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Advances in the Characterization of Supercooled Clouds for Aircraft Icing Applications

Richard K. Jeck
Federal Aviation Administration
William J. Hughes Technical Center
Airport and Aircraft Safety
Research and Development Division
Atlantic City International Airport, NJ 08405

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16. Abstract

Approximately 28,000 nautical miles (52,000 km) of select, in-flight measurements of cloud water concentrations, droplet sizes, temperatures, and other variables in supercooled clouds over portions of North America, Europe, and the northern oceans have been condensed into a computerized database for deriving a worldwide, statistical description of aircraft icing conditions aloft. The data are compared with the currently accepted envelopes of icing cloud variables specified in Title 14 Code of Federal Regulations Parts 25 and 29 Appendix C for the design of aircraft ice protection equipment. There are differences, along with some deficiencies, unrealistic trends, and difficulties in the use of Appendix C. As a result, suggestions are made for updating, modernizing, and improving the currently accepted envelopes in Appendix C.

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TABLE OF CONTENTS

			Page
EXECUTIVE SUMMARY			xiii
1.	INTRODUCTION		1
	1.1	Background	1
		1.1.1 The Icing Hazard	1
		1.1.2 Extreme Value Envelopes for Supercooled Cloud Variables	1
	1.2	Purpose of This Study	5
2.	THE BASIC VARIABLES		5
	2.1	Supercooled Liquid Water Content	6
		2.1.1 Layer Clouds	7
		2.1.2 Convective Clouds	9
	2.2	Droplet Median Volume Diameter	10
		2.2.1 Layer Clouds	14
		2.2.2 Convective Clouds	15
		2.2.3 Large Droplets	16
	2.3	The SLWC Versus MVD	16
		2.3.1 Implications for Natural Icing Test Flights	18
		2.3.2 Implications for Design and Computations	18
	2.4	Air Temperature	18
	2.5	Horizontal Extent	19
		2.5.1 Conventional Design Distances	22
		2.5.2 Demonstrated Icing Protection Zones	22
3.	COMPARISON WITH APPENDIX C ENVELOPES		23
	3.1	The SLWC Versus MVD Envelopes and the LWC Adjustment Curves	23
		3.1.1 Layer Clouds	24
		3.1.2 Recommendation for Consideration	25
		3.1.3 Convective Clouds	26

3.1.4 Recommendation for Consideration 27

3.2 Temperature Versus Altitude Envelopes 28

3.2.1 Layer Clouds 28
3.2.2 Suggested Extensions to the Envelope 29
3.2.3 Convective Clouds 31
3.2.4 Suggested Extensions to the Envelope 33

4. OTHER DEPENDENCIES 35

4.1 Seasonal Variations 35

4.1.1 Seasonal Definitions 35
4.1.2 The SLWC Versus Freezing Level Height 36

4.2 Altitude Variations 40

4.2.1 What About Altitude Limited Aircraft? 40
4.2.2 The SLWC Versus Altitude 41

5. SAMPLE APPLICATIONS—SELECTING DESIGN POINTS 48

5.1 Example 1, The 7000-ft Altitude Case 49

5.1.1 The Conventional ADS-4 Method 49
5.1.2 The LWC Percentile Method 49

5.2 Example 2, The 2500-ft, Low Altitude Case 50

5.2.1 The Altitude Priority Method 50
5.2.2 The Conventional ADS-4 Method 50
5.2.3 The LWC Percentile Method 50

6. CONCLUSIONS ABOUT THE APPENDIX C ENVELOPES 51

6.1 Figures 1 and 4: LWC Versus MVD Curves 51
6.2 Figures 2 and 5: Icing Temperature Limits Versus Altitude 52
6.3 Figures 3 and 6: LWC Adjustment (F-factor) Curves 52
6.4 Other Facts and Conclusions From the Data 52

7. REFERENCES 53

APPENDICES

A—Explanation of the Variables Used in the Database

B—Sources of Data

C—The Origin and Interpretation of Horizontal Extent Specifications and the LWC Factor Curves in 14 CFR Parts 25 and 29 Appendix C

D—Comparison of Liquid Water Content Curves in 14 CFR Parts 25 and 29 Appendix C to LWC Percentiles Derived From the Modern Database

E—The Frequency of Occurrence of Supercooled Liquid Water Content Values

F—Computerized Versions of 14 CFR Parts 25 and 29 Appendix C

G—Differences Between Russian and American/European Versions of 14 CFR Parts 25 and 29 Appendix C

H—Glossary

LIST OF FIGURES

Figure		Page
1	Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions (LWC versus mean effective drop diameter)	2
2	Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions (ambient temperature versus pressure altitude)	2
3	Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions (LWC factor versus cloud horizontal extent)	3
4	Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions (LWC versus mean effective drop diameter)	3
5	Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions (ambient temperature versus pressure altitude)	4
6	Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions (variation of LWC factor with cloud horizontal extent)	4
7	The LWC Frequencies in 23,000 nmi of Supercooled Layer Clouds	6
8	The LWC Frequencies in 5000 nmi of Supercooled Convective Clouds	7
9	The 3500 Supercooled Layer Cloud Events, Regardless of Horizontal Extent (23,000 nmi contributing)	8
10	The 3200 Supercooled Convective Cloud Events, Regardless of Horizontal Extent (5000 nmi contributing)	10
11	The MVD Frequencies in Supercooled Layer Clouds (12,400 nmi contributing)	12
12	The MVD Frequencies in Supercooled Cumuliform Clouds (4300 nmi contributing)	12
13	Duration of MVDs in Layer Cloud Icing Encounters (13,700 nmi contributing)	13
14	Duration of MVDs in Convective Cloud Encounters (5000 nmi contributing)	13
15	The 99th Percentile LWC for Icing Encounters With Different MVDs at 0° to -10°C in Stratiform Clouds	15
16	Layer Cloud Icing Events for all Temperatures Regardless of Horizontal Extent (12,400 nmi contributing)	17
17	Cumuliform Cloud Icing Events for all Temperatures Regardless of Horizontal Extent (4300 nmi contributing)	17

18	Air Temperature Frequency for Layer Clouds in the Database (23,000 nmi contributing)	18
19	Air Temperature Frequency for Convective Clouds in the Database (5050 nmi contributing)	19
20	The 3500 Supercooled Layer Cloud Events	20
21	The 3200 Supercooled Covective Cloud Events	21
22	The Entire Supercooled Cloud Database 6700 Icing Events Totaling 28,000 nmi in Icing Conditions	21
23	Example of Indicating Protection Zones on Continuous Maximum Envelopes	23
24	Appendix C Envelopes Converted to a Distance-Based Format	24
25	Natural 99th Percentile Limits to LWC (and HE) for 10°C Temperature Intervals in Stratiform Clouds With Average MVDs (10 to 20 µm)	25
26	The 99th Percentile LWCs for Icing Encounters in Convective Clouds With MVDs = 15-25 µm	27
27	Observed Icing Events in Layer Clouds (22,900 nmi contributing)	29
28	Proposed Extension of Temperatures Versus Altitude Envelope for Continuous Maximum Conditions	30
29	Average Temperature Versus Altitude AGL for Layer Cloud Icing Events	30
30	Convective Cloud Icing Events From all Seasons (5000 nmi contributing)	31
31	Convective Cloud Events for Cold Season (Winter) Only (2930 nmi contributing)	32
32	Convective Cloud Events for Mild Season (Spring and Autumn) Only (1720 nmi contributing)	32
33	Convective Cloud Events for Warm Season (Summer) Only (410 nmi contributing)	33
34	Proposed Extensions of Temperature Versus Altitude Envelope for Intermittent Maximum Conditions	34
35	Average Temperature Versus Altitude for Convective Cloud Icing Events	34
36	Observed Icing Events in Supercooled Layer Clouds Regardless of Horizontal Extent (23,000 nmi contributing)	37
37	Observed Icing Events in Supercooled Convective Clouds Regardless of Horizontal Extent (5000 nmi contributing)	38

38 Observed Seasonal Limits to SLWC and Horizontal Extent for Icing Encounters in Stratiform Clouds 39

39 Observed Seasonal Limits to SLWC and Horizontal Extent for Icing Encounters in Convective Clouds 40

40 Supercooled Layer Cloud Events Versus Altitude AGL, Regardless of Horizontal Extent (23,000 nmi contributing) 42

41 Supercooled Layer Cloud Events Versus Pressure Altitude, Regardless of Horizontal Extent (23,000 nmi contributing) 43

42 Supercooled Convective Cloud Events Versus Altitude AGL, Regardless of Horizontal Extent (5000 nmi contributing) 44

43 Supercooled Convective Cloud Events Versus Pressure Altitude, Regardless of Horizontal Extent (5000 nmi contributing) 45

44 The 99th Percentile Limits to SLWC (and Horizontal Extent) as a Function of Altitude (AGL) for all Supercooled Clouds With Average MVDs (10 to 20 µm) and Highest Temperatures Available at the Indicated Altitude (Summertime Concective Clouds Excluded) 46

LIST OF TABLES

Table		Page
1	The SLWC in 23,000 nmi of Layer Clouds	7
2	The SLWC in 5000 nmi of Convective Clouds	9
3	Amounts of Data by Season	35
4	Seasons Defined by Freezing Level Height	36
5	Fractions of an Exposure That the Indicated LWCs may be Expected to Last, According to the Statistics in Table 1	49
6	Fractions of an Exposure That the Indicated LWCs may be Expected to Last, According to the Statistics in Table 1, but Limited by the 2500-ft Curve in Figure 44	51

LIST OF ACRONYMS

AD	Averaging distance
AGL	Above ground level
ASL	Above sea level
ASSP	Axially scattering spectrometer probe
AWACS	Airborne warning and control system
CFR	Code of Federal Regulations
CONUS	Conterminous (or contiguous) United States
ED	Exposure distance
FAA	Federal Aviation Administration
FSSP	Forward scattering spectrometer probe
HE	Horizontal extent
IPHWG	Ice Protection Harmonization Working Group
JAR	Joint Aviation Requirements
LWC	Liquid water content (of clouds)
MAD	Maximum average diameter
MED	Mean-effective diameter
MVD	Median volume diameter (of cloud droplets)
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
nmi	Nautical mile
OAT	Outside air temperature
PA	Pressure altitude
PMS	Particle Measuring Systems
RMC	Rotating multi-cylinders
SCPP	Sierra Cooperative Pilot Project
SLWC	Supercooled liquid water content
TAS	True airspeed
UHD	Unidirectional horizontal distance
WB	Weather bureau

EXECUTIVE SUMMARY

A primary goal of this research was to comprehensively evaluate, with suggestions for possible improvement, the meteorological criteria used over the past 40 years for the design of in-flight ice protection equipment for aircraft. These criteria were promulgated in Title 14 Code of Federal Regulations (CFR) Part 25 Appendix C. Six figures appear in 14 CFR Part 25 Appendix C and are repeated in 14 CFR Part 29 Appendix C: (1) maximum probable liquid water content (LWC) of cold clouds as a function of air temperature and a representative cloud droplet size, (2) expected temperature extremes in icing conditions as a function of altitude, and (3) curves for adjusting LWC values according to the averaging distance of interest. The first three figures, known as continuous maximum envelopes, are for stratiform type clouds. The next three, known as intermittent maximum envelopes, are for cumuliform clouds. Hereafter, these figures will be referred to simply as Appendix C.

In the late 1970s, the helicopter community began calling for hoped-for relief from the large design values of LWC in Appendix C by requesting new envelopes tailored to the lower altitudes where helicopters operate. There was also a general interest in re-evaluating the envelopes against new data being obtained from modern, electro-optical, cloud probing instruments coming into use on meteorological research aircraft. As a result, a new data gathering and analyses effort was begun by the Federal Aviation Administration (FAA) and is reported on here. About 28,000 nautical miles (nmi) of measurements, both old and new, have been collected to permit a comprehensive re-evaluation of these envelopes for the first time.

The basic question for regulatory concerns is, do the graphs and curves in 14 CFR Parts 25 and 29 Appendix C need to be changed?

The answer depends on whether a more realistic representation of the icing environment is desired, or whether a simplified set of design criteria is acceptable, or whether a more versatile depiction is preferred, and whether the graphics are to be modernized for the computer age, or some combination of these.

Viewed as a simple engineering depiction of overall limiting values for LWC, median volume diameter (MVD), and true outside air temperature (OAT), the existing Appendix C envelopes, while not completely accurate, and potentially misleading in some respects, probably remain acceptable for selecting conservative, or at least adequate, design values for ice protection systems for ordinary icing conditions. No safety hazard is expected to result if the present envelopes are kept unchanged, but they are unhelpful for some applications, such as providing altitude-limited LWCs, determining most probable MVDs, and plotting test points.

A more realistic representation of the extreme values in Appendix C would include

- replacing figures 1 and 4 with recomputed 99th percentile LWC curves in a LWC versus distance format.

- expanding the temperature versus altitude envelopes in figure 5 to include summertime icing conditions at high altitudes.

- eliminating figures 3 and 6 as unnecessary if an LWC versus distance format is adopted.

A simplified set of design criteria would result from

- replacing figures 1 and 4 by a short table of LWC values corresponding to the statistical 50%, 90%, 95%, 99%, and 99.9% limits to LWC for each cloud type, as determined from the large data set now available.

- eliminating figures 3 and 6 as being unnecessary if the above tables are adopted.

- limiting drop size selection to a single, critical value (20 or 25 µm) for use with LWCs for conservative estimates of ice accretion amounts, rates, and shapes.

A more versatile set of design curves would include

- replacing figures 1 and 4 with 50%, 90%, 95%, 99%, and 99.9% LWC curves in a LWC versus distance format.

- adding seasonal- and altitude-limited LWC curves.

- eliminating figures 3 and 6 as unnecessary if a LWC versus distance format is adopted.

All proposals de-emphasize MVD as a variable and promote exposure distance (horizontal extent) as a more useful variable instead.

In any case, a modernized version of Appendix C would convert the new or old figures to computerized spreadsheet charts for a cleaner appearance, ease of use with word processors, and the ability to customize the figures for particular applications.

The rationale behind each of these possibilities is explained in the main body of this report.

These new types of envelopes and curves are recommended for consideration as an improved and more informative picture of icing conditions aloft. Basically, they emphasize practical utility and the elimination of unnecessary features. New information can be added, such as seasonal dependences of LWC on temperature and altitude, and probability curves for LWC, temperature, and MVD. Such information has been called for as an aid in

- selecting design values of LWC and temperature as a function of altitude, for altitude-limited or scenario driven applications. These are especially of interest for military aircraft, but they also apply to helicopters in general.

- selecting realistic (naturally occurring) combinations of LWC, MVD, and OAT for icing wind tunnel tests or computerized ice accretion models.

- setting realistic expectations for finding various values of LWC, MVD, and OAT during test flights in natural icing conditions.

- providing operational guidance to weather briefers and forecasters in determining typical and maximum expected icing conditions as a function of altitude and temperature aloft, by season of the year.

1. INTRODUCTION.

1.1 BACKGROUND.

This report covers one phase of a research project to improve the understanding and quantitative description of aircraft icing conditions in the atmosphere.

1.1.1 The Icing Hazard.

The aircraft icing hazard comes from the fact that in clouds that are free of snow or ice crystals, undisturbed cloud droplets generally remain liquid even at temperatures down to -10°C or colder, creating a common but unstable condition called supercooling. When a passing aircraft intercepts these droplets at temperatures below 0°C, they freeze nearly instantaneously to form ice on exposed and unprotected aircraft surfaces. Accumulated ice adds weight, increases drag, and decreases the aerodynamic efficiency of airfoils. The amount of ice that accumulates depends on the size, shape, speed, and temperature of the exposed object, and on in-cloud variables such as the liquid water concentration (LWC), the sizes of the cloud droplets, the air temperature along the flight path, and the duration of the exposure. Information on the range and frequency of occurrence of various values of these variables is obtained from instrumented research flights through these subfreezing clouds, which are the most common source of ice accumulation on aircraft in flight.

The first systematic measurements of cloud water content and of the sizes of unfrozen droplets at various temperatures and altitudes were collected on research flights over the United States in the late 1940s [1-5]. This was a cooperative effort by the U.S. Weather Bureau (WB) and the National Advisory Committee for Aeronautics (NACA). These original data are the basis of the currently accepted extreme value envelopes for these in-cloud variables, as promulgated in the Code of Federal Regulations (CFR) [6 and 7].

1.1.2 Extreme Value Envelopes for Supercooled Cloud Variables.

Title 14 CFR Parts 25 and 29 Appendix C (herein referred to as Appendix C), contain six figures showing (1) maximum probable LWC in supercooled clouds as a function of air temperature and a representative droplet size for clouds, (2) the range of air temperatures expected in icing conditions as a function of altitude, and (3) curves for adjusting the probable maximum LWC values according to the averaging distance (AD) of interest. These figures are reproduced here as figures 1-6, for ready reference. The first three figures, known as continuous maximum envelopes, are for stratiform type clouds. The next three, known as intermittent maximum envelopes, are for cumuliform clouds.

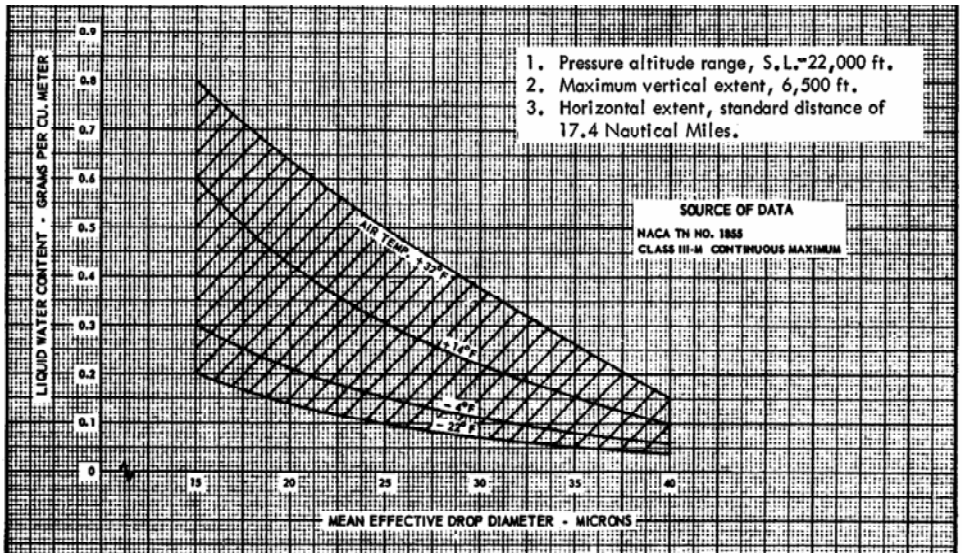

Figure 1. Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions (LWC versus mean effective drop diameter)

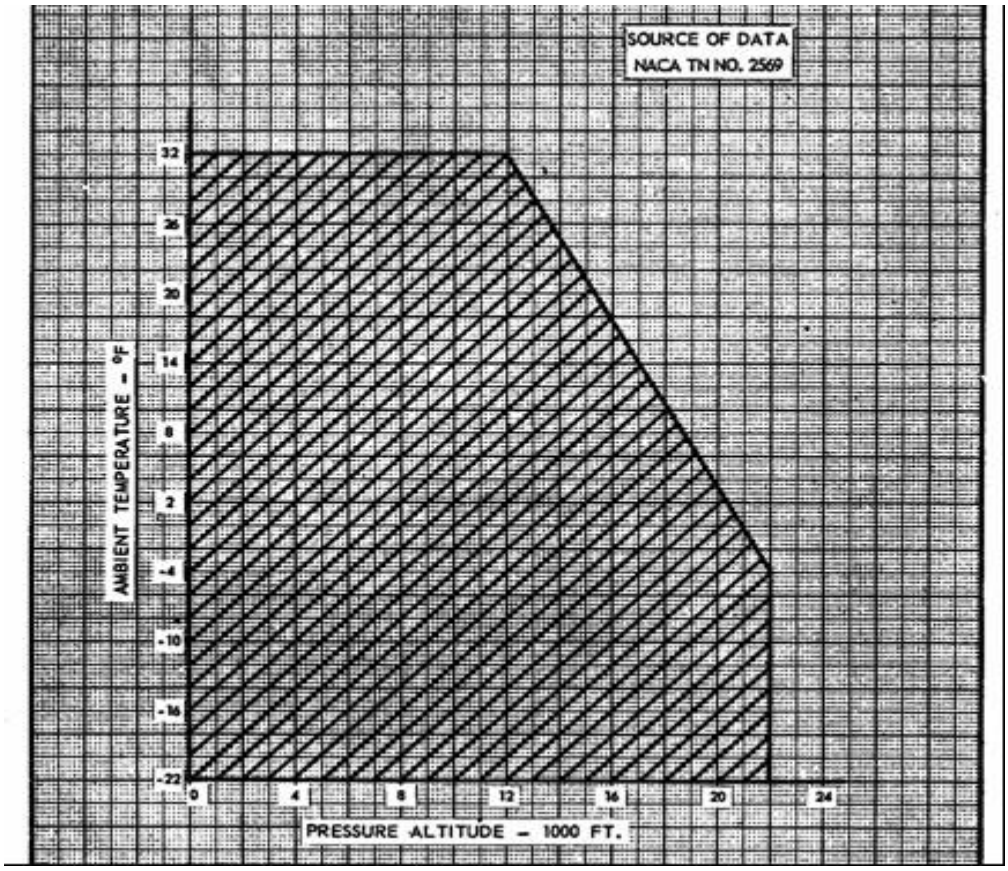

Figure 2. Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions (ambient temperature versus pressure altitude)

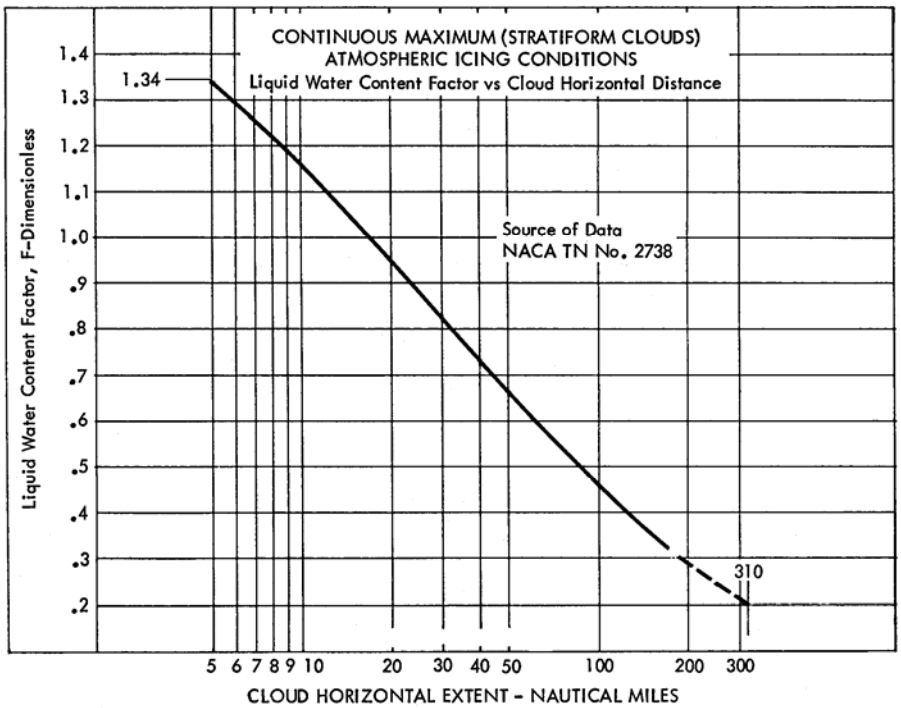

Figure 3. Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions (LWC factor versus cloud horizontal extent)

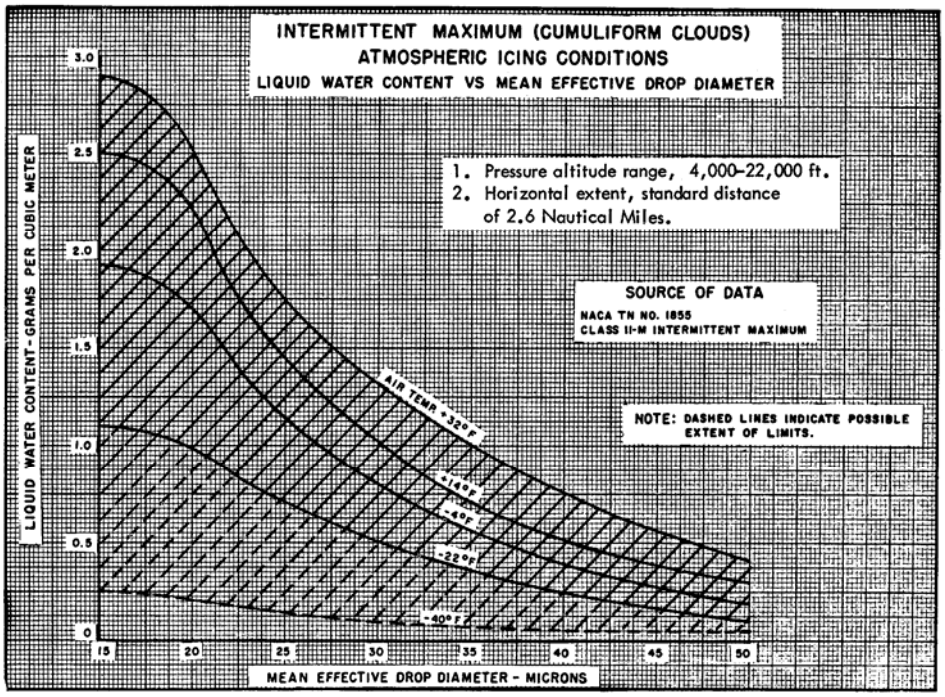

Figure 4. Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions (LWC versus mean effective drop diameter)

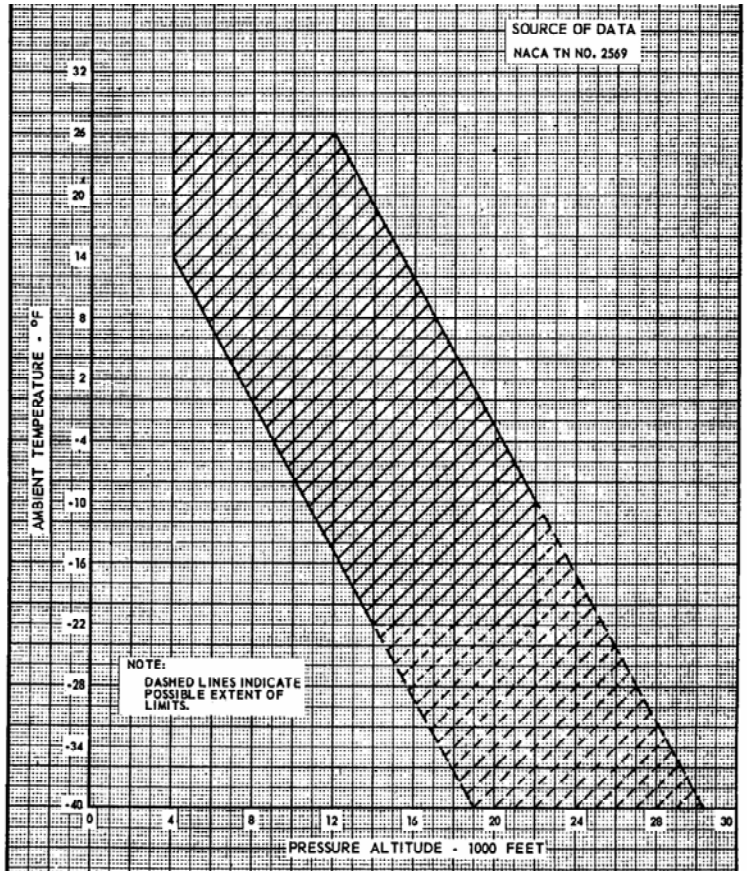

Figure 5. Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions (Ambient temperature versus pressure altitude)

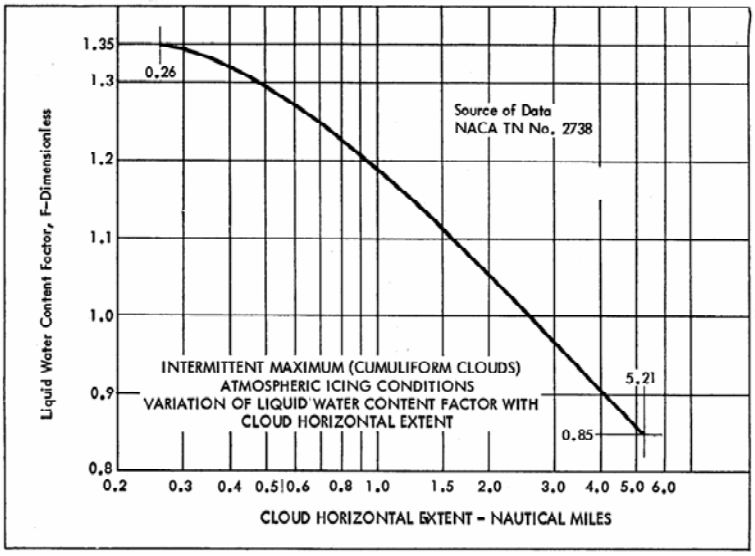

Figure 6. Intermittent Maximum (Cumuliform Clouds) Atmospheric Icing Conditions (Variation of LWC factor with cloud horizontal extent)

The Appendix C envelopes were originally proposed [2] in 1949 based on analyses of about 3,000 nautical miles (nmi) of airborne measurements in supercooled clouds[1] at altitudes to about 20,000 ft (6 km) over the United States during the winters of 1945 through 1948. Since that time, these envelopes have served as the accepted meteorological data for use in the design of ice protection equipment on civil transport category aircraft. They are also used for guidance in conducting icing wind tunnel tests and demonstration flights in the process of certificating aircraft for flightworthiness in icing conditions.

Experience over the past 40 years has given the LWC curves in figures 1 and 4 the reputation of being adequately conservative, but they do have some shortcomings as will be described below.

In the late 1970s, the helicopter community began calling for hoped-for relief from the large design values of LWC depicted in figures 1 and 4 by requesting new envelopes tailored to the lower altitudes where helicopters operate. There was also a general interest in re-evaluating the envelopes against new data being obtained from modern, electro-optical, cloud-probing instruments coming into use on meteorological research aircraft. As a result, a new data gathering and analyses effort was begun under Federal Aviation Administration (FAA) sponsorship. Approximately 28,000 nmi of supercooled cloud measurements, both old and new, have now been collected into a computerized database to answer these issues. Another 7000 nmi of measurements in glaciated (ice crystal and snow) clouds and 4700 nmi of measurements in freezing rain and freezing drizzle conditions have been collected to produce engineering design criteria for these icing environments. This comprehensive data compilation effort is the first of its kind since the late 1940s. An initial report on the supercooled cloud results for altitudes below 10,000 ft (3 km) was published earlier [8], followed by a suggested set of LWC extremes for this lower altitude range [9]. Other reports on the glaciated clouds [10] and various analyses of the supercooled cloud database [11] have been issued in the meantime. This report is intended to be the final data analysis report for supercooled clouds at all altitudes and worldwide conditions.

1.2 PURPOSE OF THIS STUDY.

The basic question for regulatory concerns is, do these graphs and curves in Appendix C need to be changed or updated? The primary goal of this research is, therefore, to comprehensively evaluate, with suggestions for possible improvement, figures 1-6, which have been used over the past 40 years for the design of in-flight ice protection equipment for aircraft.

2. THE BASIC VARIABLES.

To begin the analyses of the supercooled cloud database, it is instructive to examine the frequency of occurrence of different values of the basic cloud variables that are relevant to aircraft icing—i.e., supercooled liquid water content (SLWC), droplet size, air temperature, and horizontal extent (HE) of the icing clouds.

[1] This was from 167 icing encounters in layer clouds and 73 in cumulus clouds [12].

2.1 SUPERCOOLED LIQUID WATER CONTENT.

An important question has always been, What are the practical maximum values of SLWC that may be expected to occur, and how do they vary with cloud type, temperature, altitude, and HE? This can be answered in several ways, as described in the following sections.

The frequency of occurrence of SLWC over the range of observed values is given in figures 7 and 8 for layer and convective clouds, respectively. The plotted points give the number of nautical miles, according to the left-hand scale, recorded in the database for each 0.1 g/m^3 increment in LWC. The rationale behind using distance endured (data miles) as a measure of frequency is explained in appendix A of this report. The solid curve gives the cumulative frequency of occurrence according to the right-hand scale. The brackets above the SLWC axis indicate the range of HEs over which LWCs in that interval have been found.

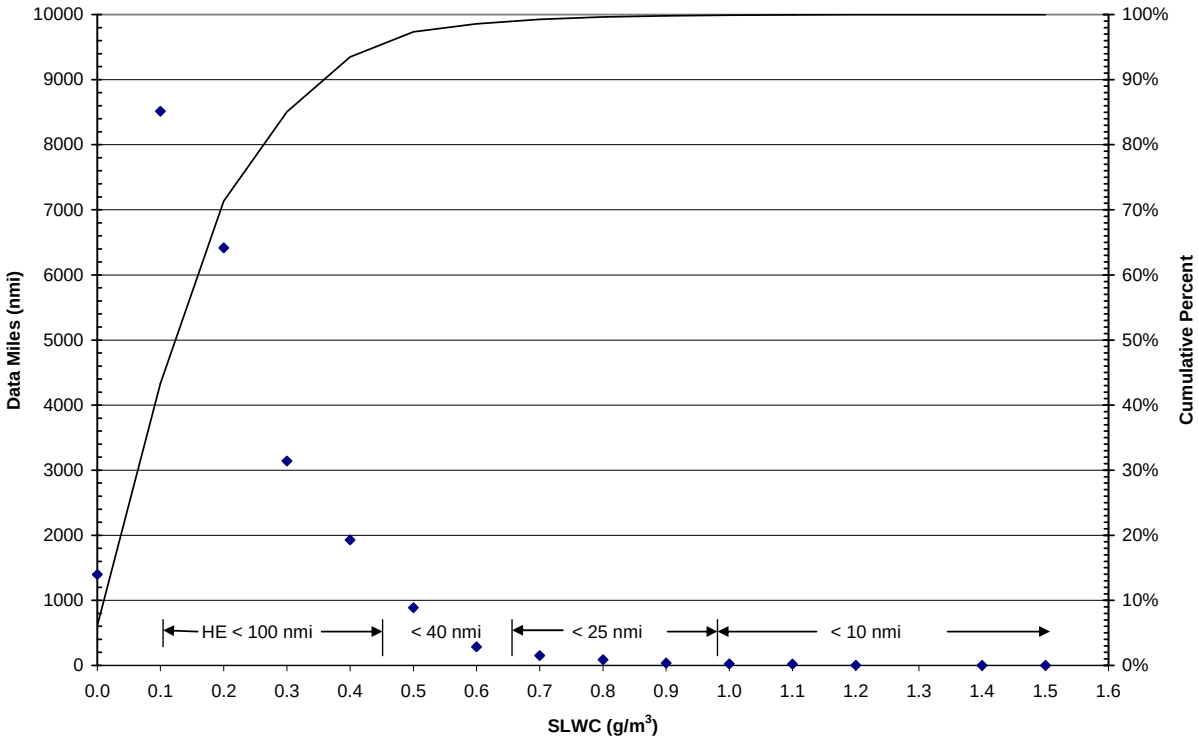

Figure 7. The LWC Frequencies in 23,000 nmi of Supercooled Layer Clouds

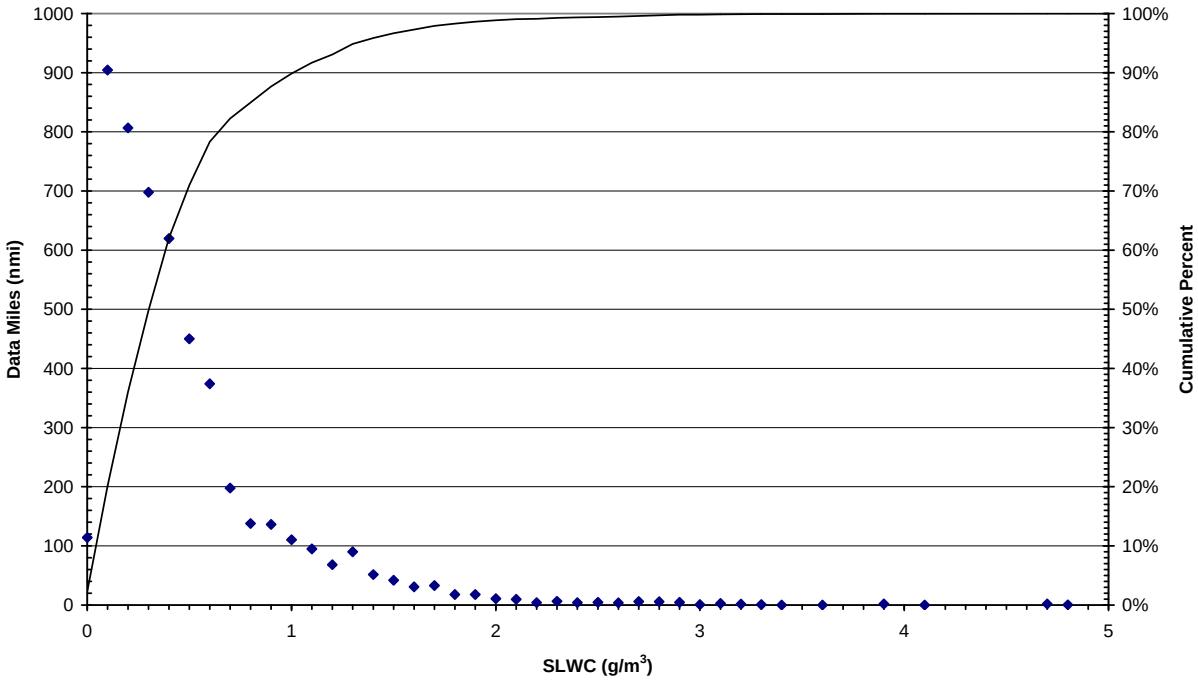

Figure 8. The LWC Frequencies in 5000 nmi of Supercooled Convective Clouds

2.1.1 Layer Clouds.

The maximum recorded values of SLWC in layer clouds are a few momentary (mostly less than 1 nmi in duration) patches of about 1.6 g/m^3, but 90% of the time, the SLWC is less than 0.35 g/m^3. Half of the time in layer clouds the SLWC is less than 0.1 g/m^3. Table 1 gives the breakdown in terms of time spent in layer clouds.

Table 1. The SLWC in 23,000 nmi of Layer Clouds

Percent of Time SLWC is Less Than Indicated	SLWC (g/m^3)	Temperature Range
50	0.12	0° to -40°C
90	0.35	0° to -20°C
95	0.45	0° to -20°C
99	0.65	0° to -20°C
99.9	1.0	0° to -15°C

Figure 9 shows the observed variation of SLWC with temperature. The largest SLWCs occur between 0° and -15°C, with maximum SLWCs decreasing more or less linearly with decreasing temperature below -15°C. The dashed lines in figure 9 are the SLWC values from the second column in the table. These allow construction of the third column, which shows the temperature range over which the SLWCs in the second column can be applied. At temperatures below the range listed in each row, the indicated SLWCs in the second column may be reduced linearly with temperature down to a minimum value of 0.1 g/m^3 at -40°C.

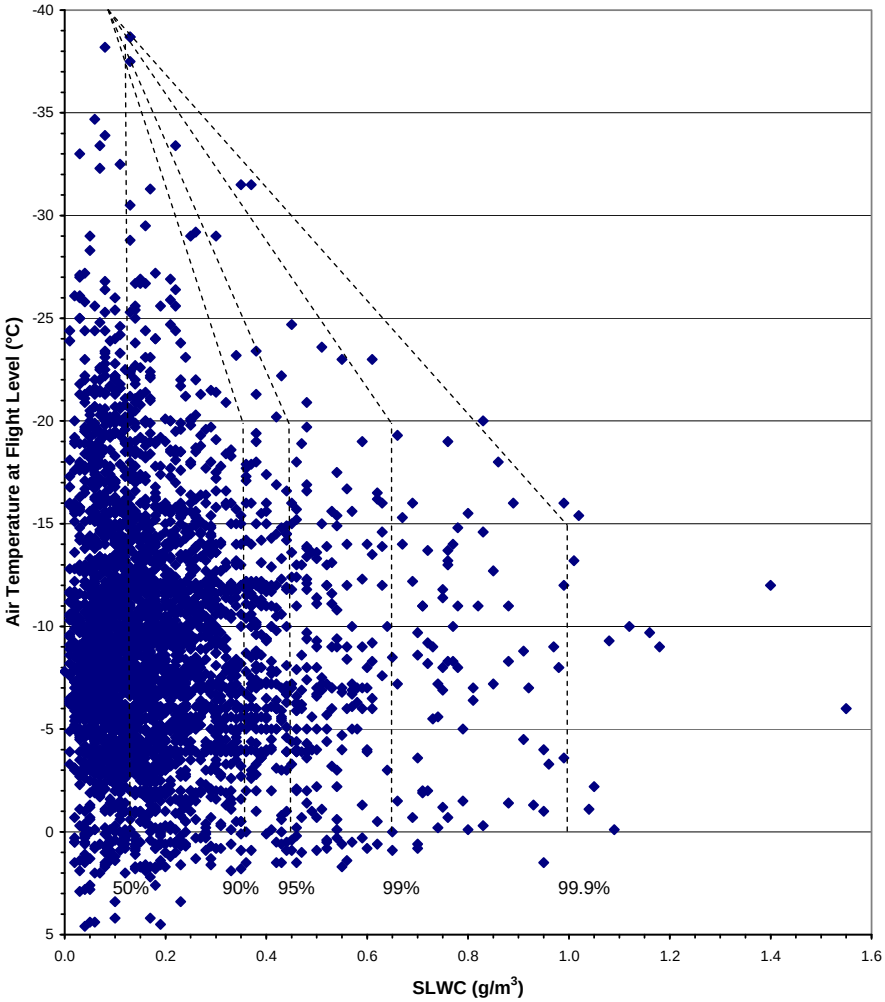

Figure 9. The 3500 Supercooled Layer Cloud Events, Regardless of Horizontal Extent (23,000 nmi contributing)

2.1.2 Convective Clouds.

The largest value of SLWC that has been documented in this database is a brief (0.2 nmi) 5.2 g/m^3, but 90% of the accumulated data miles are in SLWCs less than 1 g/m^3. Altogether, 99% of the time in convective clouds was in SLWCs less than 2.1 g/m^3, and 99.9% of the time it was less than 3.2 g/m^3, as shown in table 2.

Table 2. The SLWC in 5000 nmi of Convective Clouds

Percent of Time SLWC is Less Than Indicated	SLWC (g/m^3)	Temperature Range
50	0.3	0 to -30°C
90	1.0	0 to -20°C
95	1.3	0 to -20°C
99	2.1	0 to -20°C
99.9	3.2	-5 to -15°C

Figure 10 shows the observed variation of SLWC with temperature for convective clouds. The largest SLWCs occur between -5° and -20°C, with maximum SLWCs decreasing more or less linearly with temperature below -20°C. As before, the dashed lines in figure 10 are the SLWC values from the second column in the table. These allow construction of the third column, which shows the temperature range over which the SLWCs in the second column can be applied. At temperatures below the ranges listed, the indicated SLWCs in the second column may be reduced linearly with temperature down to a minimum value of 0.3 g/m^3 at -30°C.

Further explanation of these tables and their interpretation and use is given in appendix E.

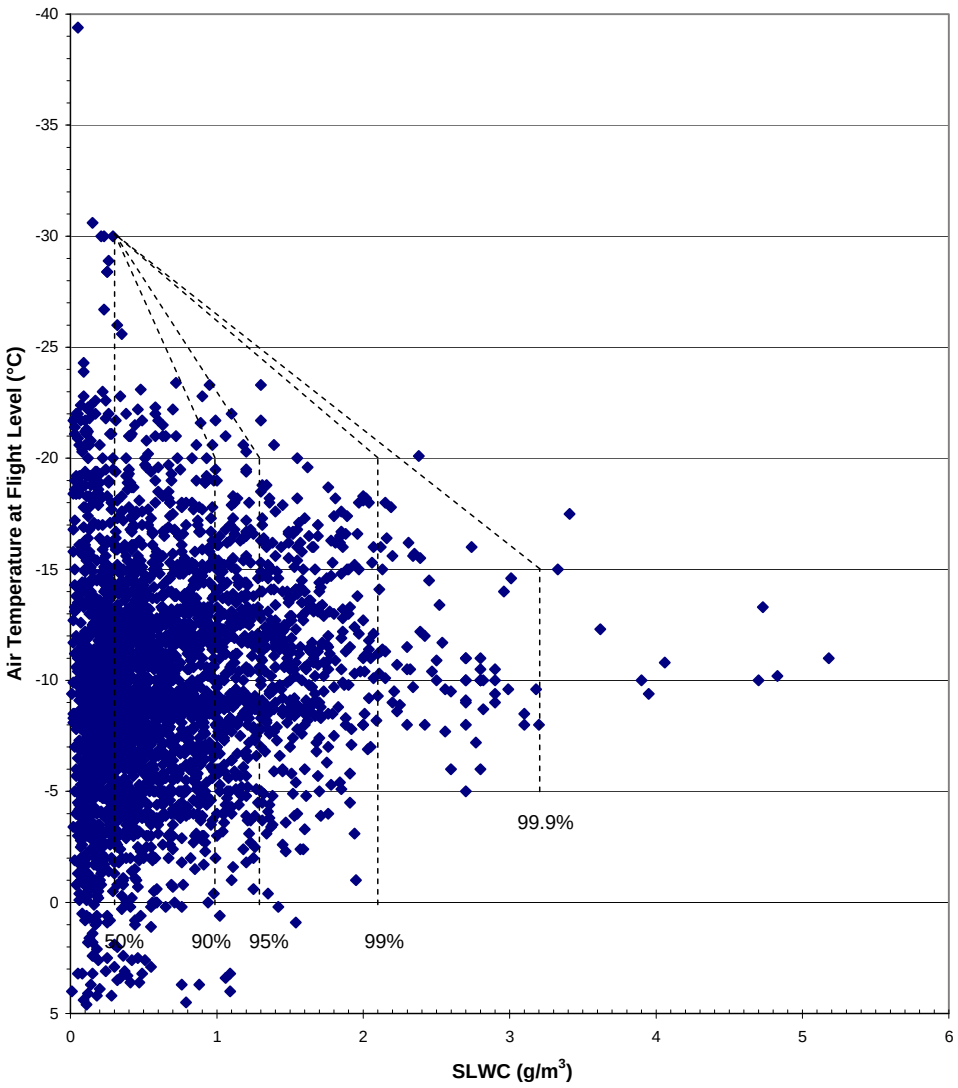

Figure 10. The 3200 Supercooled Convective Cloud Events, Regardless of Horizontal Extent (5000 nmi contributing)

2.2 DROPLET MEDIAN VOLUME DIAMETER.

Cloud droplets are routinely found in the size range of 1 to 50 µm, with the largest concentrations around 5 to 20 µm and few, if any, droplets found with diameters greater than about 50 µm (see figure B-1, for example). In some cases, droplets may be present in sizes up to 100 to 300 µm, but anything larger will fall out as precipitation unless sufficiently strong updrafts are present to keep such large droplets suspended.

