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THE PSYCHROMETRIC PROPERTIES OF A MK2C ORDINARY MERCURY IN GLASS THERMOMETER FITTED WITH A TUBULAR WICK.

BY

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AP

1. Introduction

This report describes work which has extended the earlier investigations of Folland (1) and Clarke (2) into the psychrometric properties of wet-bulb thermometers used by the Meteorological Office. It is primarily concerned with the thermometer wet-bulb system comprising the Mk 2/C ordinary mercury-in-glass thermometer (MGT) and a tubular cotton wick.

The psychrometric equation enables ambient water vapour pressure to be derived from measurements of wet-and dry-bulb temperatures, as follows:

$$e = e_s(W) - Ap(T - W) \qquad \ldots\ldots\ldots (1)$$

where T is dry-bulb temperature

W is wet-bulb temperature

e is ambient water-vapour pressure (VP)

$e_s(W)$ is saturated VP (SVP) at temperature W

P is atmospheric pressure

A is the psychrometric coefficient

The MO Hygrometric Tables (3) use a value of $A = 0.799 \times 10^{-3}K^{-1}$ for thermometers in an unventilated Stevenson screen, and $A = 0.67 \times 10^{-3}K^{-1}$ for an Assman psychrometer.

Folland (1) has investigated, both theoretically and experimentally, the effect of stem heat conduction on A with specific reference to the Mk 2/C ordinary MGT and the Mk 2 Electrical Resistance Thermometer (ERT). It was shown that the Mk 2/C MGT fitted with a traditional muslin-cap wick yields a value of A significantly greater than that used in the Hygrometric Tables. By fitting an extension to the muslin cap wick (Fig 1a) it was found that stem heat conduction could be reduced, with a consequent decrease in the effective value of A. Now the value of A is at all times dependent upon the rate of ventilation, but instrumental error can be minimised by using a wick extension that yields the appropriate value of A under mean screen conditions. A similar result was demonstrated for the Mk 2 ERT and Clarke (2) determined such an Optimum Wick Length for the Mk 4 ERT.

Folland's investigation also showed that the mean ventilation rate for a Stevenson screen in the UK has probably been over-estimated historically. The value of $A = 0.799 \times 10^{-3} K^{-1}$ was originally determined with reference to a mean ventilation rate of 1.25 ms^{-1}, whereas a value of 0.6 ms^{-1} is now believed to be more representative for the British Isles.

This report evaluates the performance of the Mk 2/C MGT wet-bulb fitted with a tubular wick, similar to those used with the Mk 2 and Mk 4 ERTs, as shown in Fig 1b. A series of experiments have been performed in the wind tunnel at the Meteorological Office Annexe at Eastern Road, Bracknell, and are described below.

The aim of this report is

a. to show the relationship between the psychrometric coefficient of the Mk 2/C ordinary MGT wet-bulb and the length of the thermometer stem covered by an extension of the wick material;

b. to use any relationship found above to determine an Optimum Wick Length for the Mk 2/C MGT wet-bulb appropriate for the mean conditions in a Stevenson screen in the British Isles, having regard to

(1) the use of hygrometric tables based on a psychrometric coefficient $A = 0.799 \times 10^{-3} K^{-1}$;

(2) a similarly exposed Mk 4 ERT wet-bulb fitted with a 42 mm tubular wick;

c. to determine the most suitable method for securing a tubular wick to the Mk 2/C MGT, having regard to the need to effect a prescribed wick-length and the possible impact of the securing method on the psychrometric coefficient of the wet-bulb.

2. Stem Conduction and the Mk 2/C Ordinary MGT wet-bulb

Fig 1a depicts a Mk 2/C MGT wet-bulb fitted with the standard muslin-cap wick and incorporating the wick extension of tubular cotton sheath described by Folland. Fig 2 (reproduced from Scientific Paper No 38, Fig 16) shows the theoretical and experimentally derived relationships between the psychrometric coefficient and ventilation rate obtained by Folland for this wet-bulb system. The data in Table 1 give an idea of the errors in the assigned values of commonly used humidity variables incurred by the use of hygrometric tables based upon a fixed value of A, for conditions of temperature and humidity appropriate to Fig 2. It can be seen that values of relative humidity (RH) computed from wet-bulb readings for an air flow-rate between 0.6 ms^{-1} and 1.25 ms^{-1} (ie actual A varying between 0.75×10^{-3} and $0.85 \times 10^{-3} K^{-1}$, from Fig 2) will be in error by less than ±1% RH. This result satisfies the WMO requirement (4) for surface measurements of RH for climatological, synoptic and agricultural meteorology. Folland also presents data and argues that the range of ventilation rates given above is representative of mean conditions in a Stevenson screen exposed at a representative location in the British Isles.

Fig 1b depicts the proposed general arrangement for the Mk 2/C MGT wet-bulb with a tubular wick, and indicates the most obvious securing points for the wick.

The crucial difference between the arrangements shown in Figs 1a and 1b is that the sensing bulb in the latter is not uniformly exposed to the surrounding air and it cannot therefore be assumed that the two systems will perform identically for any given wick extension. Indeed, since the glass sheath around the thermometer is joined to the thermometer just above the sensing bulb, it is very likely that only a limited control over stem heat conduction can be exerted by extending the wick in the manner shown.

3. Experimental Method

The experimental method was essentially that described in DS 161. The psychrometric coefficient of a wet-bulb is determined for a number of air velocities by exposing it, in a wind-tunnel, to an air-stream having a stable, measured temperature and dew-point and an accurately controlled flow-rate. The procedure was followed for a Mk 2/C MGT with tubular wick of various lengths, and also with a muslin-cap in order to compare the results obtained with those in Scientific Paper No 38. A Mk 4 ERT wet-bulb with a full-length (78 mm) wick was used as a control wet-bulb, and a second Mk 4 ERT, for which the wick-length was varied, was also included.

A commercial precision chilled-mirror dewpoint hygrometer (DPH), having traceability to the US National Bureau of Standards (NBS), was used to measure dew-point. The Meteorological Office Mk 3 DPH which provided the standard for both Scientific Paper No 38 and DS 161 is no longer functioning, and neither was it at the time of the experiments described herein. A comparison of the two 'standards' has therefore not been possible. In principle, the commercial instrument used for these experiments should provide measurements of sufficient accuracy to allow the psychrometric coefficient of a wet-bulb to be computed with an accuracy better than $\pm 0.015 \times 10^{-3} K^{-1}$ (see Annex B) but, in practice, variations of air temperature in space and time make such a target difficult to realise even in the relatively stable conditions obtainable in the Meteorological Office wind tunnel.

Wind-speed was measured with the standard wind-tunnel pitot-static tube connected to a precision water manometer. A baffle, in the form of a sheet of plywood with a regular matrix of holes drilled through it, was used to break down large eddies in the air-flow which tend to cause irregularities in the air-flow at low ($< 1\ ms^{-1}$) velocities. This was the baffle used for DS 161.

The Mk 4 ERT sensors (for dry- and wet-bulb temperature measurements) were used in conjunction with the Mk 1 DTI having a resolution of 0.1°C.

Annex A gives estimates of all the instrumental errors for the measured quantities. Annex C shows the experimental layout.

4. Results

Analysis of the data collected during this trial reveals problems which are a common feature in psychrometry. Even within the apparently stable environment of the wind-tunnel, noise in the temperature measurements can be of a significant magnitude and it is important always to refer to the behaviour of the control wet-bulb. For this reason the control data will be considered first.

4.1 Control Data

Fig 3 compares the control data obtained during this trial with the corresponding data reported in Scientific Paper No 38 and DS 161. It can be seen that both the Mk 2/C MGT with muslin-cap (curve B) and the Mk 4 ERT with 78 mm wick (curve D) wet-bulbs yielded significantly lower values of the psychrometric coefficient than those reported in the earlier works (curves A and C respectively). The uncertainty in curve C is, in fact, quite large ($\pm 0.04 \times 10^{-3} K^{-1}$), and is due in part to the lower claimed accuracy for the Meteorological Office Mk 3 DPH used as a reference (untraceable) for DS 161. Thus, curves C and D are within experimental error, but this error has an implication for the accuracy of humidity measurements, as can be deduced from Table 2. The data in Table 2 are theoretical values calculated for the mean conditions experienced during this trial.

The negative bias apparent in curves B and D, when compared with the work reported in Sci. Paper No 38 and DS 161 was a consistent feature of this trial. It is worth mentioning that in recent years similar uncertainty has been voiced concerning the value of A appropriate to the Assmann psychrometer. Wylie (4) has carried out extensive laboratory and field trials and concluded that a value of $0.62 \times 10^{-3} K^{-1}$ is to be preferred to the widely accepted $0.67 \times 10^{-3} K^{-1}$ used in the Meteorological Office Hygrometric Tables for aspirated psychrometers, and this has been endorsed by WMO (5). Schurer (6) has corroborated Wylie's findings and has reported a measured value of $0.63 \times 10^{-3} K$ for a ventilation rate of $2.4 \; ms^{-1}$. Annex D presents estimates of the effects of various contributions to instrumental error in the Assman psychrometer.

This discrepancy in psychrometric coefficients is equivalent, for ambient conditions of 19°C and 35% RH (see Table 2), to a difference of 2% RH.

Fig 3 curve D is quite consistent with the proposition of a lower psychrometric coefficient at high ventilation rates, and suggests that the values derived in DS 161 for the Mk 4 ERT may well be too high. Such a conclusion would compromise the stated aims of this report. And since the Assman psychrometer has historically been the reference for humidity measurements, it follows that the psychrometric coefficient applied to unventilated Stevenson screen readings also should be reduced in proportion 0.62/0.67, i.e. $A = 0.75 \times 10^{-3}\ K^{-1}$

Fig 4 shows the RMS deviations in values of A obtained for the Mk 4 ERT control wet-bulb at different ventilation rates. A similar relationship between the two was noted in DS 161, though with slightly smaller variability. In particular, it was found that the variability at 5 ms^{-1} continued the downward trend with increasing ventilation rate, in distinct contrast to the extreme variability obtained during this trial.

4.2 Direct Comparison of Mk 2/C MGT wet-bulb and Mk 4 ERT with 42 mm wick

A pilot trial was carried out in September 1983 to identify the length of wick required for Mk 2/C MGT wet-bulb to obtain identical readings with a Mk 4 ERT having a 42 mm wick. A second Mk 2/C MGT with a 50 mm tubular wick was used as a control wet-bulb. The results of this trial were not conclusive but are included to illustrate the magnitude of the noise problem and to justify the decision to carry out the main trial using a Mk 4 ERT with 78 mm wick as a control wet-bulb, since the longer wick tends to confer less variability.

