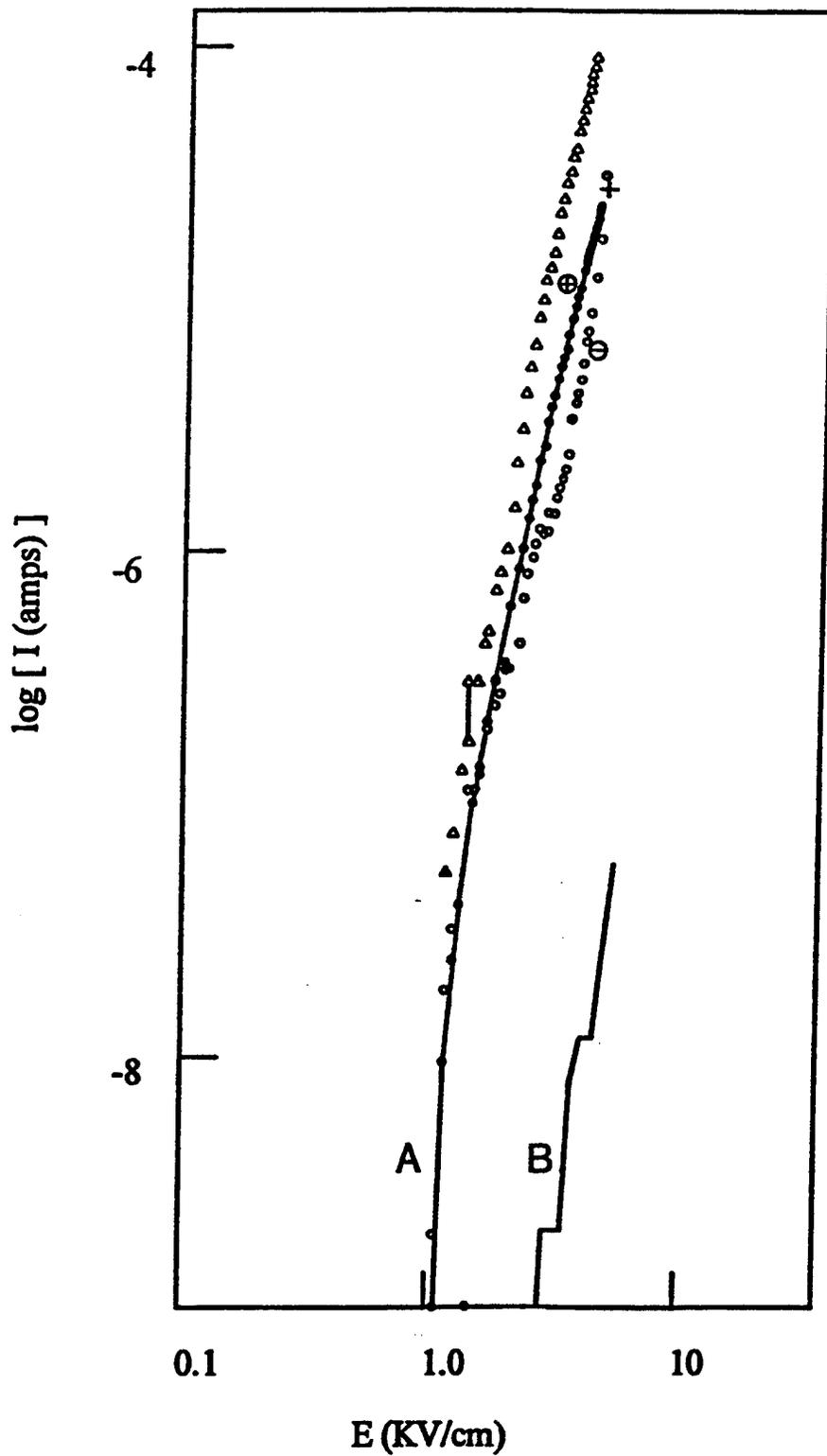
Figure 7. Measured Current I (Amperes) as a Function of Applied Electric Field E (kV/cm); (A) Wetted Substrate(s); (B) No Substrates; for Key, See Text.

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measured (curve B) when no moistened substrates were in place, or if only a dry substrate were resting upon the bottom disc. The key to Figure 7 is as follows. Filled dots: substrate on lower electrode, positively charged; hollow dots: substrate on lower electrode, negatively charged; triangles: substrates on both electrodes; electrode spacing 10 cm.

The values of I are seen to be much lower for Curve B than those obtained with moist substrates, by a factor of between 1,000 and 10,000. We see that I is slightly sensitive to the polarity of E, and that when both discs were wetted the current was larger than for either disc alone.

