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THE EFFECTS OF ATMOSPHERIC HUMIDITY AND TEMPERATURE ON THE ENGINE POWER AND TAKE-OFF PERFORMANCE OF A HASTINGS I

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F O R E W O R D

The purpose of ICAO Circulars is to distribute information bearing upon the progress of ICAO's work more widely than would be possible for the ordinary series of documents.

The present circular publishes a national study on two of the important parameters affecting the performance of aeroplanes, namely the humidity and the temperature of the air. The effect of temperature on performance has already been the subject of one special ICAO meeting, and the effects of atmospheric humidity and temperature will be discussed again, together with other parameters affecting performance, at future meetings.

The report reproduced in this circular records work done in the United Kingdom. It was presented to ICAO by the Government of the United Kingdom with the suggestion that it might be published as ICAO Circular.

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Report No. A.A.E.E./Res/248

AEROPLANE AND ARMAMENT EXPERIMENTAL ESTABLISHMENT BOSCOMBE DOWN

The effects of atmospheric humidity and temperature on the engine power and take-off performance of a Hastings 1

by G. Jackson, B.A., D.I.C.

SUMMARY

Flight tests have been made to assess the effect of changes in humidity on the engine power, fuel flow and take-off performance of a Hastings 1. The investigation also enabled the effect of changes in air temperature to be deduced.

It has been established that engine power decreases with increasing humidity and that the reduction is greatest at take-off engine speed and boost. Independent meteorological information suggests that the specific humidity will rarely exceed 2½ per cent. The investigation has shown that this degree of humidity causes a reduction in take-off power of approximately 10 per cent compared with operation in completely dry air at the same temperature. Two thirds of this reduction are accounted for by the displacement of dry air and the effective richening of the mixture; the remainder is attributed to the effect of humidity on the combustion process.

For 2½ per cent humidity the increase in take-off distance to clear a 50 foot screen is calculated to be 17 per cent.

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M.O.S. refs: (Res/Eng/7009/M508
(PDSR (A) Bi-monthly Item No. 4.2(d)

For the specification of take-off conditions, humidity is a parameter of the same order of importance as temperature.

At constant humidity the rate of decrease of power with increase of temperature is not significantly different from the value given by the standard formula below full throttle height.

No effect of humidity on fuel consumption has been detected. The rate of decrease of fuel consumption with increase of temperature is consistent with the assumption of constant indicated specific consumption except at take-off rating, when the decrease is greater than that corresponding to this assumption.

Report No. A.A.E.E./Res/248

AEROPLANE AND ARMAMENT EXPERIMENTAL ESTABLISHMENT BOSCOMBE DOWN

The effects of atmospheric humidity and temperature on the engine power and take-off performance of a Hastings 1

by G. Jackson, B.A., D.I.C.

1.- Introduction

During a meeting in 1947 arranged by the International Civil Aviation Organization[1], attention was drawn to the lack of information on the effect of atmospheric humidity on engine power and the consequent effect on take-off performance. The one modern flight investigation[2] on this subject, together with a report of the poor take-off performance of a Hastings aircraft under humid conditions[3], indicated that the effect was of sufficient magnitude to be of importance in assessing the permissible take-off weight of aircraft.

To obtain quantitative information on the effects of humidity, flight tests have been made on a Hastings aircraft in various climatic conditions.

2.- Description of aircraft

2.1 General. The tests were made on a production Hastings Mk.1, number TG.503, fitted with cranked exhaust tail pipes (Mod. No. P536). The air supply for both filtered and ram air was taken from the leading edge entries.

Take-off weight was 72,500 lb. and take-off flap setting 20°. Undercarriage and flaps were left down for the take-off climb. Take-off tests were made with the cooling gills one third open and with filtered air; other tests with gills closed and ram air. All the tests were made with the superchargers in M. gear.

2.2 Engine details and limitations. The aircraft had four Hercules 101 engines with Hobson R.A.E. injector carburettors. The port inner was changed in the course of the tests. Engine and injector numbers are given below.

		Port Outer	Port Inner		Stbd. Inner	Stbd. Outer
			First	Second		
Engine Number	Manufacturer's	H 137003	H 137014	H 137082	H 137103	H 137025
	A.M.	A 496079	A 496041	A 497306	A 494152	A 495887
Injector Type		BH 5/1	BH 5/1	BH 5/1	BH 5/1	BH 5
Injector Number		59564	DIN 1142	DIN 1719	Z 66674	Z 59724

The engine limitations at the time of the tests were as follows:

Rating	Engine Speed R.P.M.	Boost lb/sq.in.
Take-off (5 min. limit)	2800	+8¼
Climb	2400	+6
Continuous Cruise (Weak mixture)	2400	+2½

2.3 Propeller details. Fully feathering De Havilland metal propellers (Blade type XPB 41974) were fitted. The propeller numbers were:

Port Outer	4A 48530
Port Inner	4A 48511
Stbd. Inner	4A 48551
Stbd. Outer	4A 48557

2.4 __Instrumentation.__ The instruments were divided into two groups. Those whose readings were required at short intervals throughout each test were mounted in an automatic observer and photographed; the remaining instruments were read visually by two observers.

2.4.1 The following instruments were fitted in the automatic observer:

4 pressure gauges from Bristol oil-operated torque dynamometers (measuring the torque of each engine)

4 charge temperature thermometers (connected to ratiometer bulbs in the induction elbow of each engine)

4 air intake temperature thermometers (connected to ratiometer bulbs in the intake duct of each engine)

1 airspeed indicator

1 altimeter Mk. 14C

1 clock

2.4.2 The following instruments were read visually:

4 engine speed indicators

4 boost gauges

4 Kent-type flowmeters

4 fuel temperature thermometers (connected to ratiometer bulbs at the flowmeter inlet of each engine)

4 gill position indicators

1 airspeed indicator

1 altimeter Mk. 14C

1 Met. Office aircraft electrical psychrometer Mk. 1 (measuring wet and dry bulb temperatures)

1 balanced bridge thermometer, Met. Office type 2-2 with an A. & A.E.E. type element (measuring dry bulb temperature)

1 mercury capillary air thermometer Mk. 2 (measuring dry bulb temperature)

The thermometer elements were mounted under the fuselage roughly in line with the wing leading edge. Three air temperature thermometers were used to obtain an accurate assessment of the ambient temperature and to enable a defective instrument to be identified. The wet bulb temperature was checked against independent meteorological observations whenever possible.

Ground level measurements of wet and dry bulb temperatures were taken on a whirling psychrometer.

3.- Scope of tests

3.1 The test programme was planned to cover two types of test:

a) Measurement of take-off distance and power, and rate of climb immediately after take-off;

b) Measurement of power and fuel consumption of the inner engines with the aircraft flying at constant pressure height, using the outer engines to maintain a fixed indicated air speed.

3.2 The original intention was to compare the results of these tests made at Khartoum (Anglo-Egyptian Sudan) in a hot and dry climate and at Bahrein Island (Persian Gulf) in a humid climate with similar temperatures. Because atmospheric humidity does in general decrease with increasing altitude, the height at which the tests under (b) were to be made was the lowest height at which level speed tests were possible at both places. This was an ICAN pressure height of 2,000 feet. It became clear at an early stage in the tests that some modification of this programme would be necessary because at Khartoum the humidity was higher than had been anticipated. In addition, the humidity gradient above the Persian Gulf was so great that at 2,000 feet the humidity was less at Bahrein Island than at Khartoum. Consequently level flight tests were made in high humidity at a pressure height of 700 feet over the Persian Gulf and at a third site, Habbaniya (Iraq), where the lower altitude tests could be repeated in low humidity.

The measurements of power on test take-offs were augmented by observations made when taking off for transit flights.

3.3 An important aspect of the programme was the planning of the tests to show up any systematic changes in engine performance which might occur and thereby mask comparatively small changes with humidity.

This was achieved by including several check tests under conditions in which the only variable to have changed by an appreciable amount was time. For this reason, and to establish the effect of temperature changes, tests were made in England, both before and after the overseas trials. These tests also provided data at intermediate humidities.

4.- Method of analysis of results

4.1 General. All the instrument readings have been corrected for instrument error.

4.2 Air Temperature and humidity. It was assumed that for each thermometer the relation between the indicated and actual temperatures was of the form

$$T_i = T_a + k\left(\frac{V}{100}\right)^2$$

where T_i = indicated temperature (°K)
T_a = actual temperature (°K)
V = true airspeed (m.p.h.)

k is a constant which was found experimentally for each thermometer installation.

It can be shown that engine power is a function of absolute, and not relative, humidity. From the several parameters used to define humidity[4] the specific humidity (or "moisture content") has been chosen as suitable. It is defined as the ratio by weight of water vapour to damp air in a particular volume of damp air and the percentage value calculated from the formula

$$q = \frac{1.6455}{2.6455\frac{p}{e} - 1} \times 100$$

where q = specific humidity
p = total atmospheric pressure
and e = water vapour pressure

e is a function[5] of the wet and dry bulb temperatures.

4.3 Power variation. Measurements of the take-off power of all engines were obtained during take-offs from the various airfields visited. The power of the two inner engines was also measured in level flight at 240 m.p.h. A.S.I. at the two nominal ICAN pressure heights of 700 feet and 2,000 feet for each of the three limiting engine conditions listed in Paragraph 2.2. Small deviations from the nominal values of engine speed and boost pressure occurred because the maximum boost and engine speed settings varied slightly from engine to engine and because precise repetition of engine control settings was not always possible within a fairly short time. Changes in airfield height caused small changes in engine power and, in level flight at the low altitudes at which many of the tests were made, it was not always possible to maintain the exact pressure height specified.

Because these deviations could have systematic effects the measured powers have been adjusted to the values corresponding to the mean engine speed, boost and pressure height for each engine in each condition. Mean values were chosen so as to minimize the corrections. The corrections were obtained from bench tests by the Bristol Aeroplane Company on this type of engine. Corrections involved were small; three observations were adjusted by 2 per cent of the brake horse power, most by less than 1 per cent.

The power variation of each engine with temperature and humidity is assumed to be represented by an equation of the form

$$P = a + bt + cq \qquad \text{.................(1)}$$

where t = air temperature (°C)
q = specific humidity (%)
P = engine power at (t, q)
a, b and c are constant coefficients and the best values of a, b and c have been found in each case by the method of least squares.

