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CONDENSATION TRAILS

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The striking and very often beautiful trails formed by aircraft have been given a variety of names, but to avoid confusion it was agreed, in 1941, to call them all "Condensation Trails". This is a very suitable name and it will be used here and, we hope, generally adopted.

Condensation trails to an Englishman signify the high-flying aircraft of the Battle of Britain, but probably they signify raiding Fortresses to a German; certainly they are commonly associated with high altitude. This association is not an invariable rule, and trails of different kinds can be formed at any level according to the temperature and humidity, and also according to the type of aircraft.

There are three main classifications:—

1. Trails due to the water in the exhaust. These are essentially associated with low temperature and cannot form unless the temperature is below a critical value which varies from about -15°F . at the ground to about -45°F . at 40,000 ft. The trails form very close behind the aircraft, as can be seen from the upper photographs of Plate I which show how the trail begins at the Spitfire's tail. These trails are the most common and we will consider them in detail later.

2. Persistent trails, due to supersaturation of the air, which can be formed at any height provided the temperature is below 32°F . (0°C .). These trails are less frequent than the others but have proved important, as we shall see.

3. Short trails, usually very tenuous, formed at moderate or high temperatures by aerodynamic effects.

EXHAUST TRAILS

The exhaust trail is the commonest and is worth careful consideration. The theory of the formation of this type of trail was first worked out, more or less independently, by Dr. G. M. B. Dobson and by Dr. A. H. R. Goldie, and we may consider the theory briefly here.

The passage of an aircraft affects the relative humidity of the air in its wake in two ways. First, the heat of the engines and also the heat produced in drag on the aircraft heats the air and tends to reduce the relative humidity. On the other hand, each pound of petrol which is burnt produces 1.4 lb. of water, and this water is thrown out in the exhaust gases. The addition of this water to the air in the wake of the aircraft will tend to raise the relative humidity. A trail will only be formed if the net effect is to raise the relative humidity and so saturate the air, and this only occurs at low temperatures.

Readers who are interested in the mathematics of the problem may like to have the following simple discussion. Suppose that a weight of petrol w grams is burnt and the heat and water vapour are left in each cubic centimetre of trail. This will add a quantity $1.4 w$ grams of water vapour to the space, but it will also add $4,300 w$ calories (the calorific value of the fuel). This heat will be taken up by the air, which will have a weight ρ grams, where ρ is the air density in grams per c.c.

of air = 0.25. Now, if e_T is the saturation water-vapour density in grams per c.c. at the temperature T , the rise in temperature will increase the capacity of the cubic centimetre to hold water by the product of the rise in temperature and $\frac{de_T}{dT}$, i.e. by $\frac{4,300 w}{\rho C_p} \cdot \frac{de_T}{dT}$; but since a quantity of water $1.4 w$ is added to the space, a trail will only be left if $1.4 w$ is greater than $\frac{4,300 w}{\rho C_p} \cdot \frac{de_T}{dT}$, i.e. if the water added is greater than the increased water-holding power due to the increased temperature.

Now w , the rate of consumption of fuel, cancels out and the only factors which vary are ρ and C_p . ρ , of course, changes from about 1×10^{-3} near the ground to about 0.2×10^{-3} at 40,000 ft., a ratio of 5 to 1. This change causes the critical temperature for trail formation to vary with height. But the variation of $\frac{de_T}{dT}$ is the predominant factor. At high

temperatures both e_T and $\frac{de_T}{dT}$ are large, but at low temperatures e_T and $\frac{de_T}{dT}$ are very small, so that below a certain temperature the humidity will be increased and a trail will be formed if the air is moist already. It will be seen that the effect of temperature is very rapid, for, within the range of temperatures which are found in the atmosphere, $\frac{de_T}{dT}$ varies through a ratio of nearly 100,000 to 1. The effect of this rapid variation of $\frac{de_T}{dT}$ is to make the effect of temperature very much more important than the effect of humidity or height in determining the onset of trails, for even if the relative humidity is quite low, the passage of the aircraft can saturate the air behind if the temperature is a little lower.

