Effects of Icing on Performance of a Research Airplane

William A Cooper,* Wayne R Sand,† Marcia K Politovich,‡ and Donald L Veal§
University of Wyoming, Laramie, Wyoming

The difference between the normal and actual rates of climb of a research airplane is used to measure the effect of icing on performance The icing conditions were encountered in the course of an extensive series of meteorological research flights in various locations and seasons Coefficients of lift and drag were determined for the airplane before and after icing encounters, and those coefficients were used to predict airplane per formance for various flight conditions The effect of icing was to increase the drag significantly, while there was little effect on the coefficient of lift In the course of these flights, characteristics of the icing clouds (such as hydrometeor size spectrum and phase, liquid water content, temperature, etc) were also measured, and those characteristics are compared to the summaries in the Federal Aviation Regulations and to the data sources on which those summaries were based Most meaurements lie within the envelopes suggested by earlier studies For volume median diameters larger than 30μm, the liquid water contents were substantially lower than indicated by those summaries, but for other diameters measured liquid water contents extended up to and, in rare cases, exceeded the limiting envelopes of the Regulations Two exceptional cases of icing associated with droplets of 40 300 μm diameter are also discussed The reduction in performance during these cases was anomalously large, although the liquid water content and volume median diameter did not indicate that these cases should have been potentially hazardous

Introduction

TO acquire the measurements needed for meteorological research, instrumented aircraft often must fly in icing conditions In this paper, the icing encountered by one such research airplane, the Wyoming Super King Air (N2UW), is examined The microphysical characteristics of the icing clouds were measured while the performance of the airplane was monitored. The observed changes in performance provide a measure of the severity of different icing environments

Some characteristics of the icing encounters were discussed by Sand et al.[1] Summaries of the liquid water contents, median volume diameters, and other characteristics of the clouds that caused airframe icing were presented, and some effects of ice accretion on performance were also discussed In this paper, we extend those considerations in two ways First, a direct comparison to the characterization of icing in the Federal Aviation Regulations[2] (Part 25, Appendix C), and to the reports on which that Appendix was based, is presented. Second, the effects of icing on the lift and drag of this air frame are studied, and the extent to which the icing hazard is characterized by summaries such as those of Appendix C is considered

Characteristics of the Research Airplane

The airplane used was a Beechcraft Super King Air Model 200T (Fig 1) with reinforced outer wing panels to ac commodate wing tip mounting of sensors and probes. This airplane, which has a heated propeller and pneumatic boots on the wings and horizontal stabilizer, is certified for flight into known icing conditions

Several modifications were made to the basic 200T air frame Wing tip pylons were added on which instruments were mounted to measure microphysical properties of clouds, and a 2 m decelerator was mounted above the fuselage for the collection of samples of ice crystals In addition, the airplane was modified by the addition of a Saunders Failsafe spar strap, which consists of a stainless steel strap extending from the inboard segment of the outer wing panels through the wheel well and under the airplane. The protrusion below the wing is minimal outboard of the engine nacelles However, below the center section, the fairing extends downward about 2 5 in

The data acquisition on this airplane is controlled by a microprocessor linked to an onboard computer The com puter converts the data to scientific units for display in the airplane, while the microprocessor controls data recording on computer compatible magnetic tape Table 1 lists the in strumentation on the airplane during these studies The following paragraphs discuss some measurements of particular importance to this paper

Cloud Droplet Sizes and Concentrations

The primary instrument for the detection of cloud droplets was a Forward Scattering Spectrometer Probe (FSSP), manufactured by Particle Measuring Systems (PMS), Inc. This probe sizes and counts individual cloud droplets by detecting the light scattered from the laser beam as the droplets pass through its aperture The detected pulses are converted to droplet size by a pulse height analyzer so that the instrument provides a continuous measurement of the complete cloud droplet size distribution Independent measurements of the droplet spectrum were made each 0 1 s (or approximately each 10 m of flight) Our instrument has undergone extensive testing and intercomparison with other devices (e g see Ref 3) and has been calibrated by use of glass beads and Mie scattering calculations [4]

Liquid Water Content

The liquid water content was calculated from the droplet spectrum measured by the FSSP In addition, a standard Johnson Williams (JW) hot wire device[5] for the measurement of liquid water content was operated During recent studies (since 1981), measurements from a CSIRO liquid water sensor[6] and a Rosemount icing probe were also recorded

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*Associate Professor Department of Atmospheric Science
†Assistant Professor and Flight Facility Manager Department of Atmospheric Science Member AIAA
‡Graduate Student Department of Atmospheric Science
§President

The JW probe has been calibrated and intercompared with many other probes in the Ottawa wind tunnel of the National Research Council of Canada [7] A sample of the calibrations was shown by Sand et al [1] Other evidence for the accuracy of the measurements was presented by Boatman,[8] who com pared measurements of liquid water content with theoretical values in unmixed cores of vigorous clouds

The liquid water contents measured by the JW probe and the FSSP were compared for a one-month period, with the result that the best fit to the simultaneous measurements was $LWC(JW) = 0\ 96 \times LWC\ (FSSP) + 0\ 01\ g/m^3$ Results from the two probes were thus in good agreement Periods when there were significant disagreements between these two probes have been excluded from this study

Ice Particles and Rain Drops

The four PMS probes listed in Table 1 provided complete information regarding the sizes and concentrations of ice crystals and raindrops In addition, the two dimensional probes recorded two dimensional images of the particles passing through their sampling apertures, so that ice particles could be distinguished from water drops on the basis of shape