A typical set of results (measurements made on the starboard outer engine at take-off) has been examined by fitting the best quadratic relation by the method of least squares. There is no significant reduction in the scatter of the experimental points and the accuracy of the test results does not appear to justify the assumption that engine power is dependent on powers of temperature and humidity higher than the first.

The mean fractional rates of change of power $\frac{1}{P_M}\frac{\partial P}{\partial t}$ and $\frac{1}{P_M}\frac{\partial P}{\partial q}$, where P_M is the engine power at the mean temperature and humidity of the tests, follow since

$$\frac{\partial P}{\partial t} = b \quad \text{and} \quad \frac{\partial P}{\partial q} = c.$$

The best[6] combined estimate for each group of results at a particular power setting is the mean with the separate values weighted in proportion to the reciprocals of their variances.

It is convenient for the discussion of the final rates of variation to quote them in terms of P_o, the mean power at zero humidity and the mean test temperature. The mean values of $\frac{1}{P_o} \frac{\partial P}{\partial t}$ and $\frac{1}{P_o} \frac{\partial P}{\partial q}$ have therefore been obtained from the above derivatives by multiplying the factor

$$\frac{P_M}{P_o} = \frac{1}{1 - \frac{1}{P_M} \frac{\partial P}{\partial q} \times q_m}$$

where q_m is the mean humidity of the tests.

4.4 Variation of take-off distances. For convenience in analysis, the take-off distance from the start of the run to a height of 50 feet above the unstick point has been divided into three parts. These parts are:

1) Ground run measures from start to unstick. The unstick speed for the aircraft as tested is approximately 115 m.p.h.;

2) Transition distance measured from the end of the ground run to the point at which the aircraft begins to climb away from the runway;

3) Climbing distance, which is the horizontal distance travelled whilst climbing to 50 feet above the unstick point at a constant speed (140 m.p.h. E.A.S.).

The three parts are treated separately.

4.4.1 Ground run. The measured values of the ground run are for the same reasons as given in Paragraph 4.3 subject to variations in addition to those caused by temperature and humidity. The corrections necessary to eliminate these variations have been applied by using the relation given in Appendix I [equation (7)].

Corrections have also been applied to give the results appropriate to zero headwing and zero runway gradient. No allowance has been made for the effect of the difference in runway surfaces or for the change of an engine (see Paragraph 6.4).

The effect of small variations in unstick speed has been eliminated by using the measured distance to 115 m.p.h. E.A.S.

We may assume that the ground run is linearly related to temperature and humidity

$$\text{i.e.} \quad S_G = d + et + f_q \qquad \dots\dots\dots\dots\dots\dots (2)$$

where S_G = ground run at (t,q).

The best values of the three constants d, e and f consistent with the experimental results have been calculated by the method of least squares and the values of $\frac{1}{S_{Go}} \frac{\partial S_G}{\partial t}$ and $\frac{1}{S_{Go}} \frac{\partial S_G}{\partial q}$ obtained.

S_{Go} is the ground run at the mean temperature and humidity of the tests.

4.4.2 Transition distance. The apparatus used for measuring take-off distances generally ceased to function before the climb was begun so that no accurate measure of the transition distance and its variation has been obtained. Probable values of the rate of variation are obtained below (Paragraph 6.4).

4.4.3 Climbing distance. The climbing distance has been investigated indirectly by measuring the rate of climb immediately after take-off. The mean true rate of climb was obtained from altimeter readings taken at 10-second intervals during a climb through 1,500 feet. Corrections have been made on the basis of equation (10) of Appendix I to give the rate of climb appropriate to a mean ICAN pressure height of 1,250 feet and the mean values of engine speed and boost.

The statistically best coefficients of an assumed linear relation between rate of climb, temperature and humidity have been calculated. It is shown in Appendix I, Section B, that the variation of the climbing distance can be expressed in terms of the variation of rate of climb.

4.5 Variation of fuel consumption. Fuel consumption was measured on the inner engines during the level flight tests. Each value quoted in the report is the mean of at least five observations. Measured volumetric rates of flow have been converted to mass flow, on which the engine behaviour depends, using the following standard A. & A.E.E. expression for the specific gravity of the fuel.

$$S.G. = 0.7421 - 0.00097 \times (\text{fuel temperature } ^{o}C)$$

The suitability of this relation was confirmed by making several measurements of the temperature-density relation for the fuel used.

Fuel consumptions have been corrected to the appropriate mean values of boost, engine speed and height assuming the indicated specific fuel consumption to remain constant for the small changes of power involved.

It is shown below that fuel consumption is not dependent on humidity. The results on each engine at each height have been analyzed by the method of least squares to give the constants g and h in the linear relation

$$Q = g + ht$$

where Q = mass fuel consumption at temperature t.

Mean values of $\frac{1}{Q_o}\frac{dQ}{dt}$ have been obtained. Q_o is the fuel consumption at the mean temperature of the tests.

5.- Results

5.1 General. The test results are tabulated at the end of the report. For the take-off tests, where the largest of the corrections described in Paragraph 4 are applied, the results are quoted both before and after correction. Corrected values only are given for the level flight tests.

5.2 Deterioration check. The change of one engine in the middle of the tests makes it impossible to obtain conclusive deterioration checks on this engine and its replacement. Furthermore, power was measured on all the engines, but fuel flow on the inner engines only, so that only one engine (the starboard inner) can be examined for consistency of fuel flow. The checks made show no evidence of deterioration. The behaviour of all the engines is similar in the final analysis and all the results have therefore been included. Details of the deterioration checks are given below.

5.2.1 Check on power. Power measurements at take-off provide the best checks for all but the port inner engines. A typical set of observation is shown in Figure 2; the other engines give similar results. In this and other figures open and solid symbols of the same shape correspond to tests made on first and second visits to a particular airfield. Comparison of these results shows that the original and repeated measurements are in good agreement. Additional checks can be made for the starboard inner engine from the level flight results, comparing tests at 700 feet at Bahrein before and after visiting Habbaniya (Figure 1) and at 2,000 feet at Boscombe Down at the beginning and end of the programme. There is no check on the first port inner; a partial check for the second port inner is the comparison of the take-off powers for the two visits to Habbaniya.

5.2.2 Check on fuel consumption. Checks for consistency of fuel consumption were obtained for the starboard inner engine from the level flight tests. At 2,000 feet tests were made at Boscombe Down at the beginning and end of the tests; at 700 feet tests were made at Bahrein both before and after visiting Habbaniya. Comparison of these results shows a good consistency. Figures 3 and 4 are typical illustrations of the results obtained.

5.3 Engine power. Two of the sets of power measurements are illustrated in Figure 1 and Figure 2 with their calculated best fitting lines. No significant difference has been measured between the derivatives for different engines and different heights and the figures illustrate typical results. The analysis is summarized in Table 6. The best estimates and 95 per cent limits of accuracy of the rates of variation of power are given below as proportions of the power P_o at the mean temperature ($28\frac{1}{2}^o$) and zero humidity for each engine condition.

Power Condition	$\frac{1}{P_o} \frac{\partial P}{\partial t}$	$\frac{1}{P_o} \frac{\partial P}{\partial q}$
Take-off	-0.00221 ±0.00066	-0.0391 ±0.0069
Climb	-0.00246 ±0.00086	-0.0297 ±0.0218
Maximum Continuous Cruise	-0.00248 ±0.00082	-0.0184 ±0.0236

The relationships between the reduction in brake horse power and the specific humidity, together with the experimental limits of accuracy, are shown by the full lines in Figure 7.

5.4 Take-off distance.

5.4.1 Ground run. The experimental results are illustrated in Figure 5. The best values of the rates of change of the ground run and their 95 per cent limits of accuracy are

$$\frac{1}{S_{G_o}} \frac{\partial S_G}{\partial t} = +0.00573 \pm 0.00867$$

$$\frac{1}{S_{G_o}} \frac{\partial S_G}{\partial q} = +0.1203 \pm 0.1125$$

5.4.2 Take-off rate of climb. The experimental rates of climb are illustrated in Figure 6. The best estimates of the variation of rate of climb and their 95 per cent limits of accuracy are

$$\frac{1}{V_{C_o}} \frac{\partial V_C}{\partial t} = -0.00564 \pm 0.01134$$

$$\frac{1}{V_{C_o}} \frac{\partial V_C}{\partial q} = +0.0121 \pm 0.1386$$

It will be seen that the random variation of ground run and rate of climb overwhelm any systematic effects of temperature and humidity.

5.5 Fuel consumption. Two sets of test results are illustrated in Figures 3 and 4. The scatter of the observations is typical of the results from the various engines and conditions, and there is no indication of any systematic variation of fuel consumption with humidity. The several values of the coefficient $\frac{1}{Q_o} \frac{dQ}{dt}$ and their 95 per cent limits of accuracy are given in Table 7.

6.- Discussion

6.1 Practical range of humidity. Because the sources of water vapour are at the earth's surface and because the capacity of air for water vapour decreases with decreasing temperature, the specific humidity of the atmosphere generally decreases rapidly with increasing height. At normal cruising altitudes humidity is so low that any effects on the aircraft are negligible; thus it is necessary to consider only surface conditions.

On the basis of information (Appendix III) supplied by the Meteorological Office it appears that the specific humidity of the atmosphere will very rarely exceed 2½ per cent. The upper limit to the change in humidity when moving at any time from any one place to any other on the earth's surface can therefore be taken as 2½ per cent. This estimate is conservative since the humidity will rarely, if ever, be zero. Mean humidities and standard deviations vary considerably from place to place and from time to time*. In the British Isles, for example, the humidity is usually in the range ¼ per cent to 1½ per cent, so that when moving from the British Isles the increase in humidity will rarely be more than 2¼ per cent.

6.2 Variation of power with humidity at constant temperature.

6.2.1 It may be seen from Figure 7 that the decrease of power is greatest at the take-off rating. The measured decrease of climbing power, although smaller, is still significant; the decrease in cruising power has not been established as significantly different from zero. The discussion which follows is restricted to the measured changes in take-off power since humidity effects are of most importance for this rating.

