AEROSPACE INFORMATION REPORT	AIR5396™	REV. A
	Issued 2001-03 Revised 2015-08 Reaffirmed 2023-01 Superseding AIR5396	

Characterizations of Aircraft Icing Conditions

RATIONALE

The information presented in this SAE Aerospace Informatino Report (AIR) is revised to reflect current icing certification procedures. The document is technically correct for Appendix C icing conditions, is mature and is not likely to change in the foreseeable future. There are additional icing condition definitions that have been developed to address supercooled large drop icing and mixed phase/ice crystal conditions. Addition of these icing conditions to this AIR would not fit within the scope of this document. Therefore, the document will not be revised in the future and the intent is to stabilize the document at its Five-Year Review.

AIR5396A has been reaffirmed to comply with the SAE Five-Year Review policy.

1. SCOPE

This SAE Aerospace Information Report (AIR) provides various graphical displays of atmospheric variables related to aircraft icing conditions in natural clouds. It is intended as a review of recent developments on the subject, and for stimulating thought on novel ways to arrange and use the available data. Included in this Report is FAR 25 (JAR 25) Appendix C, the established Aircraft Icing Atmospheric Characterization used for engineering design, development, testing and certification of civilian aircraft to fly in aircraft icing conditions.

1.1 Purpose

Research on aircraft icing conditions in the atmosphere has been conducted intermittently since the 1940s. But, until recently, only the data gathered during the first few years of flight research had been condensed into extreme value envelopes and publicized for use in the design of ice protection systems for aircraft. One purpose of this AIR is to assemble in one document some new ideas on displaying icing-related variables and using them for various applications.

1.2 Field of Application

This report presents atmospheric data that describes the aircraft icing environment. The report contains four different approaches in displaying and using the data:

1.2.1 Currently Accepted Civil Design Envelopes ("FAR-25, Appendix C").

1.2.2 U.S. Air Force Trial Design Envelopes.

1.2.3 Distance-Based Envelopes.

1.2.4 A Nomogram and Statistical Approach.

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2. REFERENCES

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2.2 Symbols

2.2.1 HE or HEX: Horizontal extent.

2.2.2 VE or VEX: Vertical extent.

2.2.3 PE or PEX: Path extent.

2.2.4 LWC: Liquid water content (mass of water per unit volume of air).

2.2.5 MVD: Median volume diameter.

2.2.6 MXD: Maximum volume diameter.

2.2.7 MND: Minimum volume diameter.

2.2.8 nmi: Nautical miles.

2.2.9 kt: Knots.

2.2.10 RWI: Rate of water interception.

2.2.11 TWP: Total water exposure, or total water path.

2.2.12 OAT: Outside air temperature.

2.2.13 CAT: Cloud air temperature.

2.2.14 FAT: Free air temperature.

2.2.15 IPS: Ice protection system(s).

2.2.16 FAA: Federal Aviation Administration.

2.2.17 NGM: Nested grid model.

2.2.18 ROP: Relative occurrence probability.

2.2.19 RDR: Real dispersion ratio.

2.2.20 SOF: Safety of flight.

2.2.21 GIS: Graphical information system.

2.2.22 PIREPS: Pilot reports.

3. AEROSPACE INFORMATION REPORT MAIN BODY

3.1 Currently Accepted Civil Design Envelopes ("FAR-25, Appendix C")

3.1.1 Introduction

Icing conditions are present in clouds above the freezing level when the clouds are in a "supercooled" state. These are clouds in which undisturbed cloud droplets remain liquid even at temperatures as low as -40 °C, a condition called supercooling. When a passing aircraft collides with these droplets, they may freeze rapidly on exposed and insufficiently heated aircraft surfaces. The amount of ice that accumulates depends on the size, shape, speed, and temperature of the exposed surfaces, and on in-cloud variables such as the size of the cloud droplets, their collective water concentration, or liquid water content (LWC), and on the air temperature along the flight path and on the duration of the exposure. It is information about the extreme values of these latter atmospheric variables that engineers must have when designing anti-icing or deicing systems on aircraft.

For the past 50 years, the set of six graphs (Figures A1 to A6), known collectively as "Appendix C" of parts 25 and 29 of the U.S. Federal Aviation Regulations (Reference 2.1.7) (and similar sections of regulations in other countries) have served as the principal source of engineering data on icing conditions in the atmosphere.

The six figures in FAR-25, Appendix C show: (a) maximum probable liquid water concentration (LWC) in supercooled clouds as a function of air temperature and cloud droplet median volume diameter (MVD), (b) expected temperature extremes in icing conditions as a function of altitude, and (c) 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.

The FAR-25, Appendix C envelopes were originally proposed in 1949 (Reference 2.1.4), based on analyses of about 3,000 nmi of airborne measurements in supercooled clouds at altitudes to about 20,000 feet (6 km) over the United States during the winters of 1945 through 1948. Since 1956 these envelopes have been used to specify the meteorological conditions for which ice protection equipment on civil transport category aircraft must be designed and certified. These envelopes were added to certification requirements for small, civil airplanes in 1973 and for civil rotorcraft in 1983. The envelopes are also used for guidance in conducting icing wind tunnel tests and demonstration flights in the process of certifying aircraft for flightworthiness in icing conditions. The envelopes have also been widely used by the military for these purposes.

3.1.2 Applications of FAR-25, Appendix C

The envelopes are typically used to select design values of temperature and maximum probable LWC for computing the maximum amount of ice expected to accumulate on unprotected components, or for computing the maximum heat requirements for anti-icing the forward surfaces of wings, tailplanes or engine inlets. For all of these applications, a combination of temperature and LWC would be selected for various operational altitudes (below 22,000 feet) for the aircraft in question. Any "critical" flight condition, such as idle descent for jet aircraft where hot bleed air is at a minimum, may require another set of temperatures and LWCs. Examples of these kinds of applications are given in Reference 2.1.14.

For airplanes with deicing equipment, such as expandable rubber boots on the leading edges of the wings, FAR-25, Appendix C is also used to determine critical ice accretions. Intercycle ice, residual ice, and runback ice are dependent on LWC, OAT, and MVD, as well as flight condition. Additionally, a maximum drop size of 40 µm or 50 µm diameter is used to design chordwise extent of the wing or tail ice protection. Ice accretion aft of protected areas must be accounted for when demonstrating safe flight in icing conditions. The envelopes are also needed for estimating the accumulation of ice on unprotected surfaces. Typically a maximum drop size of 40 µm or 50 µm diameter is used to compute the chordwise extent of the wing or tail that must be covered by the active portion of the boot. Nothing else seems to be needed from FAR-25, Appendix C, except to demonstrate by flight tests that the boots operate properly in the expected extreme temperatures and in the available LWCs, and that they efficiently shed ice accretions that may accrete in. FAR-25, Appendix C icing conditions. The envelopes may still be needed as before for estimating the accumulation of ice on unprotected components, however.

3.1.3 Limitations of FAR-25, Appendix C

Although the FAR-25, Appendix C envelopes are suitable for selecting extreme values of LWC for various combinations of air temperature, MVD, and exposure distance, they do not contain all the information about the icing environment that is often desired. For example, they do not give the probability that particular values of LWC or MVD will be found in icing clouds. Designers of military aircraft may want to have a reduced ice protection capability in order to save power, weight, and payload. In this case it would be useful to have information on the probable occurrence of various values of LWC in icing conditions. It may be acceptable to design for lesser LWCs that will be exceeded 10% of the time, for example. The FAR-25, Appendix C envelopes give only larger LWCs, those that may be exceeded 1% of the time.

As another example, notice that the LWC versus MVD envelopes (Figures 1 and 4 of FAR-25, Appendix C [Figures A1 and A4 in this report]) are arbitrarily cut off at an MVD of 15 µm. This is because the envelopes are simply a graphical representation of a collection of recommended design points proposed in NACA TN-1855 (Reference 2.1.4). An MVD of 15 µm was apparently thought to be the minimum MVD worth considering for the size of the wings and tail sections in use at the time (1940). But today there are concerns that rotor blades and thin, natural laminar flow (NLF) airfoils have significant collection efficiency for droplets smaller than 15 µm in diameter.

Finally, Reference 2.1.11 shows that maximum expected LWCs are altitude dependent, but this fact is not reflected in the Appendix C envelopes.

Thus, the envelopes are really only design envelopes and are not complete descriptions of the icing atmosphere in all aspects.

3.1.4 New Approaches

In the late 1970s, the helicopter community began calling for relief from the large design values of LWC by requesting new envelopes tailored to the lower altitudes where helicopters operate. There was also a general interest in re-evaluating the FAR-25, Appendix C envelopes against new data being obtained from modern, electro-optical, cloud probing instruments coming into use on aircraft instrumented for cloud physics research. As a result, a new data gathering and analyses effort was begun under FAA sponsorship. About 28,000 nmi of measurements, both old and new have been collected into a computerized database (Reference 2.1.24) in order to answer these issues.

