JOURNAL OF AIRCRAFT
Vol. 30, No. 1, Jan.–Feb. 1993

Aerodynamic Effects of Ground De/Anti-Icing Fluids on Fokker 50 and Fokker 100

J. van Hengst*
Fokker Aircraft B.V., Amsterdam, The Netherlands

Flight tests on the Fokker 50 and Fokker 100 have been carried out to investigate the aerodynamic effects of Type I and Type II ground de/anti-icing fluids. The flight tests were performed February 12–19, 1990 at Gardermoen Airport in Norway. Five fluid manufacturers participated in the test program by supplying their commercially available Type II fluids. Some experimental Type II fluids were also tested on the Fokker 50 wing only. These experimental fluids are intended for commuter-type aircraft applications. This article describes the flight test and presents some test results and conclusions.

Nomenclature

CAS = calibrated air speed
C_D = drag coefficient
C_L = lift coefficient
C_M = pitching moment coefficient
DE = elevator deflection
LH = lefthand
MAX TO = maximum takeoff
M_{MO} = maximum operating Mach number
MTOW = maximum takeoff weight
m.a.c. = mean aerodynamic chord
RH = righthand
T.O.D. = takeoff distance
t_{LOF} = time to liftoff
V_{LO} = liftoff speed
V_R = rotation speed
V_S = stall speed in clean state
V_2 = takeoff safety speed
W = weight
α_R = angle-of-attack reference system
Δ = increment
δ_e = elevator deflection
θ = pitch acceleration

Introduction

IT has long been known that roughness in general, and roughness due to ice, frost, or snow accumulated over the entire lifting surface in particular, seriously degrades the aerodynamic characteristics of the lifting surfaces.[1–4]

In connection with the dangers during takeoff and climb following ground operations in icing conditions, the Federal Aviation Regulations (FAR) sections 91.527, 121.629, and 135.227 prohibit pilots from taking off with aircraft that have frost, snow, or ice adhering to their wings, control surfaces, or propellers. Deicing and anti-icing fluids have been developed to protect aircraft from ground icing.

Deicing fluids are water/glycol mixtures that contain at least 80% glycols, ethylene glycol or propylene glycol, or a mixture of both. These fluids are used to remove the ice from aircraft surfaces. They provide protection against refreezing only when precipitation conditions do not occur. Deicing fluids are coded as Type I fluids.

Anti-icing fluids, coded as Type II, have a glycol content of at least 50%. They contain a thickener system which, due to its pseudoplastic film-forming properties, provides protection against refreezing during precipitation for a period known as the holdover time. These fluids are used for deicing and anti-icing operations. The use of Type II fluids in 100% concentration or a mixture of 75% Type II and 25% water is limited by the Association of European Airlines (AEA) to aircraft with a rotation speed higher than 85 kt. This minimum speed is necessary to ensure that the fluid is sufficiently sheared off the lifting surfaces during the takeoff run.

In a joint NASA/Boeing/AEA effort, an investigation has been conducted into the aerodynamic effects of deicing and anti-icing fluids using a half-model and a two-dimensional model representing the 65% wing station, both of a 737-200 Adv. airplane.[5–7]

From this investigation it was found that the fluids cause both a transitory loss of lift and an increase in drag during takeoff. The aerodynamic effects of most older-generation Type II fluids were found to be noticeably worse than Type I fluids. New generation Type II fluids, offering much longer holdover times, imposed no greater aerodynamic effects than Type I fluids.

Results from wind-tunnel tests with simulated fluid roughness on a half-model of the Fokker 100 and on a complete model of the F27, were used to study the aerodynamic effects of Type I and Type II fluids on the performance characteristics of the Fokker 100 and Fokker 50. In the wind-tunnel tests the roughness caused by fluid when flowing off the wing surface at rotation was simulated by means of carborundum particles.

It was concluded from this study[8] that for the Fokker 100 no performance corrections need to be applied when the de/anti-icing treatment has been applied before takeoff. A similar conclusion was reached for the Fokker 50: this, however, was done by reading across the F27 experience to the Fokker 50. From an aerodynamic point-of-view the wing and empennage of the Fokker 50 are the same as those of the F27, and the use of de/anti-icing fluids on the F27 has been normal practice over many years of winter operation throughout Scandinavia.

