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CONDENSATION TRAILS FROM AIRCRAFT

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CONDENSATION TRAILS FROM AIRCRAFT

The physical factors which could favour formation of cloud behind aircraft are :—

(i) Pressure reduction above and behind wings and propeller

(ii) Water vapour supplied from engine exhaust

(iii) Nuclei of condensation or sublimation (possibly not previously available in adequate numbers) supplied by engine exhaust

(iv) Turbulence caused by propeller or jet leading to mixing of layers of air

(v) Effects connected with electric charges.

The factors tending to prevent cloud formation or to dissipate cloud when formed are :—

(i) Heat supplied by radiator and engine

(ii) Heat equivalent of work done by the propeller

In assessing the relative importance of these factors the chief guide is the observational fact that most of the cases of cloud formation occur at very high levels and very low temperature.

EXHAUST TRAILS

Physical theory.—A preliminary discussion[1]* of the factors mentioned above led to the conclusion that the majority of trails were probably due to the condensation of water vapour from the engine exhaust. Further discussion of the condensation of water vapour from engine exhaust is given in detail in two papers[2,3], and may be summarized on the following lines.

The effects of the engine are (i) to add water vapour to the air in the trail behind the aircraft and (ii) to heat the air. These factors affect the relative humidity in the trail in opposite directions. The water vapour is one of the products of combustion of the fuel ; the heat also comes from the combustion of the fuel, partly directly in the exhaust products, partly from the radiator, partly through work done on the air by the propeller or jet. Briefly the reason for the condensation is that when air is very cold the amount of water which it can hold in the form of invisible vapour is extremely small. At −45° C., for example, it is only about 1/180 of the amount retainable at +15° C. It is in these conditions that the addition of the small amount of water from the exhaust matters so greatly that it may not be compensated for by all the heating available.

* The index numbers refer to the bibliography on p. 10.

However, condensation trails have been observed on a few occasions at levels and temperatures corresponding to points on Fig. 1 between the lines I and W, and therefore for forecasting purposes it is probably better to use the line I as indicating the critical immunity temperatures and levels.

TABLE II—SATURATION VALUES OF WATER VAPOUR WITH RESPECT TO ICE AND TO WATER AND THE RATIO BETWEEN THEM

Temp-erature	Saturation vapour pressure over		Ratio: water/ice	Temp-erature	Saturation vapour pressure over		Ratio: water/ice	Temp-erature	Saturation vapour pressure over ice
	ice	water			ice	water			
°A.	gm./m.^{3}	gm./m.^{3}		°A.	gm./m.^{3}	gm./m^3		°A.	gm./m.^{3}
273	4·8472	4·8479	1·00	248	0·55246	0·70509	1·28	222	0·033923
272	4·4795	4·5233	1·01	246	0·45539	0·59255	1·30	220	0·026622
271	4·1363	4·2180	1·02	244	0·37413	0·49634	1·33	218	0·020794
270	3·8178	3·9309	1·03	242	0·30630	0·41439	1·35	216	0·016171
268	3·2462	3·4078	1·05	240	0·24999	0·34470	1·38	214	0·012515
266	2·7505	2·9359	1·07	238	0·20330	0·28579	1·41	212	0·0096405
264	2·3285	2·5419	1·09	236	0·16472	0·23606	1·43	210	0·0073868
262	1·9651	2·1870	1·11	234	0·13298	0·19418	1·46	208	0·0056316
260	1·6535	1·8764	1·13	232	0·10694	0·15915	1·49	206	0·0042706
258	1·3875	1·6057	1·16	230	0·085714	0·12992	1·52	204	0·0032206
256	1·1605	1·3700	1·18	228	0·068407	0·10559	1·54	202	0·0024158
254	0·96826	1·1657	1·20	226	0·054373	0·085504	1·57	200	0·0018007
252	0·80570	0·98884	1·23	224	0·043038	0·068914	1·60		
250	0·66817	0·83632	1·25						

The above values of the densities of saturated water vapour were calculated from the values of saturation vapour pressure adopted by the Twelfth Conference of Directors, International Meteorological Organization, 1947. In the calculation the value of the gas constant for water vapour[6] was taken as $R_v = 4 \cdot 6150 \times 10^6$ erg/gm. °A.