It is with this expanded database that several icing practitioners have experimented with different ways of analyzing and displaying the data for their particular applications. Three different sets of examples have been contributed to this Aerospace Information Report. They are intended to familiarize the interested reader with some of the possibilities, stimulate new ideas, and to otherwise provide data displays that may be useful to diverse practitioners. Two of these contributions resulted from particular military needs. The other resulted from attempts to overcome the difficulties of comparing icing flight test data (which are averaged over variable flight distances) to the FAR-25, Appendix C envelopes.

3.2 U.S. Air Force Trial Design Envelopes (contributed by Henry E. Bertolini)

3.2.1 Introduction

The United States Air Force has pioneered the concept of Integrity Programs as a primary tool for weapon system development. This began with the structural integrity programs: ASIP and ENSIP for airframes and engine structures respectively. The success of these programs led to the desire to implement the integrity philosophy to systems and their software. Under the Integrity Program tasking entitled Characterizations and Analyses lies the Environment Characterization, of which the Flight Icing Environment is a subset. An accurate environmental definition is required, as design stress environmental spectra, design duty cycle and usage characterizations are performed utilizing these data. It has been determined that current Mil-Standard definitions of the icing environment are not sufficient for use in the Integrity Program approach to weapon system development. Ongoing development programs within Aeronautical Systems Division at Wright-Patterson AFB also found the current definitions cumbersome and not indicative of reality. The search for data that reflects the actual icing environment has resulted in the characterization contained herein.

3.2.2 Data

Some early icing data and collection methods were reviewed (References 2.1.1 to 2.1.6). It is apparent that the limitations of these efforts are reflected in the current MIL-Standard. Although a large spectrum of icing conditions are documented in the early NACA Technical Notes, it appears that the current curves were based on a "critical drop size" and hence some data (which we now consider important) were not included in the final curves. This decision may have been based on droplet impingement studies utilizing thick wing sections at moderate speeds. Whatever the case, the current curves do not define the limits of the icing environment but rather are design envelopes to be used for ice protection system design. Our goal is to define the environment for usage in the heretofore mentioned integrity programs. The shortcomings of the current envelopes are revealed when an attempt is made to find an intersection of drop size, temperature and LWC that appear in nature. These attempts are futile and do not serve the purposes of environment definition. The Federal Aviation Administration had concerns that the current FAR-25, Appendix C envelopes (Reference 2.1.7) (the source of the MIL-Standard curves) were overly conservative for some types of aircraft and the FAA Technical Center undertook a project to create an icing data base "of recent measurements of icing parameters recorded by research aircraft using modern cloud physics instruments" (Reference 2.1.8). It is this data base, developed and managed by Dr. Richard Jeck, formerly with the Naval Research Laboratory, upon which the characterizations contained herein were constructed. (References 2.1.9, 2.1.10, and 2.1.11).

3.2.3 Flight Icing Environment Envelopes

It must be clarified that these envelopes are for supercooled clouds only. Two sets of envelopes have been constructed; one set for layered clouds (Figures B1A and B4A) and one set for convective clouds (Figures B1B and B4B). The four charts in each set are: Temperature versus Altitude, Liquid Water Content versus Temperature, Liquid Water Content versus Altitude, and Horizontal Extent versus Liquid Water Content. The envelopes given represent 99.9% of icing conditions, that is, these data are the result of a 0.001 probability analysis (Reference 2.1.1). These envelopes are a compromise between environment definition and utility for engineers and designers. Note that these charts are preliminary and input from all interested parties is highly encouraged. The shortcomings and possible additions will be discussed later. Our hope is to coordinate the final version of these charts with all of the DOD and with the future FAA envelopes so that, as much as possible, they are the same. We wish to alleviate the burden that two sets of criteria place on the manufacturers.

3.2.4 Using the Charts

Figure B1A, Temperature versus Altitude encompasses 99.9% of icing conditions in layered clouds. Figures B2, Liquid Water Content versus Temperature and Figure B3A, Liquid Water Content versus Altitude define limits of liquid water content in layered clouds based on temperature and altitude respectively. Figure B4A, Horizontal Extent versus Liquid Water Content defines a LWC factor based on the length (in nmi) of the icing encounter in layered clouds. Figures B1B to B4B contain the same information for convective clouds.

Figure B1A presents the temperature/altitude envelope in which icing conditions in layered clouds may be encountered by aircraft in normal flight operations. It does not indicate the severity of those conditions. Figure B2A presents the range of LWCs that can be found at the temperature of interest. Figure B3A presents the range of LWCs possible at the altitude of interest. The curves on Figures B2A and B3A define the limits of LWC based on temperature and altitude respectively. As the data of Figures B2A and B3A are normalized to a 17.4 nmi cloud, Figure B4A further factors the LWC for horizontal extent. The convective cloud information is presented in the same manner on Figures B1B to B4B.

3.2.4.1 Examples of Chart Usage

3.2.4.1.1 Layered Clouds Example No.1

3.2.4.1.1.1 Choose an altitude/temperature combination. 10k feet at -20 °C (Figure B1A).

3.2.4.1.1.2 Check LWC range based on temperature choice. 0.0 to 0.7 g/m^3 (Figure B2A).

3.2.4.1.1.3 Check LWC range based on altitude choice. 0.0 to 0.9 g/m^3 (Figure B3A).

3.2.4.1.1.4 Determine limiting factor. Temperature limits LWC at 0.7 g/m^3.

3.2.4.1.1.5 Choose LWC from range based on limiting factor. Choose maximum for this example: 0.7 g/m^3. NOTE: Any LWC up to the maximum value is a valid choice.

3.2.4.1.1.6 Choose extent and determine LWC factor. Choose 50 nmi. Yields factor of 0.66 (Figure B4A).

3.2.4.1.1.7 Result: 50 nmi icing encounter at 10k feet at -20 °C with LWC of 0.46 g/m^3.

3.2.4.1.2 Layered Clouds Example No.2

3.2.4.1.2.1 Choose an altitude/temperature combination. 10k feet at -10 °C (Figure B1A).

3.2.4.1.2.2 Check LWC range based on temperature choice. 0.0 to 1.0 g/m^3 (Figure B2A).

3.2.4.1.2.3 Check LWC range based on altitude choice. 0.0 to 0.9 g/m^3 (Figure B3A).

3.2.4.1.2.4 Determine limiting factor. Altitude limits LWC at 0.9 g/m^3.

3.2.4.1.2.5 Choose LWC from range based on limiting factor. Choose maximum for this example: 0.9 g/m^3. NOTE: Any LWC up to the maximum value is a valid choice.

3.2.4.1.2.6 Choose extent and determine LWC factor. Choose 50 nmi. Yields factor of 0.66 (Figure B4A).

3.2.4.1.2.7 Result: 50 nmi icing encounter at 10k feet at -10 °C with LWC of 0.59 g/m^3. [As expected the warmer temperature supports a higher maximum LWC and in both cases the horizontal extent factors the normalized cloud to a lower LWC.]

3.2.4.1.3 Convective Clouds Example No.1

3.2.4.1.3.1 Choose an altitude/temperature combination. 20k feet at -25 °C (Figure B1B).

3.2.4.1.3.2 Check LWC range based on temperature choice. 0.0 to 1.3 g/m^3 (Figure B2B).

3.2.4.1.3.3 Check LWC range based on altitude choice. 0.0 to 3.5 g/m^3 (Figure B3B).

3.2.4.1.3.4 Determine limiting factor. Temperature limits LWC at 1.3 g/m^3.

3.2.4.1.3.5 Choose LWC from range based on limiting factor. Choose maximum for this example: 1.3 g/m^3. NOTE: Any LWC in this range is a valid choice.

3.2.4.1.3.6 Choose extent and determine LWC factor. Choose 1.0 nmi. Yields factor of 1.19. (Figure B4B).

3.2.4.1.3.7 Result: 1.0 nmi icing encounter at 20k feet at -25 °C with LWC of 1.55 g/m^3.

3.2.4.1.4 Convective Clouds Example No.2

3.2.4.1.4.1 Choose an altitude/temperature combination. 20k feet at -15 °C (Figure B1B).

3.2.4.1.4.2 Check LWC range based on temperature choice. 0.0 to 3.4 g/m^3 (Figure B2B).

3.2.4.1.4.3 Check LWC range based on altitude choice. 0.0 to 3.5 g/m^3 (Figure B3B).

3.2.4.1.4.4 Determine limiting factor. Temperature limits LWC at 3.4 g/m^3.

3.2.4.1.4.5 Choose LWC from range based on limiting factor. Choose maximum for this example: 3.4 g/m^3. NOTE: Any LWC in this range is a valid choice.

3.2.4.1.4.6 Choose extent and determine LWC factor. Choose 1.0 nmi. Yields factor of 1.19 (Figure B4B).

3.2.4.1.4.7 Result: 1.0 nmi icing encounter at 20k feet at -15 °C with LWC of 4.0 g/m^3. [Again the warmer temperature supports a higher LWC and the horizontal extent factors the LWC of the normalized cloud to a higher value.]