6.2.2 For the maximum humidity given above, the reduction in take-off power is 9.8 per cent ±1.9 per cent of the power in dry air. The difference between the humidity of the British Isles and the world-wide maximum could cause a power reduction of 8.8 per cent ±1.6 per cent. A power reduction of 8.8 per cent corresponds to a temperature rise of 40°C, below full throttle height, so that it is possible for humidity changes to be equal in importance with changes in temperature. It must, however, be emphasized that large changes in humidity are encountered much less frequently than large changes in temperature. High values of absolute humidity occur only in the lower levels of the atmosphere, in areas of comparatively small extent and in certain seasons of the year (Figures 9 and 10) whereas high temperatures exist for long periods over wide areas.

6.2.3 Considering conditions with the British Isles, the humidity variation (Paragraph 6.1) will cause variations in take-off power of up to approximately 5 per cent at a given temperature. This maximum power variation would be caused by a temperature change of 23°C and since the actual temperature range is of this order corrections for humidity and temperature are of the same order of importance.

6.2.4 The experimental results give only a measure of the overall reduction in power for the type of engine tested. We may assess the generality of the results by considering separately some of the effects which would be

* Variations in humidity are often related with variations in temperature.

expected. First, the presence of water vapour necessitates the displacement of dry air and indicated horse power depends on the dry air consumption. When dry air consumption is the only variable, indicated power is directly proportional to dry air pressure. Consequently power would be expected to be less in humid air than in dry air by the same proportion for any reciprocating engine. The loss in power is generally referred to as the displacement loss. Secondly, for the particular carburation system tested, the fuel flow has been shown (Paragraph 5.5) to be unaffected by changes in humidity. Hence as humidity increases and the proportion of dry air in the total flow to the engine decreases, so the dry-air/fuel ratio decreases. When air/fuel ratio is the only variable the effect of a change in air/fuel ratio depends on the shape of and operating point on the consumption loop for the engine. Richening of the mixture causes a power loss when running at a richer and an increase at a weaker mixture than that for maximum power. The magnitude of the power change due to this richening effect may be expected to vary for different engine types and carburation systems.

The magnitudes of these two effects on the engines tested are discussed in Appendix II and compared with the mean experimental values in Figure 7 and in the following table. It will be seen that the measured effect is only partly accounted for in this way; the difference is given in the final column of the table.

Power Condition	$\left(\frac{1}{P_o}\frac{\partial P}{\partial q}\right)$ %			
	Experimental	Displacement	Richening	Residual
Take-off	-3.91	-2.10	-0.51	-1.30
Max. Climb	-2.96	-2.01	-0.28	-0.67
Maximum Continuous Cruise	-1.83	-2.07	+0.36	-0.12

Only at take-off power is the residual loss significantly different from zero (see Figure 7). In this case it amounts to 50 per cent of the sum of the displacement and richening losses. This additional loss has been observed in previous tests[2] and ascribed to a decrease in thermal efficiency caused by the presence of water vapour during the combustion process. Such a loss would be expected to vary with air/fuel ratio but the evidence obtained on this variation is not significant. It is also probable that the residual loss would vary for different engines (and possibly for different installations) because of the different pressures and temperatures within the engines.

6.3 Variation of power with temperature at constant humidity. The mean rates of change of power with temperature are not significantly different from the value of -0.00257 given by the standard formula for an engine operating below full throttle height

$$\frac{1}{P}\frac{\partial P}{\partial t} = -\frac{1.1}{400 + t} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

at the temperature $28\frac{1}{2}°C$.

6.4 Variation of take-off distance. The limits of accuracy of the measurements of ground run and take-off rate of climb are very wide. It is a common experience to find that take-off distances and speeds are subject to large random variations, particularly in the tropics where high temperatures often produce disturbed conditions at and near ground level. In examining the results, no allowance has been made for the change of an engine or for the variability of the runway coefficient of friction. The effect of the first factor is small (0.4 per cent decrease in total power) and insufficient data is available to make accurate allowance for the second. Brief descriptions of the runway surfaces are given in Table 9.

Because of the wide limits of the direct measurements the rates of change of take-off distance with temperature and humidity have also been derived indirectly from the measured changes of take-off power using the relations deduced in Appendix I. The derived values are given below. The limits represent the 95 per cent limits of accuracy of the measured power changes.

	$\frac{1}{S_o}\frac{\partial S}{\partial t}$	$\frac{1}{S_o}\frac{\partial S}{\partial q}$
Ground run	+0.00829 ±0.00083	+0.0594 ±0.0087
Transition distance	+0.00845 ±0.00094	+0.0652 ±0.0098
Climbing distance	+0.00802 ±0.00154	+0.0967 ±0.0161

These values do not differ significantly from the experimental results and probably give better estimates of the mean rates of change. Accepting these values and taking a typical test take-off as having ground run, transition distance and climbing distance in the proportions* 3:6:1, the total increase of take-off distance to clear 50 feet would be 16.6 per cent ±2.5 per cent as the humidity rose from zero to 2.5 per cent. The increase in distance varies but little with variation in the proportions of the three parts of the take-off; the more usual proportions 2:1:1 would lead to an increase 17.5 per cent ±2.7 per cent.

An increase in temperature by 15°C would increase the take-off distance by a further 12.4 per cent ±1.4 per cent.

The full lines drawn in Figure 5 and Figure 6 are fitted about the mean experimental values at the mean slopes deduced from the power changes. The broken lines indicate saturation at each particular temperature. The fact that some points lie beyond this line means no more than that the scatter of distance and rate of climb measurements is large.

6.5 Variation of fuel consumption. Under the conditions of constant boost, pressure height and engine speed in which fuel consumption was measured, the fuel flow delivered by the Hobson - R.A.E. injectors would not be expected to vary with humidity. No variation has been detected.

The carburation system is designed to maintain a constant indicated specific consumption. The fuel consumption should therefore vary according to the relation

$$\frac{1}{Q}\frac{\partial Q}{\partial t} = \frac{1}{IHP - s/c\ HP}\frac{\partial P}{\partial t}$$

where IHP = indicated horse power,
s/c HP = supercharger horse power
and it is assumed that s/c HP $\propto$ IHP.

Using the powers tabulated in Appendix II, Section A, the design variations of fuel consumption for the measured power changes have been calculated and are compared with the experimental values in the following table.

*The transition distance, defined in Paragraph 4.4, is long because the climbing speed chosen (140 m.p.h.) is high compared with the unstick speed (115 m.p.h.). The proportions are based on a small number of approximate measurements of transition distance.

Power Condition	$\frac{1}{Q_0} \frac{\partial Q}{\partial t}$	
	Design	Experimental
Take-off	-0.00189 ±0.00056	-0.00378 ±0.00026
Climb	-0.00213 ±0.00074	-0.00306 ±0.00054
Maximum Continuous Cruise	-0.00208 ±0.00069	-0.00240 ±0.00060

The two values are significantly different only at take-off engine speed and boost, when the experimental variation is numerically the larger.

It may be noted that the standard formula for a temperature compensated carburettor at constant boost,

$$\frac{1}{Q} \frac{dQ}{dt} = - \frac{1}{400 + t},$$

gives the value -0.00234 at 28½°C. Numerically, this is significantly smaller than the experimental values at both take-off and climb ratings, but not significantly different from the experimental value in the cruise condition, for which it is mainly used.

7.- Conclusions

7.1 It has been established that brake horse power decreases with increasing humidity and that the greatest fractional rate of decrease is at take-off power. As the specific humidity increases at constant temperature from zero to the maximum probable value of 2½ per cent, the take-off power of the engines tested decreased by approximately 10 per cent. This reduction is approximately 50 per cent greater than the sum of the displacement and richening losses.

7.2 The rate of decrease of cruising power with increasing humidity at constant temperature has not been established as significantly different from zero. Any decrease would generally be unimportant since humidity is low at normal cruising altitudes.

7.3 For 2½ per cent humidity, the increase in take-off distance to clear a 50 foot screen corresponding to the measured decrease in power is approximately 17 per cent at constant temperature.

7.4 The rate of change of power with temperature alone is not significantly different from the standard value.

7.5 Both the extreme range of humidity and the variations within the British Isles are sufficiently large for the effects on take-off power and performance to be as important as the effects expected from changes in temperature.

7.6 No effect of humidity on fuel consumption has been observed. At constant humidity the measured effect of temperature on fuel consumption may be represented by the design condition of constant indicated specific fuel consumption except at take-off power, when the rate of decrease would be underestimated.

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APPENDIX I

VARIATION OF TAKE-OFF DISTANCE WITH POWER AND AIR DENSITY

A. Take-off distance from start to climb-away

To find the variation of take-off distance with air density and engine power we may assume that the acceleration is constant during take-off. This approximation can be made for both the distance up to unstick and the distance between the unstick point and the start of the climb away. The acceleration has different values for the two stages.

Thus, assume $S \propto \frac{1}{\sigma a}$

where S = distance,

σ = relative density of air

and a = acceleration.

Then $$\frac{\sigma}{S}\frac{dS}{d\sigma} = -\frac{\sigma}{a}\frac{da}{d\sigma} - 1 \qquad \text{..........(1)}$$

Now $$a = \frac{T - D}{W}$$

where T = mean thrust,

D = mean drag

and W = aircraft weight.