The positions of I and W (i.e. the neutral lines for saturated atmosphere) depend on the amount of water vapour in the exhaust and the amount of heat contributed, provided both go into the same trail of air, and do not depend on the cross-section of this trail.

If the atmosphere is initially below saturation with respect to ice (humidity, say, 60 per cent.) then the cross-section of the trail into which the exhaust vapour and engine heat are discharged is an important consideration in determining whether condensation will occur or how long it will continue behind the machine.

The diagram could be revised to apply to any cross-section of trail by lowering or raising all the percentages in proportion to the increase or decrease in cross-section of trail.

It is possible to examine the extent to which the position might be improved by removing water vapour from the engine exhaust or by adding heat to the air.

Roughly the result is that adding even 30 per cent. more heat (this means that the total heat put into the air would then slightly exceed the whole energy derivable from the fuel used in the engine) would only reduce the immunity temperature by about 3°. Removing 30 per cent. of the water vapour by condenser would lower the immunity temperature by about 3·5° and removing 60 per cent. would reduce it by about 8·5°. Another way of putting it is to say that the complete immunity level for a saturated atmosphere would, in these three cases, be raised by roughly 1,200, 1,500 and 4,000 ft. respectively. Thus, for a condenser to be really useful it would need to be capable of removing a high proportion of the exhaust water.

