Appendix 6

Freezing Precipitation on Lifting Surfaces

Myron M. Oleskiw, Ph.D.

April 23, 1990
Updated September 1991

National Research Council Canada
Institute for Mechanical Engineering
Cold Regions Engineering

Conseil national de recherches Canada
Institut de génie mécanique
Ingénerie 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

		Page
	ABSTRACT	i
	RÉSUMÉ	ii
	LIST OF TABLES	iv
	LIST OF SYMBOLS	v
1.0	INTRODUCTION	1
2.0	QUANTITY OF PRECIPITATION ACCUMULATED	1
	2.1 Precipitation Recorded on the Surface Weather Record	1
	2.2 Relating Precipitation Rate to Visibility	2
	2.3 Precipitation Inferred from Surface Weather Record Visibility	3
	2.4 Precipitation Inferred from Transmissometer Data	4
	2.5 Estimating Precipitation During C-FONF's Station Stop at Dryden	7
3.0	FREEZING OF THE ACCUMULATED PRECIPITATION	8
	3.1 Thermodynamic Influences upon the Accumulated Precipitation Layer	8
	3.2 Terms in the Heat Balance Equation	9
	3.3 Evaluating the Heat Balance Equation	15
4.0	CONDUCTION OF HEAT INTO THE WING FUEL TANKS	19
	4.1 Estimating Wing Tank Fuel Temperatures During C-FONF's Stop at Dryden	19
	4.2 Evaluating the Rate of Freezing of the Precipitation Layer	25
5.0	DISCUSSION AND SUMMARY	28
6.0	REFERENCES	30
	DOCUMENTATION FORM	

CONTENTS (Cont'd)

LIST OF TABLES

Table		Page
1	Weather at Dryden, Ontario on 1989 March 10	2
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.	4
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.	5
4	Integration of precipitation rate during the station-stop of C-FONF at Dryden on 1990 March 10.	7
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.	16
6	Outside air and fuel tender temperatures at Dryden, Ontario on 1989 April 5 and April 6.	20
7	Prediction of fuel tank temperatures at various station-stops of a Fokker F-28 flight from Winnipeg to Toronto on 1989 April 16.	22
8	Prediction of fuel tank temperatures during the flight segments of Fokker F-28 C-FONF on 1989 March 10.	24
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.	27

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_{ft}	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

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

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

$$R = 2.68\times10^{5}\,V^{-1.56}. \tag{3}$$

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)	TRANSMISSOMETER 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 $kg{\cdot}m^{-3}$. 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:

$$q_a + q_f + q_v + q_k + q_m + q_s = q_c + q_e + q_i \ , \tag{4}$$

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:

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

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} $J{\cdot}m^{-2}{\cdot}K^{-4}{\cdot}s^{-1}$), $a = 8.1\times10^{7}$ 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 Nu_C is the wing Nusselt number which in turn is related to 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

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

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

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

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 $\mathrm{m \cdot s^{-1}}$) 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 $\mathrm{Re_D} = 1.86\times10^5$, 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:

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

for $\mathrm{Re_D} = 1.86\times10^5$, and

$$1.05 \le \frac{Nu_D}{\sqrt{Re_D}} \le 1.4 \tag{24}$$

for $Re_D = 7.7 \times 10^5$. 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):

$$C_s = 0.286\, V^{-1.286} \tag{25}$$

for C_s in g·m^{-3} and V in km, we obtain a value for the mass concentration of $C_s = 4.06 \times 10^{-4}$ kg·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·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·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 $m \cdot s^{-1}$ 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 $m \cdot s^{-1}$ 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 $m \cdot s^{-1}$ and $X/C = 0.03$). The high airspeed near the point of minimum aerodynamic pressure (167.9 $m \cdot s^{-1}$ as compared to the freestream value of 67 $m \cdot s^{-1}$) 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_{f_i}) to predict the fuel temperature (t_{f_τ}) during flight at altitude of duration τ_a:

$$t_{f\tau} = t_T + (t_{fi} - t_T)e^{-\tau_s/12} \ . \tag{26}$$

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:

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

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	AIR TEMP.	WEIGHT	TEMP.	WEIGHT	MEAS. TEMP.	CALC. TEMP.	MEAS. TEMP.	CALC. TEMP.
	(min)	(°C)	(lb)	(°C)	(lb)	(°C)	(°C)	(°C)	(°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.

LOCATION & TIME (UTC)	FLIGHT TIME (min)	FLIGHT AIR TEMP. (°C)	STATION STOP AIR TEMP. (°C)	REFUELLING FUEL WEIGHT (lb)	REFUELLING FUEL TEMP. (°C)	WING TANK FUEL WEIGHT (lb)	WING TANK FUEL 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·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·h^{-1}. Between 18:00 and 18:10 UTC, these precipitation rates are believed to have varied between 1.1 and 4.5 mm·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·m^{-2}·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·m^{-2}·s^{-1} respectively.

With a wind speed of 2 m·s^{-1} and thus a wing Reynold's number of $\mathrm{Re}_C = 5.2\times10^5$, Eq. 20 may be used to determine the wing Nusselt Number ($\mathrm{Nu}_C = 1950$). From Eq. 17 we can then calculate the value of the convective heat transfer coefficient ($h_C = 13.4$ W·m^{-2}·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·m^{-2}·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·m^{-2}·s^{-1}).

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

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

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 $kg \cdot m^{-3}$, then the thickness of the near 0.55 $kg \cdot m^{-2}$ 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 $k_p = 0.47\ W \cdot m^{-1} \cdot K^{-1}$. The thickness of the aluminum skin used in these calculations is $T_s = 4$ mm. Since the thermal conductivity of the aluminum, estimated at $k_s = 138\ W \cdot m^{-1} \cdot K^{-1}$ (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 ($L_f = 3.34 \times 10^5\ J \cdot kg^{-1}$); and the mass per unit area of the precipitation layer (0.55 $kg \cdot m^{-2}$). This product is equal to $1.84 \times 10^4\ J \cdot m^{-2}$. Now, since the specific heat capacity of JP4 fuel is $c_p = 1.93 \times 10^3\ J \cdot kg^{-1} \cdot K^{-1}$, and the density of JP4 is approximately 789 $kg \cdot m^{-3}$, 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 $k_f = 0.14\ W \cdot m^{-1} \cdot K^{-1}$ (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 $q_i = 106\ J \cdot m^{-2} \cdot s^{-1}$.

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 $5.6 \times 10^{-5}\ kg \cdot m^{-2} \cdot s^{-1}$ to $1.3 \times 10^{-3}\ kg \cdot m^{-2} \cdot s^{-1}$ (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.)		($W \cdot m^{-2}$)	($W \cdot m^{-2}$)	($W \cdot m^{-2}$)	($W \cdot m^{-2}$)	($W \cdot m^{-2}$)	(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 $mm \cdot h^{-1}$) 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

National Research Council of Canada
9 Institute for Mechanical Engineering

SPONSORING OR PARTICIPATING AGENCY/AGENCE DE SUBVENTION OU PARTICIPATION

Commission of Inquiry into the Air Ontario Crash at Dryden, Ontario
10 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

Appendix 7

Human Factors Aspects of the Air Ontario Crash at Dryden, Ontario: *Analysis and Recommendations to the Commission of Inquiry*

Robert L. Helmreich, Ph.D.

December 12, 1990

Human Factors Aspects of the Air Ontario Crash at Dryden, Ontario: Analysis and Recommendations to the Commission of Inquiry into the Air Ontario Crash at Dryden, Ontario

Robert L. Helmreich, Ph.D
NASA/University of Texas Aerospace Crew Research Project[1]

Austin, Texas
December 12, 1990

1. The author's research reported here was sponsored by NASA-Ames Research Center Cooperative Agreement NCC2-286, Robert L. Helmreich, Principal Investigator. The opinions reported herein are those of the author and do not represent the position of NASA. All data collected in air carriers is maintained in secure databases and is conducted under a strict confidentiality agreement specifying that no organizations or individuals will be identified.

