ICING DEGREE MODERATE TO SEVERE: IF AND WHERE IN CLOUDS

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Abstract

During the first years of the research project on the 'Icing of Aircraft' at the DFVLR, the investigations concentrated on determining how the normalized ice accretion and the normalized degree of icing depend on the physical properties of clouds. They were conducted on icing flights with the DFVLR icing research aircraft. The total icing-flight time of 28 hours extended over three winter half-years. These icing flights showed that, on the whole, the normalize degree of icing corresponded to the degree of icing related to the aircraft, of type Do 28. Nevertheless, about 7% of the flights measured normalized degrees of icing as trace or light, whereas the degree of icing related to the aircraft could become moderate or severe. This was always the case when both the leading edge and the underside of the wing were become iced. The ice accretion could extend to 70 cm, infact far beyond the boots which pneumatically de-ice this type of airplane. The roughness of the ice layer could be as much as 15 mm. The analysis of all icing flights over one winter shows that the underside of the wings always iced up when the temperature was high (mean value -3.7°C) and the median volume diameter (it is a criterion for particle size distribution) was large (mean value 26.5 μm). The value for the total water content did not differ according to the whether the underside of the wing collected ice or not. Because of the relatively high temperatures at which the wing accreted ice, the ice was elastic, and could not be completely removed by the pneumatic deicer. The vertical structure of the clouds meant that the hazard of severe icing was limited to narrow bands in the cloud.

1 Introduction

The Institute for Atmospheric Physics of the German Aerospace Research Establishment (DFVLR) has been conducting the 'Icing of Aircraft' research project for some years. Initially work concentrated on determining the connection between clouds' physical parameters and normalized ice accretion thickness, and the normalized and aircraft related degree of icing. For conducting investigations, a DFVLR aircraft of type Do 28 was equipped as an icing research aircraft. The degree of icing was determined during flights through icing clouds, while simultaneous measurments were made of the clouds' physical parameters which were relevant to icing: temperature, total water content, particle size distribution and, with restrictions, the particles' phase. The normalized degrees of icing used here were defined by the U.S. National Coordinating Committee for Aviation in 1964 (3). In these definitions the ice accretion thickness of 1/2 inch in the direction of flow on a 1/2 inch rod is related to the flight distance in clouds required for the accumulation of 1/2 inch of ice. The shorter the flight distance in clouds needed to accrete 1/2 inch thickness of ice, the more intense is the degree of icing.

Specifically:

Normalized degree of icing	Flight distance in clouds
Trace	80 NM
Light	40 NM
Moderate	20 NM
Severe	10 NM

Reference (4) defines normalized degrees of icing similarly, but they relate to a 3 inch diameter rod. References (4, 5, 6 & 7) contain data that relate the normalized degrees of icing to the clouds' physical parameters: temperature, total water content, particle size distribution and particle phase. The normalized degrees of icing are used in airworthiness certificates, in icing forecasts and for calibrating ice warning instruments.

Besides these normalized degrees of icing, there are degrees of icing that are based on the restrictions to flight that are caused by different amounts of icing on an aircraft. In 1968, while considering potential deicing and anti-icing equipment, the USA Subcommittee for the Aviation Meteorological Services in the Office of the Federal Coordinator for Meteorology gave the following definitions for aircraft related degrees of icing: (4):

Trace

Icing becomes perceptible. Rate of accumulation is slightly greater than rate of sublimation. It is not hazardous even if deicing/anti-icing equipment is not used, unless encountered for an extended period of time - over one hour.

Light

The rate of accumulation may create a problem if flight is prolonged in this environment (over one hour). Occasional use of deicing/anti-icing equipment removes (prevents) accumulation. It does not present a problem if the deicing/anti-icing equipment is used.

Moderate

The rate of accumulation is so great that even short encounters become potentially hazardous and use of deicing/anti-icing equipment is necessary, or a diversion must be made.

Severe

The rate of accumulation is so great that deicing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.

Only three aircraft related degrees of icing have been defined by ICAO. They are (8):

Light

Neither course nor altitude must be changed.

Moderate

A change of course and (or) of altitude may be necessary.

Severe

An immediate change of course and (or) altitude is necessary.

During the icing flights undertaken in the winter months of three years, only the normalized degrees of icing trace and light were encountered. The degree of icing related to the aircraft - in this case a research aircraft of type Do 28 - usually matched the normalized degree of icing, and were also trace or light. In a few cases of mismatch between the normalized and aircraft related degrees of icing, the normalized degree of icing was always trace or light whereas the aircraft related degree of icing could become moderate or severe. This was always the case when not only the leading edge, but also the underside of the aircraft's wing was iced.

Section 2, which follows, briefly describes the icing research aircraft, the determination of the accretion of ice, and the measurement of the clouds' physical parameters. Section 3 shows the temporal sequence of two different kinds of icing on the wings of the Do 28 by means of two series of pictures from icing flights in the winter 1984/85. They are described by the values of the clouds'physical parameters. In the first case only the leading edge of the wing was iced. Both the normalized and the aircraft related degrees of icing were trace or light. In the second case both the leading edge and the underside of the wing became iced. While the normalized degree of icing was trace and light, the aircraft related degree of icing was moderate up to severe. To provide a statistical relationship of the dependence of both different kinds of icing of the wing to clouds'physical parameters, there is a summary of all the results of the winter 1984/85. Two diagrams present how the clouds' physical parameters for total water content, temperature, and median volume diameter vary with height above the cloud base for a stratus cloud and a stratus/cumulus cloud. These diagrams are fairly typical for both of these kinds of clouds and form part of a project to document vertical cloud profiles (9). The pictures in section 4 show the temporal development of another event where the underside of the wing iced severely during the icing flights of last winter 1987/88. Section 5 summarizes the results presented in this paper.

2. The measurement of the icing and of the clouds' physical parameters

The following only briefly describes those measurements, whose results were used in this paper. A complete and detailed description must be taken from the literature (1, 2).

