TECHNICAL MEMORANDUMS

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No. 499

DANGER OF ICE FORMATION ON AIRPLANES

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By W. Kopp.

Aeronautical experts exphasize the fact that ice formation on airplanes occurs comparatively seldom. It may, however, in individual cases, become such a menace as to render a complete account of the conditions for its occurrence very desirable. Such an account will help the meteorologists to issue timely warnings against this danger and may also open the way toward its control or prevention. In a previous paper, Dr. Hebner** has already brought together a few viewpoints on this problem without, however, aspiring to make his report a complete account. A few additional and correcting remarks may therefore be permitted.

In commercial air transportation, cases of ice formation are much less frequent than in transoceanic or other long-distance flights for special purposes, during which it may be unavoidable to fly through extensive cloud areas. It is necessary, however, to consider the ice danger even in commercial flying, since cases have occurred already where regular transport airplanes have had to climb to higher levels, in order

*From "Erfahrungsberichte des Deutschen Flugwetterdienstes" (Reports of the German Aeronautical Weather Service). This translation was made and submitted by The Daniel Guggenheim Fund for the Promotion of Aeronautics.
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to avoid dangers of this type.

Mr. Hebner's report discusses the danger of ice formation not only when flying in fog and clouds, but also in rain, when the rain is falling from warmer through colder strata with temperatures below freezing. Unfortunately, no actual instances of ice formation are quoted, from which the nature of the ice and the immediate cause of the eventual forced landing may be deduced. It would be a great help if the meteorologist had the opportunity to gather information in this respect, so that he would know just what particular point to keep in mind in making his forecast. Due to this lack of data, it will be necessary to discuss the problem from a purely meteorological angle.

As emphasized by Hebner, in fog (or clouds) at low temperatures, the ice coating is formed by subcooled water droplets congealing as they strike the airplane, the temperature of which is likewise below freezing. However, it seems to be of the greatest importance to discuss the nature of the deposit in a more general way. Three main types may be distinguished.

1. Hoarfrost (Rauhreif) is formed by <u>sublimation</u> and consists of fine crystals, arranged in the direction of flight of the airplane, on the windward edges of the wings, etc. This type of deposit will hardly affect the maneuverability of the airplane, or cause any trouble by changing the profile of the wings or propellers. The deposit is very seldom so thick that the increased load would necessitate a landing. <u>This type</u>

of deposit may form when the fog is very thin or even unnoticeable. It is usually assumed that a temperature below -10°C (14°F) is required for the formation of hoarfrost.

2. Rime (Rauhfrost) occurs when the number of water droplets in the air is larger. In this case the visibility is, of course, poorer and a flight is therefore rarely started. However, since humidity conditions may show strong local variations, one cannot always avoid flying through dense fog banks. Then a considerable deposit of rime may occur which, however, affects the maneuverability of the airplane less than it adds weight and changes the profiles. The latter changes probably affect the wings less than the propellers. Of course the latter will not, as stated by Hebner, work irregularly and lose R.P.M. (which is the affair of the engine), but they will lose in efficiency.

3. Ice (Rauheis) forms when the temperatures are not very low and the subcooled drops are so large that they flow together before congealing. In deposits of this kind the bad effects on the maneuverability must be considered as well as the increase in weight, while the effect on the profiles is of less importance. It should also be added that, in case of ice formation, the visibility may be relatively better, due to the larger drops, than in the previous case, which may lead to an underestimation of the danger. However, as has been stated be-

fore, the experience of the pilots themselves must finally determine which type of deposit should be regarded as most dangerous.

It is hardly possible to state, even approximately, how far an airplane can fly through subcooled fog. In one case it is possible to travel long distances (even several hundred kilometers); in another case the catastrophy may come within 5 or 10 kilometers (3 to 6 miles). At any rate, it is peculiar that, under apparently similar conditions, ice will sometimes form, but at other times will not. Often, after a flight which is trouble-free at the start, ice will form with great rapidity. This seems to indicate that, besides the subcooling, another factor must also be considered, namely, the strong supersaturation of the fog with ice. Before entering into a discussion of this factor, we must, however, determine when ice formation in fog is most likely to occur.

Few experimental data are available on this question. We may, however, with a certain amount of justification, make use of the material collected by W. Peppler* concerning ice formation on kites and kite strings in clouds, since the principle is the same, whether we speak of clouds or of fog. Peppler's table is reproduced below.

*Beiträge zur Physik der freien Atmosphare, Vol. 10.