It has been customary[2] in aircraft icing applications to represent cloud droplet populations by a single, size-related variable—the mass median, or median volume diameter (MVD). The MVD is useful because, for droplets smaller than about 100 µm in diameter, it has been shown to give the same ice accretions in computations as those using the full LWC versus drop size distributions. Thus, the MVD is a convenient simplification. It is the droplet size that equally divides the LWC associated with a given droplet size distribution. Half the LWC is in droplets smaller than the MVD and half is in droplets larger than the MVD.

The LWC versus MVD characterizations in Appendix C, (figures 1 and 4 of this report) allow for MVDs up to 50 µm, based on the original NACA data. The large droplets implied by such large MVDs are of special concern in some applications. For example, since both the catch efficiency and the percent of chord affected on a given airfoil increase with droplet size, the presence of large droplets will dictate the need for wider expanse of rubber boot for use in deicing the leading edge of wings. Therefore, the accuracy of any LWC versus MVD characterization can be important for large MVDs. As another example, currently available spray nozzles used in wet wind tunnels have a relatively long tail in the large end of the droplet size distribution they produce. It is commonly found that when the water pressure is adjusted to increase the LWC of the spray output, the increase in LWC is produced almost entirely from an increase in the number and/or size of the droplets in the tail of the distribution. This is an undesirable outcome if the resulting combination of LWC and MVD is outside the limits observed in natural clouds. These considerations focus attention on the larger values of MVD in the database.

Figures 1 and 4 imply that all MVDs in the range 15 to 40 µm are likely to occur with similar probability. This assumption can be tested with the data collected here. Figures 11-14 show the observed frequency of occurrence for MVDs in this range. Frequencies are expressed in terms of the number of nmi that have been recorded in the database for each increment in MVD. The solid curve is the cumulative frequency of occurrence according to the right-hand ordinate scale.

[2] The MVD is customarily used in American and western European practice, whereas the mean droplet diameter is customarily used in Russian practice [13].

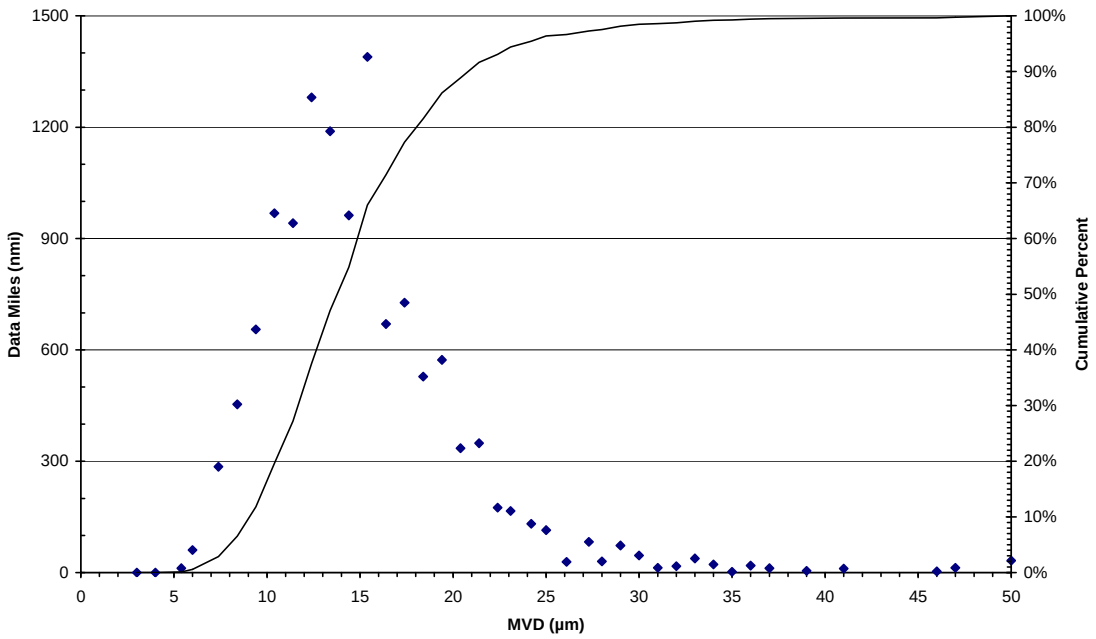

Figure 11. The MVD Frequencies in Supercooled Layer Clouds
(12,400 nmi contributing)

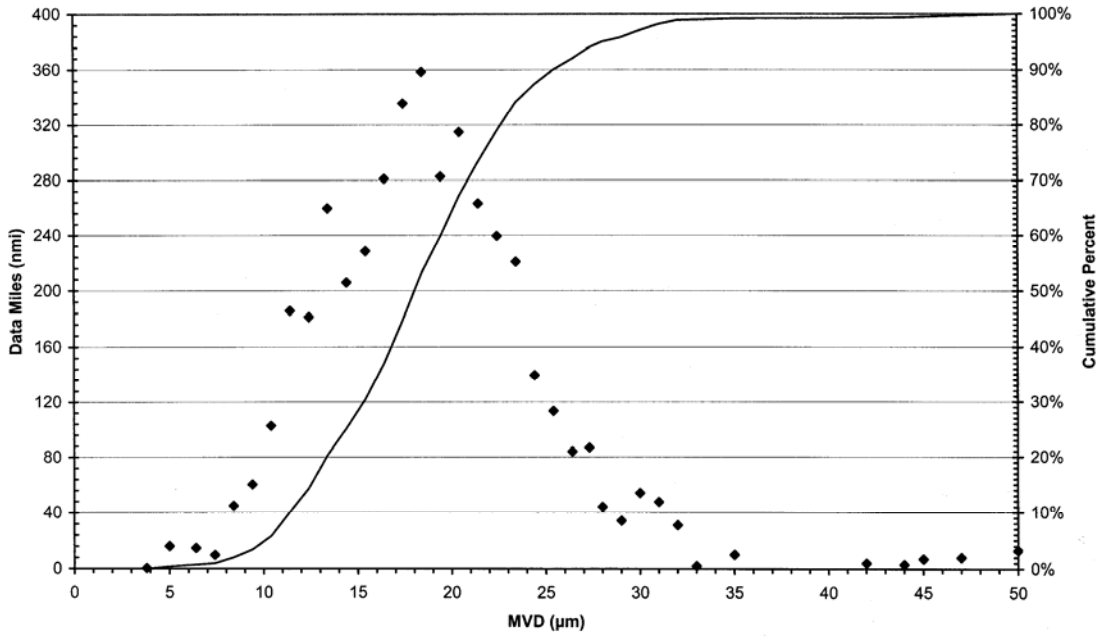

Figure 12. The MVD Frequencies in Supercooled Cumuliform Clouds
(4300 nmi contributing)

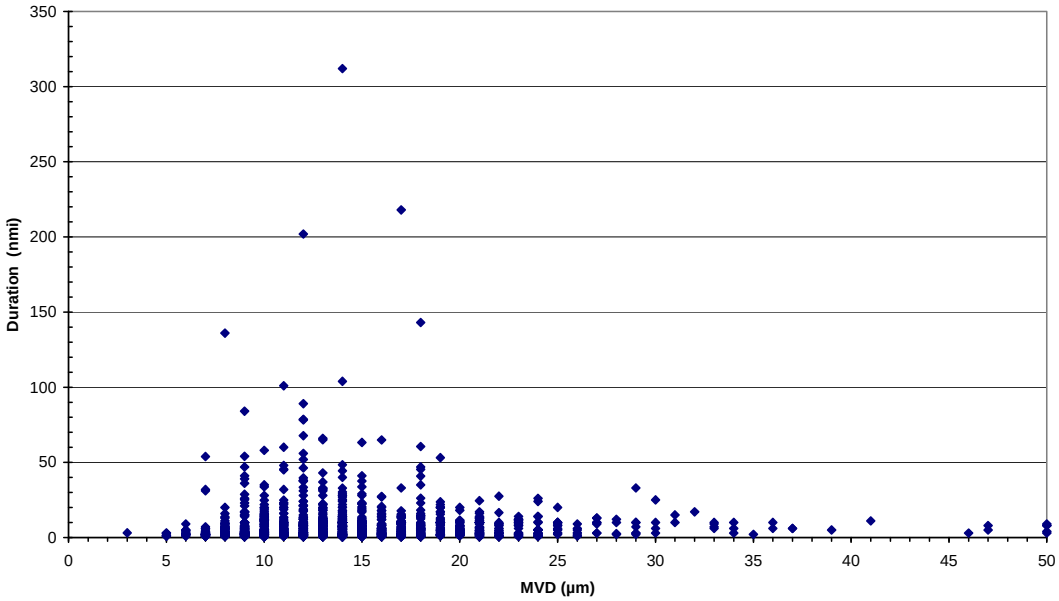

Figure 13. Duration of MVDs in Layer Cloud Icing Encounters
(13,700 nmi contributing)

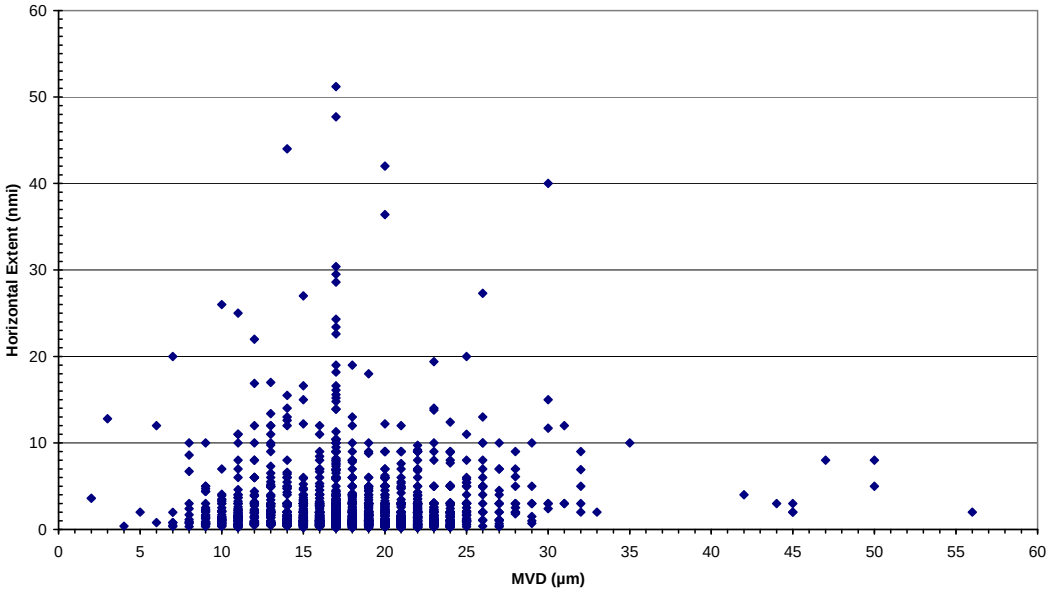

Figure 14. Duration of MVDs in Convective Cloud Encounters
(5000 nmi contributing)

It is clear that clouds have a strong preference for MVDs in the 10- to 25-µm range, with an apparent equilibrium near 15 µm. It is a common observation that MVDs increase gradually in this range with height from cloud base to cloud top. Small MVDs are found mostly in newly formed cloud parcels, such as at cloud base, where the droplet size distribution is still growing toward 15 µm. MVDs larger than 15 µm are from nearer cloud top or are from cloud parcels where drizzle-sized drops are present. In the latter case, once the drizzle falls out, the MVD reverts back toward 15 µm. Further conclusions for layer clouds and convective clouds are described as follows.

2.2.1 Layer Clouds.

Figure 11 shows that the mode (most frequent) MVD is about 15 µm. About 80% of all MVDs fall in the 10-µm interval from 10 to 20 µm. (About 50% of the MVDs are contained within a narrower 5-µm interval centered at 15 µm.) Only about 10% of MVDs are larger than 20 µm and about 10% are smaller than 10 µm. The few (1.5%) MVDs larger than 30 µm are probably due to occasional occurrences of freezing drizzle. This means that if drop sizes were not measured during icing test flights in natural layer clouds, one could safely assume that the MVD is within the 10 to 20 µm range with 80% confidence. On the other hand, about 55% of the MVDs are smaller than 15 µm. This means that if MVDs of 15 µm or greater are required during natural icing flight tests, to be within the range covered in Appendix C (figure 1), then about half of the flight time in icing conditions will be wasted because the available MVDs will be too small.

Another way of looking at MVD probabilities is shown in figure 15. There, the maximum probable LWC for various MVDs is displayed as well as the longest distance that a given combination of LWC and MVD can be expected to last. The larger the MVD, the shorter its HE and the rarer its occurrence. Obviously, MVDs near 15 µm are a preferred or equilibrium state for stratiform clouds, and are where LWCs can be the largest and last the longest.

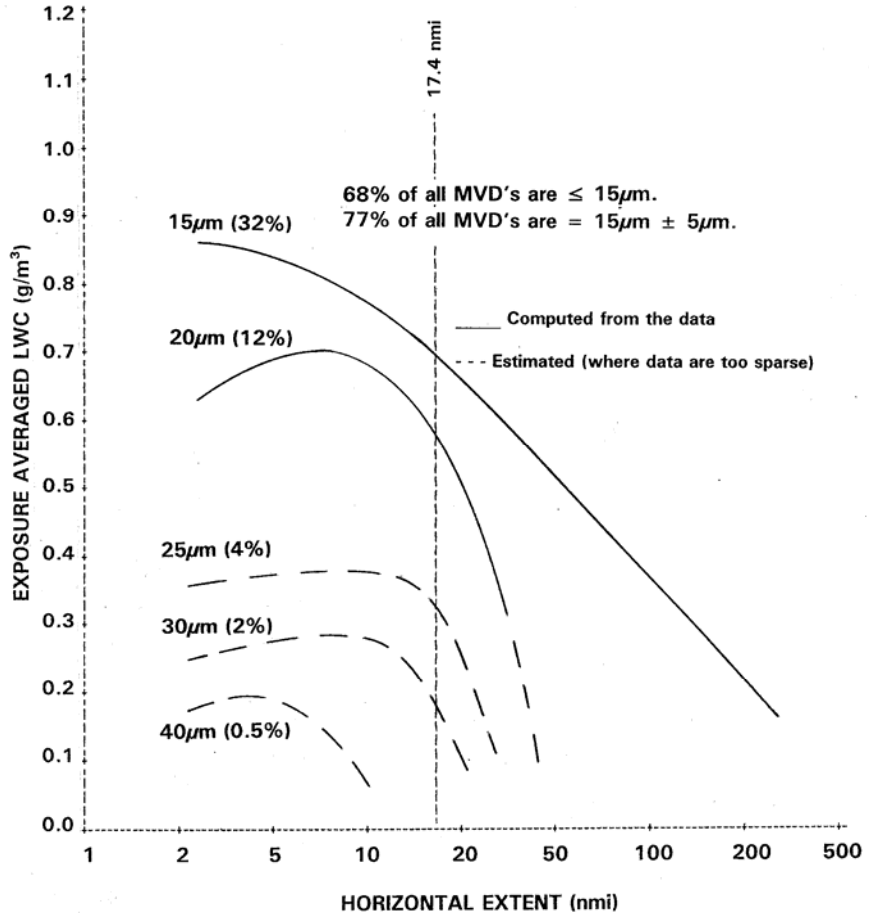

Figure 15. The 99th Percentile LWC for Icing Encounters With Different MVDs at 0° to -10°C in Stratiform Clouds (Curves will be lower for temperatures below -10°C. Percentages give the relative frequency of MVDs larger than the indicated value.)

2.2.2 Convective Clouds.

In this case, the MVDs are a little larger, and figure 12 shows that the mode (most frequent) MVD is now about 18 µm. About 80% of all MVDs fall within the 13 µm interval from 12 to 25 µm. (About 50% of the MVDs are confined to the narrower 7-µm interval centered at 18 µm.) Only about 10% of MVDs are larger than 25 µm and about 10% are smaller than 12 µm. The few (3%) MVDs larger than 30 µm are probably due to drizzle-sized drops forming in strong updrafts in some of these convective clouds. This means that if drop sizes were not measured during icing test flights in convective clouds, one could safely assume that the MVD is within the 12- to 25-µm range with 80% confidence. In convective clouds, about 25% of the MVDs are smaller than 15 µm. This means that if MVDs of 15 µm or greater are required during natural icing flight tests to be within the range covered in Appendix C (figure 4), then about 25% of the flight time in icing conditions will be wasted because the MVDs will be too small.

2.2.3 Large Droplets.

The MVDs 35 µm and larger represent only 1% of all the data miles in the entire database, or 0.5% of all the events.

Obviously, in freezing drizzle or freezing rain, the MVD and the entire precipitation droplet size distribution will be quite large. Typical droplet sizes are 100 to 500 µm for drizzle and 0.5 to 3 mm for freezing rain. Freezing rain drops are really melted snow flakes or melted ice crystals that have fallen through an elevated warm air layer and then back into subfreezing air below that. Such large unfrozen droplets do not exist above the freezing level in the originating cloud, except occasionally in some large and strongly convective cloud systems.

Modern, laser-based, cloud droplet size spectrometers are capable of continuous, high-resolution measurements of droplet size distributions. The Particle Measuring System (PMS) forward scattering spectrometer probe (FSSP) droplet probes cover the diameter range of 2 to 30 µm or 3 to 45 µm. In most cases, the entire supercooled droplet population is confined to these ranges. The PMS 1D-C or 2D-C probes cover the diameter range of 20 to 300 µm or 25 to 800 µm, respectively. In most clouds above the freezing level, the only particles detected by these probes are ice crystals, if anything.

In this database, the only modern data with supercooled droplets in the range 50 to 300 µm diameter are those few that have been identified in some flights by the University of Wyoming in the Sierra Cooperative Pilot Project (SCPP) in California and by the German Aerospace Research Establishment in Germany. These encounters with unusually large supercooled droplets resulted in dramatic reductions in performance by the aircraft, but in spite of the large droplets, the MVD remained less than 35 µm. This result has called into question the use of the MVD alone to characterize the droplet size distribution when drizzle is present. In these Wyoming flights, the presence of the large droplets was apparently much more important than the MVD could indicate. It may be necessary to document the actual droplet size or LWC distribution when large droplets are present. Or perhaps at least a maximum droplet size should be reinstated as attempted by the original NACA researchers.

It may be possible that other cases of large droplets have gone undetected in some of the modern flights, since not all of the research aircraft carried a 1D-C or 2D-C probe. As a result, the LWC versus MVD envelopes (figures 1 and 4) in the region beyond 35 µm should be considered as uncertain, at least, and subject to further study.

2.3 THE SLWC VERSUS MVD.

Figures 11 and 12 show that MVD occurrences peak sharply about the mode values of 15 and 18 µm for layer and convective clouds, respectively. But what about the LWCs? At what MVDs do the largest LWCs occur? Figures 16 and 17 show the results. For convective clouds (figure 17), the largest LWCs appear to occur at MVDs near the mode—between 20 and 25 µm. That is, the most common MVDs also contain the largest LWCs, and the LWCs decline rather sharply either side of the mode MVD. For stratiform clouds (figure 16), the distribution of the largest LWCs is wider, although taking into account the frequencies of occurrence in figure 11, most of the time spent in the larger SLWCs is still in the vicinity of the mode MVD.

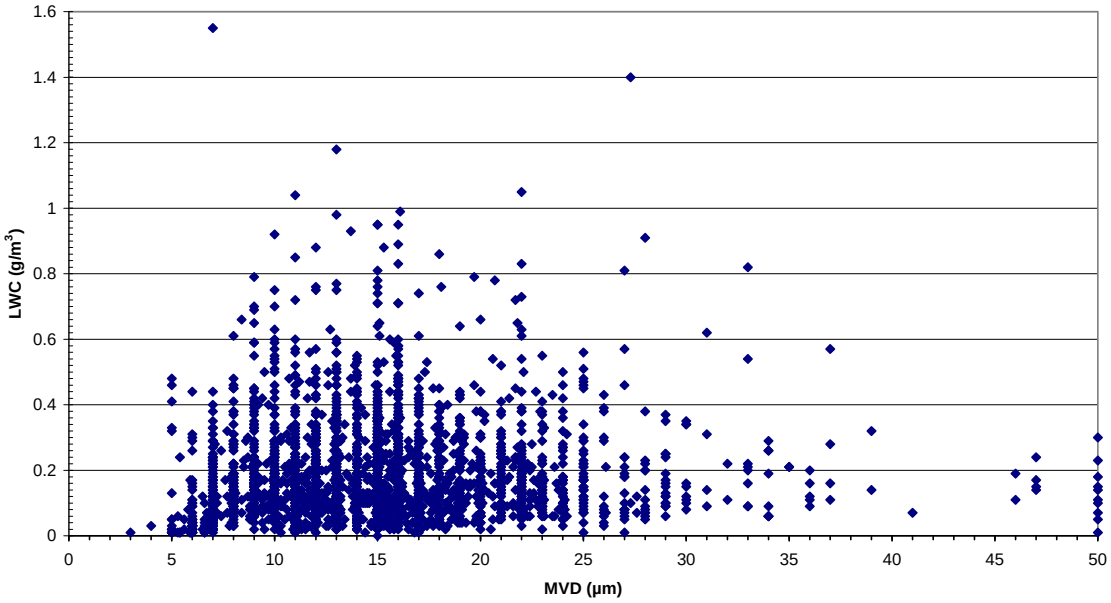

Figure 16. Layer Cloud Icing Events for all Temperatures Regardless of Horizontal Extent (12,400 nmi contributing)

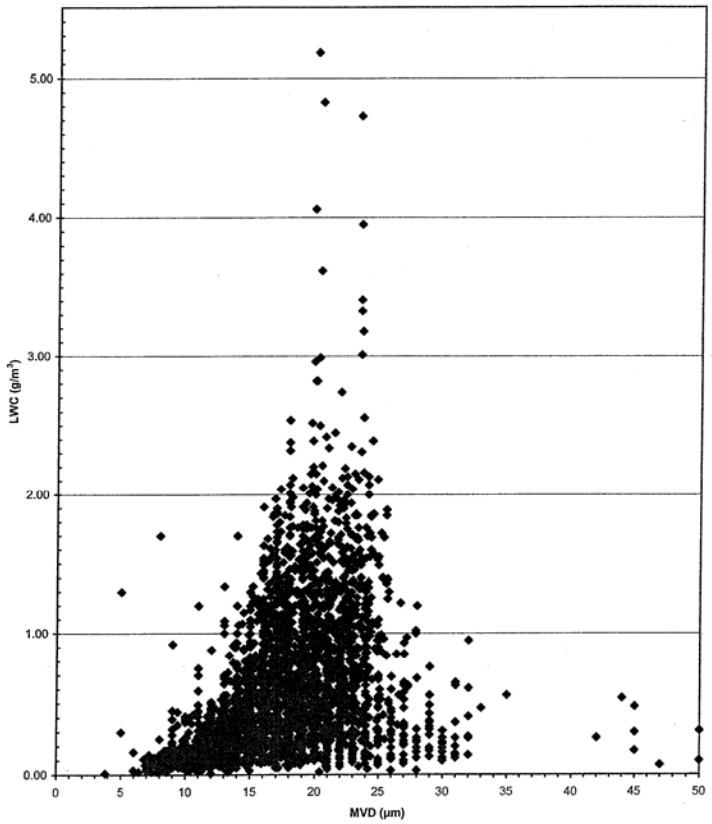

Figure 17. Cumuliform Cloud Icing Events for all Temperatures Regardless of Horizontal Extent (4300 nmi contributing)

2.3.1 Implications for Natural Icing Test Flights.

The results shown in figures 16 and 17 mean that if drop sizes were not measured during the flights, one can be confident that the largest LWCs will only occur for MVDs between about 15 and 25 µm for convective clouds. In fact, any LWC greater than 1 g/m^3 is practically a guarantee that the MVD is between 15 and 25 µm, or an LWC greater than 0.5 g/m^3 is an indication that the MVD is larger than about 13 µm.

2.3.2 Implications for Design and Computations.

Figures 11 through 17 indicate that one needs to be mainly concerned about MVDs in the range of 10 to 20 µm for layer clouds and 10 to 25 µm for convective clouds. These can be termed the critical MVD ranges. MVDs above or below these ranges are infrequent, and the LWCs there are small. Figures 13, 14, and 15 show that MVDs larger than 35 µm do not last very long anyway—less than 10 nmi each occasion. So, systems designed for the larger SLWCs in the critical MVD ranges should be more than adequate for the occasional and brief passage through larger MVDs, except for freezing rain and possibly for sustained freezing drizzle[3]. However, MVDs larger than about 30 µm may increase the roughness of the ice accretions.

2.4 AIR TEMPERATURE.

The frequency of occurrence of various icing event temperatures[4] is given in figures 18 and 19. The air temperatures recorded in the database are most frequently in the range of about -5° to -15°C. The lowest temperature for any event in the database is about -39°C for both convective clouds and layer clouds.

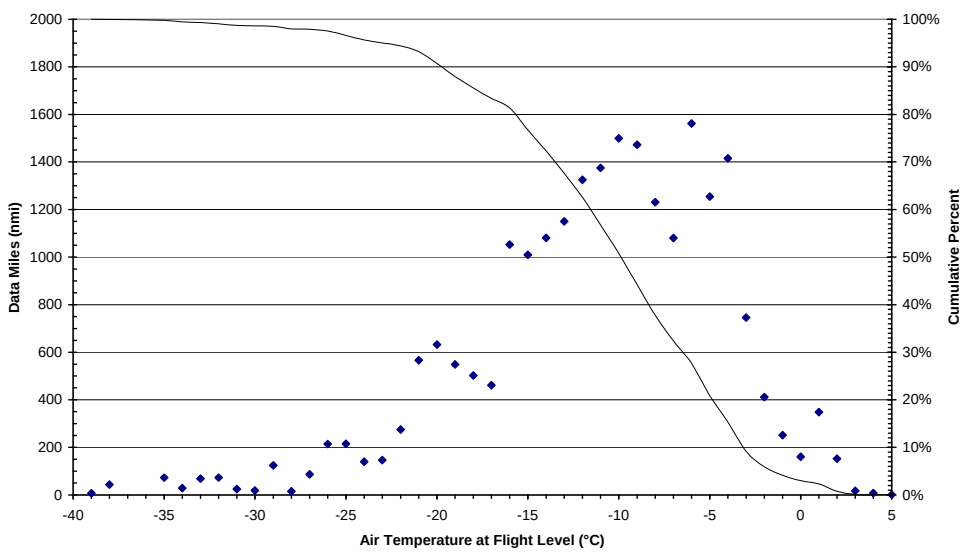

Figure 18. Air Temperature Frequency for Layer Clouds in the Database (23,000 nmi contributing)

[3] At this writing, American and European airworthiness authorities are considering freezing drizzle and freezing rain for separate treatment as icing conditions of concern.

[4] These are true air temperatures, sometimes called static or outside air temperature (OAT) and not total or indicated air temperatures.

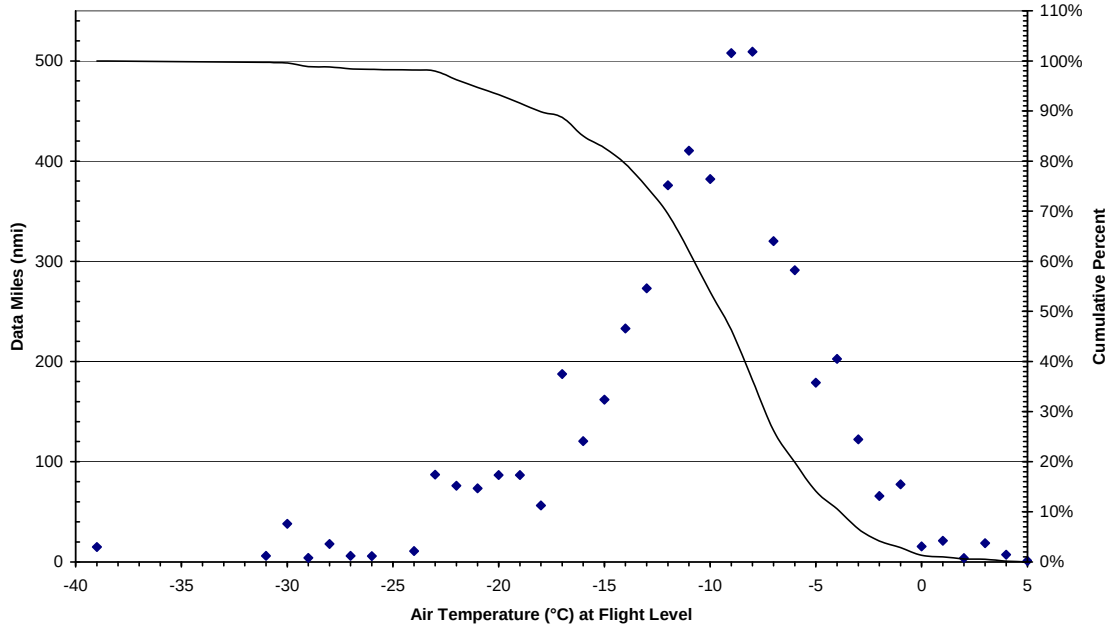

Figure 19. Air Temperature Frequency for Convective Clouds in the Database (5050 nmi contributing)

To some extent, the frequencies of occurrence seen among the various variables in the database do not represent the natural frequencies of occurrence that would result from truly random samples in the atmosphere. There are some sampling biases such as described here for the temperature data.

Figures 18 and 19 show that a majority of the samples occurred at temperatures in the vicinity of -10°C. This result is partly due to the popularity of the -10°C flight level among researchers in cloud seeding (weather modification) experiments. About 35% or more of the modern data came from cloud seeding projects.

Figures 18 and 19 also show that only about 10% of the samples occurred at ambient air temperatures above -3°C and 10% below -20°C. The shortage of data at temperatures between -3° and 0°C is due to the intentional avoidance of this temperature regime by both the modern and the NACA flights. The NACA researchers required lower temperatures to avoid runoff or shedding of ice from their rotating cylinder devices. The low frequency of measurements at temperatures below -20°C is due to the difficulty in finding clouds that have not already glaciated at those temperatures. Clouds that are composed entirely of snow or ice crystals (i.e., no supercooled droplets) are not considered here. Reference 10 describes 7000 nmi of measurements obtained separately for characterizing these snow and ice crystal clouds.

2.5 HORIZONTAL EXTENT.

The horizontal extent of icing conditions is of interest for at least four reasons. One is the obvious need to know how long an aircraft may be exposed to icing conditions at various temperatures and SLWC amounts so that adequate anti-icing or deicing equipment can be designed. Another is for the simulation of icing conditions in wet wind tunnels where the operators need to know how long to expose a test object to a given spray setting of SLWC and MVD. A third application is the

numerical modeling of the buildup of ice shapes on surfaces. Here, the computer program needs to know how long various combinations of SLWC and MVD typically persist before changing to different values in natural clouds. And finally, icing flight test crews need to know how long the icing exposures must be to qualify as acceptable tests.

In practice, HEs of icing encounters can be anything from a few hundred meters to hundreds of nautical miles. The wide range of values is shown in figures 20-22.

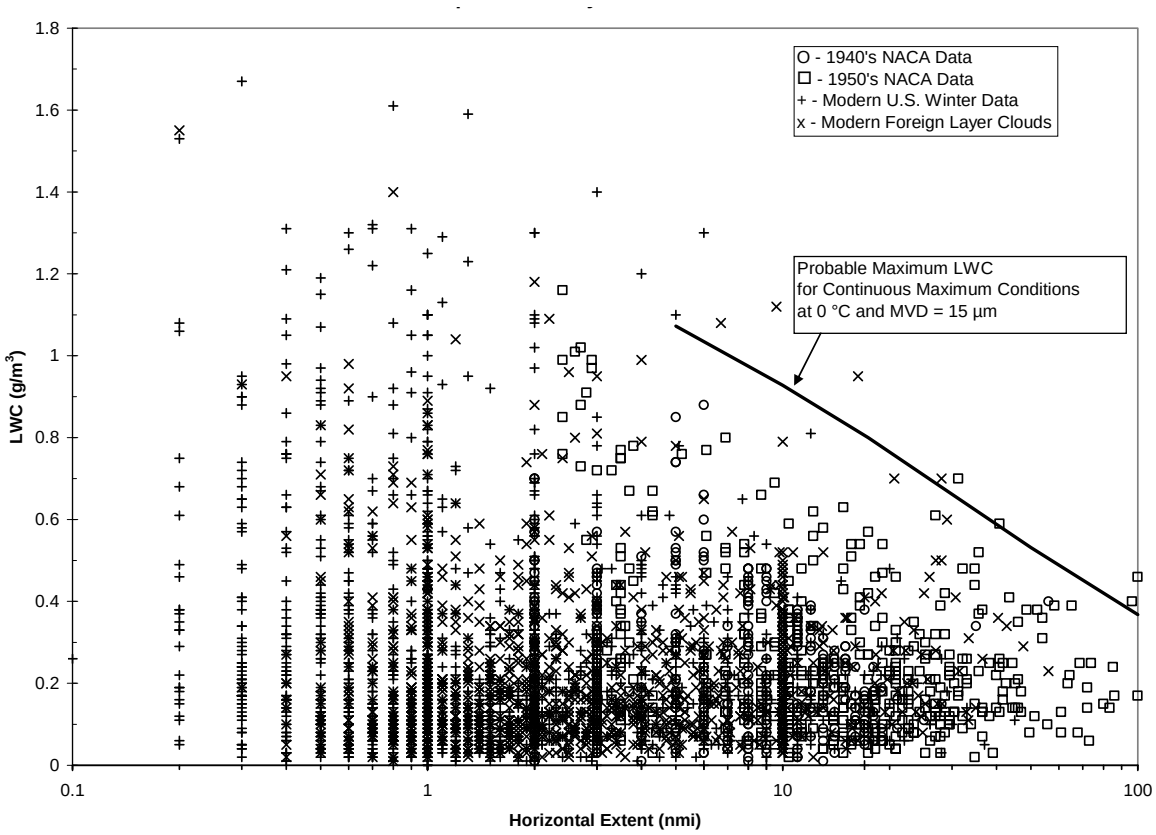

Figure 20. The 3500 Supercooled Layer Cloud Events

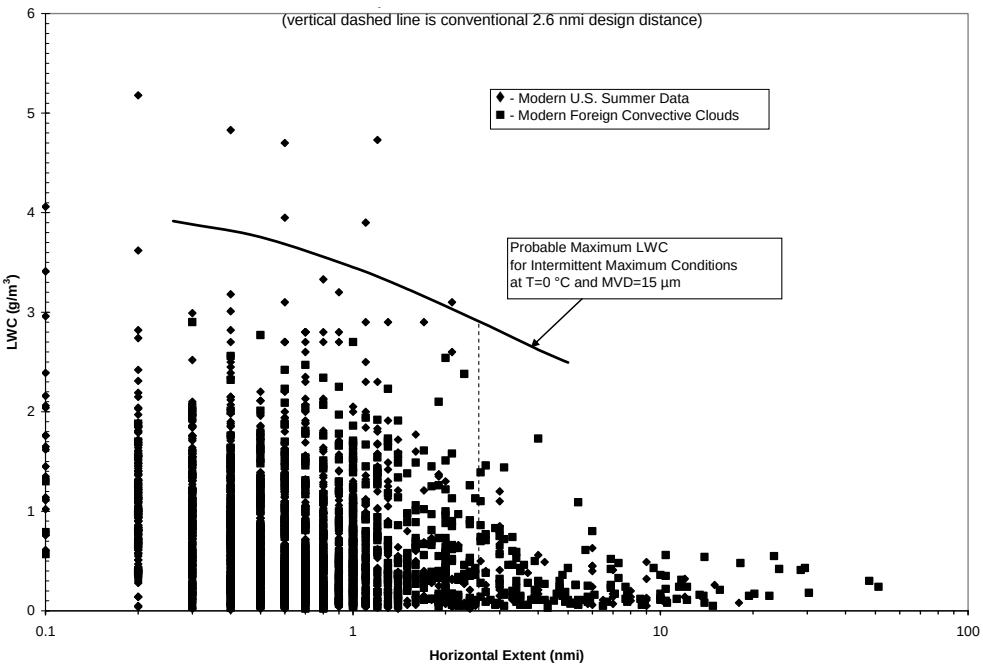

Figure 21. The 3200 Supercooled Covective Cloud Events
(Vertical dashed line is conventional 2.6-nmi design distance.)

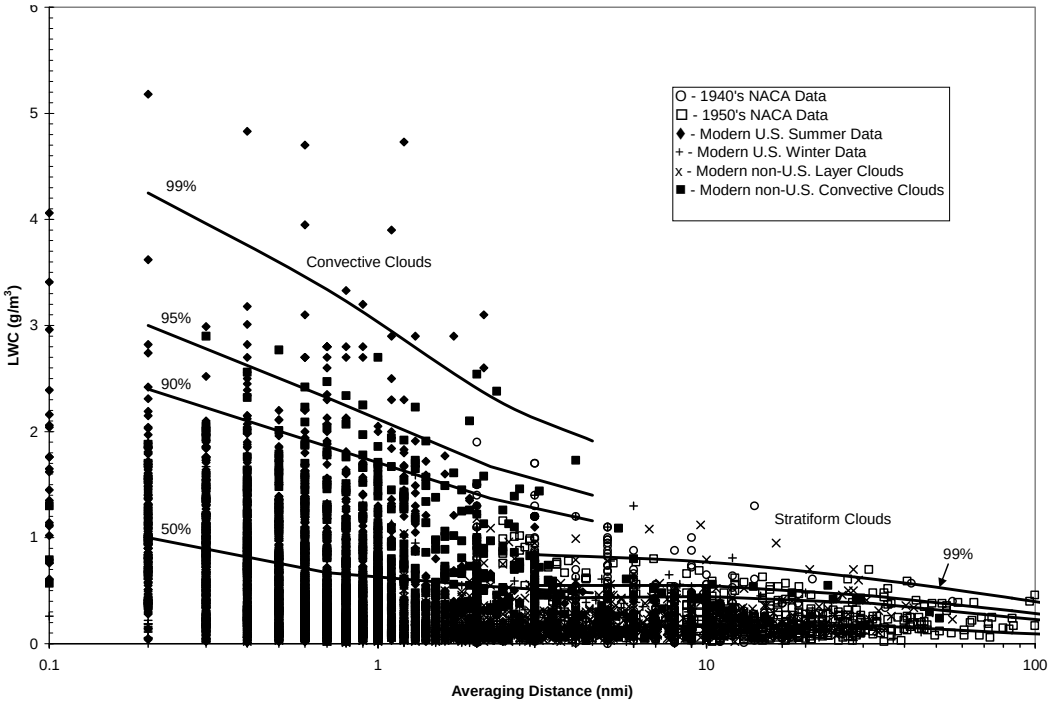

Figure 22. The Entire Supercooled Cloud Database
6700 Icing Events Totaling 28,000 nmi in Icing Conditions
(LWCs greater than 1.6 g/m^3 are from convective clouds.)

2.5.1 Conventional Design Distances.

The existing Appendix C envelopes (figures 1 and 4) were built around a fixed design exposure of 17.4 nmi for layer cloud exposures and 2.6 nmi for convective cloud exposures. Other design distances can be chosen, if needed, to fit particular applications, and figures 3 and 6 were provided to enable the user to adjust the design values of SLWC in figures 1 and 4 to match other exposure distances. These distance-based adjustments have already been incorporated into the LWC curves added to figures 20-26.

The precise distances of 2.6 and 17.4 nmi are not that important. The LWC values that the NACA researchers originally recommended for design use [2] are simply assigned to these distances for reference purposes. But some pilots have interpreted these distances to mean that icing certification is limited to exposures no longer than that. They wonder whether in-service exposures longer than these reference distances exceed the certification limits for the airplane and are therefore illegal, dangerous, or at least risky. Some icing practitioners have attempted to construct realistic design scenarios by postulating sequences of alternating intermittent (2.6 nmi) and continuous (17.4 nmi) cloud intervals. The original intent of the NACA recommendations was that the LWC design values should be considered to apply to indefinitely long (i.e., continuous) exposures, for layer clouds at least.

The confusion gets worse when icing test flight exposures are being evaluated. Some question whether icing exposures shorter than the reference distances qualify for certification credit. Some try to compensate for low LWCs during flight tests by flying longer than the reference distances in the available icing conditions.

Some argue that for testing thermal ice protection systems, it is only necessary to fly in the available icing conditions until the surface temperatures of the protected components stabilize. Then, if the available heat is adequate, the system is considered to be satisfactory for any duration, at least for temperatures no colder and LWCs no greater than the tested values.

For testing pneumatic boots, some crews continue in icing conditions until a 0.5 inch or more of ice builds up. This is to ensure that the boots can remove such an amount and that the airplane can fly without problems before the boots are activated.

For unprotected surfaces, a 45-minute exposure or a 3-inch ice accumulation seems to be the current norm, so the reference distance does not even apply.

2.5.2 Demonstrated Icing Protection Zones.

For purposes of documenting and interpreting the significance of icing test exposures, users can simply block out areas of figures 20-26 over which the ice protection system has been demonstrated to be adequate [11]. For example, a 50-nmi exposure at 0.2 g/m^3 would cover all shorter exposures at all lesser LWCs and all warmer temperatures, too. Graphically, this could be shown by blocking out the lower left-hand section of any of figures 20-26, for example, up to 0.2 g/m^3 and out to 50 nmi. Figure 23 shows that particular example. Other exposures at other average LWCs over other distances can be added, as available, to broaden the area of coverage.

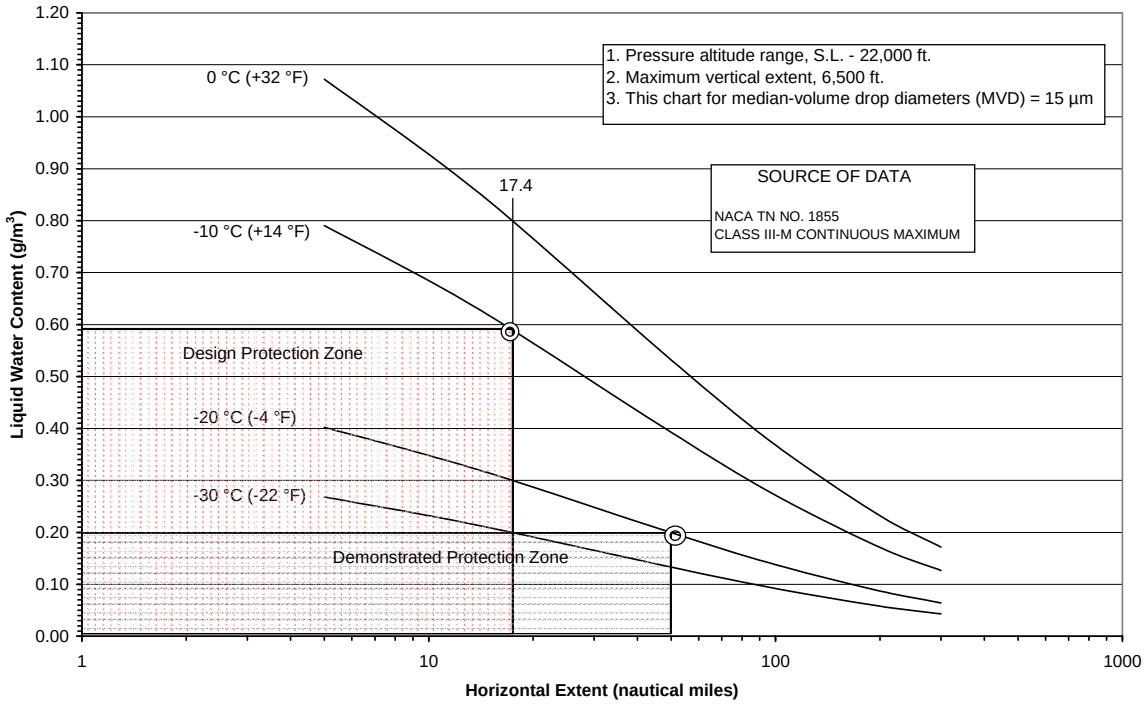

Figure 23. Example of Indicating Protection Zones on Continuous Maximum Envelopes

3. COMPARISON WITH APPENDIX C ENVELOPES.

The standards of comparison are still the six sets of curves, or envelopes, incorporated in Appendix C [6 and 7]. For convenience, the six figures in Appendix C are reproduced here as figures 1 through 6, in the same order. These figures summarize the range of values of supercooled cloud variables to be considered in the design of ice protection equipment for aircraft. The curves in figures 1 and 4 depict probable maximum values of LWC to be expected as an average over a fixed, standard distance in layer and cumuliform clouds, respectively, at the indicated flight level temperatures. Figures 2 and 5 outline the range of temperatures to be expected in icing conditions aloft. Figures 3 and 6 provide adjustment curves for use in converting the LWC values shown in figures 1 and 4 to values appropriate for HE other than the standard distances. All curves and envelopes are based on data obtained in the U.S. during the late 1940s [1-5]. Because of the larger amount of data that has been compiled here now, it is of interest to compare this whole new collection of measurements with the envelopes and curves in figures 1-6.

3.1 THE SLWC VERSUS MVD ENVELOPES AND THE LWC ADJUSTMENT CURVES.

The principal sets of envelopes in Appendix C are the curves depicting maximum probable LWC as a function of MVD for 10°C intervals of ambient temperature (figures 1 and 4). LWC versus MVD were already plotted in figures 16 and 17, but these cannot be compared directly with the envelopes in figures 1 and 4. This is because the latter are drawn specifically for 20- (17.4-nmi) and 3-mile (2.6-nmi) averages, respectively, whereas the data points in figures 16 and 17 are from a wide range of different averaging distances (ADs). It is not possible to legitimately convert most of these to an equivalent 17.4 or 2.6 nmi average to compare them with figures 1 and 4.

The only correct way to compare these data with Appendix C is by means of distance-based plots as shown in figures 20-26. There, LWCs can be easily plotted without having to adjust them to match the standard ADs. The probable maximum curves for LWC in figures 1 and 4 are combined with the distance adjustment (F-factor) curves in figures 3 and 6 and show up as the curves drawn in figures 20-26.

Notice in figure 6 that the LWC adjustment curve for cumuliform clouds applies only to HEs up to 5 nmi. Longer distances are covered by the curve for layer clouds (figure 3). Nevertheless, figures 20-22 show that some of the cumuliform cloud events are, in fact, longer than 5 nmi, and many of the layer cloud events are shorter than 5 nmi.

Figure 22 is a composite of figures 20 and 21. Figure 24 is a composite of figures 1 and 4. This side-by-side presentation gives a useful perspective to the comparison of the LWC behavior of the short and long HEs.