Fig 5 shows a time-series plot of the data values obtained over a one-hour period during which the air flow was maintained at a velocity of 1 ms^{-1}. The wet-bulb temperatures shown are those for the two control sensors, and it can be seen that the distinct dip in dry-bulb and dew-point temperatures measured is not apparent in the wet-bulb temperatures. As a consequence of this there is a sharp rise in the values derived for the wet-bulb psychrometric coefficients. In addition the two wet-bulb measurements appear to converge with time, as the Mk 4 ERT temperature decreased at half the rate shown by the Mk 2/C wet-bulb. The two thermometers have very similar time-constants as dry-bulbs, but no data is available for their comparative performance as wet-bulbs and here wick length may be critical. It is well known that wet-bulbs have a faster time-response than equivalent dry-bulbs due to the greater heat transfer rate at a water/air turbulent interface. Fig 6 shows temperature difference as a function of wick-length between the experimental Mk 2/C MGT wet-bulb and the Mk 4 ERT control wet-bulb (42 mm wick), for the time-series in Fig 5. The value obtained with a 78 mm wick appears to be spurious. Fig 5 shows (compare observation times) that the dew-point was steady, the dry-bulb was falling, and the two control wet-bulbs exhibited equal and opposite change! The value at 20 mm may also be regarded with some suspicion because of the behaviour of the control wet-bulbs previously discussed (observation time 1550 GMT).

It is possible to conclude that the Mk 2/C MGT wet-bulb with a wick-length equal to or greater than 30 mm will give similar results to a Mk 4 ERT (42 mm wick) at a ventilation rate of 1 ms^{-1}. However, the value of the psychrometric coefficient derived here for the Mk 4 ERT is significantly less than that given in DS 161, and has a large variability. Fig 3 curve E shows the relationship given in DS 161, which indicates a value of $A = 0.79 \times 10^{-3}K^{-1}$ at 1 ms^{-1} whereas that measured in the time-series of Fig 5 was $0.70 \times 10^{-3}K^{-1}$ with a RMS deviation of $0.02 \times 10^{-3}K^{-1}$. Fig 7 shows the variation of psychrometric coefficient with wick-length obtained for the Mk 2/C MGT wet-bulb at 1 ms^{-1} ventilation rate.

4.3 Variation of psychrometric coefficient of the Mk 2/C MGT Wet-bulb with ventilation rate, for different wick-lengths

Fig 8 shows values of psychrometric coefficient (A) plotted for wick-lengths of 50 mm, 20 mm and 15 mm and ventilation rates in the range 0.6 – 5 ms^{-1}. The curves drawn were fitted subjectively to data selected from that available to be representative of stable conditions with a well-behaved control wet-bulb. (A well-behaved control wet-bulb was one that was consistent with curve D of Fig 3.)

It will be seen that the data are rather noisy, although there is a suggestion that the data are coherent within the ranges 0.6 – 1.25 ms^{-1} and 1.25 ms^{-1} – 5 ms^{-1}, but that the two sets of data are not consistent with each other. This implies that there may have been a gross error in the measurement of effective ventilation rate, much greater than the notional accuracy of the instrumentation concerned. The most probable cause of such an error is the presence of large scale eddies in the tunnel at low air velocity – the prevention of which was the purpose of the baffle already described.

Fig 9 compares the curves of psychrometric coefficient vs ventilation rate already given in Figs 3 and 8. If it is accepted that a wick-length in the range 30 – 50 mm for the Mk 2/C MGT will result in broad equivalence with a Mk 4 ERT with a 42 mm wick, then there is clearly a significant uncertainty in values of relative humidity derived from these wet-bulbs.

Figs 11 and 12 show the predicted errors for the Mk 2/C MGT with 20 mm and 50 mm wicks respectively, based on curves B and C of Fig 9. Corresponding errors for the Mk 4 ERT with 42 mm wick predicted by DS 161 are shown in Fig 10. It will be seen that there is a significant uncertainty in derived RH due to the uncertain ventilation rate of a Stevenson screen. Fig 13 gives curves of error vs ventilation rate at 35% RH for the three wet-bulb systems, which shows that there will be an uncertainty of about 3% RH, at 35% RH, in the mean instrumental error attributable to the uncertainty in the absolute accuracy of the psychrometric coefficient.

4.4 Methods of securing the wet-bulb wick

Various combinations of the securing points indicated in Fig 1b were tried. Cotton thread taken from muslin-cap wicks was used, and tied tight. No systematic effect was noted and therefore no recommendation can be made on instrumental grounds for an optimum method.

4.5 Variability of the Mk 2/C MGT Wet-bulb

The comparison reported at 4.2 included two Mk 2/C MGT wet-bulbs with 50 mm tubular wicks as controls (one of which was used to compare **securing** methods). Both controls performed identically and yielded a mean psychrometric coefficient of $0.73 \times 10^{-3}K^{-1}$ at a ventilation rate of 1 ms^{-1}, within a range of $0.715 - 0.755 \times 10^{-3}K^{-1}$. This compares with the value of $0.77 \times 10^{-3}K^{-1}$ obtained by Folland for a long wick (Fig 2) and $0.70 \times 10^{-3}K^{-1}$ for the experimental wet-bulb (Fig 8 Curve C) with 50 mm wick. Both control wet-bulbs read 0.15°C higher than the experimental wet-bulb with 50 mm wick, with a dew-point depression of 7.5°C.

This variability in the performance of the Mk 2/C MGT wet-bulb demonstrates that fine-tuning the system through wick-length adjustment is likely to be frustrated. The performance of the wet-bulb has not even been shown to correlate with variations in critical dimensions of the sensing area of the thermometer. Table 3 gives values for some relevant dimensions for a small sample of Mk 2/C MGTs and the tolerances called for by BS 692 (against which the thermometers are purchased). Thermometers 1200/82 and 98857/80 were the two control wet-bulbs and 76312/69 was the experimental wet-bulb for the results reported in 4.2 and are denoted (C) and (X) as appropriate. This small sample indicates a range of characteristic shape, from those with long thin necks (78907/69) to those with short fat necks (1200/82) and Fig 1c shows tracings of photographs of these two extreme examples.

The difference in performance of the experimental wet-bulbs compared to the control wet-bulbs is not explained by the data in Table 3. Thermometers 1200/82 and 98857/80 behaved indistinguishably but differently from 76312/69, and yet if classified by neck dimensions 98857/80 (stoutish) would be grouped with the latter rather than with 1200/82 (stout). The extremes of long thin necks were noted only after the wind-tunnel trials had been completed, and so no data has been obtained for performance of such a thermometer as a wet-bulb. But with such variation between morphologically similar thermometers it should be expected that dissimilar thermometers will exhibit even greater variation in wet-bulb performance. In particular, the finding at 4.4 that securing method is not critical to wet-bulb performance may not be generally valid.

5. Discussion

From the foregoing it is quite clear that a precise equivalence for the Mk 2/C MGT and Mk 4 ERT wet-bulbs is not forthcoming from this trial and that the uncertainty in the values of psychrometric coefficient obtained is greater than was sought.

As was pointed out in DS 161, the deliberate introduction of limited stem heat conduction to a wet-bulb thermometer produces a system with inherent variability and that this, when combined with experimental uncertainties, makes precise comparisons difficult.

In order to reduce the experimental uncertainty it will be necessary to have the accuracy of the precision dew-point hygrometer verified by an absolute humidity standard and to investigate more thoroughly the low speed characteristics of the Meteorological Office wind-tunnel. NPL (7) will shortly be offering a humidity standard traceable to a gravimetric hygrometer manufactured by SIRA and it is planned to take advantage of this facility at the earliest possible time.

Fig 6 indicates that the Mk 2/C MGT wet-bulb system is not very sensitive to change in wick-length for wicks greater than about 25 mm, but is extremely sensitive to wick-lengths of less than 20 mm. Reference to Fig 1a shows that 20 mm is also probably a minimum reproducible wick-length. Given these findings it is likely to be most prudent to use a wick-length that is easily repeatable and gives agreement with the current Mk 4 ERT wet-bulb system. The optimum wick-length would then be some length in excess of 30 mm. A 20 mm wick would seem to effect a compromise between the twin aims of accuracy and compatibility with the Mk 4 ERT, given the current uncertainty in absolute accuracy. However, the wick-length would be fairly critical and would not necessarily be repeatable between wet-bulbs or even for the same wet-bulb when changing wicks. Use of a long wick would obviate the need for precision in setting-up and also, perhaps, the need for it to be secured. From the operational point of view, tying at point B (Fig 1b) is likely to result in an increase in the number of broken thermometers.

Taking a detached view, the ideal solution would be to use long wicks on all thermometers and either use appropriate tables or correct the wet-bulb depression according to the relative humidity.

Tinkering with the instrumentation system is not good practice and leads to uncertainty, whereas to keep wick-lengths constant over time and correct them according to the best information available would allow for retrospective correction for climatological purposes. Given the uncertainty even for Assman psychrometers, it seems logical to change the tables, or apply corrections, rather than change the instrumentation system every time new data comes to light.

6. Conclusion

6.1 A wick-length of 50 mm for the Mk 2/C MGT wet-bulb should give good agreement with a Mk 4 ERT having a 42 mm wick, for mean conditions in a Stevenson screen in the British Isles.

6.2 Compatibility of a Mk 2/C MGT wet-bulb with the Meteorological Office Hygrometric Tables is still a matter of uncertainty. The expected error in RH derived, using the tables, from an unventilated Mk 2/C MGT wet-bulb with a 50 mm wick is ±2% RH when based on the results of Design Study 161, but between -2.5% RH and -5% RH when based on the results of this trial, for ambient conditions of 19°C and 20% RH.

6.3 The performance of the Mk 2/C MGT wet-bulb with tubular wick has not been shown to be affected in any systematic way by the methods of securing investigated.

6.4 The results of this trial support the recommendation by WMO for a lower value ($0.62 \times 10^{-3}K^{-1}$ instead of $0.67 \times 10^{-3}K^{-1}$) of psychrometric coefficient for the Assman psychrometer. This conclusion itself may have ramifications for the value of psychrometric coefficient applied to a wet- and dry-bulb system in an unventilated Stevenson screen.

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INSTRUMENTAL ACCURACY

1. ERTs

The ERT - Mk 1 DTI combination was carefully calibrated in a water-ice mixture, and in a stirred water bath against a certificated Inspector's thermometer. The accuracy of the ERT measurements can be estimated as $\pm 0.05^{\circ}C$ because although the resolution of the indicator is $0.1^{\circ}C$, it can be arranged to calibrate at an intermediate temperature with the indicator flipping between two values. Thus $0^{\circ}C$ can be set quite accurately because the indicator flips between $+0^{\circ}C$ and $-0^{\circ}C$. The indicator was initially set up using a substitution resistance for $0^{\circ}C$ and $99.5^{\circ}C$ and then adjusted for a calibration of the sensors in a water/ice mixture at $0^{\circ}C$. The calibration in stirred water was carried out at ambient temperature and in all cases no adjustment was required to give agreement with the Inspector's thermometer.

2. Inspector's Thermometer

This instrument had a correction certificate from Met O 16c Test Room conferring an accuracy of $\pm 0.025^{\circ}C$.

3. Dew-point Hygrometer

This instrument has a certificate for the system measuring the mirror temperature from the US National Bureau of Standards. The manufacturer claims an accuracy of $\pm 0.15^{\circ}C$ for dew-point measurements. Below $20^{\circ}C$, dew-point is given with a resolution of $0.01^{\circ}C$. The analogue output from the sensor was monitored on a chart recorder so that a mean value could be obtained.