It should also be noted that between the wind-tunnel tests and operational takeoff experience with fluids on the F27, a discrepancy exists which may be caused by the low wind-tunnel test Reynolds number and noncorrect representation of the fluid roughness at model scale.

On the basis of this study it was also decided to investigate the effects of ground de/anti-icing fluids at full-scale through flight trials on fully-instrumented Fokker 50 and Fokker 100 test aircraft.

Presented as Paper 91-0785 at the AIAA 29th Aerospace Sciences Meeting, Reno, NV, Jan. 7–10, 1991; received March 24, 1991; revision received Aug. 2, 1991; accepted for publication Aug. 22, 1991.

*Head, Aerodynamics and Aeroelasticity Department. Member AIAA.

Flight Tests

The objectives of the flight tests were 1) to verify flowoff behavior; 2) to check takeoff performance; and 3) to validate flight handling. The tests were performed at Gardermoen Airport, Norway, February 12–19, 1990. Weather conditions during the tests were favorable, with ambient temperatures ranging from −5 to +2°C and zero-to-calm winds. Fully instrumented A/C No. 11243—the second Fokker 100 prototype, and A/C No. 10685—the Fokker 50 prototype, were utilized for the flight trials (Fig. 1). The Fokker 50 and Fokker 100 are new generation high performance, twin-engined aircraft developed for short-to-medium commercial passenger and cargo transport.

The Fokker 100 is designed to carry 107 passengers with a maximum operating speed of M_{MO} = 0.77 and altitude of 35,000 ft. The aircraft is powered by two Rolls-Royce Tay 650 turbofan engines. The Fokker 50 is designed to carry 50 passengers. Powered by two Pratt & Whitney Canada PW125 turboprop engines driving Dowty six-bladed constant speed propellers, its maximum operating speed and altitude are M_{MO} = 0.507 and 25,000 ft.

Busy Bee of Norway contributed to the test program by placing its facilities at the airport at the disposal of the Fokker team.

Additional Instrumentation

In addition to the test instrumentation already fitted to the aircraft, video and photograph cameras were installed on the aircraft. In order to record the flow behavior on the upper surface of the Fokker 100 wings, cameras were mounted on the escape hatch windows (Fig. 2).

On the Fokker 50 a camera was located on top of the vertical tail looking at the RH wing outside the nacelle station. A camera on top of each nacelle focused on the leading edge of both LH and RH outboard wings, and a camera was mounted on the RH aft fuselage to record the flow behavior on the lower side of the RH horizontal tail and elevator (Fig. 3).

Fig. 1 Test aircraft at Gardermoen airport.

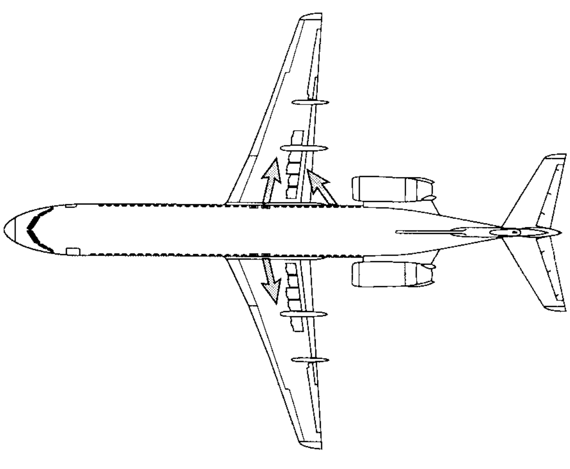

Fig. 2 Inboard locations of cameras.

Fluids Tested

Five fluid manufacturers participated in the program by supplying their commercially-available Type II fluids. The fluids were applied on Fokker 50 and Fokker 100 wings and horizontal tailplanes in 100% concentrated form, as well as diluted with 25% demineralized water (denoted as 75%/25% in Table 1).

All fluids were colored by the manufacturers to enhance video registration. In addition to supplying their commercially-available fluids, the manufacturers also provided some experimental Type II fluids for testing as identified in Table 2. These experimental fluids are intended for application on commuter aircraft operating with low takeoff rotation speeds. The fluids were tested in 100% concentrated form on the Fokker 50 wings only; an exception was Union Carbide Canada's UC5.1 which was tested on the Fokker 100 wings. Also tested was Kilfrost DF, a Type I fluid which is in use at Gardermoen Airport.