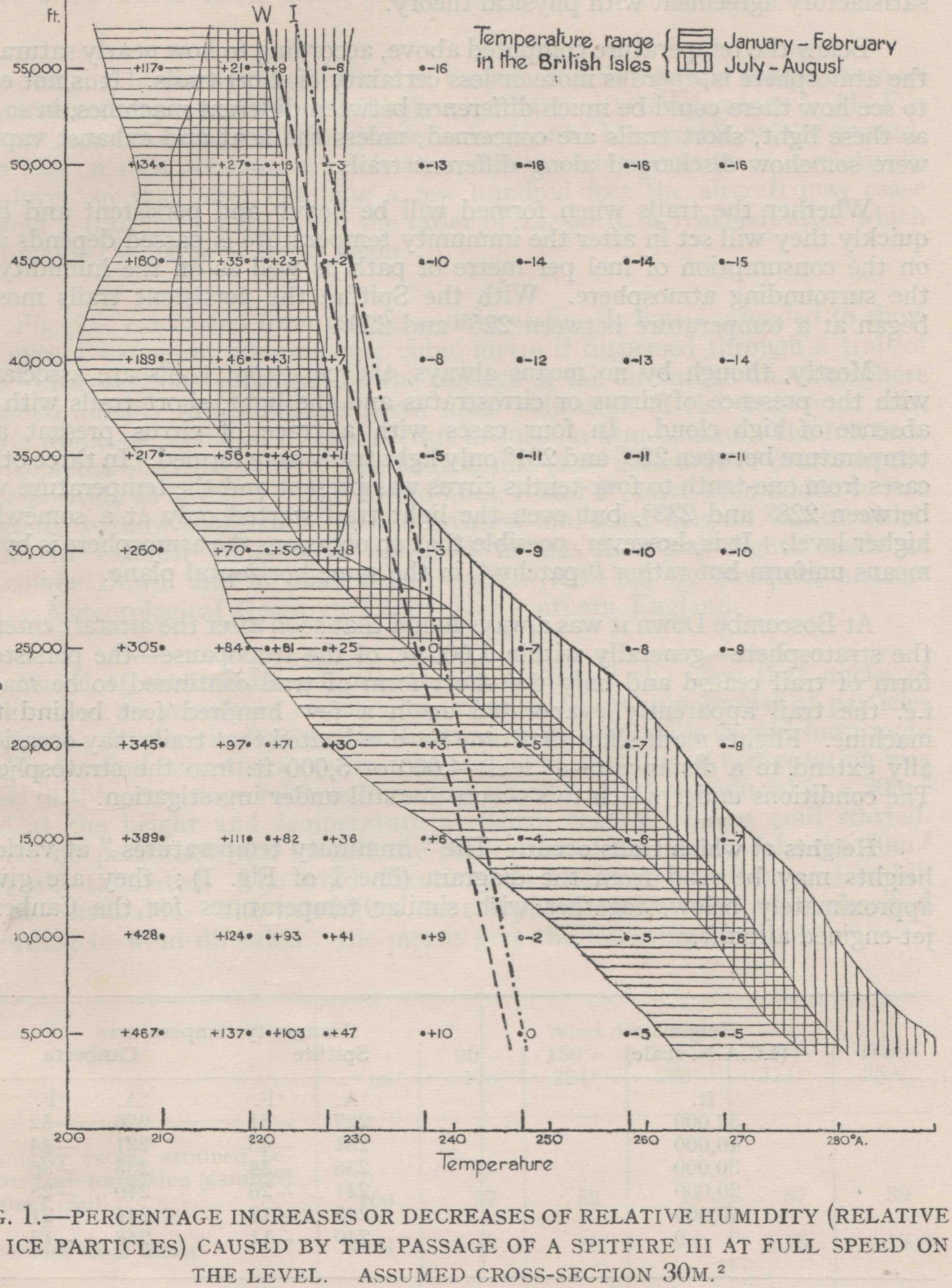

FIG. 1.—PERCENTAGE INCREASES OR DECREASES OF RELATIVE HUMIDITY (RELATIVE TO ICE PARTICLES) CAUSED BY THE PASSAGE OF A SPITFIRE III AT FULL SPEED ON THE LEVEL. ASSUMED CROSS-SECTION 30M.²

Practical results.—Our first precise knowledge about these trails came from the fine series of high-altitude flights made at Boscombe Down during 1941 by Wing-Commander Longbottom. A typical trail is shown at Fig. 3. In the first 100 ascents made at Boscombe Down with a Spitfire the highest temperatures at which short trails formed were 234° on two occasions, 236° on one occasion and 237° on one occasion. The upper limit of 237° would correspond to about 85 per cent. of the fuel energy going as heat into the trail, which gives very satisfactory agreement with physical theory.

Below the temperature computed above, according to how nearly saturated the atmosphere is, there is more or less certainty of short trails. It is not easy to see how there could be much difference between different machines, in so far as these light, short trails are concerned, unless the heat and exhaust vapour were somehow discharged along different trails.

Whether the trails when formed will be heavy and persistent and how quickly they will set in after the immunity temperature is passed depends also on the consumption of fuel per metre of path as well as on the humidity of the surrounding atmosphere. With the Spitfire the persistent trails mostly began at a temperature between 225° and 229°.

Mostly, though by no means always, the persistent trails are associated with the presence of cirrus or cirrostratus and the light, short trails with an absence of high cloud. In four cases with a trace of cirrus present and temperature between 220° and 231° only light trails were formed. In three other cases from one-tenth to four-tenths cirrus was present and the temperature was between 228° and 233°, but even the light trail started only at a somewhat higher level. It is, however, possible that on occasions the atmosphere is by no means uniform but rather " patchy " in the same horizontal plane.

At Boscombe Down it was always found that soon after the aircraft entered the stratosphere—generally within 1,000 ft. of the tropopause—the persistent form of trail ceased and only the short form of trail continued to be made, i.e. the trail apparently evaporated again a few hundred feet behind the machine. Flights made since that time have indicated that trails may occasionally extend to a distance of at least 4,000 or 5,000 ft. into the stratosphere. The conditions under which this occurs are still under investigation.