4. Pitot-static Sensor

The pitot-static probe was connected to a precision manometer having a nominal resolution of 0.001 in $H_{2}0$. Because the relationship between dynamic pressure and air velocity is non-linear, the accuracy of velocity measurements is best expressed in tabular form as below.

Velocity (ms^{-1})	Dynamic Pressure (in $H_{2}O$)	Estimated Accuracy of Velocity Measurement (ms^{-1})
0.6	0.001	$\pm 0.15\ ms^{-1}$
0.9	0.002	$\pm 0.15\ ms^{-1}$
1.1	0.003	$\pm 0.1\ ms^{-1}$
1.3	0.004	$+ 0.1\ ms^{-1}$
1.44	0.005	$\pm 0.08\ ms^{-1}$
1.6	0.006	$\pm 0.08\ ms^{-1}$

The accuracy of effective ventilation rate values using measurements is dependent upon the control of the air flow. The measurements made by the pitot-static probe are only representative of the ventilation rate for essentially laminar, axial flow. Any deviation from axial flow due to large scale eddies could result in quite misleading measurements with the pitot-static probe. On the other hand small scale turbulence can be tolerated provided the flow is predominantly axial. It is thus difficult to estimate an uncertainty for measurements of ventilation rate.

5. Atmospheric Pressure

The PAB used had a calibration certificate conferring an accuracy of ±0.2 mb.

ACCURACY OF DERIVED PSYCHROMETRIC COEFFICIENT (A)

1. The absolute error in A can be approximated (Clarke (2)) to

$$\delta A = \frac{\sqrt{(\delta W \beta_W)^2 + (\delta D \beta_D)^2}}{P(T-W)} \quad \text{.......... B.1}$$

where W, P, T are as given for equation (1) in section 1.

δW, δD are the instrumental uncertainties in the measurements of W, D

$$\beta_W = \frac{d}{dT} e_s(W)$$

and $\beta_D = \frac{d}{dT} e_s(D)$

2. Using Hooper's polynomial with Sargent's coefficients (8)

$$e_s(T) = \exp(a + bT + cT^2 + dT^3 + eT^4 + fT^5 + gT^6) \quad \text{.......... B.2}$$

$$\therefore \beta_T = \frac{d}{dT} s(T) = (b + 2cT + 3dT^2 + 4eT^3 + 5fT^4 + 6gT^5)\, e_s(T) \quad \text{.......... B.3}$$

with b = $7.266296315 \times 10^{-2}$, c = $-2.996403370 \times 10^{-4}$

d = $1.160464233 \times 10^{-6}$, e = $-4.606513971 \times 10^{-9}$

f = $2.315159066 \times 10^{-11}$, g = $-1.103513358 \times 10^{-13}$

3. After Annex A, substituting

$\delta W = 0.05°C$ $\delta D = 0.15°C$ $W = 11°C$ $D = 3°C$ into B.3 yields

$\beta_W = 0.87$ mb K^{-1}

$\beta_D = 0.54$ mb K^{-1}

and further substition into B.1 with $T = 19°C$, $P = 1000$ mb

$\delta A = 0.012 \times 10^{-3}$ mb K^{-1}

ie relative error in A is about 2% for typical wind tunnel conditions and the instrumental uncertainties given at Annex A.

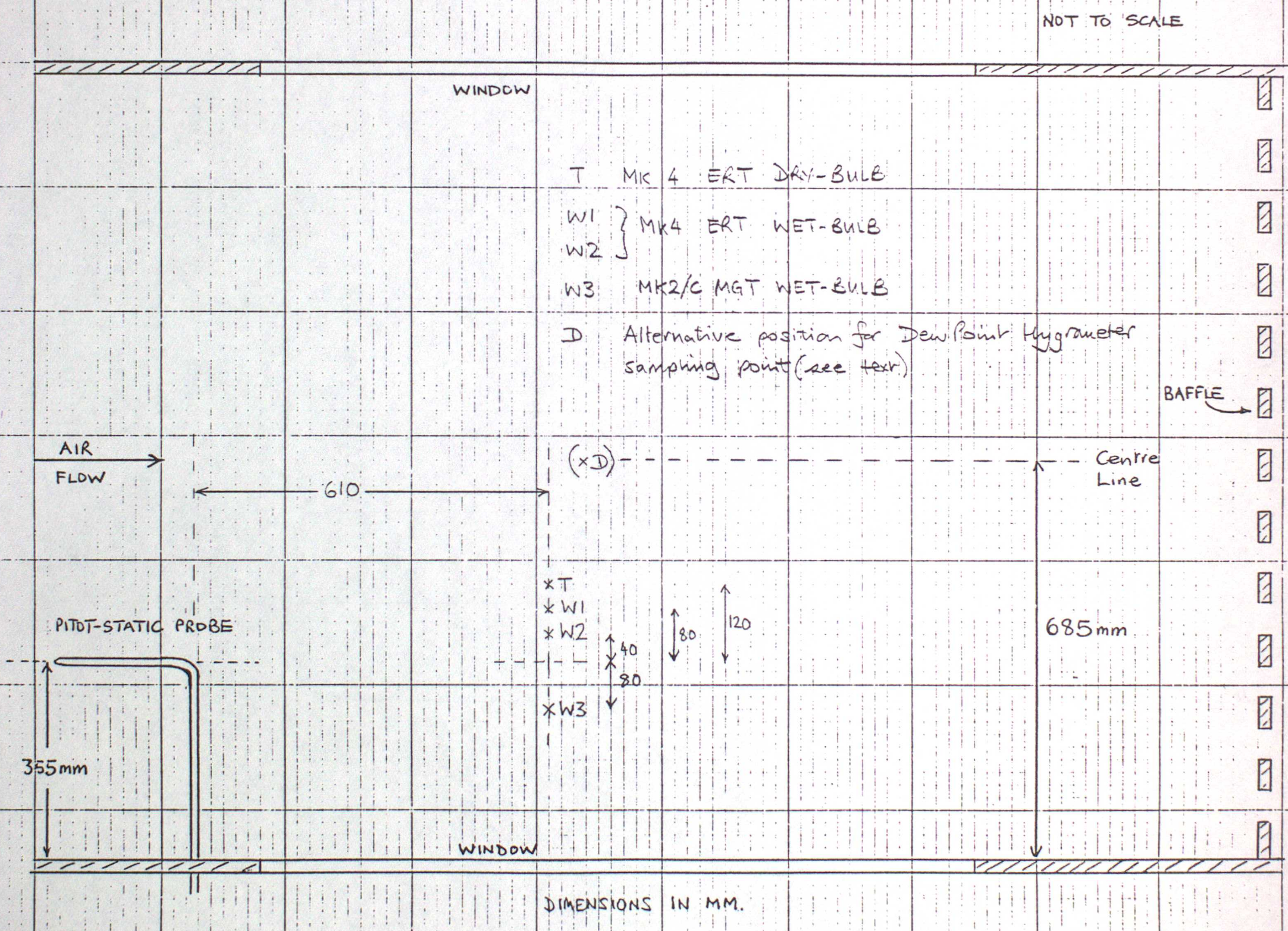
ANNEX C

Experimental Layout

Fig C.1 shows that experimental layout in the wind-tunnel experimental volume. Initially a sampling tube for the DPH was used, with its inlet at point D. Experiment indicated that the DPH sampling could as well be done at the mouth of the wind-tunnel, where the air velocity is low, and the instrument seemed to be more stable when used in that way.

The MGT thermometers were necessarily positioned near the observation window, and were read using a magnifying lens and a light to illuminate the scales at the observation time.
The holes in the baffle were of 67 mm diameter at a spacing of 85 mm between centres.

FIG C.1 EXPERIMENTAL LAYOUT



ANNEX D

INSTRUMENTAL ERROR FOR ASSMANN PSYCHROMETER

RH %	T=10°C, %RH ERROR DUE TO ε(T-TW)	ε(A)	ε(P)
25	± 0.8	-2.8	± 1.1
50	± 0.9	-1.8	± 0.7
75	± 1.1	-0.8	± 0.3
90	± 1.1	-0.4	± 0.25

RH %	T=20°C, %RH ERROR DUE TO ε(T-TW)	ε(A)	ε(P)
25	± 0.5	-2.1	± 0.8
50	± 0.7	-1.2	± 0.5
75	± 0.8	-0.6	± 0.2
90	± 0.8	-0.2	± 0.1

for ε(A) = 0.05K-1 x 10^{-3} (Tables assume 0.667K^{-1} x 10^{-3})

ε(T-TW) = 0.1°C (Error of +0.05°C dry, -0.05°C wet)

ε(P) = 30mb (Tables assume p=1000 mb)

True RH = Measured RH - Error
True T = Measured T - Error

TABLE 1: WET-BULB DEPARTURE (ΔW) AS A FUNCTION OF
ACTUAL PSYCHROMETRIC COEFFICIENT (A)
AND ITS CONSEQUENCES FOR HUMIDITY CALCULATIONS
USING AN ASSUMED VALUE FOR A

THE VALUES GIVEN BELOW ARE CALCULATED FOR AN AIR TEMPERATURE OF 21.5 C AND RELATIVE HUMIDITY 58% WITH P = 1000.0 MB AND A = 0.799E-03 K

THUS DEW-POINT TEMPERATURE (D) = 12.8 C
WET-BULB TEMPERATURE (W) = 16.5 C
SVP AT WET-BULB TEMP (E)= 18.8 MB

A ($K^{-1} \times 10^{-3}$)	ΔW (°C)	ΔE (MB)	ΔD (°C)	ΔRH (%)
0.624	-0.5	-0.6	-1.0	-3.7
0.649	-0.4	-0.5	-0.9	-3.2
0.674	-0.3	-0.4	-0.7	-2.6
0.699	-0.3	-0.3	-0.6	-2.1
0.724	-0.2	-0.2	-0.4	-1.5
0.749	-0.1	-0.2	-0.3	-1.0
0.774	-0.1	-0.1	-0.1	-0.5
0.799	0.0	0.0	0.0	0.0
0.824	0.1	0.1	0.1	0.5
0.849	0.1	0.1	0.2	0.9
0.874	0.2	0.2	0.4	1.4
0.899	0.2	0.3	0.5	1.8
0.924	0.3	0.4	0.6	2.3
0.949	0.3	0.4	0.7	2.7
0.974	0.4	0.5	0.8	3.1

Measured (X) = True (X) + ΔX

TABLE 2 : WET-BULB DEPARTURE (ΔW) AS A FUNCTION OF ACTUAL PSYCHROMETRIC COEFFICIENT (A) AND ITS CONSEQUENCES FOR HUMIDITY CALCULATIONS WHEN USING AN ASSUMED VALUE FOR A