Performance Monitoring

The torque delivered by the left engine was measured and recorded to permit monitoring of airplane performance Additional measurements related to performance included the ground speed and drift angle (determined by a Doppler radar until 1982, and since then by an inertial navigation system); the indicated airspeed; angle of attack; yaw, pitch, and roll angles; and vertical and (since 1982) horizontal acceleration

State Parameters

The primary temperature sensor was designed to remain dry during flight through clouds [9] It was supplemented by another temperature sensor, Rosemount Model 102; although not similarly protected against wetting, it was deiced The dew point, pressure, airplane position and altitude, and other parameters listed in Table 1 were also recorded

Comparison to FAR, Part 25, Appendix C

The data sources used for these studies are listed in Table 2 All cloud regions colder than 0°C where the instruments worked reliably have been included General characteristics of

Fig 1 Research airplane N2UW as modified with wing tip pylons, decelerator (tube on top), and noseboom.

Table 1 Instrumentation on the research airplane

Measurement	Instrument	Manufacturer	Response	Accuracy	Resolution
Temperature #1	Platinum resistance	Rosemount Model 102	<1 s	±0 5 C	<0 1 C
Temperature #2 (reverse flow)	Platinum	NCAR design Minco element	<0 5 s	±0 5 C	<0 1 C
Dew point	Cooled mirror	Cambridge Model 137C3	3 C/s (slew rate)	±0 5 C (>0 C) ±1 0 C (<0°C)	0 3 C
Heading[a]	Magnetic	King KP1 553	1 s	± 1 deg	0 1 deg
Altitude	Pressure	Rosemount 1201FA1B1A	15 ms	±4 mb	0 3 mb
Altitude	Radar altimeter	Stewart Warner APN 159	152 m/s (slew rate)	2 4 m or 1%	0 07 m
IAS	Differential pressure	Rosemount 831 CPX	25 ms	±1 mb	0 1 mb
Rate of climb[a]	Differential altitude	Rosemount 1241 A 4BCDE	50 ms	1% to 4 5 km 2% to 8 km	0 25 m/s
Position	VOR	King KNR 615	1 s	1.5 deg	
	DME	King KDM 705A	1 s	0 4 km	0 2 km
	INS	Litton LTN51			
Vertical acceleration[a]	Stabilized accelerometer	Humphrey SA-09 0502 1	10 μs	0 002 g	
Pitch roll[a]	Stabilized accelerometer	Humphrey SA 09 0502 1	10 μs	0 2 deg	
Ground speed[a]	Doppler radar	Singer	1 s	0.17% ± 2 m/s	0 5 knot
Drift angle[a]	Doppler radar	Singer	2 s	0 2 deg	0 2 deg
Yaw attack angles	Differential pressure	Rosemount 858AJ28	0 1 s	0 2 deg	<0 1 deg
Turbulence	Pressure	M R I	3 s	10%	1%
Liquid water content[b]	Hot wire (JW)	Bacharach Instruments Model LWH	<1 s	0 2 g/m^3	0.1 g/m^3
Liquid water content	CSIRO hot wire	University of Wyoming	~10 ms	0 1 g/m^3	0 05 g/m^3
Liquid water content	Icing probe	Rosemount	>5 s		
Droplet size	FSSP	PMS	0 1 s	2 μm	2 μm
Hydrometeor size and shape	1DC	PMS	0 1 s	12 5 μm	12 5 μm
	2DC	PMS	μs	25 μm	
	2DP	PMS	μs	200 μm	

[a] Also measured by the inertial navigation system (INS) since 1981 [b] Also measured by the FSSP

Table 2 Sources of data

Date	Area	Flight hours
Winter 1978	California	104
Winter 1979	California	116
Winter 1980	California	99
Winter 1982	California	8
Summer 1978	Montana	91
Summer 1979	Montana	156
Summer 1980	Montana	140
Summer 1981	Montana	170
Winter 1978	Utah	35
Summer 1978	Florida	35
Spring 1978	Kansas	38
Summer 1980	Illinois	24
Winter 1981	Michigan	45
Winter 1981	Great Plains	30
Total		1091