The Type II fluids were supplied in barrels and pumped into the deicing truck (an Elephant *B*), using a Blagdon double membrane pump. Samples of the fluids were taken before and after spraying for fluid viscosity measurements.

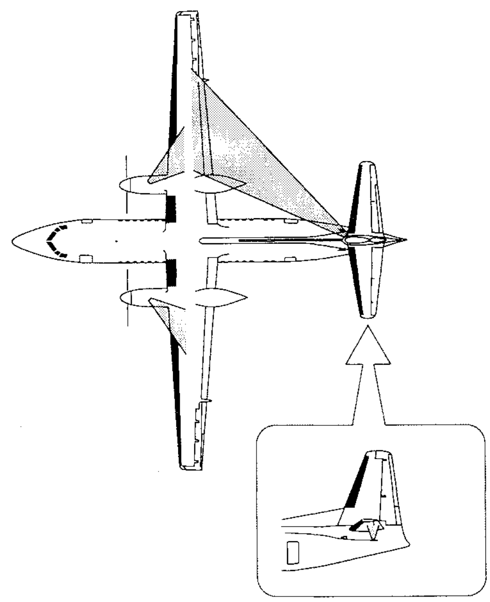

Fig. 3 Outboard camera positions.

Table 1 Type II fluid tested

Manufacturer	Trade name	Concentration
Kilfrost	ABC-3	100% and 75%/25%
Hoechst	1704 LTV/88	100% and 75%/25%
BASF	Aerex 200	100% and 75%/25%
SPCA	AD-104	100% and 75%/25%
Union Carbide Canada	AAF-250-3	100%

Table 2 Experimental Type II fluid tested

Manufacturer	Trade name	Concentration
Kilfrost Ltd.	DF-3	100%
Hoechst AG	1788 LTV	100%
SPCA	AD-106	100%
Union Carbide Canada	UC 5.1	100%

Only Hoechst AG 1788 LTV is commercially available at this moment.

Test Procedure

In principle, the same test procedure was followed on both Fokker 50 and Fokker 100 aircraft. Before testing the fluids, a takeoff was performed in the clean state by each aircraft for reference purposes. The AEA two-step deicing treatment was applied at the start of each fluid test. This treatment comprises a first-step/deicing carried out with a mixture of hot water and (Kilfrost DF) Type I fluid, followed by a second-step/anti-icing with the Type II fluid to be tested. After fluid treatment the aircraft was taxied to the runway for takeoff. It was observed that the expired time between fluid treatment and takeoff was 5–15 min.

On both aircraft a takeoff configuration was selected to obtain a low value of rotation speed, and hence, a short takeoff run. This was to enable a maximum amount of fluid to remain on the wings at liftoff.

For the Fokker 50, normal "all-engines" continued takeoffs were performed with maximum takeoff power. All tests were performed in the same configuration, i.e., a weight of 18,000 kg (39,680 lb), c.g. at 33% m.a.c. and flaps 15. At a rotation speed of approximately 97 kt, the aircraft was rotated using the normal, established technique. After liftoff, the flight director was followed which commands the aircraft towards a pitch attitude of about 11 deg with an airspeed of V_2 + 10 kt corresponding to 107 kt.

The handling characteristics of the aircraft have been checked with aileron doublets and in low speed maneuvering during 40-deg banked turns at 1.25 V_s with flaps 15 and power for level flight.

During the runs the flowoff behavior of the fluid was recorded on video. After each landing a visual inspection was carried out on the aircraft for any residual fluid.

For the Fokker 100, normal takeoffs were made using MAX TO power with an aircraft weight of 31,500 kg (69,445 lb), c.g. at 26% m.a.c. and flaps 15. Rotation speed was approximately 114 kt, with liftoff at 123 kt. A climb to 1500 ft was executed at constant speed, after which the aircraft was leveled off. An aileron doublet and LH and RH 40-deg banked turns were made to check handling, and each flight was completed by a full-flaps landing. A series of special runs was made during which the aircraft was rotated to a constant angle of pitch at a low speed (approximately 60 kt) and then accelerated until liftoff. These constant pitch runs were made with a clean wing and then with Kilfrost ABC-3 Type II fluid on the wing.