Introduction and Overview

At the request of the *Commission of Inquiry into the Air Ontario Crash at Dryden, Ontario*, evidence assembled in the course of investigation into the causes of the crash was examined in terms of human factors and organizational issues. Material reviewed included reports of the Operations Group and the Human Performance Group, interviews with relevant personnel, and sworn testimony presented before the Commission. When viewed from a research perspective, the body of facts suggests an operational environment that allowed an experienced crew to reach a flawed decision regarding the safety of take-off during snowfall with accumulating contamination of the aircraft's wings.

The absence of direct evidence from voice or flight recorders initially seems to be a serious hindrance to the investigative effort. In fact, the lack of this type of evidence has resulted in a more extensive exploration of broader issues, including regulatory and organizational factors than might otherwise have been conducted. Because of the depth of the investigation, the lessons to be gained from this in-depth investigation may prove to be of value for the governance of flight operations and the training of crews.

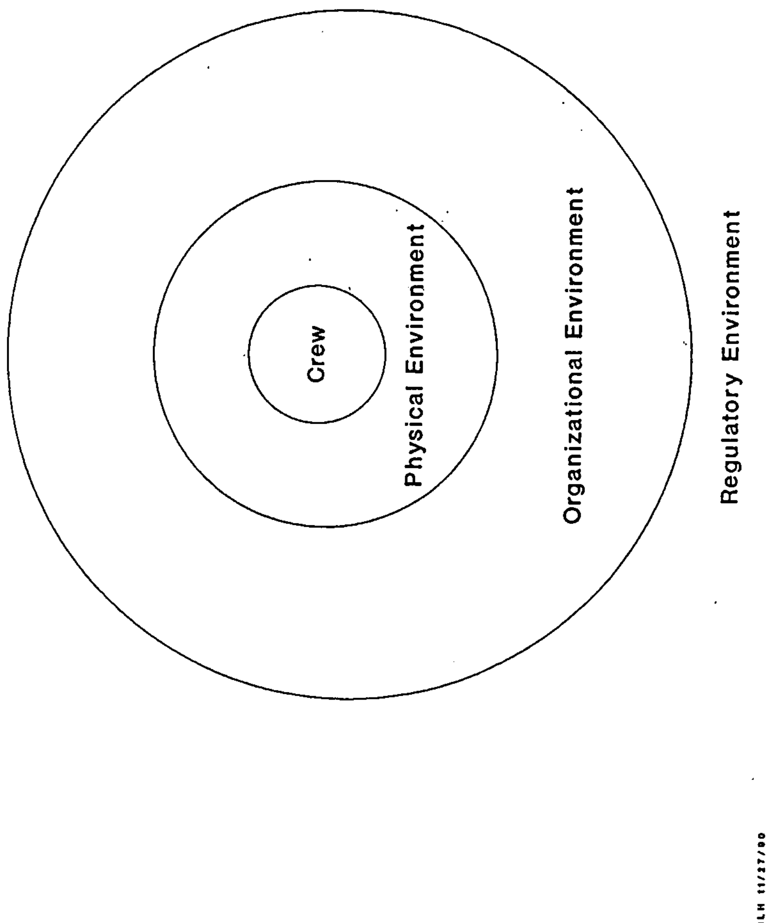
It may be useful to outline the background for the author's opinions. They grow out of more than twenty years experience conducting research into the multiple determinants of human behavior and performance under the sponsorship of agencies such as the National Science Foundation, the Office of Naval Research, the National Aeronautics and Space Administration, and the Federal Aviation Administration. Current investigations are under the auspices of the NASA/University of Texas Aerospace Crew Research Project, directed by the author. Included in the project are investigations of personality factors relative to pilot and Astronaut selection, group dynamics, aircraft characteristics such as automation, and organizational issues such as the development and influence of subcultures (Helmreich & Wilhelm, 1990; Helmreich, in press).

Another central element of the research is evaluation of the effectiveness of training in *Crew Resource Management* (*CRM*: Helmreich, 1991). *CRM* training is aimed at improving crew coordination, decision making, situational awareness, and interpersonal communications. It stresses the importance of utilizing all available resources inside and outside the cockpit and the development of an effective team including cabin crewmembers in the process. The concept of *CRM* is becoming widely accepted and is an integral part of training in many organizations. Only recently, however, has empirical research demonstrated that such training can affect flightcrew behaviour (Helmreich, Chidester, Foushee, Gregorich, & Wilhelm, 1990; Helmreich, Wilhelm, Gregorich, & Chidester, 1990).

Underlying the research is the fact that the behaviour of flightcrews in any given situation is determined by a number of simultaneously operating factors. These include: 1) the regulatory environment - operational standards and supervision; 2) the organizational environment - the culture and behavioural norms of the organization including morale, policies and standards, organizational stability and change, and available resources; 3) the physical environment - meteorological and operating conditions and the aircraft, including its condition and capabilities; 4) the crew environment - interpersonal coordination and communications including cockpit, cabin, and ground personnel, and individual characteristics of crewmembers - training, experience, motivation, personality, attitudes, fatigue, and stress both from the immediate operational situation and significant personal life events (Foushee & Helmreich, 1988; Helmreich, 1990). Figure 1 shows graphically the environments surrounding flight operations. Events and circumstances exemplifying these categories will be discussed as they relate to the Dryden crash and possible reasons for the actions of the crew of Air Ontario Flight 363.

The results of this analysis suggest that the concatenation of multiple factors from each category allowed the crew to decide to take off with contaminated wings. According to this view, no single factor taken in isolation would have triggered the crew's behaviour prior to and during take-off, but in combination they provided an environment in which a serious procedural error could occur. This array of contributory influences without a single, proximal cause warrants classification of the accident as a system failure. The analysis will attempt to define these influences and their inter-relationships. Observations and suggested counter-measures will also be provided.

Figure 1. Flightcrew Environments:
Factors Influencing Behaviour



Human Factors of the Air Ontario Crash 4

History of the Trip. The crew reported in at Winnipeg at approximately 0630CST Monday, March 6, for a five day trip in Fokker F-28, registration CFONF, involving six legs per day ending at 1530CST. The trip schedule and crew pairings are shown in Figure 2. Captain George Morwood had flown with the two flight attendants before, but none had flown with First Officer Keith Mills. After flying the Monday, March 6 sequence, Captain Morwood was displaced Tuesday by Captain Robert Nyman and Wednesday by Captain Alfred Reichenbacher. He resumed the trip for Thursday, March 9 and Friday, March 10.

On March 10, the crew checked in at Winnipeg at approximately 0640 and discovered that the Auxiliary Power Unit (APU) was inoperative. The aircraft departed for Dryden at 0749, approximately 10 minutes late after waiting for de-icing. It was further delayed at Dryden by poor weather at Thunder Bay. At Thunder Bay the flight was refueled on the basis of a passenger load of 55. However, an additional 10 passengers were added, placing the aircraft over the computed maximum allowable gross weight for take off. After some debate over course of action, the aircraft was defueled and the additional passengers retained. The flight departed Thunder Bay 64 minutes late and arrived at Dryden 1130CST. The aircraft was refueled at Dryden with an engine running because there were no ground start facilities there. Contrary to Air Ontario policy stated in the cabin manual, passengers remained on board during refueling.

During the stop at Dryden snow was falling and accumulating on the wings. First Officer Mills commented on the radio to Kenora at 1200, "...quite puffy snow, looks like its going to be a heavy one". Shortly after beginning to taxi, a passenger asked Flight Attendant Katherine Say when the plane was going to be de-iced. The flight attendants did not inform the flightcrew of these expressed concerns about the need to de-ice.

The flight was delayed for approximately four minutes while a light aircraft landed. At 1207CST the flight was cleared to Winnipeg and at 1209 First Officer Mills transmitted that the flight was about to take off. The aircraft lifted off but never left ground effect and crashed into trees beginning 126 meters from the end of the runway. The aircraft was destroyed by impact and fire. Both pilots, one flight attendant, and twenty-one passengers were killed. Forty-four passengers and one crew member survived with injuries. The chronology for March 10 is shown in Figure 3.