THE VALUES GIVEN BELOW ARE CALCULATED FOR AN AIR

TEMPERATURE OF 19.0°C AND RELATIVE HUMIDITY 35%

THUS DEW-POINT TEMPERATURE (D) = 3.0 °C
WET-BULB TEMPERATURE (W) = 11.5 °C
SVP AT WET-BULB TEMP (E) = 13.6 MB

FOR ASSUMED VALUE OF A = 0.799E-03 K . AND P = 1000.0 MB

A	ΔW (°C)	ΔE (MB)	ΔD (°C)	ΔRH (%)
0.624	-0.9	-0.8	-3.0	-6.6
0.649	-0.7	-0.6	-2.5	-5.6
0.674	-0.6	-0.5	-2.0	-4.6
0.699	-0.5	-0.4	-1.6	-3.7
0.724	-0.3	-0.3	-1.1	-2.7
0.749	-0.2	-0.2	-0.7	-1.8
0.774	-0.1	-0.1	-0.4	-0.9
0.799	0.0	0.0	-0.0	-0.0
0.824	0.1	0.1	0.3	0.8
0.849	0.2	0.2	0.7	1.6
0.874	0.3	0.3	1.0	2.4
0.899	0.4	0.4	1.3	3.2
0.924	0.5	0.5	1.5	4.0
0.949	0.6	0.6	1.8	4.7
0.974	0.7	0.6	2.1	5.4

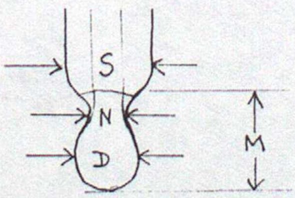
MEASURED(X)=TRUE(X)+ΔX

TABLE 3: DIMENSIONS OF A SAMPLE OF MK 2/C MGTs

	Serial No	S	N	D	M
(X)	76312/69	12.7	6.2	9.6	14.8
	78115/69	13.1	5.0	10.2	17.0
	78907/69	12.8	4.4	10.2	17.0
	95197/77	13.2	5.4	10.0	14.6
	96323/77	13.2	5.2	10.1	14.6
	98127/79	12.7	5.2	9.9	15.3
	98351/80	12.9	4.4	9.9	16.0
(C)	98857/80	13.4	6.0	10.0	14.7
	98863/80	13.5	6.6	10.3	13.7
(C)	1200/82	12.7	6.5	10.2	13.0
	Mean	13.0	5.5	10.0	15.1
	RMS Dev.	0.29	0.76	0.20	1.2
	BS 692 Tolerance	14.00 (max)	5.0–6.5 *	8.5–11.0	–

* BS 692 specifies stem diameter

Key:



(X) Denotes experimental wet-bulb thermometer (see text).

(C) Denotes control wet-bulb thermometer.

All dimensions in mm.

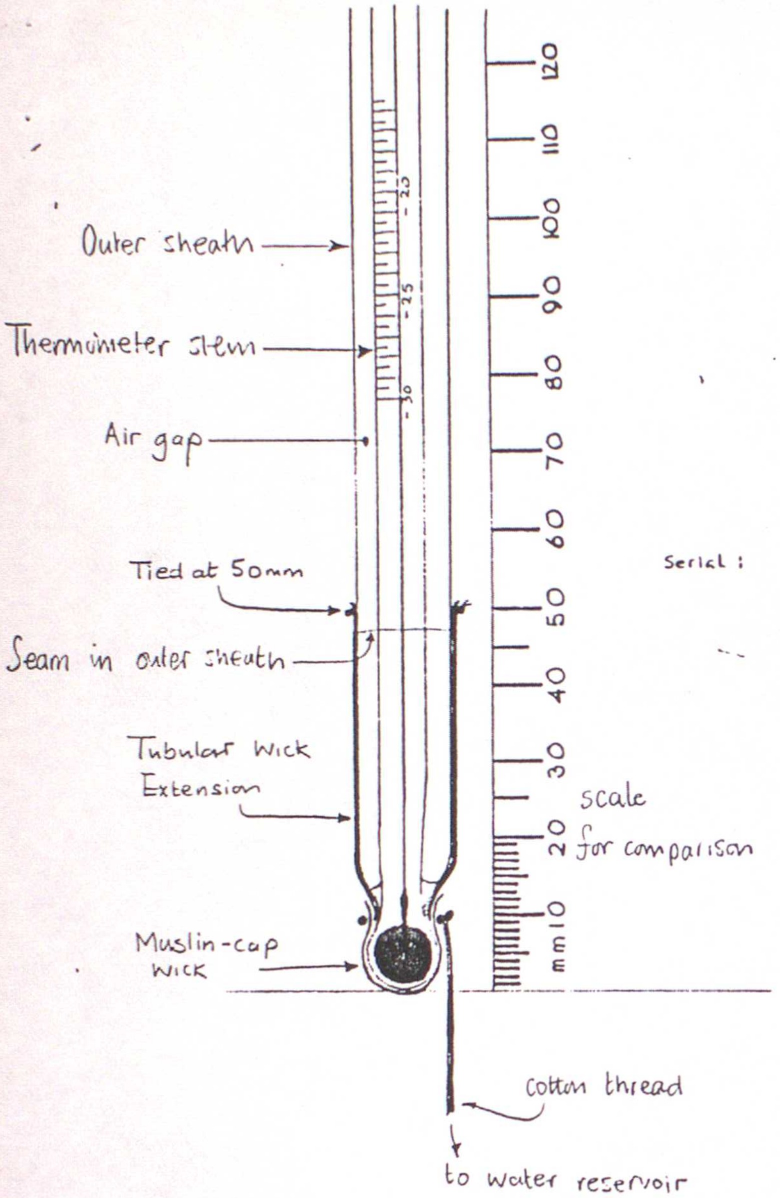


Fig 1a: Mk 2/C Ordinary Mercury-in-Glass Thermometer showing muslin-cap and tubular wick-extension as described in Scientific Paper 38.

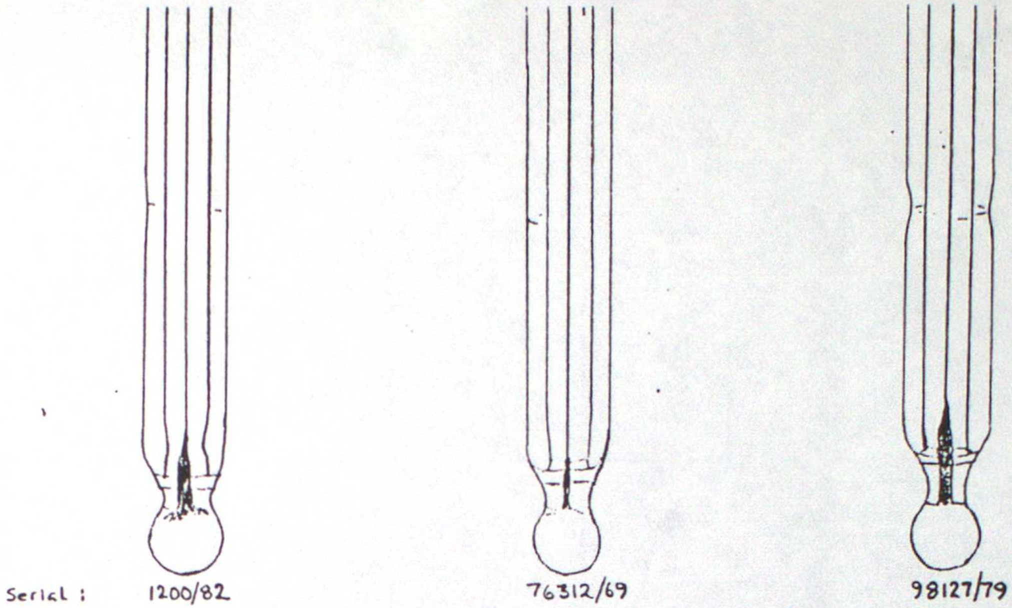


FIG 1c : Comparison of Mk2/C Thermometer Bulbs

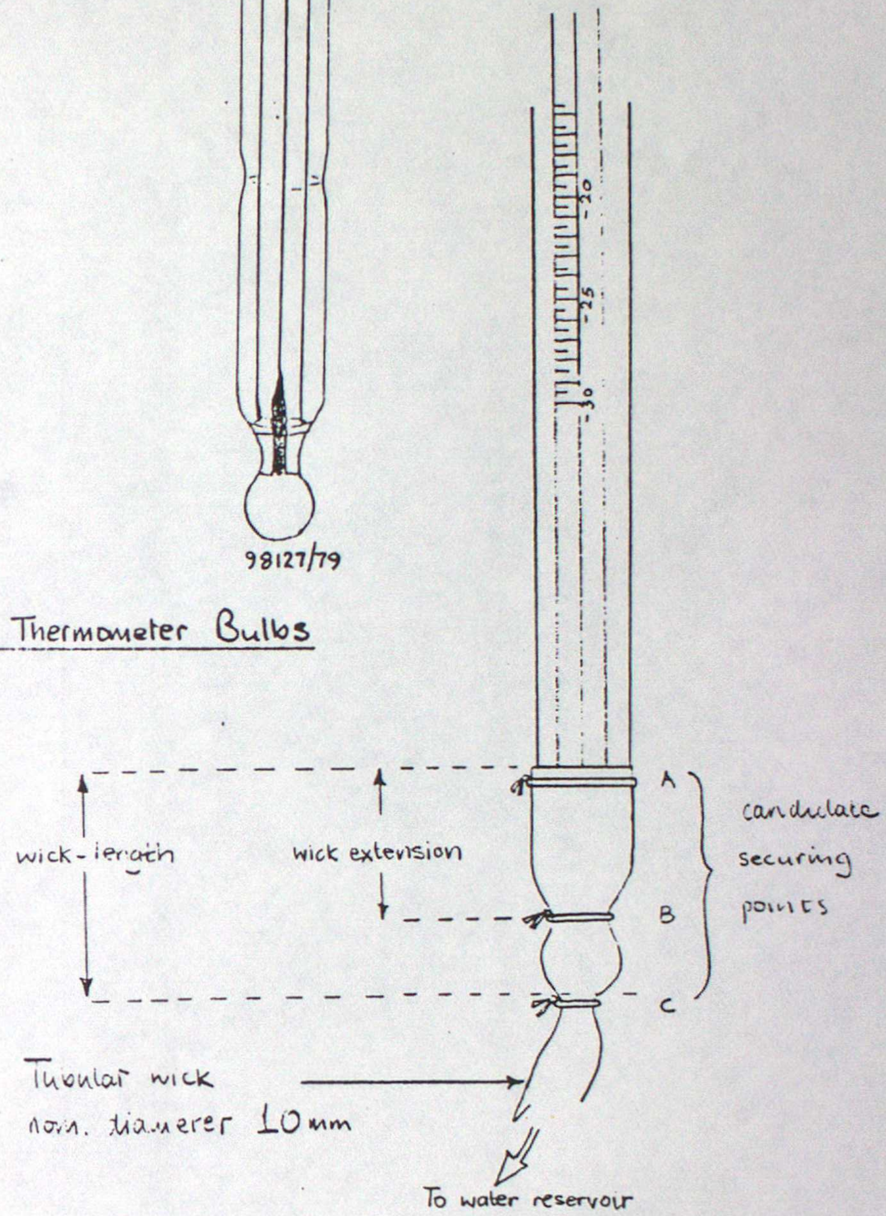


Fig 1b : Mk2/C Ordinary MGT Wet-bulb using tubular wick, showing possible securing points