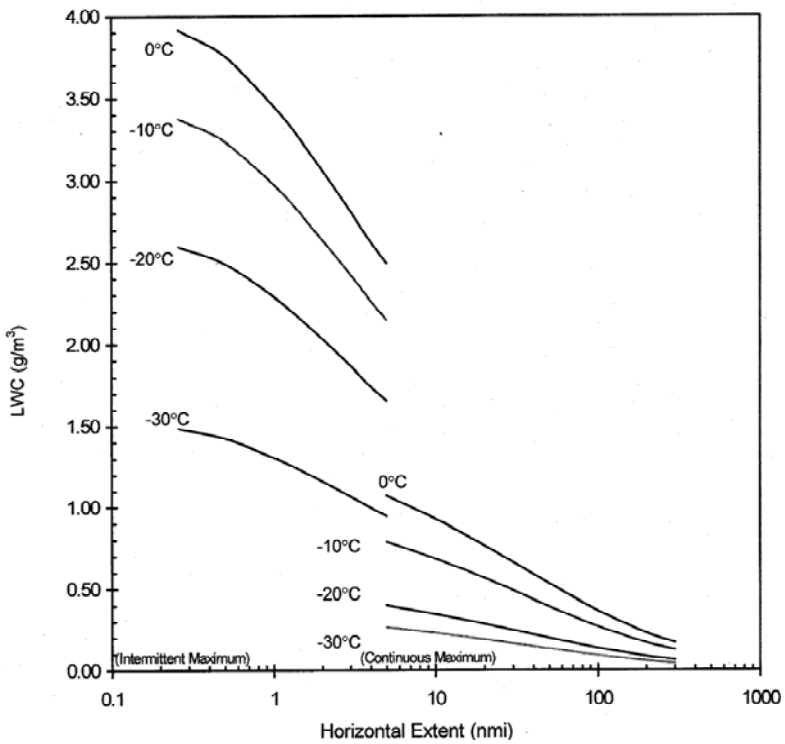

Figure 24. Appendix C Envelopes Converted to a Distance-Based Format
(for MVD = 15 µm) (Logarithmic HE scale)

3.1.1 Layer Clouds.

The probable maximum LWC curve for 0°C in figure 1, as adjusted for distance per figure 3, is constructed in figure 20 by first positioning the largest expected LWC (i.e., 0.8 g/m^3 from figure 1) at the 17.4 nmi point on the graph. The LWC adjustment curve (figure 3) is then used to plot the fractional LWC to be expected, according to the 1940s data and analyses, at other HEs between 5 and 300 nmi. (The reader may consult reference 11 for more details on how this is done.)

The curve in figure 20 appears to be in reasonable agreement with the largest observed LWCs, both in magnitude as well as in its slope or curvature, except for a few events that lie above the curve. More detailed comparisons are given in appendix D, where a refined analysis of the larger dataset now available reveals the following differences with the figure 1 curves. In particular:

- Temperature dependence: According to the modern database, the extreme LWCs do not decrease with temperature in the 0° to -10°C range (figure D-2), contrary to figure 1.

- 99th percentile LWC values: The curves in figure 1 were originally estimated [8 and 5] to be 99th percentile values, but the reanalyses here shows them to be sometimes greater (figure D-3) and sometime less (figure D-4) than the actual 99th percentile values.

- HEs: At the colder temperatures (<-20°C), the actual HEs are less than anticipated by figure 3 (see figure D-5).

3.1.2 Recommendation for Consideration.

As a result of these differences, refinements to the figure 1 (or figure 24) LWC envelopes are proposed in figure 25. These new curves are more realistic and their adoption would update the current design criteria in Appendix C. The old figures may not be seriously flawed, but they are overconservative in some details and underconservative in others.

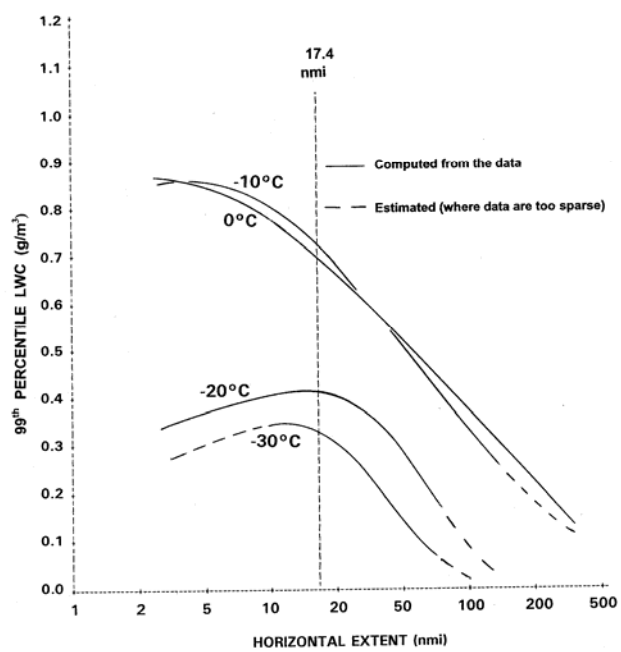

Figure 25. Natural 99th Percentile Limits to LWC (and HE) for 10°C Temperature Intervals in Stratiform Clouds With Average MVDs (10 to 20 µm)

3.1.3 Convective Clouds.

The probable maximum LWC curve from figure 4 for cumuliform clouds at 0°C is compared with the available data in figure 21. More detailed comparisons are given in appendix D, where a refined analysis of the larger dataset now available reveals the following differences with the figure 4 curves. In particular:

- Temperature dependence: The LWC does not decrease with temperature in the 0° to -10°C range (figures D-6 to D-9), contrary to figure 4.

- 99th percentile LWC values: Nevertheless, the curves in figure 4 consistently overestimate the 99th percentile values (figures D-6 to D-10), except when summertime convective clouds are included for temperatures of -10°C and colder (figures D-9 and D-11).

- HEs: In all cases, the actual exposures in convective icing conditions can extend up to ten times longer than the 5-nmi limit anticipated by figure 6.

For convective clouds, it must be decided whether or not to include summer clouds in the mix. Practically all LWCs above about 2 g/m^3 are from summer convective clouds and these obviously skew the distribution highly for HEs shorter than about 2.5 nmi.

Refinements to the curves in figure 4 (or figure 24) are proposed in figure 26, where summer and nonsummer clouds are accommodated separately. For the most part, all 99th percentile LWC curves are lower than the intermittent maximum curves of Appendix C. That is, the existing intermittent maximum curves are more conservative and correspond more closely to the 99.9^{th} percentile values of LWC than 99th percentile values. More detailed comparisons are given in appendix D. If 99th percentile LWCs are desired for design criteria, then the new curves in figure 26 are a better approximation. The lower set of curves (i.e., summer clouds excluded) in figure 26 are appropriate for helicopter and other operations below 10,000 feet in altitude.

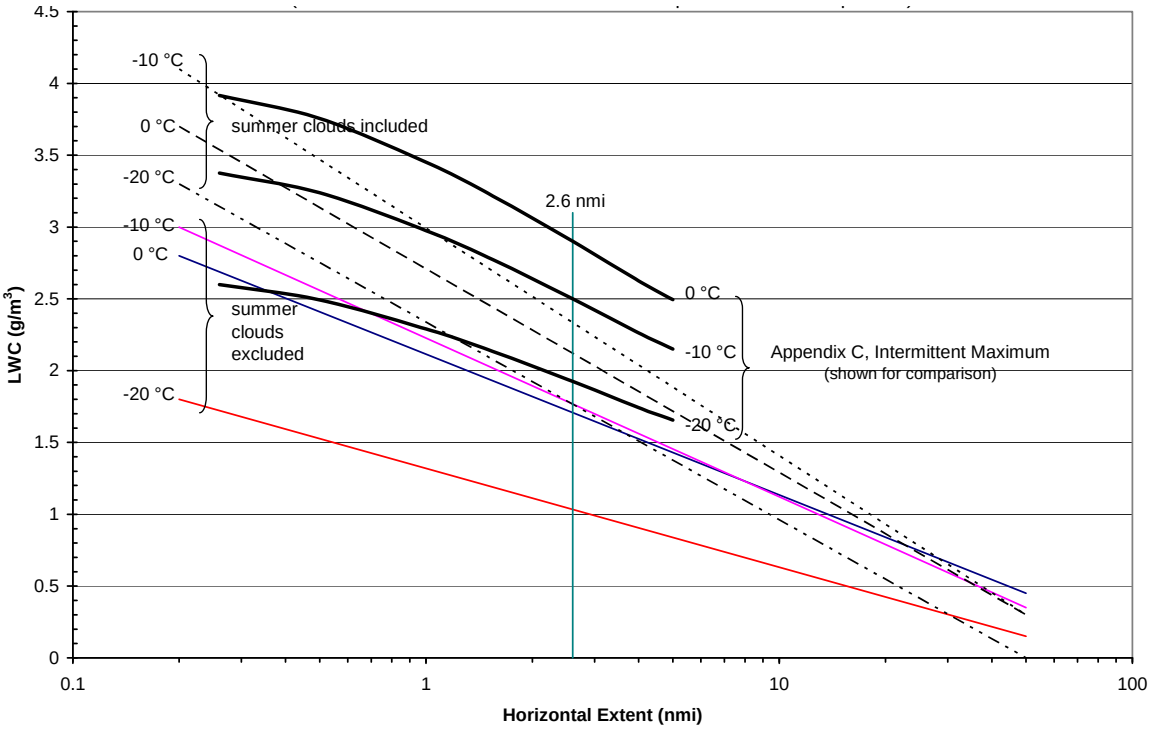

Figure 26. The 99th Percentile LWCs for Icing Encounters in Convective Clouds With MVDs = 15-25 µm
(Intermittent maximum curves for MVD = 15 µm shown for comparison.)

3.1.4 Recommendation for Consideration.

For most design purposes, it would be adequately conservative to compute water catch rates or ice accretions using a single representative drop size from the upper end of the critical MVD ranges, which would be 20 µm for layer clouds and 20 or 25 µm for convective clouds. This is in conformity with both Western and Russian [13] conventional practice, which mostly ignores the full range of MVDs anyway and regularly uses just 20 µm for computational purposes.

Reducing the drop size selection to a single value for design purposes would simplify the design criteria by eliminating figures 1, 3, 4, and 6, and replacing them with either of three possibilities instead:

a. Figure 24 consolidates figures 1, 3, 4, and 6 into a single, distance-based graph for a fixed value of MVD. Maximum values for LWC can be picked off figure 24 for any exposure distance and temperature of interest.

b. Figures 25 and 26 are similar to figure 24 except that 25 and 26 use newly computed 99th percentile values of SLWC from the enlarged database. Due to the better statistics, these limiting curves are more realistic than those currently in Appendix C (and figure 24).

c. The SLWC frequency tables 1 and 2 are a new approach based on the overall SLWC averages in the database. These simple tables have the following advantages:

- They are independent of horizontal extent. Thus, in both a 10- and 100-nmi exposure in layer clouds, statistically speaking, 99% of the distance is expected to be spent in SLWCs less than 0.65 g/m^3, 90% in less than 0.35 g/m^3, and so on.

- They avoid the problem of uncertain interpolation between 10°C temperature curves in the other figures. Each percentile value of SLWC applies to a relatively wide range of temperatures. Below the indicated temperature range, the SLWC values can be reduced in a simple linear fashion with decreasing temperature.

- They apply to MVDs in the critical range of 15 to 25 µm and are, therefore, compatible with the conventional practice of reducing the drop size selection to a single value of 20 µm.

- They permit a selection of SLWC percentiles for added versatility. Civil practice will probably be limited to 99th percentile values, but military users have always wanted more freedom to reduce the SLWC requirements if weight or power tradeoffs made that desirable.

In any case, impingement limits can still be computed using 40- or 50-µm-diameter droplets as is the current practice.

3.2 TEMPERATURE VERSUS ALTITUDE ENVELOPES.

Figures 2 and 5 contain envelopes that enclose the temperatures observed by the NACA and WB researchers in the 1940s in icing conditions at pressure altitudes up to 22,000 ft. In figures 27-35, these envelopes are superimposed on scatterplots of all the in-cloud temperatures recorded in the database for supercooled layer and cumuliform clouds, respectively.

3.2.1 Layer Clouds.

It is seen in figure 27 that all temperatures less than 0°C fit nicely within the envelope except for a number of points below the depicted limits and a few points to the right of the envelope. These outlying points are all from the NACA-instrumented commercial and weather reconnaissance flights of the early 1950s. The points below the envelope are all wintertime data from the North Atlantic, North Pacific, Alaska, or the Arctic Ocean north of Alaska. They represent LWCs up to 0.35 g/m^3. These data all have in common the fact that they occurred at far north locations outside the conterminous (or contiguous) United States (CONUS). They were also collected after publication of the NACA report [4] upon which these temperature versus altitude envelopes are based.

Further examination of the figure shows that in-cloud temperatures less than -10°C have practically never been observed at pressure altitudes below about 2000 ft.

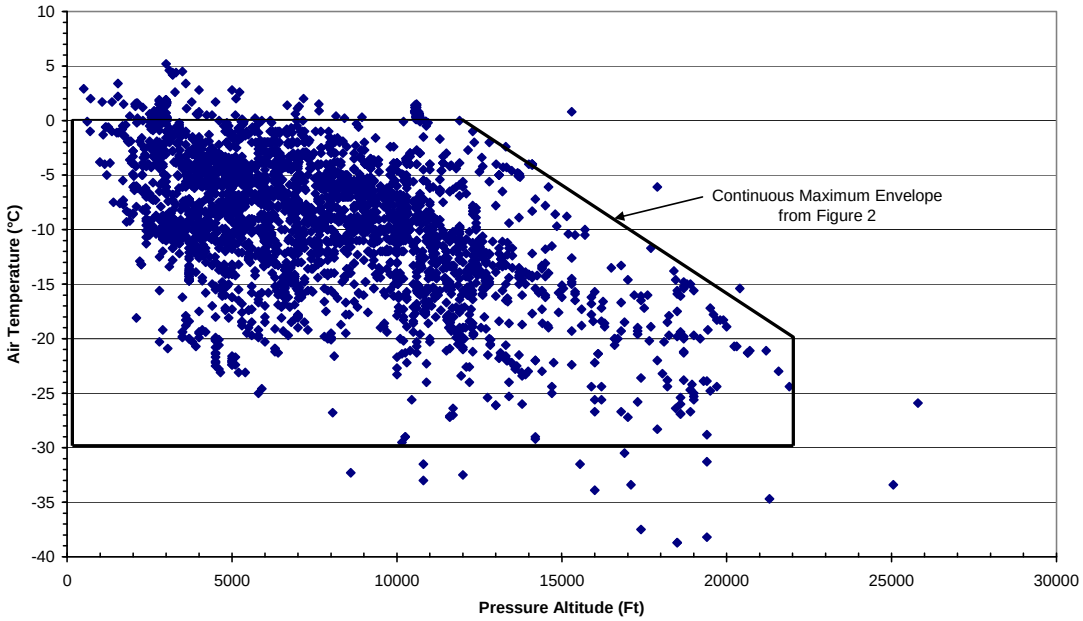

Figure 27. Observed Icing Events in Layer Clouds
(22,900 nmi contributing)

3.2.2 Suggested Extensions to the Envelope.

The conclusions are that if the temperature versus altitude envelope for layer clouds is to represent worldwide conditions, then the envelope should be extended to -40°C to include the far north data available from the later NACA flights [15]. In addition, the left side of the envelope could be trimmed to more closely outline the observed temperatures at the lower altitudes. Thirdly, there have been suggestions that the envelope be extended up to +3°C (+37°F) or so, considering the possibility of icing in engine inlets due to cooling of the intake air by 3°C or more by expansion during suction. These suggested extensions are shown in figure 28.

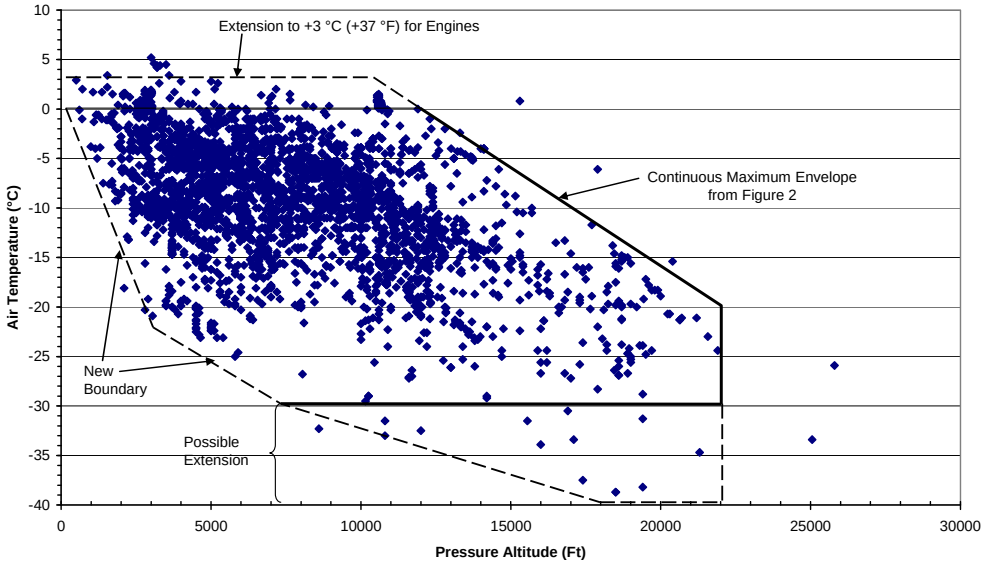

Figure 28. Proposed Extension of Temperatures Versus Altitude Envelope for Continuous Maximum Conditions

Alternatively, simple curves representing the average, observed, in-cloud temperatures versus altitude can also be presented for each season separately. Figure 29 shows these for stratiform clouds. The seasons in this case are defined in terms of the local freezing level height, as will be discussed in section 4.1.2.

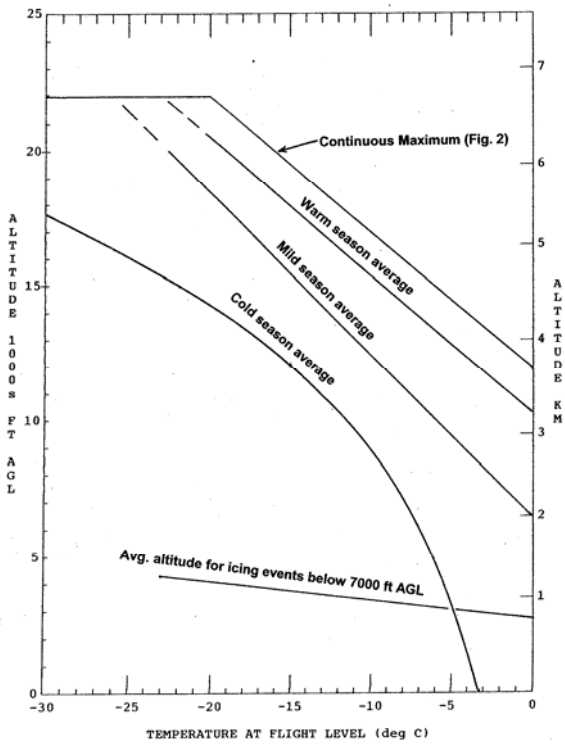

Figure 29. Average Temperature Versus Altitude AGL for Layer Cloud Icing Events

3.2.3 Convective Clouds.

Figure 30 shows all the temperature measurements in convective clouds superimposed on the temperature versus altitude envelope from figure 5. An abundance of points lie outside the accepted envelope, mostly above and to the right (high altitude) side of the envelope at temperatures above -25°C. Figures 31 to 33 have been added here to help analyze these outliers further. Figures 31 to 33 contain data exclusively from winter, spring, and summer cumuliform clouds, respectively. Together they show that all outlying points are from summer or mild season clouds (figures 32 and 33). The winter data fall almost entirely within the envelope except at the top (figure 31). The outliers are from the modern measurements, almost exclusively. The reason is simply that few NACA flights took place in warmer weather clouds because the primary interest at that time was in wintertime icing conditions.

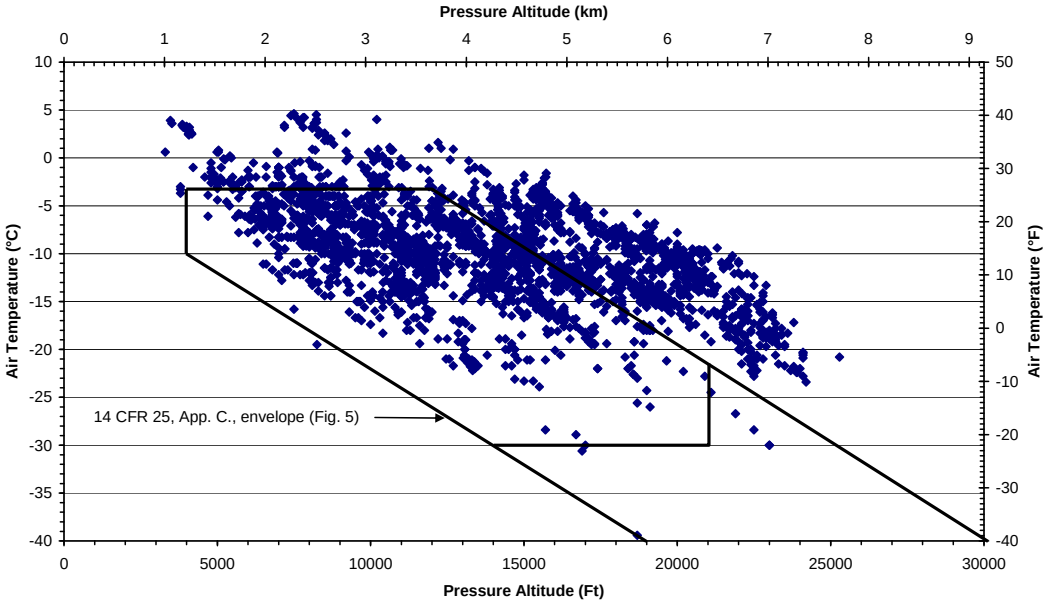

Figure 30. Convective Cloud Icing Events From all Seasons
(5000 nmi contributing)

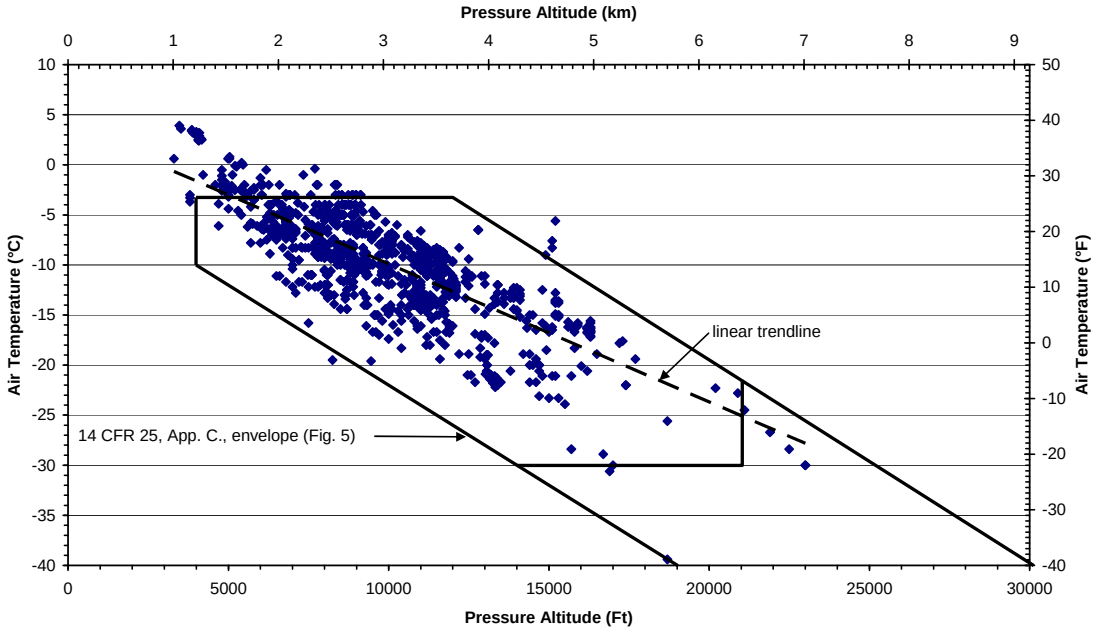

Figure 31. Convective Cloud Events for Cold Season (Winter) Only
(2930 nmi contributing)

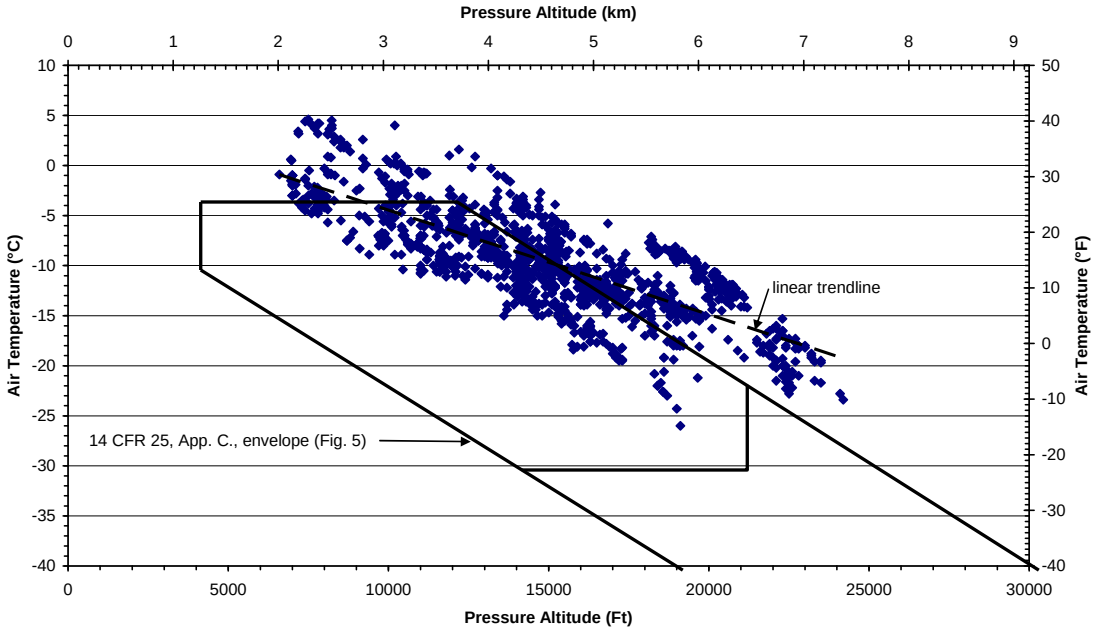

Figure 32. Convective Cloud Events for Mild Season (Spring and Autumn) Only
(1720 nmi contributing)

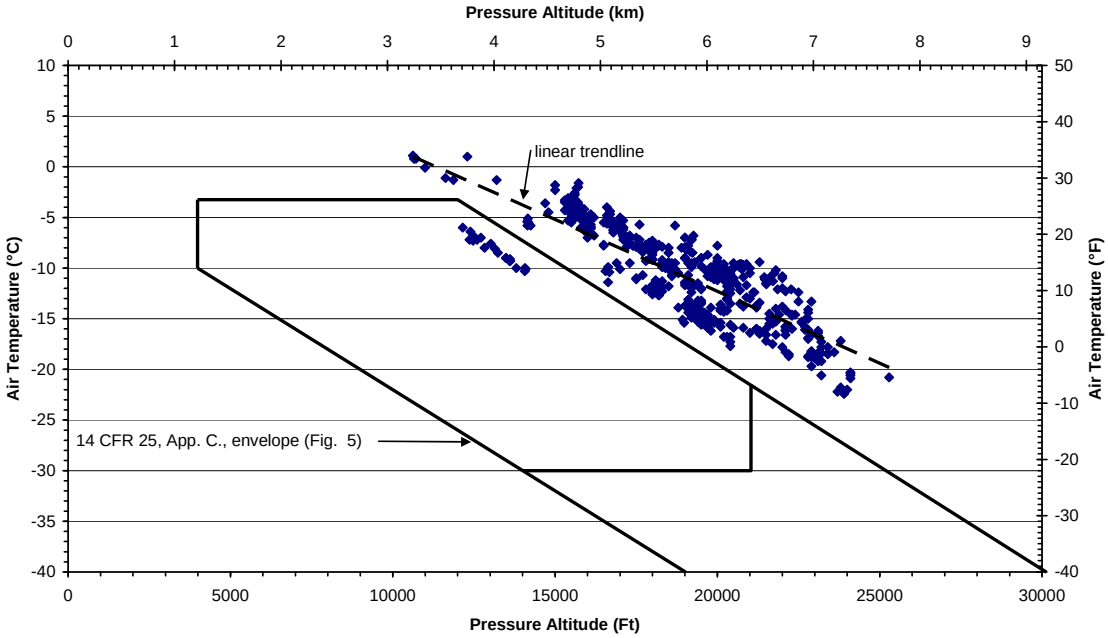

Figure 33. Convective Cloud Events for Warm Season (Summer) Only
(410 nmi contributing)

3.2.4 Suggested Extensions to the Envelope.

The conclusion is that the existing temperature versus altitude envelope for cumuliform clouds (figure 5) represents winter conditions satisfactorily, but if warmer season clouds are to be included, then one of the following changes will have to be made. Either the envelope will have to be enlarged to be all-inclusive, or a supplementary envelope will have to be provided to cover the warmer season clouds. There is also the possibility of extending the envelope to +3°C, as mentioned above, for layer clouds. These suggested extensions are depicted in figure 34. Contrary to the extension from -30° to -40°C suggested in the currently accepted envelope (figure 5), the data in figures 30 to 34 show that an extension is needed to higher altitudes but not necessarily to temperatures below -30°C.

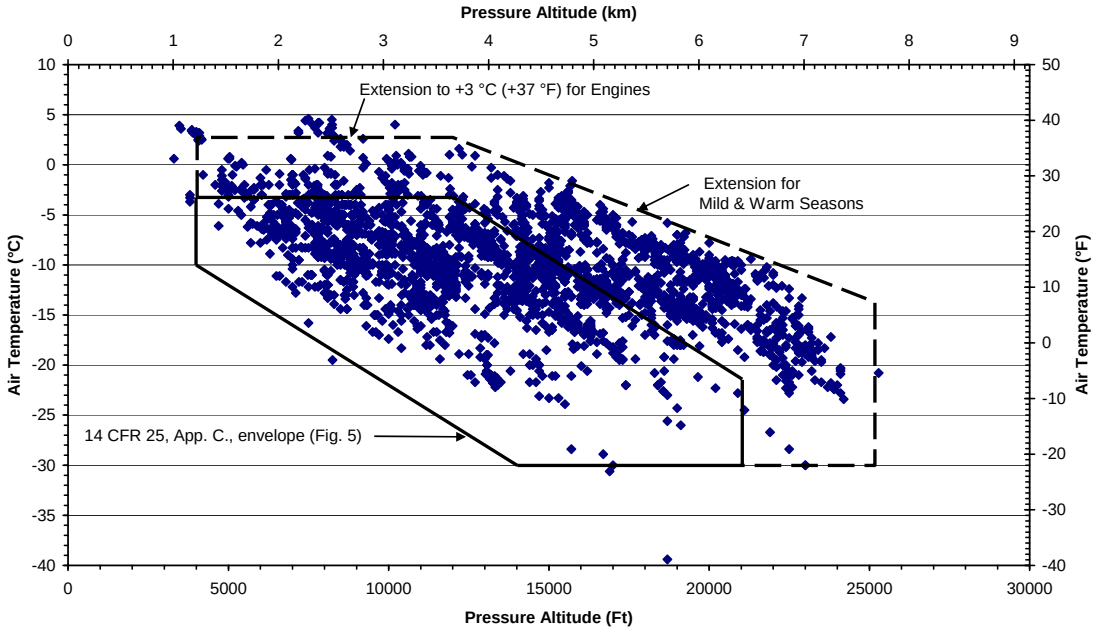

Figure 34. Proposed Extensions of Temperature Versus Altitude Envelope for Intermittent Maximum Conditions

Alternatively, simple curves representing the average, observed, in-cloud temperatures versus altitude can also be presented for each season separately. Figure 35 shows these for convective clouds.

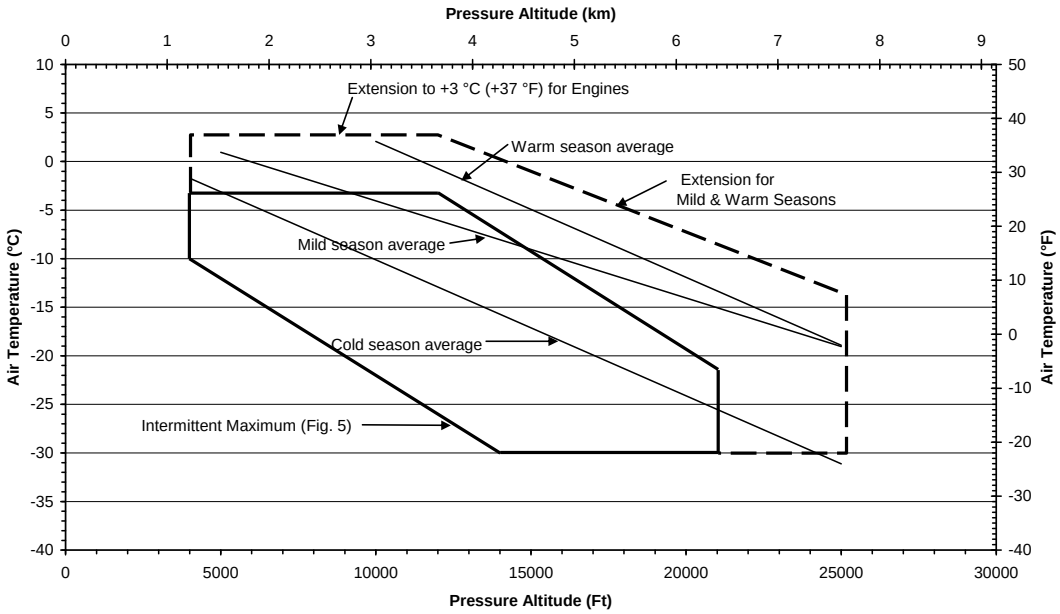

Figure 35. Average Temperature Versus Altitude for Convective Cloud Icing Events

4. OTHER DEPENDENCIES.

The following analyses are not necessarily recommended as formal material for inclusion in Appendix C. But they are helpful as realistic, supplementary information for use by icing practitioners who want a better understanding of the icing environment. The additional graphs and statistics herein can be used by design engineers for a refined selection of variable values, by test flight crews for realistic expectations in natural icing conditions, and by icing forecasters for guidance in estimating the possible values of icing variables at various altitudes.

4.1 SEASONAL VARIATIONS.

Aircraft icing is primarily a wintertime problem, so naturally, most of the data collection has been in cold season clouds. Table 3 indicates the amounts of data, in terms of in-cloud flight distances, that have been compiled here for the different seasons of the year.

Table 3. Amounts of Data by Season

Season	Cloud Type	Data Miles	
		U.S.	Non-U.S.
Winter	Layer	6,313	12,765
	Convective	2,171	838
Spring and Autumn	Layer	821	2,459
	Convective	810	846
Summer	Layer	174	466
	Convective	258	119
Totals (nmi)		10,547	17,493

These amounts of data are expected to be adequate for characterizing winter icing conditions, but are of questionable adequacy for warmer season icing conditions. The latter contain the largest intermittent values of SLWC, but are also confined to the higher altitudes in localized, convective clouds. The precise characterization of these warm season clouds may be less important than for wintertime icing conditions, however. Winter icing clouds can be widespread and, therefore, less avoidable, with subfreezing temperatures occurring all the way down to ground level.

The altitudes at which icing conditions occur are dependent, of course, on the season of the year and the geographical location. Icing occurs only near or above the freezing level, which, in summer-like weather, is well above 10,000 ft (3 km) above ground level (AGL). This limits the occurrence of summertime icing to thunderstorms, primarily, or to other convective clouds reaching above the freezing level. In the winter, icing conditions may be found at all altitudes down to ground level, but the layer clouds predominate and thunderstorms (with their potentially large LWCs) are rare when surface temperatures are low. It is informative to explore this behavior further, as is done in the following sections.

4.1.1 Seasonal Definitions.

A practical way of analyzing for seasonal effects is to separate the data according to the height of the freezing level at the time and place of the measurements. Data obtained when the freezing

level is low can be considered to be winter data. High freezing levels correspond to summer-like conditions. That is, the seasons may be defined in terms of a measurable property of the atmosphere rather than by the calendar. This way, any ambiguities due to latitude or geographic location are conveniently removed. For example, data from Florida in January would be correctly grouped with the summertime data if the freezing level there were high enough at the time. For present purposes, the seasons are arbitrarily defined as follows in table 4.

Table 4. Seasons Defined by Freezing Level Height

Season	Freezing Level Height (AGL)
Cold (winter)	Below 5,000 ft (1.5 km)
Mild (spring and autumn)	Between 5,000 and 10,000 ft (3 km)
Warm (summer)	Above 10,000 ft (3 km)

4.1.2 The SLWC Versus Freezing Level Height.

One type of plot that helps to predict the maximum SLWC to be expected for each season is shown in figures 36 and 37. Each plotted symbol in these two figures represents a measurement at an altitude somewhere above the indicated freezing level. For example, the points plotted at 3000 ft (0.9 km) were all obtained from a variety of altitudes for cases where the freezing level was known or estimated to be at 3000 ft AGL. The data indicate the maximum SLWC to be expected for each season. For example, during the cold season, the largest expected SLWC is indicated by data for freezing levels in the range of 0-5000 ft (0-1.5 km) AGL. For the mild season, the largest SLWC to be expected is indicated by the data from freezing levels from 5,000 to 10,000 ft (1.5-3 km) AGL.

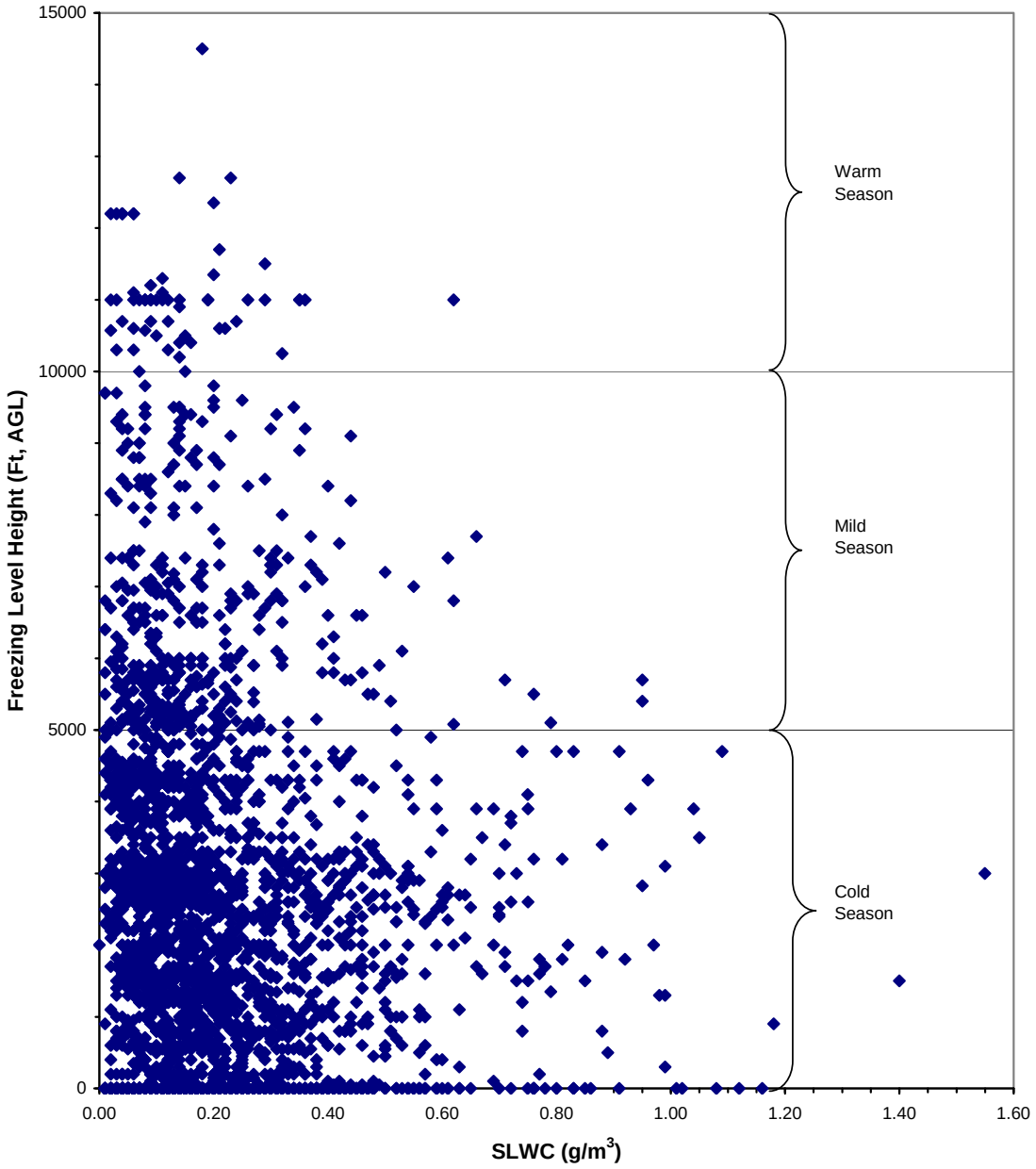

Figure 36. Observed Icing Events in Supercooled Layer Clouds Regardless of Horizontal Extent (23,000 nmi contributing)

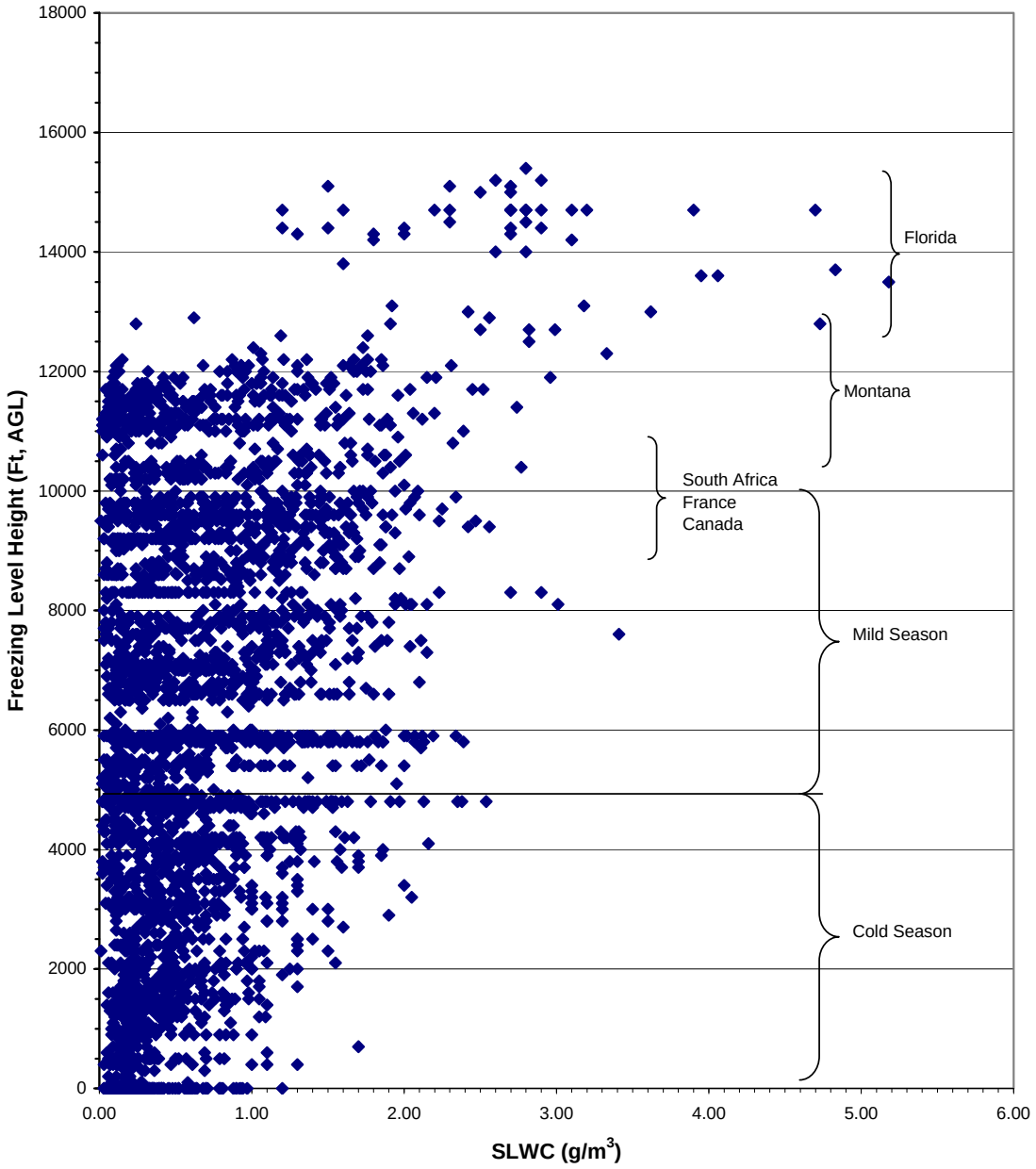

Figure 37. Observed Icing Events in Supercooled Convective Clouds Regardless of Horizontal Extent (5000 nmi contributing)

Figures 36 and 37 demonstrate opposite trends for the two classes of cloud types. Not surprisingly, the maximum probable LWC increases for convective clouds as the freezing level rises. This, of course, simply reflects the fact that convective clouds tend to be shallow in the cold season and deeper in the warm seasons. More moisture, stronger convection, and deeper convective clouds become possible as the near-surface temperatures rise. For layer clouds, however, the probable maximum values of SLWC decrease from winter to summer, i.e., as the freezing level rises. This is due to the fact that the deeper, nonglaciated layer clouds occur in the lower altitudes (e.g., below 10,000 ft (3 km) or so). Only thinner clouds (altostratus, cirrostratus, etc.) are found at the higher altitudes.

4.1.2.1 Layer Clouds.

All the layer cloud data (figure 36) show a gradual trend toward smaller SLWCs with increasing freezing level height above 5000 ft (1.5 km) AGL. Although there are progressively fewer data available for higher freezing levels, this trend toward smaller SLWCs is believed to be real and not just a result of inadequate sampling. The largest SLWCs appear to be confined to conditions where freezing levels are below 6000 to 7000 ft (2 km) AGL.

Another way of displaying the seasonal dependence is shown in figure 38. There, the lines simply circumscribe the largest SLWCs recorded in the database for stratiform icing encounters. All-weather icing conditions would be designed for the cold season SLWCs in figure 36 or for the cold season limit in figure 38. The mild and warm season SLWCs are less demanding, but could be used in special cases or scenario-driven exercises. These may include estimates of ice accretion amounts on some component of the aircraft during loiter above elevated freezing levels, or during some other flight profile in nonwinter conditions.