Heights at which trails occur.—The " immunity temperatures " at various heights may be read from the diagram (line I of Fig. 1) ; they are given approximately below, together with similar temperatures for the Canberra jet-engined aircraft.

Height (I.C.A.N. scale)	Immunity temperatures Spitfire		Canberra	
ft.	°A.	°F.	°A.	°F.
50,000	227	−51	226	−52
40,000	231	−43	231	−44
30,000	236	−34	235	−36
20,000	241	−26	240	−28
10,000	245	−18	244	−21
0	249	−11	248	−13

Comparison with the extremes of temperature experienced at various heights shows that in the British Isles exhaust trails are not likely to be formed, unless under extreme conditions of cold, below about 14,000 ft. ;

as a rule they will be found to begin between 20,000 and 30,000 ft. The average heights (in round figures) at which the above immunity temperatures are reached in different months are as follows :—

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					feet						
21,000	21,000	21,000	22,500	24,000	26,000	28,500	28,500	27,000	25,000	22,500	21,500

It is obvious, however, that in parts of Canada and Siberia the temperature at ground level may on occasions fall below the immunity temperature (—11° F.), and on such occasions trails are liable to be formed by aircraft on the ground. As a rule on such occasions there is an inversion of temperature at a relatively low level, so that after climbing a few hundred feet the aircraft may cease making a trail until a height of the order of 12,000 ft. is reached, after which trail-making is liable to occur again.

Fig. 2 is calculated from the same data as Fig. 1, but is intended to show the excess water—in grammes per cubic metre if dispersed through a trail of 30m.^{2} cross-section—produced by the passage of the aircraft in an atmosphere assumed already saturated. It gives some indication of the density of trail which would be produced by the aircraft in such an atmosphere. The full lines are isopleths of excess water. The neutral line (zero excess) is of course in the same position as in Fig. 1. The dotted lines, P and P′, have been added to this diagram to show approximately the greatest and least heights within which persistent exhaust trails were observed in the first 200 flights made at Boscombe Down, and in more recent flights (1949–50) by Mosquito aircraft of the Meteorological Research Flight over southern England.

Nuclei of sublimation.—Findeisen has expressed the view that nuclei of sublimation are mainly of continental origin and probably consist of particles of quartz. If there is anything in this idea, persistent trails should form more readily in wind currents of continental origin. To test this, a computation was made of the percentage relative humidity which would be produced in a 30m.^{2} trail at the height and temperature at which each persistent trail started. Where no persistent trail formed the highest humidity attained in the 30m.^{2} trail was tabulated. The wind directions as measured at 9Km. at Larkhill are also available. The humidities, as computed above, were then classified according to wind direction ; the means give the following result :—

	Wind direction					
	0°–89°	90°–179°	180°–224°	225°–269°	270°–314°	315°–359°
Humidity excess attained before trail formation (assumed 30m.^{2} trail)	100	37	52	71	87	89
Difference from mean . .	+28	−35	−20	−1	+15	+17
Percentage of cases with no persistent trail	63	20	12	50	20	68
Difference from mean . .	+24	−19	−17	+11	−19	+29