2.1 The icing research aircraft

The DFVLR icing aircraft of type Do 28 is a high-wing aircraft with two propellers. Fig. 1 shows the mounting points or the actual instruments used to measure the normalized icing thickness and the physical parameters of the clouds - total water content, particle size distribution and temperature. The boots for pneumatic deicing at the front of the wings and the location and direction of visual and photographic observation of the icing on the wing are also marked.

2.2 Measuring the icing of one of the wings

Fig. 2 shows one of the wings as it appears to the flight engineer who has the task of determining the icing by observation and photography. Part a) of Fig. 2 shows only the leading edge of the wing is iced, part b) shows both the leading edge and the underside of the wing are iced. Measuring the thickness of the ice accretion on the leading edge was accomplished by means of a measuring disc mounted at the end of one of the wings where there is no pneumatic deicing, see Fig. 3.
The extent of the ice accretion on the underside of the wing was measured using the 30 cm wide deicing boots, and a black scale on the part of the wing that was painted white. Data on the roughness of the accreted ice were estimated, and represent the maximum difference between the troughs and peaks of the ice structure.

2.3 Measurement of the clouds' physical parameters

The measurement of the static air temperature was made with a Rosemount platinum wire restistance thermometer, which was installed in a housing with a deicer. Determining the particle size distribution and hence the median volume diameter was determined from the output of the PMS-instruments FSSP (ϕ 0.5 to 47 μm) and OAP (ϕ 20 to 600 μm). The total water content was measured using a Johnson-Williams hot wire instrument. Qualitative information about the phase of the cloud particles that is, about the proportions of solid and fluid particles in the cloud were derived from the signals of a backscatter probe and a Csiro-King hot wire instrument (10).

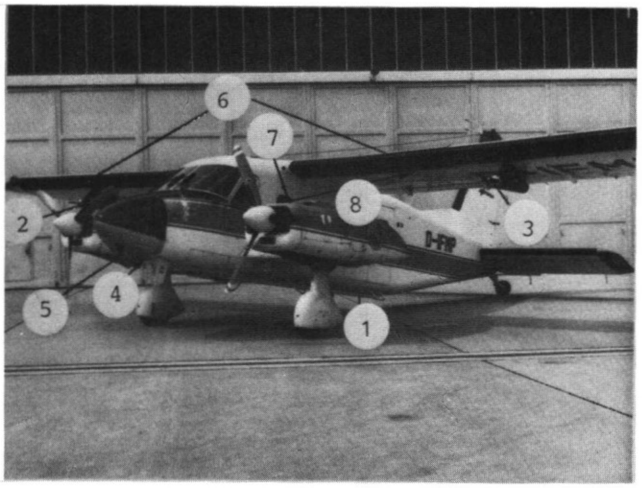

Figure 1. Icing Reserach Aircraft Do 28 of German Aerospace Research Establishment (DFVLR)

1 Location of cylinders for determining normalized ice accretion thickness respectively normalized icing degree

2/3 Probe for measuring cloud particle size distribution respectiveley median volume diameter

4 Probe for measuring total water content

5 Probe for measuring temperature

6 Pneumatic boots for deicing

7 Location for observing and photographing icing of wing

8 Main direction for observing and photographing icing of the wing

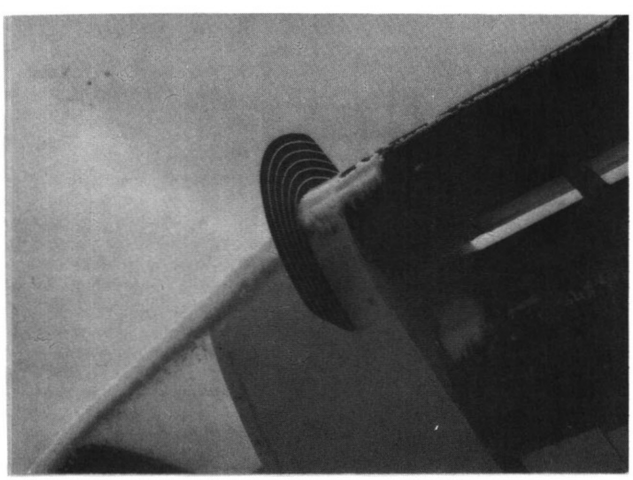

Figure 3. The outmost end of the wing with measurement disc for determining ice accretion thickness on the front edge

a

b

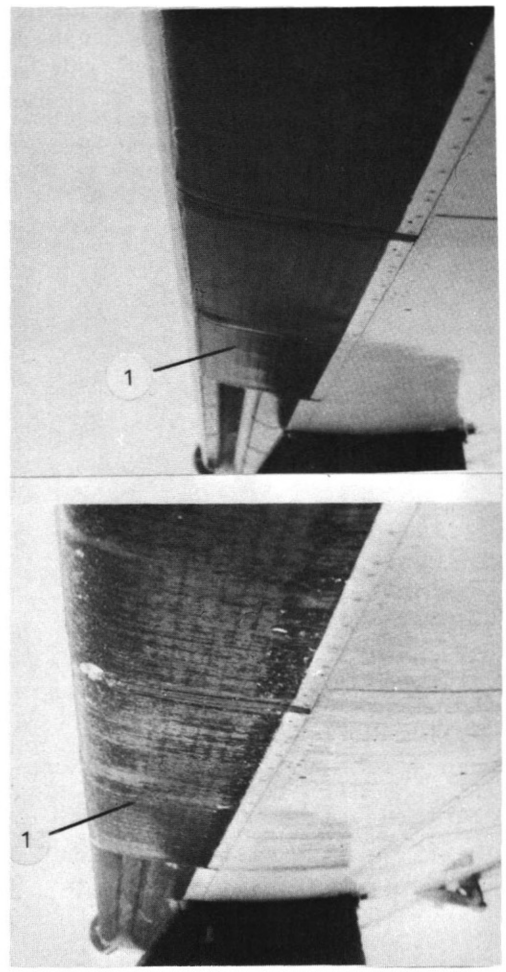

Figure 2. The underside of one of the wings of the icing research aircraft

a Icing only on the front edge

b Icing on the front edge but also on the underside

(1 Black boot for pneumatic deicing, extent in the width 30 cm)

3. Results of the icing flights in the winter 1984/85

On all the icing flights so far, the normalized degree of icing was between trace and light, but sometimes the normalized degree of icing nearly reached moderate. The normalized degree of icing was determined using the diagram in Fig. 4 (6, 7). The aircraft related degree of icing, here related to a Do 28, nearly always lay between trace and light. But whenever both the leading edge and the underside of the wing were iced, then the normalized icing was rated as between trace and light, although the aircraft related degree of icing was capable of being moderate to severe. The aircraft related degrees of icing became moderate to severe, whenever the Do 28 could not maintain its research velocity of 120 kt ($\approx$ 220 km/h) because the wings were so heavily iced.