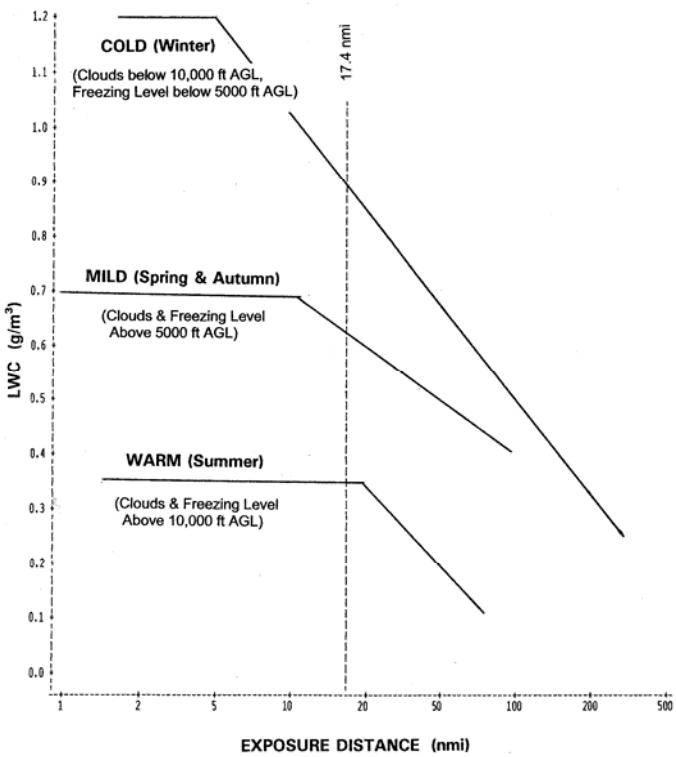

Figure 38. Observed Seasonal Limits to SLWC and Horizontal Extent for Icing Encounters in Stratiform Clouds

4.1.2.2 Convective Clouds.

According to the data in figure 37, as long as the freezing level is below 5000 ft AGL (i.e., winter conditions), the maximum value of SLWC should be less than about 2 to 2.5 g/m^3 for convective encounters at any altitude. Similarly, the maximum SLWC for the mild season is 2.5 to 3 g/m^3, and for summer conditions it is up to 5 g/m^3. These numbers are not adjusted for HE, however, so

the larger LWCs are likely to occur only over short distances. A distance-based plot like that in figure 21 reveals this fact.

Figure 39 shows the seasonal dependence of maximum observed SLWC as a function of HE for convective cloud encounters. The effect of summer clouds is marked, but it is only important for short distances. For encounters of 10 nmi or longer, the seasonal differences are negligible.

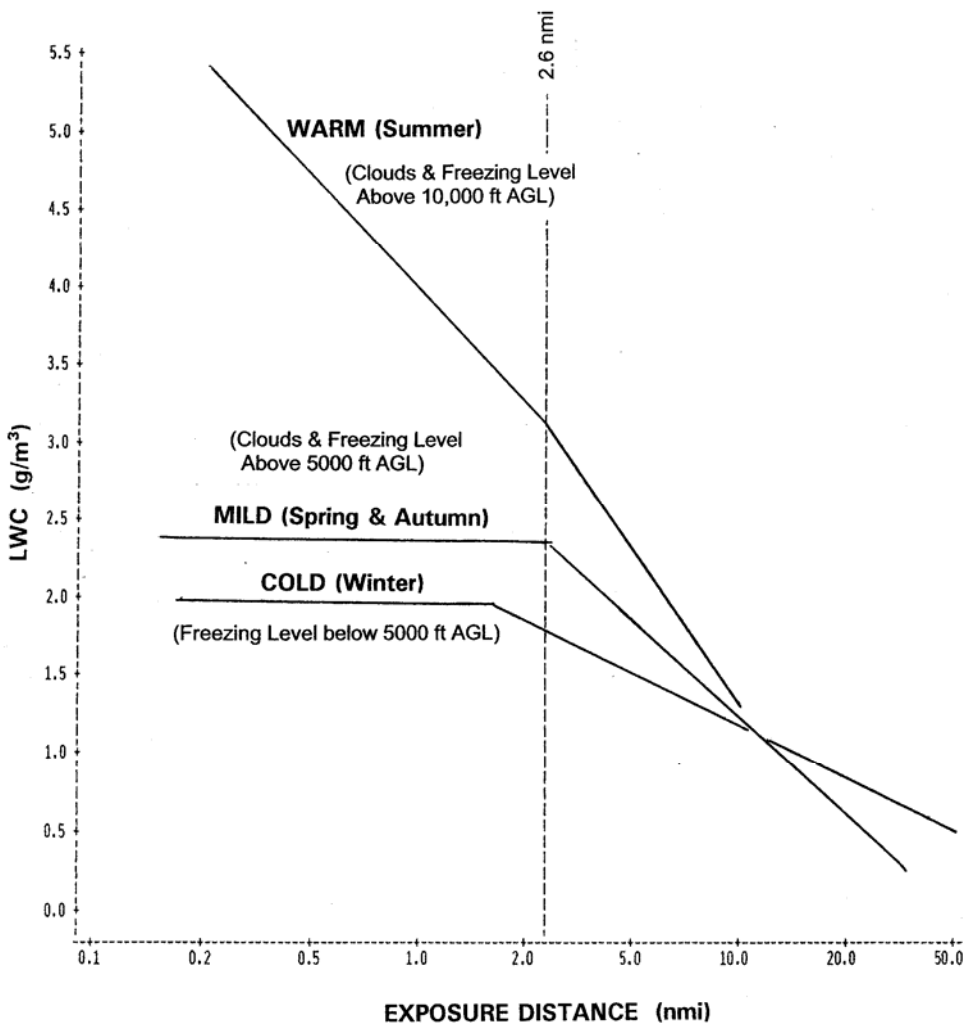

Figure 39. Observed Seasonal Limits to SLWC and Horizontal Extent for Icing Encounters in Convective Clouds

4.2 ALTITUDE VARIATIONS.

4.2.1 What About Altitude Limited Aircraft?

The envelopes in figures 1 and 4 are supposed to provide design criteria suitable for icing conditions to be found anywhere up to 22,000 ft (6 km). This was the altitude range of most propeller-driven, civil transport aircraft in use at the time these envelopes were drawn up. But what if a military designer is only interested in icing conditions likely at some specific altitude,

such as below 1,500 ft (1 km) for cruise missiles, or at 20,000 ft (6 km) for an airborne warning and control system (AWACS) airplane on station? Or what about helicopters, unmanned aerial vehicles (UAVs), or unpressurized aircraft that typically operate below 10,000 ft (3 km) above sea level (ASL)?

The envelopes in figures 1 and 4 reveal no differences with altitude, except indirectly through the temperature dependence shown in figures 2 and 5. That is, if the designer begins by selecting a representative temperature for the desired altitude in figure 2 or 5, then this temperature may lower the maximum expected LWC to be considered (for that altitude). The knowledge that temperatures generally decrease with increasing altitude can lead one to falsely conclude that LWC extremes also decrease with altitude, as the temperature dependence of the envelopes in figures 1 and 4 seem to suggest. On the contrary, the data shows that for stratiform type clouds, the maximum LWC decreases only above about 10,000 ft (3 km). For convective clouds, the maximum possible LWC actually increases with altitude up to at least 20,000 ft (6 km).

4.2.2 The SLWC Versus Altitude.

The overall altitude dependence of SLWC is presented in figures 40-44. The importance of these plots is that they emphasize the fact that the maximum expected SLWCs are altitude dependent, as was originally pointed out by Hacker and Dorsch [4]. This fact has been lost in the Appendix C envelopes, where the annotation implies that the extreme SLWCs may be expected at any altitude from sea level to 22,000 ft for layer clouds and from 4,000 to 22,000 ft for convective clouds.

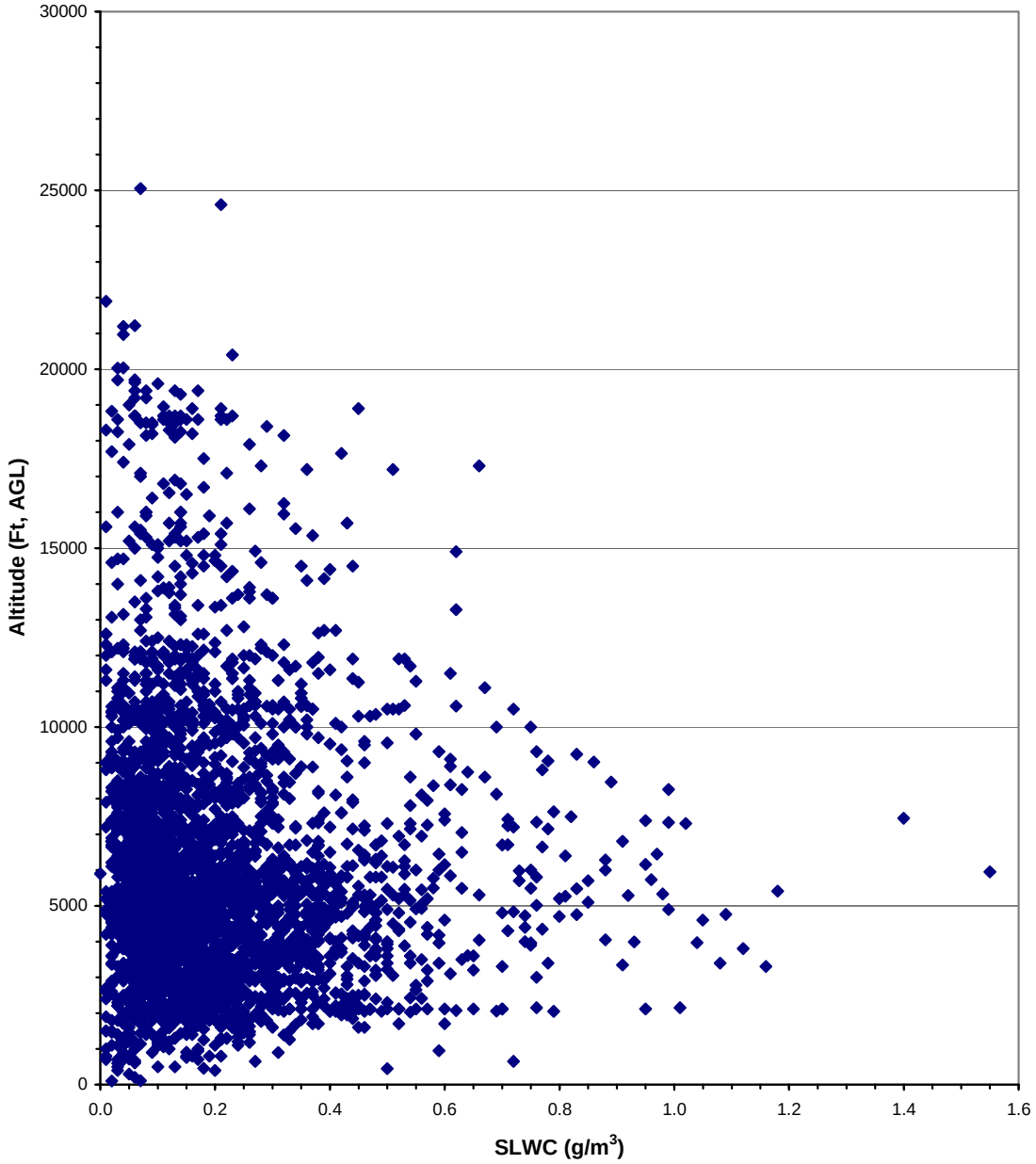

Figure 40. Supercooled Layer Cloud Events Versus Altitude AGL, Regardless of Horizontal Extent (23,000 nmi contributing)

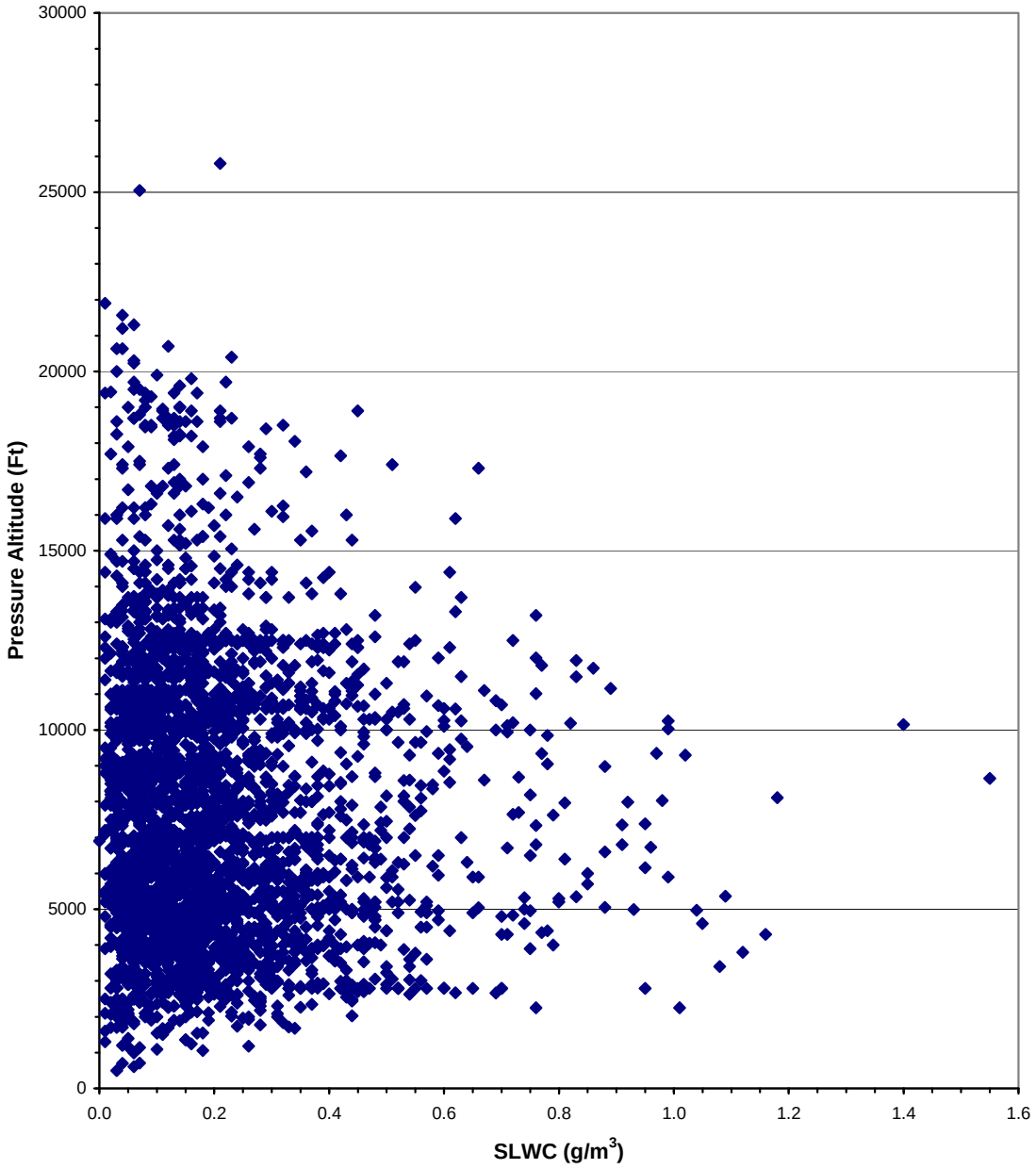

Figure 41. Supercooled Layer Cloud Events Versus Pressure Altitude, Regardless of Horizontal Extent (23,000 nmi contributing)

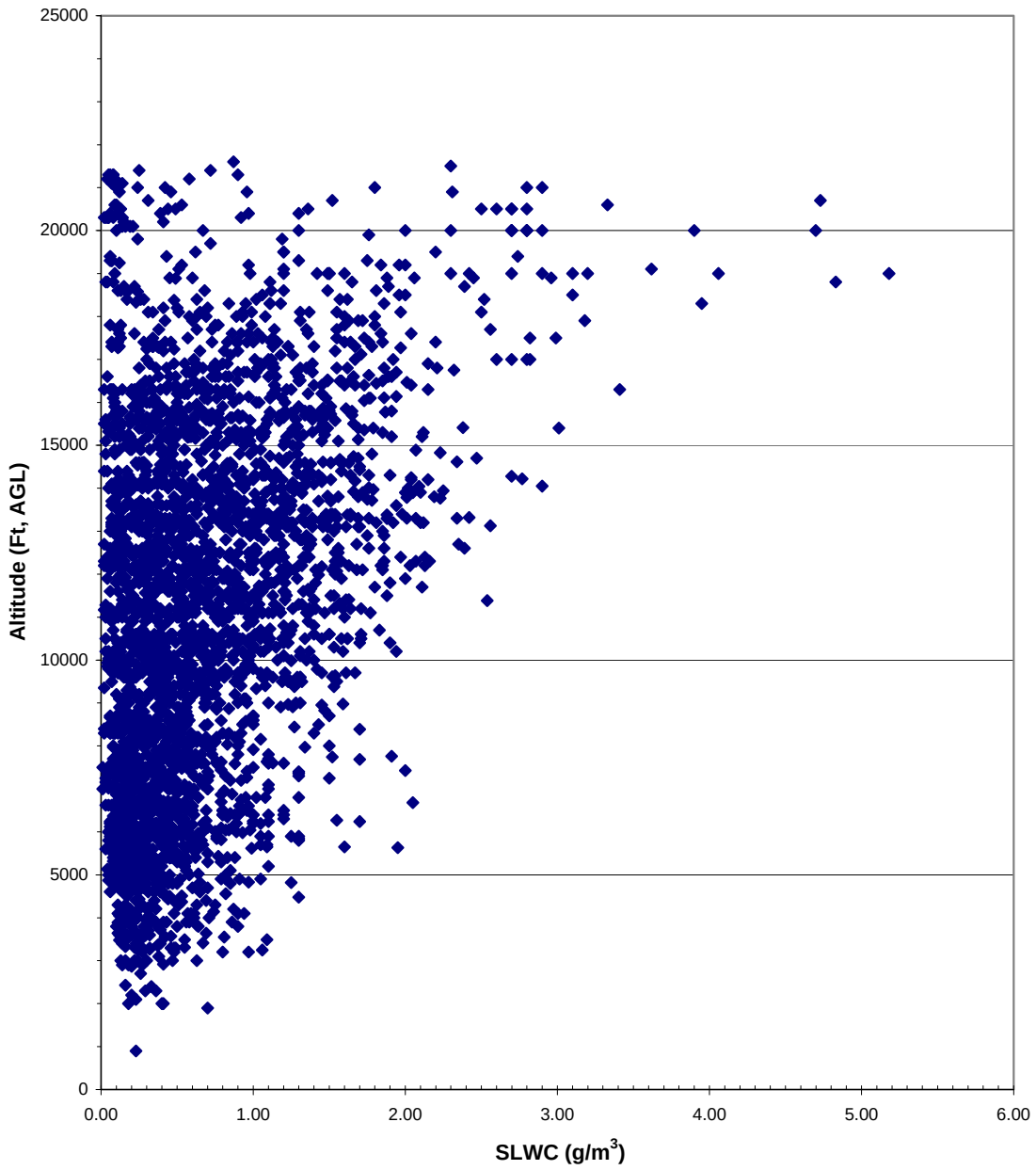

Figure 42. Supercooled Convective Cloud Events Versus Altitude AGL, Regardless of Horizontal Extent (5000 nmi contributing)

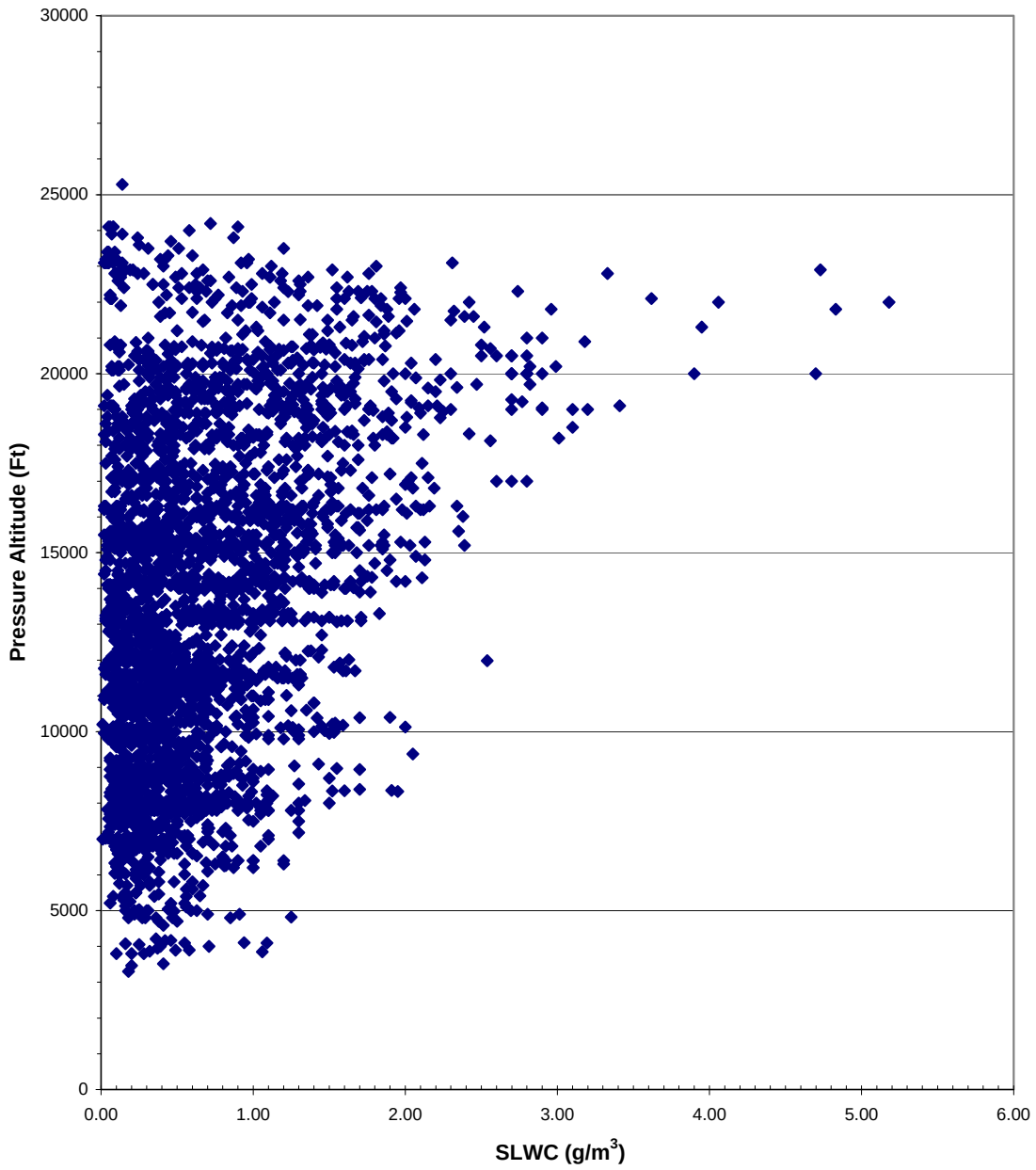

Figure 43. Supercooled Convective Cloud Events Versus Pressure Altitude, Regardless of Horizontal Extent (5000 nmi contributing)

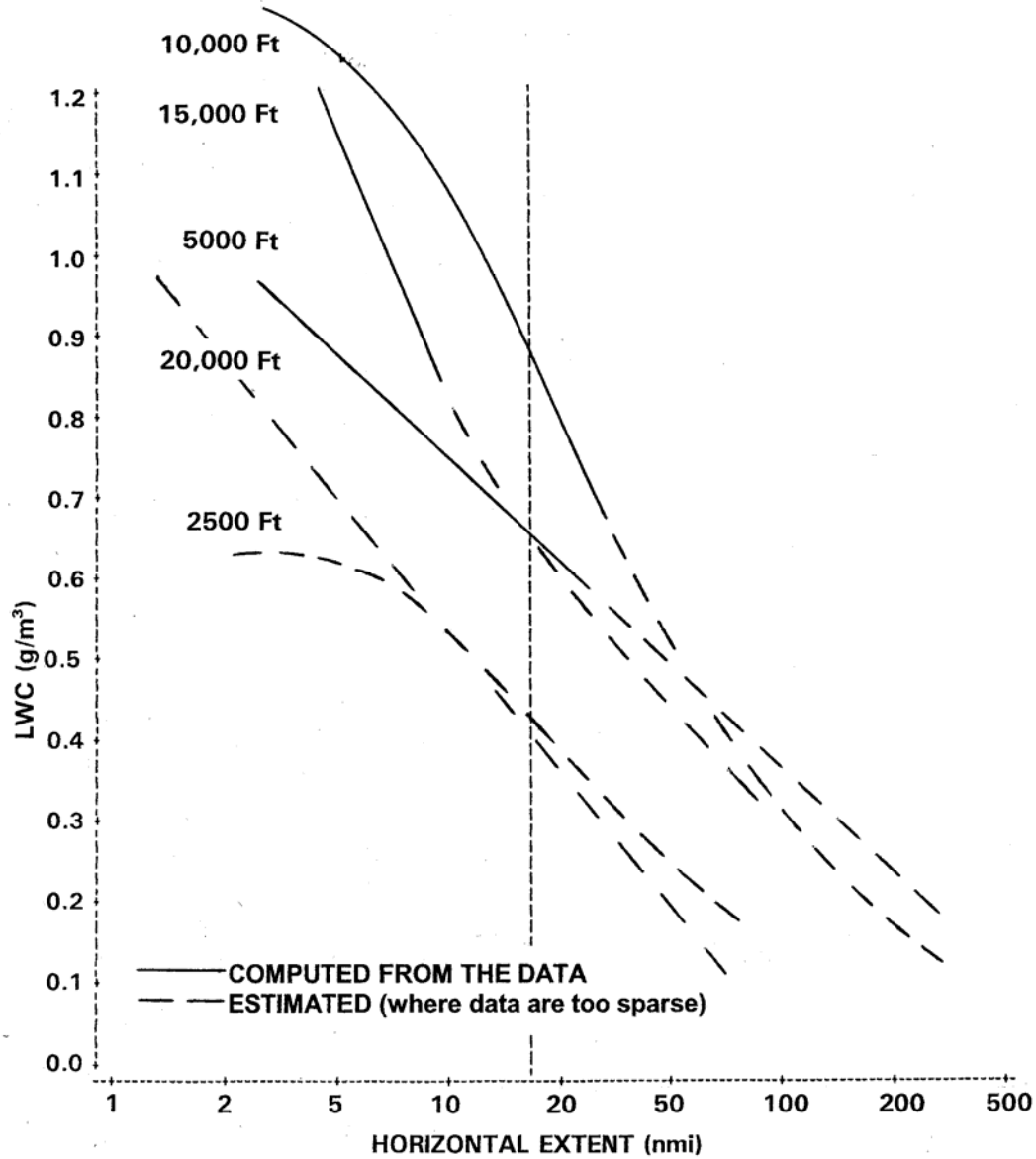

Figure 44. The 99th Percentile Limits to SLWC (and Horizontal Extent) as a Function of Altitude (AGL) for all Supercooled Clouds With Average MVDs (10 to 20 µm) and Highest Temperatures Available at the Indicated Altitude (Summertime Concective Clouds Excluded) (To convert these curves to ASL, add the local elevation to the AGL height for each of the curves; see text.)

4.2.2.1 Layer Clouds.

Figures 40 and 41 show that the largest SLWCs in layer clouds occur below 10,000 ft (3 km) AGL or ASL. In other words, the most severe icing conditions (in terms of SLWC) associated with supercooled layer clouds (i.e., the continuous maximum envelopes of figure 1) will be found only in the lower altitudes. On the contrary, the most severe icing associated with convective clouds is found only well above 10,000 ft (3 km) AGL. Although the continuous maximum envelopes

(figure 1) may be applied to any altitude, they will be overly conservative for altitudes above about 10,000 ft ASL or AGL. Actually, the built-in temperature dependence of the Appendix C envelopes helps to reduce these discrepancies in cases where reduced temperatures are used.

4.2.2.2 Convective Clouds.

In convective clouds (figures 42 and 43), the largest SLWCs occur only well above 10,000 ft. The largest SLWCs to be expected in any season in supercooled convective clouds at 10,000 ft (3 km) AGL or ASL are perhaps 2 g/m^3. These figures also show that the intermittent maximum envelopes (figure 4) will be overly conservative for all altitudes below about 15,000 ft (4.5 km) AGL or ASL.

The Appendix C envelopes (figures 1 and 4) also contain the hidden assumption that operational aircraft will be exposed to different values of SLWC with about the same frequencies as they occur in the database. But an aircraft spending most of its flight time in convective clouds between 15,000 ft (4.5 km) and 25,000 ft (7.6 km) may exceed the probable maximum SLWCs obtained from figure 4 considerably more often than the expected exceedance probability of about 1% (i.e., once in 100 penetrations). This is because the aircraft will be exposed more often to the largest SLWCs that are present only in these higher-altitude clouds, as figures 42 and 43 show.

Notice that in figure 43, no convective clouds are shown below about 3500 ft ASL. This recalls the fact that figure 4 is said to be applicable only to altitudes above 4000 ft pressure altitude (PA). But figure 42 clearly shows that SLWC can be found down to at least 2000 ft AGL in convective clouds. The reason there are no data below about 4000 ft in figure 4 or figure 43 is that all convective cloud cases in the database (including the old NACA data) were obtained above terrain with an elevation of 2000 ft or more. If any of the supercooled convective clouds were formed closer to sea level in winter, then they would be recorded at altitudes lower than 4000 ft. But low-based convective clouds are rare when the freezing level is near sea level. Instead, one finds mostly stratiform clouds anyway.

4.2.2.3 All Clouds Together.

Figure 44 shows another way of presenting the altitude dependence of SLWC. In this case, it is for both layer and convective clouds together, except that summer convective clouds have not been included, making the graph applicable to cold and mild season conditions. The solid portions of the curves in figure 44 are obtained using a Weibull extrapolation of the data where enough measurements are available for reliable statistics. The dashed portions are best estimates where data are sparse.

The curves show that maximum SLWCs increase with altitude up to about 10,000 ft (3 km) and then decrease for higher altitudes. Individual curves show the 99th percentile SLWC as a function of AD (HE) near the indicated altitude.

Some other conclusions about the curves in figure 44 are that the range of 5,000- to 15,000-ft altitude makes no difference for encounters of about 50 nmi or longer. The curves come together for these long encounters. Similarly, for icing encounters at 2,500 or 20,000 ft, the probable maximum SLWCs are the same for encounters longer than about 7 nmi.

4.2.2.4 Above Ground Level or Above Sea Level?

Note that although the curves are drawn for altitudes AGL, they also apply to altitudes ASL when the local surface elevation is near sea level. For higher elevations, the ASL equivalent is obtained by adding the local elevation to each of the curves. For example, at an elevation of 2500 ft (0.75 km), the 2500-ft AGL curve is also the 5000-ft ASL curve (for that location), the 5000-ft curve is also the 7500-ft ASL curve, and so on. This has the effect of reducing LWCs at a given height ASL over higher elevations and pushing the maximum LWCs to higher altitudes ASL. Thus, if one is interested in the worst-case LWC at 10,000 ft (3 km) ASL for helicopters or unpressurized airplanes, the 10,000-ft AGL curve, as shown in figure 44, referenced to sea level is the one to use.

5. SAMPLE APPLICATIONS—SELECTING DESIGN POINTS.

This section illustrates the use of the herein proposed envelopes or characterizations described above and compares the results with those obtained using the conventional Appendix C design criteria (figures 1-6). The examples follow some of those given in technical report ADS-4 [16].

The conventional procedure usually begins by postulating a flight condition that is thought to be important or representative for the aircraft under consideration. A common example illustrated in ADS-4 for the light twin-engine airplane is a cruise condition at 7000 ft (2 km) ASL.

The LWC versus MVD envelopes (figure 1) give the design engineer the maximum LWC to be expected as an average over a 17.4-nmi icing encounter, depending on the temperature and representative droplet size. An appropriate temperature is usually selected by consulting a most probable temperature versus altitude curve (figure 1-16 in ADS-4) or by specifying some other temperature appropriate to the specific application. For an altitude of 7000 ft, the most probable temperature from figure 1-16 of ADS-4 is 17°F (-8°C). For estimating thermal requirements for a running-wet anti-icing system, an OAT of 0°F (-18°C) has been used (see page 4.1-23 in ADS-4). This temperature is needed not only to obtain a design value of LWC from figure 1, but it is also used in heat balance equations for computing how much heat must be applied to the forward portion of the wings.

An MVD of 20 µm is conventionally used along with a standard exposure distance of 17.4 nmi. At an airspeed of 200 mph (174 kt), a standard encounter will last 0.1 hour (6 minutes). If the anti-icing system can prevent ice for a 6-minute exposure at the design values of LWC, true airspeed (TAS), and OAT, then it can probably prevent ice indefinitely under these conditions. This is based on the knowledge that if the actual exposure is longer, then the average LWC will be even less than the design value because the average LWC tends to decrease with increasing HE.

In a complete design exercise, these design values would then be used for further computations, such as the heat requirements, estimated drag increases, speed losses, and increased power requirements due to ice accretion amounts on unprotected surfaces [16]. The interest here is only to illustrate the process of selecting the design values themselves and to compare the result obtained from conventional and alternate procedures introduced here.

5.1 EXAMPLE 1, THE 7000-FT ALTITUDE CASE.

The variables to be determined are OAT, MVD, HE, and LWC.

5.1.1 The Conventional ADS-4 Method.

This method obtains a fixed value of LWC from figure 1 of Appendix C for a given set of values for OAT, MVD, and HE.

- OAT = -8°C (from most probable curve, figure 1-16 in ADS-4)
- MVD = 20 µm (conventional assignment)
- HE = 17.4 nmi (standard design distance)
- LWC = 0.46 g/m^3 (from figure 1 of Appendix C)

Note: The LWC obtained from figure 1 is insensitive to the altitude, except indirectly through the most probable temperature curve. That means that if a single temperature were chosen regardless of altitude, the design LWC would be the same for all altitudes from sea level to 22,000 ft—the range of applicability for figure 1.

5.1.2 The LWC Percentile Method.

This method assumes that the LWC intercepted along the flight path during any exposure of any length will be distributed in the same ratios as in table 1.

- OAT = - 8°C (from the cold season average curve in figure 29)
- MVD = 20 µm (upper end of critical MVD range for layer clouds)
- HE = arbitrary (LWC result is independent of exposure distance)
- LWC = 0.26 g/m^3 (computed as follows, from table 5):

  Table 5 is constructed from table 1 assuming, for design purposes, that every icing exposure can be represented by the listed threshold LWCs, each lasting for the indicated fraction of the exposure.

Table 5. Fractions of an Exposure That the Indicated LWCs may be Expected to Last, According to the Statistics in Table 1

LWC (g/m^3)	Percent of Distance	Distance (nmi) Out of 17.4 nmi	Distance (nmi) Out of 100 nmi
1.0	0.9	0.16	0.9
0.65	4	0.7	4
0.45	5	0.9	5
0.35	40	7	40
0.12	50	8.7	50

The average LWC for the entire exposure is computed as follows, using columns 1 and 2 of table 5, and does not depend on the exposure distance (HE).

$$\text{Average LWC} = \frac{1(0.9) + 0.65(4) + 0.45(5) + 0.35(40) + 0.12(50)}{99.9} = 25.75/99.9 = 0.26\ g/m^3$$

This value is roughly half of that obtained from figure 1 for the standard distance of 17.4 nmi. This method is simpler than the conventional Appendix C method, but the average LWC is lower than that derived from Appendix C for encounters out to about 60 nmi. For longer encounters, the average LWC from the Appendix C method drops below 0.26 g/m^3. The LWC percentile method also limits the indicated LWC exposures to much shorter distances than are possible in the extreme.

5.2 EXAMPLE 2, THE 2500-FT, LOW ALTITUDE CASE.

The variables to be determined are OAT, MVD, HE, and LWC.

5.2.1 The Altitude Priority Method.

This method reads the LWC directly from the altitude-limited curves in figure 44.

- OAT = - 4°C (from the cold season average curve in figure 29)
- MVD = 20 µm (upper end of critical MVD range for layer clouds)
- HE = 17.4 nmi (standard design distance)
- LWC = 0.44 g/m^3 (from the 2500-ft curve in figure 44)

5.2.2 The Conventional ADS-4 Method.

This method obtains a fixed value of LWC from figure 1 of Appendix C for a given set of values for OAT, MVD, and HE.

- OAT = -4.5°C (from most probable curve, figure 1-16 in ADS-4)
- MVD = 20 µm (conventional assignment)
- HE = 17.4 nmi (standard design distance)
- LWC = 0.53 g/m^3 (from figure 1 of Appendix C)

Note that compared to the altitude-direct curves in figure 44, figure 1 overestimates the LWC for this low altitude case.

5.2.3 The LWC Percentile Method.

This method uses the same percentile values of LWC as before, but the maximum applicable horizontal extents may be limited, as shown in table 6, by the 2500-ft curve in figure 44.

Table 6. Fractions of an Exposure That the Indicated LWCs may be Expected to Last, According to the Statistics in Table 1, but Limited by the 2500-Ft Curve in Figure 44

LWC (g/m^3)	Percent of Distance	Distance (nmi) Out of 17.4 nmi	Distance (nmi) Out of 100 nmi
1.0	N/A*	-	-
0.65	4	0.7	4
0.45	5	0.9	5
0.35	40	7	30 max.**
0.12	50	8.7	50

* LWCs larger than about 0.65 g/m^3 are not possible at 2500 ft or below, according to the 2500-ft curve in figure 44.
** 30 nmi is the longest that a LWC of 0.35 g/m^3 can last, according to the 2500-ft curve.

$$\text{Average LWC} = \frac{0.65(4) + 0.45(5) + 0.35(30) + 0.12(50)}{89} = 21.35/89 = 0.24\ g/m^3$$

6. CONCLUSIONS ABOUT THE APPENDIX C ENVELOPES.

6.1 FIGURES 1 AND 4: LWC VERSUS MVD CURVES.

Although the original data collection flights were only in winter and spring icing conditions over parts of the United States, the existing curves appear to represent all-season stratiform and convective icing conditions (excluding freezing rain and freezing drizzle) for the United States and Europe. They enclose about 99% of all measurements obtained by the research flights of the 1940s [12]. A mathematical evaluation in 1952 [5] showed that this "was roughly equivalent to a probability of 1/1000 that all three variables (LWC, MVD, and OAT) represented by a single point (in figure 1) would be exceeded simultaneously." The LWC curves themselves, however, are thought to represent the 99th percentile value of LWC for a given MVD and OAT. No other evaluations of the envelopes have since been published.

Analyses of the larger dataset now available show that:

- Depending on the temperature and exposure duration, figure 4 sometimes overestimates and sometimes underestimates the larger LWCs that can be found in deep cumuliform clouds in the summertime. These clouds may be a concern for turbine engine inlets where ice may form and then dislodge to cause possible damage to the compressor blades.

- Figure 1 overestimates maximum LWCs in stratiform clouds above 10,000 ft AGL and figure 4 overestimates maximum LWCs in convective clouds below 15,000 ft AGL.

- The LWC versus MVD format, being tied to a fixed reference distance, severely limits the versatility and usefulness of these curves for plotting and comparing test points, which come from variable distances.

- Figures 1 and 4 also contain some hidden deficiencies and omissions, which convey an incomplete and sometimes inaccurate or misleading representation of natural icing conditions. The missing information includes the fact that

  - the figures imply that all MVDs are equally probable, but MVDs near 15 µm are highly preferred by clouds.

  - LWCs do not necessarily decrease with decreasing temperature from 0° to -15°C.

  - the larger LWCs do not occur at the lowest altitudes.

6.2 FIGURES 2 AND 5: ICING TEMPERATURE LIMITS VERSUS ALTITUDE.

Figure 2 is an all-season envelope enclosing all recorded icing encounters except for a few high-altitude events at temperatures between -30° and -40°C.

It is recommended that the envelope be modified by adding some modest extensions and some seasonal average temperature versus altitude curves.

Figure 5 adequately covers wintertime convective clouds but misses high-altitude summertime icing conditions.

It is recommended that an extension of the warmer temperatures to higher altitudes be added to accommodate mild- and warm-season icing conditions. Seasonal average temperature versus altitude curves can also be added to aid the user in selecting representative temperatures.

6.3 FIGURES 3 AND 6: LWC ADJUSTMENT (F-FACTOR) CURVES.

These curves are based on small amounts of original data and are reasonably realistic for MVDs near 15 µm. But figure 3 overestimates maximum probable LWCs in layer clouds for MVDs of 20 µm and larger. Figure 6 falls well short of HEs out to 30 nmi that have been since recorded in convective cloud icing conditions.

It is proposed that figures 3 and 6 be eliminated, either by absorbing them into figures 1 and 4 converted to the LWC versus HE format or by adopting simple LWC percentile tables. In either case, figures 3 and 6 are not needed.

6.4 OTHER FACTS AND CONCLUSIONS FROM THE DATA.

- Comparison of the 17,500 nmi of available data from outside of CONUS with 10,500 nmi from within shows no significant differences except for

  - the usual differences in droplet numbers and sizes in continental versus maritime clouds

  - the 1950s icing rate measurements over the northern oceans and Alaska. The latter indicate some cloud water contents larger than those seen in layer clouds over

CONUS. It is unknown whether these larger LWCs are real or due to calibration uncertainties when converting icing rates to LWC.

- The old NACA data and the modern data compare favorably with each other in the determination of LWC and MVD, even though the measuring techniques are radically different.

- The worst icing conditions (in terms of LWC) are below 10,000 ft for stratiform clouds and above 10,000 ft (in the summertime) for convective clouds. Appendix C wrongly implies that maximum LWCs are the same over the entire 22,000-ft altitude range.

- MVDs are much less variable than previously thought. Eighty percent of all MVDs are within ±5 µm of the mode at 15 µm for layer clouds and within ±6 µm of the mode at 18 µm for convective clouds. Appendix C wrongly implies that all MVDs are equally probable.

- The most common MVDs also contain the largest LWCs. The slope of the LWC versus MVD curves in figure 1 of Appendix C wrongly implies that the LWCs continue to increase with decreasing MVD below 15 µm.

- Mean Effective (Drop) Diameter (MED) is an ambiguous, old-fashioned term associated with the rotating multicylinder (RMC) method. For clarity, and to modernize Appendix C, MED ought to be replaced by MVD. Fortuitously, MED and MVD are usually about the same, numerically.

- LWCs do not appear to decrease with decreasing temperature from 0° to -10°C, contrary to the temperature dependence shown in Appendix C.

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APPENDIX A—EXPLANATION OF THE VARIABLES USED IN THE DATABASE

A.1 DATA MANAGEMENT PHILOSOPHY.

The data originally obtained from various sources (digital tapes and tabular reports) have been computerized in a condensed, standardized format according to the following scheme.

A.2 BASIC AVERAGING INTERVALS.

Modern, electronic, and electro-optical cloud physics probes and sensors provide digitized measurements, typically once per second or more, during flight in clouds. A reel of data tape may, therefore, contain 3600 or more individual readouts from each sensor per hour of flight. Naturally, these large numbers of samples have to be reduced in some way to obtain a manageable set of data. The data that are available from technical reports or journal articles have already been condensed to averages over some arbitrary time or distance intervals. For the high-resolution data available directly from the digital tapes, the following averaging scheme has been devised.

Each variable (liquid water content (LWC), air temperature, droplet number density, etc.) is averaged over continuous, uniform portions of clouds as defined in table A-1. These averaging intervals are termed "events." If the aircraft is still in continuous clouds at the end of one event, then a new averaging interval (event) immediately begins and continues until the next significant change in cloud properties occurs. Otherwise, the next event does not begin until the aircraft enters another continuous, uniform section of cloud.

This averaging scheme has a number of advantages.

- It avoids inflexible, fixed intervals such as 1-minute averages, or averages over entire cloud passes. (These are undesirable if they wash out useful detail otherwise available with modern, high-resolution measurements.)

- The events can be short enough to resolve any significant changes in cloud characteristics along the flight path, i.e., the natural variability in clouds can be preserved and documented.

- Intervals of uniform, constant conditions within clouds can be preserved whole so their durations and characteristics can be documented without the ambiguity that would occur if the average included voids or adjacent parcels having significantly different or variable properties.

- The averages can resolve extremes of LWC or other variables without dilution.

- The averages can preserve altitude-dependent changes in cloud properties observed during ascents or descents through clouds.

- The scheme can accommodate broken or scattered cloud conditions as well as widespread continuous clouds.

- Not only are data available on the extents of individual, uniform cloud intervals, but the overall horizontal extent of continuous or semicontinuous icing conditions is available simply be summing the extents of consecutive events.

Although these rules were designed for the modern data, the National Advisory Committee for Aeronautics (NACA) data can be formally accommodated as well. The NACA measurements were timed exposures of rotating multicylinders in the airstream during flight through subfreezing clouds. The exposure times were usually 1 minute or more, and the data, therefore, represent an average over these intervals.

A.3 DATA MILES AS A MEASURE OF FREQUENCY OF OCCURRENCE.

During the early phases of this project, it became clear that usage of number of cases or number of events, as is conventionally done to represent the frequency of occurrence of any of the variables, was unsatisfactory. The deficiency was twofold. First, momentary icing events would incorrectly carry just as much statistical weight as long-lasting events. Thus, there was no way to emphasize the statistical importance of an extended encounter with an extreme value of LWC, for example, compared to a relatively insignificant, brief encounter. Second, the reader would have no information as to whether a given number of events represented 5 miles or 500 miles of in-flight measurements.

Data miles were, therefore, chosen as the most informative measure of frequency of occurrence. The term is defined as the distance flown (in nautical miles) during an individual icing event. This convention automatically weights each icing event (or measurement of LWC, for example) by its duration or extent. The other principal advantage is that the reader can easily judge the statistical significance of a data set by the number of data miles it represents.

A.4 DATA FORMAT.

Table A-1 gives the rules of defining uniform cloud intervals. Table A-2 lists all variables that have been selected to describe the events. Table A-3 lists specific entries for the variables WEATHER, PRECIP, CLOUDYTYP, and AGCYID in table A-2. A sample printout of all the variables associated with a few representative events is given in table A-4.

One or two code letters from table A-1 are assigned to the variable EVENTDEF to indicate why the sample averaging interval was terminated. That is, all measured variables are averaged over the flight path in the cloud until one of the following events occurs.