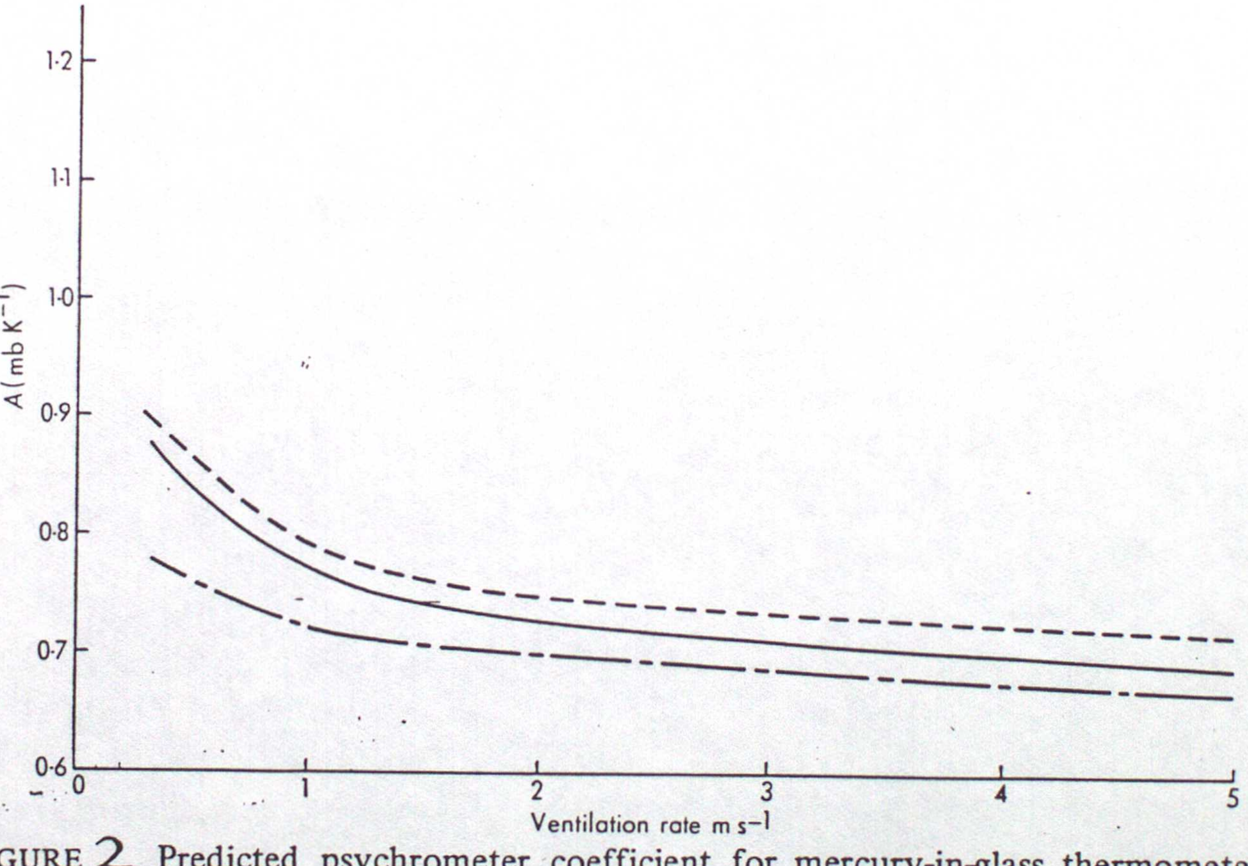


FIGURE 2 Predicted psychrometer coefficient for mercury-in-glass thermometer with long wick, $\overline{T + T_w} = 18°C$

Solid lines denote predicted values; dashed lines denote experimental values; dots and dashes indicate values based on Wylie's corrections for predicted values. From Folland, Sci Paper 38

FIG 3: PSYCHROMETRIC COEFFICIENT (A) vs. VENTILATION FOR CONTROL WET-BULB THERMOMETERS

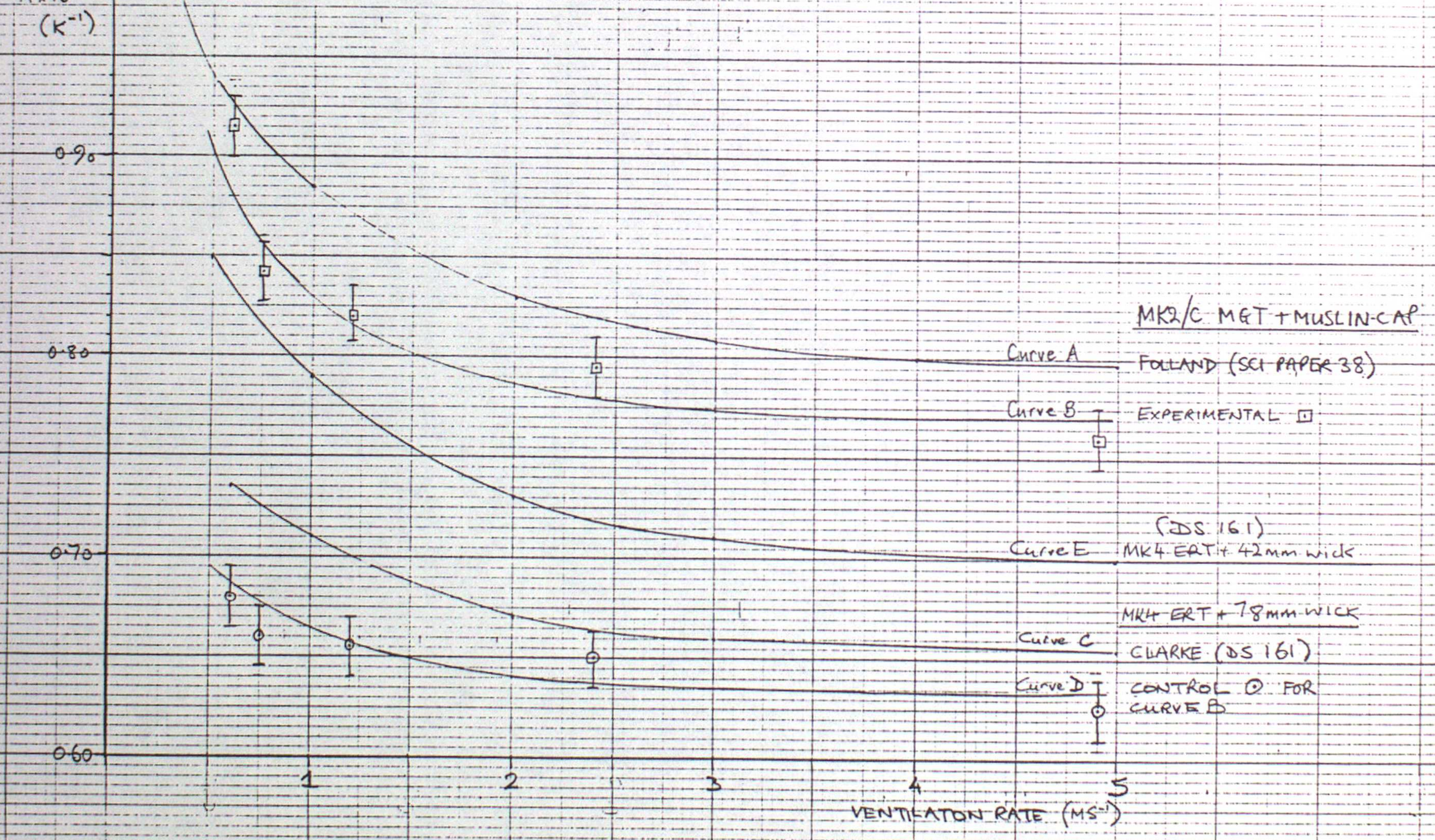


FIG 4: RMS Deviation of Psychrometric Coefficient

Derived for MK4 ERT control wet bulb (7.8mm wick)
using precision DPH as a reference