3.2.4.1.5 Convective Clouds Example No. 3

3.2.4.1.5.1 Choose an altitude/temperature combination. 20k feet at -30 °C (Figure B1B).

3.2.4.1.5.2 Check LWC range based on temperature choice. 0.0 to 0.5 g/m^3 (Figure B2B).

3.2.4.1.5.3 Check LWC range based on altitude choice. 0.0 to 3.5 g/m^3 (Figure B3B).

3.2.4.1.5.4 Determine limiting factor. Temperature limits LWC at 0.5 g/m^3.

3.2.4.1.5.5 Choose LWC from range based on limiting factor. Choose maximum for this example: 0.5 g/m^3. NOTE: Any LWC in this range is a valid choice.

3.2.4.1.5.6 Choose extent and determine LWC factor. Choose 1.0 nmi. Yields factor of 1.19 (Figure B4B).

3.2.4.1.5.7 Result: 1.0 nmi icing encounter at 20k feet at -30 °C with LWC of 0.6 g/m^3.

3.2.4.2 Application of the New Characterization

What impact would this new environment have on current uses of the MIL-Standard envelopes? To examine the implications we have chosen an icing condition suggested by JSSG-2007 (Reference 2.1.12); Low Altitude Loiter. The changes to LWC dictated by the new characterization are shown in the accompanying charts. In this case the pressure altitude, flight speed, and ambient temperature were used to determine the values necessary to utilize the charts as in the previous examples. The duration values were used to determine the required horizontal extent. Using the Layered Cloud Charts we see that the LWC is limited by altitude and it is further modified by the horizontal extents (HE). Notice that the LWCs are most severe for the short durations and least severe for the longest exposure (11 minutes or 35.2 nmi). For the short durations the new envelopes yield less severe LWCs but for the longer durations the LWCs become more severe. Interestingly, if the Convective Cloud Charts are used for the short duration exposures (2 minutes or 6.4 nmi) the results are the same for this particular example. This example demonstrates but one possible implication. Actually we would expect the new envelopes to be used in a broader sense that is to determine all of the test condition parameters. And possibly the new envelopes would indicate a vastly different combination of temperature and altitude, not just LWC, as the critical case(s).

3.2.4.3 Questions about the New Envelopes

Is this method of presentation acceptable? Is presentation of the "limits" all that is required? Is more information needed: probability of occurrence, duration versus altitude, droplet size (MVD) versus altitude or some relevant parameter (if one can be found)? All of these questions (and likely many more) must be addressed before consideration for incorporation into a MIL-PRIME can occur.

This characterization has been adopted as the specified icing environment in a current USAF program. We anticipate that the lessons learned during this program will be extremely valuable in the effort toward a new and universal icing environment definition.

3.3 Distance-Based Envelopes (Contributed by Richard K. Jeck) (Reference 2.1.22)

3.3.1 Introduction

Over the past several years, a computerized database of some 28,000 nmi of inflight measurements of icing conditions has been assembled at the FAA Technical Center. One purpose of this project was to explore new ways to quantitatively describe icing conditions aloft. Possible uses are for engineering design guidance, improving forecasts of inflight icing conditions, providing realistic values of LWC and droplet sizes for icing wind tunnel tests and computer modeling of icing conditions, and providing realistic expectations and guidance for flight tests in natural icing conditions.

At the present time, the only quantitative descriptions of icing conditions aloft are those generated by civil aviation authorities, or by military design bureaus. These organizations need them as engineering design criteria for ice protection equipment on aircraft. These criteria simply specify the maximum expected values of LWC as a function of temperature and cloud droplet size in clouds above freezing level. In the U.S. these descriptions are found in Appendix C of the Federal Aviation Regulations, Parts 25 and 29 (FAR-25 and FAR-29) (Reference 2.1.7). Figure A1 shows the criteria for stratiform clouds. This graphical presentation is often called a characterization, and the limiting curves are often referred to as design envelopes.

Although this existing characterization has served for selecting design values of LWC, it has some self-limiting features which hamper its wider use. It is in the spirit of exploring alternate ways of describing icing conditions, and attempting to overcome some of these limiting features that this methodology is presented. This methodology is therefore for the purpose of information exchange only, and to relate some of the insight that has been gained by exploring alternate approaches.

3.3.2 The LWC versus MVD Characterization

There are several variables involved in describing the icing-related properties of clouds. These are LWC, droplet sizes, temperature as a function of height in the clouds, and the vertical and horizontal dimensions of clouds. For simplicity and convenience, the droplet size distributions are usually represented by a single variable, the median volume diameter (MVD). The early researchers of the subject in the late 1940s and early 1950s originally recommended a number of discrete LWC, MVD and temperature and altitude combinations for use in the design of aircraft ice prevention equipment (Reference 2.1.4). Although the horizontal extent of icing conditions is generally quite variable, for design purposes the NACA researchers simply recommended fixed distances of one-half mile, 3 miles, or “continuous”, depending on the cloud type. Somewhere along the way, the discrete tabular combinations were converted to a graphical format (Figure A1, for example), as they appear today in FAR-25 and FAR-29. LWC and MVD were selected as primary variables, with temperature serving as a governing parameter. But the maximum probable LWC also varies (inversely) with averaging distance, so the magnitude of the LWC versus MVD characterization will change for different averaging distances. This complication was managed by establishing the characterization in Figure A1 for a fixed averaging distance (20 statute miles) and then providing a correction factor for adjusting the LWC limits for other distances. The correction factor was supplied as an experimentally derived curve (Figure A3).

There are several problems with this arrangement. One is that it is difficult to plot test points on Figure A1 because the test exposures are usually different from the fixed reference distance for which the envelopes are drawn. There is usually no valid way of converting the actual LWC to what it may have been if the exposure had been equal to the reference distance. The only dependable way is to shrink or stretch the envelopes along the LWC dimension (by applying the LWC adjustment factor curve) to conform to the actual exposure distances each time. A similar problem arises when trying to compare various points on the envelopes to each other when, as usual, the exposure distances are different. In other words, the present arrangement does not easily accommodate the fact that exposure distances are really variable.

3.3.3 The LWC versus HE Characterization

One way to overcome this problem is to bring exposure distance right up front as a primary variable. MVD can be treated as a controlling parameter, like temperature. Figure C1 shows all the available LWC averages from the database for stratiform clouds, plotted in the LWC versus HE format. In order to plot these points on Figure A1, they would all have to be converted somehow to an averaging distance of 20 statute miles (17.4 nmi). There are major uncertainties in trying to do that legitimately. Alternately, Figure A1 would have to be re-scaled (using Figure A3) for each of the averaging distances used in Figure C1. This would result in a large number of graphs like Figure A1, one for each averaging distance, and the situation would be unwieldy at best. In Figure C1 the data points all fall naturally in place on a single graph, no matter what their averaging distance.

3.3.4 Sample Overlays

Figure C2 shows the observed upper limits to LWC as a function of temperature and horizontal extent. This characterization can be used in the same way as Figure A1, except that here it is easier to visualize the influence of averaging distance on maximum probable LWC. It shows that as the clouds get colder, not only does the maximum available LWC decrease, but also a given LWC can be sustained only over shorter distances. This is no doubt a result of the fact that the lower the temperature, the more difficult it is to maintain a supercooled cloud - the clouds are more likely to turn into ice crystals.

Figures C2 and C3 can also be used by forecasters to determine the worst case icing conditions aloft. The temperature-limited curves give the maximum LWC to be expected at any flight-level temperature, and they also show the longest distance a given LWC may be expected to last.

Figure C3 overlays the observed upper limits to LWC (and HE) as a function of MVD. It shows that the maximum probable LWC and the allowed HE both decrease as MVD moves away from about 15 microns. (Both the mean value and the most common value of MVD occur at about 15 microns.) This means that the farther the MVD deviates from about 15 microns, the harder it is to maintain or find that condition. Statistically, only 2% of the recorded MVDs exceed 30 microns, for example, and the longest recorded exposure to 30-micron MVD droplets is only a little more than 20 nmi.

3.3.5 “Tracking” the LWC

Figure C4 illustrates the natural way test data can be plotted in a HE-based format. In addition to the usual test “points” (the large black dots) representing the overall average of the LWC at the end of the exposure, the entire history of the LWC measurements can be plotted, if desired. That is, all points begin somewhere along the left side of the figure (at HE=0) and migrate somewhere to the right until the measurement is terminated.

3.3.6 Converting to Exposure Time

Figure C4 also illustrates the ability to plot results in terms of exposure times instead of distance. Just divide the HE scale by the airspeed of interest. This is convenient for wind tunnel or computer model runs where exposures are usually expressed in time intervals. Figure C4 shows that a wet wind tunnel running at 1 g/m^3 and 200 kt will exceed the limit of natural icing conditions if the exposure lasts longer than about 3 or 4 minutes.

3.3.7 The RWI versus HE Characterization

Figure C5 shows a similar graph with the ordinate converted to rate of water interception (RWI). This is done by simply multiplying LWC by a fixed value of airspeed (200 kt in this case). RWI is of importance in anti-icing applications, for example. The RWI characterization shows how long a given RWI can be expected to last in natural icing conditions, and it can be used to plot RWI test points (and RWI histories) as before.