Frequency of Various Temperatures at Cloud Base

Temperature in° C	4.1 / 6.0	2.1 / 4.0	0.0 / 2.0	-0.1 / -2.0	-2.1 / -4.0	-4.1 / -6.0	-6.1 / -8.0	- 8.1 / -10.0	-10.1 / -12.0	-12.1 / -14.0	Mean temp.
Frost formation	2	0	10	52	47	34	21	18	8	2	-4.0
Ice formation	1	7	29	38	15	6	3	1	1	0	-1.0

From these figures it may be seen that frost or rime most frequently occurs with temperatures around -4°, and ice with temperatures around -1°, at the base of the cloud layer. The temperature in the interior of the cloud may therefore be assumed to be approximately -6° in the former, and -4° in the latter case. Peppler also gives the temperature for the various cloud forms at times of ice or frost formation and finds (at the base of the clouds):

Fog	Nimbus	Stratus	Cumulus	Stratacumulus
-2.7°	-1.0°	-3.1°	-3.2°	-5.1°

Rime or frost are therefore, corresponding to the lower temperatures, more frequent with stratiform clouds, while ice is more frequently formed in nimbus clouds. This is clearly shown by the following table given by Peppler.

	Stratus	Nimbus	Cumulus	Stratus Cumulus	Alto-Stratus & Alto-Cumulus
Rime or Frost formation	110	62	5	40	1
Ice formation	38	56	4	18	3

The data below are characteristic of a typical rime-producing cloud:

Cloud base	Cloud top	Mean temperature	Temperature lapse rate ground-cloud base	Temperature lapse rate in cloud
530 m	950 m	-5.0^{o}	$0.68^{o}C/100$ m	0.65

Judging from the lapse rates, this is a case of an almost saturated air mass from the ground up to the cloud. Frequently fog actually occurs in the surface layers. The conclusion is therefore obvious that fogs and clouds at the above quoted temperatures are especially dangerous to flying. However, as stated above, under almost identical conditions, ice may sometimes occur and sometimes not.

The statistical material, concerning the relation between ice or frost formation and the weather situation, shows that the danger is greatest in the transitional zone between a low-pressure and a high-pressure area.

Cases of Ice or Frost

Cyclone				Zone of transition	Anticyclone			
West 41	North 14	East 16	South 76	95	West 17	North 16	East 15	South 33

The frost and ice formations here discussed may, of course, also occur on the ground but, even if allowed to continue for long-time intervals, do not become so intense as to indicate any real danger. We must therefore consider another element responsible for the suddenness of the ice formation. This element is the occasional strong supersaturation of the atmosphere with ice.

At the negative temperatures with which we are concerned, the supersaturation is easily computed as the difference between the observed relative humidity and the relative humidity to be expected in case of saturation over ice.

If we represent graphically the mount of supersaturation over ice at various negative temperatures, assuming the recorded relative humidity to be 100%, we obtain the curve in Figure 1.

If an airplane should meet with such supersaturations, ice or frost will form and we are probably justified in regarding the curve as a measure of the flying possibilities in temperatures below 0° and with 100% relative humidity.

Subcooling and supersaturation are the usual phenomena at temperatures below freezing. The intensity may vary, however. In typical winter stratus with very cold air below and warm air above, the supersaturation often begins at the lower surface and increases upward. Not infrequently the winter stratus locally reaches clear down to the ground, in spite of which the horizontal visibility in the surface layer may be sufficient from the viewpoint of flying. Examples of this nature will be given below. The following observation shows how streng the supersaturation may be, even at the ground. During the winter of 1927, I had the opportunity to observe a frost deposit of 1 cm at the ground. The horizontal visibility was 1.5 km. The tops of the 80-meter radio towers were occasionally obscured. Ascending one of the towers, I found that at 20 m elevation a 1-centimeter thick rope had a maximum diameter of 3 cm, while the same rope at 80 m had a maximum diameter of 9 cm from the deposit of rime. An airplane from the east might easily have been forced to fly toward its goal at an elevation of 80 to 100 meters. Very intensive ice formation would then have resulted. Still thicker frost formations are often observed in the 800 to 1000-meter mountains in central Germany (Mittelgebirge) where a deposit of 3 cm per hour may often be observed. Still higher mountains are often free from deposits since they reach through the frost clouds into the dry layers above.

The danger of flying in supersaturated air layers is increased by the more or less rapid sublimation of water vapor (high pressure over water) on the already ice-coated airplane (lower pressure over ice). This process is intensified if the ice-coated airplane already has a lower temperature than the surrounding air. To illustrate this, one may point to an example from the cloud theory. If an ice crystal from a colder layer falls through a warmer but supersaturated water cloud amorphous ice is then deposited very rapidly on the crystal. A. Wegener believes that the greatest known hailstones have to be explained in this way. If, instead of an ice crystal, we assume an airplane to be coming from a colder into a warmer supersaturated layer, then an intensive or even catastrophical ice formation is possible. One may ask if the airplane does not very rapidly assume the temperature of the surrounding air, especially if it is an all-metal one. However, in the first place, the changes in elevation usually take place so rapidly as to make a certain lag in the temperature unavoidable. In the second place, the ice coating on the aluminum is strongly insulating, as is best seen from a comparison of the heat conduction coefficients of aluminum and ice (aluminum, 34-35; ice 0.568, 0.5, 0.23, according to the nature of the ice).

