Freezing precipitation on lifting surfaces / Précipitation glaçante sur les surfaces portantes

Oleskiw, M. M.

https://doi.org/10.4224/21276139

Technical Report (National Research Council of Canada. Institute for Mechanical Engineering. Cold Regions Engineering); no. IME-CRE-TR-003, 1991-09

National Research Council Canada
Conseil national de recherches Canada

Institute for Mechanical Engineering
Institut de génie mécanique

Cold Regions Engineering
Ingénierie des régions froides

NRC·CNRC

Freezing Precipitation on Lifting Surfaces

M.M. Oleskiw

Technical Report
Rapport technique

1991/09
IME-CRE-TR-003
NRC No. 32124

UNLIMITED
UNCLASSIFIED
ILLIMITÉE
NON CLASSIFIÉE

Canada

UNLIMITED
UNCLASSIFIED

ILLIMITÉE
NON CLASSIFIÉE

FREEZING PRECIPITATION ON LIFTING SURFACES

PRÉCIPITATION GLAÇANTE SUR LES SURFACES PORTANTES

M. M. Oleskiw, Ph.D.

Institute for Mechanical Engineering
Technical Report

Institut de génie mécanique
Rapport technique

1991/09

IME-CRE-TR-003
NRC no. 32124

R. Frederking, Head/Chef
Cold Regions Engineering Program/
Programme d'ingénierie des régions froides

J. Ploeg
Director General/
Directeur général

ABSTRACT

As a part of its investigation, the Commission of Inquiry into the Air Ontario Crash at Dryden, Ontario asked the National Research Council to estimate the quantity and form of the precipitation adhering to the Fokker F-28's wings during its ill-fated take-off attempt.

Since precipitation measurements at Dryden were not taken sufficiently frequently to determine the quantity of precipitation which fell during the aircraft's stopover at Dryden, an empirical formula, utilizing the visibility recorded by the weather observer and by a transmissometer, was used to provide an estimate of 1.38 mm of snowfall.

A thermodynamic analysis of the influence of the take-off roll upon the precipitation layer on the wings indicated that no significant change occurred during this interval. However, the wing tank fuel temperature during the final stopover was calculated to be below 0°C. Therefore, heat removed from the lower part of the precipitation layer could have caused it to freeze. As a result, when the upper snow layer was blown away during the take-off roll, it likely left behind, on the wing, a very rough ice layer with potentially serious effects on the aircraft's aerodynamic performance.

RÉSUMÉ

La Commission d'enquête sur l'écrasement d'un avion d'Air Ontario à Dryden (Ontario) a demandé au Conseil national de recherches Canada d'estimer la quantité et la forme de précipitation qui a adhérée aux ailes du Fokker F-28 au moment de sa malheureuse tentative de décollage.

Puisque les mesures de précipitation à Dryden n'ont pas été prises assez fréquemment pour déterminer la quantité de neige qui a tombée durant l'escale de l'avion à Dryden, une formule empirique, utilisant la visibilité notée par l'observateur météorologique et par un transmissomètre, a été employée pour donner une estimation de 1.38 mm de la chute de neige.

Une analyse thermodynamique de l'influence du roulement au décollage sur la couche de précipitation sur les ailes a indiqué qu'il n'y avait pas eu de changement considérable pendant cet intervalle. Toutefois, la température du carburant dans les réservoirs des ailes de l'avion durant l'escale finale était moins de 0°C. Par conséquent, la chaleur transmise de la plus base partie de la couche de précipitation aurait pu geler celle-ci. À cause de ça, quand la plus haute couche de neige s'est envolée durant le roulement au décollage, elle a probablement laissé une couche de givre très rugueuse sur les ailes, avec des effets possiblement sérieux sur le fonctionnement aérodynamique de l'avion.

CONTENTS

CONTENTS (Cont'd)

LIST OF TABLES

CONTENTS (Cont'd)

LIST OF SYMBOLS

Symbol		Units
a	Constant	K^3
a_∞	Speed of sound in the freestream flow	$m\cdot s^{-1}$
C	Mean aerodynamic chord of the wing	m
C_p	Pressure coefficient	
c_p	Specific heat at constant pressure	$J\cdot K^{-1}\cdot kg^{-1}$
C_s	Mass concentration of the snowflakes in the air	$kg\cdot m^{-3}$
D	Cylinder diameter	m
$e_{0°C}$	Saturation vapour pressure over the precipitation layer's surface	kPa
e_a	Saturation vapour pressure just outside the boundary layer	kPa
h	Convective heat transfer coefficient	$W\cdot m^{-2}\cdot K^{-1}$
h_C	Local convective heat transfer coefficient over a wing	$W\cdot m^{-2}\cdot K^{-1}$
h_D	Local convective heat transfer coefficient over a cylinder	$W\cdot m^{-2}\cdot K^{-1}$
I	Mass flux of accreting snowflakes	$kg\cdot m^{-2}\cdot s^{-1}$
k	Constant	
k_a	Thermal conductivity of air	$W\cdot m^{-1}\cdot K^{-1}$
k_f	Thermal conductivity of wing tank fuel	$W\cdot m^{-1}\cdot K^{-1}$
k_m	Fraction of precipitation layer in liquid form	$W\cdot m^{-1}\cdot K^{-1}$
k_p	Thermal conductivity of the precipitation layer	$W\cdot m^{-1}\cdot K^{-1}$
k_s	Thermal conductivity of aluminum	$W\cdot m^{-1}\cdot K^{-1}$
L_e	Latent heat of evaporation at 0°C	$J\cdot kg^{-1}$
L_f	Latent heat of fusion	$J\cdot kg^{-1}$
m_1	Mass of liquid 1	kg
m_2	Mass of liquid 2	kg
Nu_C	Wing Nusselt number	
Nu_D	Cylinder Nusselt number	
p_a	Local air pressure just outside the boundary layer	kPa
p_∞	Static pressure	kPa
q_a	Heat flux to cool the precipitation layer to the freezing point	$W\cdot m^{-2}$
q_c	Heat flux due to convection	$W\cdot m^{-2}$
q_e	Heat flux due to evaporation or sublimation	$W\cdot m^{-2}$
q_f	Heat flux to freeze the unfrozen portion of the precipitation layer	$W\cdot m^{-2}$
q_i	Heat flux due to conduction into the wing of the aircraft	$W\cdot m^{-2}$
q_k	Heat flux from kinetic energy of the impinging snowflakes	$W\cdot m^{-2}$
q_m	Heat flux from freezing the partially-melted impinging snowflakes	$W\cdot m^{-2}$
q_s	Heat flux from short and long-wave radiation	$W\cdot m^{-2}$
q_v	Heat flux from frictional heating of the air in the boundary layer	$W\cdot m^{-2}$
R	Precipitation rate	mm/h

CONTENTS (Cont'd)

Symbol		Units
r	Recovery factor for viscous heating	
Re_C	Wing Reynold's number	
Re_D	Cylinder Reynold's number	
T	Thickness of accumulated snow layer	m
T_f	Thickness of a given volume of wing fuel	m
T_p	Thickness of precipitation layer	mm
T_s	Thickness of the aluminum skin of the aircraft wing	m
t_a	Local air temperature just outside the boundary layer	°C
t_f	Temperature of wing tank fuel	°C
t_{fi}	Fuel temperature before flight	°C
$t_{f\tau}$	Fuel temperature after flight at altitude of duration τ	°C
t_m	Temperature of mixture of liquids 1 and 2	K
t_p	Temperature of the precipitation layer	°C
t_T	Total air temperature at altitude	°C
t_w	Wet-bulb temperature	°C
t_1	Temperature of liquid 1	K
t_2	Temperature of liquid 2	K
V	Visibility	km
V_a	Local air velocity	$m \cdot s^{-1}$
V_∞	Aircraft airspeed	$m \cdot s^{-1}$
β	Local collision efficiency	
ν_∞	Kinematic air viscosity	$m^2 \cdot s^{-1}$
ρ_s	Snow density	$kg \cdot m^{-3}$
ρ_∞	Freestream air density	$kg \cdot m^{-3}$
σ	Stefan-Boltzmann constant	$W \cdot m^{-2} \cdot K^{-4}$
τ	Time to freeze snow layer	s
τ_a	Duration of flight at altitude	s

FREEZING PRECIPITATION ON LIFTING SURFACES

1.0 INTRODUCTION

In a letter dated 1989 June 20, Mr. D. J. Langdon of the Canadian Aviation Safety Board (now the Transportation Safety Board of Canada, CTSB) wrote to the Low Temperature Laboratory (now Cold Regions Engineering) of the National Research Council (NRC) requesting assistance in the investigation of the 1989 March 10 accident to Fokker F-28 Mk1000, registration C-FONF, at Dryden, Ontario. Witness testimony to that point had indicated that snow had been seen to fall on the wings of the aircraft during its station-stop at Dryden, and some witnesses had reported that the snow had appeared to turn to ice during the take-off roll.

Mr. Langdon (acting on behalf of Mr. J. Jackson, an advisor to the Inquiry) requested that the following analyses be performed:

- an estimation of the weight of snow per unit area which could have collected on the aircraft prior to take-off;
- a determination of whether or not wet snow crystals could have stuck to the leading edge of the wing during take-off; and
- a determination of whether or not snow on the surface of the wing could have turned to ice (as reported by witnesses) through the mechanisms of adiabatic and evaporative cooling of the airflow over the wing.

This report addresses these requests in the three sections which follow. Section 2 attempts to estimate the amount of snow which would have accumulated on the aircraft during its station-stop at Dryden. Section 3 presents an analysis of adiabatic and evaporative cooling of the wing and its effects on the precipitation extant and impinging on the wing during the take-off roll. Finally, Section 4 discusses the possibility of the wing surface being cooled by the fuel in the wing tanks, and what effect that might have had on the precipitation.