Hence $$\frac{\sigma}{a}\frac{da}{d\sigma} = \frac{T}{T - D}\;\frac{\sigma}{T}\frac{dT}{d\sigma} \qquad \text{............(2)}$$

But $$TV_i = \eta P \sqrt{\sigma}$$

where V_i = mean equivalent airspeed (assumed constant),

η = airscrew efficiency

and P = engine power.

$$\therefore \frac{\sigma}{T}\frac{dT}{d\sigma} = \frac{\sigma}{\eta}\frac{d\eta}{d\sigma} + \frac{\sigma}{P}\frac{dP}{d\sigma} + \frac{1}{2} \qquad \text{............(3)}$$

Since η is a function of the airscrew parameters C_P and J ,

$$\frac{\sigma}{\eta}\frac{d\eta}{d\sigma} = \frac{C_P}{\eta}\frac{\partial\eta}{\partial C_P}\frac{\sigma}{C_P}\frac{dC_P}{d\sigma} + \frac{J}{\eta}\frac{\partial\eta}{\partial J}\frac{\sigma}{J}\frac{dJ}{d\sigma} \qquad \text{...........(4)}$$

From the definitions of C_P and J ,

$$\left.\begin{array}{l}\dfrac{\sigma}{C_P}\dfrac{dC_P}{d\sigma} = \dfrac{\sigma}{P}\dfrac{dP}{d\sigma} - 1 \\ \text{and } \dfrac{\sigma}{J}\dfrac{dJ}{d\sigma} = -\dfrac{1}{2} \text{ at constant } V_i\end{array}\right) \qquad \text{............(5)}$$

Combining equations (1) to (5),

$$\frac{\sigma}{S}\frac{dS}{d\sigma} = -1 + \frac{T}{T-D}\left[\frac{1}{2}\left(\frac{J}{\eta}\frac{\partial\eta}{\partial J} - 1\right) + \frac{C_P}{\eta}\frac{\partial\eta}{\partial C_P} - \frac{\sigma}{P}\frac{dP}{d\sigma}\left(1 + \frac{C_P}{\eta}\frac{\partial\eta}{\partial C_P}\right)\right] \quad \text{..(6)}$$

Substituting the appropriate numerical values (Table 8) in equation (6) and expressing σ in terms of pressure p, temperature t and percentage specific humidity q, we have for the ground run S_G between start and unstick

$$\frac{dS_G}{S_G} = -1.66\left[\frac{dp}{p} - \frac{dt}{t+273} - \frac{dq}{164.55}\right] - 1.26\frac{dP}{P} \qquad \text{...........(7)}$$

and for the transition distance S_T between unstick and the start of the climb

$$\frac{dS_T}{S_T} = -1.60\left[\frac{dp}{p} - \frac{dt}{t+273} - \frac{dq}{164.55}\right] - 1.42\frac{dP}{P} \qquad \text{...........(8)}$$

B. <u>Rate of climb and climbing distance</u>

For climbs at constant equivalent airspeed and weight, we have

$$V_C \propto \frac{T - D}{\sqrt{\sigma}}$$

where V_C = rate of climb,

σ = mean air density during climb

and T and D are the mean thrust and drag during the climb.

By a similar method to that used in Section A above, it can be shown that

$$\frac{\sigma}{V_C}\frac{dV_C}{d\sigma} = \left[\frac{1}{2}\frac{D}{T-D} - \frac{T}{T-D}\left(\frac{C_P}{\eta}\frac{\partial\eta}{\partial C_P} + \frac{1}{2}\frac{J}{\eta}\frac{\partial\eta}{\partial J}\right)\right] + \frac{T}{T-D}\left(1 + \frac{C_P}{\eta}\frac{\partial\eta}{\partial C_P}\right)\frac{\sigma}{P}\frac{dP}{d\sigma} \quad ..(9)$$

For the aircraft tested, this equation becomes

$$\frac{dV_C}{V_C} = 0.36\left[\frac{dp}{p} - \frac{dt}{t+273} - \frac{dq}{164.55}\right] + 2.34\ \frac{dP}{P} \quad ....(10)$$

The distance S_C covered in climbing through a fixed height interval at a fixed equivalent airspeed varies according to the relation

$$S_C \propto \frac{1}{V_C\sqrt{\sigma}}$$

Hence $$\frac{dS_C}{S_C} = -0.86\left[\frac{dp}{p} - \frac{dt}{t+273} - \frac{dq}{164.55}\right] - 2.34\ \frac{dP}{P} \quad ......(11)$$

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APPENDIX II

CALCULATION OF COMPONENT EFFECTS OF HUMIDITY ON ENGINE POWER

A.- Displacement Loss

Indicated horse power is proportional to dry air consumption if humidity alone is varying, dry-air/fuel ratio and thermal efficiency being assumed constant.

i.e. $$\frac{d(IHP)}{IHP_o} = -\frac{e}{p}$$

where e = water vapour pressure

p = total atmospheric pressure

and IHP_o = indicated horse power in dry air.

i.e. $$\frac{d(BHP)}{BHP_o} = -\frac{e}{p}\,\frac{IHP_o}{BHP_o}$$

$$= -\frac{2.6455}{\frac{164.55}{q} + 1}\,\frac{IHP_o}{BHP_o}$$

where q = specific humidity (per cent)

The mean ratio of indicated horse power to brake horse power for the engines tested is calculated as in the following table. Pumping losses are neglected.

Rating	BHP_o	Friction HP	Super-charger HP	HP for Accessories	IHP_o	IHP_o/BHP_o
Take-off	1485	230	227	22	1964	1.322
Max. Climb	1239	170	137	22	1568	1.267
Max. Continuous Cruise (Weak Mixture)	994	170	109	22	1295	1.305

The change in brake horse power can now be calculated for any value of humidity. Some results are given below.

The practical range of humidity is so small that the relation between power and humidity may be taken as linear.

Rating	% Decrease in BHP		
	q = 1%	q = 2%	q = 3%
Take-off	2.11	4.21	6.27
Max. Climb	2.02	4.03	6.00
Max. Continuous Cruise	2.08	4.15	6.19

B.- Effect of Variation in Mixture Strength

The ratio by weight of dry air to fuel is reduced by the factor $(1 - \frac{q}{100})$ when the specific humidity is q%.

The air/fuel ratio can be obtained from the measured values of power and fuel consumption by calculating first the indicated specific fuel consumption. The consumption loop for the engine type then gives directly the effect on IHP of a change in air/fuel ratio.

Some values for the engines tested are given below. The change in power is expressed in terms of the BHP at zero humidity as in Section A above.

Rating	% Change in BHP		
	q = 1%	q = 2%	q = 3%
Take-off	-0.51	-1.03	-1.54
Max. Climb	-0.28	-0.57	-0.85
Max. Continuous Cruise	+0.36	+0.72	+1.08

C.- Effect on Supercharger

Changes in total mass flow of air, water vapour and fuel through the engine and changes in density and specific heat of this mixture will cause small changes in supercharger performance and the driving power required. These effects are small and have been neglected in the analysis.

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APPENDIX III

NOTES ON THE DISTRIBUTION AND VARIATION OF ATMOSPHERIC HUMIDITY

Two charts showing the distribution of the average specific humidity (or moisture content) of the atmosphere in gm/gm. at mean sea level between 40°N and 40°S for January (Figure 9) and July (Figure 10) are reproduced in this report. High specific humidity is necessarily associated with high temperature (Figure 8) so that the highest values occur at the surface in hot climates.

Figures 9 and 10 have been constructed from charts of average vapour pressure at mean sea level by means of the formula

$$q = \frac{.622}{p - .378e} = \frac{1.6455}{2.6455\ p/e - 1} \qquad \text{............(1)}$$

where q is the specific humidity in gm/gm
p is the atmospheric pressure
e is the vapour pressure.

For the approximate values given on the chart it has been assumed that the atmospheric pressure at mean sea level is constant and equal to 1000 mb.

In compiling the original charts of vapour pressure the long-period averages of observed vapour pressure at station level were reduced to sea level by means of the empirical formula

$$e_h = e_o \ (1 - 0.000076h) \qquad \text{............(2)}$$

where e_h is the vapour pressure at station level
e_o is the vapour pressure at M.S.L.
h is the height of the station above M.S.L. in feet.

This formula is applicable only to averages and not to individual values.

To obtain the average specific humidity q_h at height h at any given place the value of q_o is read from the chart for the appropriate month, e_o is computed from equation (1) assuming that p = 1000 mb., e_h is then computed from equation (2) and q_h is obtained from equation (1) using this value of e_h and substituting the average station level pressure for p. If frequent computations are to be made tables of equivalent values of q_o and e_o can be compiled, from equation (1) and similarly values of e_h for different values of e_o and h.

The table overleaf gives the average vapour pressure and its standard deviation in each of the four seasons and hence shows the fluctuations likely to be experienced from day to day. A measure of the average variation during the day is given by the values of the diurnal range. The table refers to a few typical stations with high humidity.

The highest average vapour pressure shown in the table is 31.8 mb. at Bahrein in July with a standard deviation of 4.7 mb. If the distribution were normal then on one occasion in twenty the vapour pressure would be expected to exceed 41.0 mb., the corresponding specific humidity being 25.9 gm/kg. Thus since so high a humidity occurs only rarely and only within a limited area, a value of 25 gm/kg may be taken as a convenient figure for the maximum specific humidity.

The meteorological data discussed in this Appendix were provided by the Meteorological Office and are reproduced by permission of the Director.

VAPOUR PRESSURE AT SELECTED TROPICAL STATIONS

Averages at the afternoon hour of observation for January, April, July and October and their standard deviations; also the diurnal ranges

Station	Position		Height feet	Time of observation (Zone Time)	Standard Deviation				Average vapour pressure AT STATION LEVEL				Period	Diurnal Range				Period
	Latitude	Longitude			JAN.	APR.	JULY	OCT.	JAN.	APR.	JULY	OCT.		JAN.	APR.	JULY	OCT.	
					mb.	mb.	mb.	mb.	mb.	mb.	mb.	mb.		mb.	mb.	mb.	mb.	
Freetown	$8^{\circ}30'$N	$13^{\circ}14'$W	40	1400	4.2	2.6	1.4	1.3	26.3	29.2	28.0	28.8	1945-47	1.1	0.7	1.7	2.0	1945-48
Sandakan	$5^{\circ}50'$N	$118^{\circ}07'$E	182	1400*	1.4	1.5	1.6	1.5	29.4	30.4	29.2	29.5	1939-41	1.8	1.5	1.7	1.9	1936-41
Manila	$14^{\circ}35'$N	$120^{\circ}59'$E	33	1300	2.0	1.7	1.0	1.4	18.6	20.0	22.5	21.5	1936-38	3.2	1.7	1.8	1.7	10 years
Batavia	$6^{\circ}30'$S	$107^{\circ}\ 0'$E	26	1300*	1.2	1.3	2.1	2.0	21.8	22.5	20.0	20.5	1938-40	1.6	2.0	2.4	2.0	1866-1935
Shaibah	$30^{\circ}25'$N	$47^{\circ}39'$E	63	1600			4.6				12.4		1938-42			4.9		1938-48
Bahrein	$26^{\circ}16'$N	$50^{\circ}37'$E	7	1500	2.8	4.6	4.7	6.4	16.0	20.9	31.8	26.3	1947-48	0.5	2.0	3.0	3.3	1947-49

* Local time

Notes

1.- Some of the frequency curves, particularly those with high values of the standard deviation, are not strictly normal, so that for these the standard deviations do not give an accurate estimate of the extremes.