Test Results

Fluid Viscosity Measurements

The viscosities of the Type II fluids used in the tests were checked in the Fokker Laboratory using a Brookfield LVF viscosimeter with spindle 1 at 0.5 rpm and spindle 3 at 6 rpm. Both checks have been performed at 20°C. Comparing the results with manufacturers' data, it can be seen (Fig. 4) that a substantial difference in viscosity exists between the various makes of fluid. In general, the test fluids agree well with their respective specifications. Most fluids do, however, show a decrease of viscosity after being pumped and sprayed. The cause of this was the Blagdon pump used to transfer the fluids from the barrels into the spray truck. The observed loss of vicosity is considered to be of minor importance.

Flight Test Measurements

In this chapter the results of the Fokker 50 and Fokker 100 are discussed separately.

Fokker 50

A survey of all tests performed is presented in Table 3.

Fokker 50 Fluid Flowoff Behavior

From the video recordings of the fluid flowoff behavior during takeoff, the following observations may be made:

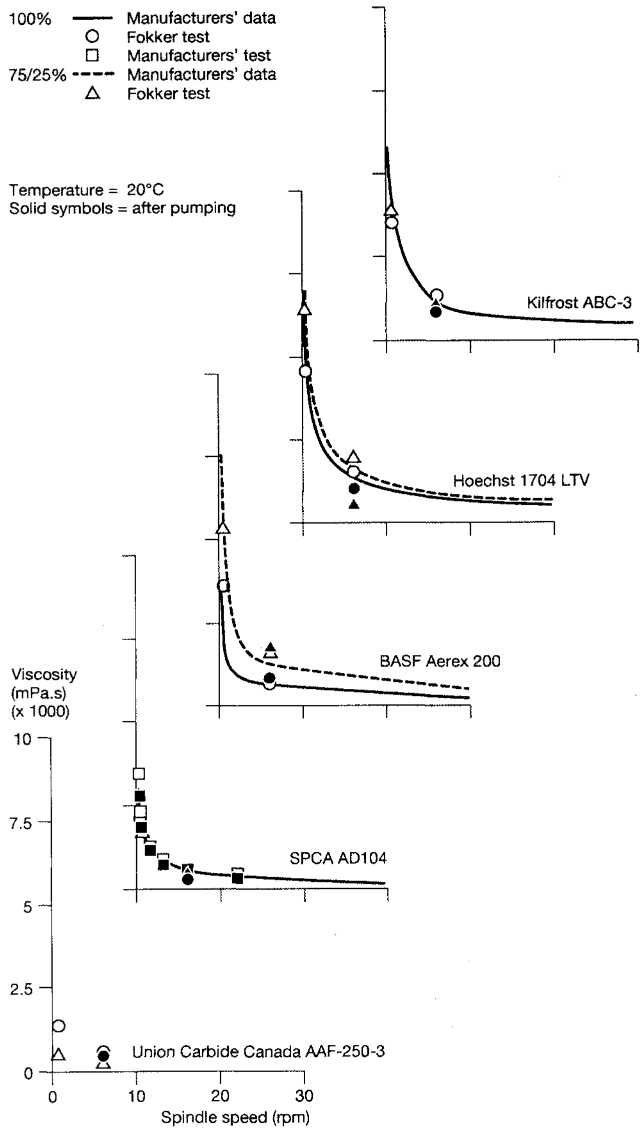

Fig. 4 Type II fluid viscosities measurements.

Table 3 Fokker 50 survey of test flights

Flight no.	Fluid	Type	Concentration
419	Clean	—	—
420	Kilfrost DF	Type I	100%
421	Kilfrost ABC-3	Type II	100%
422	Kilfrost ABC-3	Type II	75%/25%
423	Hoechst 1704 LTV	Type II	100%
424	Hoechst 1704 LTV	Type II	75%/25%
425	Hoechst 1788 LTV	Exp. Type II	100%
426	Kilfrost DF3	Exp. Type II	100%
427	SPCA AD106	Exp. Type II	100%
428	SPCA AD104	Type II	100%
429	SPCA AD104	Type II	75%/25%
430	BASF Aerex 200	Type II	100%
431	BASF Aerex 200	Type II	75%/25%
432	UCC AAF-250-3	Type II	100%

1) In the area behind the propellers the fluids already begin to flow at engine start due to the effect of the slipstream.