2.0 QUANTITY OF PRECIPITATION ACCUMULATED

2.1 Precipitation Recorded on the Surface Weather Record

With respect to estimating total precipitation accumulation on the upper surfaces of the Fokker F-28 aircraft during its station-stop at Dryden, the aircraft movements of interest are: the time of arrival from Thunder Bay (17:40 UTC); and the time of take-off from Dryden (18:10 UTC). During this time period, the weather details of interest at the Dryden Airport, as observed and reported on the Atmospheric Environment Service (AES) Surface Weather Record, are noted in Table 1. Column 1 shows the recorded

Table 1. Weather at Dryden, Ontario on 1989 March 10

TIME (UTC)	DRY BULB TEMP. (°C)	DEW POINT TEMP. (°C)	WEATHER	VISIBILITY (mi)	SNOWFALL RATE WATER EQUIVALENT (mm/h)
17:00	1.0	-4.0	very light snow grains	14	0
17:07			light snow grains	14	0 to 2.5
17:23			-	14	0
17:42			light snow	14	0 to 2.5
17:48			light snow	2.5	0 to 2.5
18:00	0.7	-3.0	light snow	2.5	0 to 2.5
18:06			moderate snow	0.375	2.6 to 7.5
18:11			light snow	0.75	0 to 2.5
18:12	0.3	-2.1	light snow	0.75	0 to 2.5

time of the observation. Columns 2 and 3 respectively give the dry bulb and dew point temperatures as measured by the observer. Column 4 records the type of weather, including the type of precipitation and its rate of accumulation. The visibility indicated in Column 5 was obtained by determining the most distant object visible to the observer. The water equivalent of the snowfall rate (quantity of water which would be measured if the snow was melted) is presented in Column 6. This rate is derived from the precipitation rate in Column 4 by the definitions presented in the AES Manual of Observations (MANOBS).

The ranges of snowfall rate indicated in Table 1 are not sufficiently precise to allow a reasonable estimate of the amount of snowfall during the F-28's station-stop. Fortunately, precipitation accumulation may also be estimated from visibility data. Two sources of visibility data from the Dryden Airport are available for analysis: the meteorological observer's data as given in Table 1; and recordings from a Transport Canada transmissometer.

2.2 Relating Precipitation Rate to Visibility

Stallabrass (1987) performed a series of experiments relating snowfall concentration with visibility, and snowfall concentration with precipitation rate. The correlation coefficient for the best-fit line relating the former two quantities for all types of snow crystals was 94.3%. Stallabrass stated that the correlation between the latter two quantities was expected to be poorer based on earlier predictions by other researchers. This was believed to be a function of the considerable variability in terminal fall velocity of the ice crystals and snowflakes, depending upon, for example, whether or not the crystals and flakes were heavily rimed or partially melted. This variability would tend to affect the rate of precipitation more than the mass concentration in the air. Despite these difficulties, Stallabrass suggested that based upon his measurements, precipitation rate R (mm/h water equivalent) could be estimated from visibility V (km) by the relationship

$$V = 0.919 R^{-0.64} \tag{1}$$

with a correlation coefficient of 0.91. Inverting this relationship with V in miles gives

$$R = 0.417 V^{-1.56} ; \tag{2}$$

and with V in feet gives

$$R = 2.68 \times 10^{5} V^{-1.56}. \tag{3}$$

Based upon Stallabrass's observations, the extreme values of the precipitation rate measured for a given visibility were approximately between 1/3 to 3 times those predicted by the best-fit line.

Given this degree of variability in the precipitation rate versus visibility relationship, an attempt has been made to compare two predictions of total precipitation accumulation at Dryden versus the recorded precipitation accumulation. Two sources of visibility data have been used: the Surface Weather Record; and transmissometer data. The actual precipitation accumulation has been assumed to be that noted by the meteorological observer during the 6 hour interval between 18:00 UTC on March 10 and 00:00 UTC on March 11. Unfortunately, no optional measurement of precipitation accumulation was noted between the measurements at these two mandatory times.

2.3 Precipitation Inferred from Surface Weather Record Visibility

Table 2 displays the estimation of total water-equivalent snowfall accumulation at Dryden between March 10 18:00 UTC and March 11 00:00 UTC as derived from the visibility data recorded on the AES Surface Weather Record. Column 1 indicates the time at which an interval begins with approximately constant visibility. Column 2 gives the length of the time interval, while Column 3 shows the visibility. The precipitation rate derived from Column 3 using Eq. 2 is given in Column 4. The accumulation of snowfall in each time interval (Column 2 multiplied by Column 4) is displayed in Column 5. The total interval length (3.8 h) is not equal to 6 h because no snow was observed to fall

Table 2. Integration of precipitation rate based upon the meteorological observer's visibility estimates for the period between March 10 18:00 UTC and March 11 00:00 UTC.

BEGINNING OF TIME INTERVAL (UTC)	INTERVAL LENGTH (h)	VISIBILITY (mi)	WATER EQUIVALENT SNOWFALL RATE (mm/h)	WATER EQUIVALENT SNOWFALL OVER TIME INTERVAL (mm)
18:00	0.10	2.5	0.10	0.01
18:06	0.08	0.375	1.93	0.15
18:11	0.52	0.75	0.65	0.34
18:42	0.30	2.5	0.10	0.03
19:00	0.35	3.0	0.08	0.03
19:21	0.65	5.0	0.03	0.02
20:52	0.13	4.0	0.05	0.01
21:00	0.12	2.5	0.10	0.01
21:07	0.30	1.5	0.22	0.07
21:25	0.37	1.0	0.42	0.16
21:47	0.30	0.5	1.23	0.37
22:05	0.33	0.75	0.65	0.21
22:25	0.25	1.0	0.42	0.11
TOTALS:	3.80			1.52

during some of the 6 h interval. The total accumulated water-equivalent snowfall is predicted as 1.52 mm. This is significantly less than the total accumulated water-equivalent snowfall recorded on the Surface Weather Record of 6.0 mm. This discrepancy will be discussed in more detail below.

2.4 Precipitation Inferred from Transmissometer Data

Table 3 presents data recorded by and interpreted from the Transport Canada transmissometer which was located near the runway on which C-FONF landed and departed on March 10. The strip-chart recorded by this device has been analysed by Mr.

Table 3. Integration of precipitation rate based upon the Transport Canada Transmissometer's visibility estimates for the 6 h period between March 10 18:00 UTC and March 11 00:00 UTC.

BEGINNING OF TIME INTERVAL (UTC)	INTERVAL LENGTH (h)	TRANSMISSIVITY (%)		VISIBILITY (ft)		WATER EQUIVALENT SNOWFALL RATE (mm/h)		WATER EQUIVALENT SNOWFALL OVER TIME INTERVAL (mm)	
		RAW	CORR.	RAW	CORR.	RAW	CORR.	RAW	CORR.
18:00	0.08	76	70	2600	2050	1.26	1.83	0.10	0.15
18:05	0.08	74	68	2400	1900	1.43	2.06	0.11	0.16
18:10	0.08	82	76	3700	2600	0.73	1.26	0.06	0.10
18:15	0.08	87	81	5000	3500	0.45	0.79	0.04	0.06
18:20	0.08	83	77	4000	2800	0.64	1.12	0.05	0.09
18:25	0.08	85	79	4500	3000	0.54	1.01	0.04	0.08
18:30	0.92	90	84	6000	4200	0.34	0.60	0.31	0.55
19:25	0.58	91	85	6000	4200	0.34	0.60	0.20	0.35
20:55	0.08	85	79	4500	3000	0.54	1.01	0.04	0.08
21:00	0.08	78	72	2900	2200	1.06	1.64	0.08	0.13
21:05	0.08	82	76	3700	2600	0.73	1.26	0.06	0.10
21:10	0.17	83	77	4000	2800	0.64	1.12	0.11	0.19
21:20	0.08	78	72	2900	2200	1.06	1.64	0.08	0.13
21:25	0.33	54	48	2600	2050	1.26	1.83	0.42	0.60
21:45	0.08	58	52	1400	1100	3.31	4.83	0.26	0.39
21:50	0.08	54	48	1250	1050	3.95	5.19	0.32	0.42
21:55	0.08	61	55	1450	1300	3.14	3.72	0.25	0.30
22:00	0.08	67	61	1850	1500	2.14	2.97	0.17	0.24
22:05	0.08	68	62	1900	1550	2.06	2.83	0.16	0.23
22:10	0.17	83	77	4000	2800	0.64	1.12	0.11	0.19
22:20	0.33	88	82	5500	3700	0.39	0.73	0.13	0.24
TOTALS:	3.70							3.10	4.78

B. Sheppard, Senior Instrument Meteorologist, Data Acquisition Systems Branch, Atmospheric Environment Service, Environment Canada. His interpretation of these data has been provided to the Inquiry in the form of a report. Mr. Sheppard has noted that at certain intervals, the transmissometer turns off its transmitting light for a short time to determine the amount of background skylight received. Two such intervals were recorded during the period of interest, and both show values of about 6%. One possible interpretation of this result, as indicated by Mr. Sheppard, is that all values taken from the transmissometer strip-chart should be reduced by 6%.

Column 1 of Table 3 indicates the time at which an interval, with approximately constant visibility (as interpreted from the sensor's strip-chart), begins. Column 2 gives the length of this time interval. Column 3 shows a representative value of transmissivity for the interval as interpreted from the strip-chart. Column 4's transmissivity has been obtained from Column 3's "raw" value by applying the 6% "correction" discussed above. Columns 5 and 6 display the visibility values obtained from Columns 3 and 4. Columns 7 and 8 give the water-equivalent snowfall rate derived from Column 5 and 6 using Eq. 3. Finally, Columns 9 and 10 exhibit the accumulated water-equivalent snowfall obtained by multiplying Column 2 by Columns 7 and 8, respectively.