Incipient manifestations of corona (e.g. hissing, or a bluish luminosity visible with the room darkened) were not observed in moist experiments for field strengths below about E = 6 kV/cm. When the substrates were thoroughly wet, however, water droplets were sometimes seen- in somewhat smaller fields- spraying from the edges of the lower disc when it was positively charged. This activity ceased once excess liquid water had been removed from a substrate under the influence of the electric field.

When liquid water was placed directly on the lower electrode without a substrate, the measured currents were the same as for the bare electrodes alone. Uniform drying of the substrates was indicated by the appearance of numerous whitish patches across their surfaces when drying was nearly complete.

If a solid object, such as a polystyrene paddle, were introduced between the electrodes, _it was observed to reduce the measured current proportionately to the electrode area that was blocked by the object_. This indicated that the charge carriers could be stopped by impacting upon solid objects placed between the electrodes.

Of the different substrate materials investigated, brown paper toweling and thin cotton cloth were found to give the most consistent results. Laboratory filter papers (Whatman Nos. 1 and 4) were highly water-absorbent but comparatively thick and difficult to dry reproduceably. Paper from table napkins worked well initially but tended to disintegrate when wet. Thin plastic sponges and meshes were durable, but less effective in producing current enhancement. Brown paper from bags was least effective of the materials investigated, probably because of its limited porosity.

The current produced from a thoroughly wet substrate in a given electric field at the beginning of a drying cycle was not as large as that produced during drying. Typically, the measured current rose by a factor of 2-3 times during drying, reaching its maximum value just before drying was complete. Completion of

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drying was indicated by a uniform whitish color of an entire substrate. Usually an edge of the substrate became detached first from the electrode, becoming levitated in the electric field when it bacame dry.

Extensive drying experiments were carried out using substrates of brown paper toweling in electric fields of strengths ranging from zero (natural, convective drying in stirred room air) to 9 kV/cm. In additional experiments, substrates of thin cotton handkerchief fabric were used in electric fields ranging from E = 5 to E = 8 kV/cm.

Figure 8 shows the measured relationship between drying time t and field strength E for room air at 25 C and 40% relative humidity, H. Single points indicate individual trials. Error bars indicate extremes and mean values of drying times at given electric field strengths. Drying time t for brown paper toweling is seen to have an inverse linear dependence upon E up to about 6 kV/cm where, as noted earlier, perceptible corona effects begin to manifest themselves and to prolong drying times. Figure 8 reveals a reduction in drying time of nearly 10-fold as E increases from 0 to 9 kV/cm.

TABLE: Measured Mass Loss Rate or Flux dM/dt (mg/min) as a Function of Electric Field Strength (kV/cm) for (A) Brown Paper Toweling and (B) Thin Cotton Cloth.