3.3.8 “Protection” Zones

Figure C6 shows one way to compare test points with design points. If an ice protection system is designed to withstand 0.5 g/m^3 of LWC over the standard distance of 17.4 nmi, then a “design protection zone” has been established which includes all lesser LWCs and all lesser HEs (for a specified range of temperatures). This zone can be depicted on the HE-based graphs as shown by the larger shaded area in Figure C6. If a subsequent test flight demonstrates that the ice protection system can withstand a certain LWC over a given distance, then a similar “demonstrated protection zone” has been established. The smaller shaded area in Figure C6 illustrates the demonstrated zone for a hypothetical test flight which found 0.3 g/m^3 over a distance of 30 nmi and was able to demonstrate that the ice protection equipment worked properly for the exposure. This scheme permits a direct comparison between design and test points, in terms of the relative size and coverage of their protection zones. Similar protection zones can also be drawn on the RWI versus HE plots, if one wants to work in terms of RWI instead of LWC.

3.3.9 The TWP versus HE Characterization

Finally, Figure C7 shows the database plotted in terms of total water exposure, or total water path (TWP). The TWP determines the eventual ice accumulations and is, therefore, important for both deicing systems and for unprotected surfaces. The TWP data points are obtained simply by multiplying each LWC by its own averaging distance. The graph shows that there is a natural upper limit to TWP, as a function of HE, just as there is for LWC. In fact, the smooth curve enclosing the largest observed TWPs can be obtained by multiplying 1 g/m^3 by values along the curve in Figure A3 and by their corresponding HEs. That is, the LWC adjustment curve in Figure A3 is still in effect, but it now appears as a limiting envelope in the TWP versus HE characterization! This suggests that TWP can be used as a design variable instead of LWC. For suitable applications, a required minimum exposure (TWP) could be selected instead of a specific value of LWC and HE. Instead of specifying 0.35 g/m^3 over 17.4 nmi, for example, one could specify a TWP of 6 g.nmi/m^3 instead. Figure C7 shows that this TWP requirement can be met by any combination of LWC and HE resulting in a TWP on or above the horizontal line drawn at TWP=6. The limiting curve also shows that a TWP of 6 can be obtained with exposures as short as 5 or 6 nmi. But the scatter in the data points shows that TWPs in the range of 6 to 12 are more likely to be found over exposures of about 17 to 50 nmi.

3.3.10 Principle of Equivalency

The above example illustrates another new possibility offered by the HE-based format. The horizontal line arbitrarily drawn on Figure C7 illustrates the fact that all the points along this line have the same value of TWP. That is, all encounters having the same product of LWC and HE are equal to each other, as far as total water exposure is concerned. For example, a 20 nmi exposure to 0.5 g/m^3 presents the same total water path as a 100 nmi exposure to 0.1 g/m^3. Thus, LWC and HE can be traded off, under appropriate conditions, to achieve a specified TWP.

Although it was not pointed out earlier, this reciprocity applies to RWI too. There, LWC and airspeed can be traded off while maintaining a constant value of RWI.

This reciprocity can ease the burden of flight tests by emphasizing total water exposures or rates of water interception rather than particular values of LWC. That is, the exact value of LWC may not be critical, in appropriate applications, as long as the total exposure or rate of exposure meets the requirements. It must be emphasized that this equivalency applies only to the variables (TWP and RWI) themselves, and not necessarily to their effects (such as ice shapes or the performance of ice protection systems). It simply means that the aircraft has been exposed to the same total amount of water or the same rate of water interception. But in most cases, TWP and/or RWI could be used as a basis for comparing exposures or gauging their adequacy. In some cases, equivalent TWPs and/or RWIs may result in equivalent effects as well, at least to a first approximation.

TWPs also have the property of being additive. This is useful in natural icing flight tests. It may provide a practical way of specifying a required minimum exposure. The aircraft can accumulate icing exposures until some minimum TWP has been met.

3.3.11 Summary

This methodology demonstrates some new insights and possibilities that come to light when LWC, RWI, or TWP are plotted against horizontal extent (HE) as a way to characterize icing conditions. The characterizations are usable for selecting realistic values of icing-related variables for a variety of purposes, including icing wind tunnel settings, computer modeling, and predicting the intensity of icing conditions aloft. The HE-based format can simplify the plotting of test points, and the equivalency properties of RWI and TWP, as well as the notion of protection zones, suggest new ways of comparing exposures and evaluating test flights. The examples and conjectures described herein are given simply to illustrate the possibilities and are not to be considered as approved procedures.

3.4 A Nomogram and Statistical Approach (Contributed by David J. Yurkanin)

3.4.1 Introduction

Much effort has been expended in an attempt to gather icing environment characterization data and present it in a fashion that it is clear and useful to those working in many different fields of aviation. Over the past four decades various analyses of an extensive accumulation of modern aircraft icing cloud research data has called into question the accuracy, applicability, and utility of the FAA standard (FAR-25, Appendix C) currently in use by government and commerce. The presentation of the data variables of concern, the inferred data relationships and trends, the perceived meaning of the plotted curves, and the consistent use of the "full" set of charts are some concerns regarding the standard. These and other issues are only partly addressed in proposals by various researchers over the years. One example of a concern would be that the Liquid Water Content (LWC) values in the main chart are normalized to a specific horizontal extent (HEX), such that test data of an arbitrary extent should not be directly compared to data curves in the chart. Another example is the use of HEX alone instead of a path extent (PEX) that would allow for phases of flight such as climb-out, approach, orbiting, and spiral descent/ascent where a vertical extent (VEX) is also desired. Yet another example would be the provision of relevant statistical information (such as frequency, percentile, and probability) on the spatial and temporal occurrence of icing, its extents, and its severity.

The issue of not changing a standard that has produced aircraft Ice Protection Systems (IPS) that function so well for the past four decades is being overcome by the above deficiencies and the need to optimize an IPS design with well-defined confidence margins in order to minimize cost, weight, and electrical power requirements. The variability and complexity of aviation icing environments (such as cloud supercooled droplets and ice crystals; precipitating, blowing, and recirculating snow; sleet and hail; freezing rain and sea spray; ice and supercooled fog, and frost) in various operational regimes (such as cruise, takeoff, climb-out, approach, and landing; ground and ship phases; and hover) require many overlapping characterizations and a very robust graphic presentation method beyond what is currently available.

The purpose of this methodology is to provide a proposal for a nomogram that can be more easily used by: (a) engineers that perform Ice Protection System design, trade study, and test; (b) technologists responsible for qualification and certification assessment; (c) program managers needing to make design, cost, and schedule decisions and even; (d) climatologists and forecasters giving operational evaluations and weather briefings. This particular format was conceived considering the historical and existing presentations, intended use, accretion environment, operational regime, and audience as well as minimizing the above deficiencies. Adoption of such a nomogram would require that the data used to define the current standards is separately applied, to generate data curves in the new format, in order to validate the applicability of any new standard to existing operational IPS designs. Any new standard should also progress through end-user "beta" testing to ensure its integrity, usefulness, and acceptance.

3.4.2 Presentation Formats

In order to efficiently formulate this new data presentation, many chart formats currently being used needed evaluation. This includes local formulations such as the common LWC-Mean Volumetric Diameter (MVD)-Outside Air Temperature (OAT) format as shown in Figure A1, the preferred Altitude-OAT icing envelope as shown in Figure D1, and the often overlooked LWC-Horizontal Extent (HEX) format as shown in Figure D2. Figure A1 shows the current FAA standard as a function of ambient temperature for layer clouds. Figure D1 shows both old and new icing envelopes, with a scattergraph of the FAA icing database, along with composite temperature and altitude histograms showing the statistical variation in the data. Figure D2 shows the horizontal extent of icing encounters, using a pre-defined set of conditions for both English and metric units, along with a scattergraph of symbols representing the institutional source of the data.

A historical review of the literature concerning icing environment data presentation in the past was also required. References 2.1.13 to 2.1.14 give an excellent summary of methods of presentation of icing variables that have been used over the years with an extensive bibliography of icing related research. References 2.1.15 to 2.1.25 are some additional works related to this subject not listed in the associated section and/or the main bibliography.

The current, widely accepted standard has its origins in a series of NACA Technical Notes based on data obtained in the late forties and early fifties and is presented in many different combinational and statistical formats. In the late sixties and early seventies much work was done with climatology and forecasting of icing conditions where that data was displayed relative to a global map or a standard weather chart. From the late seventies to date the greatest advancement of characterization methodology and philosophy has been produced.

As stated by Newton (Reference 2.1.19), there needs to be a delineation between environment characterization (forecasting or climatology) and engineering standardization (design, certification, or qualification) mainly because the character and usage of the information is for such different purposes. Even so, a common baseline data format would be beneficial to all those involved (researcher, designer, forecaster, pilot). The types of charts used over the years seem to fall into either of these classes, and typically combine two or three cloud physical variables in some non-functional manner or represent those variables using a statistical method such as probability, percentiles, or frequency. They are used in research reports, specifications, standards, handbooks, guides, and reference manuals. The current FAR 25, Appendix C standard is actually a "set" of combinational charts, that must be used together in order to choose appropriate sets of variables, without statistical information.