The total interval length at the bottom of Column 2 of Table 3 is, to within the resolution of the interpretation of the strip-chart, the same as for the comparable quantity in Table 2. The total accumulated water-equivalent snowfall values displayed at the bottoms of Columns 9 and 10 are significantly higher than the 1.52 mm of Table 2. The "corrected" value is 80% of the 6.0 mm measured over the interval by the meteorological observer. However, in comparing the "corrected" visibility values in Table 3 with those made by the meteorological observer, it is evident that the subtraction of 6% from all "raw" transmissivity values to obtain the "corrected" ones has resulted in "corrected" visibility values which are significantly lower than those noted by the observer. A case in point is the time period surrounding 19:15, where the observer recorded a visibility value of 3 mi (15,840 ft) as compared to the "corrected" value of 4200 ft. Evidently, while this correction may be appropriate for lower values of tranmissivity, it should not be equally applied to "raw" values near the upper limit of transmissivity (in the range of 87 to 100%). Even the "raw" value of transmissivity at this time indicates a lower value of visibility (6000 ft) than noted by the observer. This may be attributed to the values of transmissivity between 18:30 and 20:00 UTC (90 or 91%) which should actually be interpreted as greater than 6000 ft. The maximum water-equivalent snowfall rate derived from the observer's visibility estimates during this period is 0.10 mm/h. If the transmissometer's values are reduced from 0.34 mm/h, then the accumulated water-equivalent snowfall over this 1.5 h period would be reduced from 0.51 mm to 0.15 mm. That would reduce the accumulated water-equivalent snowfall for the 6 h period from 3.10 mm to 2.74 mm.

The net result of this analysis is to indicate that if the observer's accumulated water-equivalent snowfall is to be "calibrated" to achieve 6.0 mm over the 6 h period, then the value of 1.52 mm from Table 2 must be multiplied by a factor of 3.95. If the transmissometer's "raw" accumulated water-equivalent snowfall (corrected for those periods when the transmissivity is 87 to 100%) is compared to the observed amount, the multiplicative "calibration" factor is 2.19.

2.5 Estimating Precipitation During C-FONF's Station Stop at Dryden

Returning to the period of C-FONF's station-stop at Dryden, Table 4 contains data from both of these methods for this time period. Columns 1 and 2 once again indicate the

Table 4. Integration of precipitation rate during the station-stop of C-FONF at Dryden on 1990 March 10.

BEGINNING OF TIME INTERVAL (UTC)	INTERVAL LENGTH (h)	TRANSMIS-SOMETER READING (%)	VISIBILITY (ft)		WATER EQUIVALENT SNOWFALL RATE (mm/h)		WATER EQUIVALENT SNOWFALL OVER TIME INTERVAL (mm)	
			TRANS.	OBS.	TRANS.	OBS.	TRANS.	OBS.
17:40	0.083	93	73920	73920	0.01	0.01	0.00	0.00
17:45	0.083	91	73920	73920	0.01	0.01	0.00	0.00
17:50	0.083	91	13200	13200	0.10	0.10	0.01	0.01
17:55	0.083	92	13200	13200	0.10	0.10	0.01	0.01
18:00	0.033	86	4700	13200	0.50	0.10	0.02	0.00
18:02	0.033	76	2600	13200	1.26	0.10	0.04	0.00
18:04	0.033	68	1900	13200	2.05	0.10	0.07	0.00
18:06	0.033	74	2400	1980	1.43	1.93	0.05	0.06
18:08	0.033	79	3000	1980	1.01	1.93	0.03	0.06
TOTALS:	0.50						0.23	0.14

beginning of the time interval and the length of the time interval respectively. The transmissometer reading is displayed in Column 3. Columns 4 and 5 exhibit a representative visibility for the interval. Column 4's data are derived from Column 3 with a correction to the observer's values when the transmissometer reading is between 87 and 100%. The data in Column 5 are converted from the values taken from the

Surface Weather Record. Columns 6 and 7 give the water-equivalent snowfall rate as derived from Columns 4 and 5. Finally, Columns 8 and 9 tabulate the accumulated water-equivalent snowfall obtained from Columns 2, 6 and 7.

Totals over the 0.5 h time interval of the accumulated water-equivalent snowfall derived from the transmissometer and the observer's notes are 0.23 mm and 0.14 mm respectively. Multiplying these two values by their corresponding "calibration" factors (as determined above), produces best estimates of water-equivalent snowfall accumulation, while the aircraft was on the ground, of 0.50 mm and 0.55 mm. These accumulations are equivalent to a mass per unit area of 0.5 and 0.55 kg m^{-2}.

In order to determine the likely thickness of this layer of precipitation, we need to know its density. Estimating an appropriate value for the precipitation layer density when it has been formed through the accumulation of wet snow is rather difficult since it can vary depending upon the conditions of snowflake formation and also upon the heat balance within the layer itself. A simplification adopted by Makkonen (1989), which will be accepted here as well, is to utilize a statistical mean value for the snow density (ρ_s) of 400 kg·m^{-3}. The higher of the two estimates of water-equivalent snowfall accumulation then gives a best value for the thickness of the precipitation layer of T_p = 1.38 mm of snow. Because of the inherent uncertainty involved in estimating snow density and precipitation rate from visibility (especially when the crystals and snowflakes are wet), the level of confidence to attribute to this value is difficult to assess.

3.0 FREEZING OF THE ACCUMULATED PRECIPITATION

3.1 Thermodynamic Influences upon the Accumulated Precipitation Layer

The state (frozen/liquid) of the precipitation which had accumulated on the wings of Fokker F-28 C-FONF by the end of its station-stop and during the aircraft's take-off roll at Dryden on 1989 March 10 can be estimated through an analysis of the thermodynamic influences upon this precipitation layer.

While the aircraft was parked near the terminal building, the precipitation layer would have been influenced by: the temperature and humidity of the surrounding air; the ambient wind speed; the quantity and temperature of continuing precipitation; the solar and long-wave radiation; and the conduction of heat in to or out of the aircraft wing. These influences could have allowed the layer to begin freezing, depending upon their relative values. Acting differentially upon the layer itself, would have been variations in the conductivity to the wing, depending upon the underlying structure of the wing and variations of its temperature. As the aircraft taxied to the runway and then began its take-off roll, the importance of the ventillation by the airflow over the wing would have increased.

In order to completely evaluate the relative contributions of these factors, an extensive numerical modelling effort of the differential equations involved would be necessary. However, because of the inherent uncertainty in estimating several of the factors, and as a result of the comparatively slow variation of the most important ones, the problem can be simplified somewhat. This section will deal with the heat balance during the aircraft take-off roll, while Section 4 will estimate net heating or cooling of the precipitation layer while the aircraft was stopped or taxiing.

3.2 Terms in the Heat Balance Equation

Following (in part) the lead of Makkonen (1984), a steady-state heat balance equation may be formulated for the processes influencing the precipitation layer:

$$q_a + q_f + q_v + q_k + q_m + q_s = q_c + q_e + q_i \ , \qquad (4)$$

with the heat fluxes (heat per unit area and time: $J \cdot m^{-2} \cdot s^{-1}$) defined as:

- q_a the heat which must be released to cool the precipitation layer from the air temperature to the freezing point;
- q_f the heat which must be released to freeze the unfrozen portion of the precipitation layer;
- q_v the frictional heating of the air in the boundary layer;
- q_k the kinetic energy converted to heat during the impact of the impinging snowflakes;
- q_m the heat released in freezing the partially-melted impinging snowflakes;
- q_s the heat added by short and long-wave radiation;
- q_c the heat removed by convection;
- q_e the heat removed by evaporation (from a wet surface) or sublimation (from frozen surface); and
- q_i the heat conducted into the wing of the aircraft.

The terms on the left hand side of Eq. 4 are sources of heat which must be dissipated if the precipitation layer is to freeze completely. The terms on the right hand side are potential heat sinks.

If all of the terms in Eq. 4 except for q_f are evaluated for a given set of conditions and a location on the wing's surface, and Eq. 4 is rearranged to solve for q_f, then the value for q_f may be substituted into Eq. 5 to determine the time τ (s) required for the accumulated snow layer of thickness T (m) to freeze:

$$\tau = \frac{L_f \rho_s k_m T}{q_f} \tag{5}$$

where L_f is the latent heat of fusion (freezing of water = 3.34×10^5 J·kg^{-1}), ρ_s is the density of the precipitation layer, and k_m is the fraction of the precipitation layer which is in liquid form.

Incorporating a suitable value for the fraction of the precipitation layer which is liquid upon its formation can be a difficult task. Makkonen (1989) was able to derive a criterion to determine whether or not snowflakes would be partially melted as they fall. For the flakes to begin to melt during their fall, the wet-bulb temperature (t_w) must be greater than 0°C. The Surface Weather Record provided by AES indicates that t_w was near -0.7°C during the station-stop of C-FONF at Dryden. This suggests that the snowflakes should not have been melting during their fall through the layer of the atmosphere nearest the ground. To better estimate the state of the snowflakes upon impact, it would be necessary to have a temperature and dew-point sounding at Dryden from which to estimate the wet-bulb temperature aloft. However, an atmospheric sounding is not taken at Dryden on a regular basis. Since the estimated sounding provided by AES was derived from actual soundings at rather distant locations (the nearest available), it contains a uncertain amount of error. Witness testimony has indicated that the snow which fell during the station-stop was in the form of large wet flakes. Since the formation of such large flakes is greatly enhanced by partial melting of the ice crystals which accumulate to form the flakes, we must assume that the snowflakes were indeed partially melted upon impact. For the purposes of this section, a value for the water fraction of the falling snow of $k_m = 0.1$ has been utilized in the calculations which follow. Section 4 will present further discussion upon the fraction of the precipitation which was melted at impact with the wings and upon the effect of this estimate on the final results.

The above discussion of the thermodynamic influences upon falling snowflakes reveals an interesting and possibly surprising fact. The snowflakes may remain completely frozen because of the convective and evaporative cooling they experience even if the air temperature is above 0°C, provided that the dew-point temperature is sufficiently low (ie. the air is sufficiently dry) that the wet-bulb temperature remains below 0°C. Using the conditions at Dryden on 1989 March 10 1800 Z as an example, the flakes could remain completely frozen at an air temperature as high as about +1.3°C. In any case, unless the snowflakes were completely melted during their fall through a very warm layer of air, they would remain at 0°C. As a result, we shall assume that the precipitation layer formed by the snow on the aircraft wings was initially at the freezing temperature, and thus that no heat would be required to cool this layer to the freezing point (ie. $q_a = 0$).