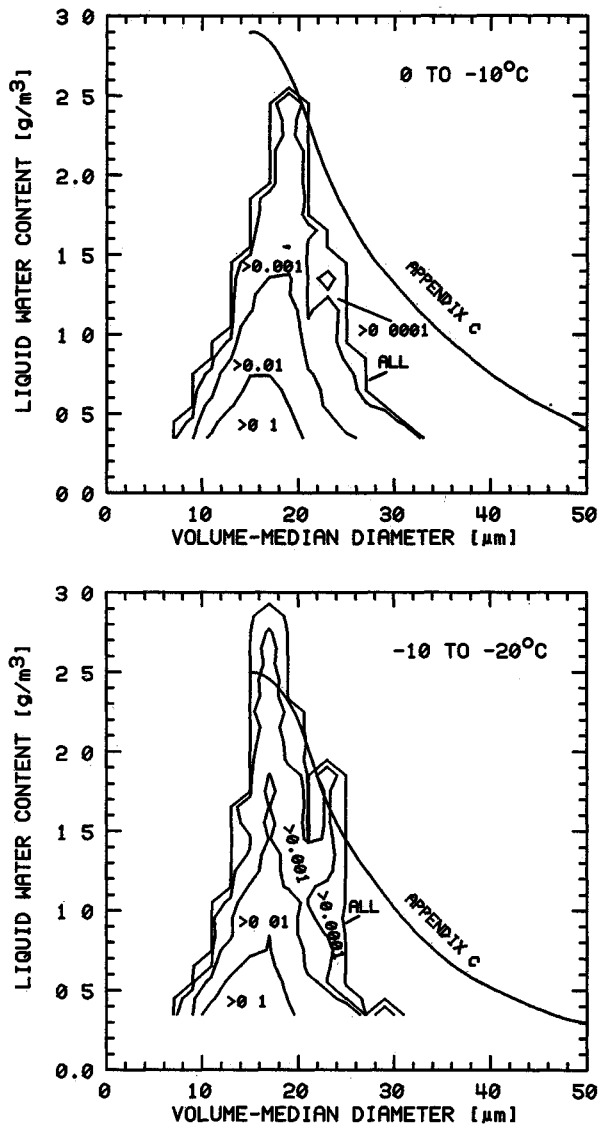

Fig 2 Comparison between the observations of this study and the envelope of FAR, Part 25, Appendix C, for the intermittent maximum distance of 2 6 n mi The outside contour (labeled all') encompasses all observations, and the other contours indicate probability densities in units of $(\mu m\ g/m^3)^{-1}$ There were 46,992 measurements used to construct the top plot (for 0 to −10 C), and 21,149 measurements used for the bottom plot (for −10 to −20 C), all having 2 6 n.mi. average liquid water contents greater than 0 3 g/m^3

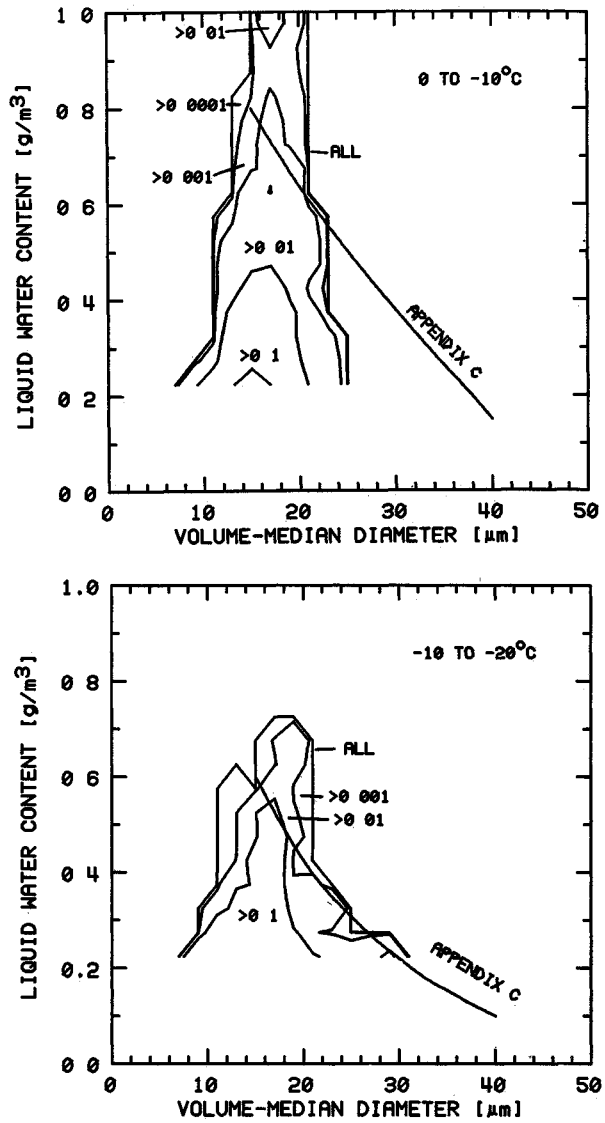

Fig 3 Comparison between the observations of this study and the envelope of FAR, Part 25, Appendix C, for the continuous maximum distance of 17 4 n mi The outside contours indicate probability densities in units of $(\mu m\ g/m^3)^{-1}$ There were 52,777 measurements used to construct the top plot (for 0 to −10 C), and 20,999 measurements used for the bottom plot (for −10 to −20°C), all having 17 4 n mi average liquid water contents greater than 0 2 g/m^3

the icing encounters can be found in Sand et al [1] Herein we specifically compare the measurements to the summaries in the Federal Aviation Regulations

The FAA requirements for certification for flight into know icing conditions are based on FAR, Part 25,[2] Appendix C (hereafter referred to as Appendix C) Appendix C defines two icing categories: continuous and intermittent The "maximum continous" icing condition is the extreme ex pected for an icing encounter lasting 17 4 n mi (32 2 km), while the "intermittent maximum" condition is the extreme expected for 2 6 n mi (4 8 km) Interpolation factors are given for use with distances other than these standard distances The nature of the icing encounters is characterized by two parameters: the average liquid water content (LWC) and the volume median diameter (D_v) D_v is defined so that half of the liquid water content is contained in droplets larger than and half in droplets smaller than D_v

For comparison to Appendix C, the measurements of LWC and D_v from the flights listed in Table 2 have been averaged over distances of 2 6 and 17 4 n mi. and then have been plotted in the format of Appendix C Values of LWC and D_v

were measured once each second (or about once each 100 m of flight) so that, for example, the 2 6 n.mi. averages were obtained from sets of approximately 48 1 s measurements Each 48-s interval was used to represent one average value, with the intervals allowed to overlap.