Figure 2. Trip Routing March 6 - 10, 1989 Air Ontario Line for Morwood/Mills

Segments	Crew
Winnipeg-Dryden	MAR 6 - Morwood/Mills
Dryden-Thunder Bay	Say/Hartwick
Thunder Bay-Dryden	MAR 7 - Nyman/Mills
Dryden-Winnipeg	Say/Hartwick
Winnipeg-Thunder Bay	MAR 8 - Reichenbacher/Mills
Thunder Bay-Winnipeg	Say/Hartwick
	MAR 9 - Morwood/Mills
	Say/Hartwick
	MAR 10 - Morwood/Mills
	Say/Hartwick

Figure 3. Air Ontario Flights 362/363 March 10, 1989

Segment	Times	Delay
Winnipeg-Dryden	0749-0819CST	13 min
Dryden-Thunder Bay	0850-0932CST	20 min
Thunder Bay-Dryden	1104-1130EST	64 min
Dryden - crash	1203-(1211)CST	

RLH 10/24/90

I. The Regulatory Environment.

The crew of Air Ontario 363 was governed by the regulations and practices of Transport Canada. Several aspects of the current regulations provided an indirect, deleterious influence on the crew's operational environment. These allowed the development of a situation which failed to provide safeguards in this case against flawed decisions concerning landing and take-off in Dryden under adverse weather conditions. The following issues are cited as relevant to the accident.

I(a). The failure to provide clear guidance for organizations and crews regarding the need for de-icing. The regulatory requirement in effect at the time of the accident prohibited aircraft from commencing a flight "...when the amount of frost, snow, or ice adhering to the wings, control surfaces, or propellor of the aeroplane may adversely affect the safety of the flight". As noted in the *Commission of Inquiry into the Air Ontario Crash at Dryden Ontario Interim Report* (1989), "...there are no existing Transport Canada-approved guidelines which dispatchers or flight and ground crews may use to assist them in making a reasoned judgment as to what amount of contamination to an aircraft's lifting surfaces would adversely affect the safety of flight". In the absence of guidelines, idiosyncratic views of the degradation caused by differing amounts of contamination could prevail. There were also no formal requirements for training in the effects of icing contamination and associated phenomena such as "cold soaking", and the differential susceptibility of different aircraft types to icing effects.

I(b). A lack of rigour in regulating and monitoring the operations of Air Ontario, Inc., following its merger and during the initiation of jet service in the F-28. Transport Canada allowed the F-28 operation to continue passenger service for a number of months without an approved Minimum Equipment List and an accepted Aircraft Operating Manual specifying standard operating procedures. Closer monitoring of the initiation of this service would have revealed other significant operational problems including inconsistent content in manuals (i.e., different manuals in the cockpit and conflicts between cabin and cockpit manuals) and problems in weight and balance computations. It would have been especially important at this time to conduct extensive line observations of crew performance in the F-28. Testimony of Transport Canada witnesses identifies a lack of resources for the enforcement of safety regulations and monitoring of flight operations.

I(c). An audit of Air Ontario operations that was delayed and incomplete in scope. Evidence from several airline mergers that have been observed in the U.S. suggests that they create conditions which warrant increased regulatory surveillance. There are always disruptions in operational effectiveness surrounding the joining of disparate operations that call for increased efforts directed toward monitoring operations and ensuring compliance with appropriate safety standards. Strikes have also been observed to create major operational problems, even after their settlement, and to interfere with effective crew-management communications. A national audit of Air Ontario was scheduled for February, 1988. While the airworthiness, passenger safety, and dangerous goods portion of the audit were completed as scheduled, the flight operations portion was postponed until July, 1988 and again until November, 1988, when it was completed. The combination of a merger, a strike, and the introduction of a new aircraft type, would seem to have mandated an extensive audit of the operation. It is noteworthy that the audit that was conducted failed to examine the most significant operational change in the organization, the initiation of jet service in the F-28. Testimony by the leader of the audit indicates that he was inexeperienced in audit procedures, was directing his first audit, and had a limited staff. The statement that examination of crew training records forms the heart of an audit certainly reflects an honest opinion. However, from the author's research experience, an alternative view can be proposed that the observable behaviour of crews in line operations is the key to understanding the level of safety and effectiveness in flight operations.

I(d). The failure to require effective training and licensing requirements for flight dispatchers and to establish regulations governing dispatch and flight following. Transport Canada had no formal requirements for the training and licensing of dispatchers and allowed a carrier such as Air Ontario to operate with a pilot self-dispatch system. While the arrangement at Air Ontario was in compliance with regulations, it practiced much less rigorous control of operations than its parent organization, Air Canada.

I(e). The lack of clear criteria for the qualifications and training of airline management, Check Airmen, and Air Carrier Inspectors. In times of rapid organizational change frequent shifts in operational conditions and practices are common as is substantial turnover in managerial positions. While organizations normally strive to maintain the highest possible level of experience and competence, in the absence of formal rules, compromises are frequent. It is suggested that more clearly defined guidelines could help organizations recognize situations where they need outside expertise to increase the safety and effectiveness of operations. In evaluating personnel, both the extent and quality of experience can serve as indicators of whether there are sufficient qualifications to direct and evaluate operations effectively. In the case of a new operation such as the initiation of F-28 service, such determinations may be difficult for those directly involved to make.

One persistent problem in the standardization of air carrier operations is the fact that regulatory inspectors and Check Airmen monitoring line operations are normally limited to working within a single aircraft type. The implication of this is that procedural variances that develop between the aircraft fleets of an organization fail to be detected by individuals who are restricted to dealing with a single component of the organization. Several airlines are adopting the policy of having evaluators monitor crew coordination and effectiveness across aircraft types to gain insight into type differences and developing subcultures.

II. The Organizational Environment.

A number of factors surrounding the nature and operation of Air Ontario created an environment conducive to operational error. At the highest level, Air Canada, despite owning controlling interest, *failed* to require Air Ontario to operate to Air Canada standards and failed to provide resources to achieve these standards. Similarly, a number of decisions and practices at Air Ontario served to allow an operation with significant safety-related deficiencies to develop and continue. The focus of this discussion is not on faulting organizations for failing to go beyond regulatory requirements. Rather, it is to discuss the *operational impact* of the organizational setting and practices that were present at this time. The factors to be discussed have been observed to impact operations in other air carriers facing similar constraints. It should be noted, however, that organizations undergoing such transformations might not be in a position to recognize their safety implications from within.

II(a). Lack of operational support from Air Canada. During the period of initiation of F-28 service, Air Canada owned a seventy-five percent, controlling interest in Air Ontario which operated under shared ("AC") flight designators. Air Canada has long experience in jet transport operations and stringent requirements for dispatch and flight following. The resources of this organization would have been highly valuable in smoothing the transition to the merged carrier and initiating jet service in the F-28. According to testimony, there were financial reasons (maintaining independent operations and pay scales) for maintaining a separation between the two carriers and there was no regulatory requirement for sharing resources and standards.

II(b). The disruptive impact of mergers and strikes. Mergers among air carriers have become increasingly frequent in recent years. In the course of our investigations, research into crew attitudes and behaviour has been conducted in several airlines which were the results of one or more mergers. As part of the research, crewmember attitudes toward management of the flightdeck are assessed using a survey instrument, the *Cockpit Management Attitudes Questionnaire (CMAQ)* (Helmreich, 1984; Gregorich, Helmreich, & Wilhelm, 1990). Attitudes regarding flightdeck management have been validated as predictors of crew performance and were derived from research implicating them as relevant in many accidents and incidents (Helmreich, Foushee, Benson, & Russini, 1986). The data show significant differences in attitudes as a function of previous organizational membership in each organization we have studied - in one case nearly a decade after a merger.[2] The results clearly indicate the existence of enduring subcultures within organizations. The issues measured by the CMAQ are shown in Appendix I. It is our premise that when cultural factors support the maintenance of differing attitudes about the appropriate conduct of flight operations, the effectiveness of flightcrew performance is likely to be compromised. Degani and Wiener (1990), in their study of normal checklist usage in air carrier operations, suggest that the stresses of merger can result in crews retaliating against management by disregarding mandated checklist procedures. The process of combining seniority lists from merging organizations also frequently results in poor relations among crewmembers from the different airlines. We have found that pejorative nicknames are often employed to label crewmembers from the opposite side of mergers.