Table A-1. Rules for Defining Uniform Cloud Intervals

Code Letter	Description
A	Aircraft exits main cloud
B	Outside air temperature (TEMP) changes by ±1.5°C
C	Outside air temperature (TEMP) rises above 0°C
D	Droplet median volume diameter (MVD) changes by ±2.5 µm
E	Aircraft changes altitude (ALT) by ±500 feet (±150 meters)
F	Icing rate changes by ±50%
G	Droplet number density (CONC) changes by ±50% or ±200 cm^{-3}, whichever is less
H	Averaging interval arbitrarily terminated
J	Aircraft encounters momentary break in cloud
K	Subsequent data from ASSP or FSSP is invalidated by snow or ice particles in the cloud

Table A-2. Description of the Principle Variables

Mission Identifiers		
Variable	Type	Explanation or Example
PROJECT	Char	CCOPE, SCPP, NEWS, CYCLES, etc. (See table 1 of report).
DATE	Num	MMDDYY that the flight took place.
AGENCY	Char	U. WYOMING (King Air), NRL (P-3), etc., where the type of aircraft is given in parentheses.
LOCATION	Char	Name of the nearest city or airport, including its three-letter code, such as DEN, SFO, STL, etc.
SURFELEV	Num	The elevation of the local surface in feet above sea level. Special missing data indicators are M, U, E, V for mountainous, unknown, estimated, and variable values (consult ELEVNOTE for additional information).
ELEVNOTE	Char	For example, an entry of 5000-8500 indicates that the surface elevation ranges between 5000 and 8500 ft in the nearby upwind vicinity of the measurements.
ALT_CONV	Char	ASL, PA, or AGL indicate that all the height or altitude data are in terms of height above sea level, pressure altitude, or height above ground level, respectively.
Cloud Information		
CLOUDGRP	Char	A letter, A, B, C, etc., denoting a group of similar type clouds being sampled.
CLOUDNUM	Num	A number, 1, 2, 3, etc., denoting which cloud in CLOUDGRP contributed to the data for the present observation.

Table A-2. Description of the Principle Variables (Continued)

Cloud Information		
Variable	Type	Explanation or Example
CLD_PASS	Char	A number 1, 2, 3, etc., indicating which pass the current observation represents through the cloud identified by CLOUDGRP and CLOUDNUM.
CLOUDTYP	Char	Conventional cloud type abbreviations such as Cu, Sc. (See table A-3).
CLD_DIST	Char	Descriptive words, such as broken or scattered, to indicate the prevailing cloud distribution.
CLDBASHT	Num	Numerical values such as 3,650 or 12,000, giving cloud base height in feet according to the convention defined by ALT_CONV for the flight in question. Special missing data indicators are U, V, and E for unknown, variable, or estimated values (consult CLDBHNOT for additional information).
CLDBHNOT	Char	Additional information on the cloud base height. For example, the entry CLDBHNOT = 11,000 (along with CLDBASHT = E) indicates that the cloud base is estimated to be at 11,000 feet.
CLDTOPHT	Num	Numerical values giving cloud top height in feet at the time of the observation. (Other usage is the same as for CLDBASHT, above.)
CLDTHNOT	Char	(Same usage as for CLDBHNOT, above.)
CLDBAS_T	Num	Numerical values giving cloud base temperature in degrees Celsius. Special symbols for missing data are U, V, and E, as above.
CLDBTNOT	Char	Additional information on cloud base temperature when CLDBAS_T = E or V.
CLDTOP_T	Num	Numerical values giving cloud top temperature in degrees Celsius. Special symbols for missing data are U, V, and E, as above.
CLDTTNOT	Char	Additional information on cloud top temperature when CLDTOP_T = E or V.
Weather Factors		
AIRMASS	Char	Conventional air mass abbreviations such as: mT = maritime tropical, McP = modified continental polar, etc.
WEATHER	Char	A coded description of the weather conditions associated with the clouds under study. A list of the code symbols are given in table A-3. For example, “Lc 200nm W & Ws Pr(S-)” means a low pressure center 200 nautical miles to the west and widespread precipitation (light snow).
Measurement-Related Variables		
ST_TIME	Char	The time, HH:MM:SS, at the beginning of the sample.
TIMECONV	Char	Time zone code applicable to ST_TIME. For example, GMT = Greewich Mean Time MDT = Mountain Daylight Time (USA) PST = Pacific Standard Time (USA).

Table A-2. Description of the Principle Variables (Continued)

Measurement-Related Variables		
Variable	Type	Explanation of Example
DURATION	Num	A number indicating the time duration (in seconds) of the cloud sample.
DISTANCE	Num	A number indicating the distance (in nautical miles) traveled by the aircraft during the sample.
EVENTDEF	Char	A letter code, A, B, C, etc., to indicate why the sample was terminated. The code is given in table A-1.
MANEUVER	Char	A description (level, slant, spiral) of the aircraft flight path during the sample.
PRECIP	Char	Conventional notation indicating the type and intensity of precipitation, if any, observed at flight level from the aircraft (a/c), or on the ground (gnd) below the cloud under study. For example: S- = light snow, G+ = heavy graupel, etc., (See table A-3).
CLDSTATE	Char	Coded notation indicating the state of the cloud particles sampled by the aircraft. For example: W = all water droplets, I = all ice particles, etc., (See table A-3).
Averaged Variables		
TAS	Num	Average True Airspeed (knots) during the sample.
ALT	Num	Average altitude (feet) during the sample, according to the convention defined by ALT_CONV.
TEMP	Num	Average outside (true) air temperature (deg, C) during the sample.
JWLWC	Num	Average value of the liquid water content (g/m^3) indicated by a hot-wire type of LWC meter (usually “Johnson-Williams” or a “CSIRO-King” model).
FLWC	Num	Average value of the LWC (g/m^3) computed from the droplet size distribution indicated by the PMS ASSP or FSSP probe.
MVD	Num	Average value of the median-volume diameter (µm) computed from the FSSP or ASSP droplet size distribution.
CONC	Num	Average value of the droplet number density (no./cm) indicated by the FSSP or ASSP.
ICE_CONC	Num	Average value of the ice particle number density (no./liter) indicated by any ice particle counter.
CONC_1DC	Num	Average value of the particle number density (no./liter) indicated by the PMS 1D-C (200X) probe.
LWC_1DC	Num	Average value of the liquid water content (g/m^3) computed from the 1D-C particle size distribution.
CONC_2DC	Num	Average value of the particle number density (no./liter) indicated by the PMS 2D-C probe.
CONC_1DP	Num	Average value of the particle number density (no./liter) indicated by the PMS 1D-P (200Y) probe.
CONC_2DP	Num	Average value of the particle number density (no./liter) indicated by the PMS 2D-P probe.

Table A-3. Description of Secondary Variables

Weather Code Symbols			
Ao = Ahead of	g = generally	S = South	Uf = Upslope flow
Am = Airmass	Hc = High pressure center	Sb = Stable, stability	Up = Upper, upper level, upper part
B = Bands	Hp = High pressure region	Sc = Scattered	u = usually
Bt = Between	Ht = Heating	Sf = Stationary front	W = West
C = Convergence	I = Inversion	Sh = Short	Wf = Warm front
Cf = Cold front	L = Layer	Sm = Slow moving	Wi = Wind(s)
Cl = Cloud(s)	Lc = Low pressure center	Sq = Squall	Wk = Weak
Cu = Cut(off)	Le = Lake effect	Sr = Strong, deep	Ws = Widespread
Cv = Convection	Li = Line(s)	St = Stationary	Wv = Wave
Cx = Complex	Ll = Low level	Su = Surface	Wx = Weather
Cy = Cyclone, cyclonic flow	Lp = Low pressure region	Sv = Severe	Wy = Westerly
D = Dense	M = Moderate, medium	Sw = Shower(s)	Z = Zone
Dy = Dry	Ml = Mid level	Sy = Southerly	* = Estimated value follows
d = due to	Mu = Multiple	s = some	? = Amount or type uncertain
E = East	N = No	T = Thin	Or = Orographic
Ey = Easterly	Ny = Northerly	Tb = Turbulence	Ot = Outside of
F = Following	nm = nautical miles	Tn = Tornado	Pg = Pressure gradient
Fl = Flight level	O = Over	Tr = Trough	Po = Possibly, possible
Fm = Fast moving	Oc = Occluded	Ts = Thunderstorm	Pr = Precipitation
Fr = Front, Frontal	Of = Occluded front	Ua = Unstable air	R = Ridge
Fw = Fair weather	Rb = Rainband	Ud = Updraft	

Precipitation Code Symbols	Cloud Names	Agency Identifier Codes (for use with AGCYID)	
A = Hail	Layer Clouds	Agency	One-Letter Code
E = Sleet	Ac = Altocumulus	AFGL	A
L = Drizzle	As = Altostratus	U. Wyoming	Y
R = Rain	Ln = Lenticular	U. No. Dakota	N
S = Snow	Ns = Nimbostratus	So. Dakota Schl Mines	S
SP = Snow pellets	Sc = Stratocumulus	U. Washington	W
ZL = Freezing drizzle	St = Stratus	MRI	M
ZR = Freezing rain	Convective Clouds	NACA	C
+ = Heavy	Cb = Cumulonimbus	NASA/LEWIS	L
- = Light	Cg = Cumulus congestus	Univ. Clermont/LAMP	F
W = Showers	Cu = Cumulus	NOAA	P
	TCu = Towering cumulus	NRL	V
		NCAR	R
		AES (Canada)	E
		ARC (Canada)	H
		ASI (USA)	O
		DFVLR (Germany)	G
		JTD, Inc. (USA)	J
		NACA Comml & Recon	Z
		So. Africa Wthr. Bur.	X
		UMIST (UK)	B
		Mt. Washington	T

Table A-4. Sample Printout of Records From the Database

REC NO.	DATE	AGENCY	AGCY ID	PROJECT	LOCATION	LOC ID	SURF ELEV	ELEVNOTE
8	790131	U. WYOMING(King Air)	Y	SCPP: 1978-79	Sacramento, CA	SAC	500	base of foothills
9	790131	U. WYOMING(King Air)	Y	SCPP: 1978-79	Sacramento, CA	SAC	500	base of foothills
10	790131	U. WYOMING(King Air)	Y	SCPP: 1978-79	Sacramento, CA	SAC	500	base of foothills
11	790131	U. WYOMING(King Air)	Y	SCPP: 1978-79	Sacramento, CA	SAC	500	base of foothills
12	790131	U. WYOMING(King Air)	Y	SCPP: 1978-79	Sacramento, CA	SAC	500	base of foothills

REC NO.	WEATHER	AIR MASS	PRECIP	CLOUD TYP	CLD_DIST	CLD STATE	CLOUD GRP	CLOUD NUM	CLD PASS	CLD BAS HT	CLDBHNOT	CLD BAS T	CLDBTNOT
8	Sr Lc W & Ws Cl, Wk	mT	.	Sc	embedded convec	M(mW+I)	A	3	1	V	4900 to 5500	V	-3.5 to -5
9	Sr Lc W & Ws Cl, Wk	mT	.	Sc	embedded convec	W	A	3	1	V	4900 to 5500	V	-3.5 to -5
10	Sr Lc W & Ws Cl, Wk	mT	.	Sc	embedded convec	W	A	3	1	V	4900 to 5500	V	-3.5 to -5
11	Sr Lc W & Ws Cl, Wk	mT	.	Sc	embedded convec	W	A	3	2	V	4900 to 5500	V	-3.5 to -5
12	Sr Lc W & Ws Cl, Wk	mT	.	Sc	embedded convec	M(W+I)	A	3	2	V	4900 to 5500	V	-3.5 to -5

REC NO.	CLD TOP HT	CLDTHNOT	CLD TOP T	CLDTTNOT	ST TIME	TIME CONV	EVENT DEF	ALT	ALT AGL	ALT CONV	MANEUVER	TAS	TEMP	DISTANCE	DURATION	CONC
8	V	6500 to 7500	V	-7.5 to ?	95759	PST	G	6700	6200	ASL	Level	173	-7.4	3.3	68	178
9	V	6500 to 7500	V	-7.5 to ?	95924	PST	G	6700	6200	ASL	Level	170	-7.5	1.6	35	108
10	V	6500 to 7500	V	-7.5 to ?	100005	PST	H	6600	6100	ASL	Level	164	-7.6	5.6	122	114
11	V	6500 to 7500	V	-7.5 to ?	100208	PST	H	6600	6100	ASL	Level	157	-7.6	2.2	50	114
12	V	6500 to 7500	V	-7.5 to ?	100258	PST	H	6600	6100	ASL	Level	158	-7.1	1.8	42	121

REC NO.	MVD	FLWC	AVG LWC	JW LWC	CONC 1DC	LWC 1DC	CONC 2DC	CONC 1DP	CONC 2DP	ICE CONC	CLWC	FRZG LVL	EST FRLVL	FRLVL AGL
8	19	0.48	0.48	X	42.9	.	14.1	.	2.1	.	.	.	3000	2500
9	18	0.25	0.31	0.36	3.4	.	0.7	.	0.1	.	.	.	3000	2500
10	16	0.19	0.25	0.30	0.4	.	0.1		0.0	.	.	.	2800	2300
11	17	0.23	0.29	0.35	1.5	.	1.0	.	0.2	.	.	.	2800	2300
12	18	0.27	0.33	0.38	273.9	.	50.3	.	6.7	.	.	.	3100	2600

APPENDIX B—SOURCES OF DATA

B.1 HISTORICAL DATA.

The first extensive set of cloud physics research flights ever undertaken were those conducted by researchers from the U.S. Weather Bureau (WB) and the National Advisory Committee for Aeronautics (NACA) during the winters of 1946 to 1950 [B-1 to B-5]. These flights were dedicated to characterizing the icing environment for the rapidly expanding, postwar commercial airline industry. The primary measurements were of supercooled liquid water content (SLWC), average droplet sizes, and ice accretion rates.

The measurement technique judged most suitable for icing research at that time was the rotating multicylinder (RMC) technique [B-6 to B-8]. Basically, a set of four to six metal, cylindrical segments of various diameters ranging from 1/8 inch (0.3 cm) to 3 inches (7.6 cm) were exposed to the free airstream as the aircraft penetrated suitable clouds above the freezing level. The cylinders were rotated slowly to allow a uniform accretion of ice on them during the timed exposure, which usually lasted 1 to 3 minutes, depending on cloud uniformity and extent. The cylinders were then withdrawn and stored at subfreezing temperatures until later when they could be weighed to determine the mass of ice that had accumulated on each. According to droplet trajectory theory, the amount of ice accreted on each cylinder depends inversely on the cylinder diameter and directly on the number and diameter of the available droplets. As a result, the 1/8-inch-diameter cylinder collects practically all impinging droplets of all sizes of interest, and the progressively larger diameter cylinders catch only the proportionately larger droplets. The average liquid water content (LWC) from all droplets encountered during the exposure can, therefore, be computed from the ice accreted on the 1/8-inch cylinder. The amount of ice accreted on each of the larger cylinders indicates the number of droplets present in various size intervals and can be used to compute an average, volume-weighted (mass-weighted) diameter for the droplet population encountered. This volume-weighted diameter is called the median volume diameter (MVD), which is the droplet diameter that divides the LWC in half. That is, half the total LWC is contained in all droplets smaller than the MVD and the other half is in all larger droplets. The RMC method does not actually measure droplet size distributions directly, but requires the analyst to assume a droplet size distribution to compute the MVD. Because of this, the NACA researchers chose to use the term mean effective diameter (MED) instead of MVD to indicate that their result was only a best guess and not an absolute measurement. The reader is referred to other reports for the details on the use of the RMC method [B-6 to B-8].

The NACA data constitute about 4700 nautical miles (nmi) of useful measurements, primarily from the north central and north western regions of the United States. These original data are the basis of current design envelopes for the icing environment, as promulgated in the U.S. Code of Federal Regulations (CFR) [B-9 and B-10].

During the period between 1950 and 1970, a number of airborne cloud physics research projects were conducted with instrumentation that was evolving to more automated, electronic and/or optically based probes and sensors. One of these was a follow-on NACA project [B-11] during the early 1950s, in which a number of commercial airliners and weather reconnaissance aircraft were equipped with icing rate meters. These meters were designed for nearly unattended operation

along routine flight routes whenever the aircraft encountered icing conditions. Useful data are available primarily from Alaska, the Aleutians, and the North Atlantic, with a smaller number of measurements from Europe and the northwestern Pacific Ocean. All flights yielded data primarily on SLWC (from the icing rate meters) and in-cloud temperatures at various altitudes and geographic locations. Drop size information was not available.

Other projects ranged from cloud seeding experiments to flights in thunderstorms and hurricanes.

Also during the 1950s and 1960s Russian researchers undertook their own extensive measurements of icing conditions [B-12]. They sampled droplet sizes by exposing coated glass slides to the air stream. Individual droplets could be counted and sized using a microscope. This methods lends itself to characterizing drop size distributions by the simple arithmetic mean diameter instead of the MVD. The LWC was measured independently with absorbent tape or other methods.

B.2 MODERN DATA.

Beginning in 1973, a new type of automated, electro-optical, cloud particle size spectrometer became commercially available from a newly formed company called Particle Measuring Systems (PMS), Inc., of Boulder, Colorado. The original model was called the axially scattering spectrometer probe (ASSP). This was soon followed by an alternate model called the forward scattering spectrometer probe (FSSP). Both models are based on the principle of forward scattering of light from individual cloud droplets passing through a narrow, illuminating beam. The intensity of the light scattered by a droplet is proportional to the square of the droplet diameter. An optical detector senses the flash of light coming from each droplet passing through a small, sensitive volume of the illuminating laser beam. A voltage pulse is generated in the detector circuit by each flash of light, with the voltage pulse height being proportional to the intensity of the flash and, therefore, to the square of the droplet diameter. A pulse height analyzer, calibrated in terms of droplet diameter, then assigns the proper diameter to the droplet and stores the result for periodic output to a digital recording medium. From the recorded droplet size distributions, one can easily compute the droplet number density (droplets per cubic centimeter of cloud along the flight path), the LWC, and other drop size dependent quantities. An example of a typical cloud drop size distribution obtained with an FSSP is shown in figure B-1.

These and other PMS probes have become standard equipment for cloud physics studies and are now in common use by cloud physics research groups. The principal advantages are good resolution of droplet sizes, high data rates (continuous sampling during the flight with accumulated droplet size spectra usually recorded every second), and direct computer compatibility. .For these reasons, modern data, at least for the present purposes, are defined to be data from flights with ASSP or FSSP probes.

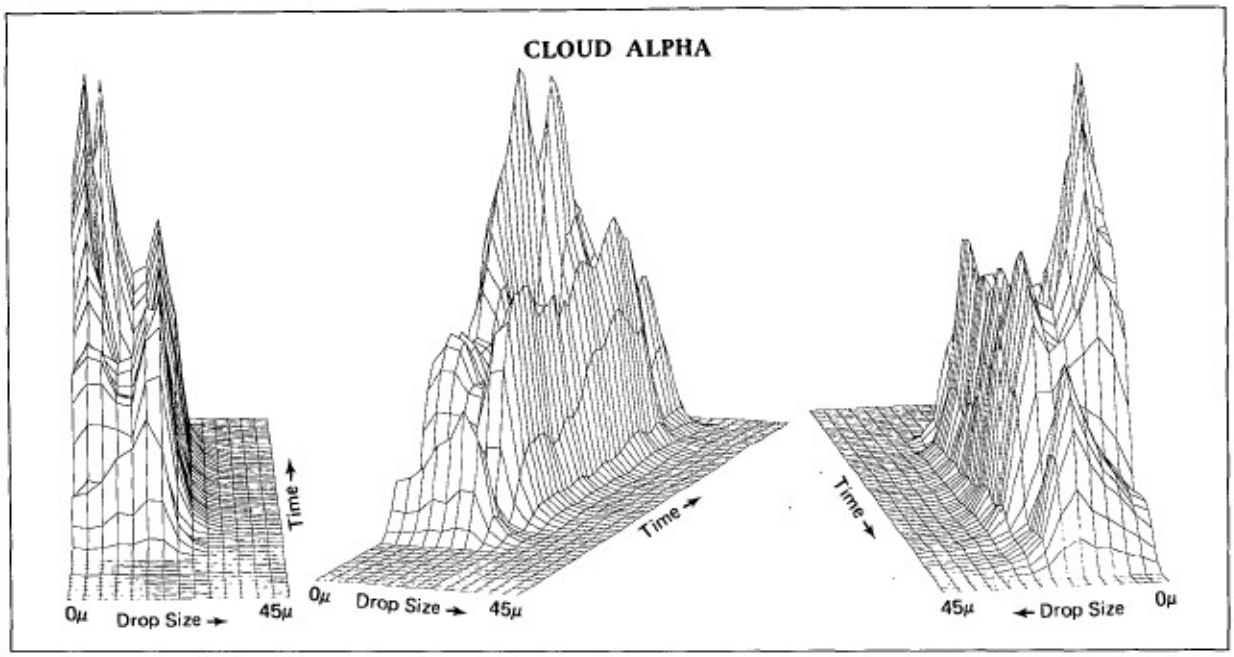

Figure B-1. Sample Drop Size Distribution From an FSSP Cloud Probe
(This illustrates the typical sharp upper limit to droplet size in
most clouds and, therefore, a sharp upper limit to MVD.)

B.3 BUILDING A NEW DATABASE.

These advances in cloud physics instrumentation, along with a growing interest in expanded cold weather operations by the helicopter industry, prompted calls in the late 1970s for new measurements of LWC and droplet sizes in low-altitude winter clouds. There were also calls for a re-evaluation of the old NACA data for accuracy and reliability, and for a study to determine whether the icing envelopes in the CFRs were representative of conditions below 10,000 feet (3 km), where most helicopter operations take place.

The author has been involved in building a new, computerized database of icing-related cloud measurements for these and other purposes. So far, about 28,000 nmi (52,000 km) of select, in-flight measurements in supercooled clouds up to 24,000 feet (7.3 km) over portions of North America, Europe, and the northern oceans have been compiled. About half of these measurements are NACA data from the 1940s and 1950s, and half are modern data. The modern measurements came from various research projects having aircraft equipped with PMS cloud droplet size spectrometers, hot-wire liquid water meters, and other complementary sensors. The modern data incorporated into the database consist of about 5800 nmi of measurements over parts of North America and about 7800 nmi over parts of Europe. Analyses have shown that the NACA data and modern data compared favorably with each other in the determination of LWC and MVD even though the measuring techniques were radically different.

Tables B-1 and B-2 list the various projects and agencies that originally obtained the measurements and the amounts of data incorporated into the new database.

Table B-1. Contributors to the U.S. SLWC Database

Project	Agency (and aircraft)	Data Miles (nmi)	Events
AFGL Icing: 1979-1980	USAF Geophysics Laboratory (C-130)	93	29
CCOPE: 1981	U. Wyoming (King Air)	901	1425
CRADP: 1982-1983	U. North Dakota (Citation)	272	113
CYCLES: 1974-1975	U. Washington (B-23)	122	26
CYCLES: 1978-1979	U. Washington (B-23)	88	32
CYCLES: 1979-1980	U. Washington (B-23)	105	63
FACE: 1978	ASI (Aero Cmmdr)	17	16
FACE: 1979	ASI (Aero Cmmdr)	4	5
FACE: 1980	ASI (Aero Cmmdr)	15	18
Great Plains Icing: 1980-1981	U. Wyoming (King Air)	597	138
Lake Snow: 1980-1981	U. Wyoming (King Air)	871	248
MRI Icing: 1979	Meteorology Research, Inc.	386	39
MRI Icing: 1979-1980	Meteorology Research, Inc.	430	88
NACA Icing 1946	NACA	580	70
NACA Icing 1946-1947	NACA	374	118
NACA Icing 1947-1948	NACA	2,112	372
NACA Icing 1948-1949	NACA	1,167	98
NACA Icing 1949-1950	NACA	480	38
NASA Icing 1983-1984	NASA/Lewis (Twin Otter)	170	65
NASA Icing 1984-1985	NASA/Lewis (Twin Otter)	108	51
NEWS: 1982-1983	NCAR (Queen Air)	138	85
NRL Icing: 1980-1981	Naval Research Lab. (P-3)	194	73
SCPP: 1978-1979	U. Wyoming (King Air)	847	517
SCPP: 1979-1980	U. Wyoming (King Air)	346	161
SCPP: 1981-1982	U. Wyoming (King Air)	35	24
SCPP: 1982-1983	U. Wyoming (King Air)	87	135
For Entire U.S. SLWC Database:		10,537	4047

NASA = National Aeronautics and Space Administration
AFGL = Air Force Geophysics Laboratory
USAF = United States Air Force
ASI = Aero Systems, Inc.
MRI = Meteorology Research, Inc.
NCAR = National Center for Atmospheric Research
NEWS = New England Winter Storms
NRL = Naval Research Laboratory
SCPP = Sierra Cooperative Pilot Project
FACE = Florida Area Cumulus Experiment
CCOPE = Cooperative Convective Precipitation Experiment
CRADP – Colorado River Augmentation Demonstration Project

Table B-2. Contributors to the Non-U.S. SLWC Database

Project	Agency (and aircraft)	Data Miles (nmi)	Events
ARC Snow: 1983	ARC/Intera (Cessna-441)	486	186
Arctic Haze: 1985	U. Washington (C131A)	199	105
Arctic Haze: 1986	U. Washington (C131A)	48	7
Acid Rain: 1982	AES (Twin Otter)	21	34
Acid Snow: 1984	AES (Twin Otter)	126	59
BPRP: 1984-1985	South African WB (Aero Cmmdr)	42	54
BPRP: 1986	South African WB (Aero Cmmdr)	56	54
	South African WB (Piper Aztec)	58	72
CASP: 1986	AES (DC-3)	437	159
	AES (Twin Otter)	111	35
CLOUDEX: 1984	AES (Twin Otter)	257	82
CaPSE: 1981	AES (Twin Otter)	399	133
DFVLR Icing: 1983	DFVLR (Do-28)	83	7
DFVLR Icing: 1983-1984	DFVLR (Do-28)	500	50
DFVLR Icing: 1984-1985	DFVLR (Do-28)	530	53
DFVLR Icing: 1985-1986	DFVLR (Do-28)	360	36
DFVLR Icing: 1986-1987	DFVLR (Do-28)	360	36
DFVLR Icing: 1987-1988	DFVLR (Do-28)	450	45
Great Dun Fell	UMIST	307	31
LANDES FRONTS: 1984	L.A.M.P. (Transall-04)	239	232
NACA Icing: 1952-1955	Eastern Airlines (L-1049)	131	6
	Northeast Airlines (CV-240)	186	18
	Northwest Orient Airlines (DC-4)	281	12
	Pan American Airlines	221	17
	Pan American Airlines (B-377)	2,503	107
	Pan American Airlines (DC-3)	142	4
	Pan American Airlines (DC-4)	77	2
	Pan American Airlines (DC-6)	103	7
	Trans World Airlines (L-1049)	100	7
NACA Icing: 1952-1955	USAF (AWS) 55th Wx Recon. Sqdn (WB-29)	245	23
	USAF (AWS) 56th Wx Recon. Sqdn (WB-29)	346	22
	USAF (AWS) 57th Wx Recon. Sqdn (WB-29)	482	26
	USAF (AWS) 58th Wx Recon. Sqdn (WB-29)	4,301	175
	USAF (SAC) 28th Recon. Wing (RB-36)	296	12
	United Airlines (DC-4)	205	13
	United Airlines (DC-6)	39	3

Table B-2. Contributors to the Non-U.S. SLWC Database (Continued)

Project	Agency (and aircraft)	Data Miles (nmi)	Events
North Sea: 1984	JTD	988	118
North Sea: 1985	JTD	398	121
Norway: 1986	JTD	46	12
PEP: 1979	U. Clermont II/Lab. Assoc. Met. (DC-7)	199	161
PEP: 1981	U. Clermont II/Lab. Assoc. Met. (Aztec)	241	254
Sweden: 1985	JTD	896	105
For Entire Non-U.S. SLWC Database:		17,494	2695

ARC = Alberta Research Council (Canada)
AES = Atmospheric Environment Service (Canada)
AWS = Air Weather Service
BPRP = Bethlehem Precipitation Research Project (South Africa)
CASP = Canadian Atlantic Storms Project
DFVLR = Deutsche Forschungs-und Versuchsanstalt Für Luft-und Raumfahrt (Germany)
JTD = JTD Environmental Services (USA)
L.A.M.P. = Laboratoire de Meteorologie Physique (France)
PEP = Precipitation Enhancement Project (Spain)
SAC = Strategic Air Command
UMIST = University Manchester Institute of Science and Technology (UK)

Table B-3 summarizes the data collected according to geographic region and contributing agency.

Table B-3. Composition of the Supercooled Cloud Database at the FAA William J. Hughes Technical Center

Location	Data Miles (nmi)	Contributor	Data Miles (nmi)	ID
CONUS	11,394	NACA/USAF	5,670	Z
AK and NORPAC	5,732	NACA/USWB	4,713	C
North Atlantic	3,069	NACA/Comml.	3,989	Z
West Germany	2,283	U. Wyoming	3,682	Y
Canada	1,837	MRI/JTD	3,144	M, J
North Sea	1,386	DFVLR	2,283	D
Sweden	896	AES	1,350	E
Spain	440	L.A.M.P.	679	F
England	307	U. Washington	565	W
Arctic	247	ARC	486	H
France	239	UMIST	307	B
South Africa	156	NASA/Lewis	278	L

Table B-3. Composition of the Supercooled Cloud Database at the FAA William J. Hughes Technical Center (Continued)

Location	Data Miles (nmi)	Contributor	Data Miles (nmi)	ID
Norway	46	U. North Dakota	272	N
		NRL	194	V
		South African WB	160	X
		NCAR	138	R
		AFGL	93	A
	28,032 nmi		28,032 nmi	

CONUS = Conterminous (or contiguous) United States
AK = Alaska
NORPAC = Northern Pacific
USWB = United States Weather Bureau

B.4 REFERENCES.

B-1. Lewis, W., "A Flight Investigation of the Meteorological Conditions Conducive to the Formation of Ice on Airplanes," NACA TN 1393, 1947.

B-2. Lewis, W. and Jones, A.R., "Recommended Values of Meteorological Factors to be Considered in the Design of Aircraft Ice-Prevention Equipment," NACA TN 1855, 1949.

B-3. Lewis, W. and Hoecker, W.H., "Observations of Icing Conditions Encountered in Flight During 1948," NACA TN 1904, 1949.

B-4. Hacker, P.T. and Dorsch, R.G., "A Summary of Meteorological Conditions Associated With Aircraft Icing and a Proposed Method of Selecting Design Criterions for Ice-Protection Equipment," NACA TN 2569, 1951.

B-5. Kline, D.B., "Investigation of Meteorological Conditions Associated With Aircraft Icing in Layer-type Clouds for 1947-48 Winter," NACA TN 1793, 1949.

B-6. Burn, R.J., et al., "Impingement of Cloud Droplets on a Cylinder and Procedures for Measuring Liquid Water Content and Droplet Sizes in Supercooled Clouds by Rotating Multicylinder Method," NACA report 1215, 1955.

B-7. Jones, A.R. and Lewis, W., "A Review of Instruments Developed for the Measurement of the Meteorological Factors Conducive to Aircraft Icing," NACA RM A9C09, 1949.

B-8. Ludlam, F.H., "The Heat Economy of a Rimed Cylinder," *Quarterly Journal of the Royal Meteorological Society*, Vol. 77, pp. 663, 1951.

B-9. Title 14 Code of Federal Regulations, Aeronautics and Space, Part 25 Airworthiness Standards: Transport Category Airplanes, Appendix C; published by the Office of the Federal Register, National Archives and Records Administration, Washington, DC.

B-10. Title 14 Code of Federal Regulations, Aeronautics and Space, Part 29 Airworthiness Standards: Transport Category Rotorcraft, Appendix C; published by the Office of the Federal Register, National Archives and Records Administration, Washington, DC.

B-11. Perkins, P.J., "Summary of Statistical Icing Cloud Data Measured Over United States and North Atlantic, Pacific, and Arctic Oceans During Routine Aircraft Operations," NASA Memorandum 1-19-59E, 1959.

B-12. Trunov, O.K., "Icing of Aircraft and Means of Combatting It," Moscow, 1965.

APPENDIX C—THE ORIGIN AND INTERPRETATION OF HORIZONTAL EXTENT SPECIFICATIONS AND THE LWC FACTOR CURVES IN 14 CFR PARTS 25 AND 29 APPENDIX C

C.1 INTRODUCTION.

The horizontal extent (HE) of icing conditions is a principal factor in the correct interpretation and application of cloud characterization data as presented in figures 1, 3, 4, and 6 of Title 14 Code of Federal Regulations Parts 25 and 29 Appendix C (herein referred to as Appendix C) [C-1 and C-2]. (These same figures have been reproduced in the main text as figures 1, 3, 4, and 6). In figures 1 and 4 (the liquid water content (LWC) versus median volume diameter (MVD) envelopes), it is stated that the plotted curves apply only to specific, standard HEs of 17.4 nmi for continuous maximum conditions (figure 1) and 2.6 nmi for intermittent maximum conditions (figure 4). The curves in these two figures represent the probable maximum LWC that is to be expected as an average during flight in the specified cloud type, temperature, and HE [C-3]. In most cases, actual HEs will differ from the standard 17.4 or 2.6 nmi. To compensate for these situations, figures 3 and 6 were developed to allow the probable maximum values of LWC in figures 1 and 4 to be adjusted for shorter or longer HEs (averaging intervals).

The origin of these LWC adjustment factor curves in figures 3 and 6, the exact meaning of the terms probable maximum and standard distance, and the reasons for specifying 17.4 and 2.6 nmi are often obscure to the typical user, however. This fact, along with an absence of instructions in Appendix C, has resulted in some uncertainty regarding the proper interpretation and use of the curves. For this reason, the purpose and meaning of these concepts as they were developed in the original National Advisory Committee for Aeronautics (NACA) technical reports will be reviewed as follows.

C.2 DEFINITION OF TERMS.

The term probable maximum was originally a qualitative term first introduced, but not defined, by Lewis in 1947 [C-4]. In 1949 [C-5], it was described as “not represent[ing] the maximum that nature could produce, but rather the maximum that would probably be encountered in all-weather aircraft operations.” Later, in 1952 [C-3], a comprehensive statistical analysis of the available icing cloud data allowed the term to be quantified. The statistical analyses concluded that the numerical values of LWC previously proposed as probable maxima actually correspond to an exceedence probability of about 1%. That is, a given probable maximum value of LWC is expected to be exceeded only once in 100 standard distances in the specified cloud type at the specified temperature.

Standard distances came about only because they were the most common exposure distances in icing clouds during the early research flights. These distances of 3 statute miles for cumuliform clouds and 10 statute miles for layer clouds were, thus, the most convenient for data reduction purposes. In reference C-3, Lewis and Bergrun proposed that the standard distances be used as design values of HE, except for layer clouds where a 20-mile design value was thought to be more suitable. This was mainly because their recommended design values of LWC corresponded better to a 20-mile averaging distance than to a 10-mile distance. They also

believed that 10 miles was probably too short to be representative of layer cloud extents, but that distances larger than about 20 miles would result in a LWC factor that was too low for realistic design purposes.

When these distances are converted from 20 and 3 statute miles to nautical miles (nmi), one obtains the 17.4 and 2.6 nmi HEs specified in figures 1 and 4 of Appendix C. Note that the nomenclature of Appendix C still today refers to these values as standard distances, however.

Bear in mind that these standard distances are entirely arbitrary because they are only recommendations by Lewis for general purpose usage. Some interpretations seem to regard them as mandatory distances, but there is no reason why different HEs cannot be specified depending on the anticipated flight missions. For example, if extended time in holding patterns at busy airports is a concern, then it may be appropriate to specify a longer HE (exposure time). For helicopters, it may be necessary to specify exposure in terms of time rather than distance if the ability to hover in icing conditions is a concern.

C.3 EVOLUTION OF THE LWC FACTOR.

The first appearance of any attempt to relate average LWC to HE was in 1947 [C-4]. Figure 13 of that reference (figure C-1 here) is a scatterplot of measured LWC averages versus the duration of the averages in flight. The sloped line is an estimated probable maximum value of LWC to be found during flight in continuous icing conditions of any selected duration. The authors carefully pointed out that the estimated line is uncertain due to the limited amount of data upon which it is based. They proposed that it be used as "a roughly quantitative indicator of the inverse relationship which exists between a specified icing condition and the probable duration of flight in that condition." It should be noted that most of the data points lie well below the line. That is, the line should not be casually misapplied to the average LWC, for example.

In this same report [C-4], the authors proposed the tentative design values shown in table C-1.

Table C-1. Early, Tentative Design Values From Reference C-4

Cloud Type	Duration at 160 mph (minutes)	LWC (g/m^3)	Average Drop Diameter (µm)	Temperature	
				(°F)	(°C)
Cu	1	2.0	20	0	-18
St or Sc	>20	0.8	15	20	-7
St or Sc	>20	0.5	25	20	-7

Cu = Cumulus
St = Stratus
Sc = Stratocumulus

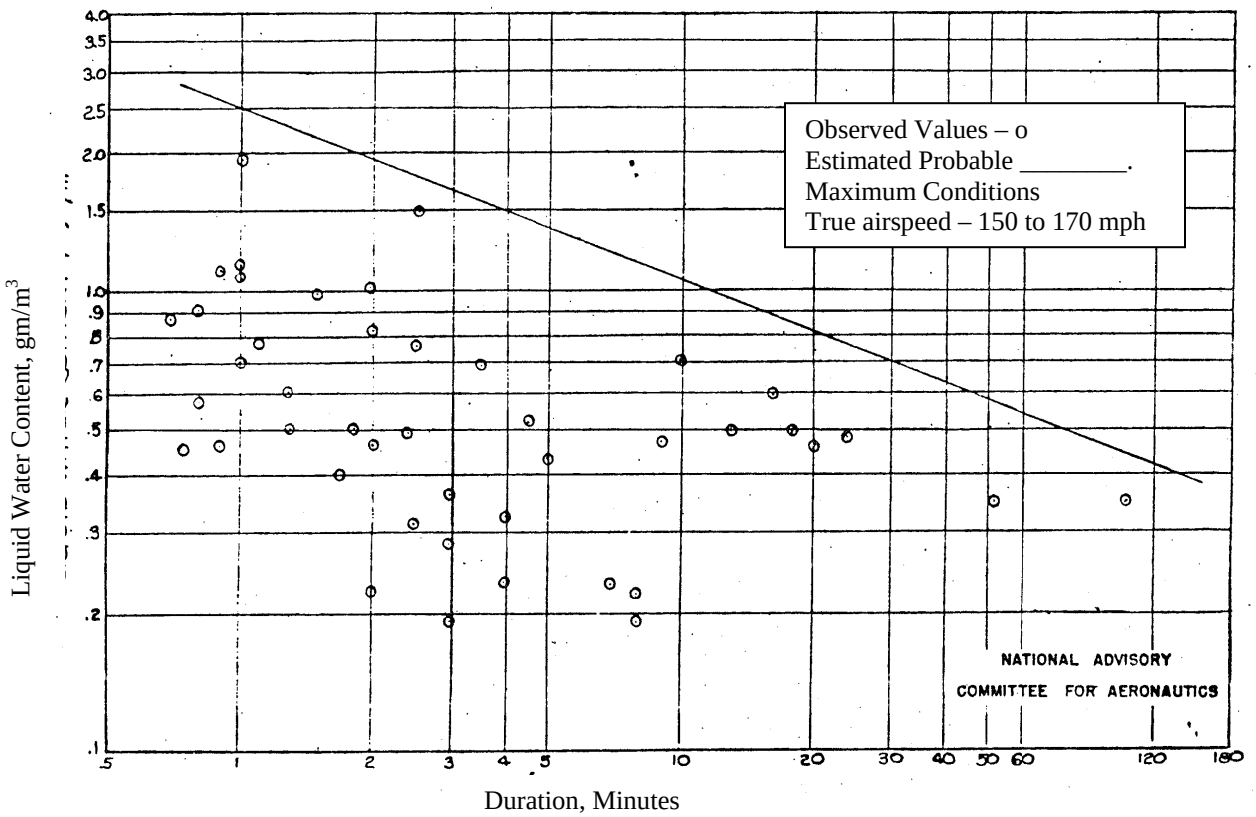

Figure C-1. Average LWC in Winter Icing Conditions as a Function of Maximum Duration of Flight in the Condition (From figure 13 of NACA TN 1393 [C-4].)

These were thought to be the most severe icing conditions likely to be encountered in the course of all-weather transport operations in the United States. The values of LWC and duration listed in table C-1 are not based completely on their figure 13, just described, but also take into account other data and observations. The 0.8 g/m^3 LWC at a duration of 20 minutes agrees with the sloped line in their figure 13, but the 2.0 g/m^3 LWC is tied to a duration of 1 minute rather than about 2 minutes as the sloped line suggests. The latter result is based on the authors' judgement that, although an average LWC of 2 g/m^3 may be encountered for a maximum of 2 minutes (at 160 mph), the most probable maximum duration is more likely to be 1 minute. The reasoning was that "it is highly unlikely that the maximum duration of two minutes will be encountered on the rare occasions when the highest water content occurs, [so] the more probable value of one minute was chosen."

During the years 1947-1949, table C-1 evolved into a revised and extended list of conditions "recommended for consideration in the design of ice-protection equipment" [C-5]. This new listing, shown as figure C-2 here, when converted into graphical form, becomes the continuous maximum and intermittent maximum envelopes in figures 1 and 4 Appendix C. The revised list for intermittent maximum conditions retains the 1-minute specification for "duration at 180 mph." This converts to the specified HE of 3 statute miles or 2.6 nmi. No specific duration or HE was given for the continuous maximum condition in this list; both were simply described as "continuous." No graphs relating LWC to HE were included.

Class	Item	Air temp. (°F)	Liquid water content (g/m³)	Drop diameter (microns)	Pressure altitude (ft)	Remarks
I – M Instantaneous, Maximum	1	32	5.0	25	18,000 to 20,000	Horizontal extent: 1/2 mile. Duration at 180 mph: 10 seconds. Characteristic: Very high liquid water content. Applicable to: Any part of the airplane, such as guide vanes in inlet ducts, where a sudden large mass of supercooled water would be critical, even though of short duration. Example: Induction systems, particularly turbine-engine inlets.
	2	14	4.5	25	22,000 to 25,000	
	3	-4	3.0	25	25,000 to 30,000	
	4	-22	2.0	20	20,000 to 30,000	
	5	-40	.5	15	20,000 to 30,000	
I – N Instantaneous, Normal	6	32	1.0	20	15,000 to 20,000	
	7	14	1.0	20	10,000 to 25,000	
	8	-4	.6	18	12,000 to 30,000	
	9	-22	.2	15	15,000 to 30,000	
	10	-40	<.1	13	15,000 to 30,000	
II – M Intermittent, Maximum	11	32	2.5	20	10,000 to 15,000	Horizontal extent: 3 miles Duration at 180 mph: 1 minute Characteristic: High liquid water content Applicable to: Any critical component of the airplane where ice accretions, even though slight and of short duration could not be tolerated. Example: Induction systems, windshields when continuous visibility is required.
	12	14	2.2		10,000 to 20,000	
	13	-4	1.7		12,000 to 30,000	
	14	-22	1.0		15,000 to 30,000	
	15	-40	.2		15,000 to 30,000	
	16	32	1.3	30	8,000 to 15,000	
	17	14	1.0		8,000 to 20,000	
	18	-4	.8		10,000 to 30,000	
	19	-22	.5		15,000 to 30,000	
	20	-40	.1		15,000 to 30,000	
	21	32	.4	50	8,000 to 15,000	
	22	14	.3		8,000 to 20,000	
	23	-4	.2		10,000 to 30,000	
	24	-22	.1		15,000 to 30,000	
	25	-40	<.1		15,000 to 30,000	
II – N Intermittent, Normal	26	32	.8	20	8,000 to 12,000	
	27	14	.6	20	8,000 to 15,000	
	28	-4	.4	18	12,000 to 20,000	
	29	-22	.1	15	15,000 to 25,000	
	30	-40	<.1	13	15,000 to 25,000	
III – M Continuous, Maximum	31	32	.8	15	3,000 to 20,000	Horizontal extent and duration: Continuous. Characteristic: Moderate to low liquid water content for an indefinite period of time. Applicable to: All components of the airplane; that is, every part of the airplane should be examined with the question in mind, "Will this part be affected seriously by accretions during continuous flight in icing conditions?" Example: Wings and tail surfaces.
	32	14	.6			
	33	-4	.3			
	34	-22	.2			
	35	-40	.05			
	36	32	.5	25		
	37	14	.3			
	38	-4	.15			
	39	-22	.10			
	40	-40	.03			
	41	32	.15	40		
	42	14	.10			
	43	-4	.06			
	44	-22	.04			
	45	-40	.01			
III – N Continuous, Normal	46	32	.3	15		
	47	14	.2			
	48	-4	.1			
	49	-22	<.1			
IV – M Freezing Rain	50	25 to 32	.15	1000	0 to 5,000	Horizontal extent: 100 miles. Duration at 180 mph: 30 minutes. Characteristic: Very large drops at near-freezing temperatures and low values of liquid water content. Applicable to: Components of the airplane for which no protection would be supplied after considering classes I, II, and III. Example: Fuselage static pressure airspeed vents.

Figure C-2. Recommended Values of Meteorological Factors for Consideration in the Design of Aircraft Ice Prevention Equipment (From table 1 of NACA TN 1855 [C-5].)

A revision of the LWC versus HE curve was published separately by Lewis in 1949, [C-6]. Here the conditions were more specific, because the curve was said to represent the maximum LWC to be expected in 1000 flights encountering icing, assuming 5% (or 50) of the flights encounter cumulus clouds. The 5% cumulus mix was based on German experience reported in a contemporary reference. The curve is reproduced here as figure C-3.

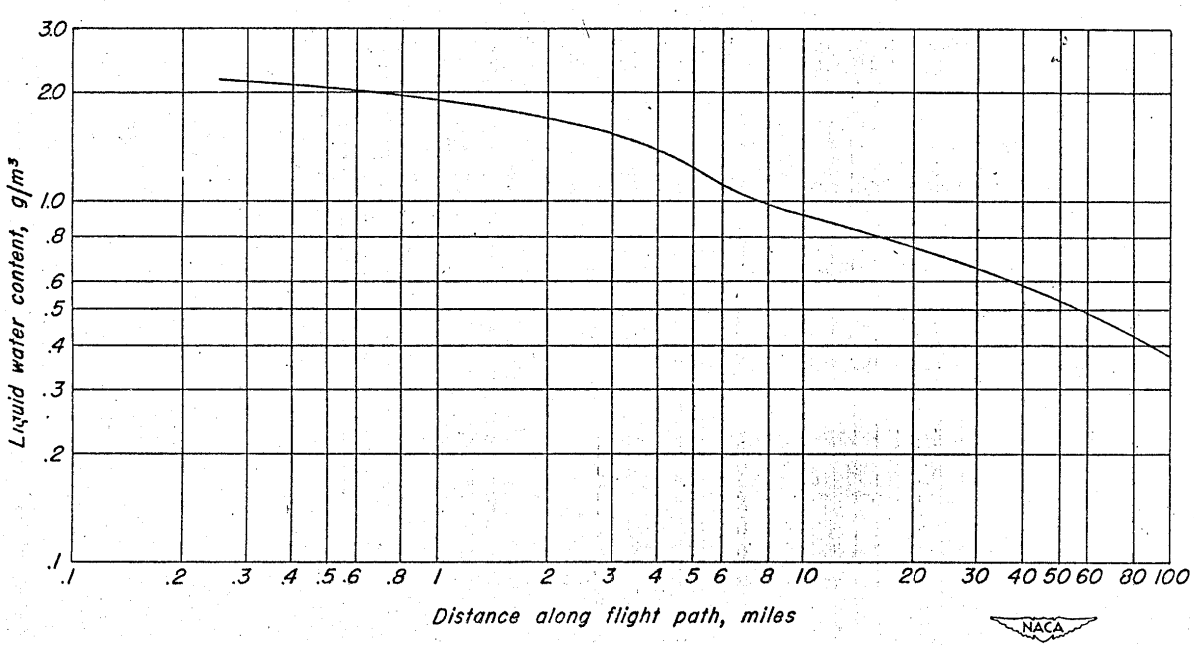

Figure C-3. Estimated Maximum Values of Average LWC to be Expected in 1000 Flights Encountering Icing, Assuming 5 Percent of Flights Encounter Cumulus Clouds (From figure 5 of NACA TN 1904 [C-6].)