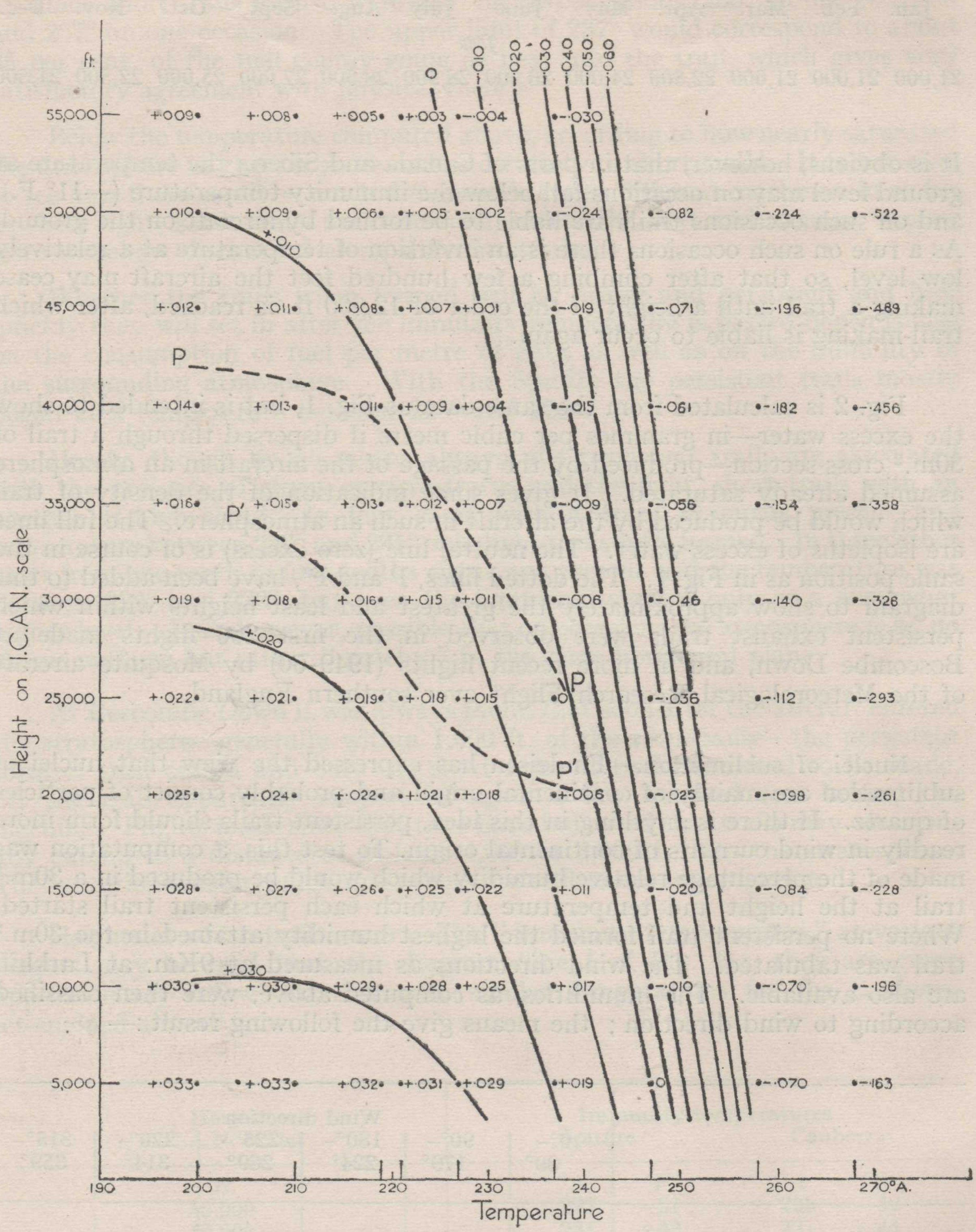

FIG. 2.—" EXCESS WATER " IN GRAMMES PER CUBIC METRE CAUSED IN A TRAIL OF 30M.^{2} CROSS-SECTION BY THE PASSAGE OF A SPITFIRE III

To face p. 8

Photo by R.A.F.

FIG. 3.—CONDENSATION TRAILS FORMED BY AIRCRAFT

November 13, 1937, 11.30 a.m.