Similarly, our data indicate that labour-management strife can have a deleterious effect on crewmembers' morale and attitudes toward their organizations. While there is no evidence to suggest that a crash has resulted directly from the impact of a strike, there is no doubt that the negative climate fostered by poor pilot-management relations is not conducive to effective team performance. In several airlines, even some years after a strike, relations among pilots and between pilots and managements remain poor.

2. A report on the impact of mergers with the organizations involved de-identified is under preparation for release in 1991.

Evidence from Air Ontario personnel supports the existence of differing sub-cultures in Austin Airways and Air Ontario with occasional categorization of former Austin Airways personnel as "Bush Pilots" who could be assumed to have informal, operational practices at variance with those of former Air Ontario flightcrews. The F-28 program was disproportionately managed by former Austin Airways personnel who could have influenced the operation in the direction of Austin Airways norms. The dominance of Air Ontario flight operations management by Austin Airways personnel also created ill-will among some former Air Ontario pilots. Morale problems and poor relations among crewmembers can interfere with effective teamwork and crew coordination.

One finding from our research into Crew Resource Management training is that it can serve to reduce differences in attitudes about flightdeck management between subcultures and between crew positions. Air Ontario management had looked into such training. Captain Robert Nyman, Director of Flight Operations, testified that the *CRM* courses available did not appear to fit the Air Ontario operation. Both the Chief Pilot and Chief Training Pilot attended a *CRM* course presented in Toronto by a major airline and reported it to be both of limited value and expensive.

II(c). High personnel turnover following the merger. In the period between the merger of the two carriers and the accident, there were substantial changes in personnel. Part of the operation was sold and the size of the combined organization was reduced from eight hundred to approximately six hundred. There was also turnover in two critical areas of management, Vice President of Flight Operations and Director of Flight Operations. Similarly, the position of Safety Officer was filled, became vacant due to a resignation, and subsequently re-filled. The lack of continuity in management could have impeded needed supervision of operational issues such as the introduction of a new aircraft type and standardization of operations following the merger. Programs such as *CRM* cannot alleviate operational problems associated with a lack of management stability and consistent direction.

II(d). Lack of organizational experience in jet operations. Air Ontario as an organization did not have experience in jet transport operations. At the time of the introduction of the F-28, efforts were made to acquire outside expertise in management and representations to this effect were made to Transport Canada. Ultimately, Captain Claude Castonguay, who had substantial jet transport operational experience (including in the F-28) was hired, but resigned after one month. Six months later he was called back to perform two line indoctrinations. In his letter of resignation, Captain Castonguay stated, "So much as I would like to keep working to establish your FK28 program, I have concluded that I cannot function in my duties as Check Pilot when I do not get the support I need." No one was subsequently hired from outside the organization to fill this role, leaving Air Ontario to manage the process with internal resources.

II(e). Deficiencies in Systems Operation Control (SOC) practices. Air Ontario operated with a dispatching system that consisted partly of full flight following and partly of pilot self dispatch. Although this system was permitted by current Transport Canada regulations, it failed to provide crews with the same level of support and resources given crews in the parent organization, Air Canada.

In the absence of regulations mandating formal training and licensing for dispatchers, Air Ontario primarily employed on the job training for dispatch personnel. For the introduction of the F-28, brief training in the operation of this type of aircraft was provided only for duty managers. In contrast, Air Canada provides its dispatchers with more formal training and operational guidelines - including rules that would forbid dispatching an aircraft with an inoperative APU into a station such as Dryden with no ground start capabilities. That the Air Ontario system was deficient is indicated by observed errors in flight releases such as fuel load calculations using wrong parameters. Indeed, the flight release for CFONF contained errors on the day of the accident.

II(f). Lack of standard operating procedures and manuals for the F-28. Service was initiated without a specific Air Ontario operating manual for the F-28. There was also no approved Minimum Equipment List for some months after passenger service began. There were inconsistencies between cockpit and cabin manuals provided crews. For example, the cabin manual required passenger disembarkation for refueling with an engine running while there was no parallel rule in the cockpit manual. Crews thus lacked formal organizational guidelines either from resources available on the flightdeck or from SOC.

II(g). Inconsistencies/deficiencies in training F-28 crewmembers. Initial training of F-28 crewmembers, including both ground school and simulator training, was contracted with Piedmont Airlines. Piedmont itself was involved in a merger with USAir which decided to achieve standardization of the merged operation by shifting all former Piedmont personnel to

USAir procedures and manuals. There were several implications of this organizational environment for Air Ontario crews. The first was that some received training from the Piedmont F-28 manual while those training later worked with the USAir manual. Since Air Ontario had not developed its own manuals, some individuals returned with the Piedmont Manual and others with that of USAir. While Air Ontario stated that the Piedmont Manual was its standard, this was not clearly communicated to crews and no efforts were made to provide all crews with the same manual. Air Ontario also failed to receive updates to the manuals it was using. Although the Fokker Aircraft Flight Manual was carried in the aircraft, there was a lack of training involving this manual and there were discrepancies between the Fokker and Piedmont manuals, for example in computing corrections for runway contamination. A second result of the Piedmont merger was a scarcity of simulator time for completing the training of Air Ontario crews. Because of this, a number of pilots were trained in the aircraft by newly qualified Air Ontario pilots rather than in the Piedmont simulator. Even with highly experienced instructors, there is an industry consensus that simulator training provides broader and more effective training.

Crewmembers surveyed by the Safety Officer following the accident generally reported their Line Indoctrination at Air Ontario to be "fair" in quality. One deficiency noted was a failure to define clearly the duties of the pilot flying and the pilot not flying.

II(h). Leadership of the F-28 program. Captain Joseph Deluce was selected as Project Manager and Chief Pilot for the F-28 and Convair 580. Captain Deluce had numerous responsibilities including line flying during the strike which preceded aircraft delivery and conducting training and line indoctrination in the F-28 for new crewmembers. He also carried Chief Pilot responsibilities for both fleets. Captain Deluce had limited operational experience in both the F-28 and the Convair 580. Airlines typically choose individuals with substantial experience in an aircraft type to be Chief Pilot.

One incident that may have had a significant impact on crewmember attitudes was the removal of an F-28 crew from a line trip to meet with the Chief Pilot for allegedly writing up too many maintenance discrepancies on the aircraft. The perception of other crewmembers of such an event would likely be of a lack of leader support for optimal operating conditions and a strong pressure to operate at all costs.

II(i). The informal culture at Air Ontario. One of the more striking findings to emerge from our research into flightcrew behaviour has been the discovery of significant differences between aircraft fleets within organizations in attitudes regarding flightdeck management and in ratings of behaviour in both line operations and Line Oriented Flight Training conducted in the simulator (Helmreich, Chidester, Foushee, Gregorich, and Wilhelm, 1990; Helmreich, 1990). These have been observed even in organizations with a strong commitment to standardization and form one of the justifications for implementing CRM training to develop common standards and values. Informal subcultures frequently tolerate or encourage practices which are at variance with organizational policies or regulatory standards.