	dM/dt	
E	A	B
0.0	9.9	
1.0	11.7	
2.0	12.1	
3.0	14.6	
4.0	19.9	
5.0	26.5	18.9
6.0	50.0	28.0
7.0	62.5	35.7
8.0	77.7	45.4
9.0	86.7	
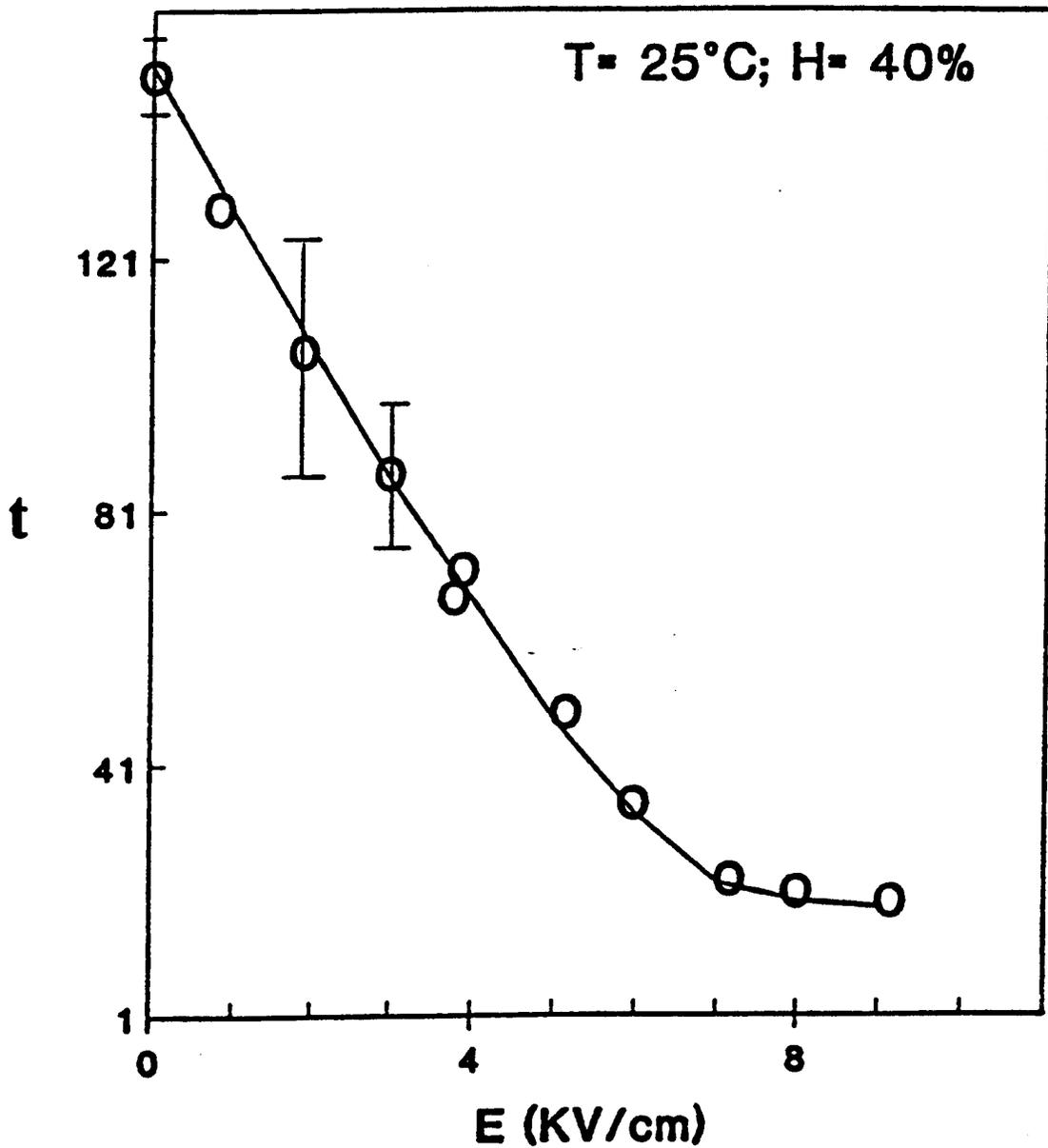
Figure 8. Measured Drying Time t (min) as a Function of Applied Electric Field E (kV/cm); T = 25 C, H = 40%

Estimated flux rates, dM/dt, of water from two kinds of substrates are presented in the TABLE on page 20 for various values of E. For all values of E, dM/dt is larger for the toweling than for the cloth. The cotton substrates initially retained a larger mass of liquid water (about 2.3 g) than did the toweling substrates (about 1.7 g). The cotton substrates took longer to dry, and dried at a lower evaporative flux rate.

In future experiments, we plan to develop preliminary studies to indicate whether liquids other than water may also exhibit similar accelerated drying in the presence of electric fields. Early work (Ref.7) indicated that many other liquids behave this way, but not to the extent that water does. In future work, it will be particularly important to attempt to identify the mechanism of accelerated drying.

The acceleration factor in the present work (up to 1000%) is so much larger than in the cited studies of Ref.12 that it appears probable that a different enhancement mechanism was operating. On the other hand, it is reassuring to note that, for equivalent conditions, the drying rates measured in our studies using two very different techniques were in reasonable accordance. It is planned that results emanating from parallel field studies of this accelerated drying phenomenon will be presented in future papers and reports in this series.

6. POSSIBLE IMPLICATIONS FOR BIOLOGICAL MATERIALS

We have discussed a great deal of experimental evidence showing that the evaporation of water from a variety of porous, wetted materials in electric fields can be accelerated or enhanced by a factor of up to 10 times or more. Many biological materials are porous, and comprise large fractions of their mass as water. Thus it seems of interest to learn **what are the effects of electric fields in air upon the water content and retention of biological materials, and thus upon their viability**? Such questions lead to other, potentially important ones; for example, **are vegetated spores in air killed by electric fields?; if not can they be dried and rendered inert by electric fields?; can they then be made to vegetate once again**?

Recently one of the authors (HRC) completed a detailed study and analysis of electric field technology adapted to specific problems in biological defense (Ref.11, June 1995). An extensive literature search had located some examples of the effects of electric fields/electrostatics upon particles. Some of these involved alternating current (AC) fields while we, at least thus far, have limited our experiments to direct current (DC) fields. Some of the earlier existing work had been carried out in liquids rather than in moist air.