The trail, of course, spreads and diffuses behind the aircraft, but if the air is generally saturated the trail cannot evaporate, or can do so only very slowly, and a very long and persistent trail is formed, as is well known. An excellent example of such a trail made by Fortress aircraft at 32,000 ft., which could be seen for some time from most parts of East Anglia, is shown on the cover photograph. If, on the other hand, the general relative humidity is low, the trail will evaporate behind the aircraft and will only appear as a short plume behind it. Actually, the really persistent trails are almost always associated with the supersaturation in the upper air, in which case the trail, once formed, thickens instead of evaporating, and after a few minutes snow can usually be seen falling from it.

Observations made from high-flying aircraft mainly confirmed this theory, as also did the known fact that the trails were often observed *on the ground* in Canada when the temperature was low. This was in accordance with the theory which predicted a temperature of about -10°F. as the critical temperature at ground level. One very striking feature of the early observations was the invariable shortening of the trail in the stratosphere, quite irrespective of whether the trails were long or short in the troposphere. (The earliest observations were mainly made by the late S/Ldr. Longbottom, D.F.C., whose work in this connexion should receive more than a passing tribute.)

The theory given above was not universally accepted; in particular it was not accepted by the Americans who regarded the marked shortening of the trail in the stratosphere as due to decrease of engine power at a great height; so, as soon as it was possible, experiments were made to investigate trail formation.

It was first necessary to develop a hygrometer capable of measuring the water content at the very low temperatures concerned. This was done by adapting

and improving the dew-point hygrometer which in its primitive form is a very old instrument. A description of the instrument which was developed is given in the 1945 Bakerian lecture to the Royal Society (*Proc. Roy. Soc. A*, Vol. 186, 1946, p. 146) and none will be given here. It will suffice to recall that the instrument measures the temperature to which the air must be cooled to make it saturated with respect to ice, and the depression of the frost point is a very convenient measure of the humidity. Zero depression, of course, means 100 per cent relative humidity. Also the relative humidity corresponding to a given depression only changes slowly according to the air temperature. If the air is supersaturated with respect to ice this is shown as air with a frost point higher than the air temperature, and this is not uncommon in the upper atmosphere.

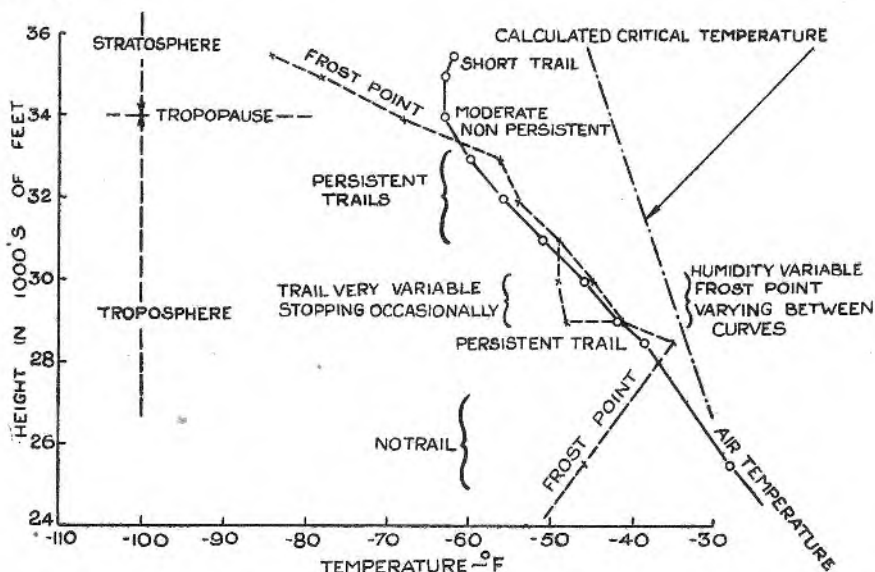


Fig. 1. The variation of temperature, frost point and condensation trail length on September 7, 1943.