Conditions at Air Ontario during the period of initiation of F-28 service would appear to have been conducive to the development of a non-standard subculture. These include previously noted lax regulatory supervision, high management turnover, the self-dispatch system with SOC personnel who lacked knowledge of the F-28 and were generally inexperienced, and the lack of clearly specified and enforced standard operating procedures. The reputation of being "Bush pilots" was attached to former Austin Airways pilots who formed a large percentage of the leadership of the F-28 program. Evidence of procedural variance is found in several reported practices. An example is writing mechanical problems or *snags* on paper to be passed to relieving crews instead of entering them in the aircraft logbook, thus permitting deferral of maintenance and avoiding the grounding of aircraft - a practice in violation of Transport Canada regulations. Others include the so-called "eighty knot check", a visual examination of the wing surfaces during take-off to ensure that contamination had blown off prior to rotation, and the practice of making overweight landings. A related fact is that Captain Deluce, the Chief Pilot, had been involved in at least two earlier, reported incidents involving take-offs with snow or ice contaminated surfaces. These suggest that the culture, at least among former Austin Airways crewmembers, may have allowed crews considerable leeway in making decisions about whether to take-off with surface contamination - a practice that was not proscribed by current Transport Canada regulations. It seems likely that the message communicated during training, and in the Fokker manual for the F-28, that *no* snow, ice, or frost should be present on wings may have been discounted to some extent by crews who had successfully operated (albeit in different types of aircraft) with some degree of contamination. Additionally, the Check Airmen appointed for the F-28 fleet were inexperienced in the aircraft and with jet operations and may not have been in a strong position to impose standards.

II(j). Maintenance problems with the F-28. A number of maintenance problems were encountered with the F-28. These were exacerbated by a lack of familiarity with the aircraft on the part of maintenance personnel and a shortage of spare parts. The Journey Log for the accident aircraft, CFONF, listed a number of problems between June and December, 1988, many deferred for extended periods. These included earlier problems with the Auxiliary Power Unit (APU) in August and October of 1988. On several occasions in 1989 the cabin filled with smoke with passengers aboard.

On the day of the accident, CFONF was dispatched with an inoperative APU and had three other deferred maintenance items including roll and yaw in the autopilot and a fuel gauge reading intermittently. Other discrepancies that were brought to the attention of the cockpit crew by the cabin crew prior to the first flight on March 10 included inoperative exit lights, dim cabin emergency floor lighting, missing oxygen masks, and problems closing the main door because of a missing clip.

II(k). Flight Attendant training. The practice of Flight Attendant training at Air Ontario discouraged flight attendants bringing operational issues to the attention of the flightdeck and questioning operations. Training stressed the competence of pilots and fostered a position of total reliance on the cockpit crew. Two examples of the results of this separation of cabin and cockpit can be seen on the day of the accident. These included the hot refueling of the aircraft in Dryden at variance with the cabin manual and the failure of the flight attendants to relay passenger concerns about de-icing to the flightdeck. In contrast to this lack of communication, the concepts taught in Crew Resource Management stress the importance of complete information exchange between the flightdeck and the cabin.

III. The Physical Environment

A number of negative factors were present in the operating environment facing the crew on March 10. These included an aircraft with mechanical problems including the inoperative APU and poor weather that had created an early delay for de-icing in Winnipeg and a subsequent hold in Dryden because of weather at Thunder Bay. Indeed the weather was unsettled in the entire region that day necessitating non-standard alternates at a greater than normal distance, thus increasing dispatch fuel requirements. There was also a change in the passenger manifest in Thunder Bay increasing the passenger load and necessitating defueling to meet weight restrictions for take off and landing at Dryden. At Dryden, there was no ground start equipment making it necessary to leave an engine running and forcing the Captain to hot refuel. Finally, snow was falling during the station stop in Dryden.

IV. The Crew Environment

A number of factors that were present in the crew environment of the accident flight have been identified through research in other organizations as significant stressors that can serve to reduce flightcrew effectiveness. These include both situational factors surrounding the operation and characteristics of individual crewmembers.

<u>Situational Factors</u>

IV(a). Crewmembers' unfamiliarity with the aircraft and their training experience. Both Captain Morwood and First Officer Mills were new to the F-28 and had fewer that 100 hours of operational experience in this aircraft type. After completion of ground and simulator training at Piedmont, Captain Morwood returned to flying the Convair 580 and his line transition to the F-28 was further delayed by the Air Ontario strike. First Officer Mills received his training in the aircraft rather than the simulator. For Captain Morwood, the delay in reinforcing his training on the line could have rendered him less effective initially. For First Officer Mills, the lack of opportunity to acquire skills and confidence in the simulator could have had a similar effect.

There is growing concern in the industry, based on several recent accidents in the U.S., about the safety implications of pairing crewmembers new to an aircraft soon after completion of line indoctrination, particularly under adverse weather conditions. There is obviously a significant learning curve in becoming comfortable with a new aircraft, particularly one substantially different from prior equipment. One of the basic premises of the crew concept of flight operations is that crewmembers support each other in service of the goal of safe and effective flight management. When *both* crewmembers are still acquiring familiarity with the aircraft, the margin of safety is reduced. Efforts are underway in the U.S. to set requirements for operational experience after initial training and to mandate scheduling of newly qualified crewmembers with those having substantial experience in the aircraft type.

IV(b). Organizational background and lack of experience working together. Several additional issues made the pairing of Captain Morwood and First Officer Mills potentially stressful. One was the fact that Morwood came from the Air Ontario organization while Mills' background was with Austin Airways. Additionally, both Morwood and Mills had been operating as Captains in their prior aircraft. Individuals accustomed to acting as pilot in command have been noted to function less effectively when paired. These factors, combined with the lack of enforced standard operating procedures (including the noted failure to specify pilot flying - pilot not flying duties in the F-28 line indoctrination), could well have reduced the effectiveness of this crew as a *team*.

This trip was also the first time that the crew had operated together and Captain Morwood was displaced for two days. Experimental simulation research conducted by NASA-Ames Research Center (Foushee, Lauber, Baetge, & Acomb, 1986) found that crew coordination and effectiveness is increased by the simple fact of working together as a team. In this study, crews who were fatigued (from a three day, multi-segment line trip) or not fatigued (coming from days off) flew an experimental simulation involving bad weather and mechanical malfunctions. The purpose of the study was to explore the effects of operationally induced fatigue on performance. The most surprising and serendipitous finding from the study was that *crews who had flown together previously performed better than crews paired for the first time whether or not they were fatigued!*

IV(c). Delays and stresses imposed by the operating environment. The initial segment of March 10 was delayed because of a need to de-ice the aircraft in Winnipeg. As noted, there were also major (APU) and minor mechanical problems with CFONF. In a radio communication, Captain Morwood commented "...everything else has gone wrong today." After the first leg, an additional delay was experienced because of poor weather in Thunder Bay. On arrival at Thunder Bay, additional passengers were taken aboard from a cancelled flight after refueling, making it necessary to remove fuel to meet weight requirements and causing it to depart more than an hour behind schedule. On arrival at Dryden, it was necessary to refuel with an engine running because of the lack of ground start capability. At the same time, snow was falling. As the Captain had fewer than 100 hours in the aircraft type, he required a higher RVR than a more experienced pilot would have. He may (or should have been) concerned that visibility would become below his minimum requirement prior to departure. The flight was already running late and a number of passengers had tight connections in Winnipeg. A final delay of approximately four minutes was incurred to await the arrival of a Cessna 150 which was experiencing difficulties because of the poor weather.

Personal Factors

IV(d). Captain George Morwood. Captain George Morwood was 52 years old and had more than 24,000 hours flying time. His operational experience was entirely in Canadian operations. He had worked for the predecessor of Air Ontario and had served as a Check Pilot and Chief Pilot for the Convair 580 at Air Ontario. He trained on the F-28 at Piedmont Airlines in January and February of 1988, but did not begin line flying in the F-28 until December, 1988. At the time of the crash he had 81 hours in the aircraft. His jet experience included approximately 600 hours in the Gulfstream G-2.

According to his record and peer reports, Morwood was above average in ability. He had shown concern with safety issues in his prior management positions and was aware of icing effects, including those caused by differential temperatures of fuel and ambient air. According to his record, he had delayed or cancelled flights because of icing. Probably based on his long experience as a Check Pilot, and Chief Pilot, Captain Morwood was reported to be in the habit of operating as an "instructor" while flying. In theory, this characteristic could be an annoyance to highly experienced junior crewmembers such as First Officer Mills who had considerable experience flying as a Captain.