2.- For an atmospheric pressure of 1,000 mb., moisture contents of 1, 1½ and 2 percent correspond to vapour pressures of approximately 16, 24 and 32 respectively.

3.- This table is reproduced by permission of the Meteorological Office.

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TABLES OF RESULTS

Table 1.- Take-off distance and power measured at take-off

Location	Test No.	ICAN Pressure Height feet	Air Temp. t °C	Specific Humidity q %	Power as Measured Distance Corrected to Zero Headwind						Corrected to Mean Engine Speed & Boost, ICAN Pressure Height 590 feet					
					Distance to 115 mph EAS feet	Brake Horse Power					Distance to 115 mph EAS feet	Brake Horse Power				
						Port Outer	Port Inner First	Port Inner Second	Stbd. Inner	Stbd. Outer		Port Outer	Port Inner First	Port Inner Second	Stbd. Inner	Stbd. Outer
BOSCOMBE DOWN	1	210	19.8	0.932		1515	1519		1463	1528		1511	1496		1446	1529
	2	85	17.8	0.728		1515	1492		1484	1566		1510	1482		1456	1552
	3	120	19.6	0.686		1530	1519		1485	1541		1523	1502		1455	1530
	4	170	24.0	0.876		1508	1491		1477	1498		1496	1471		1439	1497
LYNEHAM	5	260	12.2	0.780		1561	1508		1531	1587		1548	1487		1504	1580
KHARTOUM	6	1420	28.4	1.087		1493	1441		1433	1498		1503	1444		1423	1499
	7	1390	34.7	1.033	3209	1478	1454		1418	1490	3370	1478	1459		1406	1492
	8	1340	27.5	1.052	3600	1477	1426		1391	1495	3755	1487	1427		1394	1495
	9	1310	33.4	1.169	3087	1491	1442		1400	1499	3230	1485	1449		1397	1491
	10	1360	23.9	0.375	3605	1546	1479		1466	1549	3738	1566	1494		1464	1563
	11	1350	29.4	0.311		1526	1527		1478	1539		1533	1516		1470	1547
BAHREIN	12	470	32.8	1.900	3547	1440	1378		1341	1449	3729	1445	1376		1327	1450
	13	480	31.1	1.645	3257	1441	1387		1354	1455	3327	1452	1390		1348	1458
	14	480	37.2	1.932	4018	1431	1379		1321	1424	3977	1440	1382		1320	1429
	15	460	33.4	2.025		1422	1363		1324	1430		1427	1369		1320	1425
HABBANIYA	16	555	38.9	0.604	3596	1498	1443		1393	1466	3583	1493	1458		1384	1472
	17	560	38.2	0.641	3082	1512	1465		1414	1498	3076	1506	1477		1405	1501
	18	540	43.6	0.527	3175	1407		1425	1379	1439	3122	1448		1422	1378	1464
	19	540	40.0	0.545	3417	1418		1435	1369	1434	3360	1455		1430	1376	1457
	20	565	28.8	0.639		1494		1446	1436	1514		1493		1408	1416	1513
BAHREIN	21	500	36.9	2.012	4095	1427		1393	1360	1422	4107	1422		1379	1338	1425
	22	440	31.1	1.784		1418		1381	1324	1450		1411		1343	1303	1449
	23	500	33.1	1.840		1406		1391	1348	1431		1409		1383	1333	1427
HABBANIYA	24	495	38.5	1.190	4047	1458		1394	1358	1452	4030	1451		1383	1364	1457
	25	500	39.0	1.081	3887	1446		1396	1359	1451	3586	1445		1394	1361	1464
NICOSIA	26	950	27.7	0.875		1487		1427	1409	1517		1489		1433	1409	1514
LUQA	27	275	22.8	1.559		1439		1403	1390	1483		1440		1404	1386	1482
BOSCOMBE DOWN	29	200	24.4	1.119		1485		1417	1421	1514		1480		1411	1409	1515
	30	305	20.6	1.214		1491		1436	1413	1493		1486		1425	1411	1507
	31	420	19.7	0.896	2994	1504		1442	1438	1521	2966	1496		1442	1438	1523
	32	420	19.7	0.896		1505		1452	1461	1529		1511		1460	1461	1529
	33	420	19.7	0.896	2989	1511		1487	1442	1519	2989	1504		1479	1442	1525
	34	420	19.7	0.896	3084	1503		1469	1439	1503	3050	1496		1473	1439	1508

Engine	Port Outer	Port Inner First	Port Inner Second	Stbd. Inner	Stbd. Outer
Mean Engine Speed R.P.M.	2730	2750	2760	2720	2760
Mean Boost lb./sq. in.	8.9	8.4	8.1	8.2	8.4

Table 2.- Rate of climb at 140 m.p.h. A.S.I.

Location	Test No.	Mean Height 1,250 ft.		Rate of Climb ft./min.
		Air Temp. t °C	Specific Humidity q %	
KHARTOUM	6	27.5	1.03	749
	7	30.3	0.97	794
	8	26.2	1.17	728
	9	27.8	1.12	757
	10	30.9	0.04	815
BAHREIN	12	33.8	0.85	754
	13	36.4	0.90	1005
	14	34.2	0.60	752
HABBANIYA	16	35.3	0.36	755
	17	36.4	0.47	892
BOSCOMBE DOWN	29	19.5	0.99	916
	30	17.6	1.07	945

Table 3.- Power and fuel flow measured in level flight.
(a) Take-off power

ICAN Pressure Height (ft.)	Location	Test No.	Air Temp. t °C	Specific Humidity q%	Brake Horse Power			Fuel Flow lb./hr.		
					Port Inner		Stbd. Inner	Port Inner		Stbd. Inner
					First	Second		First	Second	
700	BAHREIN	12	35.2	1.130	1403		1324	1116		1142
		13	31.9	1.520	1415		1317	1124		1130
		14	34.3	1.400	1411		1305	1127		1126
	HABBANIYA	16	38.4	0.334	1473		1367	1115		1115
		17	39.6	0.398	1463		1360	1118		1116
		18	43.8	0.254		1380	1337		1104	1093
		19	42.5	0.254		1401	1353		1090	1111
	BAHREIN	21	34.2	1.831		1364	1285		1141	1141
		22	34.2	1.523		1369	1295		1150	1142
	BOSCOMBE DOWN	28	13.0	0.760		1472	1458		1231	1216
		29	18.9	0.792		1463	1422		1210	1199
		30	19.1	0.810		1457	1415		1210	1223
2040	BOSCOMBE DOWN	2	8.9	0.504	1544		1520	1227		1240
		3	11.2	0.650	1515		1496	1237		1239
	KHARTOUM	7	32.8	0.913	1443		1361	1124		1126
		8	26.6	1.104	1454		1372	1163		1152
		9	30.8	0.852	1462		1364	1137		1153
		10	30.4	0.119	1498		1408	1130		1159
	BAHREIN	12	38.3	0.135	1472		1373	1100		1122
		13	34.7	0.112	1474		1396	1134		1122
	BOSCOMBE DOWN	28	9.9	0.690			1492			1236
		29	18.1	0.923			1449			1201

Engine	Port Inner		Stbd. Inner
	First	Second	
Mean Engine Speed R.P.M.	2750	2760	2720
Mean Boost lb./sq.in.	8.4	8.1	8.2

Table 4.- Power and fuel flow measured in level flight.
(b) Maximum climbing power

ICAN Pressure Height (ft.)	Location	Test No.	Air Temp. t °C	Specific Humidity q%	Brake Horse Power			Fuel Flow lb./hr.		
					Port Inner		Stbd. Inner	Port Inner		Stbd. Inner
					First	Second		First	Second	
700	BAHREIN	12	32.2	1.558	1173		1141	811		859
		13	32.0	1.490	1187		1120	818		846
		14	34.8	0.994	1200		1151	841		865
	HABBANIYA	16	38.5	0.353	1221		1185	828		865
		17	38.9	0.442	1228		1183	829		857
		18	44.6	0.215		1154	1171		848	856
		19	42.6	0.196		1185	1170		865	853
	BAHREIN	21	34.1	1.883		1152	1130		872	884
		22	34.3	1.376		1169	1146		893	898
	BOSCOMBE DOWN	28	12.8	0.753		1260	1242		944	945
		29	19.6	0.785		1239	1208		931	907
		30	19.5	0.784		1246	1212		922	922
2040	BOSCOMBE DOWN	2	8.9	0.504	1271		1253	891		913
		3	11.2	0.650	1302		1266	907		925
	KHARTOUM	7	32.9	0.985	1240		1201	842		891
		8	26.4	1.143	1227		1164	861		866
		9	31.2	0.837	1246		1183	868		884
	BAHREIN	12	38.0	0.125	1226		1178	820		849
		13	34.8	0.036	1234		1202	837		865
	BOSCOMBE DOWN	28	10.1	0.716			1276			955
		29	17.8	0.950			1237			926

Engine	Port Inner		Stbd. Inner
	First	Second	
Mean Engine Speed R.P.M.	2750	2760	2720
Mean Boost lb./sq.in.	8.4	8.1	8.2

Table 5.- Power and fuel flow measured in level flight.
(c) Maximum continuous cruising power (weak mixture)

ICAN Pressure Height (ft.)	Location	Test No.	Air Temp. t °C	Specific Humidity q%	Brake Horse Power: Port Inner First	Brake Horse Power: Port Inner Second	Brake Horse Power: Stbd Inner	Fuel Flow lb./hr.: Port Inner First	Fuel Flow lb./hr.: Port Inner Second	Fuel Flow lb./hr.: Stbd Inner
700	BAHREIN	12	34.0	1.168	970		963	463		463
		13	32.2	1.470	961		968	462		470
	HABBANIYA	16	38.3	0.265	946		973	453		461
		17	39.3	0.409	939		971	452		460
		18	44.0	0.297		880	975		452	457
		19	42.8	0.215		875	979		450	460
	BAHREIN	21	33.7	1.971		859	951		460	470
		22	34.0	1.613		874	962		460	485
	BOSCOMBE DOWN	28	12.6	0.709		947	1048		485	499
		29	18.8	0.766		933	1025		478	490
		30	19.7	0.924		934	1022		480	494
2040	BOSCOMBE DOWN	2	8.9	0.501	1033		1051	486		488
		3	11.2	0.650	1031		1039	486		484
	KHARTOUM	7	32.9	0.985	986		990	464		476
		8	27.0	1.110	1016		1030	482		485
		9	31.2	0.771	989		986	461		463
		10	30.5	0.053	996		1021	464		472
	BAHREIN	12	38.4	0.092	968		983	453		468
		13	34.3	0.145	984		1002	464		469
	BOSCOMBE DOWN	28	10.1	0.517			1064			506
		29	18.3	0.673			1044			506