2) After brake release during the ground roll at approximately 40 kt, the fluid on the wing area not affected by the propeller slipstream starts to flow with the usual wavy pattern. Upon rotation at approximately 97 kt (corresponding to around 22 s after brake release) the wing leading edges back to 25% of wing chord are visually clean from fluid. At this moment, fluid shed from the wing is seen on 50% of the flap chord.

3) No secondary wave is noticed.

4) At rotation, only a small amount of fluid flows from the upper side of the horizontal tail to the lower side of the elevator by way of the elevator gap.

Fokker 50 Takeoff Performance

Observing the times to reach rotation, liftoff, and a height of 35-ft (Fig. 5), confirmed pilots' comment that no irregularities were encountered during the takeoffs performed. Time from brake release to rotation as obtained from the AFM are shown for reference. From parameters recorded during takeoff, the lift-coefficient vs angle of attack have been calculated. The results for liftoff and 1 s after liftoff are shown in Fig. 6. The moment of liftoff was determined as the average time of opening of LH and RH ground flight switches. As a reference, a line which has a slope as obtained from early flight test data, was drawn through the clean aircraft datum point.

With Type I deicing fluid only a small lift loss (< -0.10) was found at liftoff. With Type II anti-icing fluids a lift loss of $\Delta C_L = -0.10$ was found at each of the two aforementioned times. The analysis was carried out over a large time interval in order to obtain the transitory behavior of the lift loss.

A simulator study was carried out in order to quantify the effect of fluid on the takeoff distance from brake release until reaching a height of 35-ft. In this study transitory lift loss ΔC_L, drag increase ΔC_D, and pitching moment change ΔC_M were used. The lift loss was derived from flight tests as already described. The initial drag increase ΔC_D and pitching moment change ΔC_M were obtained from wind-tunnel tests and their transitory behavior were taken to be analogous to the lift loss.

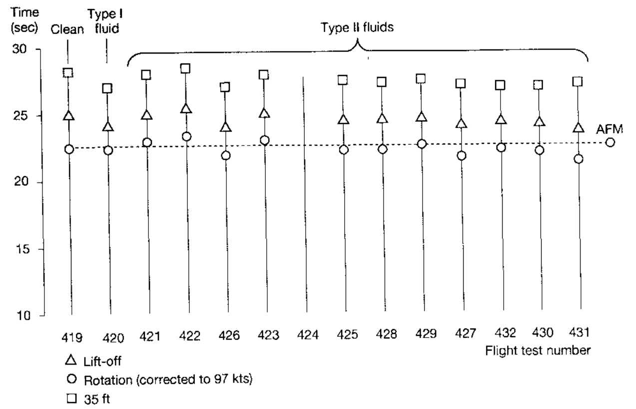

Fig. 5 Effect of fluids on Fokker 50 takeoff times.

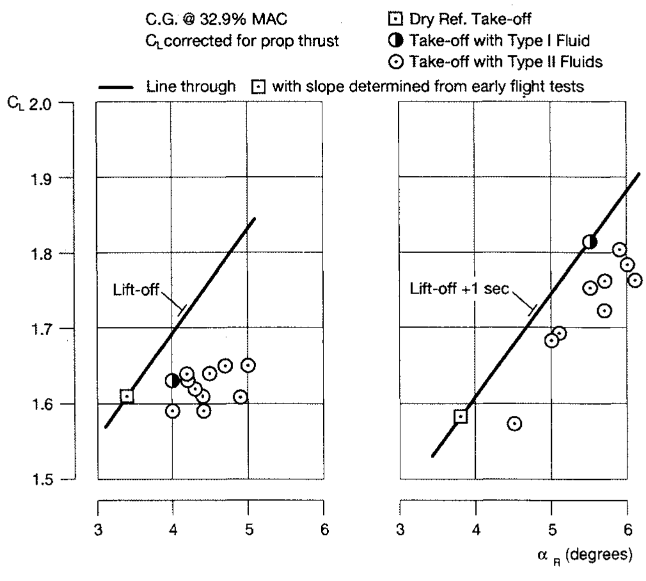

Fig. 6 Effect of fluids on Fokker 50 lift curves.