Actual data points supporting this curve were limited to only five selected averaging intervals. These were 10 sec (0.5 mile), 1 min (3 miles, 3 min (10 miles), 5 min (15 miles), and 20 min (60 miles), as determined to a large extent by the fixed timing intervals used in the flights before 1948. The portion of the curve representing conditions 3 miles or less in extent gives the maximum LWC to be expected in 50 encounters with cumulus clouds. The position of the curve at 0.5 and 3 miles is based on data from 26 and 47 flights, respectively. The actual HE of most cumulus clouds investigated by the NACA researchers was from 1 to 3 miles. The data for the 10-second (1/2 mile) averages were regarded as representative for cumulus clouds, while the averages for 1 minute (3 miles) are subject to some error but are regarded as approximately representative.

The curve for distances of 10 miles and greater represents the LWC expected to occur once in 950 flights in layer clouds. The position of the curve at 10 miles is based on data from 51 flights, and the position from 15 to 100 miles is estimated from only 11 flights. The greatest HE included is 100 miles.

Associates of Lewis proposed an alternate LWC versus HE curve in 1951 [C-7]. Figure 2 of that report (figure C-4 here) showed the curve lying at somewhat larger values of LWC and extending to distances of about 350 miles.

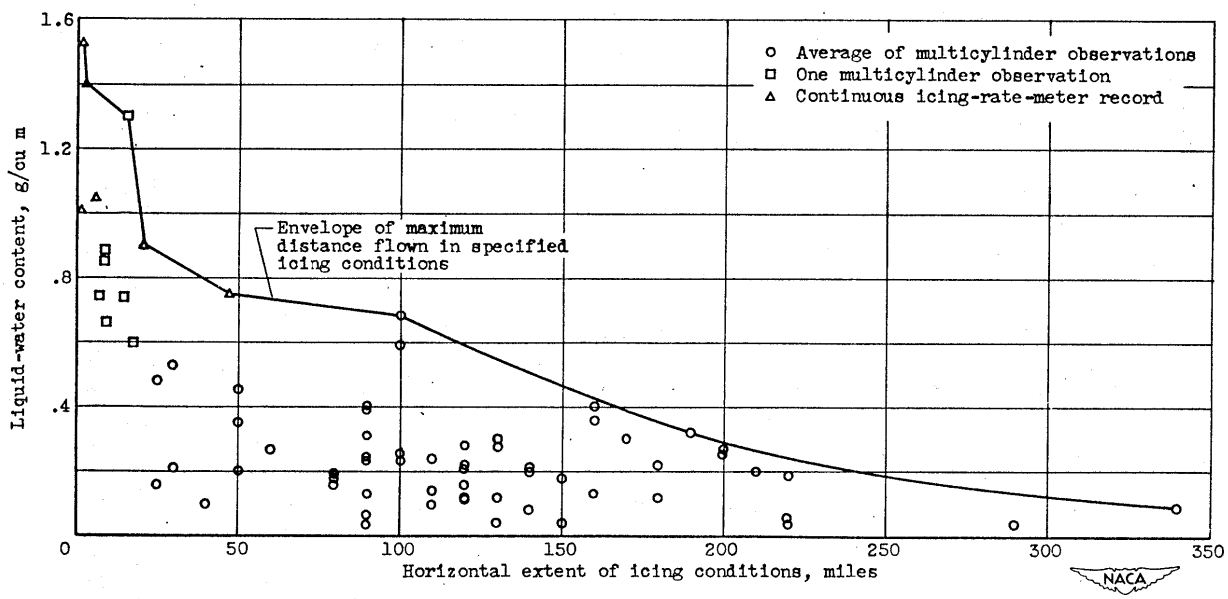

Figure C-4. Maximum Distances Flown During 57 Icing Flights in Relation to Average Measured LWC of Supercooled Stratiform Clouds
(From figure 2 of NACA TN 2306 [C-9], 1951.)

Other NACA researchers issued yet another variation of this curve in 1951 [C-8], and it fell at even larger values of LWC (figure C-5 here).

The last version of the LWC versus HE curves appeared in 1952 as figure 8 in the authoritative report by Lewis and Bergrun [C-3]. The LWC curve was now presented in terms of a dimensionless multiplying factor instead of directly in units of LWC (g/m^3). This allowed the LWC dependence to be displayed as two separate curves, one for cumulus clouds up to 6 statute miles (5.2 nmi) in extent, and one for layer clouds from 6 to about 100 statute miles. This last version was based solely on the earlier version by Lewis and Hoecker [C-6], and it apparently ignored the intervening versions with the somewhat larger LWC values and with distances beyond 100 miles [C-8 and C-9]. This final version also specified standard distances of 3 statute miles for cumulus clouds and 10 statute miles for layer clouds. These choices were based mainly on the fact that they were the typical exposure lengths during the research flights. Moreover, the authors suggested a design value of 20 miles instead of the standard distance of 10 miles for layer clouds. This was based on their conclusion that 10 miles is too short for layer clouds, but that distances longer than about 20 miles would result in too low a LWC factor for design purposes.

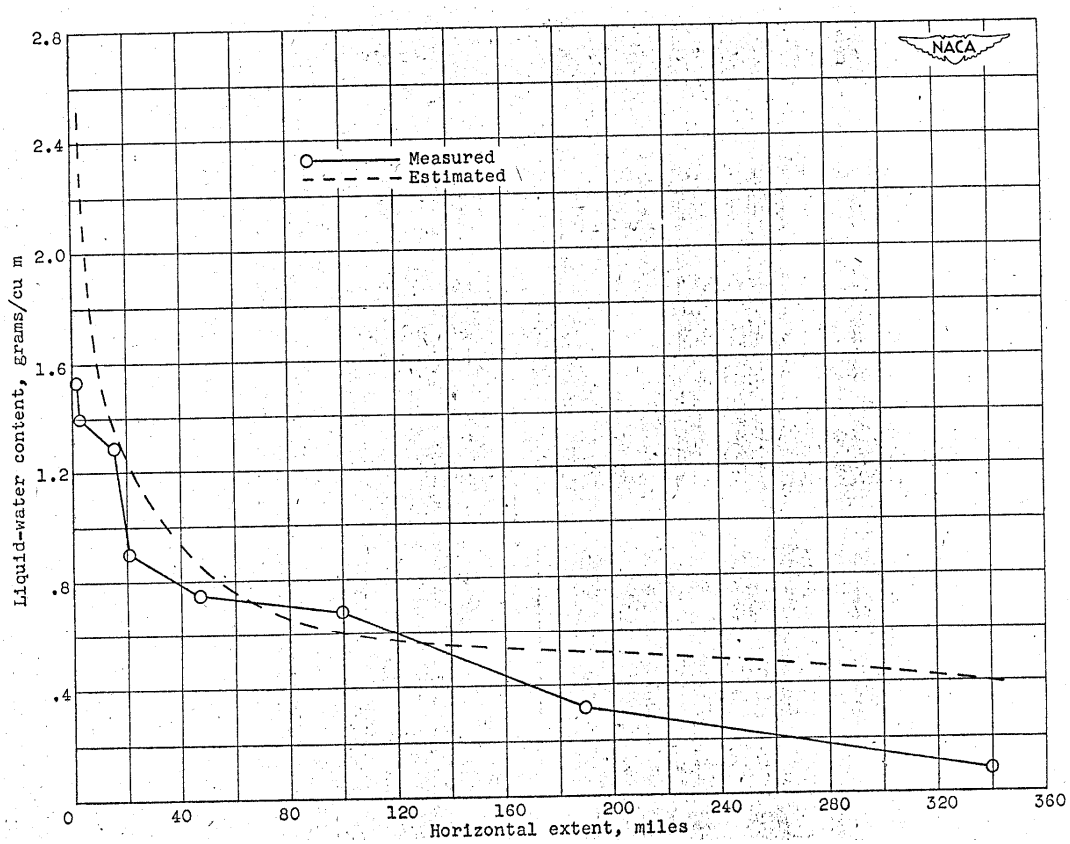

Figure C-5. Maximum HE of Icing Encounters in Relation to Average LWC
(From figure 5 of NACA TN 2569 [C-8].)

The versions of these curves that finally appeared as figures 3 and 6 of Appendix C are referenced directly to figure 8 of Lewis and Bergrun [C-3], although only figure 6 of Appendix C appears to exactly correspond. The curve in figure 3 has been raised somewhat above Lewis and Bergrun's curve so that the unit value (F = 1.0) point on the curve lies at 17.4 nmi (20 statute miles) instead of at 10 statute miles where Lewis and Bergrun had it. Figure 3 has also been extrapolated anonymously to 300 nmi from the approximate 100 nmi extreme in reference C-3.

C.4 SUMMARY.

The LWC adjustment factor curves in figures 3 and 6 of Appendix C evolved out of a tentative curve suggested by Lewis in 1947 [C-4]. Lewis' original curve was intended to be a roughly quantitative indicator of the fact that the maximum probable LWC to be expected in icing conditions decreases as the HE of the continuous cloud system increases. Eventually, the curve was divided into more quantitative-looking forms in figure 8 of reference C-3 (figure C-6 here), but they were still based on a small number of flights. For that reason, Lewis reminded readers that the assumed representativeness of the curves was still uncertain. The curves were finally given an official status when they were incorporated into the design criteria as figures 3 and 6 of Appendix C.

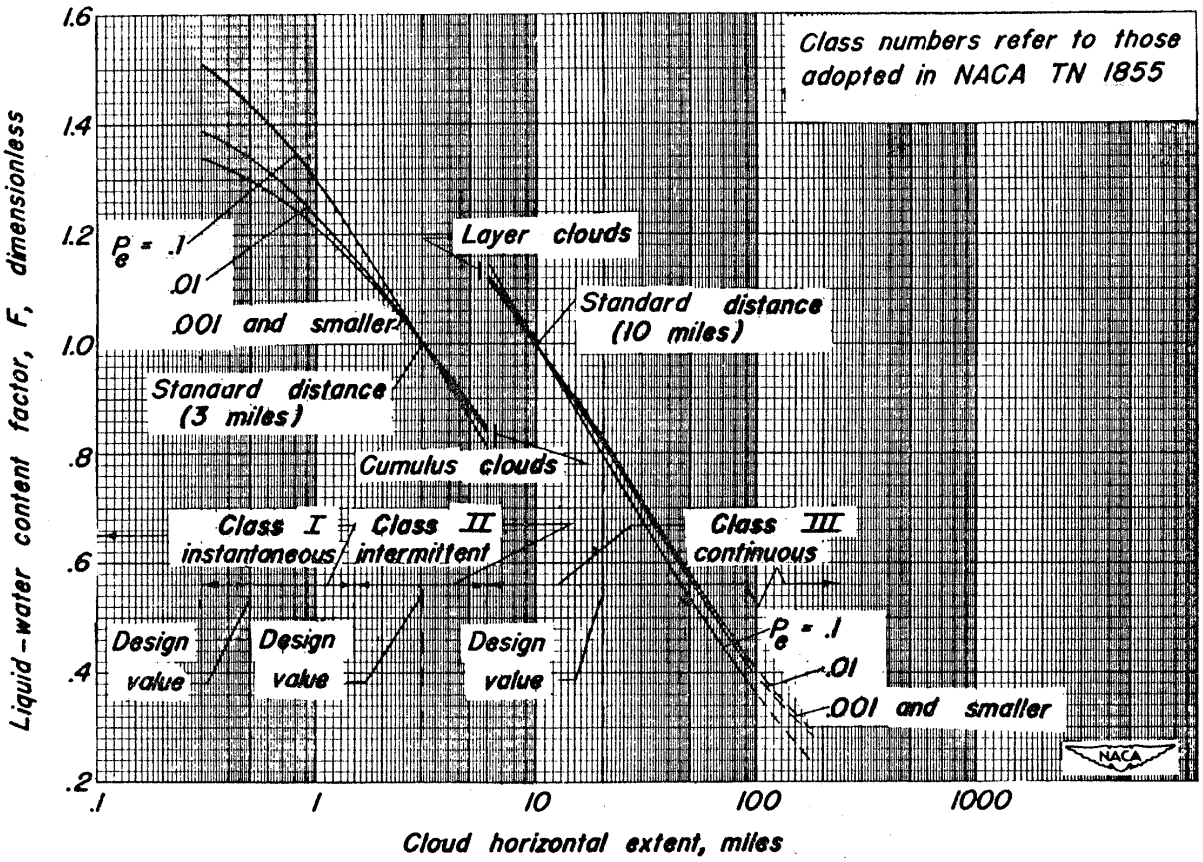

Figure C-6. Variation, With HE, of the Factor by Which Values of LWC Should be Multiplied to Include the Effect of Horizontal Cloud Extent (From figure 8 of NACA TN 2738 [C-3].)

C.5 APPLICATION OF THE LWC FACTOR CURVES.

The original purpose of these curves, as explained by Lewis, et al. [C-4, C-6, and C-3], was to estimate the maximum probable LWC to be expected as an average during flight for various distances through continuous icing conditions. The brief instructions accompanying the set of graphs in Appendix C are noncommittal in describing how these curves are to be applied. As a result, users have interpreted the instructions variously and have proposed other ways of employing the LWC adjustment factor curves. These mostly involve attempts to justify substituting longer exposures to compensate for smaller than desired LWCs during test flights. This practice is not a correct use of the LWC factor, however. The factor actually represents only the maximum probable LWC to be expected as an average versus the averaging distance in the cloud.

C.6 REFERENCES.

C-1. Title 14 Code of Federal Regulations, Aeronautics and Space, Part 25 Airworthiness Standards: Transport Category Airplanes, Appendix C, published by the Office of the Federal Register, National Archives and Records Administration, Washington, DC.

C-2. Title 14 Code of Federal Regulations, Aeronautics and Space, Part 29 Airworthiness Standards: Transport Category Rotorcraft, Appendix C; published by the Office of the Federal Register, National Archives and Records Administration, Washington, DC.

C-3. Lewis, W. and Bergrun, N.R., "A Probability Analysis of the Meteorological Factors Conducive to Aircraft Icing in the United States," NACA TN 2738, 1952.

C-4. Lewis, W. "A Flight Investigation of the Meteorological Conditions Conducive to the Formation of Ice on Airplanes," NACA TN 1393, 1947.

C-5. Lewis, W. and Jones, A.R., "Recommended Values of Meteorological Factors to be Considered in the Design of Aircraft Ice-Prevention Equipment," NACA TN 1855, 1949.

C-6. Lewis, W. and Hoecker, W.H., "Observations of Icing Conditions Encountered in Flight During 1948," NACA TN 1904, 1949.

C-7. Khrgian, A.Kh. (editor), "Cloud Physics" ("Fizika Oblakov"), Leningrad, 1961.

C-8. Hacker, P.T. and Dorsch, R.G., "A Summary of Meteorological Conditions Associated With Aircraft Icing and a Proposed Method of Selecting Design Criterions for Ice-Protection Equipment," NACA TN 2569, 1951.

C-9. Kline, D.B. and Walker, J.A., "Meteorological Analysis of Icing Conditions Encountered in Low-Altitude Stratiform Clouds," NACA TN 2306, 1951.

APPENDIX D—COMPARISON OF LWC CURVES IN 14 CFR PARTS 25 AND 29 APPENDIX C TO LWC PERCENTILES DERIVED FROM THE MODERN DATABASE

The liquid water content (LWC) curves in figures 1 and 4 of Title 14 Code of Federal Regulations Parts 25 and 29 Appendix C (herein referred to as Appendix C) are thought to represent approximately the 99th percentile values of LWC to be found in nature, according to an analysis performed in 1952 [D-1]. The original dataset upon which the 99th percentile estimate was based consisted of about 3000 nmi of measurements in stratiform clouds and approximately 500 nmi of data in cumuliform clouds from the late 1940s. The modern database contains 23,000 nmi of measurements in stratiform clouds and 5,000 nmi in convective (cumuliform) clouds. This database, which is almost 10 times larger, should give better statistics, and a modern Weibull method of analysis [D-2 and D-3] should result in more reliable values for the 99th percentile values of LWC.

This appendix shows detailed comparisons between the Appendix C LWC curves and the 99th and 99.9th percentile values of LWC obtained from the modern database of supercooled cloud variables.

D.1 CONTINUOUS MAXIMUM.

Figure D-1 gives the continuous maximum LWCs for 15-µm median volume diameters (MVD) (from Appendix C figure 1) converted to the distance-based format. This conversion is necessary to compare data from a wide range of averaging distances (horizontal extents (HE)). The LWC values at 17.4 nmi in figure D-1 match those at 15 µm in Appendix C figure 1. The curves in figure D-1 are obtained simply by multiplying the 17.4-nmi LWCs by F-factors obtained from Appendix C figure 3 for the range of horizontal extents [D-4]. (The reader should be mindful that the F-factor curves themselves are coarse estimates of the distance behavior, based on a relatively small number of data points, as explained in appendix C of this report.)

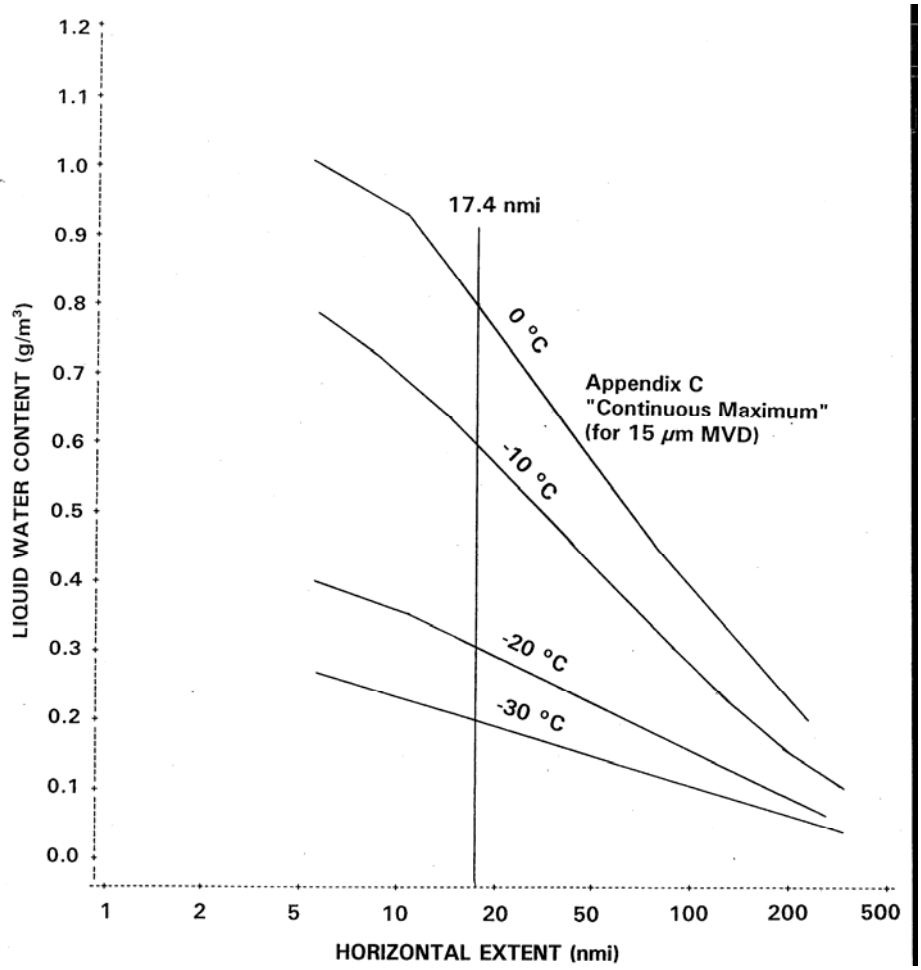

Figure D-1. Continuous Maximum LWCs (for 15-µm MVDs) in a Distance-Based Format

Figure D-2 compares the curves in figure D-1 (shown as dashed lines in figure D-2) to actual 99th percentile curves derived from the new database. The conclusions are:

- According to the database, there is really no decrease in expected maximum LWC between 0° and -10°C.

- The Appendix C curves slightly overestimate the 99th percentile LWCs for 0°C and slightly underestimate LWCs for -10°C.

- At -20° and -30°C, the Appendix C curves underestimate the 99th percentile LWC for intermediate averaging distances centered at the standard design exposure distance of 17.4 nmi.

- While the Appendix C curves may be acceptable for design purposes, the new 99th percentile curves give an improved picture that is more realistic. The new curves have already been proposed in figure 24 of this report as one possible updated replacement for figure 1 of Appendix C.

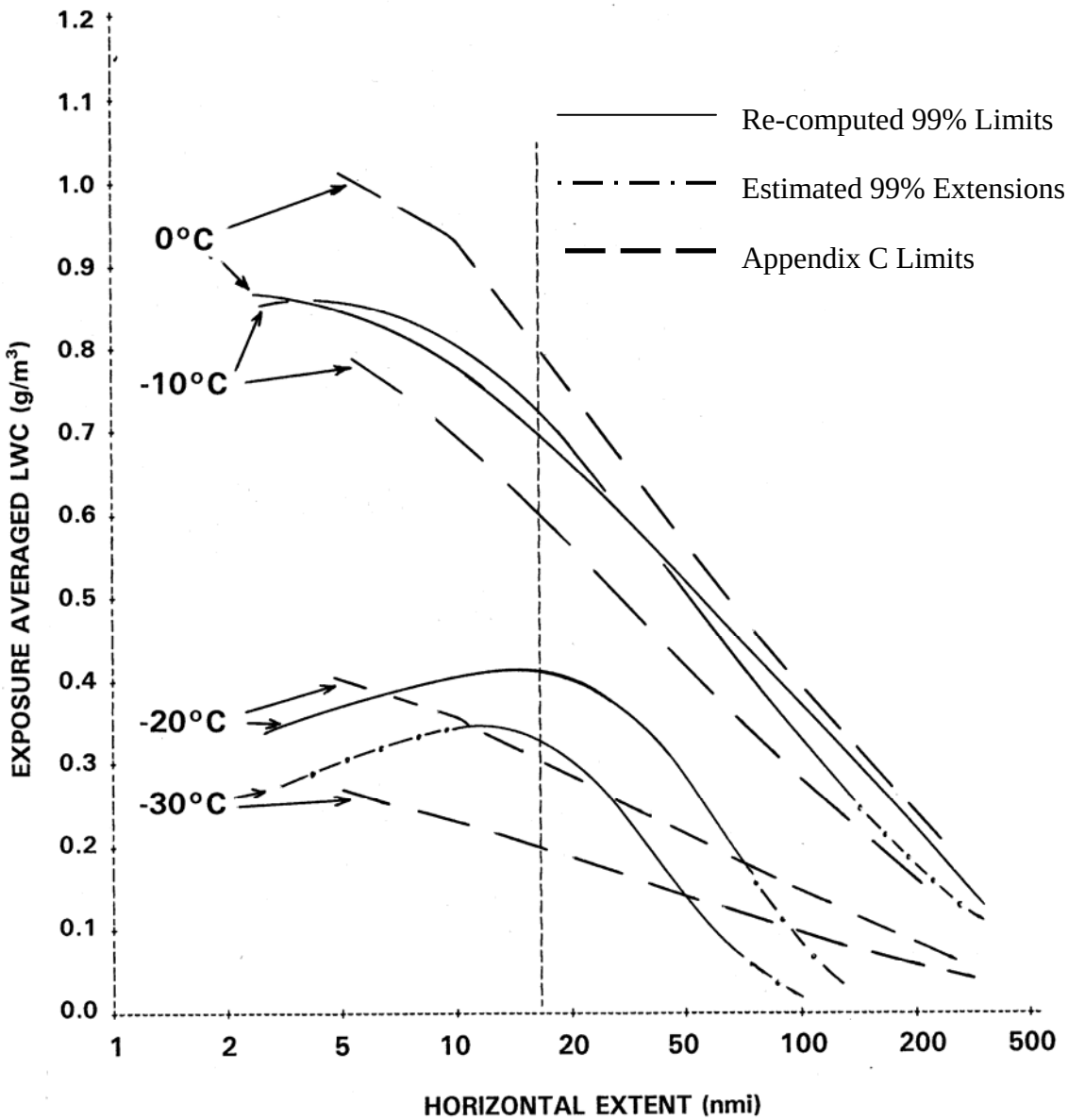

Figure D-2. Comparison of Continuous Maximum and Recomputed 99th Percentile Limits to LWC (All curves apply to stratiform clouds with MVDs from 10 to 20 µm diameter.)

Figures D-3 to D-5 show another way to compare Appendix C with the new database. These figures compare the individual curves in figure D-1 with several percentile curves derived from the database. Figure D-3 shows that the existing continuous maximum LWC curve for 0°C lies between the 99th and 99.9th percentiles. Figure D-4 shows that the -10°C curve falls below the 99th percentile, lying between it and the 95th percentile values. In both cases, the shape and extent of the Appendix C curves are remarkably good. Figure D-5 shows a contracted and humped set of curves that are only coarsely approximated by the linear Appendix C curve. In this case, the Appendix C curve mostly underestimates the 99th percentile, except for the shortest and longest distances.

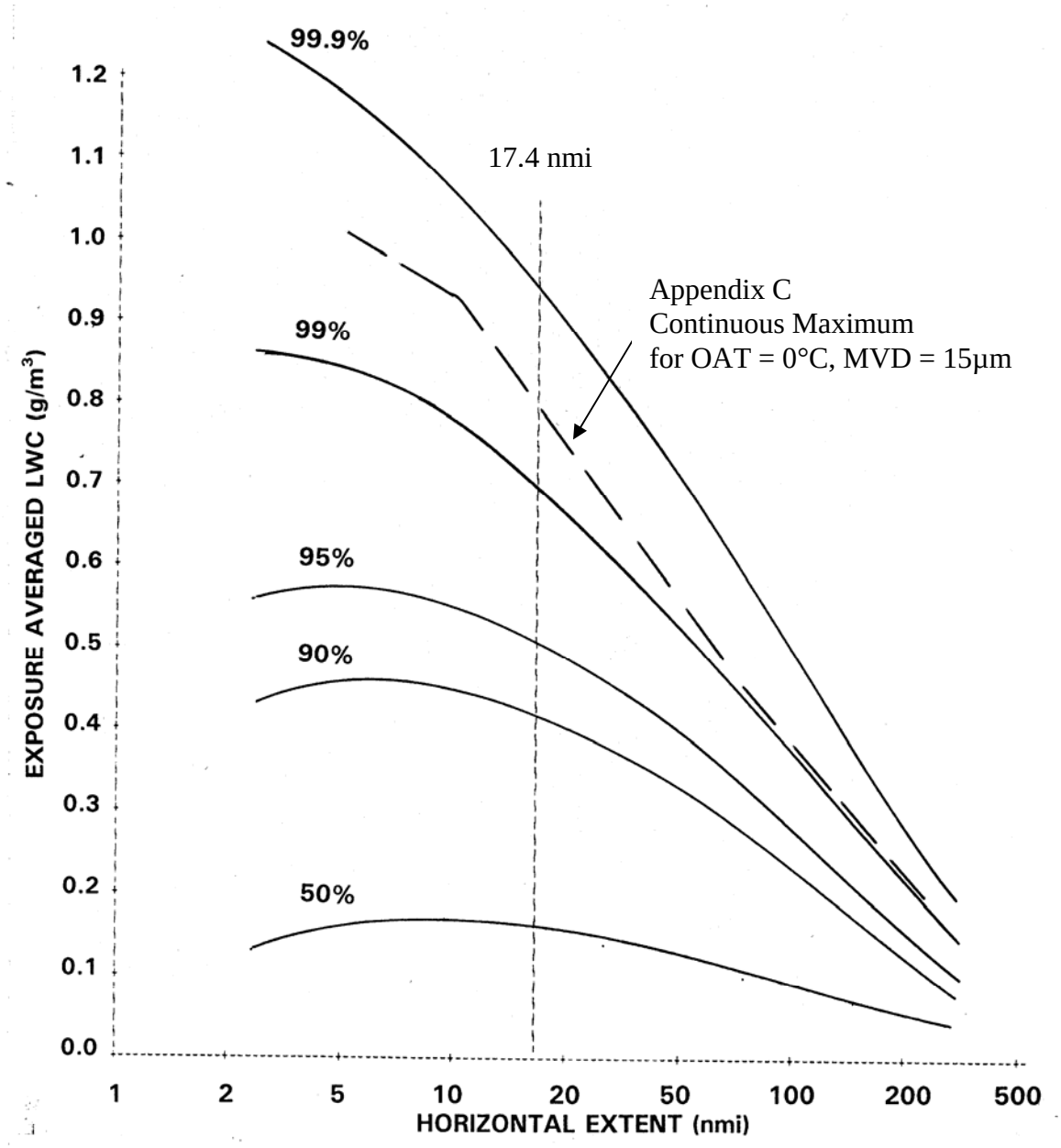

Figure D-3. Comparison of Continuous Maximum LWC to LWC Percentiles (Risk Levels) for Layer Clouds With MVD = 10 to 20 µm and Outside Air Temperature up to 0°C

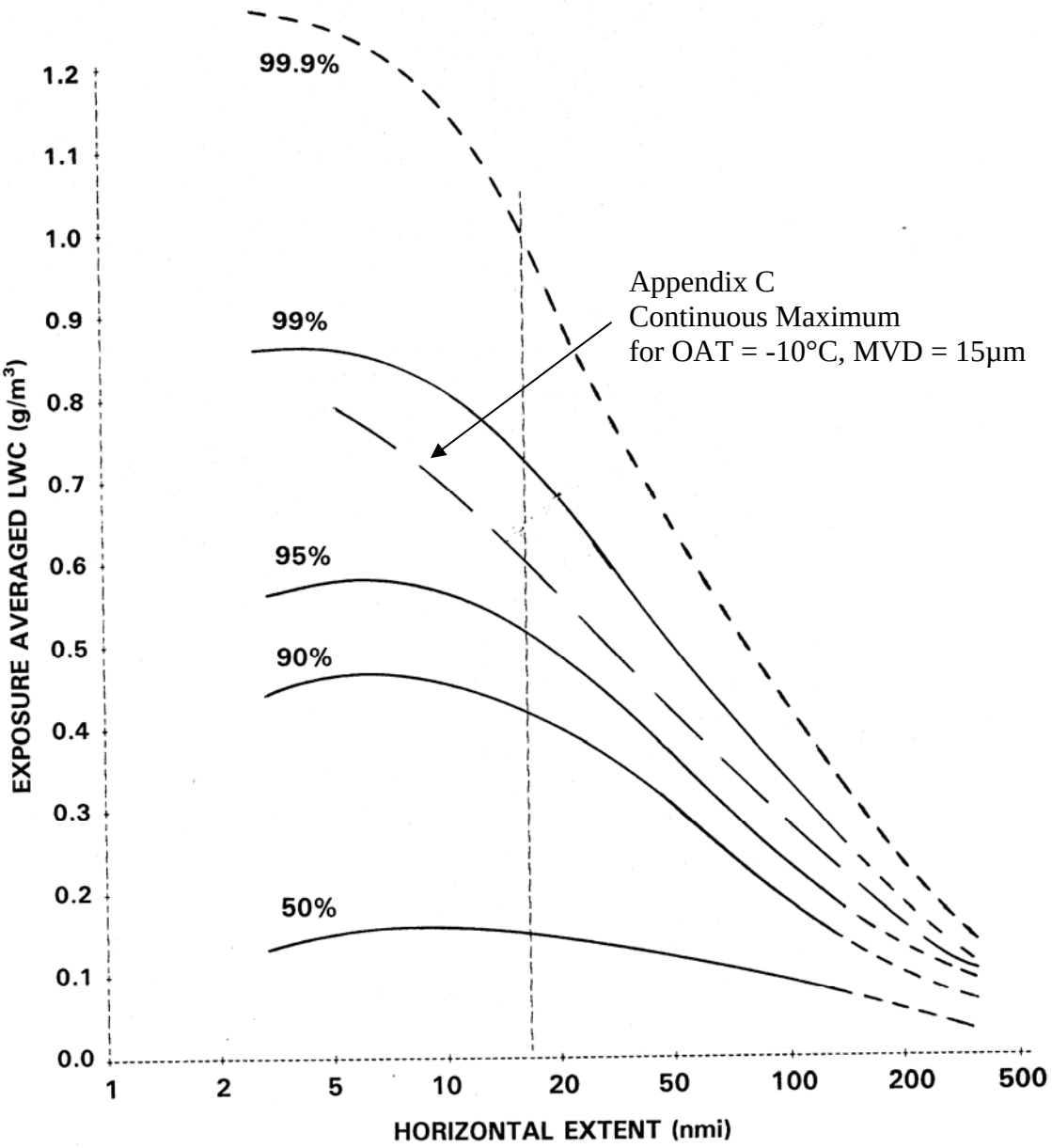

Figure D-4. Comparison of Continuous Maximum LWC to LWC Percentiles (Risk Levels) for Layer Clouds With MVD = 10 to 20 µm and Outside Air Temperature up to -10°C

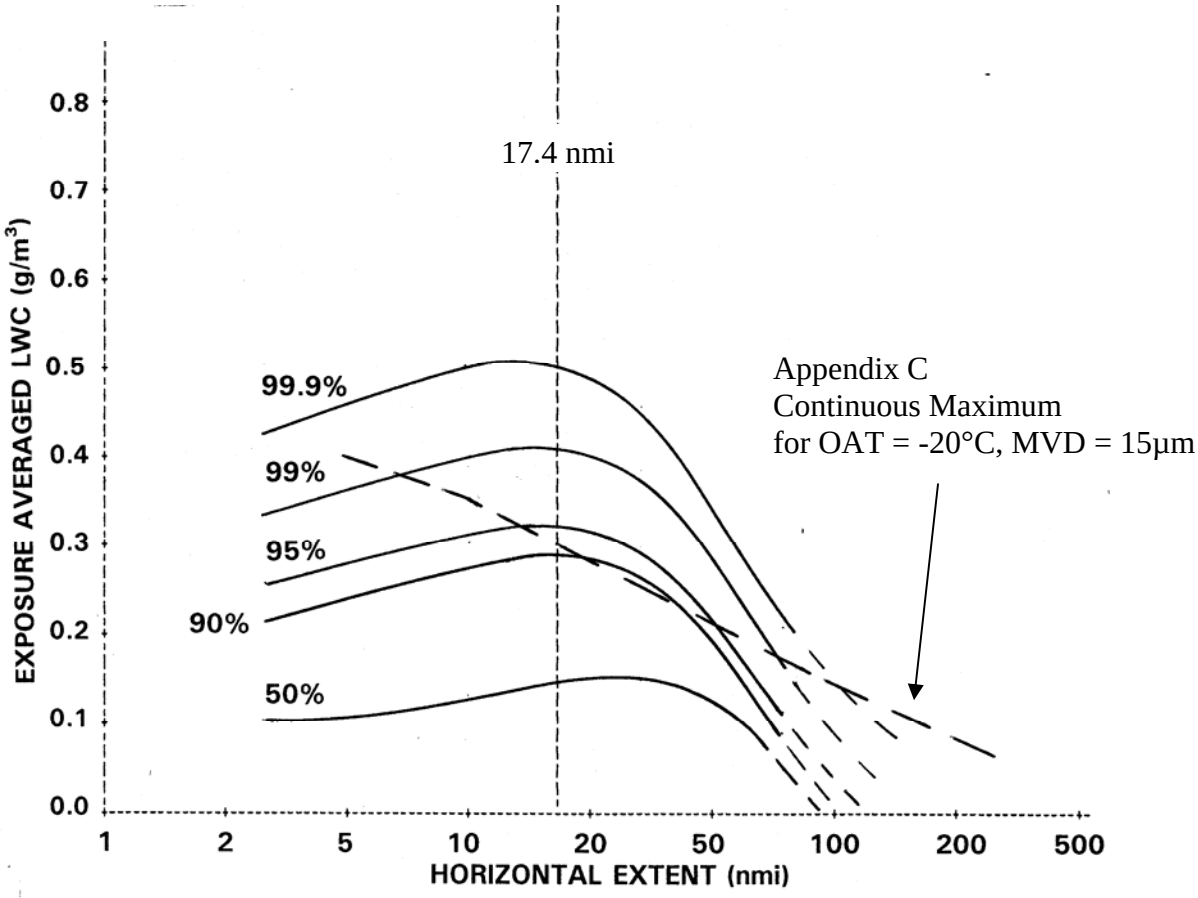

Figure D-5. Comparison of Continuous Maximum LWC to LWC Percentiles (Risk Levels) for Layer Clouds With MVD = 10 to 20 µm and Outside Air Temperature up to -20°C

D.2 INTERMITTENT MAXIMUM.

Figures D-6 to D-11 show similar comparisons for cumuliform (intermittent maximum) clouds, except that comparisons with and without summer clouds are shown separately. In all cases, the Appendix C curves extend out to only 5 nmi, whereas encounters as long as 30 nmi or more have been recorded in the database.

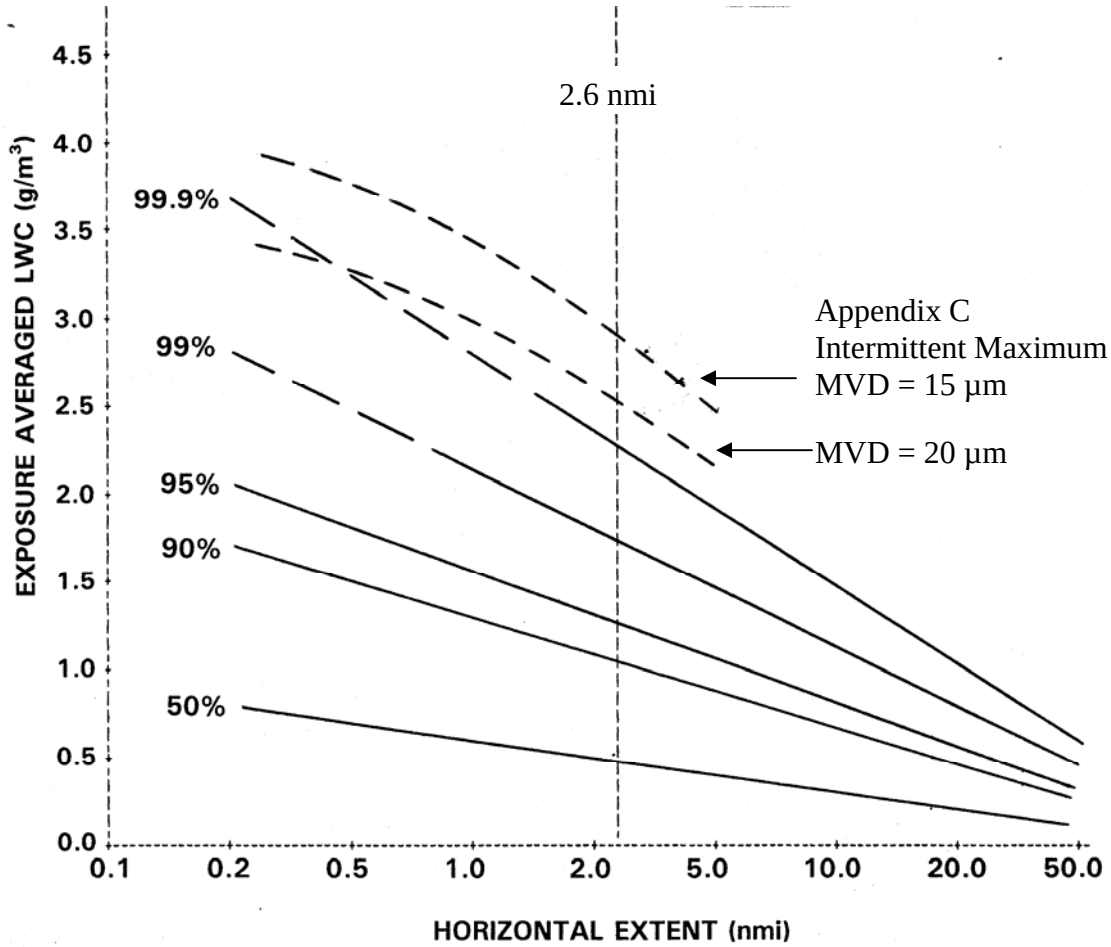

Figure D-6. Comparison of Intermittent Maximum LWC to LWC Percentiles (Risk Levels) for Cumuliform Clouds With MVD = 10 to 25 µm and Outside Air Temperature up to 0°C (Summer Clouds Excluded)

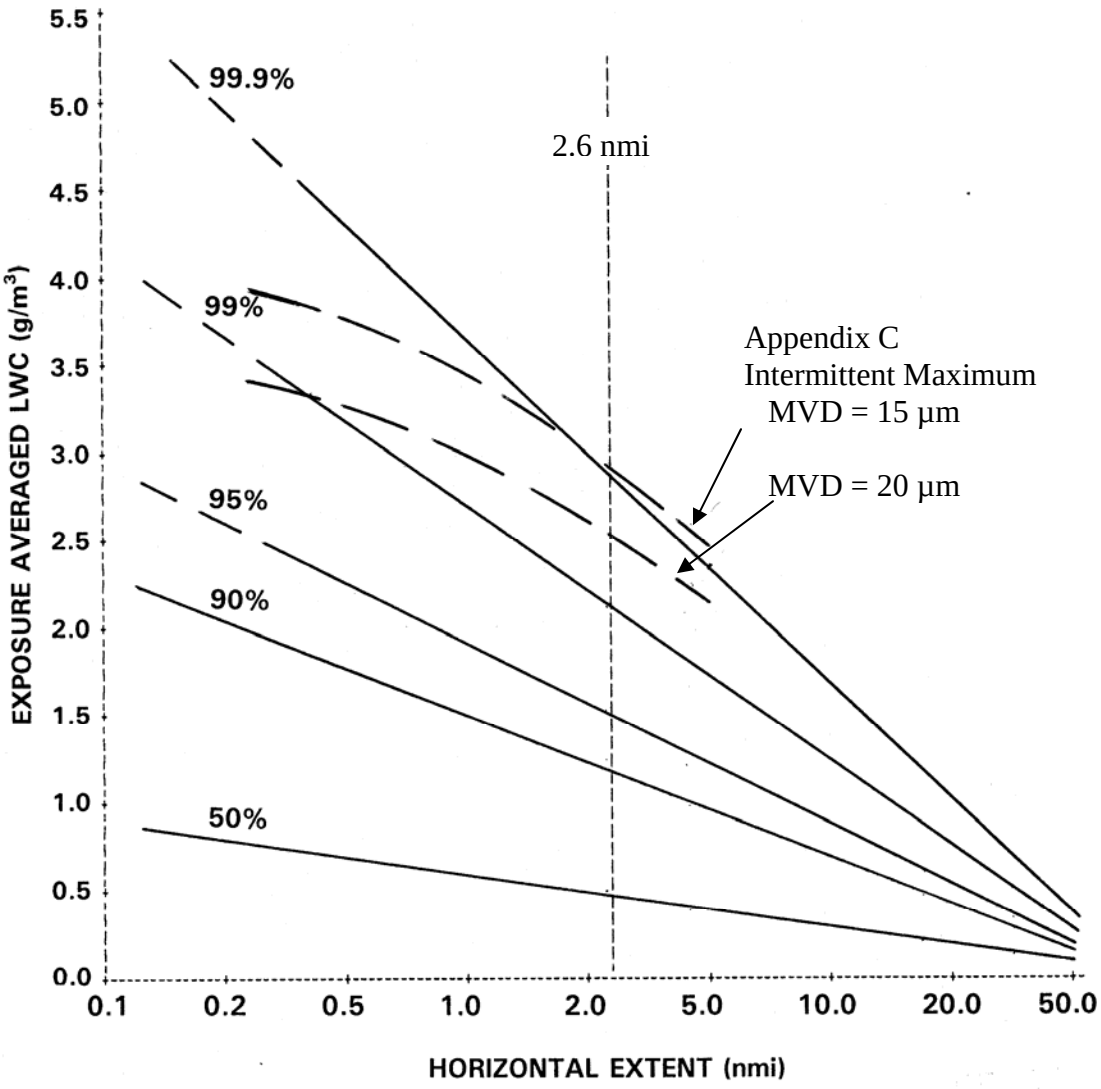

Figure D-7. Comparison of Intermittent Maximum LWC to LWC Percentiles (Risk Levels) for Cumuliform Clouds With MVD = 10 to 25 µm and Outside Air Temperature up to 0°C (Summer Clouds Included)

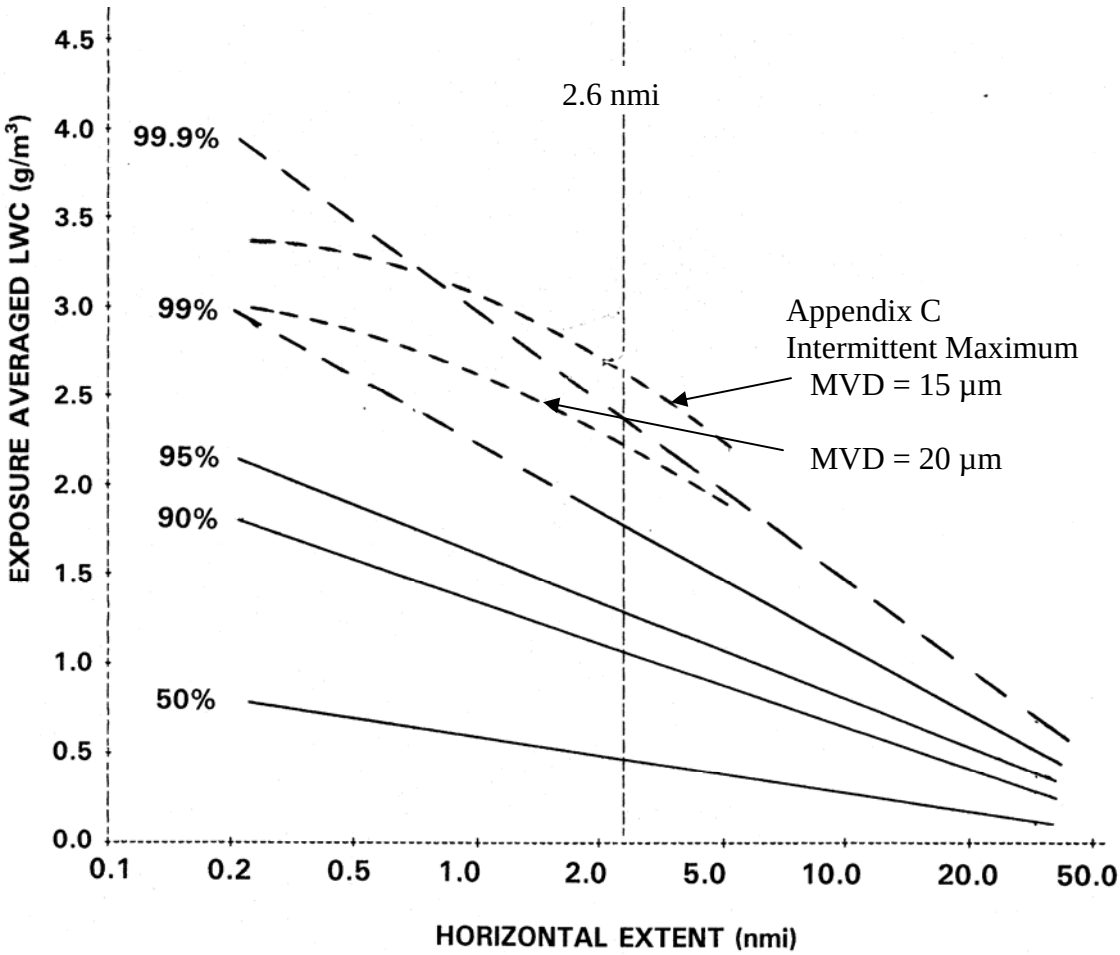

Figure D-8. Comparison of Intermittent Maximum LWC to LWC Percentiles (Risk Levels) for Cumuliform Clouds With MVD = 10 to 25 µm and Outside Air Temperature up to -10°C (Summer Clouds Excluded)