Figures 1 and 2 illustrate the results of two ascents; only the high altitude part is shown, because the temperature at lower levels is far too high to permit trail formation. The diagrams show air temperature and frost point plotted against height, and indicate the trails which were formed. It will be seen that when the air is saturated, or supersaturated, the trail is very long or persistent, and when the air is dry the trail shortens. Figure 1 shows how the air dries and the trail shortens in the stratosphere, but Figure 2 shows it in a very much more striking way. The invariable extreme dryness of the stratosphere is a remarkable feature of all the results which have been obtained. The average relative humidity 3,000 ft. into the stratosphere in temperate latitudes is probably about 2 per cent. It is hardly remarkable that the condensation trail from an aircraft rapidly evaporates and is always short in the stratosphere.

The Americans, in refusing to accept the observation that the trails are always short in the stratosphere, missed the first hint of this which is, perhaps, one of the more surprising discoveries in recent meteorology.

It might be wondered why a trail is formed at all since the air is so very dry. This, of course, is due to the overwhelming effect of the low temperatures.

TRAILS DUE TO SUPERSATURATION OF THE AIR

Before we consider the production of trails in supersaturated air we must first consider the meaning of the term when applied to the upper air.

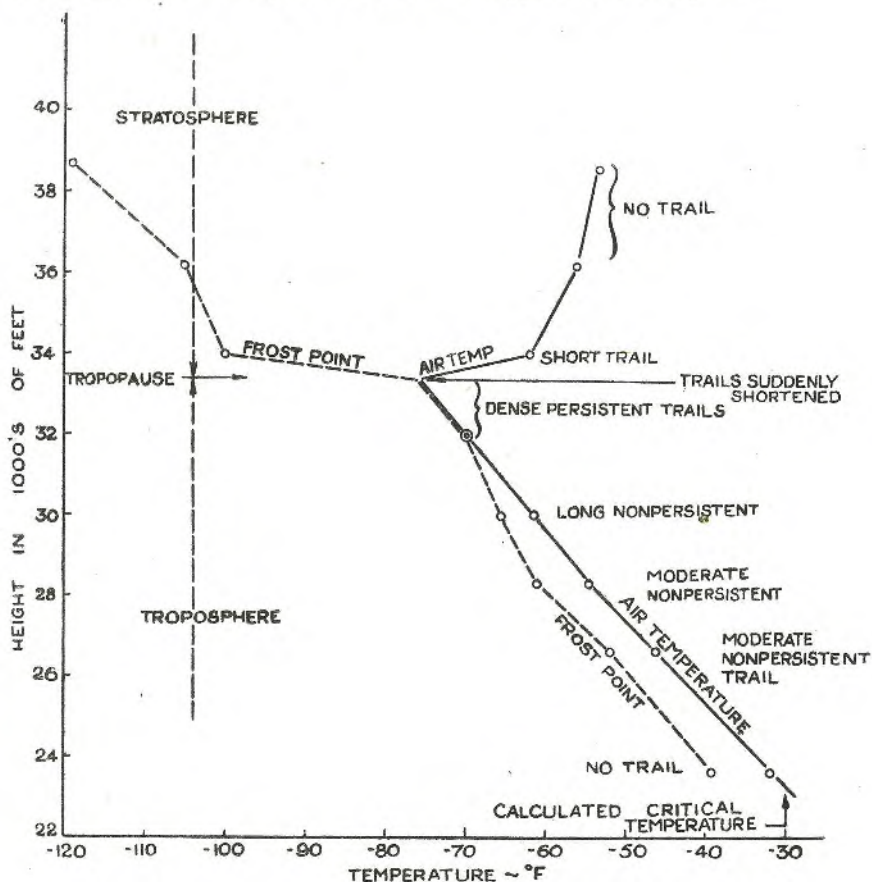


Fig. 2. The variation of temperature, frost point and condensation trail length on May 30, 1945.