The flights generally were conducted to study precipitation formation processes and, hence, emphasized regions with high liquid water content. The probabilities characterizing these flights are overestimates of the probabilities of similar icing encounters during routine flight operations. Regions of high liquid water content were often penetrated repeatedly, further increasing the exposure to icing conditions

The respective data for the intermittent maximum and the continuous maximum distances are shown in Figs 2 and 3 Data from all temperatures less than 0 C have been com bined, and herein are compared to the <0 C (or most in clusive) limit of Appendix C

The intermittent-maximum icing envelopes of Appendix C encompass our data well for drop sizes smaller than about 25μm The envelopes could be reduced to about 70% of the indicated liquid water contents, and only about 1% of the measurements would lie outside them The continuous maximum envelopes were exceeded in about 1% of the icing encounters, but the authors attribute this primarily to the flight patterns which frequently returned to regions where the icing was the greatest

The primary discrepancy between the authors' observations and the envelopes of Appendix C is that no values of $D_v > 30$ μm were found associated with liquid water contents greater than 0 2 g/m^3, although the envelopes of Appendix C en compass considerably higher liquid water contents for D_v from 30-50 μm The FSSP, the primary instrument used to determined these sizes, measured diameters up to 45 μm when appropriate, and those measurements have been sup plemented by measurements that cover the entire hydrometeor size spectrum

To study this discrepancy we have examined some other sources Lewis et al ,[10,11] the primary sources of data for the charts in Appendix C, show only four observations with D_v exceeding 40 μm None of the four observations exceeds the liquid water threshold used for the plots presented herein (0 2 g/m^3 for continuous icing and 0.3 g/m^3 for intermittent icing) Jeck[12] also found no values of D_v larger than 35 μm

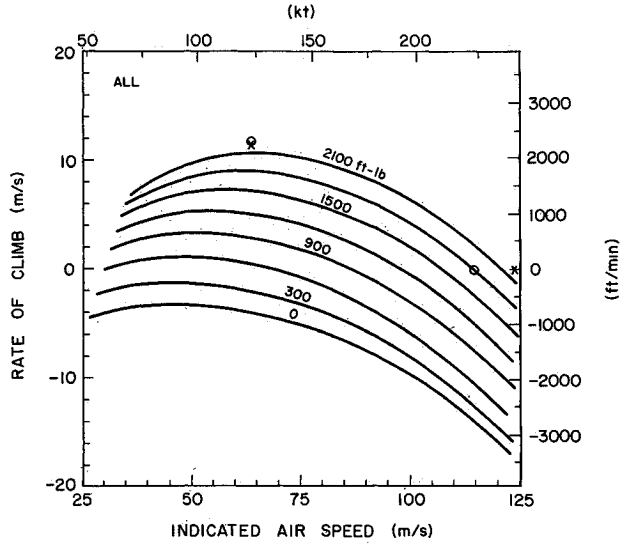

Fig 4 Rate of climb as a function of airspeed and power setting for a clean airframe weighing 12,000 lb and an air density 80% of standard Parameters on the curves represent engine torque (per engine) in ft lb The points marked o" are taken from the pilot manuals for the Beechcraft 200T, while nearby points marked '×" are corresponding points from the calculations A propeller rotation rate of 1700 rpm was assumed

and no values larger than 30 μm in regions where the liquid water content exceeded 0 2 g/m^3 Thus, we have not found data to support the extension of the envelopes to drop diameters exceeding 35 μm.

With this major exception these new observations gen erally support the envelopes of Appendix C. This is a useful result for two reasons First, the data used by Jones and Lewis,[13] on which Appendix C is based, were collected primarily in the wintertime in the northern United States It was an admitted weakness in the data set that icing in other parts of the country or in other seasons was not represented The inclusion of observations from the Great Plains, Florida, and California is thus a useful addition Second, the data presented herein come from a new generation of cloud physics instrumentation, which provides high resolution measure ments In particular, the droplet size spectrum is measured in 15 size intervals spanning sizes from 1 45 μm, and additional measurements span the entire hydrometer size range These instruments provide a very complete characterization of the microphysical properties of the icing clouds and make the analysis of large data sets possible

Effects of Ice on Performance

Theory

The accretion of ice on an airframe affects performance primarily through induced aerodynamic changes and through effects on the powerplant The latter will not be considered in this report; torque delivered by the left engine was measured and recorded, and these records verify that there has been no reduction in power which could be attributed to the effects of icing The weight of the accreted ice seldom amounts to more than a few percent of the airplane weight, so that effect will also be ignored in the following discussion. Another possible effect of icing is to reduce the efficiency of the propellers, but since the propellers on this airplane are deiced and normally stay clean, we have used the propeller efficiencies quoted by the manufacturer

The predominant effects of icing can then be described by the effects on the lift and drag of the airframe The development followed herein is to determine coefficients of lift (C_L) and drag (C_D) for the clean airframe and for the airframe after icing has occurred In addition to separating the effects on lift and drag, this procedure has the advantage that once C_L and C_D are known the performance of the airplane can be calculated for various power settings, air speeds, and air densities Thus, a short set of flight maneuvers, sufficient to determine C_L and C_D, permits prediction of the performance of the airplane for a wide range of possible flight conditions