Engine	Port Inner: First	Port Inner: Second	Stbd. Inner
Mean Engine Speed R.P.M.	2750	2760	2720
Mean Boost lb./sq.in.	8.4	8.1	8.2

Table 6.- Variation of power with temperature and humidity

Engine Condition	ICAN Pressure Height (ft.)	Engine	$\frac{1}{P_M}\frac{\partial P}{\partial t}$ and 95% limits		$\frac{1}{P_M}\frac{\partial P}{\partial q}$ and 95% limits		Mean $\frac{1}{P_M}\frac{\partial P}{\partial t}$ and 95% limits		Mean $\frac{1}{P_M}\frac{\partial P}{\partial q}$ and 95% limits	
Take-off	590*	Port Outer	-0.00147	±0.00054	-0.0359	±0.0088	-0.00229	±0.00068	-0.0405	±0.0072
		1st Port Inner	-0.00097	±0.00094	-0.0504	±0.0143				
		2nd Port Inner	-0.00164	±0.00092	-0.0419	±0.0155				
		Stbd. Inner	-0.00258	±0.00050	-0.0473	±0.0080				
		Stbd. Inner	-0.00213	±0.00036	-0.0334	±0.0057				
	700	2nd Port Inner	-0.00341	±0.00029	-0.0506	±0.0051				
		Stbd. Inner	-0.00252	±0.00055	-0.0273	±0.0114				
	2040	1st Port Inner	-0.00202	±0.00044	-0.0351	±0.0121				
		Stbd. Inner	-0.00416	±0.00040	-0.0435	±0.0120				
Climb	700	2nd Port Inner	-0.00303	±0.00062	-0.0255	±0.0126	-0.00253	±0.00088	-0.0305	±0.0224
		Stbd. Inner	-0.00245	±0.00063	-0.0423	±0.0110				
	2040	1st Port Inner	-0.00169	±0.00137	-0.0064	±0.0388				
		Stbd. Inner	-0.00281	±0.00127	-0.0249	±0.0396				
Cruise	700	2nd Port Inner	-0.00304	±0.00080	-0.0246	±0.0152	-0.00253	±0.00083	-0.0187	±0.0240
		Stbd. Inner	-0.00291	±0.00048	-0.0276	±0.0083				
	2040	1st Port Inner	-0.00199	±0.00112	-0.0092	±0.0295				
		Stbd. Inner	-0.00214	±0.00061	-0.0065	±0.0185				

* Measurements during take-off Remaining results from level flight tests.

Table 7. – Variation of fuel consumption with temperature

Engine Condition	I.C.A.N. Pressure Height (ft.)	Engine	$\frac{1}{Qo}\frac{dQ}{dt}$ and 95% limits		Mean $\frac{1}{Qo}\frac{dQ}{dt}$ and 95% limits	
Take-off	700	2nd Port	-0.00383	±0.00060	-0.00378	±0.00026
		Stbd.	-0.00363	±0.00067		
	2040	1st Port	-0.00393	±0.00072		
		Stbd.	-0.00378	±0.00053		
Climb	700	2nd Port	-0.00322	±0.00078	-0.00306	±0.00054
		Stbd.	-0.00314	±0.00127		
	2040	1st Port	-0.00288	±0.00131		
		Stbd.	-0.00299	±0.00148		
Cruise	700	2nd Port	-0.00245	±0.00033	-0.00240	±0.00060
		Stbd.	-0.00264	±0.00105		
	2040	1st Port	-0.00226	±0.00126		
		Stbd.	-0.00220	±0.00148		

Table 8.- Calculated efficiency derivatives for Hastings propellers

(Calculated from propeller manufacturer's data)

	$\frac{J}{\eta} \frac{\partial \eta}{\partial J}$	$\frac{C_P}{\eta} \frac{\partial \eta}{\partial C_P}$
Ground Run	+ 0.44	-0.16
Transition	+ 0.30	-0.05
Climb	+ 0.27	0

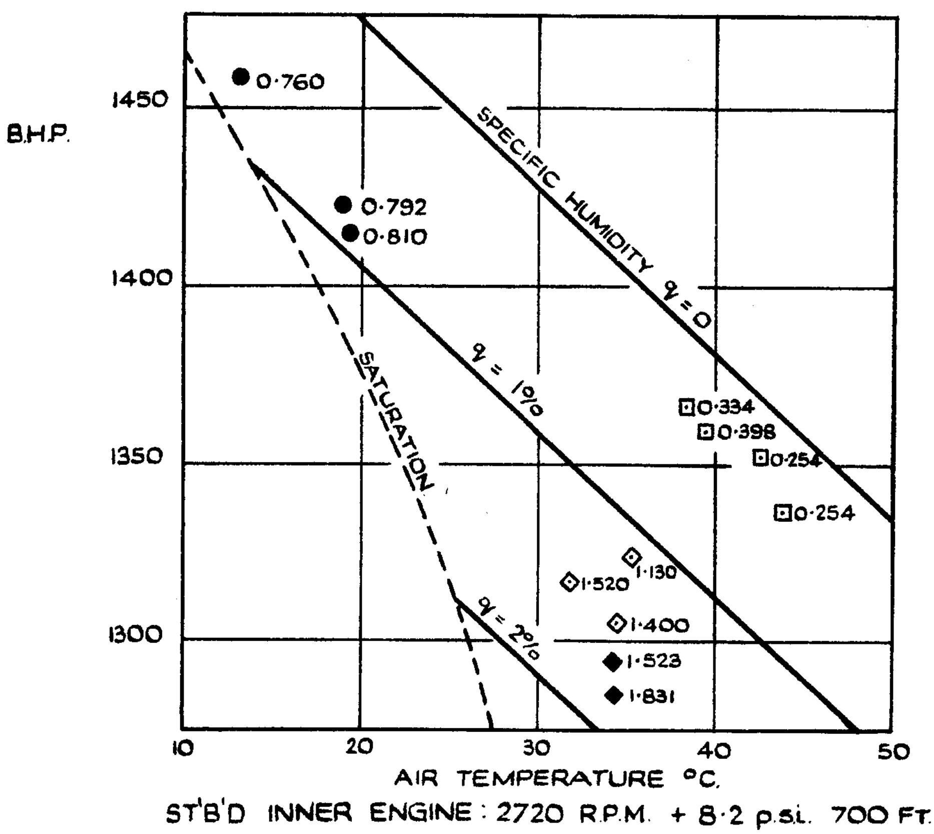
Table 9.- Brief descriptions of runways used for measured take-offs

Location	Description
Boscombe Down	Concrete
Khartoum	Bitumen
Bahrein	Perforated steel planking on sand
Habbaniya	Tarmac on concrete