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For example, in saline solutions (electrolytes) steady-state AC fields as small as 100 V/cm can significantly affect microscopic organisms. Bacteria have a highly frequency-dependent complex dielectric constant. With no field, particles are disoriented. With a field, nonspherical, elongated particles tend to align themselves parallel to or perpendicular to the direction of the field. E. coli in water, e.g., orient in fields of 50-80 V/cm, but require 120-200 V/cm to form "pearl chains."

Similar behavior was reported for Euglena gracilis in the frequency range 0.1 - 100 mHz. Perpendicular and parallel elongations of the giant amoeba Chaos carolinensis have been observed at frequencies from 1 Hz to 10 mHz. Perpendicular elongation at field strengths up to about 15 V/cm can be repeated many times without apparent damage to the amoeba. A Chaos was elongated twice during a half-hour, but was normal again 5-10 minutes after the field was removed. Larger field strengths cause complex and variable effects.

One way in which electric fields and electrostatic forces can affect biological and other aerosol particles regards their long-range transport (Ref.13). Aerosols can be scavenged by precipitation particles and cloud hydrometeors (rain, hail, snowflakes, ice crystals) with an efficiency which is highly sensitive to the electric charges on the hydrometeors. This mechanism will deplete the concentrations of aerosol particles engaged in long-range transport; and since the scavenging efficiencies are sensitive to particle size, it will also change the aerosol size distributions.

Enhanced precipitation scavenging of aerosol has been examined in initiatory laboratory experiments in which water drops carrying charges representative of those found in raindrops fell through a cloud of aerosol particles whose sizes could be varied within the range 0.1 to 10 um. The scavenging efficiencies were found to be much greater than the classical (non-electrical) values, sometimes by two orders of magnitude. The authors will discuss results of this research independently of the present report (Ref.13).

There exists no really significant historical record of the kinds of electrical experiments employing organisms that we could propose to carry out using the electric field technology described in this report. For example, suspensions of small organisisms in water could be placed on substrates on the bottom electrode shown in Figure 1, and covered with thin cotton cloth which could be tied to the support rod underneath the electrode, thus securing the sample to the top of the electrode, where both the sample and the securing cloth cover could be further wetted with water or other liquids. After various experimental procedures, the samples could be analyzed for changes introduced in this way.

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7. CONCLUSIONS AND RECOMMENDATIONS

Conclusions that seem warranted by this work include the following:

- a substrate is required on an electrode surface to allow accelerated evaporation to be observed; currents measured for liquid water placed directly on an electrode are the same as for a dry electrode;

- a solid object such as an insulating sheet passed between two electrodes reduces the current proportionately to the blocked area of the electrodes;

- in electric fields of up to 7-9 kV/cm, the evaporation of liquid water from wetted materials such as thin cotton cloth is accelerated or enhanced by factors of up to 10 times;

- liquids other than water, including organics, also behave this way, but the enhancement factor is less than that for water;

- some limited studies of the behaviors of microorganisms under the influence of electric fields in water solutions, e.g., saline, have been published; these show modified behavior of the organisms even under small field strengths, e.g., 50-100 V/cm;

- the mass density of moist air is about 1/1000th that of liquid water and water solutions; thus electrical conductivity currents in the vapor are much smaller than those in the liquid, and the electric fields driving these currents should be proportionately larger;

- no literature is known to exist on the effects of static electrical fields upon microorganisms that rest upon conductive surfaces in air and that carry currents driven by the electric fields;

It is difficult to formulate recommendations under the current circumstances because there is little historical record of research into the effects of electric fields on living organisms. And yet, interesting new technology has been discovered and demonstrated that might produce unexpected and important results if applied to these organisms. This could strengthen our capabilities in biological defense.

Pure research is what would be required here, i.e., investment of time and money with no expectation of what results would be obtained, or whether they would have any value whatsoever to our biological defense mission. Small-scale experiments could be carried out in parallel with ongoing research using apparatus already at ERDEC. The authors are of the opinion that at least these initial experiments should be undertaken now.

Accordingly, the authors put forth the following recommendations:

● beginning with small electric fields (100 V/cm), a few selected kinds of organisms which are easily analyzed should be subjected to these fields on the bottom electrode of the apparatus shown in <u>Figure 1</u>; they should be analyzed before and after exposure for properties including viability, and secured to the electrode by thin cotton cloth, stretched taut, and initially well-wetted with water;

● drying rates should be determined by the methods described in this report;

● results of each set of experiments should dictate the conduct of the next set;

● measurements should be conducted at progressively greater electric field strengths, consistent with results;

● other effects should be investigated, including particle levitation upon drying (if unrestrained), blocking of charge carriers by solid objects placed between the electrodes, and use of liquids other than water to wet the organisms.

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