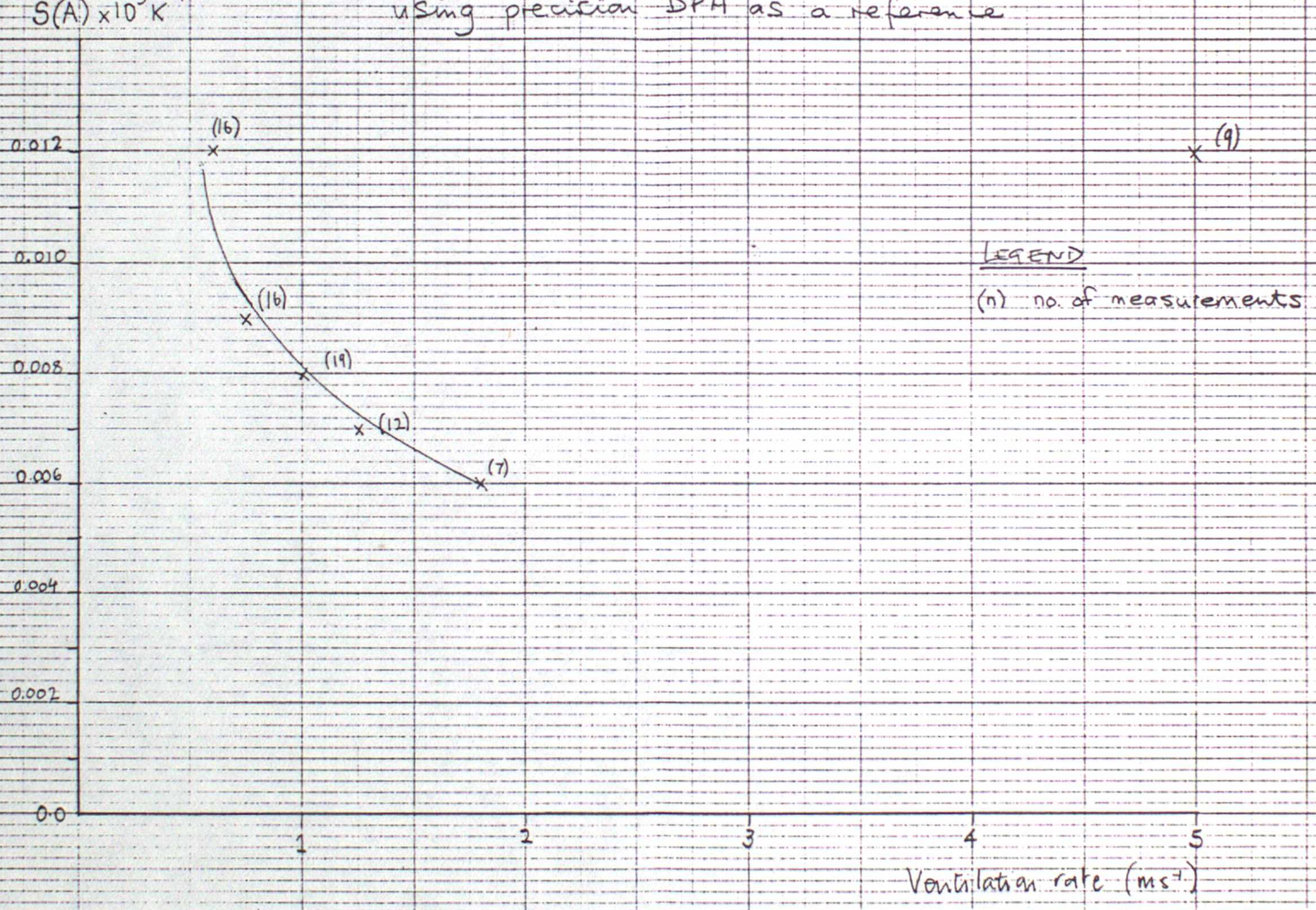


FIG 5

RESPONSE OF REFERENCE WET-BULBS TO CHANGE IN TEMPERATURE AND DEW-POINT FOR CONSTANT AIR-FLOW OF 1 MS^{-1}

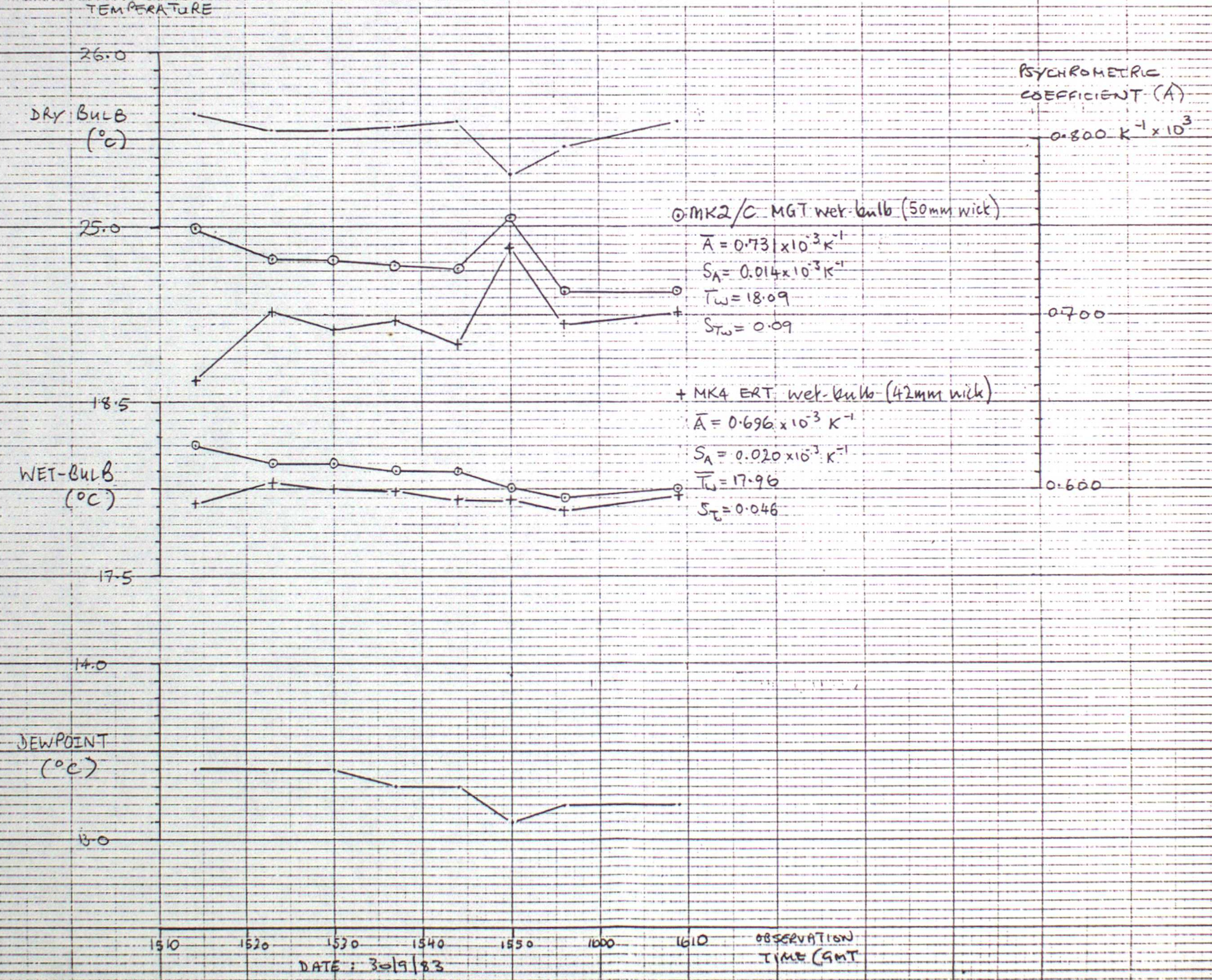


FIG 6

COMPARISON OF EXPERIMENTAL WET-BULB (MK2/C MGT WITH WICK LENGTH VARIED) WITH MK4 ERT WET-BULB (42 mm wick) FOR AIR-FLOW RATE OF 1 ms^{-1}