The horizontal and vertical equations of motion form the basis for the calculations. The approach was similar to that of Lenschow [14] Measurements of angle of attack, pitch, in dicated and true airspeed, and vertical and horizontal ac celeration were used, along with the measured torque from the engines, the known propeller rotation rate, and the propeller efficiencies quoted by the manufacturer From these measurements, the effective coefficients of lift and drag were found; these were used with the wing area of 28 m^2, although lift and drag actually result from the effects of the entire airframe

C_L was determined as a function of angle of attack, and C_D as a function of C_L^2 Prior to the installation of the inertial navigation system in 1982, the horizontal acceleration needed to determine C_D had to be determined from differentiating ground speed measured by a Doppler radar Because of poor resolution in that procedure, fits to the data yielded inac curate functional dependences of C_D, therefore only mean values of C_D (without dependence on C_L) have been deter mined for cases before 1982 This still provides useful results because induced drag, normally the source of strong dependence on C_L, is not included in the drag coefficient as

formulated by Lenschow, but rather is explicitly included in the equations of motion as a separate term dependent upon lift

Once C_L and C_D were determined the predicted rate of climb of the airplane was determined as a function of in dicated airspeed and power setting For unaccelerated flight, the horizontal and vertical equations of motion specify two relationships among the four variables thrust, angle of attack (α), pitch (θ), and indicated airspeed For specified thrust and indicated airspeed, the rate of climb in still air can be found from $w = V(\alpha - \theta)$, where w is the rate of climb and V is the true airspeed The effects of altitude and temperature are incorporated when thrust is obtained from torque and when true airspeed is obtained from indicated airspeed

Application to the Clean Airframe

The coefficients of lift and drag were determined for the clean airframe by use of special maneuvers which covered a range of angles of attack and airspeeds. Since this airplane has been modified from the standard 200T configuration by the addition of pylons and instruments, it was important to determine these values experimentally rather than to rely upon those quoted by the manufacturer Also, the ability to calculate realistic performance values serves as a check on the procedures

An inertial navigation system was used to provide accurate measurements of accelerations and orientation angles Several sets of maneuvers were used Porpoising maneuvers involved varying pitch angle with repeated climbs and descents at constant power settings A set of acceleration deceleration maneuvers with no altitude change was also flown to isolate the effects of the coefficient of drag

The coefficients determined by a least squares fit to data from the combined maneuvers were: $C_L = 0\ 220 + 6\ 16\alpha$ and $C_D = 0.024 + 0\ 033 C_L^2$. Individual flight segments yielded coefficients that varied by about $\pm 5\%$ from these

Figure 4 shows the performance deduced from the combination of all maneuvers For comparison two points selected from the Beechcraft manuals are also shown The maximum climb rate is close to that obtained from these coefficients of lift, although the maximum speed for level flight is somewhat less than predicted The discrepancy at high airspeed may be the result of increased drag due to the modifications to the airplane, or it may reflect poor ex trapolation far from the 70 100 m/s airspeed range in which we normally operate and in which these tests were conducted The predicted rates of climb deduced from the different sets of porpoising maneuvers varied by about 1 m/s (rms deviation) in the 60-100 m/s range, so flight maneuvers of about 3 min duration can be used to predict rates of climb with this precision

As a check on the accuracy of the predictions, a comparison was made of the predicted rates of climb with actual rates of climb at the start of all flights Only those periods of the flights before any icing was encountered were considered The rms error in the prediction[1] was 1 2 m/s, even though there were some variations in weight of the airplane that were not taken into account Thus, the predicted rates of climb for the clean airplane have an overall accuracy of about 1 2 m/s

Effects of Typical Icing Encounters

Sand et al [1] showed that, for this airplane with ice protection equipment in use, the path integral of the super cooled liquid water content (termed the potential ac cumulation) correlated well with the effects on performance The rate of climb decreased by about 1 8 m/s for any ac cumulation (partly attributable to the ice protection systems, including ice vanes) and decreased an additional 0 45 m/s for each additional g/cm^2 of potential accumulation The effect on performance showed no correlation with D_v

Since a potential accumulation of 1 g/cm^2 corresponds to flight through a 10 km region of 1 g/m^3 liquid water content, these results indicate that this airplane can fly with ease in the icing conditions described in Appendix C For example, in the extreme intermittent maximum liquid water content (3 g/m^3 over a distance of 2 6 n mi), the corresponding reduction in climb ability is only about 2.5 m/s For the extreme con tinuous maximum condition (0 8 g/m^3 over 17 4 n mi) the corresponding reduction is about 3 m/s Since this airplane can climb at 5 10 m/s under the typical conditions where ice is encountered there is ample reserve performance to handle such icing encounters

An example of the performance of the airplane after an icing encounter is shown in Fig 5 On March 3, 1980, icing conditions were encountered upwind of the Sierra Nevada Mountains of California The icing encounter was entirely in