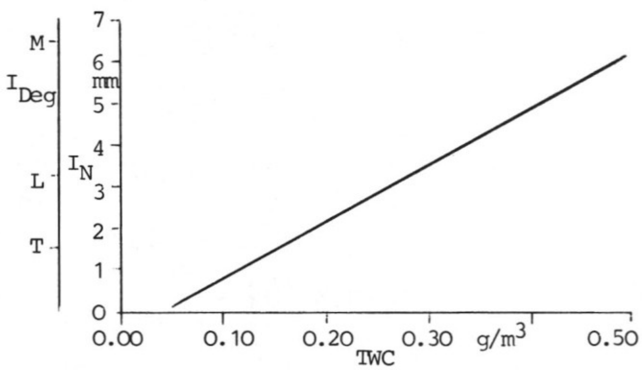

Figure 4. The normalized icing degree I_{Deg} and the normalized icing thickness I_N on a cylinder with a diameter of 12.5 mm in dependence on total water content TWC

Temperature: 0 to $-16^{\circ}C$

Particle size distribution (MVD): 13 to 340 µm

Phase of particles: Fluid or mixed

The results of the icing flights during the winter 1984/85 were used because during that winter the underside of the wing iced most often, because those results are completely evaluated, and because the large number of measurements allowed an initial statistic analysis.

3.1 Different types of icing on the wings of the Do 28

In each case there are photographs documenting the temporal sequence of the icing of the wing and tables containing the corresponding physical parameters of the clouds and the cloud situation. A time difference of 5 min between the photographs means a flight distance in clouds of about 20 km. The photograph which was taken immediately after deicing has been specially marked.