At temperatures above the freezing point, water (that is the chemical substance H_2O) can only exist as liquid or vapour, and the saturation vapour pressure is the vapour pressure over water. It is quite possible in *very* clean air to obtain supersaturation, and C. T. R. Wilson showed that supersaturation of some 400 per cent is necessary to produce cloud in the cleanest possible air. In practice, in the atmosphere, significant supersaturation at temperatures

above 0°C . is never found—as soon as the humidity begins to exceed 100 per cent cloud begins to form.

Below the freezing point, water can exist either as ice or supercooled liquid, and vapour. The supercooled water is, however, unstable and will readily freeze, and as every pilot knows, supercooled water-drops, which cause icing on aircraft, are only too common. Now at a given temperature, below 0°C . of course, the saturation vapour pressure over ice is less than the saturation vapour pressure over supercooled water. The difference in the two vapour pressures is at a maximum at about -10°C . ($+15^{\circ}\text{F}$.), but the ratio of the two increases as the temperature gets lower. At -75°C . (-105°F .) air saturated with respect to ice has a humidity of only 50 per cent with respect to supercooled water. It is therefore quite possible for the air to be supersaturated with respect to ice without being supersaturated with respect to water. Supersaturation with respect to water is never found in the atmosphere, but *supersaturation with respect to ice is quite common*. Apparently, nuclei which assist in forming the water-drops do not serve to form ice crystals, and the nuclei which are necessary to form ice crystals are rare or are only effective at low temperatures, and significant supersaturations with respect to ice exist quite easily. (A very beautiful piece of research into this problem has been made by B. Cwilong, and is referred to in the Royal Society paper mentioned above.)

A detailed discussion of the interesting problems involved is out of place here; but it must be noted that there is no difficulty, if the air temperature is below 0°C ., in obtaining a region where the air is supersaturated with respect to ice and where the provision of the necessary nuclei can produce a cloud of ice crystals.

An aircraft seems to produce the nuclei and leave them in the exhaust gases, and as a result it will leave a trail if the air is supersaturated whatever the temperature. The only restriction is that, in the atmosphere, significant supersaturation will only be obtained if the air is below 0°C . We saw, however, that if the temperature is low the passage of the aircraft will increase the humidity; if, then, the air is already supersaturated, a trail will be formed immediately behind the aircraft, and it will persist and perhaps thicken until it falls out as snow.

Should the temperature be above the critical temperature the passage of the aircraft will temporarily decrease the supersaturation. But just as at low temperatures in dry air the humidity returns to its original value, and the trail formed by an aircraft evaporates, so at high temperatures in supersaturated air the supersaturation returns at a distance behind the aircraft, and a trail of cloud is then formed by condensation upon the nuclei left by the aircraft. A persistent trail is thus formed, detached from the aircraft by a distance which depends upon the conditions.

Trails produced in this way have not proved unimportant. On one raid made by Bomber Command on Nuremburg a loss of 93 aircraft was incurred, due very largely to the assistance given to German night fighters by trails formed at a temperature much too high for exhaust trails of the type we have

considered above. An excellent example of this was shown in a less unfortunate way on February 4, 1944 when Fortress aircraft, circling while making formation, made trails which eventually produced a continuous sheet of cirrus cloud at an unusually low level over most of Southern England. These trails were formed at any level from 14,000 ft. to 23,000 ft. at temperatures between -7°F . and -21°F . which are too high for exhaust trails.