The just-described conditions for sudden and violent ice formation may occur:

1. During flights in surface fog.
2. When the airplane descends from colder through warmer (supersaturated) layers.

There is special danger in these phenomena during trans-oceanic flights.

It is therefore difficult to agree with Hebner, who holds the opinion that the subcooled and supersaturated layers in the atmosphere are of small extent. On the contrary, these layers may be very extensive, both vertically and horizontally, especially at the beginning of a new period of cyclonic activity. As already shown, this is also the time when the ice danger reaches its maximum. It is just when the frost on the ground begins to melt and rain or sleet begins to fall that warning against flight should be given, even if the temperature at the ground may already be around or even above freezing.

Lastly, it is also desirable to take a stand with regard to sleet (Eisregen). Sleet (frozen raindrops) will not in itself lead to ice formation. The rain that hits the airplane and sticks to it will hardly produce any real change of profile, but may affect the maneuverability of the airplane to a considerable degree. Eventually, it should be possible to guard against this result. It may be mentioned that falling subcooled water droplets have often been observed in spite of the friction currents which might prevent the subcooling. In the case of subcooled rain, the ice coating on the airplane must necessarily be thinner than the corresponding ice formation on the ground, since its thickness depends only on the time during which the still or moving object is exposed to the rain. The thickest ice layers formed on the ground by rain below the freezing point have had a thickness of 2 to 3 centimeters. This would correspond to a load of about 20 kilograms per square meter. This, however, is an extreme case. In the problem of ice formation on airplanes, rime plays much the more important role.

Now let us glance at a few examples of the various types of ice formation.

Ascent of December 30, 1927, at Lindenberg

Elevation m	Temperature deg.	Humidity %	Supersaturation in %	Visibility at ground
120 (ground)	-6.0	95.0	0.6	7 km
500	-9.0	91.7	8.3	

Stratus clouds, frost and ice on kite strings.

Take-off possible, but supersaturation increases rapidly with elevation, therefore danger of ice formation in spite of rather good visibility.

December 3, 1927

Elevation m	Temperature deg.	Humidity %	Supersaturation in %	Visibility at ground light fog
120 (ground)	-6.0	92	-	3½ km
300	-8.0	98	5.4	
400	0.0	40	-	

Stratus at less than 100 meters above the ground; frost on kite string.

Take-off possible, but supersaturation increases upward, therefore danger of ice formation in spite of rather good visibility.

December 14, 1927

Elevation m	Temperature deg.	Humidity %	Supersaturation in %	Visibility
120 (ground)	-0.2	98	-	At ground 800 m; Vertical visibility 110 m.
400	-2.0	100	1.9	
920	-6.0	100	5.6	

Frost on string, 7 mm of ice, kites will not stay in air.

Although both vertical and horizontal visibilities may be regarded as sufficient, a flight would be dangerous. Note especially that the temperature at the ground is around 0°C, from which fact one should not conclude that the danger is small. The greatest danger of ice formation is in flying <u>downward</u> through this layer of air.

December 22, 1927

Elevation m	Temperature deg.	Humidity %	Supersaturation in %	Visibility at ground hazy
120 (ground)	- 7.0	92.5	-	4 km
280	-10.0	95.0	4.1	
600	- 2.0	100.0	1.9	

Intensively subcooled rain (Eisregen), instrument and kites covered with ice. Cloud base between 200 and 300 meters.

The visibility would permit a flight. Supersaturation rapidly increases with elevation. An attempt to fly through the cloud layer in order to find layers with temperatures above freezing would be a mistake. The airplane would reach supersaturated air at -2.0°C with a temperature difference of 8°C and with a coating of ice.

In summarizing, the following may be said:

1. Rime seems to play the more important role in the formation of ice on airplanes, and forms rapidly in supersaturated layers.

2. Rain falling from warmer through colder layers, seems

to be of secondary importance.

3. The temperatures in case of ice formation are slightly below 0°C, in rime formation between -2° and -10°C. At very low temperatures ice formation is rather unusual.

4. In very high clouds ice formation almost never occurs, as experience in the airplane ascents at the observatory at Lindenberg has shown.