3.1.1 Only the leading edge of the wing was iced

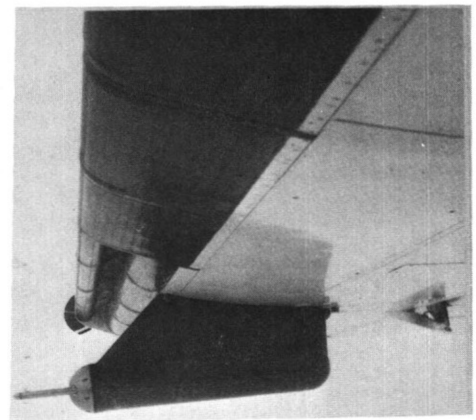

Figure 5. 12.35h

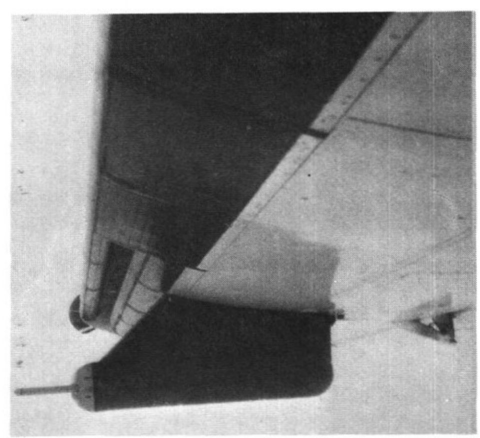

Figure 6. 12.40h

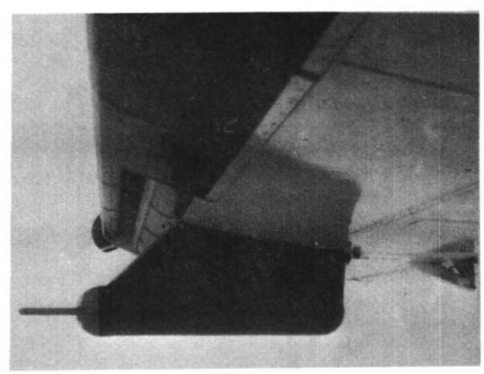

Figure 7. 12.59h

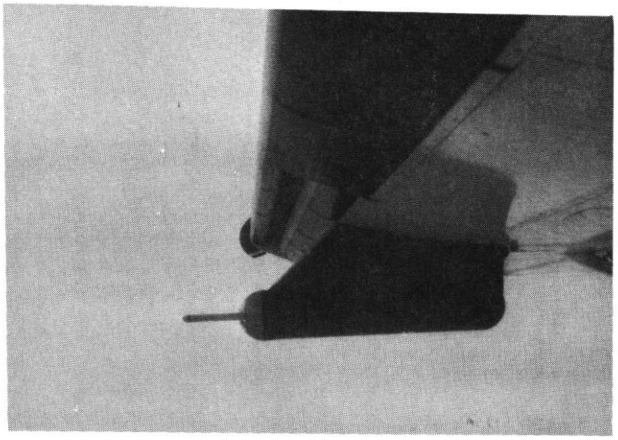

Figure 8. 13.05h

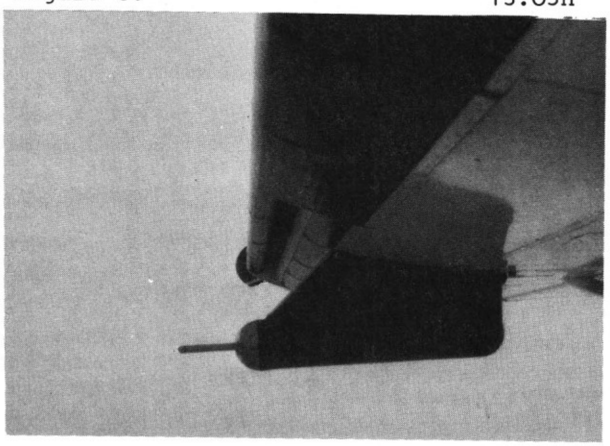

Figure 9. 13.15h

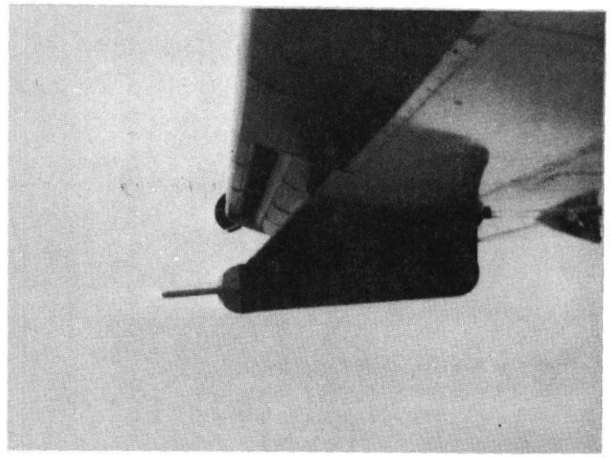

Figure 10. 13.23h

Type of icing

Normalized icing degree	Aircraft referred icing degree	Icing on wing: Thickness on front edge [mm]	Icing on wing: Extension on underside [cm]	Icing on wing: Roughness [mm]	Sort of ice
trace	trace	2	< 5	<1	rime

Cloudphysical parameters

Temperature [^{o}C]	Total water content [g/m^3]	Particle size distribution: Median volume diameter [μm]	Particle size distribution: Mean diameter [μm]	Phase of particles
-8.8 to -9.7	0.06 to 0.19	13 to 19	9 to 18	fluid

Cloud parameters

Class of cloud	Base of cloud [m]	Top of cloud [m]	Thickness cloud [m]	Heigh of measurement above cloud base [m]	Cloud above measuring cloud and height [m]	Air mass
Ac/As	1200	2500	1300	1200	?	mP

Table 1. Type of icing, cloudphysical parameters and cloud parameters describing the situation documented by the figures 5 to 10.

3.1.2 The leading edge and also the underside of the wing was iced

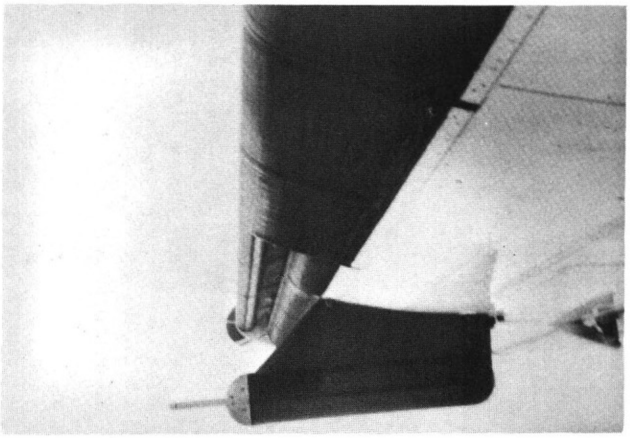

Figure 11. 10.47h

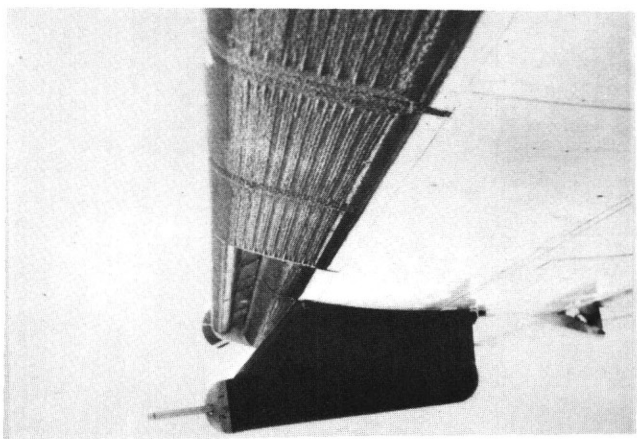

Figure 12. 10.52h

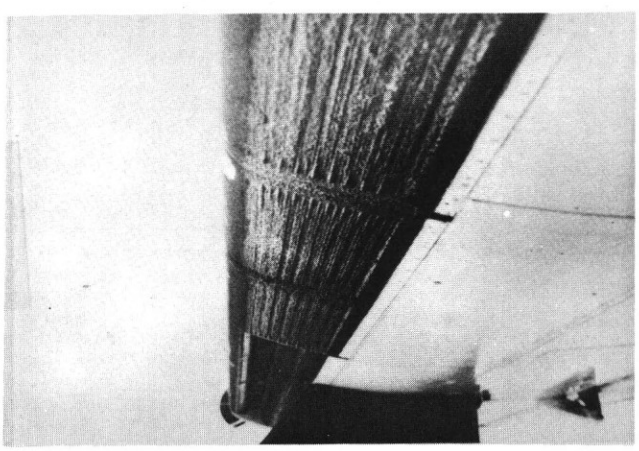

Figure 13. 10.53h

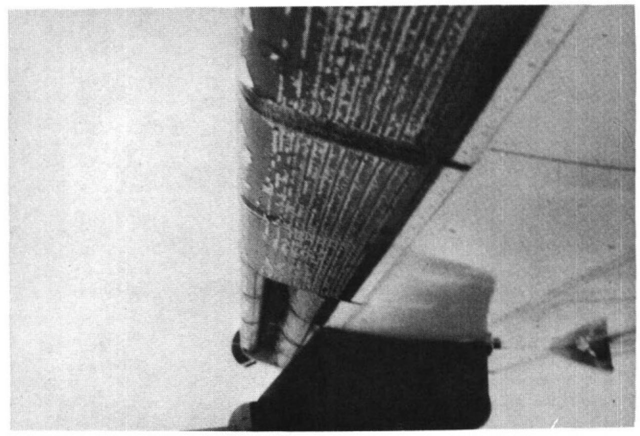

Figure 14. 11.04h (just after deicing)