Captain Morwood was reported to have a strong commitment to on time operations and a high level of concern for his passengers. There were a number of delayed passengers with connecting flights in Winnipeg on March 10. In addition, Morwood had a scheduled personal trip immediately following his last flight segment. These factors could have heightened motivation to complete the scheduled flying.

IV(e). First Officer Keith Mills. Keith Mills was 35 years old and had more than 10,000 hours flight experience. He began flying for Austin Airways as DHC6 Co-pilot in 1979 and became a Captain on the Hawker-Siddely HS748 in February 1988. He completed F-28 ground training in January, 1989 and aircraft training at Air Ontario. At the time of the crash he had 65 hours in the F-28 and approximately 3,500 jet hours in the Cessna Citation.

Mills had some record of difficulties with "stick and rudder" aspects of flying, but he met all regulatory requirements for competence. His failure to receive simulator training in the F-28 and Morwood's long experience and reputation as a perpetual "instructor" may have made Mills somewhat reluctant to practice optimal crew resource management concepts and to provide operational suggestions to Captain Morwood. Mills also had a scheduled personal trip at the end of his last flight segment.

V. The Situation of March 10

The picture that emerges from examination of the regulatory and organizational environments in which this crew was operating is one of an array of factors which served to undermine their effectiveness and to increase the stress of flight operations. None of these factors taken alone is likely to *cause* an accident - as evidenced by the fact that the F-28 was operated without incident or accident for months prior to March 10. However, when these factors were combined with the particular conditions of the physical environment (the inoperative APU, lack of facilities at Dryden, weather conditions, pressures to take off, etc.) the margin of safety was clearly reduced. Factors in the crew environment such as the operational unfamiliarity of the crew with each other and the aircraft doubtless exacerbated the situation.

V(a). Environmental Stressors. In considering the crew's actions on March 10, the environmental factors that may have been perceived as stressors should be reviewed. Psychological stress can serve to reduce individual and team effectiveness especially in the areas of interpersonal communications and coordination and decision making. Relevant classes of stressors include time pressure, and frustrations associated with inadequate resources and sub-optimal operating conditions. Captain Morwood and First Officer Mills faced a number of these conditions throughout their day. It may provide a useful context for the situation at Dryden to summarize them chronologically.

1. On accepting the aircraft in Winnipeg, the APU was found to be unserviceable. As noted previously, there were three additional, deferred maintenance items and other items in the cabin reported by the flight attendants.

2. The marginal weather throughout the region forced an initial delay for de-icing and the adoption of a distant alternate with a consequent requirement to carry additional fuel.

3. It was necessary to plan for "hot refueling" in Dryden because an engine would have to be left running. This may have triggered additional concerns because of company policy (and a stated requirement in the Fokker Publication on Cold Weather Operation) that the aircraft could not be de-iced with the engines running. However, it is not clear whether Captain Morwood had received a company memorandum about de-icing policy for the F-28.

4. SOC dispatched the flight with a clearly erroneous Flight Release. Testimony from pilot witnesses indicated little confidence in the SOC operation. It may have been a source of frustration or concern for the crew on this date to have been dispatched with no explicit accommodation for the unserviceable APU under adverse weather conditions.

5. Both crewmembers had fewer than 100 hours in the F-28. In addition to the stress imposed by lack of familiarity with the aircraft, Captain Morwood had more restrictive limits for visibility because of his low experience level in type. This could have added to his concerns about getting in and out of stations with poor weather.

6. The flight was delayed on its initial stop in Dryden because Thunder Bay weather was below landing limits.

7. There was considerable confusion surrounding the loading of additional passengers in Thunder Bay and the need to defuel the aircraft to meet weight restrictions. The crew had to communicate with SOC through a radio relay by Air Canada since there was no direct communications link from the flightdeck. This situation increased the delay of the flight to more than an hour on departure from Thunder Bay.

8. The fire trucks required for hot refueling were not in position on the aircraft's arrival at Dryden. This factor added to the accumulating delay and probable frustration of the crew over the disruptions surrounding the day's operations.

9. The date of the accident was the beginning of the March school break. There were many passengers with connections to make. The crew expressed concern over this in radio communications.

10. As the flight landed in Dryden, it began to snow, with the fall increasing during the stop. While the reported visibility was above minima, the actual visibility may have been at or below the Captain's minima at the time of take off.

While none of these issues alone can be considered an overwhelming stressor, taken in concert they indicate a taxing operational environment.

From the perspective of hindsight, it seems likely that a change in any one of a number of conditions might have provided the extra margin of safety needed. For example, a more stringently regulated and managed dispatch system would probably have precluded operations into Dryden on the return from Thunder Bay. An effective training program in Crew Resource Management could have resulted in a review of the operational situation involving both pilots and led to a critical evaluation of the decision to take off without de-icing. Similarly, training that encouraged cabin crewmembers to share operational concerns with flightcrews and pilots to listen to such concerns might also have triggered further consideration of the implications of accumulating contamination on the aircraft.

The issues discussed in preceding sections have an empirical basis as significant influences on flightcrew behaviour, but a weighting of each as a determinant of the outcome of Flight 363 cannot be made from the available record. Nor can the decision processes surrounding the take off from Dryden be specified in the absence of Cockpit Voice Recorder evidence. However, it is possible to envision a likely scenario for the crew's actions based on consideration of the four sets of determinants of crew behaviour described previously. It must be stressed that this represents a *post hoc* reconstruction that may be erroneous in part or whole.

VI. A Scenario for Crew Decision Making in Dryden

In retrospect, the decision to operate into Dryden on the return from Thunder Bay without a functioning APU was questionable, but understandable. The initial stop in Dryden was uneventful, despite a delay because of weather conditions in Thunder Bay. Although the forecast for the region showed a risk of freezing precipitation, on approach to Dryden conditions were VFR. Making the stop would minimize passenger disruption. However, once on the ground in Dryden, the weather and operational situation deteriorated. At the same time, the crew had conducted a day of flying that must be considered stressful because of the mechanical problems with CFONF, increasing delays, the changed passenger load resulting in additional delay, and the crew's relative inexperience in F-28 operations. While on the ground in Dryden, the following issues faced the Crew:

1. Considerations surrounding refueling with an engine running
2. Pressures to get passengers to Winnipeg for connections
3. The inconvenience of stranding passengers in Dryden with limited facilities
4. Logistic problems surrounding de-icing with an unserviceable APU and no ground start capability
5. The need to import ground start equipment if both engines were to be shut down and consequent long delay
6. Snowfall during the stop causing both aircraft and runway contamination and deteriorating visibility that might be below minimums for the Captain
7. The implications of contamination on the aircraft
8. The implications of contamination on the runway (including conflict between Fokker and Piedmont manuals in this area)
9. The additional delay posed by the arrival of the Cessna 150
10. Planned personal trips which would be impacted by long delay in Dryden

One of the effects of psychological stress (including that imposed by time pressure) is an inability to process multiple sources of information as effectively as under more relaxed conditions. As listed in the previous section, a case can be made for the fact that the crew, and especially Captain Morwood as pilot in command, was under considerable stress by the time the flight stopped for the second time in Dryden. It may also be inferred that the operating standards of Air Ontario and the absence of formal training and organizational endorsement of crew coordination concepts, would have tended to preclude rigorous *crew* evaluation of the operational situation.

Surrounding the decision to take off are several critical questions. One is whether the crew was aware of the safety implications of the accumulating snow. As noted, Captain Morwood had a history of concern and awareness of icing risks. He had delayed the initial flight of the day for de-icing. Testimony by a representative of Transport Canada included an incident when Captain Morwood insisted on going back to the gate in the Convair 580 for de-icing even though the Inspector had remarked that the snow seemed dry and the propellers were blowing it off the wings. Also, a 1983 letter from Air Ontario management endorsing the Captain's authority to de-ice when circumstances require was found in Captain Morwood's flight bag at the accident scene.