To face p. 9

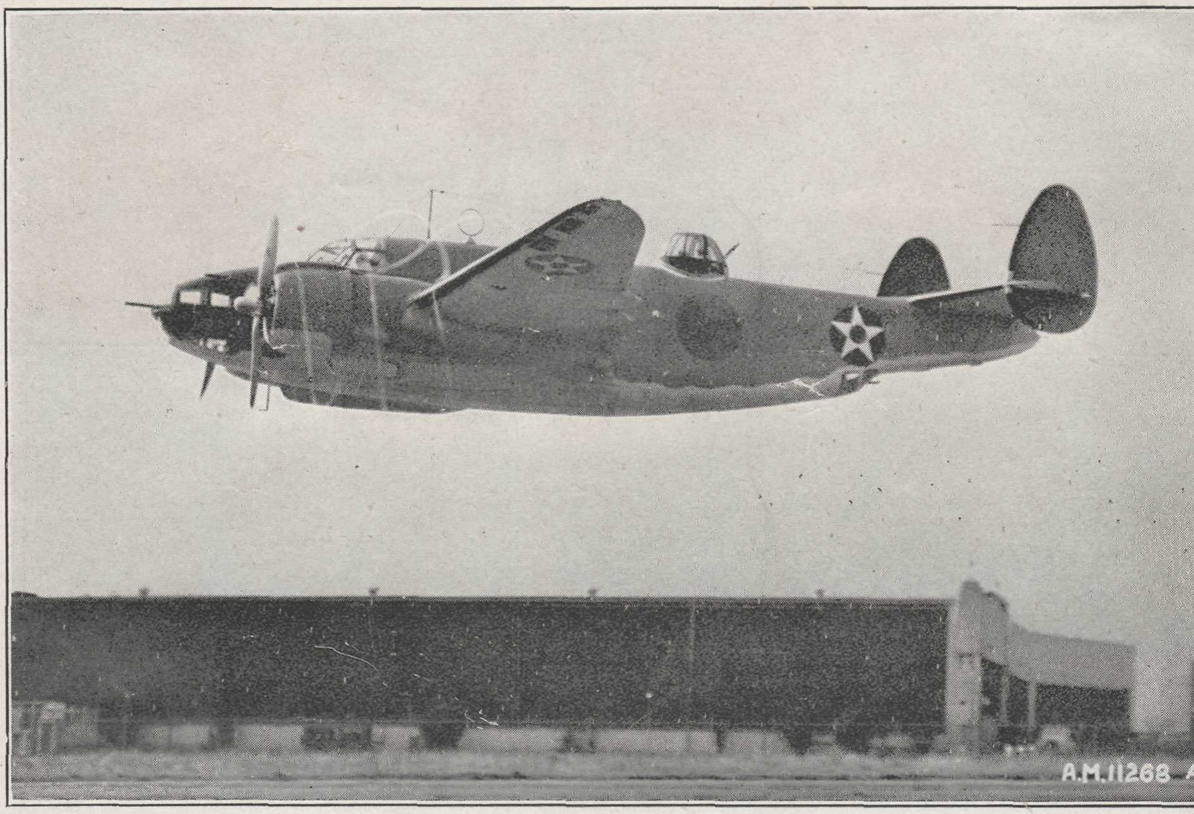

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FIG. 4.—PROPELLER-TIP CONDENSATION TRAILS