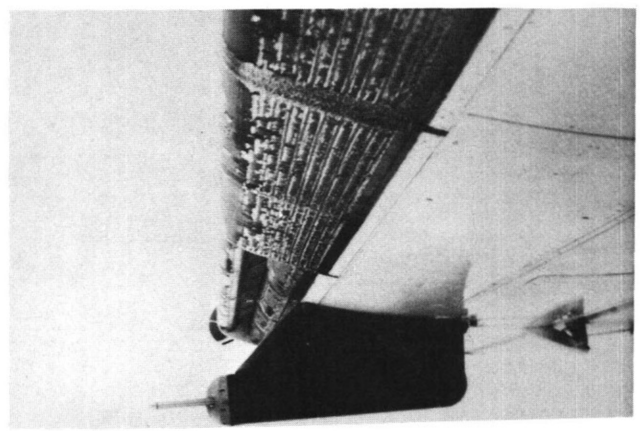

Figure 15. 11.12h

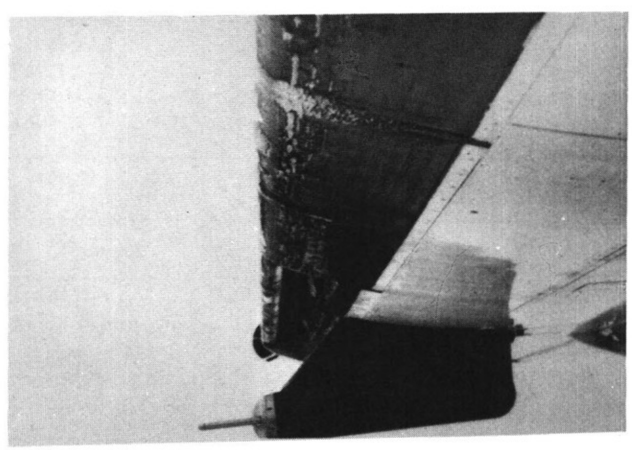

Figure 16. 11.23h

Type of icing

Normalized icing degree	Aircraft referred icing degree	Icing on wing Thickness on front edge [mm]	Extension on underside [cm]	Roughness [mm]	Sort of ice
trace	moderate to severe	5	>30	<5 (up to 10)	clear and rime

Cloudphysical parameters

Temperature [°C]	Total water content [g/m^3]	Particle size distribution Median volume diameter [/um]	Mean diameter [/um]	Phase of particles
-3.3 to-4.1	0.12	31 to 37	25 to 29	fluid

Cloud parameters

Class of cloud	Base of cloud [m]	Top of cloud [m]	Thickness of cloud [m]	Heigh of measurement above cloud base [m]	Cloud above measuring cloud and height [m]	Air mass
Ac/As	1400	> 3200	>1800	1460 1800	?	mS

Table 2. Type of icing, cloudphysical parameters and cloud parameters describing the situation documented by the figures 11 to 16.

3.2 Summary of the results of the winter 1984/85: degree of icing and icing of the wing; degree of icing and the clouds'physical parameters

The following two tables, 3 and 4, summarizes the results of all the icing flights of the winter 1984/85. Table 3 gives the normalized degrees of icing, and the values for the icing of the wing, which were measured simultaneously. This was subdivided into the aircraft related degrees of icing trace to light and moderate to severe. The values for the icing of the wing are the ice accretion thickness on the leading edge of the wing, the extent of the ice accretion on the underside and the roughness of the ice. Table 4 contains the clouds' physical parameters relevant to icing, namely temperature, total water content and median volume diameter for aircraft related degrees of icing trace to light and moderate to severe.

Normalized icing degree trace to light	Normalized icing degree trace to light
Ice accretion thickness on the front edge of the wing up to 25 mm	Ice accretion thickness on the front edge of the wing up to 25 mm
Extension of icing on the underside of the wing ≤10 cm	Extension of icing on the underside of the wing >30 cm (up to 50 cm)
Roughness 1 to 2 mm	Roughness up to 10 mm
Do 28 aircraft referred icing degree trace to light	Do 28 aircraft referred icing degree moderate to severe

Table 3. The normalized icing degree and the icing situation on the wing for the Do 28 aircraft referred icing degrees trace to light and moderate to severe.

T [°C] -7.8 (-4.2; -10.8)	T [°C] -3.7 (-2.0; -7.9)
TWC [g/m³] 0.19 (0.04; 0.44)	TWC [g/m³] 0.12 (0.05; 0.31)
MVD [µm] 14.5 (11.0; 18.5)	MVD [µm] 26.5 (15.0; 36.5)
Do 28 aircraft referred icing degree trace to light	Do 28 aircraft referred icing degree moderate to severe

Table 4. The icing relevant cloudphysical parameters temperature T, total water content TWC, and median volume diameter MVD for Do 28 aircraft referred icing degrees trace to light and moderate to severe.

3.3 Dependence of clouds' physical parameters relevant to icing on cloud parameters

The diagrams in Fig. 17 and 18 represent the changes in the clouds' physical parameters relevant to icing: total water content, temperature and median volume diameter as they vary according to the height above the cloud base. The Fig. 17 is for a stratus cloud and Fig. 18 is for a stratus/cumulus cloud (mixed cloud). Both the diagrams are based on measurements taken in the winter of 1984/85 and are typical for these two types of clouds. They are part of a work in progress to document vertical profiles (9). This documentation will form the basis of an extended climatology of clouds' physical parameters that are relevant to icing so as to imrpove the forecasting of critical icing.