The frictional heating of the air in the boundary layer will be given by:

$$q_v = \frac{h r V_a^2}{2 c_p} \tag{6}$$

where h is the convective heat transfer coefficient (see below), r is the recovery factor for viscous heating (either 0.85 for a laminar boundary layer, or 0.90 for a turbulent boundary layer), V_a is the local air velocity ($m \cdot s^{-1}$) just outside the boundary layer at a given location on the wing, and c_p is the specific heat of air at constant pressure ($1004\ J \cdot K^{-1} \cdot kg^{-1}$).

The local air velocity V_a at some point on the wing can be estimated in the following way. First, the local air pressure just outside the boundary layer (p_a) is obtained from a rearrangement of the following definition of the pressure coefficient (see, for example, Houghton and Brock, 1970):

$$C_p = \frac{p_a - p_\infty}{\frac{1}{2}\rho_\infty V_\infty^2} \tag{7}$$

where V_∞ is the airspeed ($m \cdot s^{-1}$) of the aircraft and p_∞ is the static pressure and ρ_∞ is the air density at a distance away from the wing. A value of $1.24\ kg \cdot m^{-3}$ has been used for ρ_∞. Appropriate values of C_p for the F-28 wing were obtained from Fokker. Next, the speed of sound (a_∞) in the freestream flow is calculated from:

$$a_\infty = \sqrt{\frac{1.4 p_\infty}{\rho_\infty}} \ . \tag{8}$$

Finally, the local air velocity V_a can be determined from:

$$V_a = \sqrt{5 a_\infty^2 \left[1 - \left(\frac{p_a}{p_\infty}\right)^{1/3.5}\right] + V_\infty^2} \ . \tag{9}$$

The kinetic energy of the snowflakes transferred to heat as the snowflakes collide with the wing's surface is:

$$q_k = \frac{IV_\infty^2}{2} \tag{10}$$

where I is the mass flux ($kg \cdot m^{-2} \cdot s^{-1}$) of the accreting snowflakes. The mass flux of the accreting snowflakes, in turn, is given by:

$$I = \beta C_s V_\infty \tag{11}$$

where β is the local collection efficiency of the wing for snowflakes and C_s is the mass concentration of the snowflakes in the air ($kg \cdot m^{-3}$).

The heat released in freezing the melted fraction k_m (estimated to be 0.1) of the impinging snowflakes may be calculated from:

$$q_m = I k_m L_f \, . \tag{12}$$

The heat added by long-wave radiation can be approximated by:

$$q_s = \sigma a (t_\infty - t_{0°C}) \tag{13}$$

where σ is the Stefan-Boltzmann constant (3.24×10^{-9} $J \cdot m^{-2} \cdot K^{-4} \cdot s^{-1}$), $a = 8.1 \times 10^7$ K^3 and t_∞ is the air temperature in the freestream flow. Eq. 10 has been obtained by linearizing the equation for the difference in the long-wave radiation emitted by the precipitation surface and the snowflake-laden air. The effect of short-wave (solar) radiation on the wing's surface during the take-off roll is difficult to estimate because of the uncertainty of the quantity of radiation which would have been able to penetrate the precipitation falling at that time. As a result, it will be assumed that the precipitation was sufficiently heavy that little solar heating occurred at this time.

The heat removed by convection to the airflow passing over the wing is:

$$q_c = h(0°C - t_a) \tag{14}$$

where t_a, the local air temperature just outside the boundary layer at a given location on the wing, is obtained from:

$$t_a = t_\infty \left(\frac{p_a}{p_\infty} \right)^{2/7} . \tag{15}$$

The heat removed by evaporation to the drier air flowing over the wing is:

$$q_e = \frac{hkL_e}{c_p p_a}(e_{0°C} - e_a) \tag{16}$$

where $k = 0.62$, L_e is the latent heat of evaporation at 0°C (2.50×10^6 J·kg^{-1}) and $e_{0°C}$ and e_a are the saturation vapour pressures over the precipitation layer's surface and the air just outside the boundary layer respectively.

If it is assumed for the moment that there is no conduction of heat into the wing of the aircraft (ie. $q_i = 0$), then Eq. 4 can now be evaluated locally at various points along the surface of the wing where the various terms may have differing relative values. In order to determine the variation of these terms during the take-off roll of the aircraft, three representative airspeeds (10, 30 and 50 m·s^{-1}) have been chosen to cover the interval of 0 to 130 kt (the airspeed interval during the take-off roll). The points which have been chosen along the wing's upper surface are at about 3% chord and at about 25% chord. The first point is intended to be representative of the portion of the wing where the pressure coefficient has its greatest negative value (at an angle of attack of -2°, during the take-off roll), whereas the second is typical of the upper wing surface in contact with the fuel cell inside the wing.

Returning for a moment to define the convective heat transfer coefficient (mentioned earlier):

$$h_C = \frac{k_a \mathrm{Nu_C}}{C} \tag{17}$$

where k_a is the thermal conductivity of air (2.41×10^{-2} J·m^{-1}·s^{-1}·K^{-1}), C is the mean aerodynamic chord of the wing (3.5 m), and $\mathrm{Nu_C}$ is the wing Nusselt number which in turn is related to $\mathrm{Re_C}$, the wing Reynold's number. This latter quantity is defined by:

$$\mathrm{Re_C} = \frac{V_\infty C}{\nu_\infty} \tag{18}$$

where ν_∞ is the kinematic air viscosity. A representative value of 1.34×10^{-5} m^2·s^{-1} has been used.

Following Pais et al. (1988), the local Nusselt number on a smooth NACA 0012 airfoil (which shall be used to approximate the characteristics of the Fokker F-28 wing) over a Reynold's number range of $7.6\times10^5 \leq \mathrm{Re_C} \leq 2.0\times10^6$ can be approximated by

$$2.4 \le \frac{\mathrm{Nu_C}}{\sqrt{\mathrm{Re_C}}} \le 4.2 \tag{19}$$

over the first 5% of the airfoil surface at an angle of attack of 0°, and by

$$2.2 \le \frac{\mathrm{Nu_C}}{\sqrt{\mathrm{Re_C}}} \le 3.4 \tag{20}$$

near the 17% point (which will be assumed to be representative near the 25% point as well).

The wing Reynold's numbers for the three representative airspeeds chosen earlier (10, 30 and 50 $m \cdot s^{-1}$) are 2.61×10^6, 7.84×10^6 and 1.31×10^7 respectively. Since the latter two Reynold's numbers do not fall within the range of application of Eqns. 19 or 20, another attempt has been made to estimate the appropriate values over the first 5% of the airfoil. For the purposes of estimating the local convective heat transfer coefficient, the forward several percent of the wing's surface may be represented approximately by the front half of a cylinder with diameter D = 0.25 m. The local convective heat transfer coefficient over the cylinder is then:

$$h_D = \frac{k_a \mathrm{Nu_D}}{D} \tag{21}$$

with the cylinder Nusselt number $\mathrm{Nu_D}$ related to the cylinder Reynold's number, in turn given by:

$$\mathrm{Re_D} = \frac{V_\infty D}{\nu_\infty} \ . \tag{22}$$

The values of the cylinder Reynold's numbers for the three airspeeds are $\mathrm{Re_D} = 1.86 \times 10^5$, 5.60×10^5, and 9.36×10^5 respectively. Žukauskas and Žiugžda (1985) give the following relationships between cylinder Reynold's numbers and cylinder Nusselt number for flow over the appropriate portions of a smooth cylinder:

$$0.6 \le \frac{\mathrm{Nu_D}}{\sqrt{\mathrm{Re_D}}} \le 1.0 \tag{23}$$

for $\mathrm{Re_D} = 1.86 \times 10^5$, and

$$1.05 \leq \frac{Nu_D}{\sqrt{Re_D}} \leq 1.4 \qquad (24)$$

for $Re_D = 7.7\times10^5$. The values for flow over a rough cylinder tend to be at least 2 to 3 times higher.

Two other quantities require calculation before Eq. 4 can be evaluated. The mass concentration of the snowflakes in the air C_s may be estimated from the visibility data of Section 2. During the time of take-off, the visibility was estimated to be 3000 ft by the transmissometer and 1980 ft by the AES observer. Using a mean value of about 2500 ft, and the relationship between visibility and mass concentration given by Stallabrass (1987):

$$C_s = 0.286\,V^{-1.286} \qquad (25)$$

for C_s in $g{\cdot}m^{-3}$ and V in km, we obtain a value for the mass concentration of $C_s = 4.06\times10^{-4}\ kg{\cdot}m^{-3}$.

The other quantity requiring estimation is the local collision efficiency of the wing for snowflakes, β. Very little information is available regarding the collision efficiency of snowflakes with objects such as wings. However, King (1985) has been able to demonstrate that snowflake trajectories in the vicinity of the disturbed airflow around an aircraft wing or fuselage may be approximated by the trajectories of appropriately-sized droplets. It appears that the relationship between the droplet and snowflake sizes is related to their terminal velocity in air. Noting that the largest snowflakes in a study by Mellor and Mellor (1988) tended to have terminal velocities in the vicinity of 1.3 $m{\cdot}s^{-1}$, and that water droplets of diameter 300 μm fall at about that same speed, the numerical model described in Oleskiw (1982) was used to calculate the trajectories of such droplets in the vicinity of a NACA 0012 airfoil under conditions equivalent to those during the take-off roll of C-FONF. These simulations indicated that for an airfoil of 3.5 m chord, in an airflow at a temperature of 0°C and a pressure of 97.1 kPa, the collision efficiencies at 10, 30 and 50 $m{\cdot}s^{-1}$ would be 25%, 31% and 32% respectively at a position about 0.03 C (ie. at a distance of about 3% of the chord length rearward from the nose. Further, it was determined that the droplets (and thus, by inference, the snowflakes) would not impact any further back along the wing than 0.19 C. Thus, the collision efficiency at 0.25 C would be 0%.