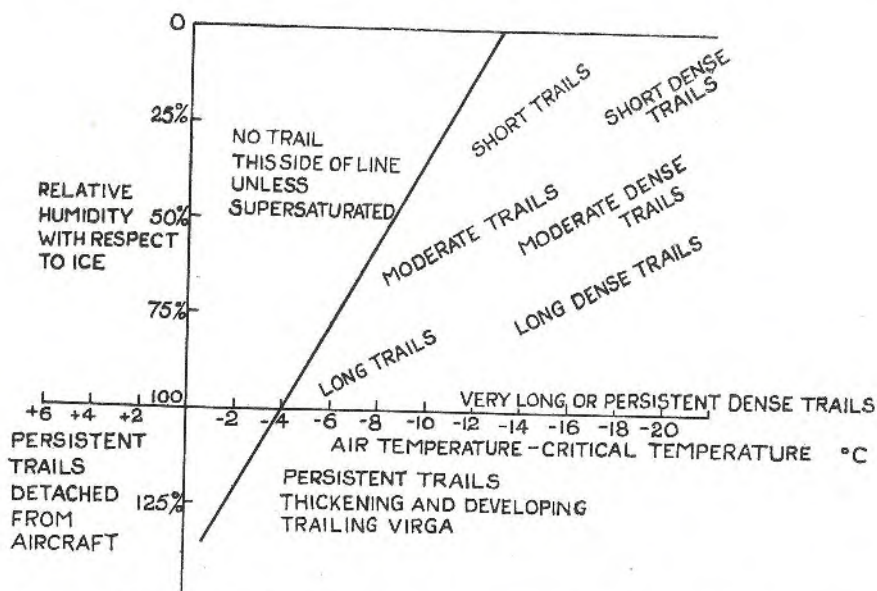


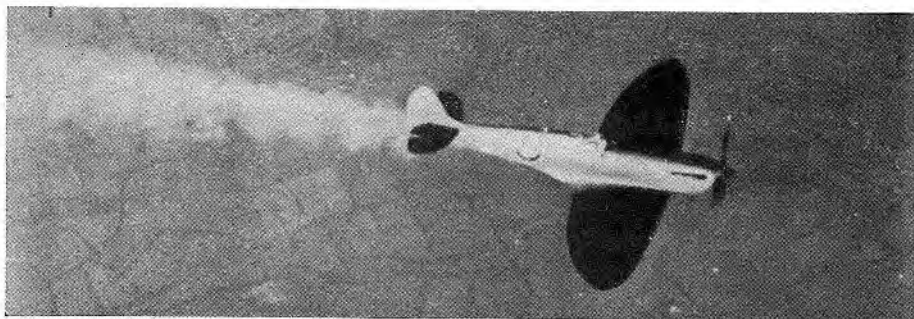
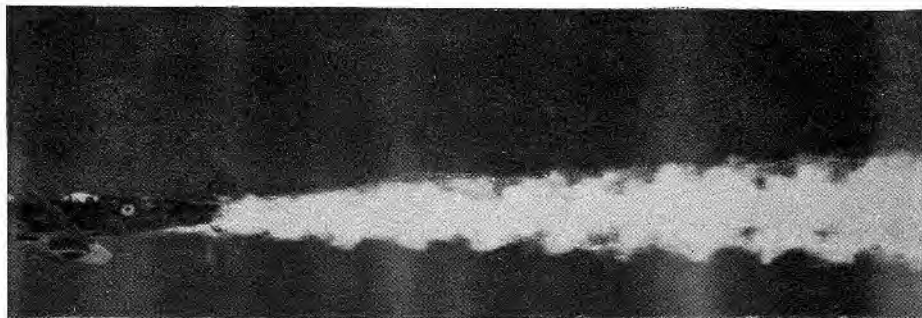
Fig. 3. The variation of condensation trail length with humidity and the depression of the air temperature below the calculated critical temperature.