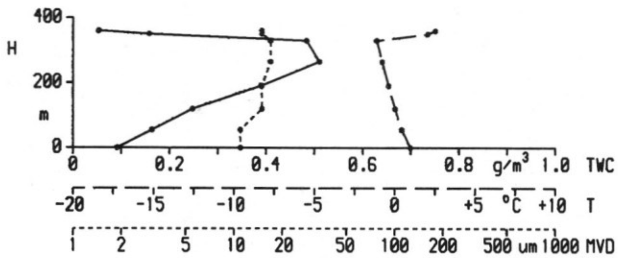

Figure 17. The icing relevant cloudpysical parameters total water content TWC,temperature T, and median volume diamter MVD in dependence on the height above cloud base H in a stratus-cloud

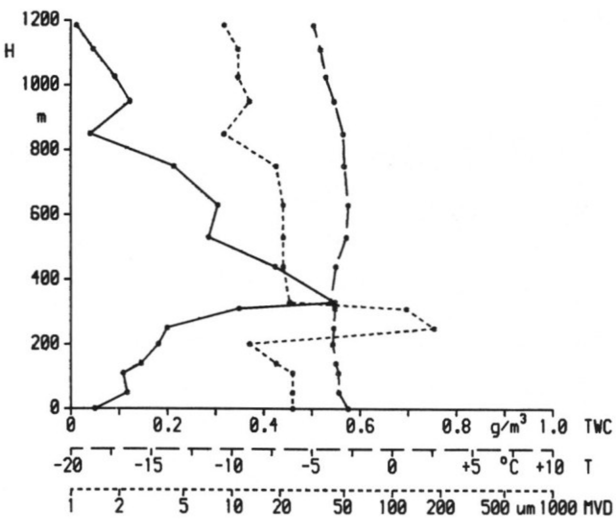

Figure 18. The icing relevant cloudphysical parameters total water content TWC, temperature T, and median volume diameter MVD in dependence on the height above cloud base H in a stratus/cumulus-cloud (mixed cloud)

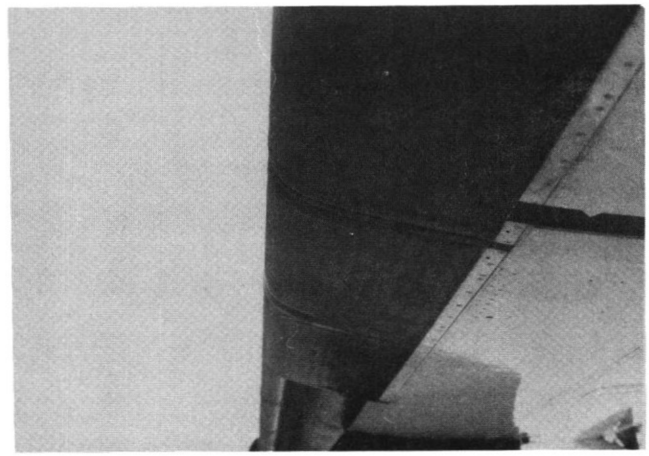

Figure 19. 10.27h

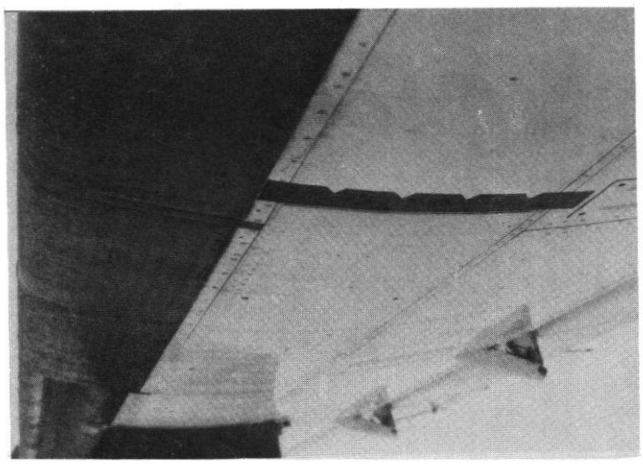

Figure 20. 10.50h

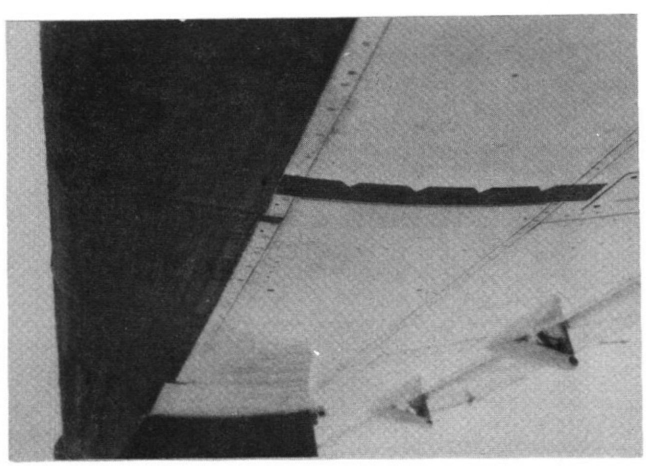

Figure 21. 10.52h

4 Results of an especially severe icing event during the icing flights in the winter 1987/88

The following Figs. 19 to 32 and table 5 document an event of especially severe icing of the underside of the wing. On this flight the normalized degree of icing was only trace, but the aircraft related icing was severe - the ice accretion on the underside of the wing extended for 70 cm and had roughness values of up to 15 mm.