It was found that the effect of Type II fluids on the takeoff distance from brake release to 35-ft screen height for a takeoff with flaps 15 and assuming an engine failure at rotation speed, was an increment of 1.7%. This translates as 23 m at MTOW (20,820 kt) where the T.O.D. = 1300 and 13 m for a weight of 17,000 kg where the T.O.D. = 764 m.

The effect of Type II fluids on the climb gradient assuming engine failure at rotation was negligible.

From this study it is concluded that no performance corrections need to be applied when the aircraft is properly de/anti-iced with Type II fluid.

Fokker 50 Longitudinal Controllability

Airframe manufacturers (other than Fokker) have reported an increase of pitch force at rotation after their aircraft have been sprayed with fluid. This pitch force phenomenon which is attributed to fluid trapped inside the elevator shroud, was not experienced with the Fokker 50 during the fluid trials. The elevator control system of the Fokker 50 has a bungee spring which holds the elevator positively deflected in the ground roll (Fig. 7). This feature prevents the fluid from collecting in the space between the shroud and the elevator balance nose. Initiation of rotation of the aircraft is accomplished by an elevator deflection of -5 deg at forward c.g.

Furthermore, the horizontal tail of the Fokker 50 due to its low location on the vertical tail plane is submerged in the propeller slipstream. At static conditions and 25% takeoff power, the velocity of the slipstream over the horizontal tail equals 34 kt. So even at this early part of the ground roll towards the takeoff position on the runway, the fluid on the horizontal tail is blown off by the propeller slipstream.

From the time histories taken during the takeoffs, the elevator characteristics were determined in terms of elevator deflection vs pitch acceleration during rotation. No adverse effects due to the fluid on the elevator were found (Fig. 8), indicating a normal pitch response to elevator input. This was also confirmed by the pilot.

Fokker 50 Flight Handling

The flight handling characteristics of the aircraft were checked from 60 s after liftoff. No adverse effects due to the fluids were found in the aileron characteristics.

Fokker 50 Postflight Inspection

After landing, following each 15-min flight of the aircraft, a visual inspection was carried out to check for any residual fluid. It was found that the surfaces treated with fluid were still covered with a thin smooth layer of viscous fluid. On the aileron upper surface more than a thin layer of fluid was

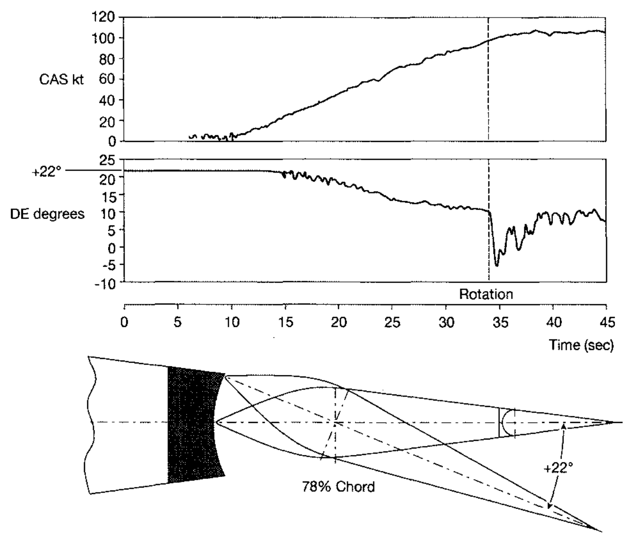

Fig. 7 Fokker 50 elevator position during initial takeoff ground roll.

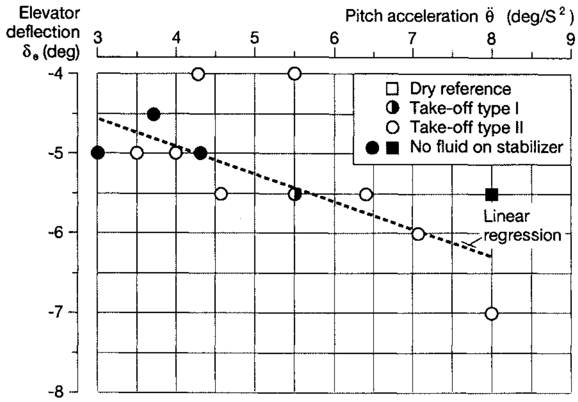

Fig. 8 Fokker 50 pitch response to elevator input.