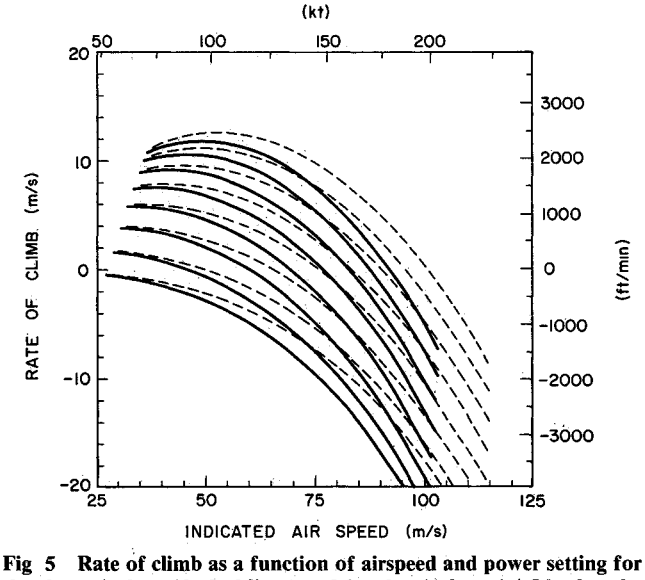

Fig 5 Rate of climb as a function of airspeed and power setting for the clean airplane (dashed lines) and for the airplane 4 4 5 h after the start of the March 3, 1980 flight and after ice accumulation (solid lines) The curves correspond to torque settings which start at zero for the lowest curve and increase in increments of 300 ft lb (per engine) The calculations assumed a weight of 10,900 lb, a pressure of 670 mb, and a temperature of −7°C

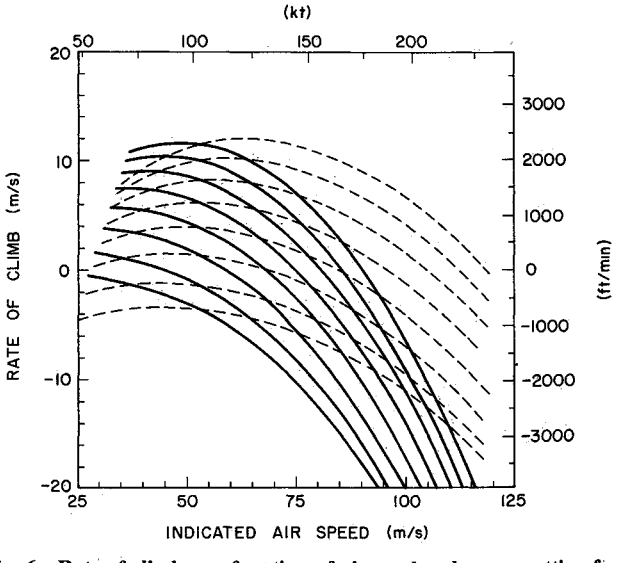

Fig 6 Rate of climb as a function of airspeed and power setting for the period 2130 2230Z on July 5, 1978 (solid lines), compared to the performance of the clean airplane (dashed lines) The curves correspond to torque settings from 0 to 2100 ft lb in 300 lb increments from bottom to top

the temperature range warmer than -10 C The liquid water content was relatively low, about 0 2 0 3 g/m^3 when averaged over 17 4 n mi , and D_v was 14 18 μm In 1 5 h, the potential ice accumulation was 11 1 g/cm^2; this would correspond to an ice thickness of about 14 cm if the ice density were 0 8 g/cm^3 and the collection efficiency were unity Actual accumulations on unprotected leading edges were 7 10 cm.

After accumulation of the ice, the performance coefficients were determined to be $C_L = 0\ 266 + 6\ 66\alpha$ and $C_D = 0\ 054$ Figure 5 shows the performance deduced from these coef ficients, along with the performance curves obtained from a segment of the flight at the same altitude but before icing occurred The primary influence of the ice was to increase the drag by about 50%, while the effect on lift was minor.

Figure 6 shows the performance curves determined after an icing encounter on July 5, 1978 This flight encountered a potential accumulation of 19 1 g/cm^2, the highest in our data set During this flight, through cumulus clouds in Montana, average liquid water contents exceeded both the intermittent and the continuous maximum criteria of Appendix C The flight altitude was near 18,000 ft where the temperature was approximately 12°C During the 2 5 h period of most intense icing, the average liquid water content was 0 23 g/m^3, and maximum values exceeded 2 5 g/m^3 The volume median diameter was 17 6 μm

In this case, the performance reduction was minor and there was little degradation in performance after the first 30 min of the 3-h icing encounter The pneumatic boots (which were used routinely during this and all icing flights) effectively prevented ice from accumulating. As in the March 3, 1980 case, the greatest effect of icing was apparent at high airspeed because the primary effect was to increase the drag of the airframe while causing little change in the coefficient of lift Figure 6 shows that, even in this case of icing beyond the limits of Appendix C, the airplane retained substantial climb ability

The above arguments suggest that this airplane has ample reserve power to fly in icing conditions such as those characterized by Appendix C, and this is verified by com fortable flight in most of the icing regions encountered during these research flights. However, in spite of this apparent safety margin, there have been two icing encounters which warranted evasive action

Potentially Hazardous Icing Encounters

The two icing encounters with the greatest effects on performance (Feb 26, 1982 and Jan 18, 1983) were discussed by Sand et al [1] Both occurred upwind of the Sierra Nevada Mountains of California. In both cases, the rate of climb of the airplane decreased to 7 9 m/s below that predicted for the clean airframe, and the reduction occurred during icing encounters lasting less than 20 min The potential ac cumulations from these cases were only about 3 g/cm^2, and the ice observed from the cockpit was not commensurate with the effect on performance When averaged over the con tinuous maximum distance of Appendix C, the liquid water content was about 0 2 0 25 g/m^3 and D_v was only about 18 μm Over the intermittent maximum distance, the average liquid water content was $<0\ 3$ g/m^3. Thus, in terms of the parameters used in Appendix C, these cases appear to be modest icing encounters with the same characteristics that caused no problems during many other flights. Yet, in these two cases, the reduction in climb ability was the greatest we have experienced, and caused the pilots to reverse course and fly out of the icing regions