Figure 1

	LOCATION.	DATE.
⊙	BOSCOMBE.	11-21/6
▷	LYNEHAM.	22/6
◁	KHARTOUM.	25-30/6
◇	BAHREIN.	7-12/7
⊡	HABBANIYA.	14-30/7

	LOCATION.	DATE.
◆	BAHREIN.	30/7-1/8
■	HABBANIYA.	1/8
+	NICOSIA.	2/8
×	LUQA.	3/8
●	BOSCOMBE.	17/8-1/9

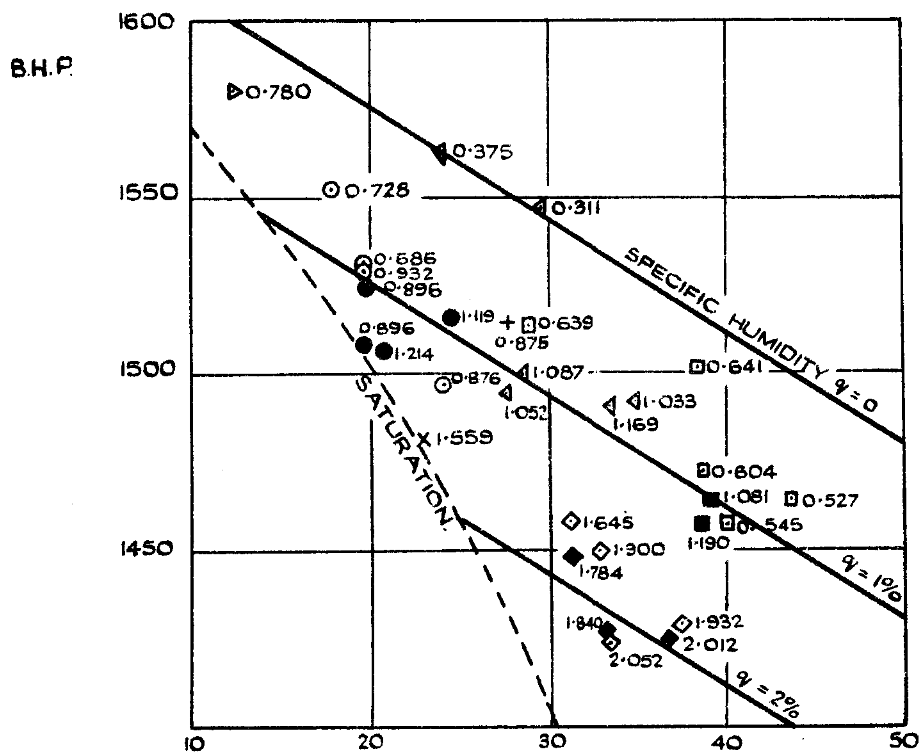


VARIATION OF TAKE-OFF POWER WITH TEMPERATURE AND HUMIDITY

Figure 2

	LOCATION	DATE
⊙	BOSCOMBE	11-21/6
▷	LYNEHAM	22/6
◁	KHARTOUM	25-30/6
◇	BAHREIN	7-12/7
⊡	HABBANIYA	14-30/7

	LOCATION	DATE
◆	BAHREIN	30/7-1/8
■	HABBANIYA	1/8
+	NICOSIA	2/8
×	LUQA	3/8
●	BOSCOMBE	17/8-1/9



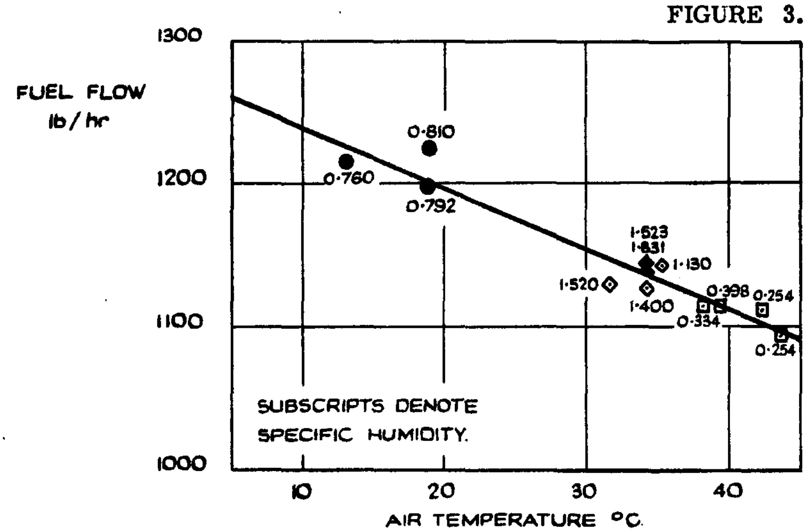
STB'D OUTER ENGINE: 2760 R.P.M. + 8·4 p.s.i. 590 FT.

VARIATION OF TAKE-OFF POWER WITH TEMPERATURE AND HUMIDITY

Figures 3 and 4

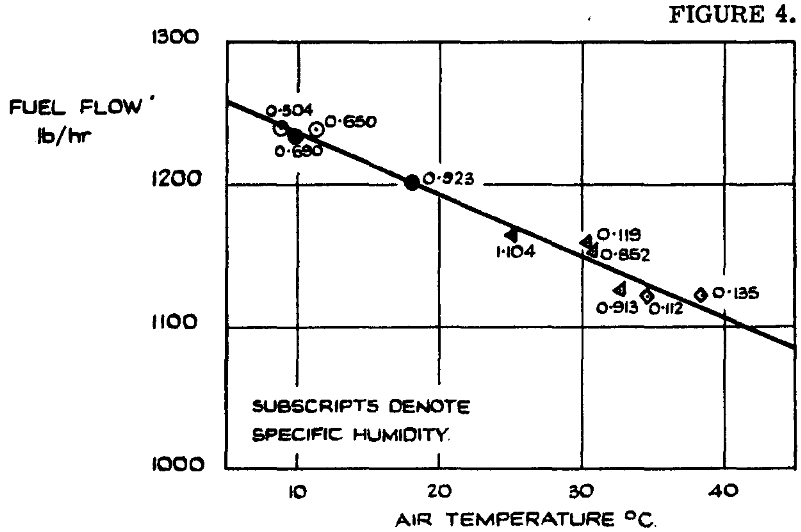
	LOCATION	DATE
⊙	BOSCOMBE	11-21/6
◄	KHARTOUM.	25-30/6
◇	BAHREIN.	7-12/7
⊡	HABBANIYA.	14-30/7
◆	BAHREIN.	30/7-1/8
●	BOSCOMBE.	17/8-1/9

FIGURE 3.



ST'B'D. INNER ENGINE : 2720 R.P.M. + 8·2 p.s.i. 700 FT.

FIGURE 4.



ST'B'D INNER ENGINE : 2720 R.P.M. + 8·2 p.s.i. 2040 FT.

VARIATION OF FUEL CONSUMPTION WITH TEMPERATURE AND HUMIDITY

Figures 5 and 6

	LOCATION	DATE
◁	KHARTOUM	25 - 30/6
◇ (open)	BAHREIN	7 - 12/7
▢ (open)	HABBANIYA	14 - 30/7
◆	BAHREIN	30/7 - 1/8
■	HABBANIYA	1/8
●	BOSCOMBE DOWN	17/8 - 1/9

FIGURE 5.

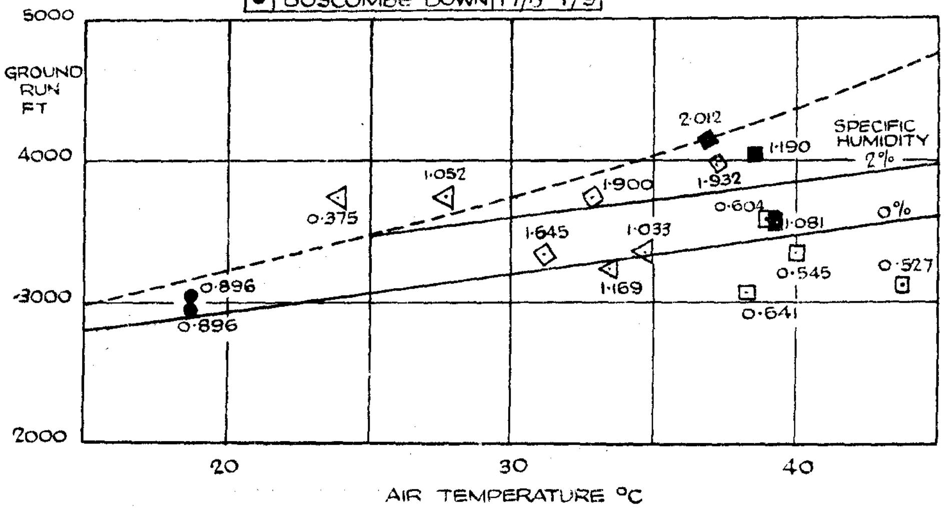
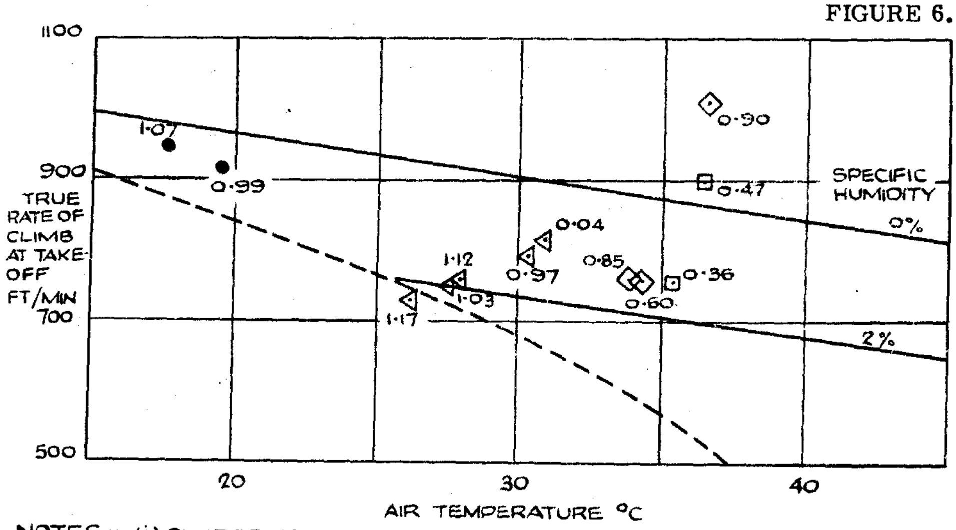


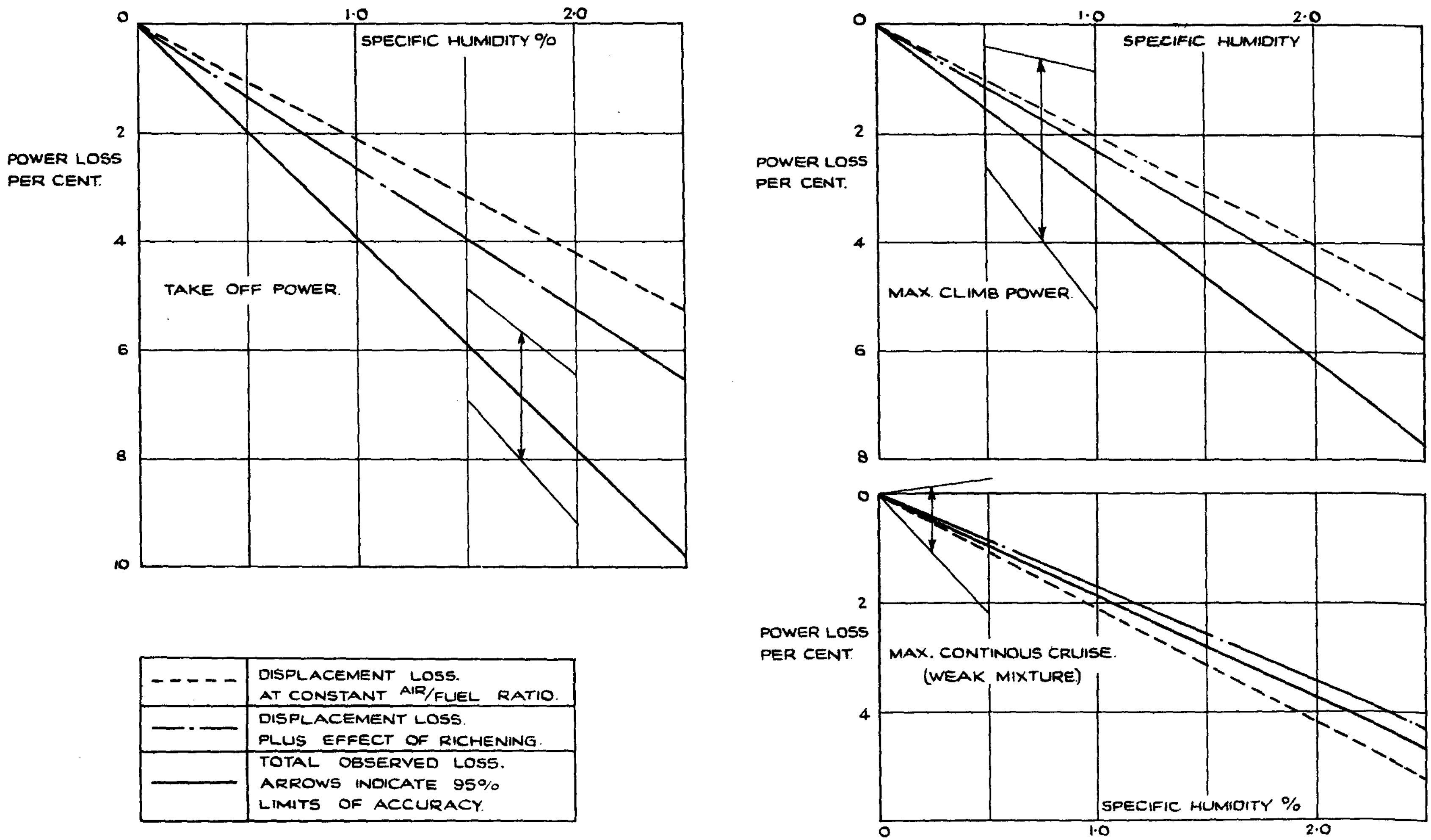
FIGURE 6.