Table 4 Fokker 100 survey of test flights

Flight no.	Fluid	Concentration
509	No fluid	——
510	Type I Kilfrost DF	100%
511	Kilfrost ABC-3	100%
512	Kilfrost ABC-3	75%/25%
513	Hoechst 1704 LTV	100%
514	Hoechst 1704 LTV	75%/25%
515	BASF Aerex 200	100%
516	BASF Aerex 200	75%/25%
517	SPCA AD104	100%
518	SPCA AD104	75%/25%
519	Union Carbide Canada AAF-250-3	100%
520[a]	Union Carbide Canada UC 5.1	100%
521	BAST Aerex 200	100%
5120	No fluid	——
5121	Kilfrost ABC-3	100%

[a]Experimental fluid II tested on wings only.

present. Fluid which has been captured in the shroud of the wing flaps was seen to have flowed over the flap following flap selection. The lower side of the aft fuselage was covered with residual fluid.

Fokker 100

A survey of all tests performed is presented in Table 4.

Fokker 100 Fluid Flowoff Behavior

Flowoff of the Type II fluids was recorded on video both during the normal takeoffs and during the constant pitch runs. From the sequence of the pictures taken during the takeoff runs, it was seen that at 40 kt (i.e., 6 s after brake release), the fluid flows with large waves over the wing upper surface. After 12 s from brake release, at 70 kt, the leading edge area was free of fluid waves. At 93 kt the leading edge area was clean and the waviness pattern in the area further aft on the wing has disappeared. At rotation, V_R = 115 kt, the wing upper surface was smooth.

At lift-off speed, V_{LO} = 123 kt, a layer of fluid moved from the stagnation area over the upper surface of the wing inboard of leading-edge fence. At 130 kt this fluid layer passed the unpainted leading edge and at 135 kt it was spread as a barely visible layer over the wing.

In the constant pitch takeoff runs the aircraft was rotated to a preselected pitch angle at approximately 60 kt. For pitch angles of 5 and 7.5 deg the flow behavior of the fluid was essentially similar to a normal takeoff run as discussed above. For pitch angles of 10 and 12 deg, however, the flowoff behavior changed dramatically. Instead of clearing the leading-edge area of the wing, the fluid did not flow aft until after liftoff. Small changes in pitch angle during the run caused fluid to flow from the stagnation area to feed the pool of fluid trapped between approximately 5 and 20% wing chord. This behavior of the fluid indicated an area of separated flow on the inner wing.

Fokker 100 Takeoff Performance

From a comparison of all the test run times to reach 100 kt CAS, rotation, and lift-off (Fig. 9) with airplane flight manual (AFM) calculated data, no abnormal behavior of the aircraft with fluid was evident during takeoff. From parameters recorded during the takeoff, the lift coefficients vs angle of attack of the aircraft at the moment of liftoff and 1 s after were determined (Fig. 10).

Also derived were the lift coefficients of the large angle of pitch test runs (open diamonds in Fig. 9). It was found from these calculations that the fluids had no effect on the lift when normal takeoffs were performed. Early rotation to large angle of pitch caused an 18% loss of lift. This result confirmed the observation of a flow separation area on the inner wing under these abnormal takeoff ground run conditions.

Fokker 100 Controllability and Flight Handling

Elevator control forces during rotation were measured throughout the test program. No abnormal behavior was found, nor was it reported by the pilots on any flight. To check the flight handling characteristics for any influence of the remaining fluid after takeoff, some maneuvers were performed after reaching an altitude of 1500 ft. Aileron control forces in a doublet and during 40-deg banked turns were measured. No influence on flight handling and maneuver margins was detected, nor was there any pilot comment.

Fokker 100 Postflight Inspection

A visual inspection of the aircraft was carried out to check for any residual fluid for each flight after landing. It was found that fluid was captured in the lift dumper shroud but following lift dumper deployment on the landing this fluid flowed over the trailing edge and adhered to the aft part of the main flap.

