R&D6697-EN-09

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ACCELERATED DRYING OF WETTED MATERIALS

FINAL REPORT ON CONTRACT DAJA45-91-M-0150

Submitted to

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January 1992

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1.PREAMBLE

The principal focus of attention during the contractual period has been on the performance of field experiments designed to establish whether - under conditions more closely representative of those existing in a militarily relevant situation than it is possible to achieve in the laboratory - the evidence for accelerated drying of wetted materials emanating from laboratory studies (1, 2, 3) can be consolidated in the field.

These field experiments have been conducted primarily in Wales (at the UMIST field research station in Waunfawr), with some supplementary studies of similar nature being performed in Colorado (in the Rocky Mountains). The major goals of the field studies conducted to date have been to devise and optimise a technique using which drying rates can be reliably and accurately determined in the field; and to examine the sensitivity of these rates to fundamental meteorological parameters such as temperature, relative humidity and wind-speed over as wide a range of conditions as possible - hopefully the entire range which might be experienced in practical or militarily significant situations.

In Section 2 of this report we outline the results emanating from the most definitive of these field experiments. In Section 3 we present some theoretical calculations which appear to illuminate aspects of the physics of this accelerated drying phenomenon. Sections 2 and 3 are reproductions of the scientific content of the first and second interim reports, dated March and August 1991, respectively.

We conclude from these field experiments and the subsidiary

theoretical analysis, coupled with extensive laboratory studies (2, 3) that the drying of wetted materials can be appreciably accelerated by electric forces, and that a technique of practical military importance, based on this phenomenon, may well be developed. However, in order to assess this possibility more fully and thereby optimise any potential practical exploitation of this process, it is crucial to perform comprehensive new field studies which (a) provide detailed quantitative information on the electrically-enhanced drying process over the same wide range of meteorological conditions as was studied in the non-electrical field investigations described in Section 2; (b) extend the range of wetting agents (liquids) studied, in the first instance by utilising organic solvents.

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FIELD EXPERIMENTS ON DRYING RATES

The primary emphasis during the latest contractual period has been to perform field experiments on accelerated drying of wetted materials. The principal justification for this decision was to endeavour to close the gap between the precisely controlled laboratory experiments described in earlier reports, and the practical situation which is the ultimate goal towards which this research is orientated. In such a situation, the wetted specimens would be much larger than those utilised hitherto, and attempts to expedite the drying would be required to take place in whatever weather conditions prevailed.

It seemed important, therefore, to conduct studies out of doors, using larger wetted specimens which were examined as they dried over as wide a range of temperature (T), relative humidity (H) and wind-speed (V) as were technically feasible and available.

The majority of these field experiments were conducted at the UMIST research station in Waunfawr, North Wales, with some supplementary ones being performed in Colorado, where higher values of T and lower values of H were available.

Although, in the longer term, it is planned to perform experiments with a variety of wetting agents and wetted substrates, the most urgent priority at this stage was deemed to be the establishment of a quantitative understanding of the physical laws which govern this accelerated drying process. Accordingly, in the current stage of the research, it was decided to perform comprehensive studies with one wetting agent and one material only. These were water and cloth, respectively.

A considerable fraction of the contractual time and effort in the most recent period was devoted to the development and

optimisation of a necessarily simple but sufficiently reliable experimental apparatus and technique to obtain valid results for the range of meteorological conditions anticipated. It was then considered logical first of all to test out and refine this system over the available range of H, T and V in the absence of imposed electric fields E. At the time of writing this intermediate objective was accomplished, necessitating, however, only a limited amount of information - not yet fully analysed - on drying rates in high electric fields. Even so, it can be asserted that the effects of strong fields on drying rates are similar to those in the earlier laboratory experiments, ie the multiplicative factors and the threshold fields for significant enhancement of drying rate are roughly the same. Consequently, the present report is confined to an account of field experiments conducted with E = 0, over a range of values of T, H and V. Analysis of high-field studies already performed, coupled with others shortly to be executed will be described in the following report.

A crucial requirement of the experimental system was that drying rates or times could be measured for both zero and Finite E, for the some conditions of T, H and V, simultaneously. This was achieved in the following manner.

Two identical squares of cloth, each of size characteristically 10cm, were each stretched between wire frames lying on a wire gauze base, inclined at a shallow angle typically 15°) to the horizontal, and orientated so that the wind washed over them. The gauze and thus the cloth squares, when wetted) was grounded. A second plane of gauze was suspended a distance X above the first, and parallel to it. A typical value of X was 3cm. This second gauze was divided electrically so that the part suspended

over one of the cloth squares was grounded, while the part suspended over the other one was connected to a variable 0-30kV supply. Thus, when the high-voltage supply was switched on, one specimen of cloth was subjected to a finite electric field E, while for the other E=0.