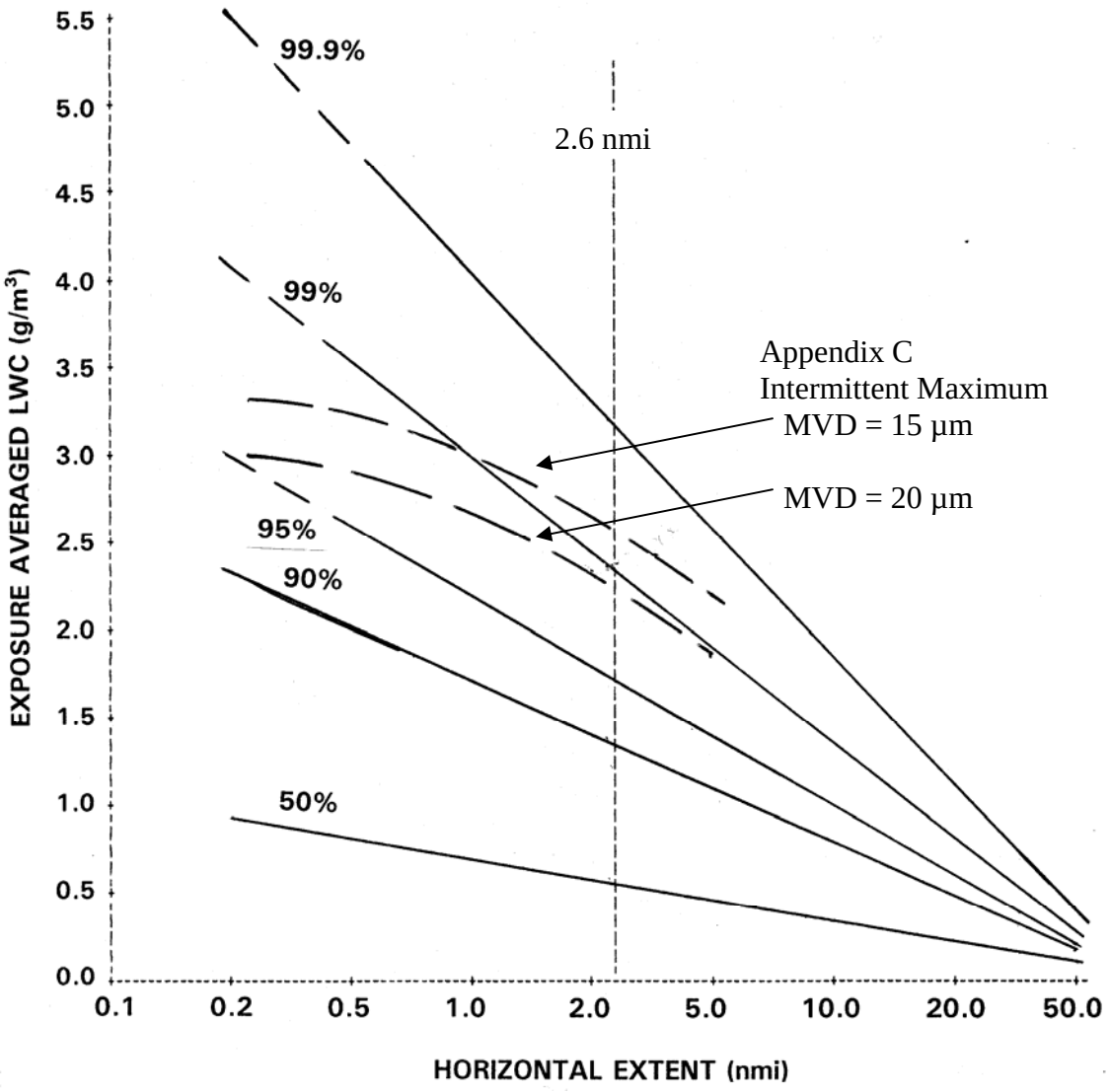

Figure D-9. Comparison of Intermittent Maximum LWC to LWC Percentiles (Risk Levels) for Cumuliform Clouds With MVD = 10 to 25 µm and Outside Air Temperature up to -10°C (Summer Clouds Included)

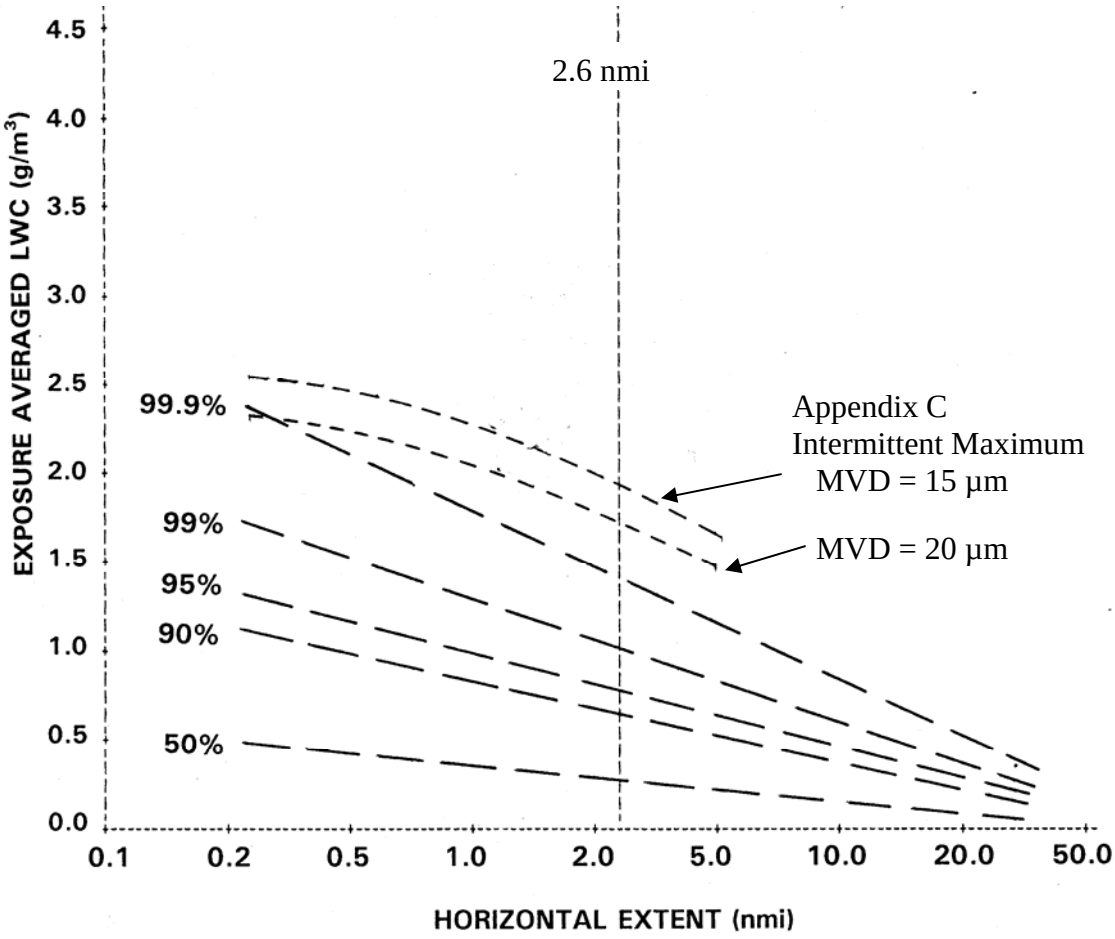

Figure D-10. Comparison of Intermittent Maximum LWC to LWC Percentiles (Risk Levels) for Cumuliform Clouds With MVD = 10 to 25 µm and Outside Air Temperature up to -20°C (Summer Clouds Excluded)

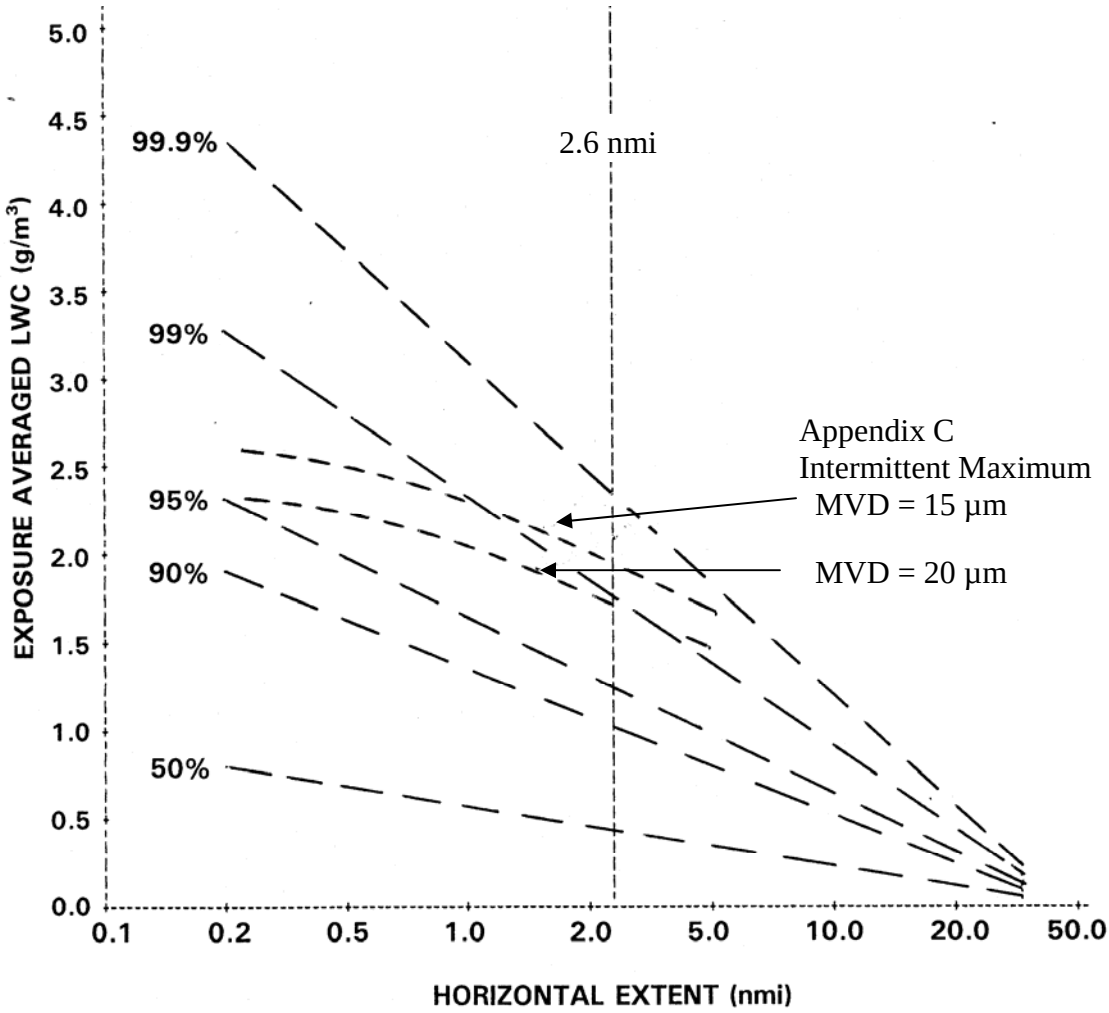

Figure D-11. Comparison of Intermittent Maximum LWC to LWC Percentiles (Risk Levels) for Cumuliform Clouds With MVD = 10 to 25 µm and Outside Air Temperature up to -20°C (Summer Clouds Included)

In figure D-6, the Appendix C curves for both 15- and 20-µm MVDs exceed even the 99.9th percentile for LWC in cold and mild season convective clouds. In figure D-7 (summer clouds included), the Appendix C curves fit better, but they still exceed the 99th percentile limits.

Figures D-8 and D-9, for -10°C, show better conformity of the Appendix C curves with the 99th percentile, especially with summer clouds included.

Figure D-10 again shows Appendix C to be excessive at -20°C for cold and mild season conditions, but there is better agreement with the 99th percentiles when summer clouds are included (figure D-11).

In conclusion, the existing Appendix C intermittent maximum curves appear to approximate the 99th percentile LWC for summer icing conditions, but the curves overestimate the probable maximum LWC in convective clouds for winter and mild season icing conditions.

To accommodate the differences between summer and winter conditions, the possible extent of convective cloud HEs out to 50 nmi, and the different temperature behavior of LWC between 0° and -10°C, the new set of curves in figure 26 of this report is proposed as one possible updated replacement for figure 4 of Appendix C. The new curves give generally lower LWCs than Appendix C, but they are consistently 99th percentile values like the new continuous maximum curves in figure 25 of this report.

D.3 DEPENDENCE ON MVD.

Figures D-12 and D-13 present yet another comparison between the Appendix C LWC curves and newly computed 99th percentile values. These figures show that, except perhaps for MVD = 15 µm, Appendix C is not very realistic in capturing the MVD dependence. The Appendix C curves are mostly overconservative, indicating LWCs mostly larger than the newly computed 99th percentile values and extending to much longer distances than are observed for MVDs of 20 µm and greater.

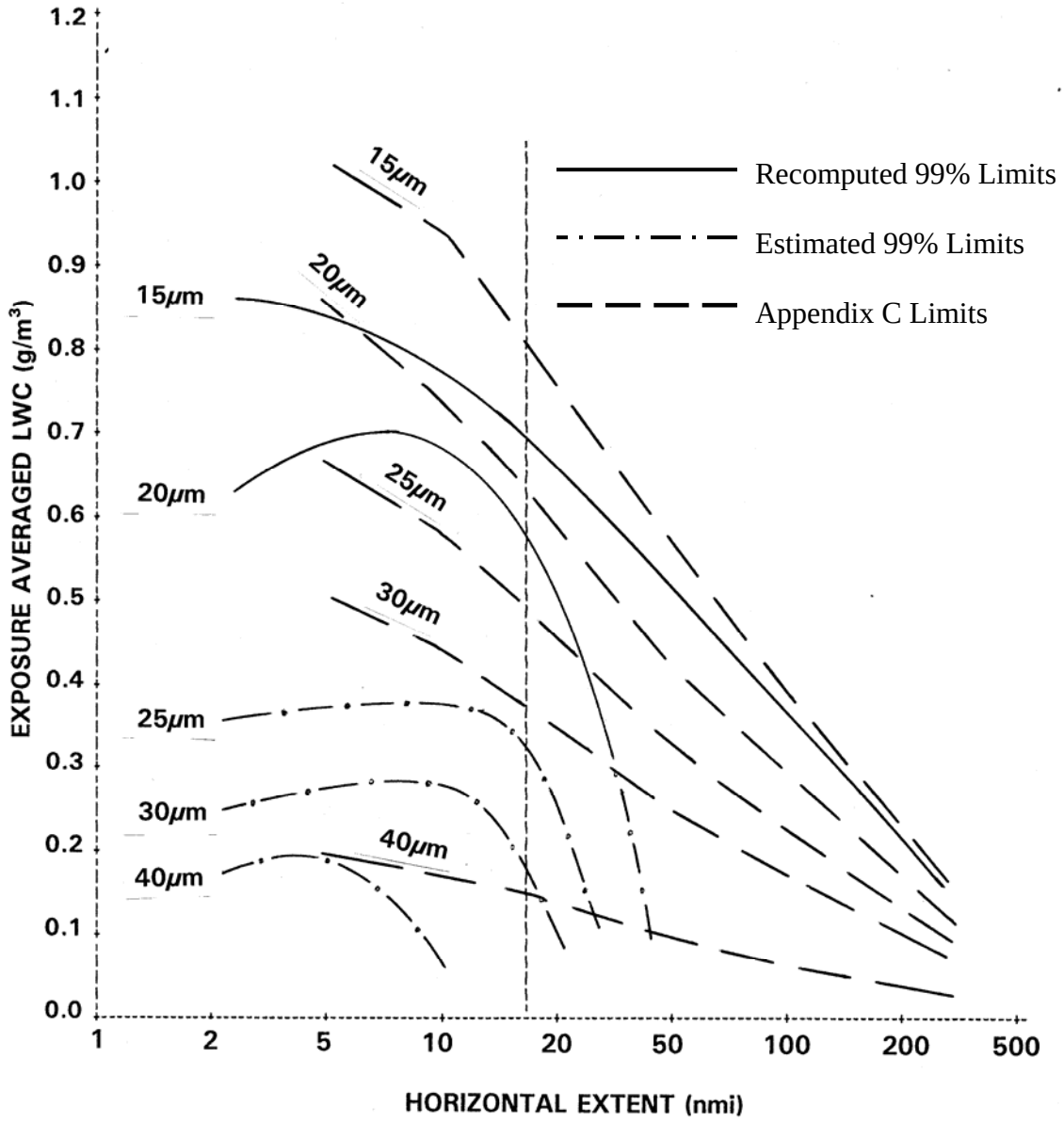

Figure D-12. Comparison of Continuous Maximum and Recomputed 99th Percentile Limits to LWC for 5 µm MVD Intervals
(All curves apply to stratiform clouds with temperatures up to 0°C.)

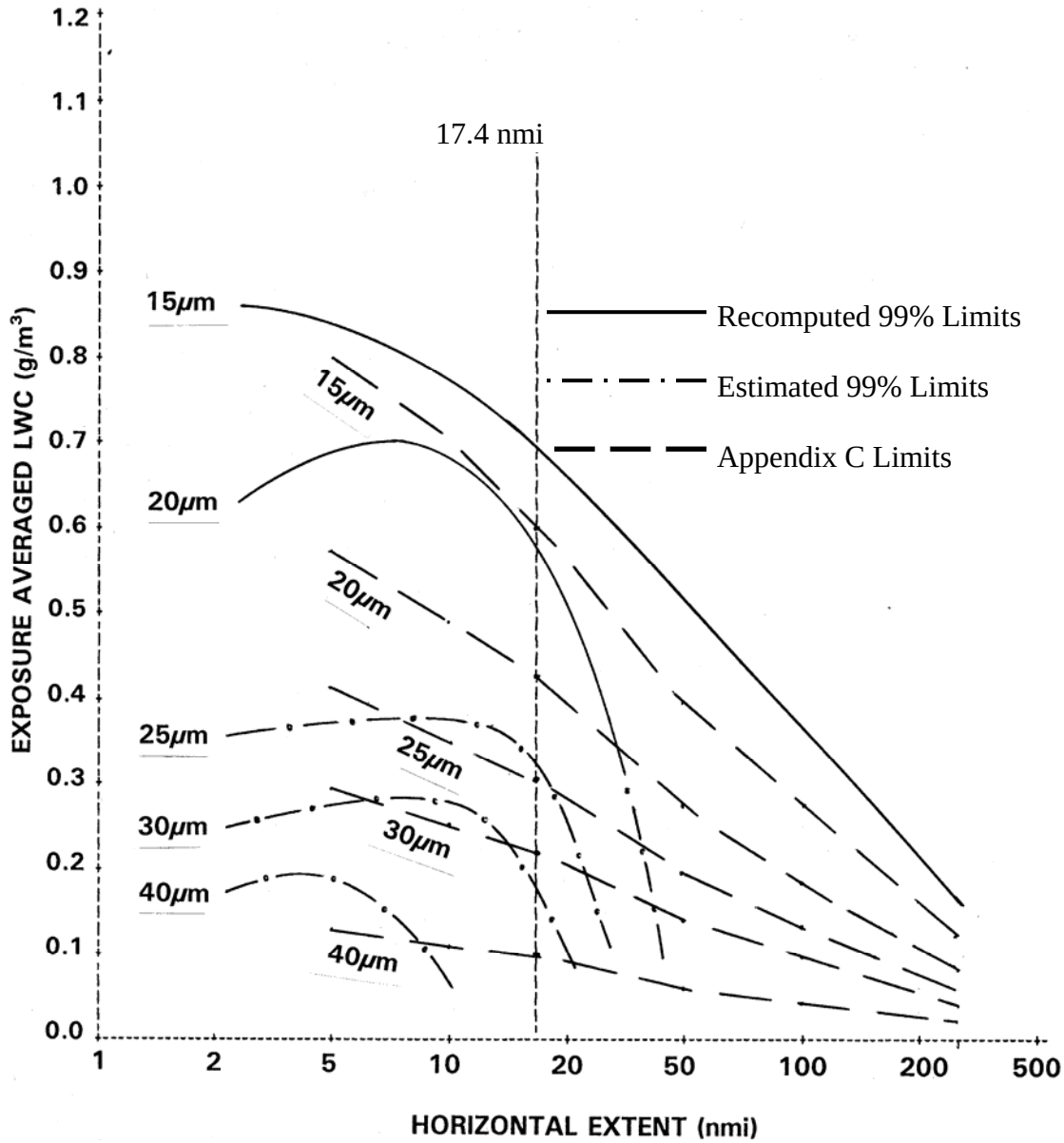

Figure D-13. Comparison of Continuous Maximum and Recomputed 99th Percentile Limits to LWC for 5 µm MVD Intervals
(All curves apply to stratiform clouds with temperatures up to -10°C.)

D.4 RECOMMENDATION FOR CONSIDERATION.

Since MVDs larger than 20 µm have relatively low LWC and are relatively short-lived, the proposal here is to ignore the larger MVDs and concentrate on the largest LWCs, which occur at about 15 µm and can last the longest. For conservative design purposes, the 15-µm LWCs can be used with a fixed 20-µm drop size, as suggested elsewhere in the main body of this report. An exercise in reference D-5 shows that the maximum water catch occurs for 20-µm drops anyway. The use of a single 20-µm design drop size avoids the unnecessary complication of

including MVD-dependent curves like figures D-12 and D-13 in a revised and otherwise simplified Appendix C.

D.5 REFERENCES.

D-1. Lewis, W., and Bergrun, N.R., "A Probability Analysis of the Meteorological Factors Conducive to Aircraft Icing in the United States," NACA TN 2738, 1952.

D-2. Masters, C.O., "A New Characterization of Supercooled Clouds Below 10,000 Feet AGL," FAA report DOT/FAA/CT-83/22, June 1983.

D-3. Kapur, K.C. and Lamberson, L.R., *Reliability in Engineering Design*, pp. 291-308, John Wiley & Sons, New York, 1977.

D-4. Jeck, R.K., "Icing Design Envelopes (14 CFR Parts 25 and 29, Appendix C) Converted to a Distance-Based Format," FAA report DOT/FAA/AR-00/30, April 2002.

D-5. Anon., "Aircraft Icing Handbook," Vol. 2, Chapter V, Section 2, Tables V 2-7 and 2-8.

APPENDIX E—THE FREQUENCY OF OCCURRENCE OF SUPERCOOLED LIQUID WATER CONTENT VALUES

As explained briefly in section 1 of this report, the percentage of time that supercooled liquid water content (SLWC) values larger than certain values occur in the entire database are given in tables 1 and 2. These tables are repeated here as tables E-1 and E-2 for ready reference.

Table E-1. The SLWC in 23,000 nmi of Layer Clouds

Percent of Time SLWC is Less Than Indicated	SLWC (g/m^3)	Temperature Range
50	0.12	0° to -40°C
90	0.35	0° to -20°C
95	0.45	0° to -20°C
99	0.65	0° to -20°C
99.9	1.0	0° to -15°C

Table E-2. SLWC in 5000 nmi of Convective Clouds

Percent of Time SLWC is Less Than Indicated	SLWC (g/m^3)	Temperature Range
50	0.3	0° to -30°C
90	1.0	0° to -20°C
95	1.3	0° to -20°C
99	2.1	0° to -20°C
99.9	3.2	-5° to -15°C

The percentiles and values listed in the tables are based on the number of nautical miles (nmi) that have been recorded for each value of SLWC in the entire database of 23,000 nmi for layer clouds and 5,000 nmi for convective clouds.

For a given exposure distance, the percentages imply that a relatively short fraction of the exposure may be expected to contain the larger SLWCs. This is illustrated in table E-3, which shows, statistically speaking, the distances over which the listed SLWCs may be expected to be exceeded during a standard 17.4-nmi exposure and a 100-nmi exposure.

Table E-3 assumes that the SLWC values will be encountered in proportion to their fractional occurrence in the layer cloud database as a whole.

Table E-3. Statistical Distribution of SLWC During Example Exposures

LWC (g/m^3)	Percent of Distance	Distance (nmi) out of 17.4 nmi	Distance (nmi) out of 100 nmi
1.0	0.9	0.16	0.9
0.65	4	0.7	4
0.45	5	0.9	5
0.35	40	7	40
0.12	50	8.7	50

The average liquid water content (LWC) for the entire exposure is computed as follows and does not depend on the exposure distance (horizontal extent).

$$\text{Average LWC} = \frac{1(0.9) + 0.65(4) + 0.45(5) + 0.35(40) + 0.12(50)}{99.9} = 25.75/99.9 = 0.26\ g/m^3$$

One could question whether it is possible to encounter one of the larger SLWCs for a longer distance than indicated by the overall statistical frequency. That is, although in 23,000 nmi of flight in stratiform icing conditions, one can expect to exceed 1 g/m^3 only 0.1% of the time (i.e., for only 23 nmi out of 23,000 nmi), is it possible that 10 or 20 nmi of the 23 nmi may be encountered all at once during a single exposure, rather than at the rate of only a few tenths of a mile per exposure as indicated by the table? The answer is as follows.

Out of a total of 3508 individual layer cloud events in the database, only 11 have SLWCs of 1 g/m^3 or more (the maximum value is 1.6 g/m^3). This means that there is one chance in 319 (3508/11) of happening upon a layer cloud segment with SLWC of 1 g/m^3 or greater. Those 11 events lasted from about 0.2 to 9.6 nmi, with an average distance of about 3 nmi.

SLWCs of 0.65 g/m^3 or greater occurred in 85 events, thus representing one chance in 41 (3508/85) of occurring. Those in the range of 0.65 g/m^3 to 1 g/m^3 lasted for distances ranging from 0.2 nmi to 31 nmi, with an average duration of 4 nmi.

Events with SLWCs of 0.45 g/m^3 or greater occurred 267 times, or once in every 13 events (3508/267). Those in the range of 0.45 g/m^3 to 0.65 g/m^3 lasted for distances ranging from 0.2 nmi to 100 nmi, with an average duration of 7 nmi.

So, if one wanted to consider the possibility that an unfortunate pilot could encounter SLWCs of 1, 0.65, and 0.45 g/m^3 for their average distances of 3, 4, and 7 nmi, respectively, followed by a regular 0.35 g/m^3 and 0.12 g/m^3 for the remainder of the exposure, then the sequence would be that shown in table E-4.

Table E-4. Special Distribution of SLWC During Example Exposures

LWC (g/m^3)	Portion of Distance	Distance (nmi) out of 17.4 nmi	Distance (nmi) out of 100 nmi
1.0	3 nmi	3	3
0.65	4 nmi	4	4
0.45	7 nmi	7	7
0.35	40%	3.4	36
0.12	50%	-	50

The average LWC for the 17.4-nmi exposure is

$$\text{Average LWC} = \frac{1(3) + 0.65(4) + 0.45(7) + 0.35(3.4)}{17.4} = 9.94/17.4 = 0.57\ g/m^3$$

and the average LWC for the 100-nmi exposure is

$$\text{Average LWC} = \frac{1(3) + 0.65(4) + 0.45(7) + 0.35(36) + 0.12(50)}{100} = 27.4/100 = 0.27\ g/m^3$$

So, the hypothetically longer exposure to the larger SLWCs would make a noticeable difference for standard-length encounters but not for long ones.

The chances of all three of these larger SLWCs being encountered in the same event is roughly (1/319)(1/41)(1/13) or once in 5 million events.

A more realistic expectation would be for encountering LWCs between 0.45 g/m^3 and 0.65 g/m^3 for 7 nmi every 13 events. In this case, the LWC would be distributed something like that in table E-5.

Table E-5. Special Distribution of SLWC Assumed to Occur Every 13 Encounters

LWC (g/m^3)	Portion of Distance	Distance (nmi) out of 17.4 nmi	Distance (nmi) out of 100 nmi
0.55*	7 nmi	7	7
0.35	40%	7	40
0.12	50%	3.4	53

*This entry is arbitrarily taken to be the average between 0.45 and 0.65 g/m^3.

The average LWC for a 17.4-nmi exposure is now

$$\text{Average LWC} = \frac{0.55(7) + 0.35(7) + 0.12(3.4)}{17.4} = 6.71/17/4 = 0.39\ g/m^3$$

and the average LWC for the 100-nmi exposure is

$$\text{Average LWC} = \frac{0.55(7) + 0.35(40) + 0.12(53)}{100} = 24.21/100 = 0.24\ \text{g/m}^3.$$

Once again, the 100-nmi exposure is practically unaffected. The 17.4-nmi exposure is 50% larger in LWC than the statistical average obtained from table E-3, but that happens only once in every 13 encounters in this case.

APPENDIX F—COMPUTERIZED VERSIONS OF 14 CFR PARTS 25 AND 29 APPENDIX C

Title 14 Code of Federal Regulations (CFR) Parts 25 and 29 Appendix C (herein referred to as Appendix C) contains six graphs of design variables that are used by designers of in-flight ice protection systems and by data analysts for icing test flights, icing wind tunnel tests, and by computer modelers of ice shapes on aircraft surfaces. The six figures have been published in the CFR since the early 1960s. Unfortunately, the published versions of some figures are a poor, muddy quality shown in figures 1-6. This makes for an undesirable appearance when these graphs are copied into technical reports or projected onto a screen during briefings, for example. The graphical grid spacing is also awkward because it is not evenly matched to the numerical scales marked along the axes. Finally, these fixed (paper) versions of the graphs are not convertible to other useful versions that have been previously demonstrated [F-1].

These graphs would be useful beyond the original vision of the suppliers if the graphs were in electronic form so they could be customized and/or imported directly into computer programs.

This can be easily done by tabulating the coordinates of the curves in figures 1-6 in a computerized spreadsheet as in tables F-1 and F-2. Then, the charting capabilities of the spreadsheet software can be used to produce clean, properly scaled reproductions of the original graphs at will. Figures F-1 through F-6 show the results.

The advantages of spreadsheet-based graphs in this example are that they:

- Modernize Appendix C
- Have a cleaner, sharper appearance than the often muddy look of the printed versions currently in the CFR
- Have a more convenient grid spacing on the vertical and horizontal axes than the printed versions in the CFR
- Are easier to size and insert electronically into word processor or other computerized documents
- Can be adjusted or customized to suit the needs of various applications
- Can be converted to other useful variables or scales [F-1]

In summary, common computer technology can modernize supplementary material that is currently available only in fixed, old-fashioned printed form in the CFR. When the CFR is made available on compact disc or other computer-compatible media, then working files, such as these spreadsheet versions of graphs, can be included and supplied directly to the user.

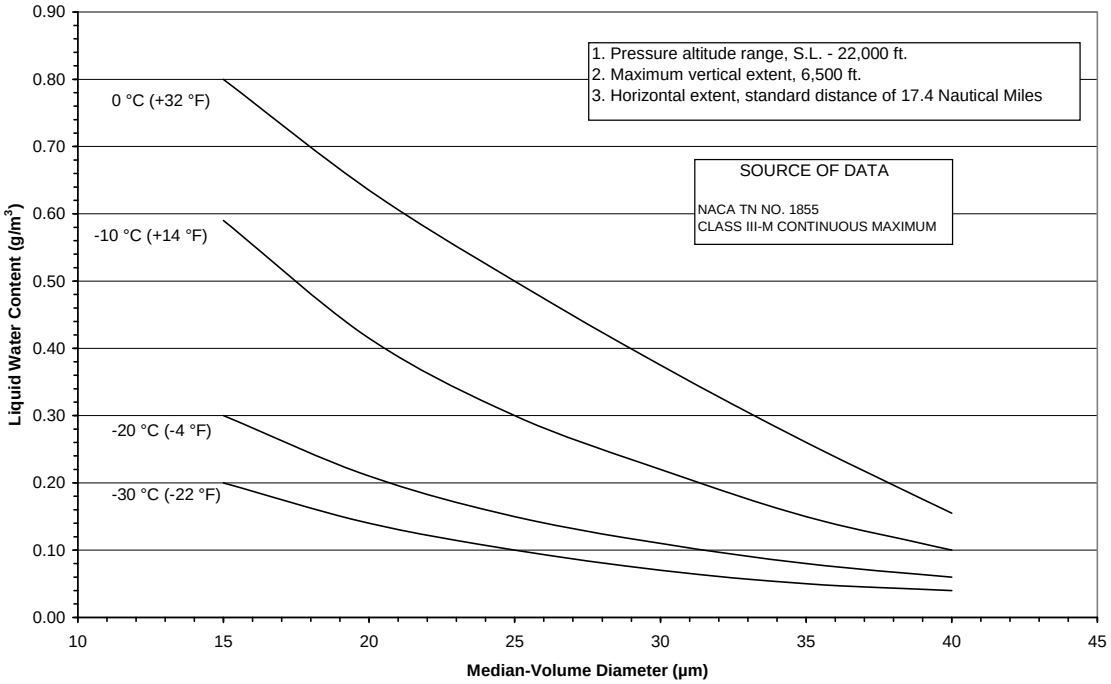

Figure F-1. Computerized Version of Figure 1 in 14 CFR Parts 25 and 29 Appendix C (Created as a chart using spreadsheet software.)

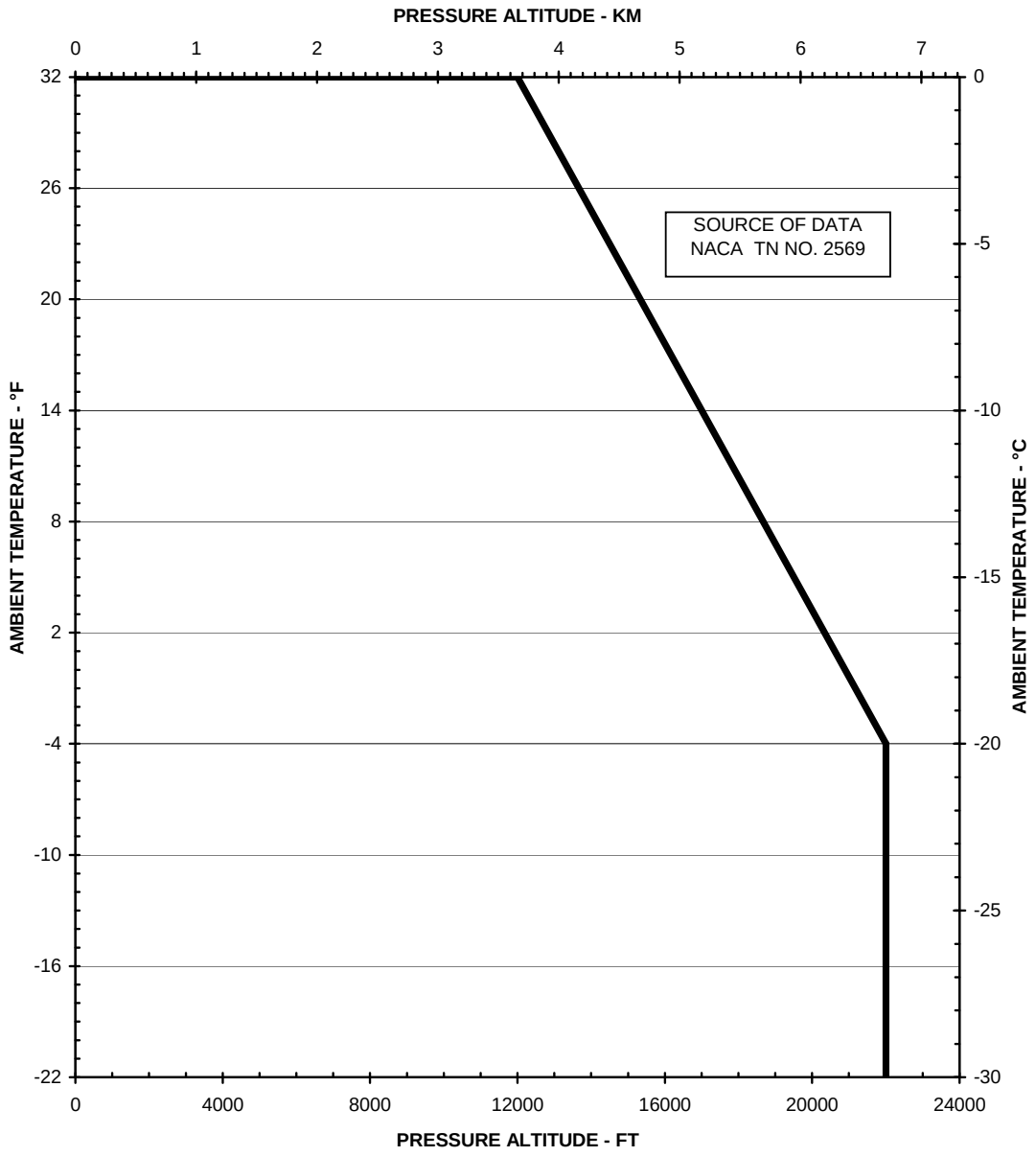

Figure F-2. Computerized Version of Figure 2 in 14 CFR Parts 25 and 29 Appendix C
(Created as a chart using spreadsheet software.)

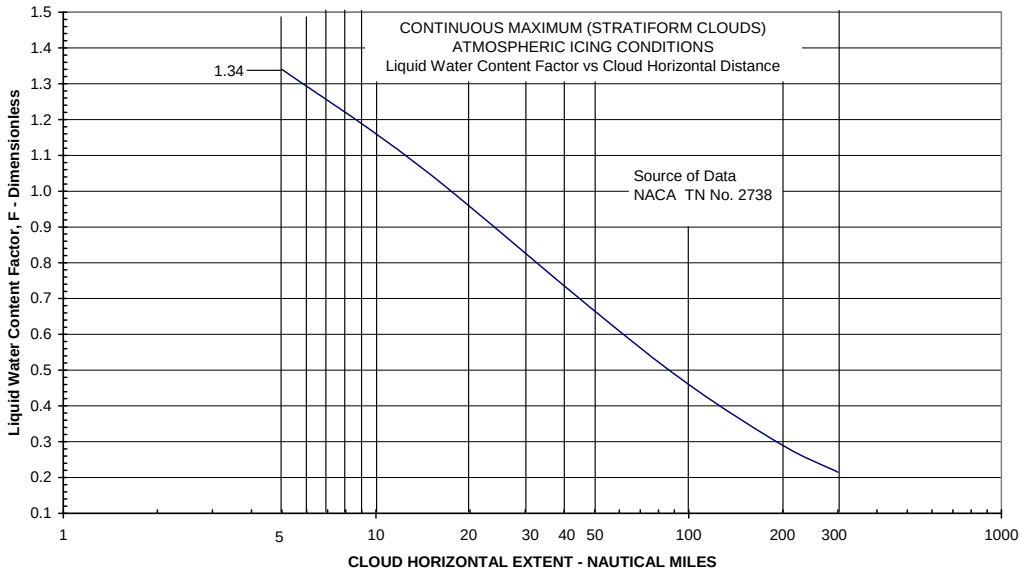

Figure F-3. Computerized Version of Figure 3 in 14 CFR Parts 25 and 29 Appendix C (Created as a chart using spreadsheet software.)

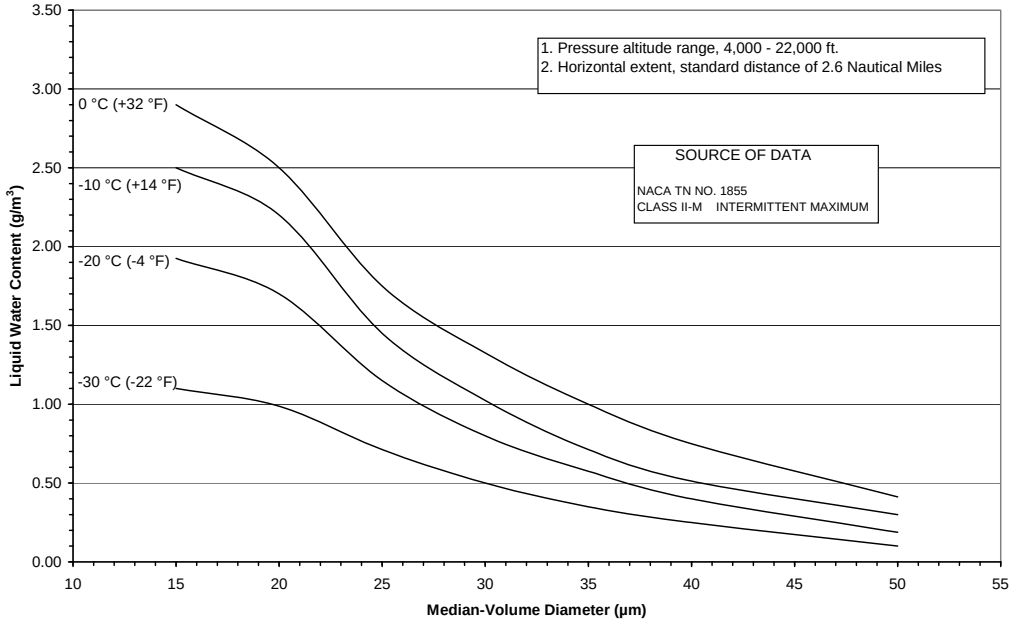

Figure F-4. Computerized Version of Figure 4 in 14 CFR Parts 25 and 29 Appendix C (Created as a chart using spreadsheet software)

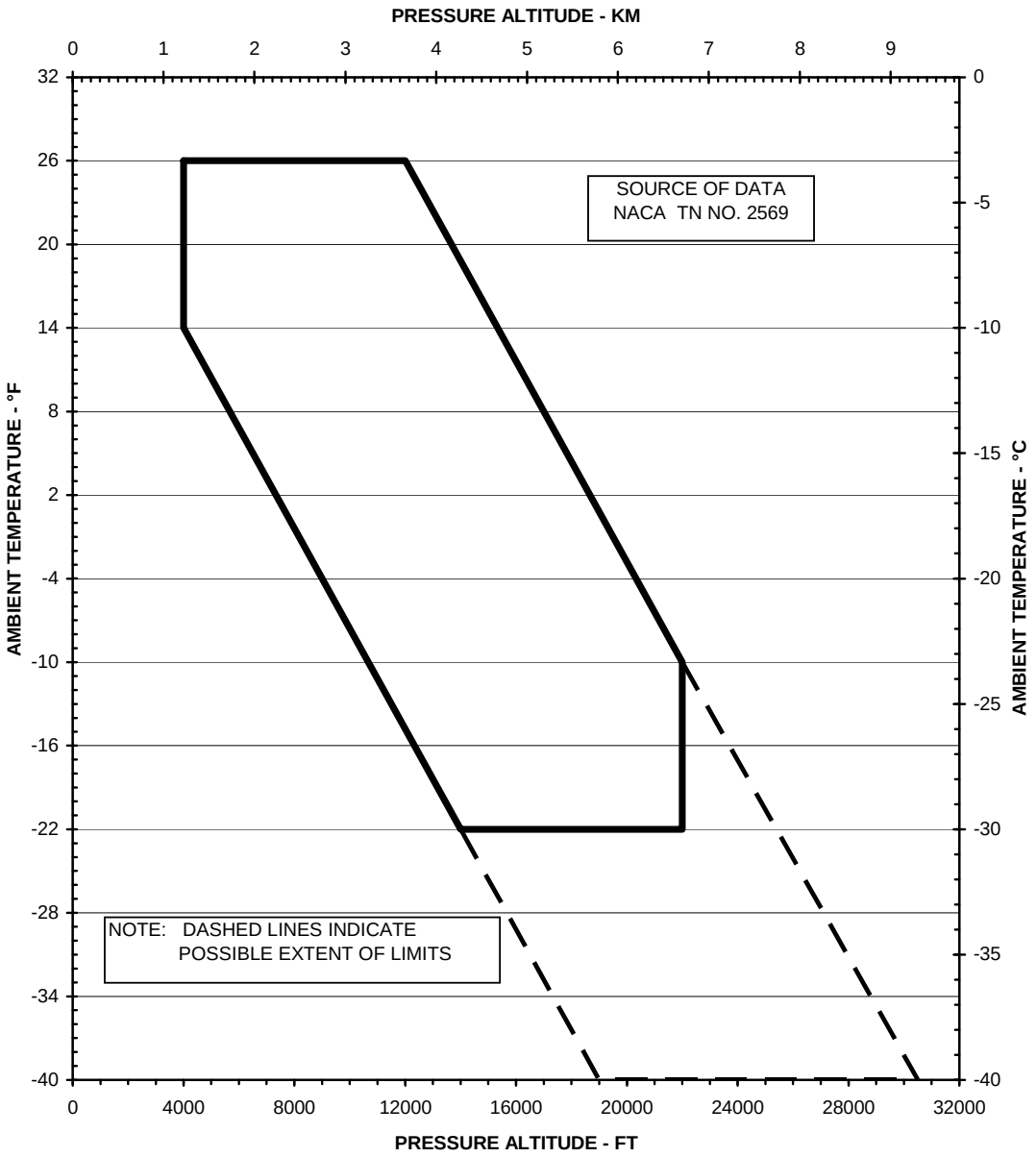

Figure F-5. Computerized Version of Figure 5 in 14 CFR Parts 25 and 29 Appendix C
(Created as a chart using spreadsheet software.)