Figure 7 (from Ref 1) shows the contributions to the potential accumulation from hydrometers of various sizes for one of the cases (Feb 26, 1982) The spectrum for Jan 18, 1983 is very similar to this one, but both differ markedly from the spectra in other icing encounters (e g , Fig 8) There were substantial contributions to the potential accumulation from hydrometeors with diameters of 40-300 μm in both of these

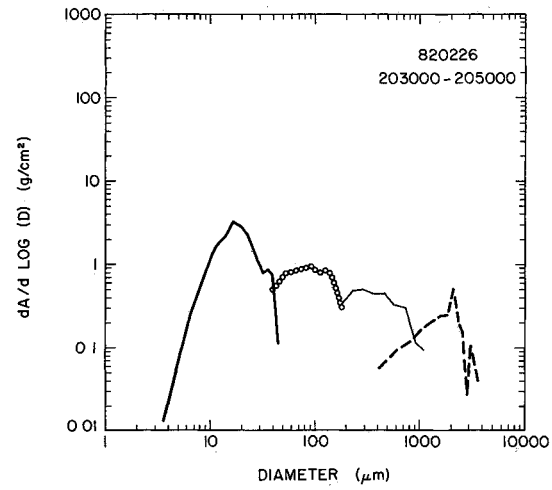

Fig 7 Contributions of different parts of the hydrometeor spectrum to the potential accumulation (A) of Feb 26, 1982 for the interval 2030 2050Z when the maximum performance degradation occurred The different curves represent measurements from the different particle measuring probes, the FSSP, 1DC, 2DC, and 2DP in order of increasing size

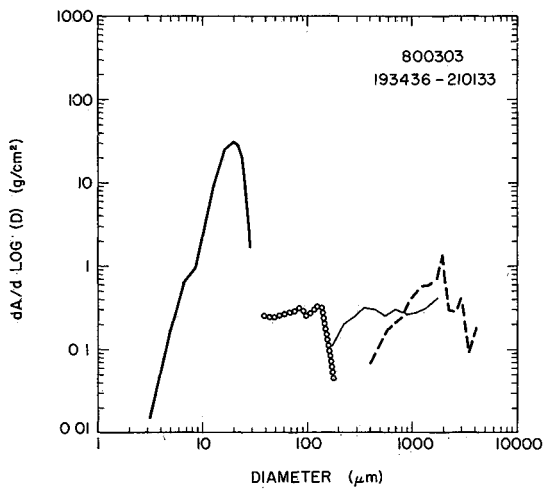

Fig 8 Contributions of different parts of the hydrometeor spectrum to the potential accumulation (A) of March 3, 1980 All hydrometeors were assumed to be spherical water drops in this calculation although the two-dimensional images indicated that all those larger than 100 μm were ice particles The plot thus represents an upper limit to the possible contributions from sizes larger than 100 μm because the mass is overestimated by the spherical assumption and the accretion ef ficiency for ice is likely much less than unity

cases, and the two dimensional images[1] showed that the hydrometeors less than 0 5 mm in diameter were water drops

Figure 9 shows the performance characteristics deduced from the period of flight after the icing encounter on Feb 26, 1982, but before the ice was melted from the airframe The coefficients of lift and drag were found to be $C_L = 0\ 257 + 3\ 65\alpha$ and $C_D = 0\ 049 + 0\ 075\ C_L^2$ just after the icing encounter (leading to Fig 9), and $C_L = 0\ 242 + 4\ 17\alpha$ and $C_D = 0\ 041 + 0\ 115 C_L^2$ 5 min later during the porpoising maneuvers In both cases, the mean coefficient of drag at the prevailing angles of attack was about 0 074, to be compared with 0 036 for the clean airframe; thus, the coefficient of drag more than doubled during this period of the flight Although there appears to be a change in the dependence of C_L on angle of attack, in the range of angles of attack from 0 4 deg the net coefficient of lift was nearly the same or slightly higher than for the clean airframe Thus, the major effect of the ice was to increase the drag substantially Figure 9 shows that the

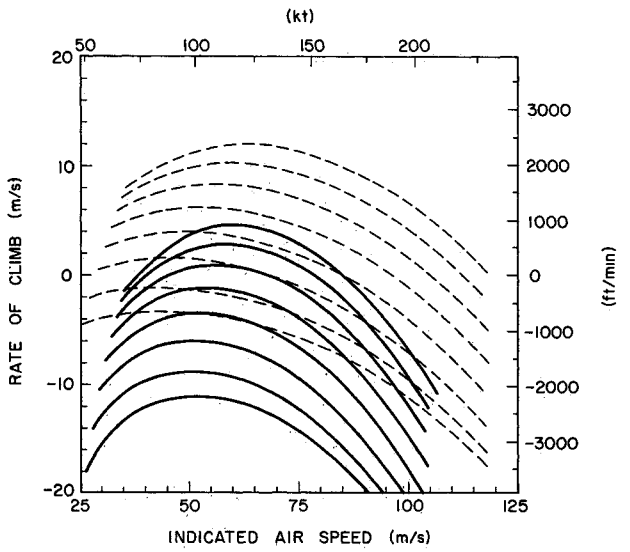

Fig 9 Performance curves for the period 2043 2045Z on Feb 26, 1982 when there was the greatest reduction in performance observed as a result of icing The solid lines indicate the deduced performance for this interval, and the dashed lines show the performance of the clean airplane without ice The curves correspond to torque settings from 0 to 2100 ft lb, in increments of 300 ft lb The assumed prop rotation rate was 1700 rpm