WING-TIP TRAILS

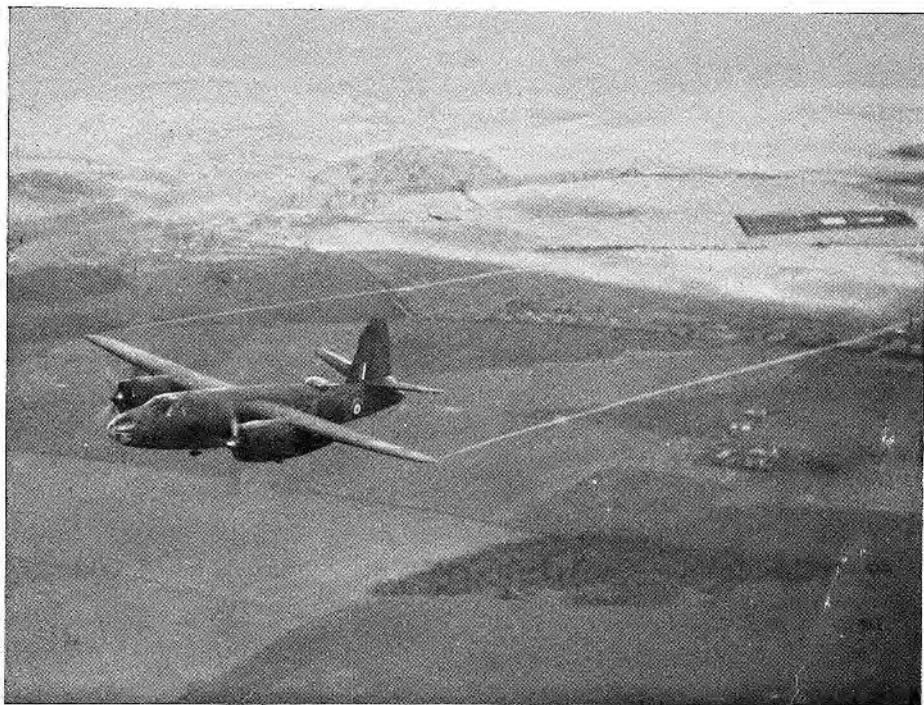
Aerodynamic trails are caused by local reduction of pressure by the wings or propeller of an aircraft; the reduction of temperature is never very large, and if the temperature is already low there will not be sufficient water made available to produce a visible trail.

The lower half of the plate shows a Marauder aircraft making wing-tip trails over Southern England. The trails, which can be seen as fine traces from the wing tips, are almost an artist's dream. They are produced only by aircraft with heavy wing loadings, such as a Marauder or a Stirling, or occasionally by a Mosquito or a Lightning doing aerobatics which increases the effective wing loading. They are usually seen in mild damp weather, because if the air is dry a trail cannot be formed and if it is very cold there is not sufficient water to make a visible trail.

Similar effects can sometimes be seen at the tips of propeller blades and also over the upper surface of an aircraft wing in flight. In all cases trails of this kind soon disperse, and we need not consider this type of trail further.



Spitfire making exhaust trails



Excluding the delicate though beautiful trails of aerodynamic origin, such as wing-tip trails, we may summarize the position of the formation of trails, either in supersaturated air or in dry air due to exhaust water vapour, in one diagram which is reproduced as Figure 3.

This diagram is not very precise, because the exact time of the commencement of a trail is not sharply defined, and also because of the difficulty of observing the length and density of the trail; but it gives a very good idea of what happens. In the figure the relative humidity *with respect to ice* is plotted against the value of air temperature minus the critical temperature calculated according to the theory of Dobson and Goldie. The various areas indicate the type of trail which will be obtained.

The interesting points to note are (a) the effect of temperature is such that the onset of trails is only delayed about 9°C . (16°F .) by a decrease in the relative humidity from 100 to 0 per cent; (b) the long trails are formed at high humidities assisted by low temperatures; and (c) the dense trails are associated with temperatures well below the critical temperatures. One peculiar feature, the reason for which is not very clear, is that the trails do not begin until about 4°C . (7°F .) *below* the calculated critical temperature. This may be due to the difference between a mathematical trail and a trail with sufficient substance to see, the additional lowering of temperature being required to provide a visible trail.

The humidity measurements made in the upper air have been carried out as part of the work of the Meteorological Research Flight and this note is published by kind permission of the Director of the Meteorological Office.

The photographs are due to R.A.F. Photographic Reconnaissance Units and also to Mr. D. J. Dearnley. The results of flights made, in 1941, by the Aeroplane and Armament Experimental Establishment, Boscombe Down, have been freely drawn upon and I have pleasure in acknowledging the great value of these results.