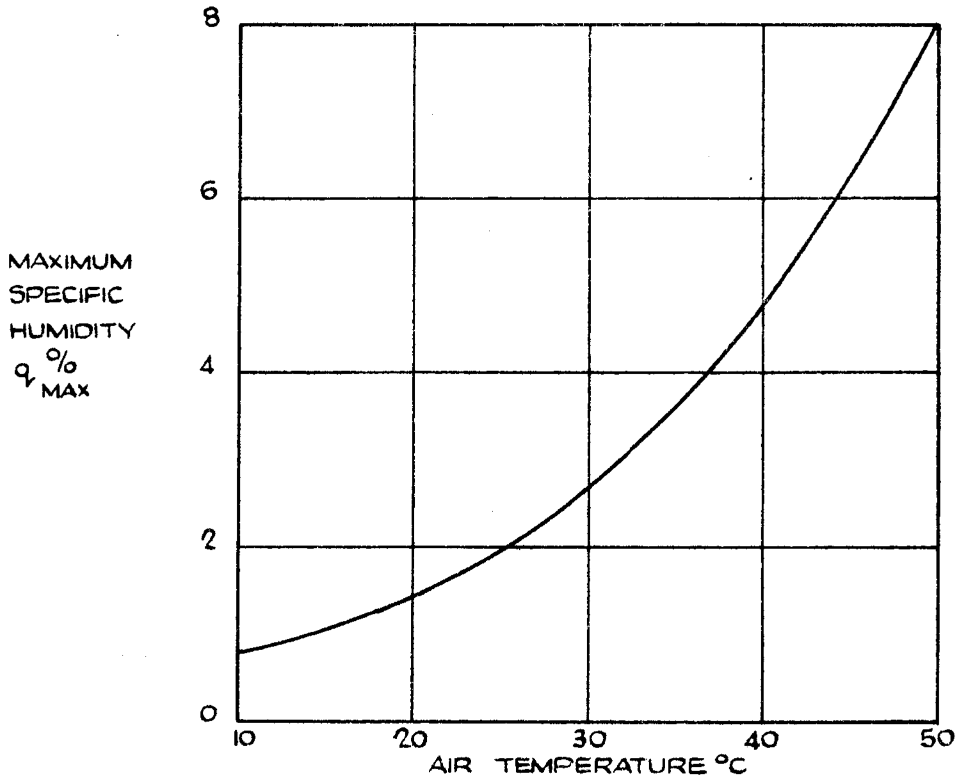
NOTES -
- (i) SLOPES OF FULL LINES ARE DERIVED FROM MEASURED POWER CHANGES
- (ii) BROKEN LINES INDICATE SATURATION LIMIT FOR THESE LINES.
- (iii) GROUND RUN AT I.C.A.N. PRESSURE HEIGHT 590 FT.
- (iv) RATE OF CLIMB AT MEAN I.C.A.N. PRESSURE HEIGHT 1250 FT.
- (v) TAKE-OFF WEIGHT 72500 lb.
- (vi) SEE PARA 6·4

VARIATION OF GROUND RUN AND TAKE-OFF RATE OF CLIMB WITH TEMPERATURE AND HUMIDITY

Figure 7



VARIATION OF POWER WITH HUMIDITY AT CONSTANT TEMPERATURE



CALCULATED FROM

$$q_{MAX} = \left(\frac{164 \cdot 55}{\frac{2645 \cdot 5}{e_{MAX}} - 1} \right) \%$$

WHERE e_{MAX} = SATURATION VAPOUR PRESSURE (mb)

VARIATION OF MAXIMUM SPECIFIC HUMIDITY WITH AIR TEMPERATURE AT 1,000mb TOTAL PRESSURE

MOISTURE CONTENT AT M.S.L. — RICHESSE EN VAPEUR D'EAU AU NIVEAU MOYEN DE LA MER — ESTADO HIGROMETRICO AL N.M.M. (NIVEL MEDIO DEL MAR)

JANUARY — JANVIER — ENERO

Provisional
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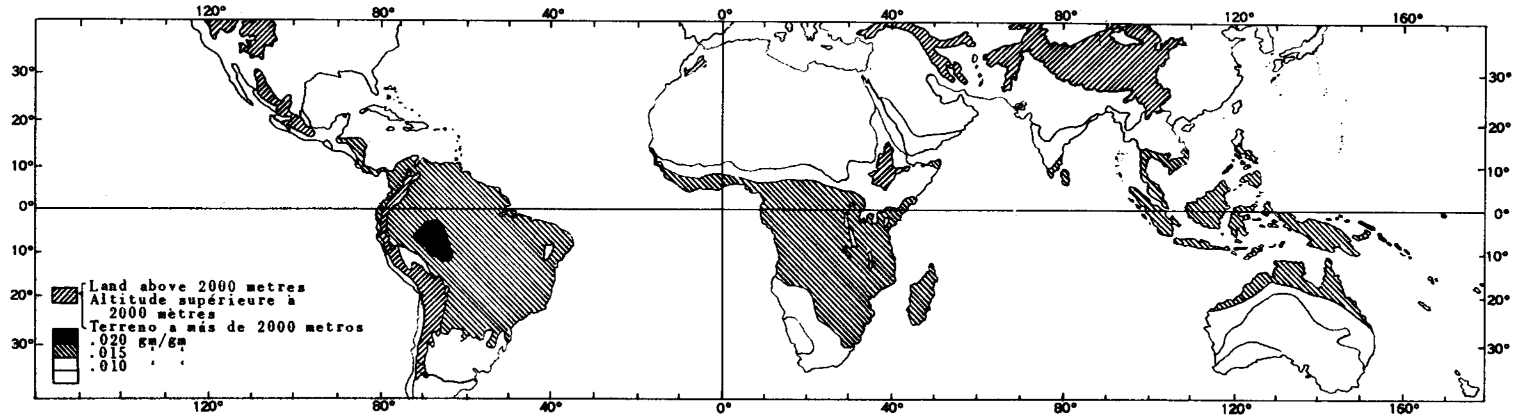

Fig. 9

MOISTURE CONTENT AT M.S.L. — RICHESSE EN VAPEUR D'EAU AU NIVEAU MOYEN DE LA MER — ESTADO HIGROMETRICO AL N.M.M (NIVEL MEDIO DEL MAR)

JULY — JUILLET — JULIO

Provisional
Provisoire
Provisional

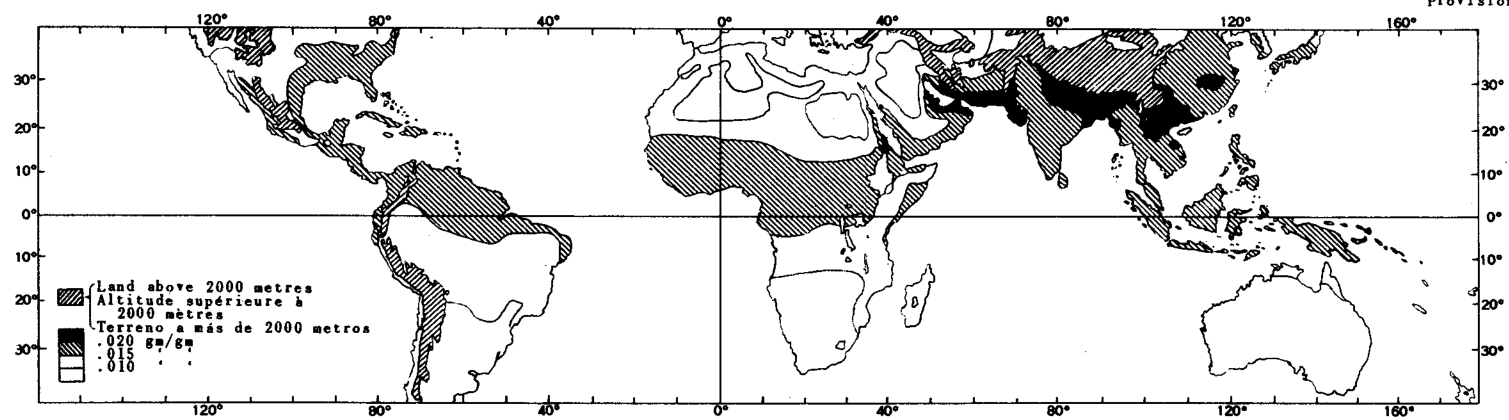

Fig. 10

Computed from a chart of average vapour pressure at M.S.L. by the formula $q = \frac{.622e}{p-.378e}$

Valeurs calculées d'après une carte des moyennes de tension de vapeur au niveau moyen de la mer, à l'aide de la formule $q = \frac{0,622h}{p-0,378h}$

Calculado según una carta de tension media del vapor al N.M.M., por medio de la fórmula $q = \frac{0.622e}{p-0,378e}$

Chart prepared in Meteorological Office, Air Ministry, London.
Carte établie par le Meteorological Office, Air Ministry, Londres.
Carta preparada en la Meteorological Office, Air Ministry, Londres.