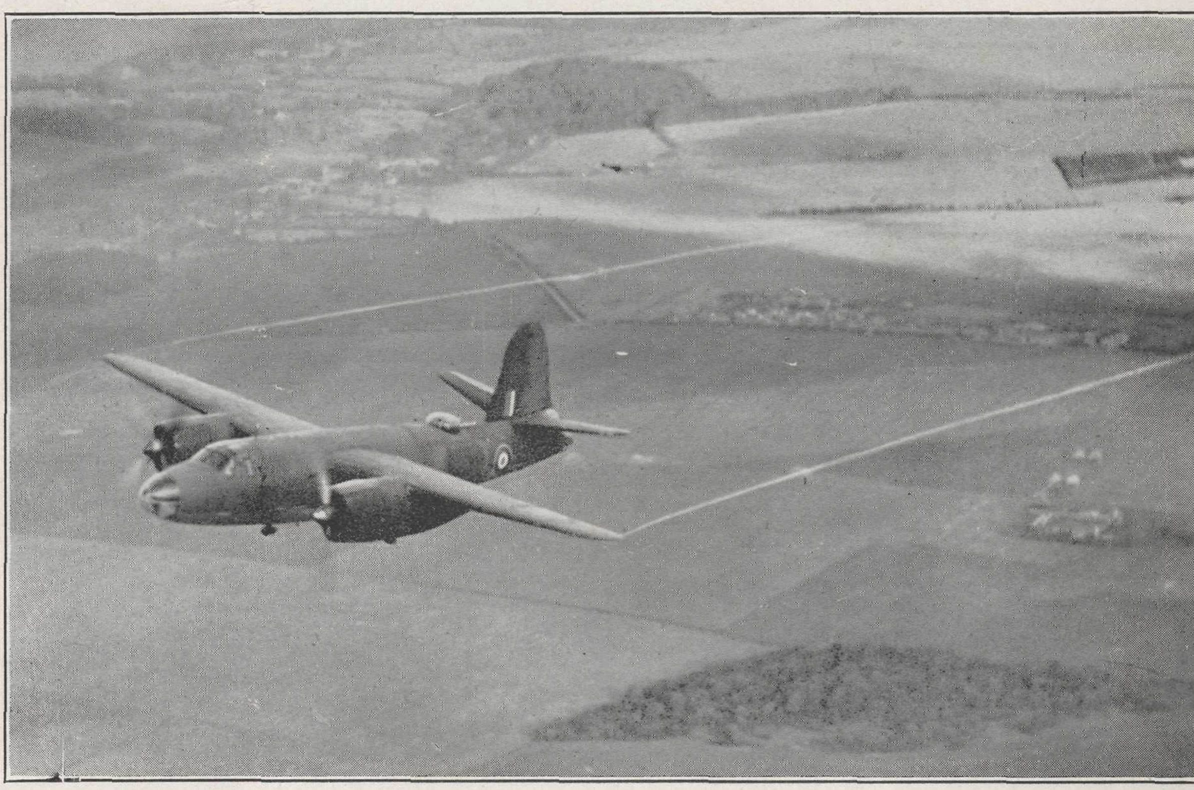

Photo by R.A.F.

FIG. 5.—WING-TIP CONDENSATION TRAILS

These figures (which depend on 106 observations and are purely relative) mean that for (9 Km.) winds from between E. and SW. there is trail formation at a relatively low excess of vapour, while for winds from between W. and E. through N. there is a definite lag in trail formation. The general result could mean that winds from the southern part of Europe (or from Africa) contain ample nuclei suitable for sublimation whilst winds from the northern seas and northern Europe are deficient in nuclei. The differences, however, might arise primarily from the differences in convection over the respective areas, convection being needed to carry up from lower levels any nuclei of terrestrial origin and incidentally also to carry up water vapour.

If, however, the differences depended mainly on water-vapour content of the air one would expect that winds from between about SW. and NW. should be marked by much more ready trail formation than is indicated by the statistics. The probability therefore is that it is nuclei of sublimation which account for the more ready formation of trails in winds from between E. and SW.

The frequency of cases of no persistent trail tells roughly the same story, but this is complicated by other causes, e.g. sufficiently low temperatures may not have been reached during the ascent.

TRAILS DUE TO PRESSURE REDUCTION

A pressure reduction δp produces adiabatically a temperature reduction δT given by

$$\delta T = 0{\cdot}29T \frac{\delta p}{p}$$

where T is temperature in degrees absolute. The maximum pressure reduction at any point on the wing of an aircraft with a speed of 350 m.p.h. at 10,000 ft. is about 170 mb. The position where this maximum pressure reduction takes place is on the top of the wing at about 15 per cent. of the chord from the leading edge of the wing. For the propeller tip on a similar aircraft the pressure reduction is of the order of 400 mb.