Some examples of climatological chart presentations that are global in nature are shown in Figure D3, showing a polar projection map of the earth with sectors giving low altitude icing probability, and Figure D4, showing an equatorial projection of the earth, with icing potential represented by exceedance frequencies as a function of altitude, at selected locations. Some other examples that focus on forecasting local environmental conditions are shown in Figure D5, a Skew T-Log P diagram overlay to estimate the most probable icing intensity in a local environment, and Figure D6, the cumulative frequencies of icing occurrence as a function of Temperature and Dew-Point Spread.

Various ways of presenting similar statistical data such as percentile curves or levels and Relative Occurrence Probability (ROP) isolines have been investigated in support of various Naval aircraft programs. Figure D7 shows a percentile curve format and Figure D8 shows a ROP format. These charts were developed to assess the cost effectiveness and safety of-flight (SOF) impact of protecting or not protecting certain components of an aircraft.

All of these charts were developed by individual users for specific reasons. What is needed now is a standardized, baseline chart format that can be understood and used by all those involved with making adverse weather aviation possible - meteorologists, climatologists, forecasters, design engineers, test engineers, aircrew, certifiers, qualifiers, and their respective technical decision makers. This same chart should accept "environment characterization" and "design standard" curves, as well as climatological and forecasting formats. The proposed format should serve as a starting point for plotting many different environment, operational, and performance variables and curve types against a standard set of variables on fixed axes.

3.4.3 Format Rationale

The factors affecting aviation systems are constituted in two aircraft-relative scales; local and global. The proposed local nomogram must be capable of interfacing to a global format that considers climatological variables such as seasonal, topographic, orographic, and airmass dependencies. This can be done by simply having multiple chart sets or ultimately a Geographical Information System (GIS) on CD-ROM with a global map display, that when a particular location or region is picked, the desired chart is displayed. By using Altitude as a vertical axis the potential for a 3-D representation of the proposed chart referenced to a globe or map is valuable and highly desirable.

With aviation systems, for the inflight phase of operation, any chart format should include Airspeed and Altitude, which is the Flight Envelope, simply because it describes the local spatial and temporal environment in which operations occur. A low altitude version of the chart could be generated for approach/climb-out, ground, and ship aviation operational environments.

Since the particular issue with aircraft icing is the phase change from water to ice, which is a strong function of temperature and pressure that varies primarily with atmospheric level, then Altitude and Temperature, which is the Icing Envelope, should also be included. It is also true that in-Cloud and precipitation icing environments are a strong function of atmospheric level.

When designing an air vehicle or determining its specified performance, the maximum operational radius or distance (Range, Specific Range, or Climb Distance) and the maximum time-on-station or total flight time (Endurance, Time-to-Climb, or Marshal Time) as a function of Gross or Payload Weight are primary variables. These are typically charted as a function of Altitude or Airspeed as well. Other important parameters affected by icing, such as Rate of Climb, could be easily adapted to a chart using Altitude and Airspeed. For other components, such as the airframe integration of the propulsion inlet, duct, and engine, variables such as Thrust and Air/Fuel Mass Flow Rate would also adapt well to such a chart.

For forecasting purposes, it is desirable to have a chart format that allows for resolution of concerns regarding icing severity definition, which may require a link back to the qualification/certification and design engineering standard charts. In Figure D5, Trace, Light, Moderate, and Severe Icing are defined there as historically used by weather forecasters. Recent research says that these icing severity degrees are actually airframe configuration dependent, not just indicative of the presence and intensity of supercooled droplet regions in clouds. Notice that the overlay of Figure D5 and its parent chart (Skew T-Log P) are actually based on Altitude (pressure level) versus Temperature like the nomogram in Figure D9.

The key vertical axis as Altitude should be evident as shown in Figure D9. The right part of the nomogram has the upper horizontal axis as Airspeed and the lower horizontal axis as the Cloud Air Temperature (see Note 4.1). The left part of the nomogram has the upper horizontal axis as Endurance and the lower horizontal axis as Range. As an example the remaining vertical axes have Payload and Rate-of-Climb. On the right a basic flight envelope line is shown along with contours of an icing envelope variable such as HEX (see Note 4.2), LWC, or MVD (see Note 4.3) and on the left is shown a family of curves for various gross weights.

Plots for the nomogram would be obtained from environment characterization data and airframe or component design/simulation data. If HEX, VEX, or PEX; LWC; and/or MVD contours are overlaid then Ice Accretion Rate R, Total Build-up, B and the Total Water Path TWP are defined by the following equations:

$$\begin{aligned} R &= LWC \times V_{\infty} \times A_f \times \eta \times (MVD) = (TWP)/\tau \times A_f \times \eta \times (MVD) \\ B &= TWP \times A_f \times \eta \times (MVD) \\ TWP &= LWC \times PEX \end{aligned} \qquad \text{(Eq. 1)}$$

where:

V = Airspeed

A_f = Component Frontal Area

τ = Exposure Duration

η = Total Collection Efficiency

Note that the variable TWP, or the Total Water Path developed by Jeck (Reference 2.1.22), can also be used within this nomogram format as long as PEX, HEX, or VEX are used appropriately. From this information and the Temperature and Altitude the amount and type of ice accretion could be determined along with associated component degradation (Aerodynamic, Weight, Impact, Electromagnetic). This nomogram would also allow for the differences in displayed variables for an unprotected, deiced, or anti-iced component. The corresponding degradation of Range, Endurance, Payload Weight, Rate-of-Climb, or any other component specific variables could be calculated via simulation or measured through testing and displayed on the left or right side of the nomogram. In so doing the chart would allow for design assessments and trade-offs since Temperature and Altitude are compromised to gain benefits in required electrical power, bleed air, or weight (shown as dashed lines in Figure D9). Once the desired performance curves are determined on the left, a set of statistical contours could be plotted on the right. This would allow determination of what kinds of degradation are the most probable, such that some sort of protection should be applied, or aid in determining where the specification could be relaxed while incurring the lowest risk.

3.4.4 Data Sources, Models, and Trends

The origins of such a nomogram evolved out of efforts to present a more accurate icing environment characterization for particular military program issues. This involved gathering a wealth of reduced icing meteorological data and interpretive models now available from various sources around the world to be used for cross-verification of trends in the data. The data sources currently being used are the FAA icing database, the NOAA/FSL icing Pilot Reports (PIREP) database, the NOCD/NCDC Global Upper Air Climatic Atlas (GUACA) database, and NCAR/ARL WISP icing forecasting correlations.

As the data were processed it was realized that the FAA charts (Reference 2.1.7) did not give a complete and accurate picture of the icing environment and icing potential as well as being in a format inefficient for design purposes. An issue in particular was the need for a "scenario extent" or distance that represented the typical exposure of an aircraft during a mission or phase of flight, not just when flying through a particular cloud type. An example chart from the analysis, presenting the icing envelope with isolines of scenario horizontal extent is shown in Figure D10.

Note that the distances can be quite long compared to individual encounters and approach those found in the FAA LWC versus HEX charts. Another requirement was information that gives the VEX of icing conditions for assessment of climb-out, approach, descent, and ascent flight patterns. An example of a VEX chart generated by employing data extracted from the FAA icing database using a detailed filter algorithm is shown in Figure D11. This chart presents the icing envelope with isolines of vertical extent. Note that the large depths of icing conditions are associated with convective clouds.

With regard to statistical data there was a need to cross-verify the trends shown within the FAA icing database. Another database of Pilot Reports (PIREPS) of icing conditions was employed. This database contains codes that represent type and severity of icing along with Nested Grid Model (NGM) computer simulation estimations of meteorological variables existing near the time of the PIREP. This data was used to generate the chart set in Figure D12. Each chart shows the icing envelope with isolines of ROP for each database. Note the reference curves on each chart show the standard atmosphere, American and Russian data, and a NACA estimate of most probable icing temperature. The trend of the isolines in each database chart show striking agreement with each other as well as with the NACA curve (seems to be a lower limit).

The major point with the data variables and chart formats in Figures D10 to D12 is that they utilize the Altitude versus CAT icing envelope for display. This versatility is what provided the realization that this type of format would be efficient as a baseline chart upon which most of the required variables could be plotted and compared. This format also could be linked to a global type presentation as well as airplane performance charts.

3.4.5 Nomogram Example

The nomogram chart is a combination of a Pressure Altitude-OAT-Airspeed presentation, which is actually a joining of the Icing and Flight Envelopes, and an Altitude-Range-Endurance presentation. This fusion of data allows direct comparison of the particular aircraft flight limit extremes and the exposure extents of icing. In actuality any performance variables of interest, typically a function of Altitude or Airspeed, can be placed on this nomogram. An example nomogram, shown in Figure D13, shows how data might be displayed.

Although very busy for display purposes, this particular nomogram could be used as an example as follows:

3.4.5.1 The flight envelope is plotted on the right chart.

3.4.5.2 The particular icing flight boundaries from the detail specification, and reductions being considered, are placed on the right chart.

3.4.5.3 The scenario HEX isolines are plotted on the right chart for layer/convective clouds.

3.4.5.4 Airspeed/HEX comparisons can then be made at various altitudes along with evaluation of specification boundary reductions on the right chart.