3.3 Evaluating the Heat Balance Equation

The derived values of the various terms in Eqns. 4 and 5 for each of the three airspeeds and each of the two positions along the wing surface are displayed in Table 5. Column 1 indexes the rows by Case Number. Columns 2 and 3 indicate the airspeed (V_∞) and the

Table 5. Derivation of the time required to freeze the layer of precipitation on the wings of C-FONF at various speeds during the takeoff roll and at two positions along the wing's surface.

CASE	CASE PARAMS.		CONVECT. HEAT TRANSFER COEFF.	SNOW MASS FLUX	PROPERTIES OF AIRFLOW JUST OUTSIDE BOUNDARY LAYER			CONTRIBUTING HEAT FLUX TERMS						NET HEAT FLUX	TIME TO TOTALLY FREEZE PRECIP. LAYER
	V_∞ ($m \cdot s^{-1}$)	X/C	h ($W \cdot m^{-2} \cdot K^{-1}$)	I ($kg \cdot m^{-2} \cdot s^{-1}$)	p_a (kPa)	V_a ($m \cdot s^{-1}$)	t_a (°C)	q_c ($W \cdot m^{-2}$)	q_e ($W \cdot m^{-2}$)	$-q_v$ ($W \cdot m^{-2}$)	$-q_k$ ($W \cdot m^{-2}$)	$-q_m$ ($W \cdot m^{-2}$)	$-q_s$ ($W \cdot m^{-2}$)	q_f ($W \cdot m^{-2}$)	τ (s)
1	10	0.03	35	1.02×10^{-3}	96.97	18.9	0.27	-9.45	52.7	-5.3	-0.1	-33.9	-0.1	3.85	4800
2	30	0.03	88	3.78×10^{-3}	96.46	44.5	-0.14	12.3	133.2	-73.9	-1.7	-126.3	-0.1	-56.50	-
3	50	0.03	114	6.50×10^{-3}	95.27	74.3	-1.11	126.2	174.8	-282.1	-8.1	-217.1	-0.1	-206.40	-
4	10	0.25	30	0	97.09	13.1	0.37	-11.1	45.2	-2.2	0	0	-0.1	31.80	574
5	30	0.25	52	0	96.74	39.1	0.09	-4.4	78.9	-35.7	0	0	-0.1	38.70	471
6	50	0.25	67	0	96.05	65.3	-0.48	32.1	101.9	-128.4	0	0	-0.1	5.50	316
7	67	0.03	132	6.80×10^{-3}	83.21	167.9	-11.4	1499.1	230.8	-1661.7	-15.3	-227.1	-0.1	-174.30	-

fractional distance along the chord from the nose, respectively. Column 4 shows the convective heat transfer coefficient from Eq. 17 (h_C) or Eq. 21 (h_D). Column 5 indicates the mass flux of accreting snowflakes (I), while Columns 6, 7 and 8 indicate the air pressure, air velocity and air temperature just outside the boundary layer (p_a, V_a and t_a respectively). The terms q_c, q_e, $-q_v$, $-q_k$, $-q_m$ and $-q_s$ (which contribute to the net heat flux) are given in Columns 9 through 14. Column 15 shows the net heat flux (q_f) obtained from the sum of Columns 9 through 14 while Column 16 indicates the time (τ) required to freeze the water fraction of the precipitation layer.

Beginning with Case 1 (10 $m \cdot s^{-1}$ and $X/C = 0.03$), the convective heat transfer coefficients predicted from Eqns. 17 and 21 are $h_C = 36.7\ W \cdot m^{-2} \cdot K^{-1}$ and $h_D = 33.3\ W \cdot m^{-2} \cdot K^{-1}$ respectively. The good agreement between these values appears to validate the approach of using a cylinder to approximate the leading edge of the wing for the purposes of obtaining appropriate convective heat transfer coefficients. Since the air temperature outside the boundary layer remains above freezing (0.27°C), the convective heat transfer (q_c) is negative. While there is significant cooling by evaporation (q_e), it is offset to a large extent by the sum of the frictional heating of the boundary layer (q_v) and the heat released by the freezing of the incoming partially-melted snowflakes (q_m). Both the kinetic energy released by the impacting snowflakes (q_k) and the heat added by long-wave radiation (q_s) make very small contributions to the overall heat balance. The net result (q_f) is an extremely slow rate of cooling at this point on the airfoil.

Case 2 (30 $m \cdot s^{-1}$ and $X/C = 0.03$) shows that the local air temperature would be reduced below freezing, thus creating some convective cooling (q_c). The evaporative cooling (q_e) is also increased, but almost exactly offset by the heat released by the freezing of the incoming snowflakes (q_m). The other significant heat source is the frictional heating of the boundary layer. The net result in this case is thus a consistent rate of heating at the precipitation layer.

In Case 3 (50 $m \cdot s^{-1}$ and $X/C = 0.03$), the air temperature outside the boundary layer has cooled adiabatically to -1.11°C, significantly increasing the convective cooling (q_c). The greater airspeed has also increased the evaporative cooling (q_e) from Case 2. The much greater heat load imposed by the frictional heating (q_v) of the boundary layer and by the influx of partially-melted snowflakes (q_m), however, results in a large overall heat gain. The temperature of the precipitation layer at this speed is predicted to increase with time.

Moving to a point on the wing further back from the leading edge (Case 4, 10 $m \cdot s^{-1}$ and $X/C = 0.25$), there is no mass flux of accreting snowflakes because the flakes do not impinge upon the airfoil this far back from the leading edge. As a result, there is no kinetic energy converted to heat (q_k) or heat released from freezing (q_m) of the snowflakes. Because of the relatively low airspeed at this point (13.1 $m \cdot s^{-1}$ versus the freestream value of 10.0 $m \cdot s^{-1}$), the temperature just outside the boundary layer remains above freezing (0.37°C), and thus the convective heat transfer (q_c) is negative. Other contributions to the heat transfer equation are small, and thus the net cooling (q_f) is small but positive. The time required to freeze the layer, however, remains very long.

Case 5 (30 m·s^{-1} and X/C = 0.25) is very similar in net effect to Case 4. The evaporative cooling (q_e) and frictional heating (q_v) of the boundary layer are greater than in the previous case, but the convective heat transfer (q_c) remains negative because of the air temperature outside the boundary layer which remains just above freezing. Again, the time required to freeze the layer at this airspeed is very long.

With the higher speeds of Case 6 (50 m·s^{-1} and X/C = 0.25), the air temperature just outside the boundary layer once again goes negative (-0.48°C), and thus some convective cooling (q_c) takes place. This cooling plus the evaporative cooling (q_e) are almost exactly offset by the frictional energy (q_v) added to the boundary layer. The net effect (q_f) is almost no heating or cooling of the precipitation layer.

Finally, in order to determine if conditions on the wing would change significantly when the aircraft rotated at an airspeed of about 130 kt, another set of calculations (Case 7) was made using the pressure coefficient distribution provided by Fokker for an angle of attack of $\alpha = 5°$ (67 m·s^{-1} and X/C = 0.03). The high airspeed near the point of minimum aerodynamic pressure (167.9 m·s^{-1} as compared to the freestream value of 67 m·s^{-1}) led to significant cooling of the airflow just outside the boundary layer (to -11.4°C) and thus to a high convective heat transfer (q_c). However this high value was more than offset by an even higher heat input from the frictional heating (q_v) of the boundary layer. The high evaporative cooling (q_e) was almost exactly matched by the heat released by the freezing of the melted fraction of the incoming snowflakes (q_m). As a result, the net effect (q_f) was a continued heating of the precipitation layer under these conditions.

The calculations of this section have demonstrated that under the assumptions that have been adopted, it does not appear that sufficient cooling would have been available during the take-off run of the Fokker F-28 at Dryden to have had any significant impact upon the state of the precipitation layer accumulated on the upper surface of the wing. In general, the adiabatic cooling of the air just outside of the boundary layer plus the evaporative cooling caused by less than saturated air are more or less offset by the frictional heating of the boundary layer in combination with the heat required to freeze the partially-melted snowflakes impacting on the wing.

Only two potentially significant heat transfers have been omitted from this analysis. Any solar radiation which might have penetrated the cloud layer and precipitation would have contributed still more heating to the accumulated precipitation. Conduction of heat into the wing, on the other hand, could have contributed to the cooling of the layer, and thus will be investigated in the next section.

4.0 CONDUCTION OF HEAT INTO THE WING FUEL TANKS

In order to estimate the effect of heat conduction into the wing of the aircraft from the layer of precipitation which accumulated during the station-stop of C-FONF at Dryden, it is necessary to realize that the wing of the Fokker F-28 contains integral fuel tanks which wet the wing skin for most of the length of the wings. These tanks are situated between wing spars located at about 12% and 56% of the wing chord back from the wing's leading edge. For the purposes of calculating heat transfers in to and out of the precipitation layer, it is thus essential to be able to determine the temperature of the fuel in the wing tanks both before and after the refuelling at Dryden. The temperature of fuel before refuelling would have been influenced primarily by: the temperature of the fuel stored in the tanks during the previous night; the temperature of the fuel which was loaded into the aircraft at various refuelling stops that morning; and by the cooling of the fuel during flight at altitudes where the outside air temperature was significantly cooler than near the ground. The temperature of the fuel after refuelling would have also been influenced by the temperature of the fuel added during refuelling at Dryden. We shall begin this section by estimating the wing tank fuel temperatures during the station-stop at Dryden.

4.1 Estimating Wing Tank Fuel Temperatures During C-FONF's Stop at Dryden

During 1989 April 5 and 6, Mr. Garry Cooke of the TSBC Winnipeg office undertook a set of measurements in Dryden at the direction of Mr. Dave Rohrer of the Inquiry staff. These measurements are reproduced in Table 6.