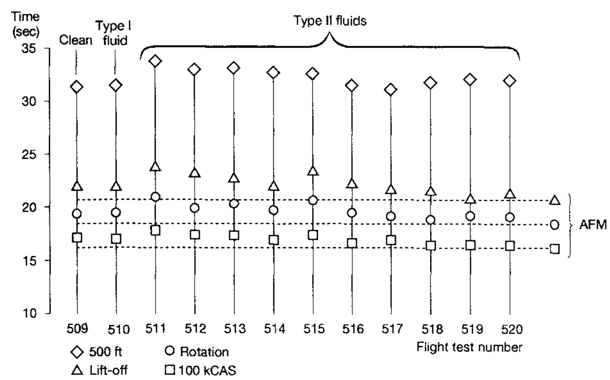

Fig. 9 Effect of fluids on Fokker 100 takeoff times.

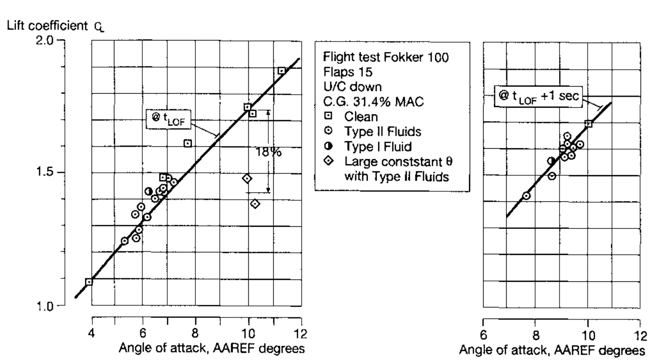

Fig. 10 Effect of fluids on Fokker 100 lift-curves.

Conclusions

Fokker 50

From the Type II fluid trials on the Fokker 50 the following conclusions were found:

1) The flowoff behavior of the fluids was satisfactory.
2) Wing leading edges were visually clean from fluid at rotation.
3) Elevator control at rotation was not affected by the fluid.
4) Flight handling characteristics as checked after takeoff were normal.
5) A small lift loss at rotation was found.
6) No performance corrections need to be applied when the aircraft is properly de/anti-iced using Type II fluid.

Fokker 100

From the Type II fluid trials on the Fokker 100 the following conclusions were found.

1) The flowoff behavior of the fluids was satisfactory.
2) Handling and control characteristics after takeoff were not affected by residual fluids.
3) No loss of lift was found at rotation during a normal takeoff.
4) Constant pitch takeoff runs with large angles of pitch caused large lift losses.
5) No performance corrections need to be applied when the aircraft is properly de/anti-iced with Type II fluid.

References

[1]Jones, R., and Williams, D. H., "The Effect of Surface Roughness on the Characteristics of the Airfoils NACA 0012 and RAF 34," ARC, R&M 1708, London, Feb. 1936.

[2]Abbott, I. H., von Doenhoff, A. E., and Stivers, L. S., Jr., "Summary of Airfoil Data, NACA TR 824, Langley Field, VA, March 1945.

[3]Ljungström, B. L. G., "Wind-Tunnel Investigation of Simulated Hoar Frost on a Two-Dimensional Wing Section with and Without High Lift Devices," FFA-AU-902, Bromma, Sweden, April 1972.

[4]Brumby, R. E., "Wing Surface Roughness Cause and Effect, D.C. Flight Approach," No. 32, Long Beach, CA, Jan. 1979.

[5]Runyan, L. J., Zierten, T. A., Hill, E. G., and Murakami, J. K., "Joint Boeing/AEA/NASA Flight and Wind Tunnel Evaluations of Aircraft Ground De/Anti-Icing Fluids," AEA De/Anti-Icing Task Force, Hamburg, Germany, July 13, 1988.

[6]Cruse, D. L., and Zierten, T. A., "Boeing/AEA Evaluation of the Aerodynamic Effects of Aircraft Ground De/Anti-Icing Fluids," Society of Flight Test Engineers 19th Annual Symposium, Arlington, TX, Aug. 14–18, 1988.

[7]Runyan, L. J., Zierten, T. A., and Hill, E. G., "Flight and Wind Tunnel Investigation of Aerodynamic Effects of Aircraft Ground De/Anti-Icing Fluids," AGARD Symposium on Flight in Adverse Environmental Conditions, Paper 24, Göl, Norway, May 8–11, 1989.

[8]van Hengst, J., "Aerodynamic Aspects of Ground Icing," *Look Twice for Ice*, Wingtips 14th ed., Advice on the Operation and Maintenance of Fokker Aircraft Cold Weather Operation, Amsterdam, The Netherlands, Dec. 1989, Chap. 1.