3.4.5.5 Given critical altitudes and airspeed/HEX combinations, degradation of the aircraft performance could be measured or simulated and plotted on the left chart.

3.4.5.6 In this case Payload-Range curves are shown with/without ice and also Altitude versus Specific Range with ice.

3.4.6 Another example of the use of the nomogram would be if isolines of flight hour density and icing exposure PEX were plotted on the right chart then a more concise assessment or trade can be performed regarding the value of protecting or not-protecting a particular aircraft or component. If isolines of icing exposure ROP are plotted instead of PEX then the importance of that protection can be evaluated. On the left chart, for example, if Payload Gross Weight lines are drawn for the clean and iced aircraft (derived from analytical and/or test results) the true cost of icing degradation effects can be presented. The nomogram can also be used for presenting individual component degradation comparisons such as ice accretion stall behavior of flight surfaces, air inlet blockage and shed ice ingestion size/potential, rotor torque rise and vibration from asymmetrical shedding, and antenna/radome performance degradation; while relating all the effects to the required flight phase/mission profile (see Note 4.4).

4. NOTES

4.1 Cloud Air Temperature (CAT) is the preferred thermodynamic state variable for the nomogram because it best defines the particular accretion environment ambient temperature. The term "cloud" refers to the dispersion of hydrometeors, not only of meteorological clouds, but precipitation and sea spray, for example. CAT represents a "wet bulb" temperature of the ambient air, not a Free Air Temperature (FAT), which infers a "dry bulb" temperature. In some accretion environments CAT and FAT are the same, and in most the difference may be inconsequential.

Outside Air Temperature (OAT), however, accounts for the static temperature drop due to the static pressure decrease around airframe components in "real fluid" flow-fields. Many researchers use OAT since their measurement devices protrude near the aircraft fuselage surface where these aerodynamic effects take place. Total Air Temperature is just the CAT plus the delta temperature gained from the flow coming to rest minus any "real" delta temperature due to heat losses from the device.

4.2 Horizontal Extent (HEX) and Vertical Extent (VEX) are estimates of the dimensions of the cloud of an accretion environment, for example, supercooled droplets. The important variable for evaluating a particular aircraft exposure is Duration, which can be obtained by dividing the flight path distance by the airspeed. The flight path distance while in icing is a function of the particular mission or purpose of the flight phase, not only HEX and/or VEX. For example, what would be the exposure of an extended descent approach with one landing abort and go-Around? What would it be for a marshaling (orbiting) and descent approach profile? It seems that ultimately a path extent (PEX) is what is desired.

4.3 The Mean Volumetric Diameter (MVD) is a single variable that describes the dispersion characteristics of a particular accretion environment. It is useful for plotting on these characterization charts, but it is not sufficient. Added variables that fully describe the droplet distribution; such as Maximum Droplet Diameter (MXD), Minimum Droplet Diameter (MND), and Real Dispersion Ratio (RDR); should be considered. RDR is the ratio of the integrated LWC of an ideal distribution (say Langmuir "B") centered at the MVD, over the integrated LWC of the entire "real" distribution. RDR gives an indication of how much LWC is present at the extremities of the distribution. These added variables are important for "installed" exposed components (such as an ice detector) where hydrometeor trajectory effects (droplet boundary layer) are important.

4.4 Some thoughts on why the current standards (FAA and Military) have been so successful for four decades of aviation Ice Protection System (IPS) design and operation are in order. First, knowing that as of 1991-1992 there are ~50,000 icing related PIREPS per year and only ~60 icing incidents per year, it might be thought that our current standard and implementation process is acceptable. However, it must be realized that most of these icing encounters were recorded because the pilots were requesting another altitude to exit from the conditions, before any severe complications could occur. Also, most of the icing accidents over the years were on unprotected airframes and by pilots with limited experience flying in icing conditions. In addition, forecast icing conditions are for the most part avoided by prudent pilots. The result is that the standard has not been "tested" as intensely as it seems. Second, the current standard is "statistically conservative," i.e., it specifies maximum conditions, such that if an IPS is designed to protect components in most of the icing envelope, it would even perform in the most severe, lowest probability conditions, such as in highly convective cells (i.e., thunderstorms). This may be called conservative design while others would call it "over-design." This has caused a heavy burden on manufacturers for certifying (qualifying) new technology, aerodynamically sensitive aircraft in icing conditions (especially helicopters) such that many aircraft are not permitted to fly in icing.

4.5 Revision Indicator

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications nor in documents that contain editorial changes only.

PREPARED BY SAE SUBCOMMITTEE AC-9C, AIRCRAFT ICING TECHNOLOGY OF COMMITTEE AC-9, AIRCRAFT ENVIRONMENTAL SYSTEMS

APPENDIX A - FIGURES FOR CURRENTLY ACCEPTED CIVIL DESIGN ENVELOPES
(FAR 25 APPENDIX C)

Pressure altitude range, S.L. to 20,000 feet.
Maximum vertical extent 6,500 feet.
Horizontal extent, standard distance of 17.4 nautical miles.

Class III-M continuous maximum.

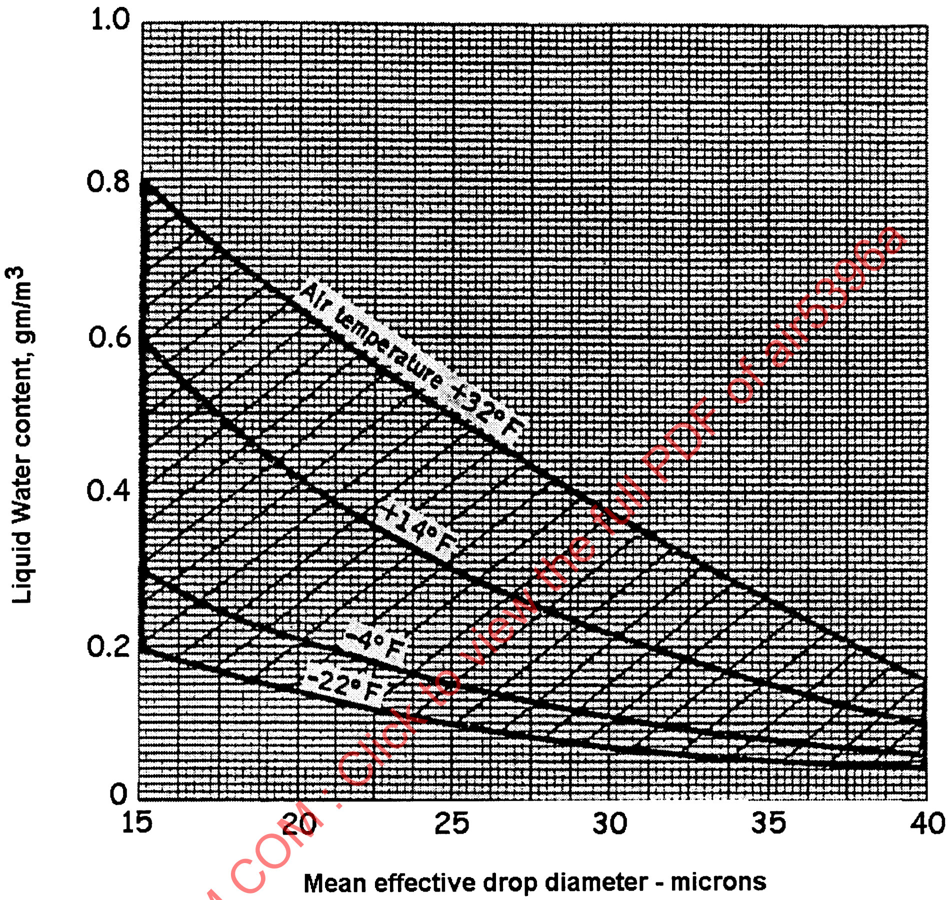


Figure A1 - FAR Part 25 (Appendix C) continuous maximum atmospheric icing conditions (stratiform clouds) - mean effective droplet diameter versus liquid water content