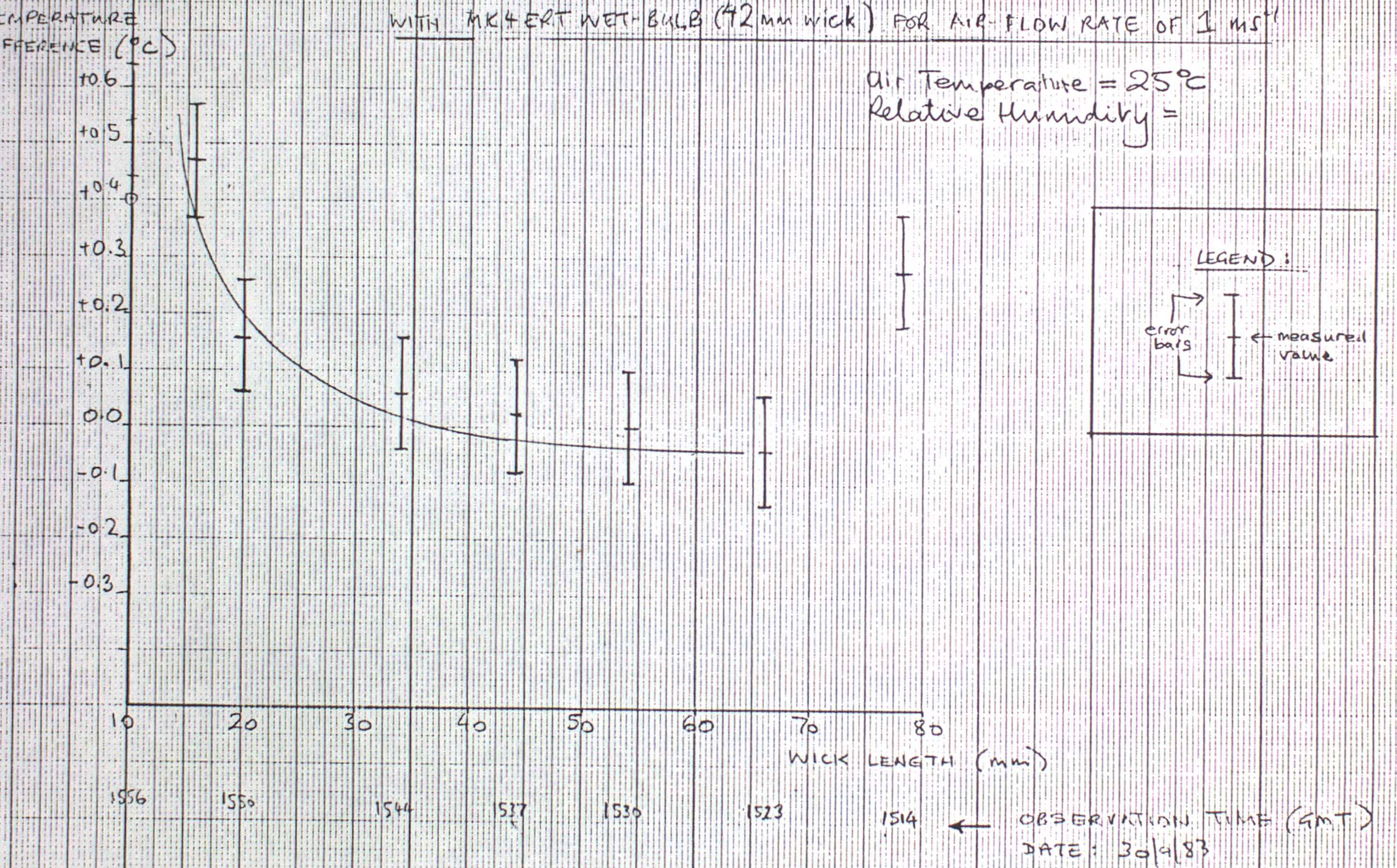


FIG 7 : PSYCHROMETRIC COEFFICIENT (A) VS WICK-LENGTH FOR MK2/C MGT WET-BULB, T=25°C RH=48%

AT A VENTILATION RATE OF 1 MS⁻¹

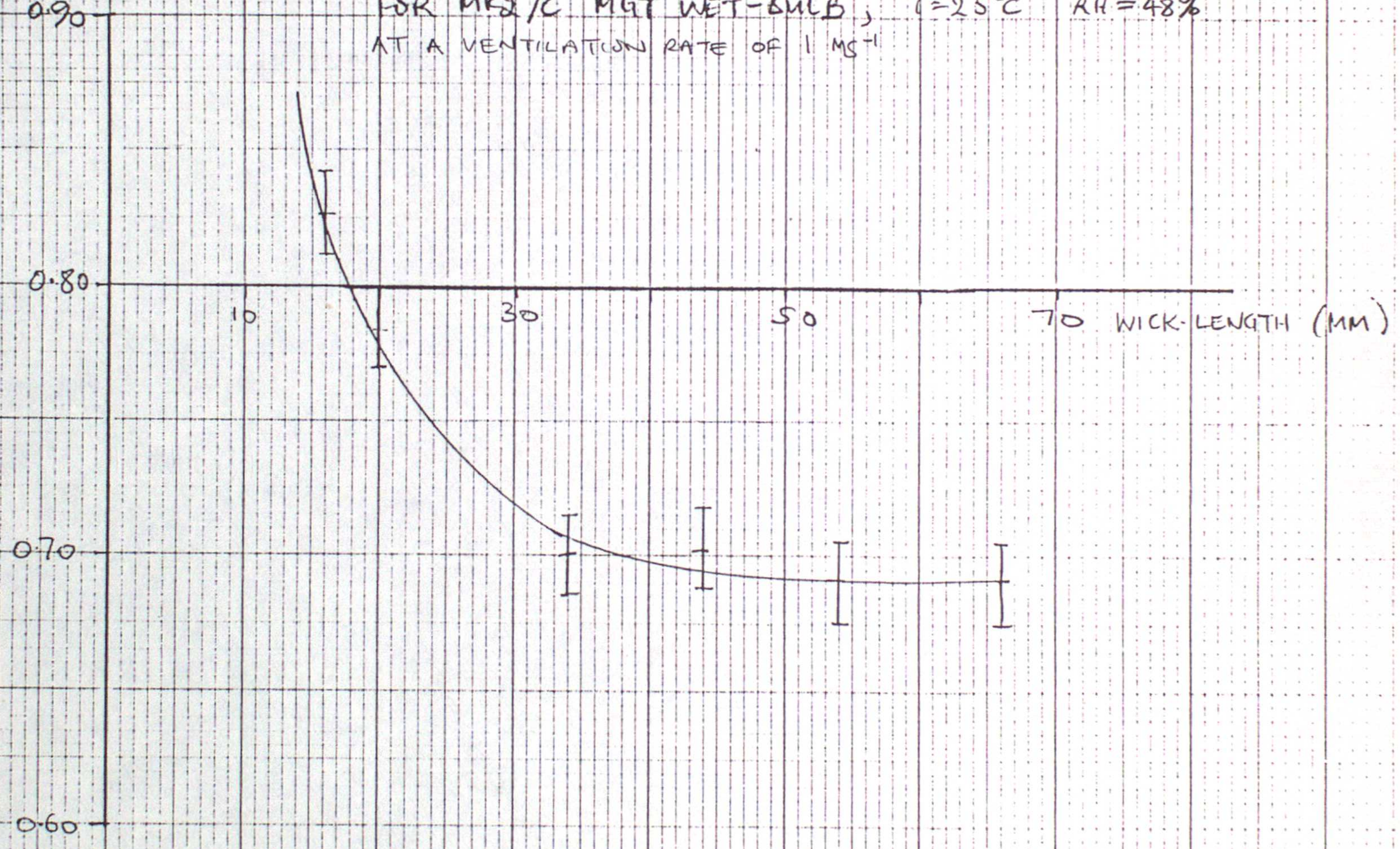
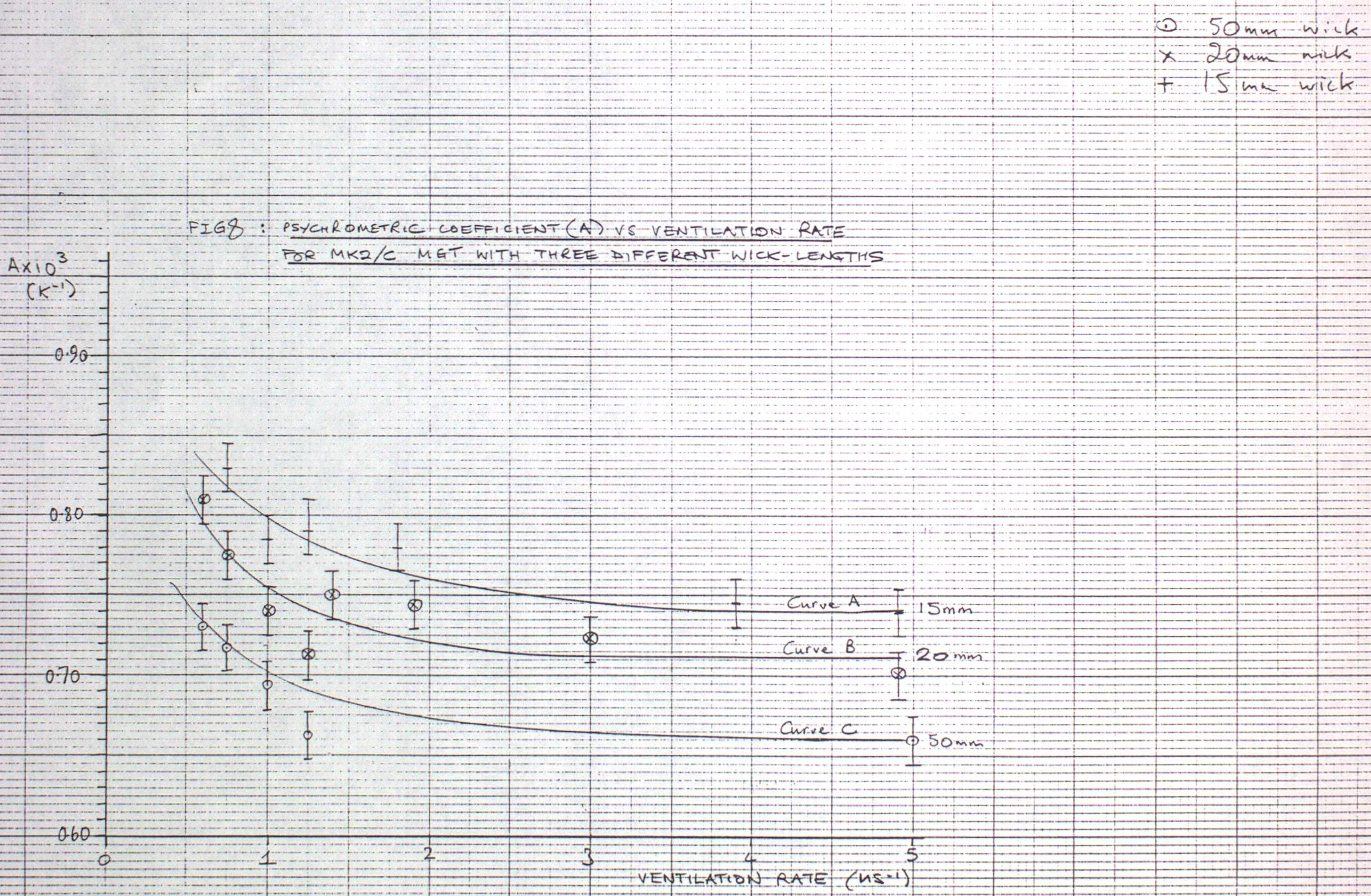


FIG 8 : PSYCHROMETRIC COEFFICIENT (A) VS VENTILATION RATE FOR MK2/C MET WITH THREE DIFFERENT WICK-LENGTHS



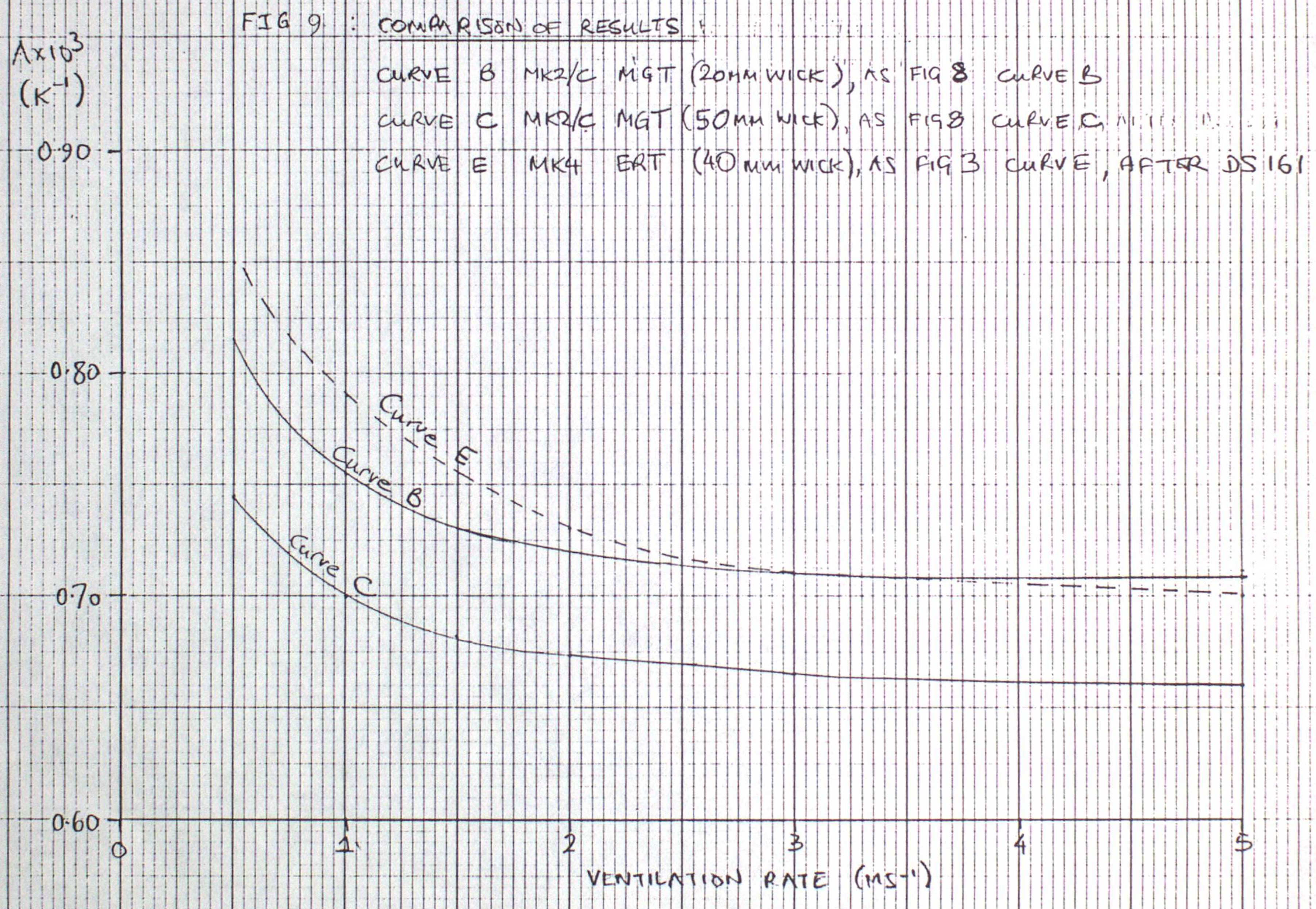


FIG 9 : COMPARISON OF RESULTS
CURVE B MK2/C MGT (20MM WICK), AS FIG 8 CURVE B
CURVE C MK2/C MGT (50MM WICK), AS FIG 8 CURVE C
CURVE E MK4 ERT (40MM WICK), AS FIG 3 CURVE, AFTER DS 161
A x 10^3 (K^-1)
0.90
0.80
0.70
0.60
0
1
2
3
4
5
VENTILATION RATE (MS^-1)
Curve E
Curve B
Curve C

FIG 10 : ERROR IN DERIVED HUMIDITY VS. RELATIVE HUMIDITY
FOR MK4 ERT WET-BULB (40mm WICK), T= 19°C
based on equivalence with Fig 9 Curve E, after DS161