Column 1 of Table 6 shows the date and time of the measured outside air temperatures. The fuel tender temperatures are displayed in Columns 2 and 3 respectively. The variation of outside air temperature over the approximately 24 h period of the measurements shows the typical diurnal variation which would be expected. The data of Column 3 indicate that the fuel tender temperature also exhibits a diurnal variation, but of lesser magnitude than that of the outside air temperature. Additionally, the diurnal cycle of the fuel temperature appears to be delayed by perhaps two hours. Both these effects are expected because of the relatively poor conductivity of the fuel, and the fact that the temperature of this volume of fuel is being changed primarily by conduction through the skin of the fuel tank as well as by convection in the fuel and in the outside air. From these data, it may be generalized that under outside air temperature variations similar to those measured during this experiment, the tank temperature in the early morning (when the outside air temperature is near its minimum) would likely be about 2°C warmer than ambient, whereas several hours later in the morning, it would likely be 2 to 3°C colder than ambient. An important assumption in these estimates is that there would be no significant solar radiation at this time of day to cause additional heating of the tank. Since, according to information provided by Mr. Dave Rohrer, the fuel at Winnipeg and Thunder Bay is also stored in above-ground tanks, we shall assume that the above relationship between outside air temperature and fuel temperature can be

Table 6. Outside air and fuel tender temperatures at Dryden, Ontario on 1989 April 5 and April 6.

DATE AND TIME (CST)	OUTSIDE AIR TEMPERATURE (°C)	FUEL TENDER TEMPERATURE (°C)
April 5 16:00	7.5	3.2
April 5 19:00	2.0	2.2
April 5 22:00	-2.0	0.0
April 6 06:15	-8.0	-5.0
April 6 09:15	-3.0	-3.5
April 6 12:15	1.5	-1.5
April 6 15:15	3.0	0.5

applied for the fuel loaded from those facilities as well.

The next step is to estimate the rate of cooling of the fuel in the Fokker F-28's wing fuel tanks during flight at altitude. Three sources of information on this subject have been consulted to aid in this determination.

Walker (1952) displays the fuel temperature in the wings of a de Havilland Comet measured during a flight at near 450 mph at an ambient air temperature of about -60°C. The fuel temperature begins at near 15°C, and decreases initially, upon ascent to altitude, at a rate of about 20°C·h^{-1}.

Mr. G.L. Borst of Propulsion Engineering, Renton Division, Boeing Commercial Airplanes has provided similar curves of the variation with time of the main wing tank fuel temperature during the flight of a Boeing 757-200 aircraft. Utilizing a temperature difference between initial tank temperature and outside air temperature during flight of about 50°C, leads to an estimate of the initial rate of change of fuel temperature of near 15°C·h^{-1}.

Mr. R. Jellema, Manager Fleet Airworthiness, Engineering Department, Fokker Aircraft has stated that the limited F-28 fuel cooling records available indicate a maximum cooling rate of the fuel in the wing tanks of about 15°C·h^{-1}. He has also provided the following relationship using the total air temperature at altitude (t_T) and the initial fuel temperature before flight (t_{fi}) to predict the fuel temperature ($t_{f\tau}$) during flight at altitude of duration τ_a:

$$t_{f\tau} = t_T + (t_{fi} - t_T)\, e^{-\tau_\mathrm{c}/2} \; . \qquad (26)$$

For an initial temperature difference (t_{fi} - t_T) of 50°C, the fuel temperature predicted by this equation drops by about 25°C during the first hour. Since this equation appears to give results similar to the others reported above, it will be utilized to predict the cooling of the fuel within the wing tanks of the Fokker F-28.

During an experiment performed by Mr. Dave Rohrer and Mr. Ron Coleman of the TSBC on 1989 April 14, the temperatures of various parameters relating to the fuel tank temperatures of the Fokker F-28 were measured at several station-stops (Dryden, YHD; Thunder Bay, YQT; and Sault Ste. Marie, YAM) during a flight from Winnipeg (YWG) to Toronto (YYZ). In order to verify the utility of Eq. 26 for the prediction of fuel temperatures as a result of flight at altitude, the data from this experiment are presented in Table 7.

Column 1 of Table 7 indicates the location and relative time of the measurements which follow. Columns 2 and 3 show the duration and temperature of flight segments at cruise altitude. Columns 4 and 5 display the quantity and temperature of the fuel uploaded into the aircraft at a given station-stop (if applicable). Column 6 gives the quantity of fuel in the F-28's wing fuel tanks just prior to take-off or upon landing. Column 7 exhibits the fuel temperature measured by draining a small amount of fuel from the wing drain valve nearest the fuselage of the aircraft. Column 8 indicates the fuel temperature predicted through the use of Eq. 26 for flight segments, and the "law of mixtures" (Eq. 27) after refuelling. If two liquids of mass m_1 and m_2 and initial absolute temperatures t_1 and t_2 (K) respectively, are well mixed together, then the absolute temperature (K) of the resulting mixture is given by:

$$t_m = \frac{(t_1 m_1 + t_2 m_2)}{m_1 + m_2} \; . \qquad (27)$$

Column 9 of Table 7 shows the temperature of the fuel in the tanks deduced from the temperature measured on the wing's lower surface nearest the fuselage. These data have been displayed because it seems significant that the temperatures measured at this location are consistently colder than the measured fuel temperature in Column 7. This may indicate that the fuel temperature displayed in Column 7 is not really representative of the fuel in the tanks. This particular location was chosen because the interior of the wing's skin is always in contact with the fuel in the wing tank at this location. It should also respond rapidly to changes in fuel temperature as a result of refuelling. A "correction" of up to 2°C was applied to the measured skin temperature when the significant difference between the skin temperature and the air temperature was believed to be influencing how well the skin temperature at this point was indicating the fuel

Table 7. Prediction of fuel tank temperatures at various station-stops of a Fokker F-28 flight from Winnipeg to Toronto on 1989 April 16.

	FLIGHT		REFUELLING FUEL		WING TANK FUEL			WING TANK FUEL DEDUCED FROM LOWER SURFACE	
LOCATION & COMMENTS	TIME (min)	AIR TEMP. (°C)	WEIGHT (lb)	TEMP. (°C)	WEIGHT (lb)	MEAS. TEMP. (°C)	CALC. TEMP. (°C)	MEAS. TEMP. (°C)	CALC. TEMP. (°C)
WPG - prior to departure					14000	10	-	4	-
Flight leg	10	-10							
YHD - upon arrival					11600	8	8.4	3	2.9
Flight leg	10	-15							
YQT - upon arrival					8700	6	6.1	1.5	1.6
Refuelling			5300	8					
YQT - prior to departure					14000	6	6.8	1.5	2.3
Flight leg	16	-24							
YAM - upon arrival					9900	2	3.0	-3	-1.0
Refuelling			1100	3					
YAM - prior to departure					11000	2	3.0	-4	-0.6
Flight leg	21	-23							
YYZ - upon arrival					6200	0	-1.2	-2	-3.2

temperature. Finally, Column 10 displays the fuel temperature predicted through the use of Eq. 26 for flight segments, and Eq. 27 after refuelling. The difference between Columns 8 and 10 is that the former is initiated upon the measured wing tank temperature, whereas the latter is initiated upon the wing tank temperature deduced from the lower wing surface temperature measurement.

Inspection of the data presented in Table 7 reveals that the calculated fuel temperatures in Columns 8 and 10 are reasonably representative of the fuel temperatures measured or estimated in Columns 7 and 9 respectively. This suggests that Eqns. 26 and 27 are appropriate means of estimating fuel temperatures in the wing tanks of the Fokker F-28.

Turning now to the flight of C-FONF on 1989 March 10, Table 8 displays the data used to predict the temperature of the fuel in the wing tanks during the station-stop at Dryden. Column 1 gives the location and approximate time for the entries which follow. Columns 2 and 3 indicate the duration and temperature of flight segments at cruise altitude. Column 4 shows the air temperature observed during the station-stop. Columns 5 and 6 exhibit the quantity and estimated temperature of the fuel uploaded to or downloaded from the aircraft's fuel tanks at a given station-stop (if applicable). These temperatures have been estimated by adjusting the measured air temperature by the relationships deduced from the data of Table 6. Finally, Columns 7 and 8 display the quantity and temperature in the F-28's wing tanks. Column 8's estimates are initialized with the predicted fuel temperature at Winnipeg, and are based upon subsequent calculations of cooling at cruise altitude by Eq. 26 and mixing during refuelling by Eq. 27.

The refuelling fuel temperature (Column 4 of Table 8) at Winnipeg (YWG) has been estimated at 0°C because the measured air temperature was steady near 0°C overnight. The fuel uploaded at Thunder Bay (YQT) was predicted to be at near -5°C based upon a minimum temperature of -7.8°C several hours earlier and an air temperature of near -3°C during the refuelling. Finally, the temperature of the fuel in the refuelling truck at Dryden was approximated by 0°C as a result of the small difference between the overnight minimum temperature (-2.3°C) and the air temperature at the time of refuelling (1.0°C). The last column in Table 8 reveals that the predicted fuel temperature in the wing tanks cooled consistently during the flight segments after departure from Winnipeg until refuelling at Dryden. In general, the fuel tank temperatures were predicted to be within about 1.5°C of the outside air temperatures at all station stops prior to the final stop at Dryden. The 3500 lb of 0°C fuel uploaded at Dryden likely warmed the wing tank temperature to about -4.7°C from the estimated -6.4°C prior to refuelling. Both of these temperatures were significantly below the ambient air temperature of between 1.0 and 0.4°C.

Table 8. Prediction of fuel tank temperatures during the flight segments of Fokker F-28 C-FONF on 1989 March 10.