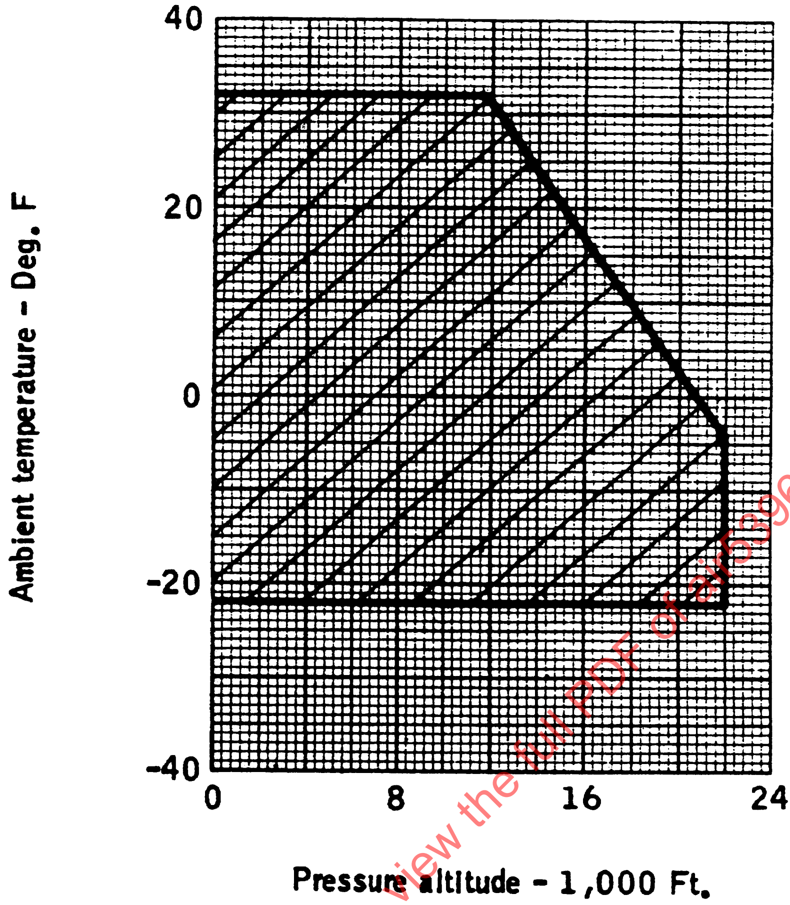


Figure A2 - FAR Part 25 (Appendix C) continuous maximum atmospheric icing conditions (stratiform clouds) - pressure altitude versus ambient temperature

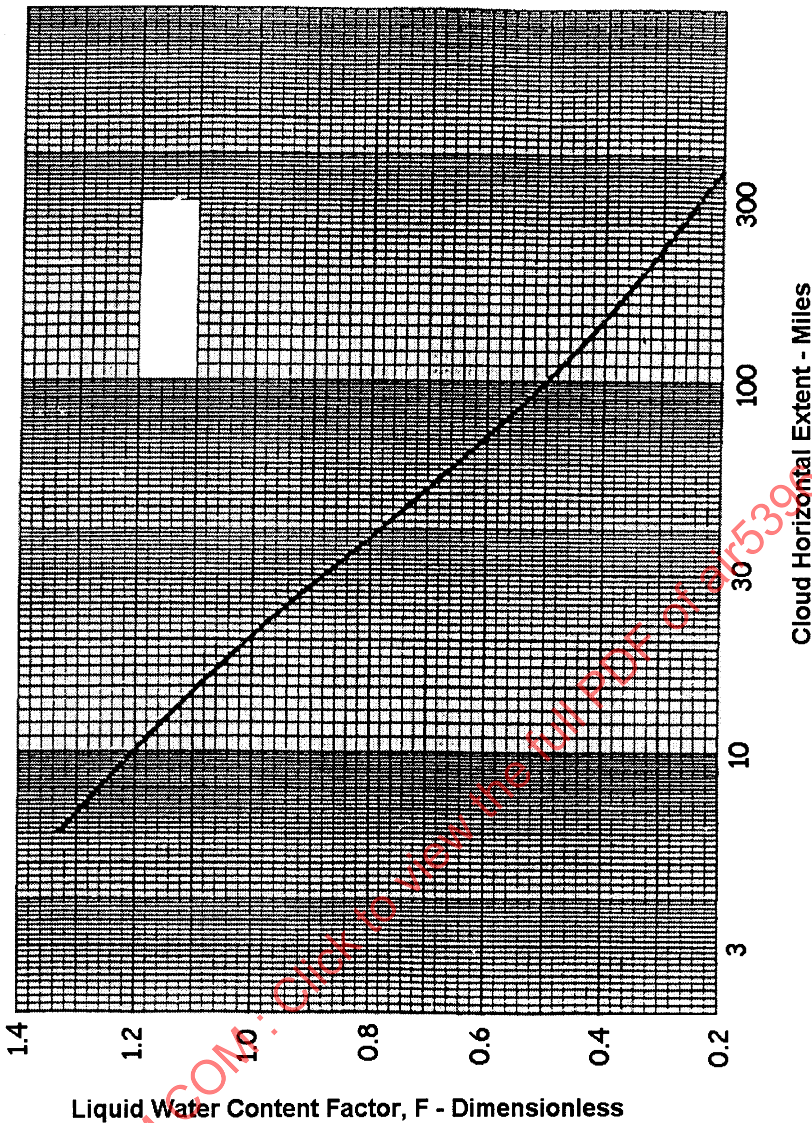


Figure A3 - FAR Part 25 (Appendix C) continuous maximum atmospheric icing conditions (stratiform clouds) - cloud horizontal extent versus liquid water content factor

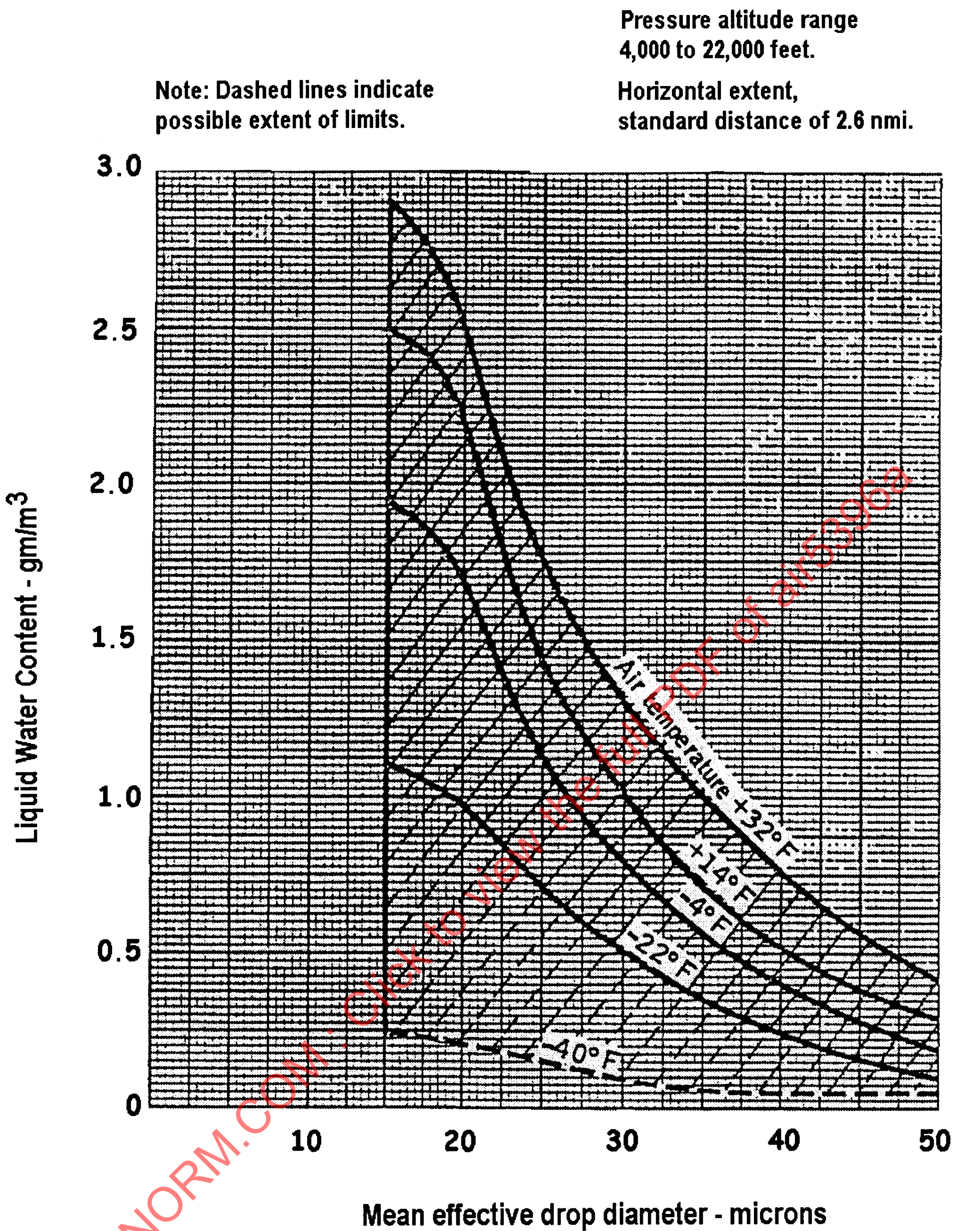


Figure A4 - FAR Part 25 (Appendix C) intermittent maximum atmospheric icing conditions (cumuliform clouds) - mean effective droplet diameter versus liquid water content