A second question is whether the crew was aware of the accumulation of snow on the wings at Dryden. The Captain visited the terminal during the stop in his shirt-sleeves and would have been aware of snow falling. During a conversation with SOC during this period, he commented to Ms. Mary Ward that the weather at Dryden was "going down." The cockpit crew also had the ability to observe the wings from the cockpit and the testimony of informed passengers indicated that snow was accumulating visibly there. It seems inconceivable that the crew would have been unaware of snow on the wings. The fact that Morwood inquired of the station manager at Dryden about de-icing facilities there also suggests awareness.

Despite his knowledge of icing and probable awareness of the snow gathering on the wings, it seems most likely that Captain Morwood weighed costs and benefits surrounding the issues listed above and concluded that the best course of action would be to take off expeditiously. Several things may have influenced this decision. One is that because of the multiple stressors involved in the situation and his focus on completing the trip, he failed to weigh the risks as heavily as the benefits from getting out before the weather deteriorated further. The ambiguity of regulations regarding icing could also have influenced his decision. Although it was noted that emphasis was placed in training at Piedmont on taking off with no wing contamination, he may not have felt that the issue was as serious in the F-28 as other aircraft given higher rotation speeds and additional opportunity to blow the accumulation off during take-off roll.

The role of First Officer Mills in this decision is, of course, indeterminate. However, based on considerations regarding experience and status it is not likely that he was heavily involved by Captain Morwood.

There was probably a misperception about the nature of the contamination as it relates to "cold soaking", the situation when portions of an aircraft are at a temperature below the ambient temperature because of having descended from altitudes where ambient air is colder or from heat transfer to areas containing fuel colder than the ambient temperature. Pilots interviewed by the author were primarily concerned with heat transfer at high altitudes and less aware of the phenomenon occurring on the ground due to cold fuel in wing tanks. The Piedmont manual which was used at Air Ontario addresses this phenomenon in a section on Cold-Weather Operations. It states:

> "When the tanks contain sufficient fuel of sub zero temperatures as may be the case after long flights at very low ambient temperature, water condensation or rain will freeze on the wing upper surfaces during the ground stop forming a smooth, hardly visible ice coating.
> During take off this ice may break away and at the moment of rotation enter the engine causing compressor stall and/or engine damage." (Piedmont F-28 Manual, Exhibit 307 3A-24-1)

A decision could well have been reached that the snow would blow off, given the large fluffy flakes coming down and the lack of accumulation on the tarmac surrounding the aircraft. The possibility that a layer of rough ice caused by cold soaking extended to the leading edge was probably not entertained by either Morwood or Mills.

Psychological pressure to complete the trip as scheduled, commonly referred to as "get home-itis", cannot be ruled out. Captain Morwood was clearly concerned about holiday passengers with connecting flights in Winnipeg and both he and Mills had personal trips planned after completion of the trip. Had the flight been cancelled in Dryden, it would have been necessary to fly in ground start equipment causing a lengthy delay and disruption of crew and passenger plans. Once on the ground in Dryden, the implications of a long delay doubtless had a subtle influence on the decision process.

A final chance to re-evaluate the situation was probably missed when the flight took its final delay for the landing of the Cessna 150. However, the accumulation of stress and frustration surrounding the day's operations had probably reduced the crew's effectiveness and decision making capabilities by this time.

While the Captain as Pilot in Command must bear responsibility for the decisions to land and take off in Dryden on the day in question, it seems equally clear that the aviation system failed him at the critical moment by not providing effective management, guidelines, and procedures that would assist him in such decisions.

In the following section, observations and suggested corrective measures are offered in the hope that they may provide greater resources for future crews who find themselves in stressful situations trying to evaluate multiple pieces of information and having to make choices among unpleasant, alternative courses of action.

VII. Observations

The following are corrective measures that could be taken to increase system safety and effectiveness. It is noted that the first recommendation of the Commission to Transport Canada was to remove the ambiguity from regulations surrounding wing contamination and that this was favorably received.

VII(a). Monitoring of air carrier operations. It would be valuable to establish guidelines for air carrier management in terms of qualifications needed for effective job performance. A similar set of standards could be established for Air Carrier Inspectors and others involved in surveillance of airline operations. Requirements for inspectors and check airmen could include training in the evaluation of human factors aspects of flight operations.

Training in the conduct of air carrier audits and requirements for qualification of audits could be strengthened. In particular, emphasis in audits should be on observation of line operations evaluating both human factors and technical proficiency.

Strengthened requirements for flight dispatch and the training of dispatchers should be developed for all airline operations.

VII(b). Winter operations. Yearly training and review of Winter operations procedures should be conducted. This should include not only general issues regarding icing, cold soaking, and de-icing procedures, but also information specific to particular aircraft types as needed.

VII(c). Common standards for major airlines and their feeder operations. Airlines operating under a common designator should maintain the same standards of training, dispatching, and performance. The need is probably greater for effective training and organizational support in smaller carriers that operate into secondary stations with fewer facilities. In many cases, pilots in regional carriers may have had less experience and less formal training. The resources of the major carriers could be highly beneficial for the safety and effectiveness of these regional carriers and could allow them to establish levels of training that they could not effect independently.

VII(d). Formal training in Crew Resource Management for all crewmembers. Accumulating experience in the U.S. and many other countries has demonstrated the importance of *CRM* training. The U.S. has encouraged this training through an Advisory Circular and it is a requirement for operating under a new Special Federal Aviation Regulation called the *Advanced Qualification Program*. Efforts are underway in the U.S. to initiate a regulatory requirement mandating *CRM* training for all air carriers operating under Parts 121 and 135 of the Federal Aviation Regulations. A copy of the *CRM Advisory Circular* and a proposed revision drafted by the author as part of a committee of the Air Transport Association are included as Appendix II and II-A. A premise of the Advisory Circular, supported by empirical research, is that a single training experience in *CRM* concepts is insufficient to provide long term changes in crew coordination and performance. Such training must be accompanied by opportunities to practice the concepts and to receive reinforcement for their use. Check Airmen and Instructors have been identified as critical to this endeavour and should be given training in the evaluation and reinforcement of human factors issues as an extension of their traditional role (Helmreich, Chidester, Foushee, Gregorich, & Wilhelm, 1989). This type of evaluation and reinforcement can and should occur both in ground training and during line checks and should center on clearly understandable exemplars of effective and ineffective performance that have come to be called ***behavioural markers*** of crew performance. Examples of these and a form for evaluation of crew performance (the *CRM/LOS Checklist*) are included as Appendix

III. There is a growing belief that this training can be effectively extended to cabin crews and other operational personnel. One can speculate that had both the flight attendants and cockpit crew completed *CRM* training and accepted its concepts, there might have been an exchange of information that would have precluded the take off.

VII(e). Crew oriented training and evaluation. The historical emphasis in aviation has been on individual, technical proficiency and both training and evaluation have centered on the performance of the individual pilot. However, data from accidents and incidents suggest that the *CRM*-related issues isolated in accidents and incidents involve failures of *crews* to operate effectively as *teams*. Many airlines and military units have reacted to this by increasing the emphasis in training and checking on crew-level performance. In checking line operations this is accomplished by including the performance of the crew as a unit as part of the evaluation and debriefing (for example, using the *CRM/LOS Checklist* as a template for evaluation).

Another approach being used increasingly (and required in the U.S. for carriers that will operate under the *Advanced Qualification Program*) is the use of *Line Oriented Flight Training (LOFT)* which involves complete crews training in simulators under realistic operating conditions including flight releases, air traffic communications, and facing a variety of operational problems including inflight emergencies. A key to the success of this training is that it is *non-jeopardy* meaning that crews are allowed to experiment with a variety of behaviours and approaches without placing their licenses at risk. Events are allowed to proceed without intervention by the Instructor and are usually recorded on videotape for subsequent review and debriefing. In its early development, *LOFT* required access to high fidelity simulators placing this form of training out of the reach of many organizations, especially regional and commuter airlines. However, recent research and theorizing (Franz, Prince, Salas, & Law, 1990; Helmreich, Kello, Chidester, Wilhelm, & Gregorich, 1990; Helmreich, Wilhelm, & Gregorich, 1988) suggests that low fidelity simulators and training devices may provide excellent settings for training in crew coordination and should make the technique available to almost all organizations.