	FLIGHT		STATION STOP	REFUELLING FUEL		WING TANK FUEL	
LOCATION & TIME (UTC)	TIME (min)	AIR TEMP. (°C)	AIR TEMP. (°C)	WEIGHT (lb)	TEMP. (°C)	WEIGHT (lb)	TEMP. (°C)
YWG: Refuelling			0.1	7100	0		
YWG: 13:30 - Prior to departure			0.1			16000	0.0
Flight leg	7	-27					
YHD: 14:19 - Upon arrival			-1.8			12800	-1.5
Flight leg	9	-27					
YQT: 15:32 - Upon arrival			-4.2			9600	-3.3
YQT: Refuelling			-3	6000	-5		
YQT: After Refuelling						15600	-4.0
YQT: Download fuel			-3	-2800	-4.0		
YQT: 16:55 - Prior to departure			-2.6			12800	-4.0
Flight leg	13	-27					
YHD: 17:40 - Upon arrival			1.0			9500	-6.4
YHD: 17:45 - Refuelling			1.0	3500	0		
YHD: 18:10 - Prior to departure			0.4			13000	-4.7

4.2 Evaluating the Rate of Freezing of the Precipitation Layer

With a knowledge of the likely fuel tank temperature while C-FONF was on the ground at Dryden, we are now ready to evaluate the heat flux terms in Eq. 4 to determine the net heat flux, and from this, the time required to freeze the water in the precipitation layer.

It was explained in Section 3 that since the precipitation layer was formed by falling wet snowflakes, it must have been at the freezing temperature as it was being formed. Thus for the first term in Eq. 4, $q_a = 0$. The wind speeds recorded by the AES observer between 17:40 and 18:10 UTC varied between 0 and 4 kt. Using this latter value (equivalent to about 2 $m \cdot s^{-1}$), it becomes apparent from comparison to values in Table 5 that at such low wind speeds, the third, fourth and sixth terms (q_v, q_k and q_s, respectively) are all near zero.

Between 17:40 and 18:00 UTC, the water-equivalent precipitation rates estimated from the transmissometer's measurements and "corrected" through the use of the procedure of Section 2, were between 0.02 and 0.22 $mm \cdot h^{-1}$. Between 18:00 and 18:10 UTC, these precipitation rates are believed to have varied between 1.1 and 4.5 $mm \cdot h^{-1}$. These four values are equivalent to mass fluxes of 5.6×10^{-6}, 6.1×10^{-5}, 3.1×10^{-4} and 1.3×10^{-3} $kg \cdot m^{-2} \cdot s^{-1}$. Utilizing Eq. 12, the heat released in freezing these partially-melted snowflakes (q_m) is thus 0.2, 2.0, 10.4 and 41.8 $J \cdot m^{-2} \cdot s^{-1}$ respectively.

With a wind speed of 2 $m \cdot s^{-1}$ and thus a wing Reynold's number of $Re_C = 5.2\times10^5$, Eq. 20 may be used to determine the wing Nusselt Number ($Nu_C = 1950$). From Eq. 17 we can then calculate the value of the convective heat transfer coefficient ($h_C = 13.4$ $W \cdot m^{-2} \cdot K^{-1}$). Since the Dryden air temperature was observed to be near 0.7°C during the period of heaviest snowfall, Eq. 14 leads us to an estimate of the value of the convective heat flux for this wind speed and temperature ($q_c = -9.4$ $J \cdot m^{-2} \cdot s^{-1}$).

The Dryden dew point temperature at 18:00 UTC was noted to be -3.0°C. Using Eq. 16 gives an estimate of the evaporative heat flux ($q_e = 25.8$ $J \cdot m^{-2} \cdot s^{-1}$).

Finally, the flux of heat conducted into the wing of the aircraft may be estimated with the following relationship:

$$q_i = \frac{t_p - t_f}{\frac{T_p}{2k_p} + \frac{T_s}{k_s} + \frac{T_f}{2k_f}} \tag{28}$$

where t_p and t_f are the temperatures of the precipitation layer (0°C) and the wing tank fuel (-4.7°C) respectively. The thicknesses of the precipitation layer, the aluminum skin of the wing and a suitable volume of tank fuel are given by T_p, T_s and T_f respectively. The thermal conductivity of the three layers are represented by k_p, k_s and k_f respectively.

In Eq. 28, the conduction is assumed to occur between the midpoints of the two outer layers.

Since it was assumed above that the density of the precipitation layer was 400 kg·m^{-3}, then the thickness of the near 0.55 kg·m^{-2} layer of precipitation as estimated in Section 2 would have been T_p = 1.38 mm of wet snow. The thermal conductivity of snow has been taken to be k_p = 0.47 W·m^{-1}·K^{-1}. The thickness of the aluminum skin used in these calculations is T_s = 4 mm. Since the thermal conductivity of the aluminum, estimated at k_s = 138 W·m^{-1}·K^{-1} (see, for example, the SAE Aerospace Applied Thermodynamics Manual), is so much greater than that of the snow or the fuel, this thickness estimate will play little part in the accuracy of the overall calculation of conductive heat flux.

It is necessary to ensure that the fuel layer is sufficiently thick that it is able to absorb the heat which might be transferred to it from the precipitation layer without significantly changing its mean temperature. Assuming again that 10% of the precipitation layer is water and the remainder snow, then the heat per unit area which must be removed to freeze the water is equal to the product of: the melted fraction of snow (0.1); the latent heat of fusion (L_f = 3.34x10^5 J·kg^{-1}); and the mass per unit area of the precipitation layer (0.55 kg·m^{-2}). This product is equal to 1.84x10^4 J·m^{-2}. Now, since the specific heat capacity of JP4 fuel is c_p = 1.93x10^3 J·kg^{-1}·K^{-1}, and the density of JP4 is approximately 789 kg·m^{-3}, then the thickness of a layer of fuel which will be warmed by 1°C in absorbing the heat from the freezing of the precipitation layer will be T_f = 12 mm. The thermal conductivity of JP4 has been taken to be k_f = 0.14 W·m^{-1}·K^{-1} (see, for example, Kays and Crawford, 1980). In addition to the layers mentioned above, there is also a layer of plastic-like material which lines the inside of the F-28's wing fuel tanks. Since this layer is likely on the order of 5 mm or less, and since the thermal conductivity of this layer is likely near that of Nylon or Teflon (both having the same conductivity as the JP4 fuel), this layer will have only a small effect upon the thermal heat flux between the precipitation layer and the fuel. Inserting all of the appropriate values from above into Eq. 28 gives a conductive heat flux of q_i = 106 J·m^{-2}·s^{-1}.

All of the above heat flux terms may now be utilized to solve for the net heat flux into or out of the precipitation layer. These data are displayed in Table 9. Column 2 of this table displays the water-equivalent snowfall rates representative of the ranges between 17:40 to 18:00 UTC and between 18:00 and 18:10 UTC. Column 3 gives the assumed water fraction of the precipitation layer formed by the accumulation of falling wet snowflakes. Columns 4 through 7 exhibit the values of the heat flux terms which contribute to the net heat flux. Column 8 shows the net heat flux while the time estimated to completely freeze the water fraction of the wet snow in the precipitation layer is given in Column 9.

As the mass flux of the falling wet snowflakes increases from 5.6x10^{-5} kg·m^{-2}·s^{-1} to 1.3x10^{-3} kg·m^{-2}·s^{-1} (Case 8 through Case 11), the heat which must be extracted to freeze the water fraction of the incoming wet snowflakes increases (Column 4 of Table 9).

Table 9. Derivation of the time required to freeze the layer of precipitation on the wings of C-FONF as a result of various snowfall rates and estimates of the initial water fraction of the layer.

CASE	PRECIP. RATE	INITIAL WATER FRACTION OF LAYER	CONTRIBUTING HEAT FLUX TERMS				NET HEAT FLUX	TIME TO TOTALLY FREEZE PRECIP. LAYER
	R	k_m	q_m	q_c	q_e	q_i	q_f	τ
	(mm h^{-1} water equiv.)		(W·m^{-2})	(W·m^{-2})	(W·m^{-2})	(W·m^{-2})	(W·m^{-2})	(s)
8	0.02	0.1	-0.2	-9.4	25.8	106	122.20	151
9	0.22	0.1	-2.0	-9.4	25.8	106	120.40	153
10	1.1	0.1	-10.4	-9.4	25.8	106	112.00	165
11	4.5	0.1	-41.8	-9.4	25.8	106	80.60	229
12	2.7	0.1	-25.4	-9.4	25.8	106	97.00	190
13	2.7	0.2	-50.9	-9.4	25.8	53.9	19.40	1900
14	2.7	0.3	-76.3	-9.4	25.8	36.1	-23.80	-
15	2.7	0.1	-25.4	-9.4	25.8	53.9	44.90	411
16	2.7	0.1	-25.4	-9.4	25.8	36.1	27.10	681

With all of the other heat flux terms remaining constant for these cases, the predicted net heat flux gradually decreases. This results in increasing estimates of the time required to totally freeze the water fraction of the precipitation layer. However, the longest time required (Case 11, 229 s), is still significantly shorter than the 600 s period between the commencement of heavier snowfall (18:00 UTC) and the approximate time of take-off (18:10 UTC).

In order to provide a baseline for the other cases which follow, another set of calculations was performed (Case 12). Here the water-equivalent snowfall rate was chosen to be the mean value (2.7 mm·h^{-1}) over the time interval 18:00 to 18:10 UTC. The time required to freeze the layer is estimated at 190 s.

In an effort to evaluate the sensitivity of the predicted time to freeze the water fraction of the precipitation layer to changes in the estimated water fraction of the falling snowflakes, another two sets of calculations (Cases 13 and 14) were performed. In

Case 13, it was assumed that the falling snowflakes were 20% water by mass. As a result of the doubled heat required to freeze the greater water fraction of the falling wet snowflakes, the net heat flux decreased to 19.4 $J \cdot m^{-2} \cdot s^{-1}$ and the time required to freeze the precipitation layer rose significantly to 1900 s. A water fraction of 0.3 (Case 14) led to a net heat flux of -23.8 $J \cdot m^{-2} \cdot s^{-1}$. These two cases demonstrate that as the water fraction of the falling snowflakes increases, this not only increases the heat which must be removed to freeze the falling flakes, it also increases the heat needed to be removed to freeze the precipitation layer. The combination of effects leads to a very rapidly increasing time to freeze the precipitation layer, eventually resulting in a predicted inability of the wing tank fuel to remove enough of the heat from the precipitation layer to allow it to freeze at all.