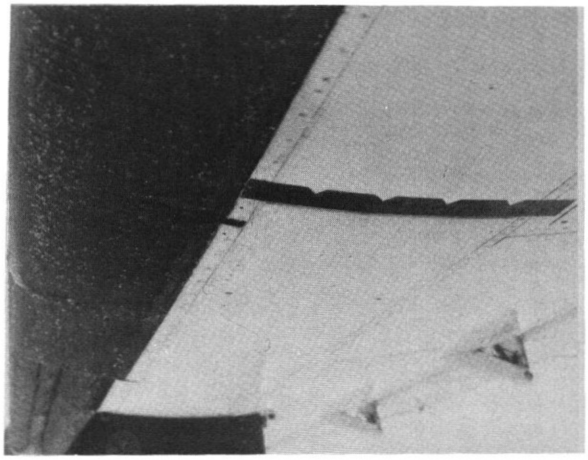

Figure 22. 10.54h

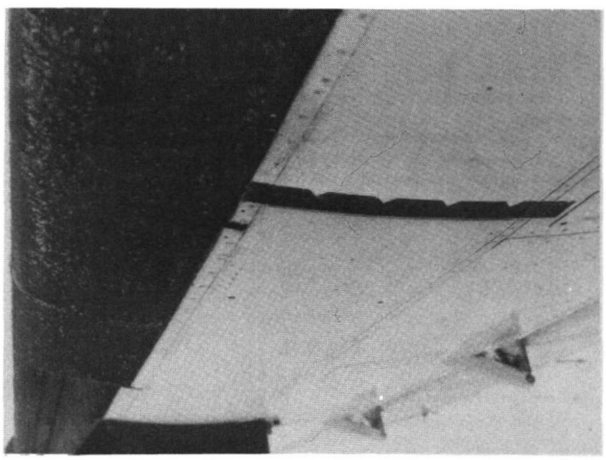

Figure 23. 10.57h

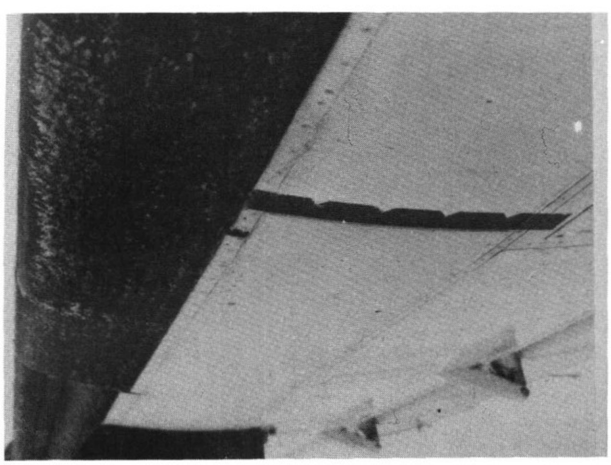

Figure 24. 10.59h

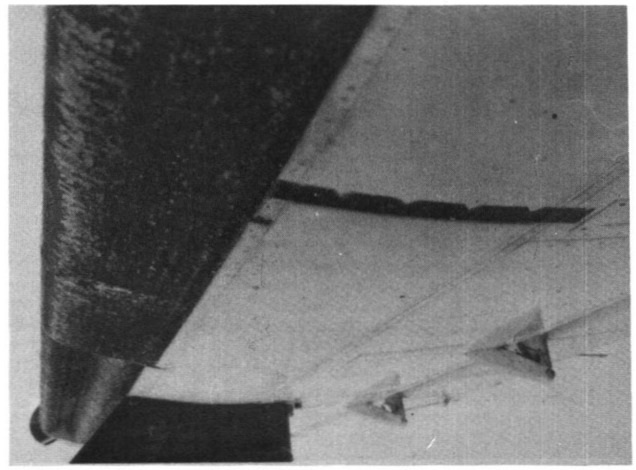

Figure 25. 11.02h

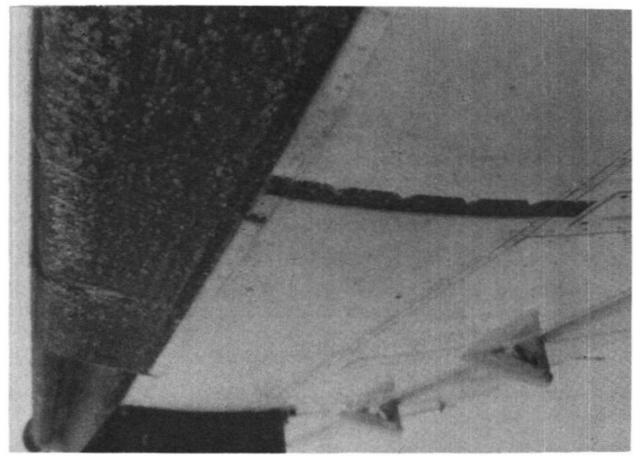

Figure 26. 11.06h

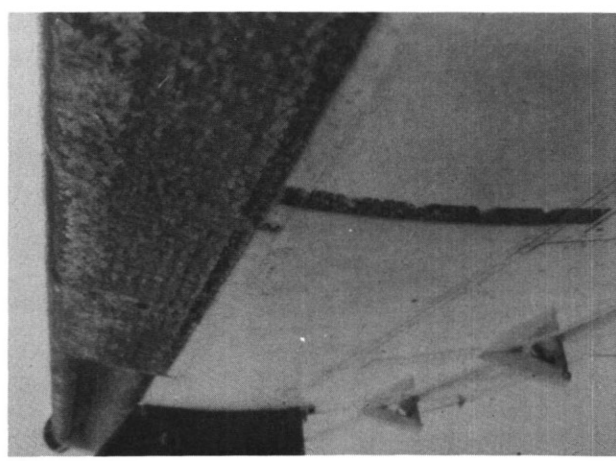

Figure 27. 11.10h

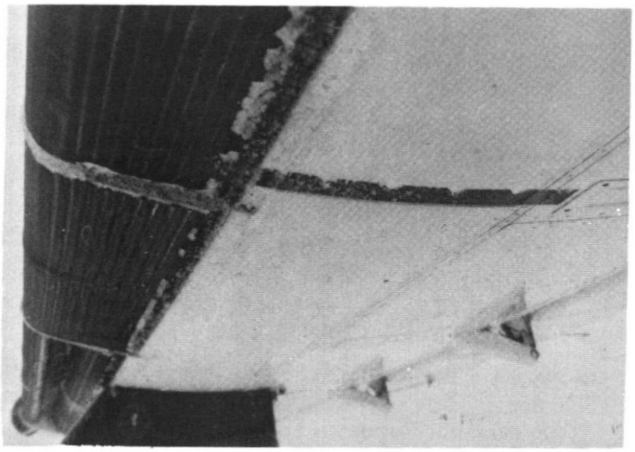

Figure 28. 11.11h (just after deicing)