VII(f). Establishment of a Safety Office in all air carriers. In addition to regulatory monitoring of air carriers, an independent Safety Office can serve an important function in isolating potential threats to safety. A Safety Officer with direct access to top management is in a position to initiate corrective action when threats to safety are uncovered. In addition to training in investigative techniques, training in human factors, database management, and analysis would also be highly desirable for Safety Officers and their staffs.

References

Degani, A., & Wiener, E.L. (1990). *Human factors of flight-deck checklists: The normal checklist* (NASA contract report 177549). Moffett Field, CA: NASA Ames Research Center.

Foushee, H.C., & Helmreich, R.L. (1988). Group interactions and flightcrew performance. In E. Wiener & J. Nagel (Eds.), *Human factors in modern aviation*, (pp. 189-227). New York: Academic Press.

Foushee, H.C., Lauber, J.K., Baetge, N.M., & Acomb, D.B. (1986) *Crew factors in flight operations III: The operational significance of exposure to short-haul air transport operations*. Moffett Field, CA, U.S.: NASA-Ames Research Center, TM 88322.

Franz, T.M., Prince, C., Salas, E., & Law, J.R. (1990). Low fidelity flight simulation: Applications for aircrew coordination training. in press.

Gregorich, S.E., Helmreich, R.L., & Wilhelm, J.A. (1990). The structure of Cockpit Management Attitudes. *Journal of Applied Psychology, 75*, 682-690.

Helmreich, R.L. (1984). Cockpit management attitudes. *Human Factors, 26*, 583-589.

Helmreich, R.L. (1990). *Studying flightcrew interaction: The intersection of basic and applied research.* Talk presented at the dedication of the NASA-Ames Research Center Human Performance Research Laboratory. Moffett Field, CA.

Helmreich, R.L. (1991). The long and short term impact of Crew Resource Management training (pp. 81-83) In *Proceedings of the AIAA/NASA/FAA/HFS Conference: Challenges in Aviation Human Factors: The National Plan.* Vienna, VA.

Helmreich, R.L., Chidester, T.R., Foushee, H.C., Gregorich, S.E., & Wilhelm, J.A. (1989). *Critical issues in implementing and reinforcing Cockpit Resource Management Training.* Austin, NASA/UT Technical Report 89-5.

Helmreich, R.L, Chidester, T.R., Foushee, H.C, Gregorich, S.E. & Wilhelm, J.A. (1990, May). How effective is Cockpit Resource Management Training? Issues in evaluating the impact of programs to enhance crew coordination. *Flight Safety Digest,* 1-17. Arlington, VA: Flight Safety Foundation.

Helmreich, R.L., Foushee, H.C., Benson, R., & Russini, W. (1986) Cockpit resource management: Exploring the attitude-performance linkage. *Aviation, Space and Environmental Medicine, 57,* 1198-1200.

Helmreich, R.L., Kello, J.E., Chidester, T.R., Wilhelm, J.A. & Gregorich, S.E. (1990) Maximizing the operational impact of Line Oriented Flight Training (LOFT): Lessons from initial observations. NASA/UT Technical Report 90-1.

Helmreich, R.L. & Wilhelm, J.A. (1990). Determinants of flightcrew behavior. In *Proceedings of the International Civil Aviation Organization Human Factors Seminar (A-276 - A-286).* Leningrad, USSR.

Helmreich, R.L., Wilhelm, J.A., & Gregorich, S.E. (1988) Notes on the concept of LOFT: An agenda for research. NASA/The University of Texas at Austin Technical Report 88-1.

Helmreich, R.L., Wilhelm, J.A., Gregorich, S.E., & Chidester, T.R. (1990) Preliminary results from the evaluation of Cockpit Resource Management Training: Performance ratings of flightcrews. *Aviation, Space, and Environmental Medicine, 61,* 576-579.

FINAL REPORT
CONTENTS

VOLUME I

PART ONE INTRODUCTION

1 Introduction

PART TWO FACTS SURROUNDING THE CRASH OF FLIGHT 1363

2 Air Ontario Flights 1362 and 1363
3 Dryden Municipal Airport and Air Ontario Facilities, March 10, 1989
4 Meteorological Information
5 Events and Circumstances at the Dryden Municipal Airport Preceding Takeoff
6 Circumstances Related to the Takeoff and Crash of Flight 1363
7 The Crash and the Response
8 Dryden Area Response

PART THREE CRASH, FIRE-FIGHTING, AND RESCUE SERVICES

9 Dryden Municipal Airport Crash, Fire-fighting, and Rescue Services

PART FOUR AIRCRAFT INVESTIGATION PROCESS AND ANALYSIS

10 Technical Investigation
11 Aircraft Crash Survivability
12 Fokker F-28, Mk1000, Aircraft Performance and Flight Dynamics

VOLUME II

PART FIVE THE AIR CARRIER – AIR ONTARIO INC.

13 Corporate History
14 Management Organization
15 The F-28 Program: Planning
16 The F-28 Program: The Auxiliary Power Unit, the Minimum Equipment List, and the Dilemma Facing the Crew of Flight 1363
17 The F-28 Program: Lack of Ground-Start Facilities at Dryden
18 The F-28 Program: Spare Parts
19 The F-28 Program: Flight Operations Manuals
20 The F-28 Program: Flight Operations Training
21 The F-28 Program: Operational Practices – Hot Refuelling and Aircraft Ground De-icing
22 The F-28 Program: Flight Attendant Shoulder Harness
23 Operational Control
24 Flight Safety
25 Management Performance
26 The Role of Air Canada: Parent/Subsidiary Implications

VOLUME III

PART SIX TRANSPORT CANADA

27 Organization
28 Conditions at Transport Canada, Early 1980s
29 Economic Deregulation and Deficit Reduction
30 The Effects of Deregulation and Downsizing on Aviation Safety
31 Aviation Regulation: Resourcing Process
32 Audit Program
33 Audit of Air Ontario Inc., 1988
34 Operating Rules and Legislation
35 Company Check Pilot
36 Contracting Out, Waivers, and Spot Checks
37 Safety Management and the Transport Canada Organization

PART SEVEN HUMAN FACTORS

38 Crew Information
39 Crew Coordination and the Communication of Safety Concerns by Passengers
40 Human Performance: A System Analysis

PART EIGHT LEGAL AND OTHER ISSUES BEFORE THE COMMISSION

41 The Aviation Accident Investigation Process in Canada
42 Aviation Incident and Occurrence Reporting and the Issue of Pilot Confidentiality
43 Objection to Production of Documents, Based on a Confidence of the Queen's Privy Council, Section 39, Canada Evidence Act, R.S.C. 1985, c.C-5
44 Inquiries Act, R.S.C. 1985, c.I-11, Section 13

PART NINE CONSOLIDATED RECOMMENDATIONS

Interim Report, 1989
Second Interim Report, 1990
Final Report

GENERAL APPENDICES

A Order in Council
B Counsel and Representatives for Parties with Standing
C Parties Granted Full, Limited, and Special Participant Status and Observer Status
D Witnesses Appearing before the Inquiry
E Inquiry Schedule
F Letter from the Chief Coroner for Ontario, July 15, 1991
G Time Sequence of Events Surrounding the Crash
H Summary of Fatalities and Survivor Injuries
I Minutes of Debriefing Meetings, Town of Dryden, March 13 and 16, 1989
J U.S. Department of Transportation, Federal Aviation Administration, Advisory Circular 120-51, Cockpit Resource Management Training, Dated December 1, 1989
K Transport Canada Response to the Interim Recommendations of the Second Interim Report, Dryden Commission of Inquiry
L Letter of Notice Sent by Commission Counsel to Affected Parties, re: Inquiries Act, R.S.C. 1985, c.I-11, Section 13
M Rulings

DSS cat. no. CP32-55/1992E (Vol. 1–3)
ISBN 0-660-14382-8 (Vol. 1–3)