Finally, in order to determine the effect upon these calculations of an increase in the total thickness of the precipitation layer, Case 12 was repeated with layers of doubled and tripled thickness (Cases 15 and 16). In the first of these two cases, as a result of the increased amount of heat which must be transferred to the wing tank fuel, the thickness of the fuel layer must be increased to maintain a small increase of temperature as a result of this heat transfer. This results in an approximately 50% decrease in the conductive heat flux (Column 8). The net heat flux is thus 44.9 $J \cdot m^{-2} \cdot s^{-1}$ and the time to freeze the precipitation layer increases to 411 s from 190 s. In the final set of calculations (Case 16), the thickness of the fuel layer which absorbs the heat from the precipitation layer is increased yet again. This further reduces the net heat flux, and results in an estimate of the time to freeze the water fraction of the precipitation layer of 681 s.

From these cases, it is evident that increasing the assumed water fraction of the falling wet snowflakes dramatically increases the time required to freeze the precipitation layer. In fact, with a snowflake water fraction of 0.3, there would no longer be conduction of heat from the precipitation layer to the wing fuel tanks, and the water in the wet snow would not freeze at all. On the other hand, increasing the depth of the precipitation layer from about 1.4 to 4.1 mm of wet snow increases the time to freeze the precipitation layer significantly, but would still allow most of the layer to freeze in the 600 s interval during the heavier snowfall (18:00 to 18:10 UTC). Further increases in the precipitation layer thickness would permit only some lower fraction of the layer to freeze, with the upper portion remaining wet snow.

5.0 DISCUSSION AND SUMMARY

The estimated thickness of wet snow which would have accumulated on the wings of C-FONF during its station-stop at Dryden on 1989 March 10 is 1.38 mm. This value has been determined from analyses of the visibility data recorded by the AES observer at the Dryden Airport, and by a transmissometer located near the runway. The relationship used to estimate precipitation rate from visibility is an empirical one, and the data from which it was derived show considerable scatter. The main uncertainty in the relationship is due to the variation in terminal velocity of the snowflakes because of variations in their size and wetness (and thus density). Since the relationship has been derived for "normal" snow, it may be expected that if the snowflakes are wet, then they will fall faster than "normal". This would permit the snowflakes to accumulate more quickly at the ground than would "normal" snowflakes, while obstructing the visibility to the same extent. Therefore, it is expected that despite the efforts in Section 2 to "calibrate" the visibility to precipitation rate relationship, unusually wet snowflakes may have contributed to a greater depth of precipitation than that estimated above.

The extensive calculations described in Section 3 lead to the conclusion that an insufficient amount of cooling to freeze the precipitation layer would have been provided by the mechanisms of: adiabatic cooling of the air as it accelerated over the wing; and evaporative cooling as a result of the comparatively dry air near the ground at the time of take-off. In general, the adiabatic cooling of the air just outside of the boundary layer plus the evaporative cooling caused by less than saturated air were more or less offset by the frictional heating of the boundary layer in combination with the heat required to freeze the partially-melted snowflakes impacting on the wing. Any impinging snowflakes during the take-off roll would thus have likely met a partially wetted precipitation layer surface, and this fact, in combination with the fact that the snowflakes themselves would likely have been somewhat wet, leads to the conclusion that many of these snowflakes would have stuck to the forward portions of the precipitation layer during the take-off roll.

The investigation of the contribution of the conductive heat flux from the precipitation layer on the wing to the wing fuel tanks shows that, under certain circumstances and in combination with the other heat flux terms, sufficient cooling might have resulted in a complete freezing of the water fraction of the precipitation layer during the 10 min interval of the heavier snowfall rate while the aircraft was on the ground (18:00 to 18:10 UTC). The assumed value of the falling snowflake's water fraction has been shown to significantly alter the time required to freeze the precipitation layer. The thickness of the precipitation layer has also exhibited a strong influence upon the freezing time. Given that the depth of the wet snow on the wings was likely greater than the best estimate of 1.38 mm calculated from the available data, it seems probable that the heat conduction into the wing fuel tanks would have permitted a lower portion of the water in the wet snow layer to have frozen, while leaving some upper portion in a partially liquid state. Because the density of the wet snow was between that of dry snow (100 $kg \cdot m^{-3}$) and ice (near 920 $kg \cdot m^{-3}$), this layer was composed of a lattice of deformed and coagulated ice crystals interspersed with air pockets and water. As the water froze in the lower portion of this layer, it would likely have left a very rough interface between the lower and upper portions of the precipitation layer. As the aircraft rolled down the runway, the remaining water in the upper portion of the precipitation layer might have been forced to drain away, possibly carrying with it some of the ice in the upper portion of the layer. The resulting very rough surface on the wings could have had a significant impact on the aerodynamic performance of the aircraft. It is interesting to note that the thermal conductivity of the aluminum skin of the aircraft is much greater than that of the wet snow, the air or the fuel in the wing tanks. As a result, the aluminum skin might have conducted heat away from the precipitation layer even further forward on the wing than the location of the wing spar forming the forward wall of the wing tanks. Thus the hypothesized rough precipitation layer surface may have extended forward to the more aerodynamically critical portions of the wing.

6.0 REFERENCES

Houghton, E. L. and Brock, A. E. 1970. Aerodynamics for Engineering Students. Second Edition. Edward Arnold (Publishers) Ltd., London.

Kays, W. M. and Crawford, M. E. 1980. Convective Heat and Mass Transfer. 2nd Edition. McGraw-Hill Book Company, New York, NY.

King, W. D. 1985. Air Flow and Particle Trajectories around Aircraft Fuselages. Part III: Extensions to Particles of Arbitrary Shape. Journal of Atmospheric and Oceanic Technology **2** (4): 539-547.

Makkonen, L. 1984. Modeling of Ice Accretion on Wires. Journal of Climate and Applied Meteorology **23** (6).

Makkonen, L. 1989. Estimation of Wet Snow Accretion on Structures. Cold Regions Science and Technology **17**: 83-88.

Mellor, M. and Mellor, A. 1988. Some Characteristics of Falling Snow. Cold Regions Science and Technology **15**: 201-206.

Oleskiw, M. M. 1982. A Computer Simulation of Time-Dependent Rime Icing on Airfoils. Ph.D. Thesis, University of Alberta, Edmonton.

Pais, M. R., Singh, S. N. and Zou, L. 1988. Determination of the Local Heat-Transfer Characterisitics on Simulated Smooth Glaze Ice Accretions on a NACA 0012 Airfoil. AIAA 26th Aerospace Sciences Meeting, Reno, Nevada, January 1988. American Institute of Aeronautics and Astronautics, Washington, D. C.

SAE Committee AC-9, Aircraft Environmental Systems, 1969. SAE Aerospace Applied Thermodynamics Manual. 2nd Edition. Society of Automotive Engineers, Inc., New York, NY.

Stallabrass, J. R. 1987. Measurements of the Concentration of Falling Snow. *In* Snow Property Measurement Workshop. Chateau Lake Louise, April, 1985. *Edited by* P. R. Kry. National Research Council Canada, Ottawa. pp. 389-410.

Walker, J. E. 1952. Fuel Systems for Turbine-Engined Aircraft. Journal of the Royal Aeronautical Society: 657-679.

Žukauskas, A. and Žiugžda, J. 1985. Heat Transfer of a Cylinder in Crossflow. *Translated by* E. Bagdonaite. *Edited by* G. F. Hewitt. Hemisphere Publishing Corporation, Washington, D. C.

REPORT DOCUMENTATION FORM/FORMULAIRE DE DOCUMENTATION DE RAPPORT

REPORT No./ NO DU RAPPORT	REPORT No./ NO DU RAPPORT	SECURITY CLASSIFICATION/ CLASSIFICATION DE SECURITÉ
1 IME-CRE-TR-003	2 32124	3 ___ Top Secret/Très secret ___ Secret ___ Confidential/Confidentiel ___ Protected/Protégée XX Unclassified/Non classifiée
DISTRIBUTION/DIFFUSION ___ Controlled/Controlée 4 XX Unlimited/Illimitée		

DECLASSIFICATION: DATE OR REASON/DÉCLASSEMENT: DATE OU RAISON

5

TITLE, SUBTITLE/TITRE, SOUS-TITRE

6 Freezing Precipitation on Lifting Surfaces

AUTHOR(S)/AUTEUR(S)

7 M. M. Oleskiw

SERIES/SÉRIE

8 Technical Report

CORPORATE AUTHOR/PERFORMING ORGANIZATION/
AUTEUR D'ENTREPRISE/AGENCE D'EXÉCUTION

9 National Research Council of Canada
Institute for Mechanical Engineering

SPONSORING OR PARTICIPATING AGENCY/AGENCE DE SUBVENTION OU PARTICIPATION

10 Commission of Inquiry into the Air Ontario Crash at Dryden, Ontario
P.O. Box 687, Adelaide Station, Toronto, ON M5C 2J8

DATE	FILE/DOSSIER	SPECIAL CODE/ CODE SPÉCIALE	PAGES	FIGURES	REFERENCES
11 1991/09	12 3741-4	13 REA00	14 31(vi)	15 0	16 12

NOTES

17 This report was requested by Mr. D. J. Langdon, Chief, Systems Engineering, Canadian Aviation Safety Board in a letter dated 1989 June 20. The request was made on behalf of Mr. J. Jackson, Investigator in Charge, Commission of Inquiry into the Air Ontario Crash at Dryden, Ontario

DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

18 ICE, ICING, DEICE, DEICING, ANTIICING, SNOW, ATMOSPHERIC PRECIPITATION

SUMMARY/SOMMAIRE

19 Please see Abstract.

ADDRESS/ADDRESSE

Dr. R.M.W. Frederking, Head
Cold Regions Engineering
Institute for Mechanical Engineering
Montreal Road, Ottawa, K1A 0R6, Canada
20 (613) 993-2439