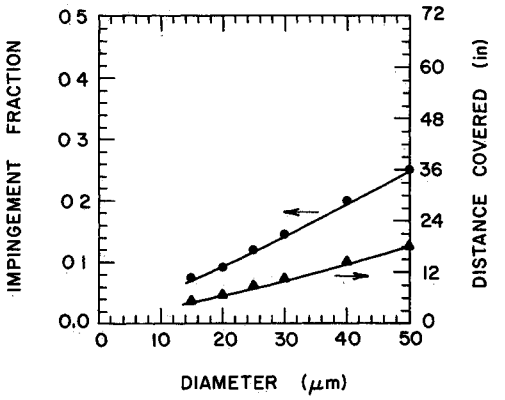

Fig 10 Impingement limits for collision with a NACA 651 208 airfoil at 4 deg angle of attack and for 200 knots true airspeed, 15,000 ft MSL, +15°F, and a chord length of 6 ft The calculations follow the procedures, and use the data, of Bowden et al [15]

performance at high airspeed was affected most, but that there was a significant effect on performance at flight speeds from 60 100 m/s as well The maximum indicated airspeed for level flight with a torque setting of 2100 ft lb (near maximum) was only about 85 m/s (~165 knots)

During maneuvers to acquire data for the performance evaluation, a pronounced buffet was experienced at indicated airspeeds of 140 knots (72 m/s) This is far above the normal 100-knot (51-m/s) stall speed of this airplane However, the aircraft was not permitted to stall, therefore, actual stall speed was not determined

It is interesting to compare the March 3, 1980 and Feb 26, 1982 cases, because the March 3 case appeared on the basis of potential accumulation and median volume diameter to present a more severe icing environment than the Feb 26 case, yet the latter in fact led to much greater degradation in performance The average liquid water contents and median volume diameters were similar in both cases, and the supercooled water was encountered at similar temperatures in relatively uniform regions of cloud. Yet the March 3 con ditions permitted flight over an extended period, while it was soon necessary to divert from the conditions of Feb 26 The major difference was that supercooled drops of intermediate size (40 300 μm) were present Feb 26, but not on March 3

The authors surmised in Sand et al.[1] that the reason for the difference in performance was that icing occurred on the unprotected lower surfaces of the wings in the Feb 26 case Although the volume median diameters were about the same in the two cases, the size distribution extended to large sizes on Feb 26 and those large drops were the ones which could accrete on the lower wing surface

Some calculations following the procedures of Bowden et al [15] illustrate the importance of large droplets Although data for the Super King Air airfoil were not available in that report, several other airfoils were discussed Figure 10 shows the fraction of the lower surface of an NACA 651 208 airfoil (with 1 8 m chord) on which ice could accrete as a function of droplet size Still larger drops, such as were present on Feb 26, 1982 and Jan 18 1983, would cover distances even greater than these These distances are substantially greater than those protected by deicing boots or heated surfaces

The pronounced effect of these large droplets indicates that the characterization of icing conditions according to the average liquid water content and volume median diameter is incomplete Although Newton[16] showed that the collection efficiency for droplets of size D_v is often close to the average efficiency of the size spectrum, D_v does not determine the *distribution* of ice over the accreting surfaces because it conveys no information regarding the breadth of the spectrum about the volume-median size Contributions from large drops may represent a minor portion of the liquid water content and still have a major influence on performance

It was found in these two unusual cases, as in the typical cases, that the primary effect of the ice was to increase the drag The amount of supercooled water in the large drop sizes was not great, but small accretions on the undersides of the wings may have disproportionate effects on performance. The primary effect of such an accretion would be to change the surface roughness Such an ice surface could have a major effect on drag if it covered a substantial portion of the lower wing surface. This change in surface roughness might also affect the stall characteristics

There are two important weaknesses in the preceding ap proach. First, possible effects of icing on propeller efficiency are not included However, such effects would be associated with small rather than large drops since large drops are likely to be shed from the rapidly moving propellers while small droplets will be collected with high efficiency The association of this icing encounter with 40 300 μm supercooled drops, the absence of any other anomaly in the microphysical characteristics, and the presence of a buffet at unusually high air speeds all indicate that the effects were not due to changes in propeller efficiency Second, the two icing encounters being discussed both occurred after installation of the Saunders Failsafe spar strap This additional structure on the lower wing surface may have worsened the effects of icing there, although the large increase measured in the coefficient of drag and the absence of significant ice accumulations on other unprotected surfaces argue against this spar strap as the primary cause of the performance reduction

Conclusions

1) The liquid water contents and volume median diameters encountered during these research flights generally were consistent with the envelopes of Appendix C, except that no icing regions were encountered in which the volume median diameter was >30 μm, while the liquid water content was >0.2 g/m^3

2) The primary effect of icing was to increase the drag of the airplane by as much as a factor of two Effects on the coefficients of lift were insignificant

3) Safe flights were conducted in regions where the liquid water contents and volume median diameters spanned the

range of conditions of Appendix C except that the conditions noted in point 1) were not encountered

4) Two unusual cases discussed in the preceding section indicate that rare but potentially hazardous icing conditions occur in which the liquid water content and volume median diameter do not characterize the hazard

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