5. Rime is deposited in the same way on metal, wood and other materials.

6. It would be wrong to disregard the possibility of ice formation when the temperatures along the whole flight path are above freezing and rising. At a very low elevation above the ground, the possibility of ice formation may again occur. Very often the strong winter temperature inversion has already disappeared when the temperature, after a period of frost, again reaches freezing. In other words, no layers with positive temperatures (above freezing) will then be found at higher elevations.

7. If the instrumental arrangements on board the airplane so allow, and in case of ice danger under a winter stratus layer from which there is no precipitation, it is usually advisable to fly through the cloud layer. Usually one will find very warm

and extremely dry air even below 1000 meters.

8. Forecasts or warnings of ice danger, which should not be issued more frequently than absolutely necessary, are possible only with the aid of temperature and humidity soundings of the upper air.

9. Lastly, it may again be emphasized that as detailed information as possible regarding the character of the ice coating is desirable.

Translation by
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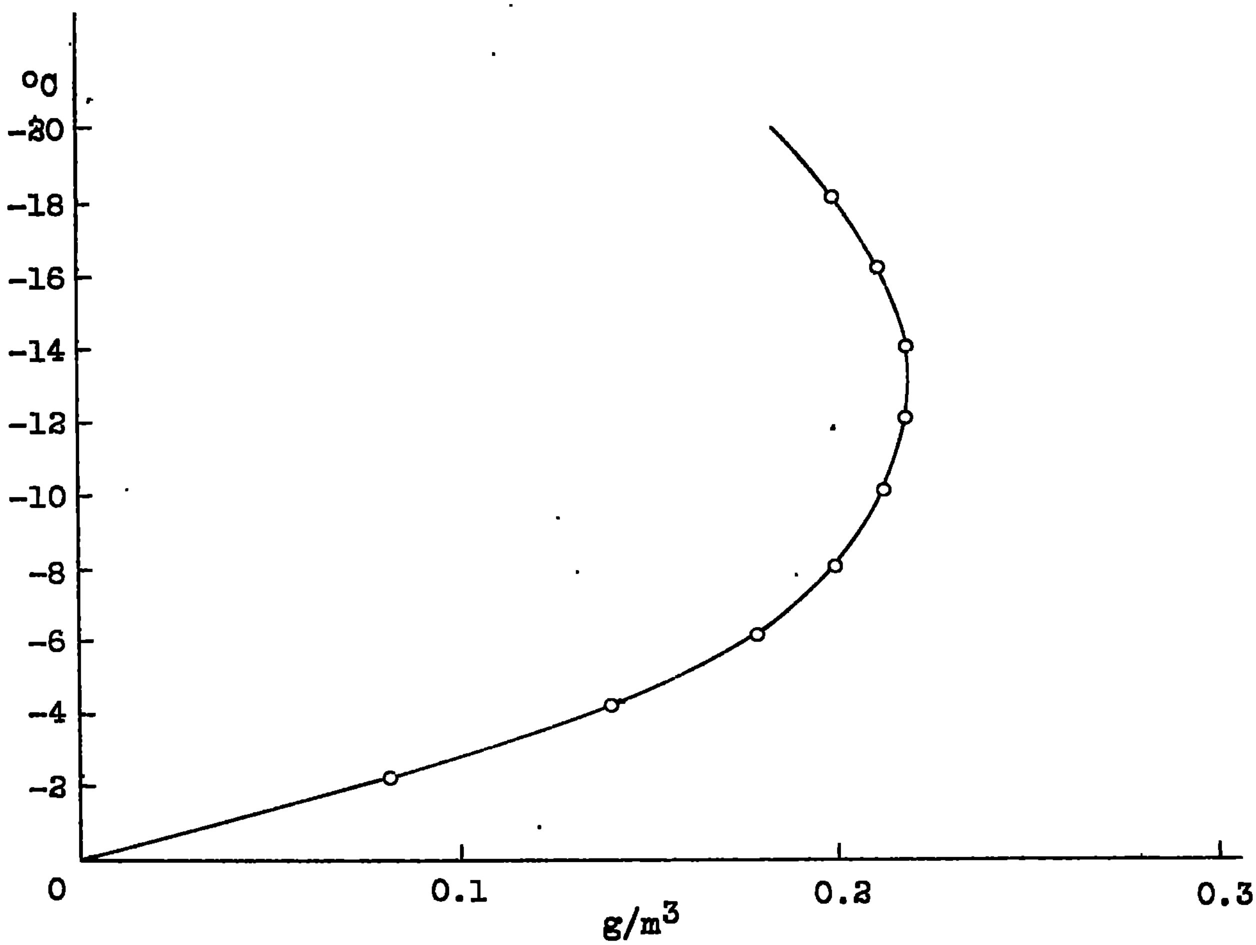

Fig.1 Supersaturation in g of water per m^3 of air at different temperatures by 100% recorded relative humidity.