Error = Computed RH - Actual RH

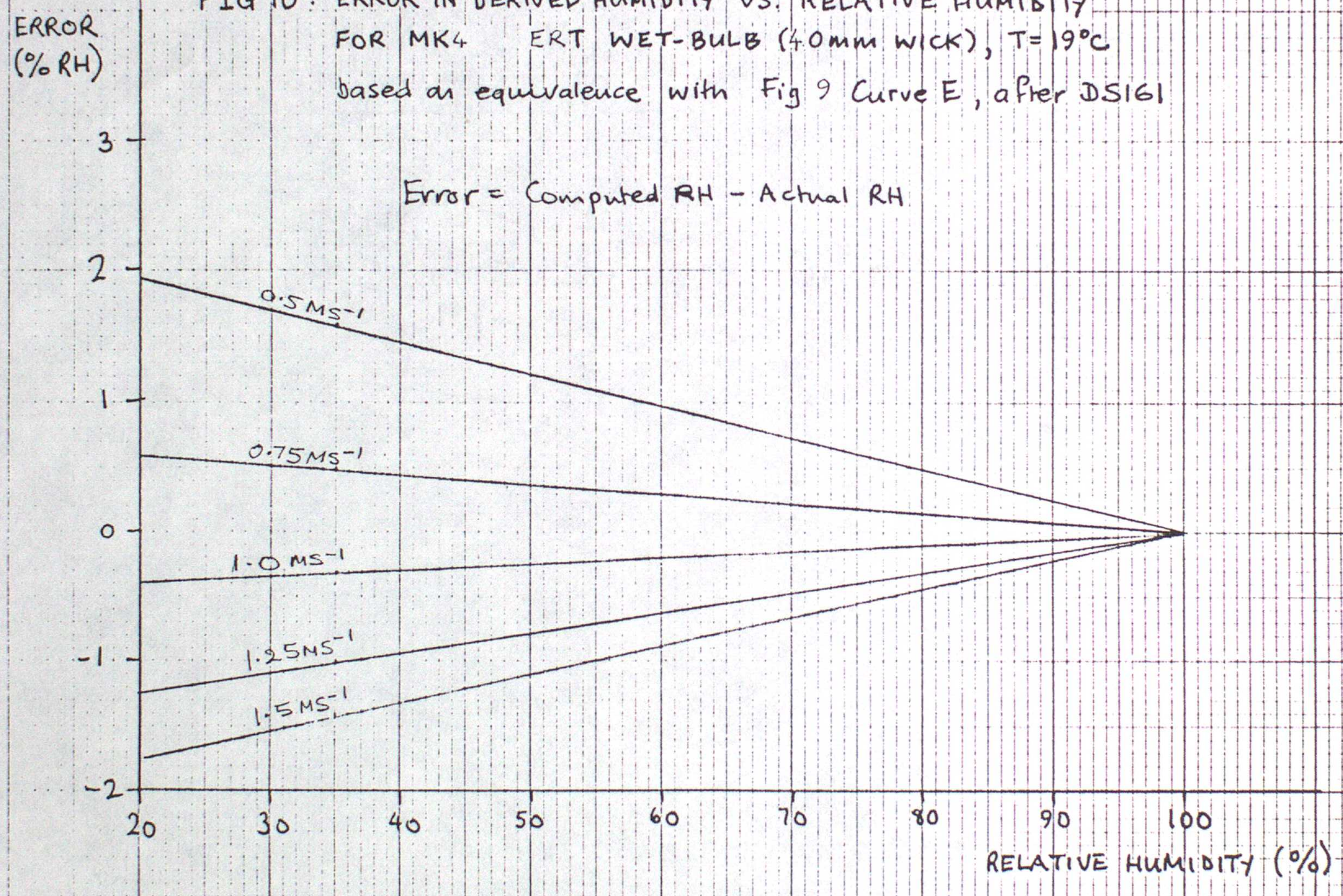
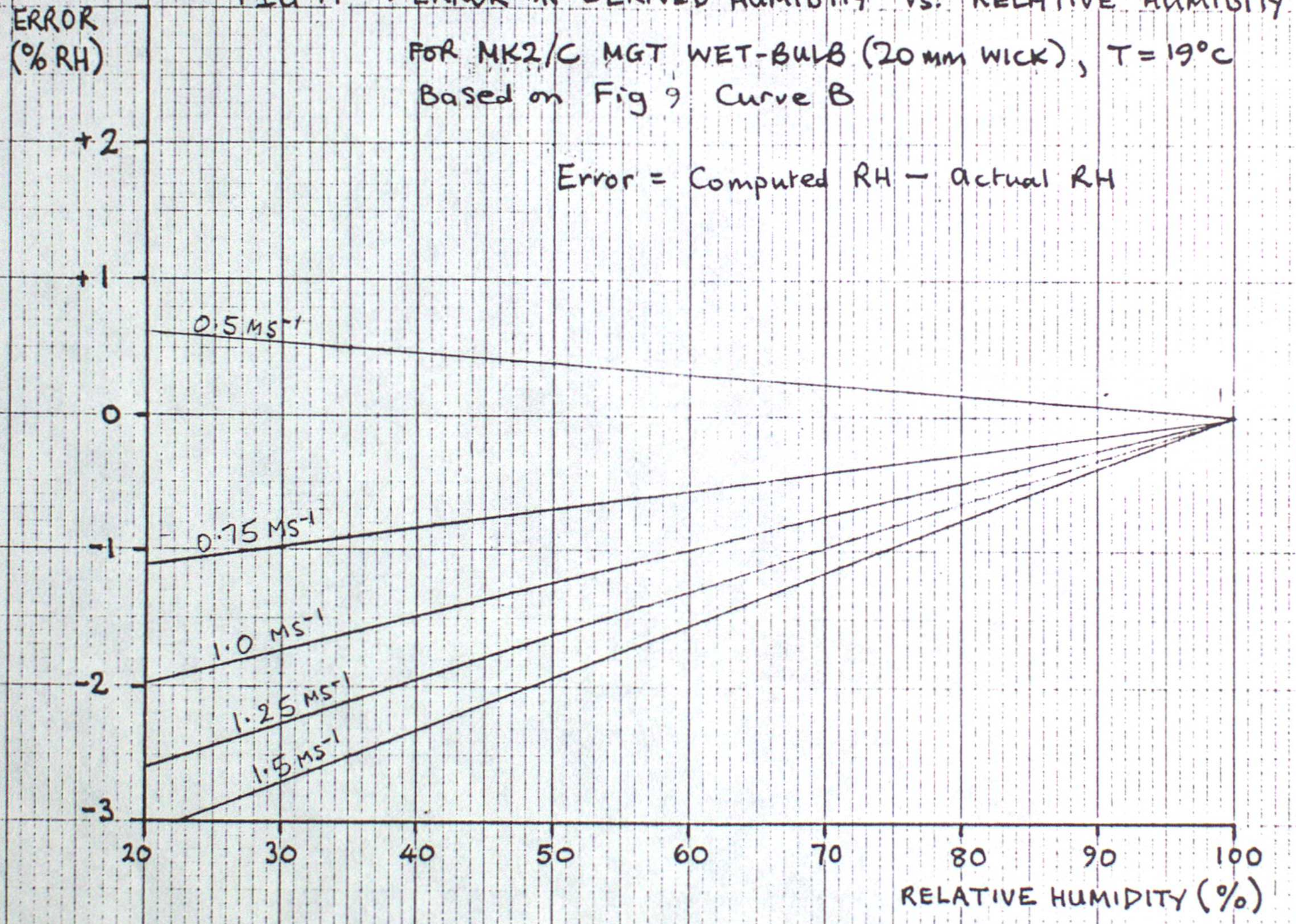


FIG 11 : ERROR IN DERIVED HUMIDITY VS. RELATIVE HUMIDITY

FOR MK2/C MGT WET-BULB (20 mm WICK), T = 19°C

Based on Fig 9 Curve B



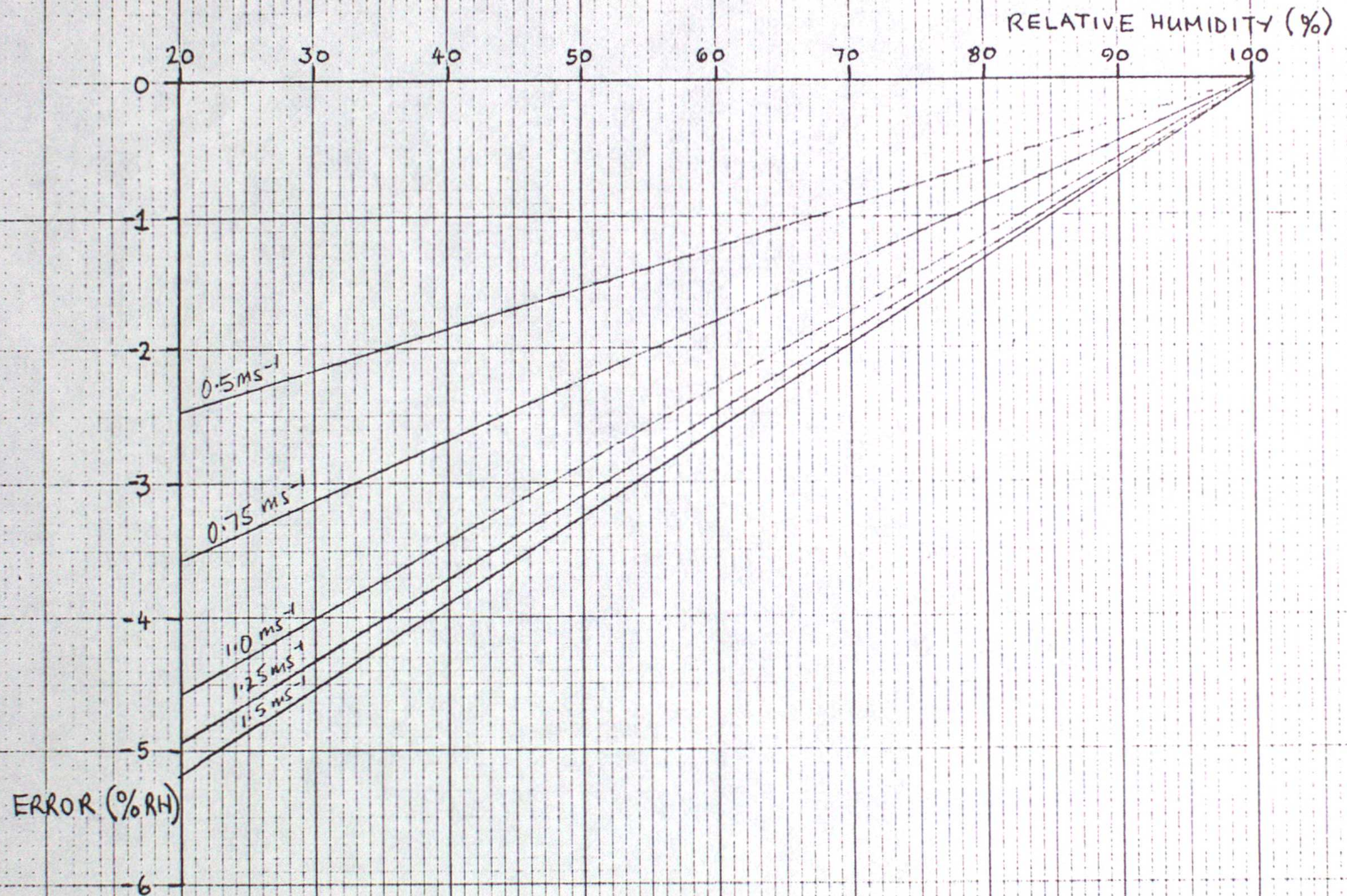


FIG 12 : ERROR IN DERIVED HUMIDITY VS. RELATIVE HUMIDITY
FOR MK2/C MGT WET-BULB (50mm WICK), T= 19°C
Based on Fig 9 Curve C

FIG 13: ERROR IN DERIVED HUMIDITY VS. VENTILATION RATE FOR MK2/C MGT WET-BULB AT 35°RH AND T=19°C

based on the corresponding curves of Fig 9

Error = Computed RH — Actual RH