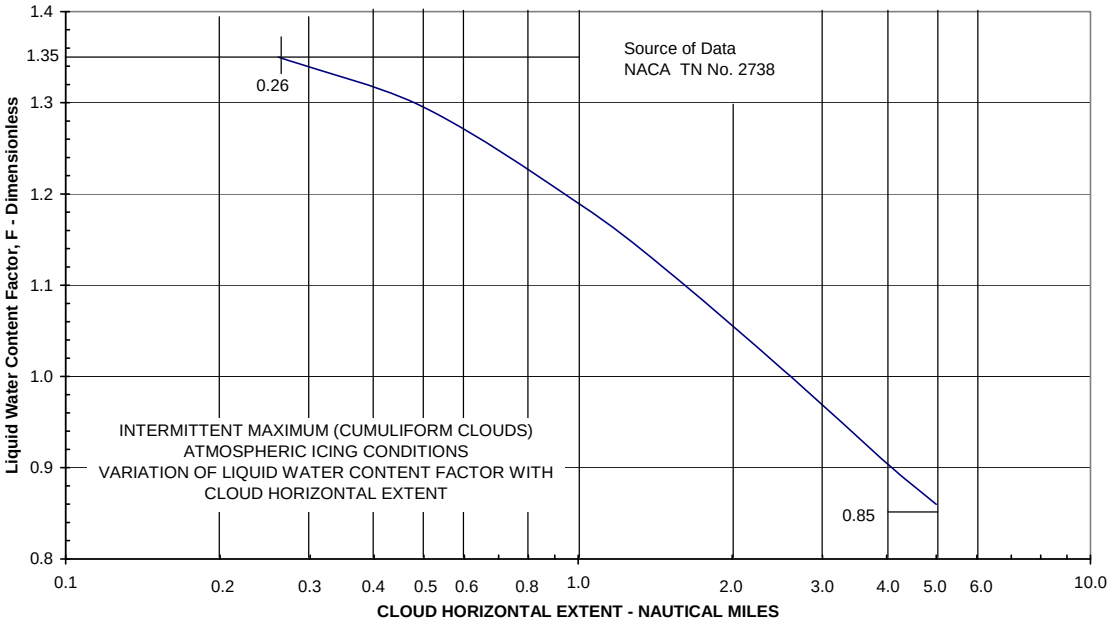

Figure F-6. Computerized Version of Figure 6 in 14 CFR Parts 25 and 29 Appendix C (Created as a chart using spreadsheet software.)

Table F-1. Coordinates for Continuous Maximum Envelopes
(14 CFR Part 25 Appendix C Figure 1)

	A	B	C	D	E	F	G	H	I	J
1	**Coordinates for Continuous Maximum Envelopes (14 CFR 25, Appendix C, Figure 1)**									
2										
3	Temperature	MVD	HE (nmi)=	5	10	17.4	50	100	200	300
4		(µm)	F-factor =	1.340	1.160	1.000	0.665	0.460	0.290	0.215
5	+32 °F (0 °C)	15	LWC (g/m^3)=	1.072	0.928	0.800	0.532	0.368	0.232	0.172
6		20	LWC (g/m^3)=	0.851	0.737	0.635	0.422	0.292	0.184	0.137
7		25	LWC (g/m^3)=	0.670	0.580	0.500	0.333	0.230	0.145	0.108
8		30	LWC (g/m^3)=	0.503	0.435	0.375	0.249	0.173	0.109	0.081
9		35	LWC (g/m^3)=	0.348	0.302	0.260	0.173	0.120	0.075	0.056
10		40	LWC (g/m^3)=	0.208	0.180	0.155	0.103	0.071	0.045	0.033
11										
12	+14 °F (-10 °)C	15	LWC (g/m^3)=	0.791	0.684	0.590	0.392	0.271	0.171	0.127
13		20	LWC (g/m^3)=	0.556	0.481	0.415	0.276	0.191	0.120	0.089
14		25	LWC (g/m^3)=	0.402	0.348	0.300	0.200	0.138	0.087	0.065
15		30	LWC (g/m^3)=	0.295	0.255	0.220	0.146	0.101	0.064	0.047
16		35	LWC (g/m^3)=	0.201	0.174	0.150	0.100	0.069	0.044	0.032
17		40	LWC (g/m^3)=	0.134	0.116	0.100	0.067	0.046	0.029	0.022
18										
19	-4 °F (-20 °C)	15	LWC (g/m^3)=	0.402	0.348	0.300	0.200	0.138	0.087	0.065
20		20	LWC (g/m^3)=	0.281	0.244	0.210	0.140	0.097	0.061	0.045
21		25	LWC (g/m^3)=	0.201	0.174	0.150	0.100	0.069	0.044	0.032
22		30	LWC (g/m^3)=	0.147	0.128	0.110	0.073	0.051	0.032	0.024
23		35	LWC (g/m^3)=	0.107	0.093	0.080	0.053	0.037	0.023	0.017
24		40	LWC (g/m^3)=	0.080	0.070	0.060	0.040	0.028	0.017	0.013
25										
26	-22 °F (-30 °C)	15	LWC (g/m^3)=	0.268	0.232	0.200	0.133	0.092	0.058	0.043
27		20	LWC (g/m^3)=	0.188	0.162	0.140	0.093	0.064	0.041	0.030
28		25	LWC (g/m^3)=	0.134	0.116	0.100	0.067	0.046	0.029	0.022
29		30	LWC (g/m^3)=	0.094	0.081	0.070	0.047	0.032	0.020	0.015
30		35	LWC (g/m^3)=	0.067	0.058	0.050	0.033	0.023	0.015	0.011
31		40	LWC (g/m^3)=	0.054	0.046	0.040	0.027	0.018	0.012	0.009
32										
33										
34										
35										
36	Table prepared by						Tabulations obtained from Figures 1 & 3			
37	Flight Safety Branch, AAR-470						in 14 CFR 25, Appendix C			
38	Airport and Aircraft Safety R&D Division									
39	FAA Technical Center									
40										

Table F-2. Coordinates for Intermittent Maximum Envelopes
(14 CFR Part 25 Appendix C Figure 4)

	A	B	C	D	E	F	G	H	I	J
41	**Coordinates for Intermittent Maximum Envelopes (14 CFR 25, Appendix C, Figure 4)**									
42										
43	Temperature	MVD	HE (nmi)=	0.26	0.50	1.00	1.50	2.60	4.00	5.00
44		(µm)	F-factor =	1.350	1.295	1.190	1.115	1.000	0.905	0.860
45	+32 °F (0 °C)	15	LWC (g/m^3)=	3.915	3.756	3.451	3.234	2.900	2.625	2.494
46		20	LWC (g/m^3)=	3.375	3.238	2.975	2.788	2.500	2.263	2.150
47		25	LWC (g/m^3)=	2.363	2.266	2.083	1.951	1.750	1.584	1.505
48		30	LWC (g/m^3)=	1.789	1.716	1.577	1.477	1.325	1.199	1.140
49		35	LWC (g/m^3)=	1.350	1.295	1.190	1.115	1.000	0.905	0.860
50		40	LWC (g/m^3)=	1.013	0.971	0.893	0.836	0.750	0.679	0.645
51		50	LWC (g/m^3)=	0.558	0.535	0.491	0.460	0.413	0.374	0.355
52										
53	+14 °F (-10 °C)	15	LWC (g/m^3)=	3.375	3.238	2.975	2.788	2.500	2.263	2.150
54		20	LWC (g/m^3)=	2.970	2.849	2.618	2.453	2.200	1.991	1.892
55		25	LWC (g/m^3)=	1.958	1.878	1.726	1.617	1.450	1.312	1.247
56		30	LWC (g/m^3)=	1.384	1.327	1.220	1.143	1.025	0.928	0.882
57		35	LWC (g/m^3)=	0.962	0.923	0.848	0.794	0.713	0.645	0.613
58		40	LWC (g/m^3)=	0.692	0.664	0.610	0.571	0.513	0.464	0.441
59		50	LWC (g/m^3)=	0.405	0.389	0.357	0.335	0.300	0.272	0.258
60										
61	-4 °F (-20 °C)	15	LWC (g/m^3)=	2.599	2.493	2.291	2.146	1.925	1.742	1.656
62		20	LWC (g/m^3)=	2.295	2.202	2.023	1.896	1.700	1.539	1.462
63		25	LWC (g/m^3)=	1.553	1.489	1.369	1.282	1.150	1.041	0.989
64		30	LWC (g/m^3)=	1.080	1.036	0.952	0.892	0.800	0.724	0.688
65		35	LWC (g/m^3)=	0.776	0.745	0.684	0.641	0.575	0.520	0.495
66		40	LWC (g/m^3)=	0.540	0.518	0.476	0.446	0.400	0.362	0.344
67		50	LWC (g/m^3)=	0.254	0.243	0.224	0.210	0.188	0.170	0.162
68										
69	-22 °F (-30 °C)	15	LWC (g/m^3)=	1.485	1.425	1.309	1.227	1.100	0.996	0.946
70		20	LWC (g/m^3)=	1.333	1.279	1.175	1.101	0.988	0.894	0.849
71		25	LWC (g/m^3)=	0.962	0.923	0.848	0.794	0.713	0.645	0.613
72		30	LWC (g/m^3)=	0.675	0.648	0.595	0.558	0.500	0.453	0.430
73		35	LWC (g/m^3)=	0.473	0.453	0.417	0.390	0.350	0.317	0.301
74		40	LWC (g/m^3)=	0.338	0.324	0.298	0.279	0.250	0.226	0.215
75		50	LWC (g/m^3)=	0.135	0.130	0.119	0.112	0.100	0.091	0.086
76										
77										
78										
79										
80	Table prepared by						Tabulations obtained from Figures 4 & 6			
81	Flight Safety Branch, AAR-470						in 14 CFR 25, Appendix C			
82	Airport and Aircraft Safety R&D Division									
83	FAA Technical Center									
84										

F.1 REFERENCE.

F-1. Jeck, R.K., "Icing Design Envelopes (14 CFR Parts 25 and 29, Appendix C) Converted to a Distance-Based Format," FAA report DOT/FAA/AR-00/30, April 2002.

APPENDIX G—DIFFERENCES BETWEEN RUSSIAN AND AMERICAN/EUROPEAN VERSIONS OF 14 CFR PARTS 25 AND 29 APPENDIX C

There are several subtle, and often confusing, differences between the Russian AP-25 Appendix C and Title 14 Code of Federal Regulations (CFR) Part 25 Appendix C (or Joint Aviation Requirements (JAR) Part 25 Appendix C). These include differences in representative drop sizes, liquid water content (LWC) envelopes, variation of LWC with horizontal extent (HE), temperature versus altitude envelopes, and assumed drop size ranges. This appendix briefly describes each of these differences and, in the light of the new database, suggests how the Russian and American/European (Western) Appendices C can be harmonized.

G.1 THE PRINCIPAL DIFFERENCES.

Although the Russian and Western atmospheric design specifications for aircraft ice protection systems are similar in concept, there are several notable differences in format, content, or detail between the two. The apparent large differences in some LWC and drop size specifications have caused concern among icing practitioners. A good summary of Russian experience and viewpoint is given in reference G-1.

G.2 REPRESENTATIVE DROP SIZES.

In Western practice, the median volume droplet diameter (MVD)[1] is used as a single drop size to represent cloud droplet populations and to substitute for the full drop size distribution in water catch and ice accretion computations. The specifications in 14 CFR Part 25 Appendix C, or JAR Part 25 Appendix C, (herein referred to as Western Appendices C) allow a range of values (MVD = 15-40 or 15-50 µm). However, past practice [G-2 and G-3] has been to use an MVD of 20 µm for these computations, due to the difficulty in accommodating variable drop sizes and more than a few representative airfoil shapes in the older, manual methods. With the ease of modern computer programs, such as LEWICE, designers are now encouraged to explore the sensitivity of the subject airfoil to a range of LWC and MVD combinations obtained from the LWC versus MVD curves in Western Appendix C.

Russian practice also selects a single, representative droplet diameter that can be successfully used instead of a more cumbersome, full drop size distribution for computing water catch and ice accretion amounts. Russian experience [G-1] has found that the *arithmetical mean droplet diameter*, rather than the MVD, gives computed water catch and chordwise extent of ice accretions that agree best with observation. Like the MVD, the mean diameter is variable in nature, averaging around 8-10 µm [reference G-4, page 95 and reference G-5, table 14]. Contrary to Western practice, however, the Russian authorities assign it a fixed, peak (maximum average diameter (MAD)) value of 20 µm for design purposes. This value of 20 µm represents a

[1] The MVD, for all practical purposes, is equal to the old mean effective diameter (MED) in the American icing literature of the 1940s and 1950s. The MED comes from the rotating multicylinder technique for measuring icing rates and estimating LWCs. It is the mid-diameter of a Langmuir-type LWC versus drop size distribution which, by trial and error, gives the best match between computed and measured ice accumulations on the set of multidiameter cylinders. The MED terminology still survives in 14 CFR Parts 25 and 29 Appendix C, which dates from that period.

practical maximum value for icing conditions over Russia, and they have, therefore, adopted it as a suitable design value.

G.2.1 CONCLUSION AND ASSESSMENT.

In adopting a fixed value of 20 µm for the average droplet diameter, the Russian authorities are specifying a worst-case (i.e., largest practical) value of average drop diameter and use it with values of LWC that are appropriate to much smaller average diameters of approximately 8-10 µm (corresponding to an MVD of about 15-20 µm). This would be similar to specifying the largest MVD in Western Appendix C to be used with all LWC values. The result is a synthetic, but ultraconservative, set of design specifications.

The net effect is not as bad as it seems, however, because of the way representative (single value) drop sizes are used in icing computations. Computerized ice accretion codes (or older manual methods) respond *only* to the numerical value of the drop size that is given them, no matter what that value represents. A drop size is simply a drop size, no matter whether it is thought of as a mean value or an MVD. Thus, Russian and Western practitioners should get the *same* results if they both use the same numerical drop size, all else being equal.

In fact, Western practice has conventionally used the same *numerical* drop size value (20 µm) for computing water catch and ice accretion amounts, too. *That is, although Russian specialists think of it as the MAD and the Western practitioners think of it as an MVD, when they both use the same numerical value as their representative drop size in calculations, LWCs and all else being equal, the results should both be the same.*

G.3 LWC ENVELOPES.

As a result of using a single drop size, the LWC versus MVD curves (figure 1 of the Western Appendix C) are not needed and are replaced in the Russian Appendix C by *distance-based* LWC versus horizontal extent curves[2] shown in figure G-1.

[2] This idea of distance-based LWC curves has also been independently proposed recently by the author [G-6].

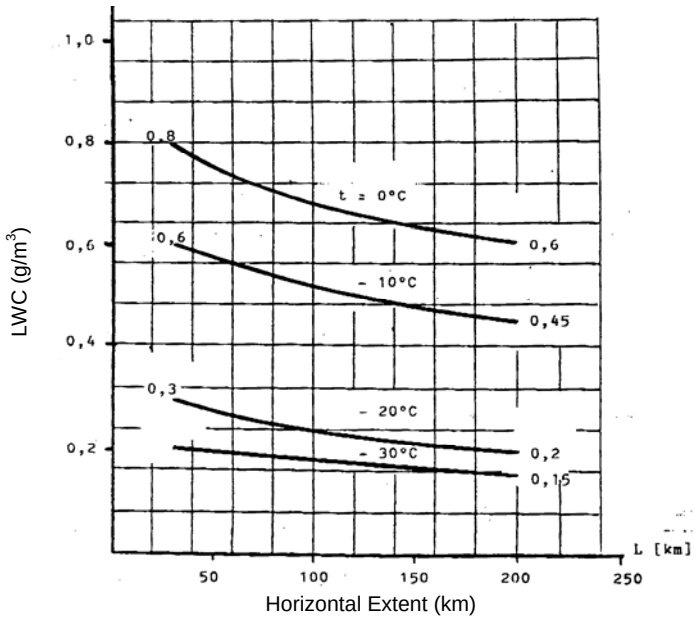

Figure G-1. Continuous Maximum LWC Design Curves in AP-25 [G-7]

The LWC dependence on horizontal extent is already built into figure G-1, and therefore, the LWC adjustment curve (figure 3 in the Western Appendix C) is unneeded and does not appear in the Russian version. The graph in figure G-1 replaces both figures 1 and 3 of Western Appendix C.

Similar changes (not shown) apply to intermittent maximum specifications.

G.3 1 CONCLUSION AND RECOMMENDATION FOR CONSIDERATION.

The Russian LWC envelopes are simpler than the Western Appendices C version because the use of a single drop size allows two graphs to be reduced to one. The distance-based LWC curves are also more convenient [G-6] for plotting and comparing flight test points, since the latter are usually averages over variable exposure distances.

The Russian and Western formats for the LWC design curves could be harmonized if Western practitioners adopted a distance-based format also, as suggested and explained in [G-6].

G.4 VARIATION OF LWC WITH HORIZONTAL EXTENT.

Based on their own data [G-1], the Russian icing specialists independently developed a distance reduction scale in which the LWC decreases less than that in figure 3 of Western Appendix C. The Russian and Western LWCs start out in agreement (for MVD = 15 µm, and MAD = 20 µm) for the standard design distance of 17.4 nmi, but they steadily diverge for longer averaging distances out to 200 km (108 nmi). A comparison is shown in figure G-2 [G-1 and G-7].

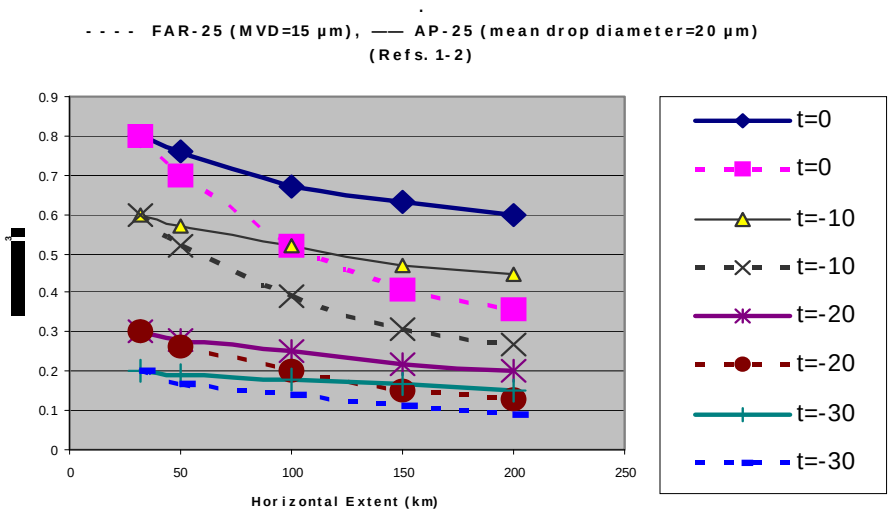

Figure G-2. Comparison of LWC Versus Horizontal Icing Extent, According to Russian AP-25 and Western Appendices C

For an MVD of 20 µm, the Western Appendix C LWCs (not shown) are 20% to 50% lower than the Russian LWCs over all distances, even at 17.4 nmi.

These differences in LWC versus horizontal extent (HE) are one reason for the differences in LWC specifications between Russian and Western Appendices C.

G.4.1 CONCLUSION AND ASSESSMENT.

The Russian design specifications for LWC are definitely more demanding than the Western requirements for MVDs greater than 15 µm and for exposure distances longer than 17.4 nmi (32 km). The original (circa 1950s) Russian specifications were apparently based on the (then) British model [reference G-4, pages 225-228]. During the 1970s, Russian researchers obtained their own flight data on icing conditions to adjust their LWC specifications to conditions over the Soviet Union. The 200-km HE requirement encompasses all operational conditions and avoids the need for any special considerations such as the 45-minute hold. The use of a 20-µm drop size specification, though large for mean diameter, brings the numerical value into the range of numerical values conventionally used by western practitioners. The net effect is that the main differences boil down to differences in LWC between the Russian and Western specifications.

G.5 COMPARISON OF LWC VALUES FOR USE IN ICING COMPUTATIONS.

For the two most commonly used MVDs in Western Appendix C, the comparison between Russian and Western design conditions can be reduced as shown in table G-1.

Table G-1. Comparison of Typical Russian and Western Design Values

Conventional Drop Size	AP-25	14 CFR Part 25	14 CFR Part 25
	20 µm (MAD)	15 µm (MVD)	20 µm (MVD)
Horizontal Extent	17.4-108 nmi (32-200 km)	17.4-108 nmi (32-200 km)	17.4-108 nmi (32-200 km)
True Outside Temperature (°C)	LWC (g/m^3)	LWC (g/m^3)	LWC (g/m^3)
0	0.8-0.6	0.8-0.35	0.63-0.28
-10	0.6-0.45	0.6-0.26	0.41-0.18
-20	0.3-0.2	0.3-0.13	0.20-0.09
-30	0.2-0.15	0.2-0.09	0.14-0.06

Note that AP-25 and 14 CFR Part 25 prescribe the same LWCs for only two situations:

a. HE = 17.4 nmi and MVD=15 µm
b. HE = 108 nmi for AP-25, while MVD = 20 µm and HE =17.4 nmi for 14 CFR Part 25

Otherwise, the AP-25 LWCs are greater than those in 14 CFR Part 25 for comparable HEs and temperatures.

G.5.1 FOR GENERAL COMPUTATIONS OF ICING RATES AND AMOUNTS.

Russian practice uses their fixed drop size (20-µm MAD) and LWCs for several HEs (e.g., 32, 100, and 200 km), although 200 km is often regarded as the standard design distance. For failed systems, a HE (and corresponding LWC) is selected that approximates the time to exit the icing conditions.

Past Western practice has used a fixed MVD (20 µm) and LWCs for the standard design distance (17.4 nmi), but recent advice has been to explore a range of MVD and LWC combinations on the subject airfoil.

G.5.2 FOR UNPROTECTED SURFACES.

Table G-2 shows typical selections for unprotected surfaces.

Table G-2. Selections for Unprotected Surfaces

Conventional Drop Size	AP-25	14 CFR Part 25
	20 µm (MAD)	20 µm (MVD)
Standard Distance	200 km	200 km (108 nmi)
True Outside Air Temperature (°C)	LWC (g/m^3)	LWC (g/m^3)
0	0.6	0.28
-10	0.45	0.18
-20	0.2	0.09
-30	0.13	0.06

The LWCs, and therefore, the expected ice accretion amounts, are in fact approximately twice as large for AP-25 (except that Russian practice limits ice depths to 75 mm (3 inches)).

G.5.3 CONVERTING MEAN DIAMETER INTO MVD.

A major concern has been the seemingly worse discrepancy that arises when the Russian mean diameter is converted to an equivalent MVD. Generally, the MVD is about 1.8 times larger than the mean diameter in a typical cloud droplet population. This means that the Russian design value of 20 µm for the mean diameter implies a corresponding value of about 36 µm for the MVD. When the Russian (and Western) standard design values of LWC (0.8 g/m^3 at 0°C, etc., for HEs of 17.4 nmi) are plotted above the 36-µm mark in the Western continuous maximum LWC versus MVD envelopes (see figure G-3), they are three to four times larger than the corresponding LWC curves at 36 µm. This has been cause for alarm because it appears that the Russian LWC design standards are much higher than the Western criteria in Appendix C.

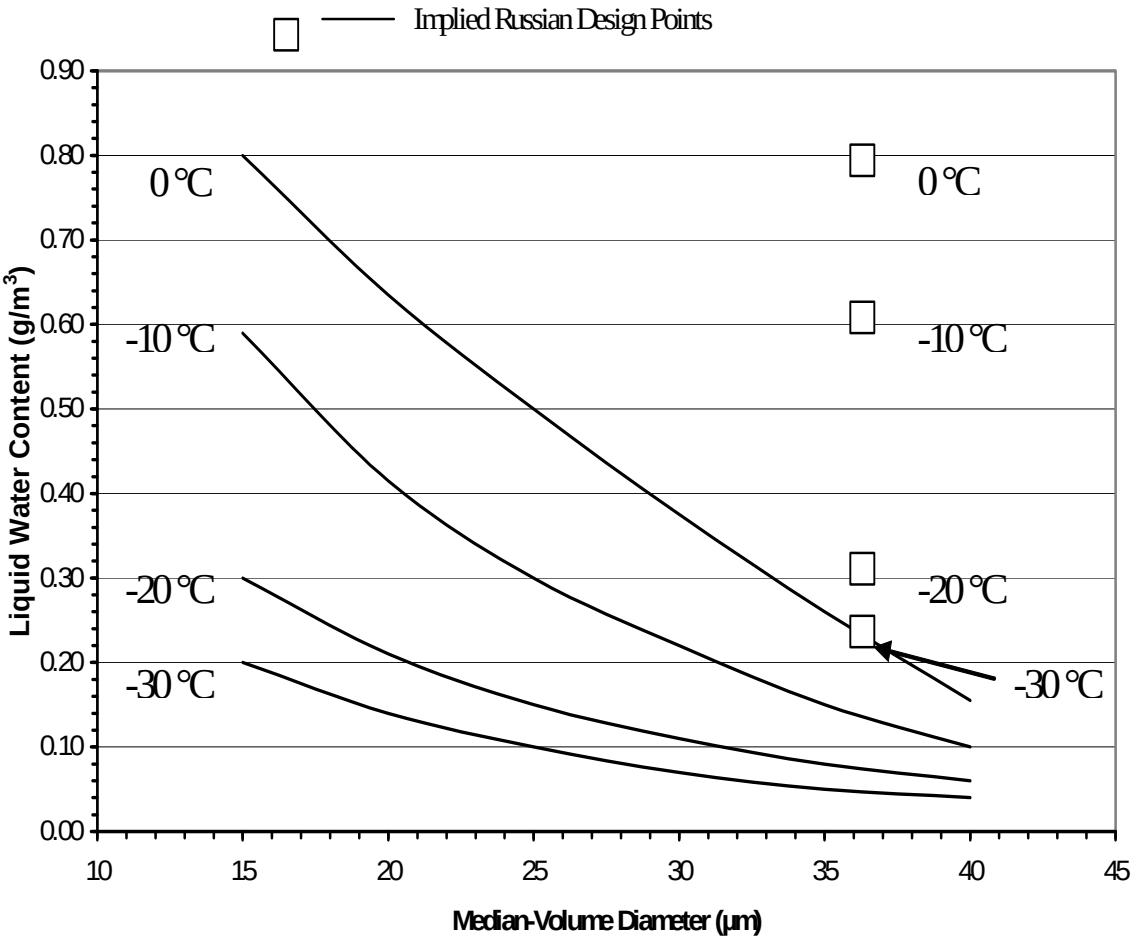

Figure G-3. Continuous Maximum (Stratiform Clouds) Atmospheric Icing Conditions LWC Versus Median Volume Drop Diameter

This comparison is deceptive, however, for two reasons. First, because it implies that to get the same results as the Russian method, Western practitioners must use a drop size of 36 µm with LWCs that are far larger than those called for in Western Appendix C. But, as explained earlier, computerized ice accretion codes (or older manual methods) respond *only* to the numerical value of the drop size that is given them, no matter what that value represents. A drop size is simply a drop size, no matter whether it is thought of as a mean value or an MVD. Thus, to get the same results, Russian and Western practitioners must use the *same* numerical drop size, not different ones.

As mentioned before, Western and Russian practice has conventionally used the same *numerical* drop size value (20 µm) for computing water catch and ice accretion amounts. Although Russian specialists think of it as the mean diameter and the Western practitioners think of it as an *MVD*, when they both use the *same* numerical value as their representative drop size in calculations, LWCs and all else being equal, the results should both be the same.

Actually, the combinations of LWC and MVD from figure G-3 never exactly match the Russian combinations in figure G-1. When the LWCs match, the drop sizes differ (15-µm MVD versus 20-µm MAD). When the drop sizes match (MVD and MAD both 20 µm), the LWCs differ.

So, the results will be different, but not as much as if the drop size (and LWC) values differ widely as in the implied design points at MVD = 36 µm in figure G-3.

Second, there is really no known conversion between MAD and MVD. That is, the MAD, being an average of the *peak* values of droplet mean diameter seen in a cloud sample, is not directly relatable to the MVD. Thus, the conversion, MVD = (1.8)x(mean diameter) cannot be applied, and the implied design point comparison in figure G-3 is not correct.

G.5.4 CONCLUSION.

Although there appear to be some major differences in the way representative drop sizes were derived in the Russian and Western icing traditions, the effect of any conceptual differences in the underlying drop size distribution is reduced when similar numerical values of *representative* drop size are used in the computations, regardless of the meaning attached to the drop size. Any remaining differences in the computational results must be due to factors other than drop size.

G.6 TEMPERATURE VERSUS ALTITUDE ENVELOPES.

The Russian versions of the ambient temperature versus pressure altitude envelopes extend to higher altitudes and, in the case of intermittent maximum icing conditions, to lower temperatures than the corresponding envelopes in the Western Appendix C. Figures G-4 and G-5 show the comparisons.

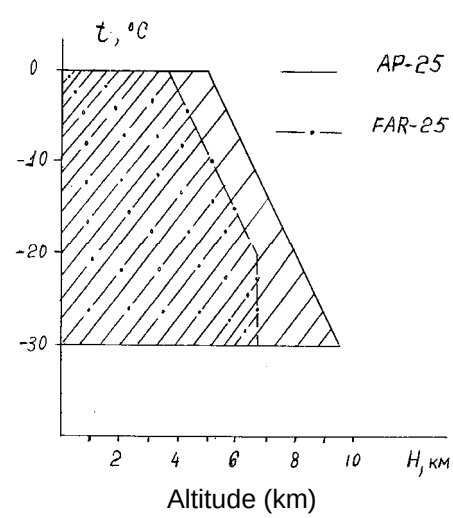

Figure G-4. Comparison [G-1] of Temperature-Altitude Envelopes for Continuous Maximum Conditions

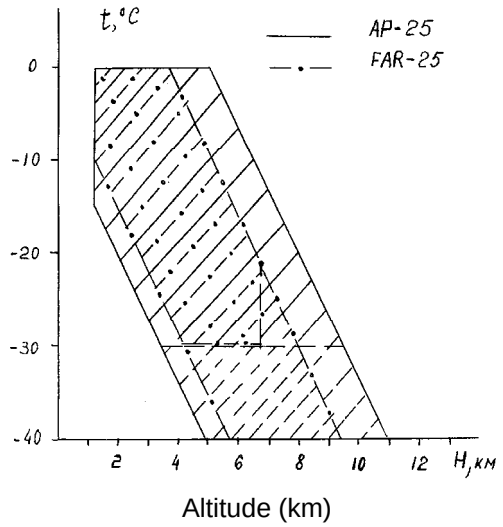

Figure G-5. Comparison [G-1] of Temperature-Altitude Envelopes for Intermittent Maximum Conditions

One reason for the differences in the intermittent maximum case is that the 14 CFR Part 25 envelopes account for only wintertime convective clouds that were sampled in the late 1940s and early 1950s. These data all fall within the published 14 CFR Part 25 envelopes. More recent data, compiled by the author from midseason and summertime convective clouds, extend over into the expanded envelopes contained in AP-25. Thus, the AP-25 intermittent maximum envelopes are probably wider due to the inclusion of summertime cloud data where higher altitudes are needed to reach subfreezing temperatures.

G.6.1 CONCLUSION AND RECOMMENDATION FOR CONSIDERATION.

Russian icing specialists [G-7] agree that the differences in temperature versus altitude envelope are probably not very important in practice. Nevertheless, the Russian and Western envelopes could be harmonized in one of two ways:

a. The Western versions could be expanded to match the Russian versions, or

b. A new, mutually acceptable version could be devised in which mild and warm season[3] extensions are added to the cold season version presently used in Western Appendix C. Suggestions of this type have been made in figures 34 and 35 of this report.

[3] Seasons can be defined by the height of the local area freezing level. A cold season environment is wherever the freezing level lies below 5000 ft AGL. The mild season has freezing levels between 5,000 and 10,000 ft AGL. The warm season is where the freezing level is above 10,000 ft AGL.

G.7 LIQUID WATER CONTENTS AT LOW ALTITUDES.

The specifications for continuous maximum conditions in Western Appendix C are stated to apply from sea level to 22,000 feet. This implies that the maximum LWCs (up to 0.8 g/m^3) can be found all the way to ground level. Clearly, this is unrealistic for two reasons. One is that fog measurements at ground level show maximum LWCs of less than about 0.3 g/m^3. The other is that LWCs generally increase with height in clouds, starting out near 0 g/m^3 at cloud base. The Federal Aviation Administration (FAA) amended 14 CFR Part 25 Appendix C in October 2007 to add a takeoff icing condition for which an LWC = 0.35 g/m^3 and MVD = 20 μm was assigned.

To be more realistic, Russian practice allows a reduction of the LWC requirements at altitudes below 1200 meters above ground level. Figures G-6 and G-7 show their linear reduction in LWC below 1200 meters. If extended to zero altitude, the LWCs would all end up at 0 g/m^3. For practical purposes, however, the reduced LWCs at 500 meters are held constant the rest of the way down. This is to allow for the possibility of reasonable amounts of LWC in fog at ground level. In particular, the curve in figure G-7 for -5°C ends up at 0.3 g/m^3 at ground level. This agrees with the LWC requirement (0.3 g/m^3) specified in 14 CFR Part 25.1093 for engine icing tests.

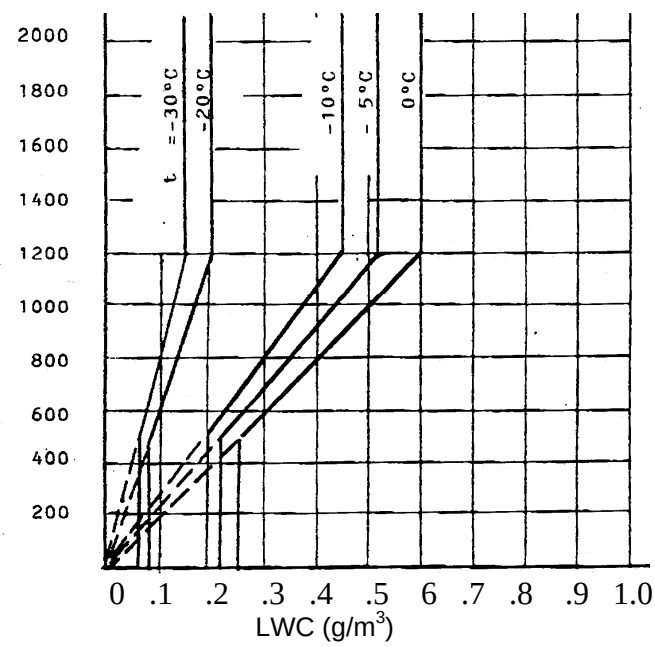

Figure G-6. Altitude-Adjusted LWCs in AP-25 Appendix C for HEs of 200 km (108 nmi)

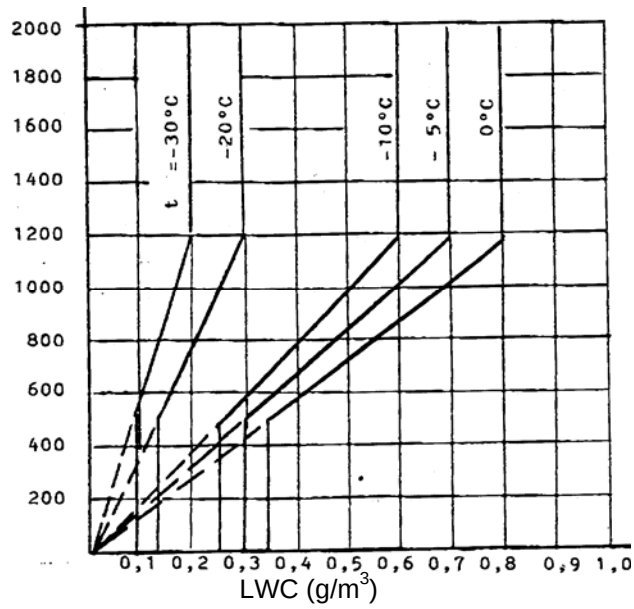

Figure G-7. Altitude-Adjusted LWCs in AP-25 Appendix C for HEs of 32 km (17.4 nmi)

G.7.1 CONCLUSION AND RECOMMENDATION FOR CONSIDERATION.

The Russian specifications add a bit of practical realism to the altitude dependence of LWC. The Russian and Western altitude dependence could be harmonized by adopting the Russian concept in figures G-6 and G-7, or by adopting the altitude-dependent LWC curves proposed in figure 44 of this report. Except for 17.4-nmi averaging distances (figure G-7), the LWCs used for other exposure distances (HEs) may still be different unless or until the Russian and Western LWCs are reconciled.

G.8 DROP SIZE RANGES.

The applicable range of drop sizes assumed in Russian practice includes freezing drizzle (maximum drop diameters between 50 and 500 µm), which they see 20%-30% of the time in natural icing flight tests in northern Russia. In contrast, Western data collected over the decades suggest that freezing drizzle occurs in only about 1% of the recorded icing encounters overall. In most modern measurements in stratiform icing clouds, the largest detected droplets are well below 50 µm in diameter. As a result, Western Appendix C is thought to be based on a smaller drop size range than AP-25 Appendix C. An examination of the original data underlying Western Appendix C shows that only an occasional MVD was detected beyond 30 µm. These larger MVDs were probably due to a few unrecognized freezing drizzle encounters. Otherwise, the MVD scale could be terminated at about 30 µm for ordinary stratiform clouds.

The presence of drizzle-sized drops means that a single MVD is less suitable for representing the whole range of droplet sizes for ice accretion computations. This has been pointed out by Russian icing specialists [G-1 and G-7] and is one reason for their choice of using the *mean* droplet diameter instead of MVD for numerical computations. The mean droplet diameter is less sensitive to a few large drops than is the MVD. The Russians also find that the mean diameter

more generally results in an acceptable match between computed and observed ice accretion amounts.

Western icing practitioners are just recently facing the freezing drizzle question as part of the so-called supercooled large droplet problem. The Federal Aviation Administration has established an international working group, called the Ice Protection Harmonization Working Group (IPHWG), which has been tasked to study and make certain recommendations on this issue. One result has been the proposal of a separate set of icing-related specifications for freezing drizzle and freezing rain. The IPHWG recommendation is to add their proposed freezing rain and freezing drizzle specifications to 14 CFR Part 25/JAR Part 25 as a new Appendix.

G.9 OVERALL CONCLUSIONS.

- The Russian and Western specifications for liquid water content (LWC) are likely to remain divergent due to apparent differences in horizontal extent dependence over the former Soviet Union as compared to North America (and western Europe).

- Representative drop sizes, maximum average diameter (MAD) and median volume diameter (MVD), are conceptually different and not convertible from one to the other. Nevertheless, if the same numerical value is used for both in single-drop size icing computations, then the results will not be affected by drop size differences.

- The Russian icing flight test environment appears to contain freezing drizzle more often than over most of North America.

  - The effects of freezing drizzle on the Russian design specifications are probably minimal, however. The MAD was purposely selected partly because it is insensitive to the presence of large drops. And freezing drizzle would add little, if any, LWC to the LWC design values for ordinary clouds.
  - Although Title 14 Code of Federal Regulations (CFR) Part 25 and Joint Aviation Requirements (JAR) Part 25 Appendix C is thought to reflect only ordinary clouds, a few freezing drizzle encounters may be responsible for extending the MVD axes beyond 30 µm out to 40 or 50 µm.
  - One way to harmonize the Russian and Western thinking on this subject is to specifically treat freezing drizzle (and freezing rain) separately from Appendix C conditions, as proposed by the International Ice Protection Harmonization Working Group (IPHWG). Otherwise, there will continue to be differences of opinion on the effects and importance of large droplets in the Appendix C specifications.

- The temperature versus altitude envelopes could be harmonized by adopting the wider Russian versions or by adding seasonal extensions onto the 14 CFR Part 25

and JAR Part 25 envelopes as is proposed in figures 29 and 34 or 35 of this report. Either way, the effect is the same—a widening of the envelopes.

- A more realistic altitude dependence for LWC could be had by adopting the graduated scale used in the Russian AP-25 Appendix C or by adopting the altitude-dependent curves proposed in figure 44 of this report.

G.10 REFERENCES.

G-1. Levchenko, V.S. and Sophin, V.A., "Main Concepts for Modeling of Standardized Cloud and Analysis of Differences between the AP-25 and FAR-25 Requirements Concerning Ice Protection," on pages 49-78 of the Proceedings of the FAA International Conference on Aircraft Inflight Icing, Volume 1—Plenary Sessions" in FAA Technical Report DOT/FAA/AR-96/81, I, August 1996. (This was from the FAA International Icing Conference held near Washington, DC in May 1996.)

G-2. Advisory Circular 20-73, "Aircraft Ice Protection," Federal Aviation Administration, 1971.

G-3. Bowden, D.T., et al., "Engineering Summary of Airframe Icing Technical Data," Technical Report ADS-4, Federal Aviation Administration, 1963.

G-4. Trunov, O.K., "Icing of Aircraft and Means of Combatting It," Moscow, 1965.

G-5. Khrgian, A.Kh. (editor), "Cloud Physics" ("Fizika Oblakov"), Leningrad, 1961.

G-6. Jeck, R.K., "Icing Design Envelopes (14 CFR Parts 25 and 29, Appendix C) Converted to a Distance-Based Format," FAA report DOT/FAA/AR-00/30, April 2002.

G-7. Levchenko, V.S., Gromov Flight Research Institute, Moscow; private communication.

APPENDIX H—GLOSSARY

Averaging distance (AD)	The flight distance over which the liquid water content (LWC) or other icing-related variables are averaged. What is included? In addition to unidirectional flight paths, the AD can include circular, racetrack, repetitive, and slant paths, unless these are specifically excluded from the analysis at hand. The AD should include only in-cloud distances, although the purpose of the computed average or the nature of the cloud sampler may allow momentary cloud gaps to be included. For example, the NACA rotating disk ice-rate meter had a 10-second response time and, therefore, cloud gaps of less than 10 seconds were not recognizable in the record. The rotating multicylinders (RMC) are another example. They were usually exposed for fixed time intervals of 1 minute or more, unless the aircraft obviously exited the cloud under study. Therefore, any momentary cloud breaks would be included as part of the AD. Modern, electro-optical droplet counters with a time resolution of 1 second or less can resolve cloud breaks with this finer resolution. Nevertheless, it may be desirable to average the cloud samples over the whole cloud or encounter. In this case, the analyst can choose to perform the average with or without including the fraction of time spent in momentary breaks, although it is generally preferable to not include breaks. Ideally, the analyst should report how the averages were computed.
Cumuliform (convective)	Clouds with marked vertical development.
Data miles	The number of nautical miles (nmi) over which usable flight data have been obtained.
Database	Refers to the computerized compilation of cloud measurements described in this report.
Encounter	1. An averaging interval consisting of one or more events added sequentially until a gap of some prescribed distance (e.g., 1 nmi or more) is reached, 2. The total distance flown in measurable icing conditions until a break of some prescribed distance is reached.
Envelope	Graphical curve(s) depicting the range or maximum expected values of a variable.

Event	The basic averaging interval—the distance over which the cloud variables are constant within the limits given in table A-1.
Exposure distance (ED)	1. The total distance flown in icing conditions until the aircraft departs the icing area. 2. The distance over which a cloud sampler is operated continuously. There are two definitions, one for the entire aircraft and one for individual measuring instruments or sampling probes. That is, in definition 2, the ED refers to the operation of a sampler rather than to the actual duration of icing clouds. For example, with RMCs, the exposure time determines the ED. For continuously recording samplers (e.g., rotating disk ice-rate meters or modern, electro-optical particle counters), the exposure time is continuous, but the maximum ED should be considered to be limited by the cloud dimension or the duration of individual encounters.
Glaciated	Composed entirely of ice particles.
Horizontal extent[1] (HE)	Any approximately unidirectional horizontal distance in icing conditions over which an average or maximum value of LWC or some other variable is of interest. The HE can be anything from a fraction to the full width of a cloud, cloud system, or expanse of icing conditions. That is, the HE is not necessarily the full (edge-to-edge) extent of a cloud or expanse of icing conditions. For example, the conventional reference or design distance of 20 statute miles (17.4 nmi) is a legitimate HE, even though the actual extent of available icing conditions may be much greater. The HE is usually of interest in connection with the maximum value of LWC that can be expected as an average over a specified value of HE.

[1] Although horizontal extent is a common term in the icing literature, it has not been defined anywhere. Therefore, it is defined here in a way that is compatible with conventional usage.

When computing averages from flight data, the HE is conventionally taken to be the longest unidirectional horizontal distance (UHD) over which the LWC is averaged. It is possible, however, to select one or more portions of this longer path for computing averages over shorter distances. This may be of interest when a long flight path is punctuated with occasional bursts of greater LWC. In that case, the overall average is of interest as well as average LWCs that are possible over shorter distances. These shorter averaging intervals are legitimate HEs, too. In figure H-1, two typical HEs are shown for a flight path which enters a cloud (icing conditions) at one edge, proceeds some distance in cloud, executes one or more racetrack patterns, and then returns to the original edge to exit the cloud.

Relationship of HE to AD and ED. The AD and ED are usually equal to or greater than the HE. This is best explained by an example. In figure H-1, typical HEs are marked off as the longest UHDs along the flight path. In this same situation, the ED for the aircraft would be the entire distance traveled inside the cloud, including all the circuits made around the racetrack pattern. The AD could be the same as or less than the ED, depending on the application. For example, if it were only of interest to know what the average LWC was during the racetrack circuits, then the AD could include only the distance spent in the racetrack or holding pattern. If it were of interest to compute a new LWC for every 17.4-nmi interval along the flight path, then the ADs would all be 17.4 nmi.

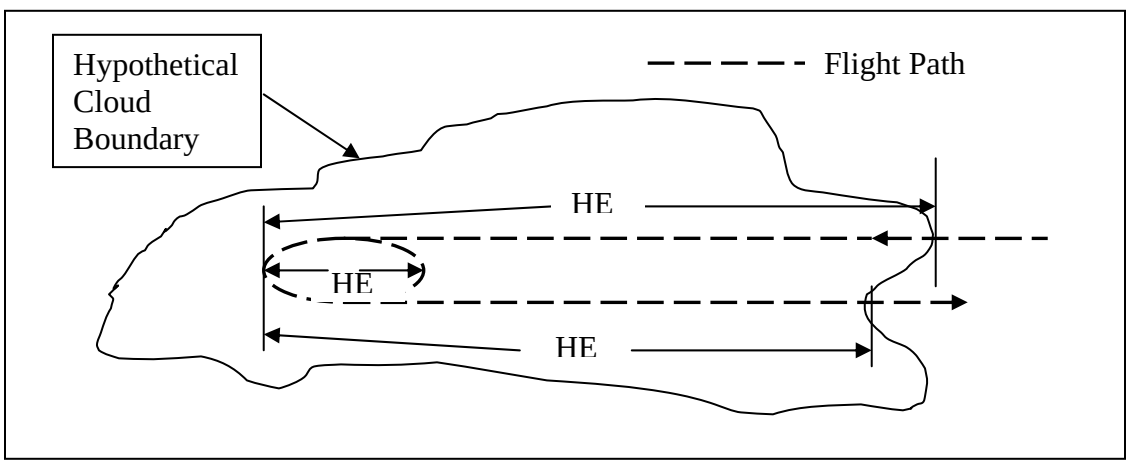

Figure H-1. Examples of Different Possible Horizontal Extents

Liquid water content — The total mass of water represented by the population of unfrozen droplets in a cubic meter of cloud (usually 0 to 4 g/m^3).

Median volume diameter (MVD)	The mass-weighted (or volume-weighted) median droplet size has the property that half the LWC is in droplets smaller than the MVD and half in larger droplets.
Probable maximum	The value of a variable that is expected to be unexceeded 99% of the time.
Stratiform (layer)	Clouds with marked horizontal development.
Supercooled	The condition of remaining liquid at temperatures below the freezing point.