The general experimental procedure was to wet both substrate squares, weigh them, place them in position, switch on the electric field and at the same time measure the three meteorological parameters T, H and V. These parameters were read periodically over the time interval t for which the specimens were allowed to dry. Acceptable values of t were found by trial and error, were typically several minutes and largely dependent upon the values of T and H.

After the period t had elapsed, the wetted specimens were weighed again and the mass loss M experienced for each was thus determined. The experiment was then repeated several times; and by performing this same sequence at various times of day on several days the experimental data outlined here were procured.

The separate influences on the drying rates of the three meteorological parameters, H, T and V are illustrated in the following figures and graphs, for which E=0 in all cases. This has been done, in each case, by holding two parameters constant which was achievable to a reasonable extent, and examining the sensitivity of M/t to the third parameter. The values of M/t in each case have been normalised to standard values $(M/t)_S$ of H, T and V which were 0.8, 20°C and 3m/s, respectively.

The influence of relative humidity H on the drying rate M/t of wetted cloth is illustrated in Figure 1, where the ordinate

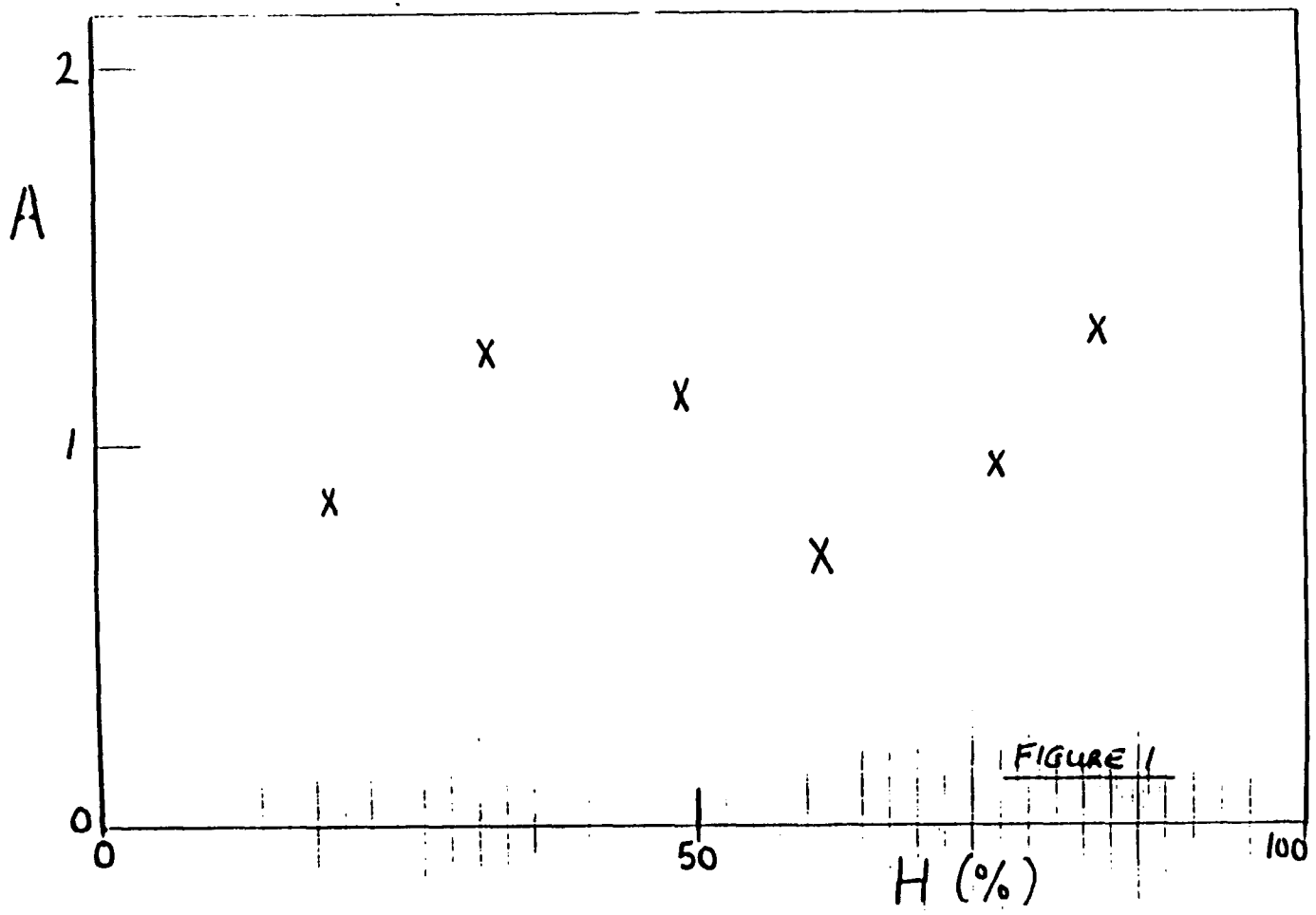

FIGURE 1

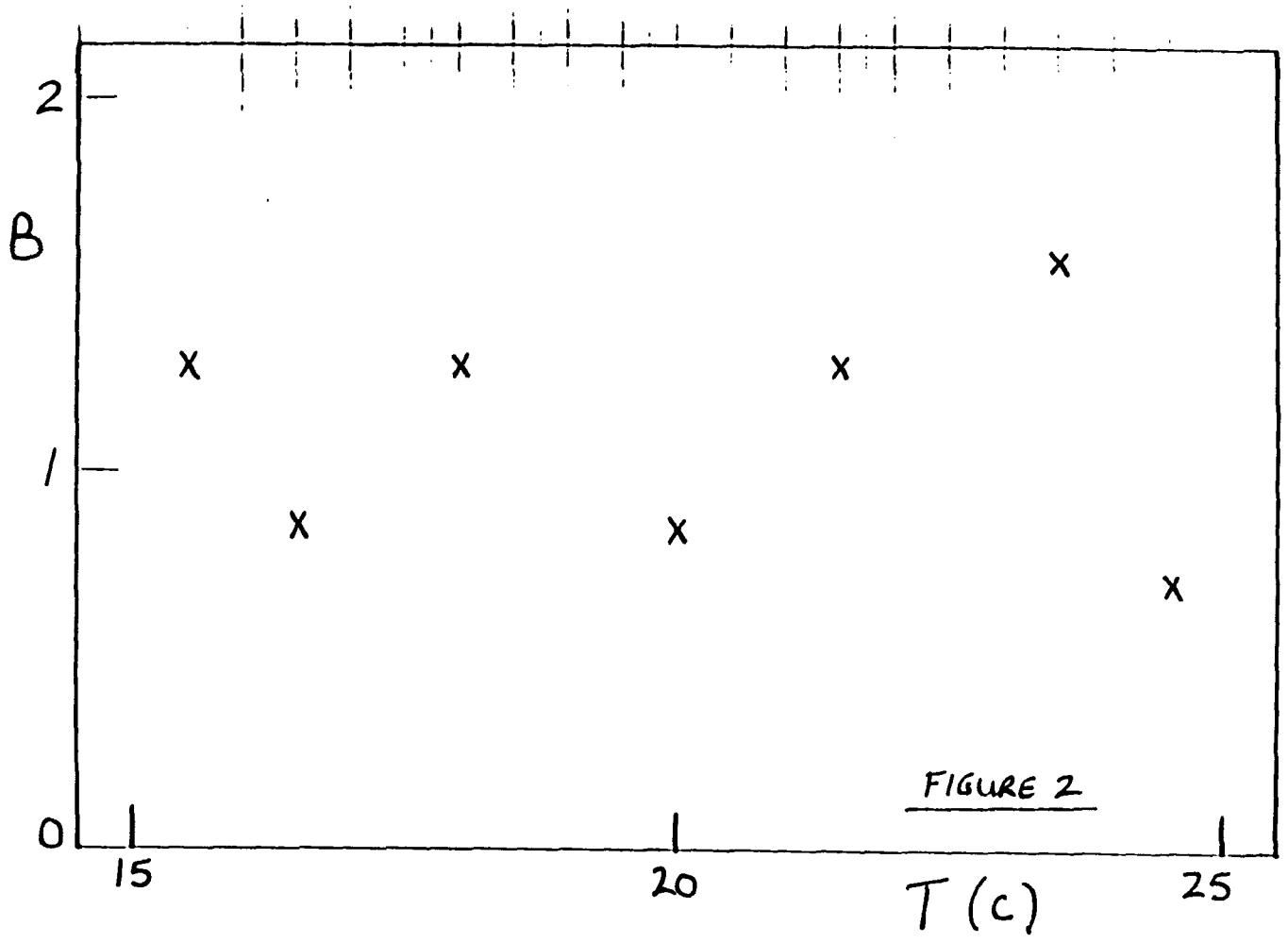

FIGURE 2

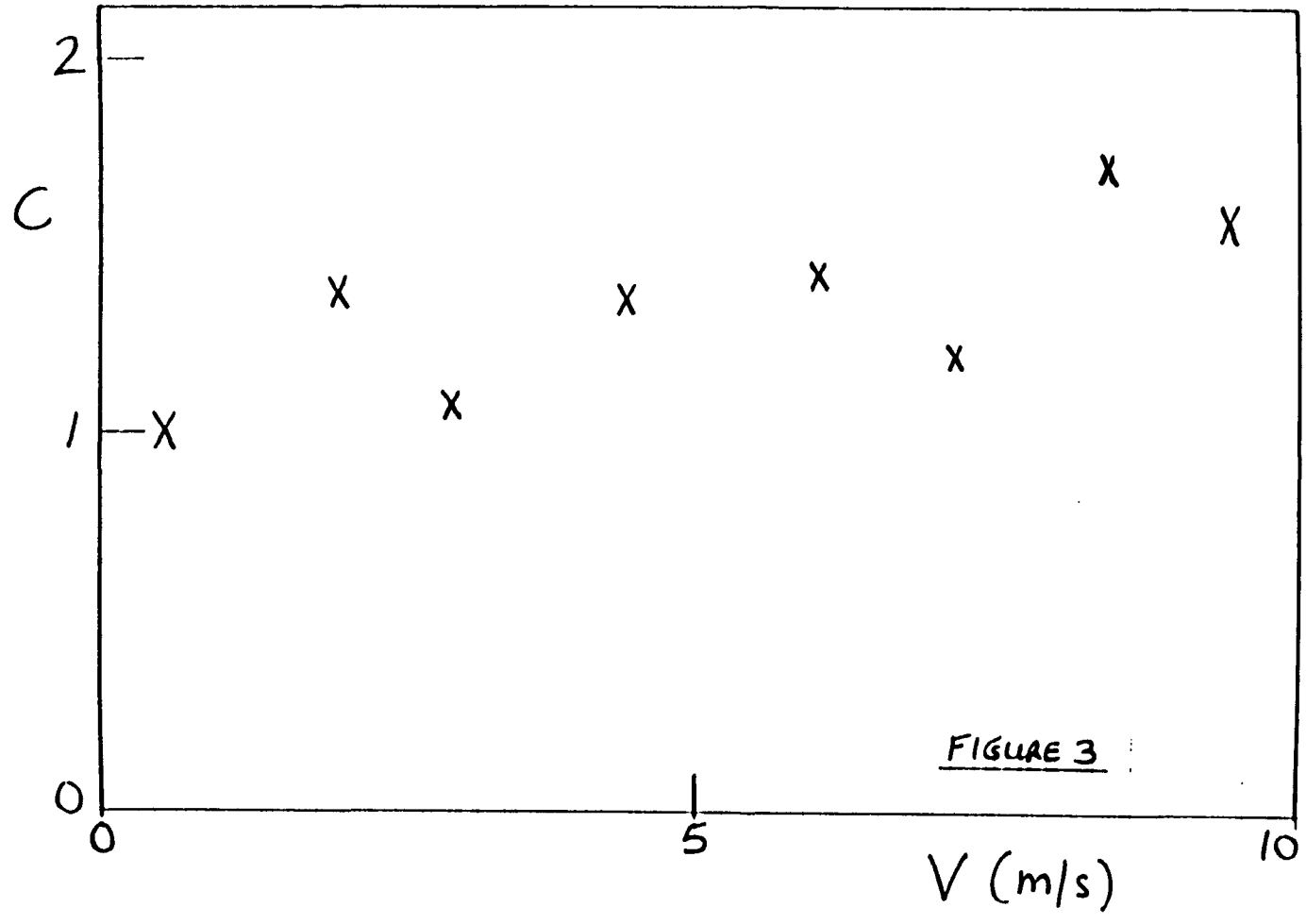

FIGURE 3

THEORETICAL STUDIES

In the two months which have elapsed between the awarding of the Contract and the specified date of this report, preparation laboratory and field work has been performed, which will be substantially consolidated over the next few months, and will constitute the kernel of the Second Interim Report, due by 30 August, 1991.

The present report focuses attention on calculations designed to enhance our knowledge of the interaction between electric forces and the evaporation of liquids, in the hope that this new information will facilitate an understanding the physics of the accelerated drying phenomenon which is the pivotal feature of our programme of work. This superior understanding is clearly desirable, in that it should help improve the efficiency with which any practical technique for accelerated drying would function.