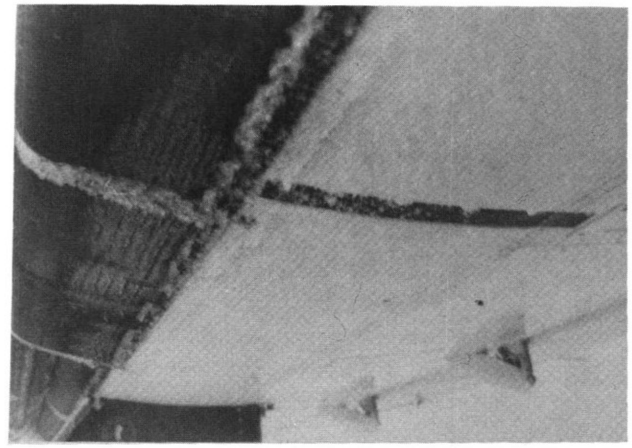

Figure 30. 11.19h

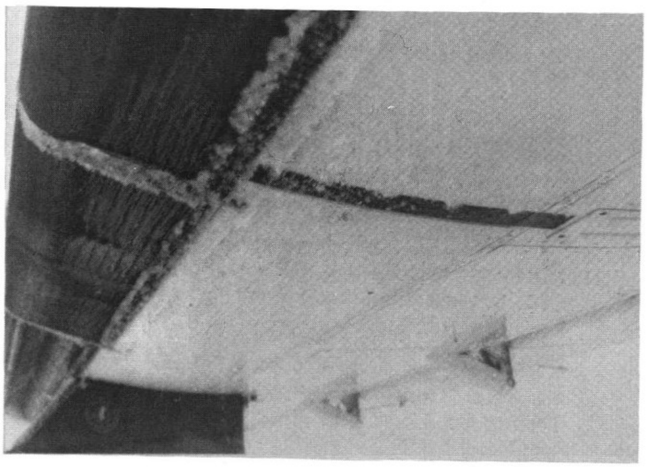

Figure 29. 11.16h

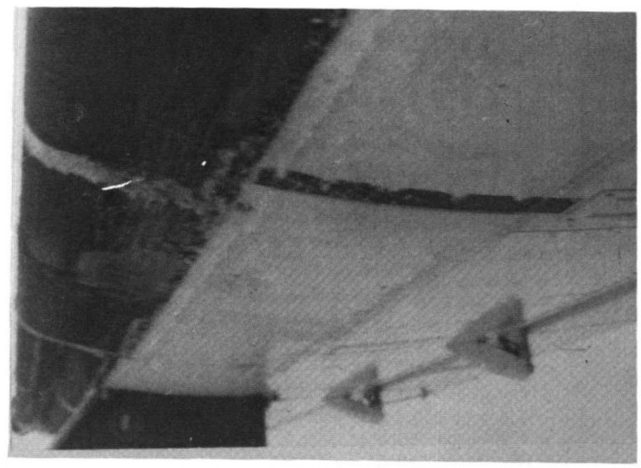

Figure 31. 11.20h

Type of icing

Normalized icing degree	Aircraft referred icing degree	I c i n g on w i n g Thickness on front edge [mm]	Extension on underside [cm]	Rougness [mm]	Sort of ice
trace	severe	10	70	15	rime

Cloudphysical Parameters

Temperature [°C]	Total water content [g/m³]	Particle size distribution Median volume diameter [µm]	Mean diameter [µm]	Phase of Particles
-2.0 to -3.6	0.14 to 0.16	29 to 222	35 to 95	fluid

Table 5. Type of icing and cloudphysical parameters describing the situation documented by the figures 19 to 32.

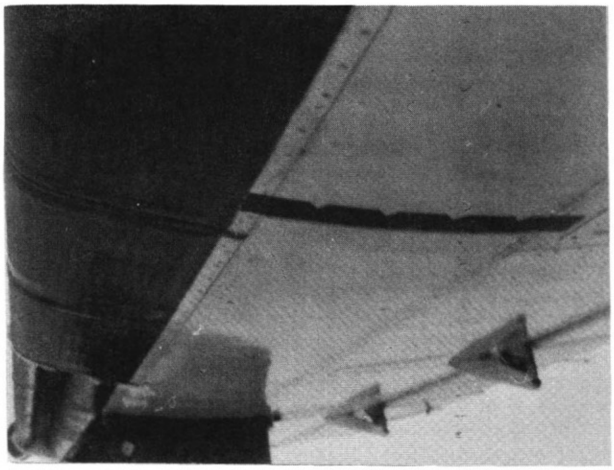

Figure 32 11.28h

5. Conclusion

During the icing flights over three years - that means a total duration of icing flights of 28 hours - the normalized degree of icing was always between trace and light. The aircraft related degree of icing, here related to the icing research aircraft of type Do 28, was also mostly trace and light. But in some cases, in fact in 7% of the total time of icing flights, the aircraft related degree of icing was moderate to severe (while the normalized degree of icing was simultaneously between trace and light). This was alsways the case when both the leading edge and the underside of the wing was iced. In these cases the ice could extend to 70 cm across the wing, which means it extended beyond the boots of 30 cm width used for pneumatic deicing. The deicing, - even in the area of the deicing boots - was incomplete (see sections 3.1.2 and 4.).

The evaluation of the icing flights in the winter 1984/85 resulted in the following (see sections 3.12 and 4.).:

The underside of the wing was always iced when the temperature was high (mean value -3.7°C) and the median volume diameter had high values (mean value 26.5 μm). The value for the total water content, on the other hand, did not differ significantly from the cases in which only the leading edge of the wing accumulated ice.

One of the examples for vertical profiles of clouds' physical parameters relevant to icing shows (see section 3.3, Fig. 18) that in the stratus/cumulus cloud (mixed cloud) we need only expect moderate to severe aircraft related icing in a narrow height band extending for about 300 m.

In (12 and 13), there is also a report of two events when the aircraft related degree of icing was severe. It is assumed that the underside of the wings had accumulated ice. Concerning the influence of the roughness of the surface of a wing, in (13 and 14) it is asserted that a roughness of less than 0.5 mm is sufficient to increase the drag coefficient by a factor of 2.

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