Condensation from pressure reduction over the wings would probably be of a highly ephemeral character were it not that the eddies around the wings tend to be shed in a fairly intense and persistent wing-tip vortex, the strength of which depends on the total span loading of the aircraft. The trails of adiabatic origin which are occasionaly seen—chiefly with large machines of heavy wing loading such as the Stirling—are mostly in the centre of the wing-tip vortex.

Experiments conducted in a wind tunnel at the National Physical Laboratory[7] indicated a possible pressure reduction of the order of 30mb. in this vortex, greater or less according to the angle of wing incidence and more persistent with rectangular than with half-taper or elliptic wing tips.

Wing-tip trails observed have commonly been of the order of 1,000 ft. long and possibly a foot or two in diameter. They are remarkable as giving the impression of smooth straight filaments with no evidence of turbulence. An excellent illustration is given at Fig. 5. The height in this instance was from about 800 to 2,500 ft., temperature about 40° F. ; the trails persisted for about 400 yd. The time required by the machine to travel this distance would be 3–4 sec. If water drops of 10μ radius were once formed they would take about this time to re-evaporate completely in air of relative humidity 90 per cent.

Propeller-tip condensation has been observed but is probably as a rule highly ephemeral (see Fig. 4). In some instances with a Boston aircraft at Boscombe Down, however, persistent trails were observed which without much doubt were formed by the propellers. When exhaust trails are formed by the Boston, the diffuse extension (according to Mr. A. W. Brewer, the Meteorological Officer on these occasions) can be followed right up to the engine exhaust. With the propeller trails no such exhaust stream was visible, but there was a plainly discernible white flickering behind the propeller which occurred only when the trails were being formed. Humidity measurements were made at the time with the Dobson ice-point hygrometer. On one occasion, at 23,000 ft. with a temperature of $-29°$ C., there was 125 per cent. relative humidity with respect to ice, 92 per cent. with respect to water. On another occasion, at 13,000 ft. at a temperature of $-7°$ C., there was even slight supersaturation with respect to water. In each case the region of formation was quite restricted, and it is very likely that meteorological conditions suitable for the formation of propeller-tip trails are rather uncommon.

BIBLIOGRAPHY

The following, except No. 6, Aeronautical Research Committee papers deal with special aspects of the problem :—

1. Goldie, A. H. R. ; Formation of cloud behind aircraft. 4956, H.A.S.42, T.A.160. 1941.
2. Dobson, G. M. B. ; Condensation trails from aeroplane engine exhaust and meteorological conditions. 4965, H.A.S.43, T.A.161. 1941.
3. Goldie, A. H. R. ; Condensation trails from aircraft. Condensation of water vapour from engine exhaust. 5032, T.4066, T.A.163a. 1941.
4. Goldie, A. H. R. ; Condensation trails from aircraft. Results of ascents Nos. 1–52 at Boscombe Down. 5092, T.A.165. 1941.
5. Lohner, H. ; Condensation trails. 5037, T.4069. T.A.164 (translation from German). 1941.
6. Sheppard, P. A. ; The physical properties of air with reference to meteorological practice and the air-conditioning engineer. *Trans. Amer. Soc. mech. Engrs, New York N.Y.*, **71**, 1949, p. 915.
7. Richards, E. J. ; Note on wing tip condensation trails. 5429, T.A.174, Ae.1876. 1941.
8. Goldie, A. H. R. ; Condensation trails from aircraft. Summary of present position. 5452, T.A.181. 1941.
9. Horrocks, H. ; Notes on the upper air ascents at Boscombe Down and the upper winds at Larkhill and Liverpool. 5449. 1941.
10. R.A.E. Departmental Note No. Met. 468 ; Interim note on "vapour trails" started by the passage of aircraft. 4955, H.A.S.41. T.A.159. 1941.

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