The following rough calculation was performed in order to see whether charging rates measured in laboratory studies of evaporating liquids and solutions are consistent with the theoretical rates deduced on the assumption that the electrification is a consequence of the removal of singly-charged individual molecules.

We consider a typical experimental result that when 0.1 N KCl solution is evaporated at a temperature T = 63°C it loses mass at a rate $dm/dt = -1.67 \times 10^{-3}$ g sec^{-1} and becomes positively charged at a rate $i = 5 \times 10^{-14}$ A. The simplifying assumptions are made that the potassium chloride is completely dissociated in solution and that the measured charging is entirely a consequence

of the removal of Cl-ions during evaporation. It is also assumed that the flux of neutral water-vapour molecules leaving the solution is many orders of magnitude greater than the flux of negative ions: comparison of the measured values of dm/dt and i indicates that this ratio is about 10^{15}. A further assumption is that the differences between the binding energies in solution of water molecules and chlorine atoms is negligible in comparison with the much larger binding energy of a chlorine ion. This additional energy is required because the removal of a charged particle from a liquid surface entails the performance of work in order to overcome the powerful short-range attractive image forces.

If we assume a spherical Cl-ion of diameter L the additional work required for the ion to overcome its electrostatic image charge is given by

$$\Sigma = \int_{x=L}^{x=\infty} \frac{e^2 dx}{x^2} = \frac{e^2}{L} \qquad (1)$$

where x represents the distance of the centre of the ion from the liquid surface and e is the electronic charge. If we take L = 2 x 10^{-8}cm it follows from equation (1) that Σ = 1.2 x 10^{-11} ergs.

The ratio of the probability of escape of a charged molecule to that of an uncharged similar molecule can be expressed by

$$P = e^{-\Sigma/kT} \qquad (2)$$

where k is Bolzmann's constant and T is the absolute temperature. Taking the measured value of T = 336° Absolute we obtain P = 10^{-112}.

Since the number of water molecules in solution is very much greater than the number of chlorine ions it is permissible to make the approximation that the fraction of evaporating molecules

that are charged is given by

$$f = 10^{-3}\ P.N.M, \qquad (3)$$

where N is the normality of the solution and M (= 18) is the molecular weight of water. The theoretical charging rate is therefore given by

$$I = \frac{(dm/dt)ef}{Mm} = \frac{10^{-3}(dm/dt)eNP}{m} \qquad (4)$$

where m (= 1.7×10^{-24}g) is 1/16 times the mass of the oxygen atom. Substitution of the above-mentioned values of (dm/dt), N and P into equation (4) yields $I = 5 \times 10^{-105}$ A, which is 91 orders of magnitude less than the experimentally determined evaporation current. The measurements, therefore, cannot be explained in terms of the removal of singly-charged unassociated ions during the evaporation process.

However, the work required to overcome the electrostatic image forces is appreciably diminished if each ion leaving the liquid surface is associated with a number of neutral water molecules. We now compute the size of agglomerate, consisting of a Cl-ion in the centre of (N_9 - 1) water molecules, required in order to obtain equivalence between the experimental and theoretical charging rates, i and I respectively; for simplicity, the agglomerate is assumed to be spherical. The work done against the electrostatic image forces in removing such an agglomerate from the liquid surface is given approximately by

$$\Sigma' = \int_{x=1N_9^{1/3}}^{x=\infty} \frac{e^2}{x^2}\,dx = \frac{e^2}{N_9^{1/3}}, \qquad (5)$$

where 1 (= 5 A) is an approximate value for the diameter of a water molecule.

In order to increase the fraction f by the factor 10^{91}

required in order to eliminate the discrepancy between i and I the energy Σ' must equal 0.18Σ. In this case we can write

$$\frac{\Sigma'}{\Sigma} = 0.18 = \frac{L}{N_g^{1/3} 1} = \frac{0.4}{N_g^{1/3}} ,$$

whence $N_g = 11$

This rough computation indicates that the measured charging rate is consistent with the theoretical value if each charged particle leaving the liquid surface during the evaporation process is contained within an agglomerate of about 10 neutral water molecules. Although observations have been made of the existence of such aggregates in the vicinity of liquid surfaces no direct evidence has been obtained of their removal as agglomerates from the liquid during evaporation. However, it should be pointed out that the energetic difficulties involved in the removal of such a cluster are considerably less than those associated with the removal of unassociated ions.