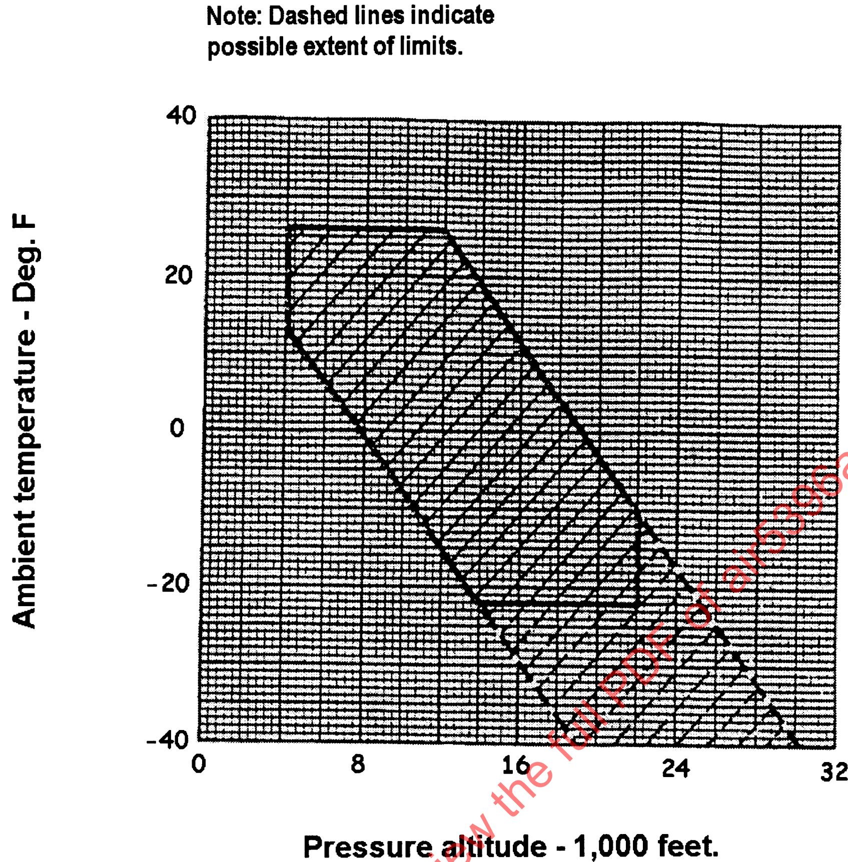


Figure A5 - FAR Part 25 (Appendix C) intermittent maximum atmospheric icing conditions (cumuliform clouds) - pressure altitude versus ambient temperature

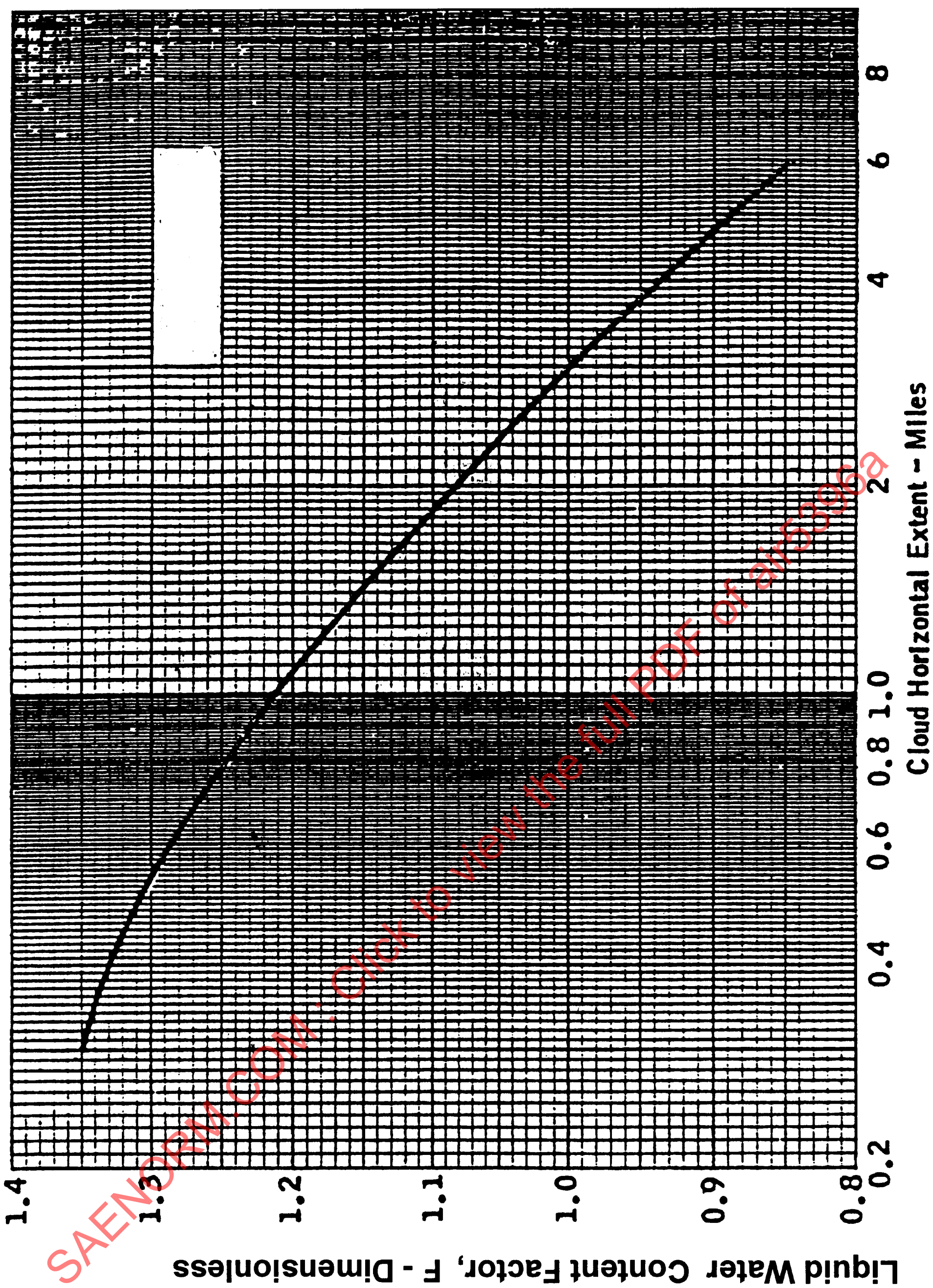


Figure A6 - FAR Part 25 (Appendix C) intermittent maximum atmospheric icing conditions (cumuliform clouds) - cloud horizontal extent versus liquid water content factor

APPENDIX B - FIGURES FOR U.S. AIR FORCE TRIAL DESIGN ENVELOPES
(CONTRIBUTED BY HENRY E. BERTOLINI)

Figure B1A

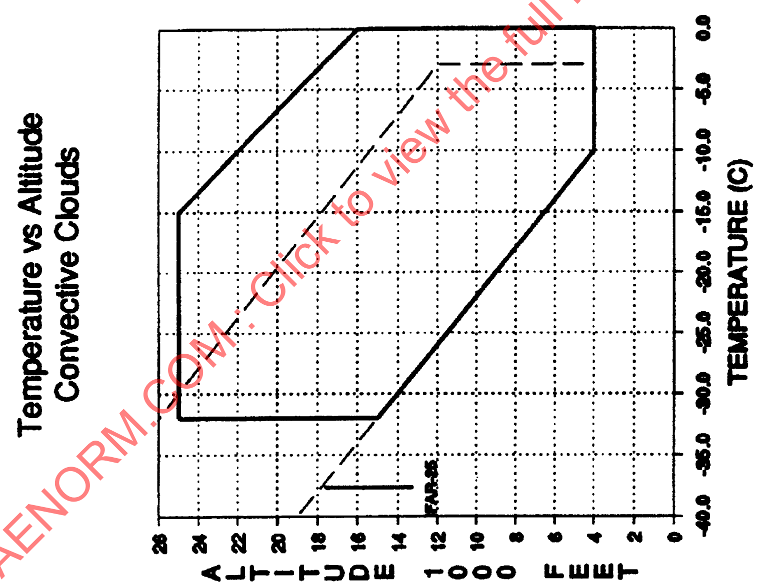


Figure B1B

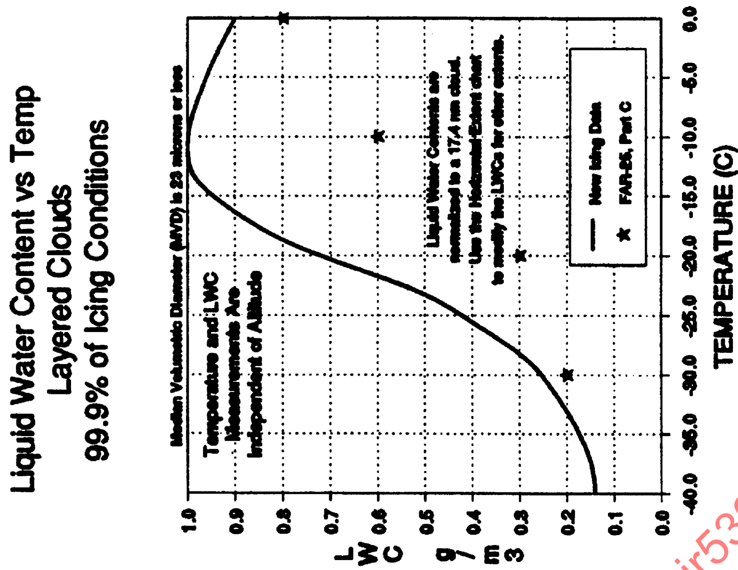


Figure B2A

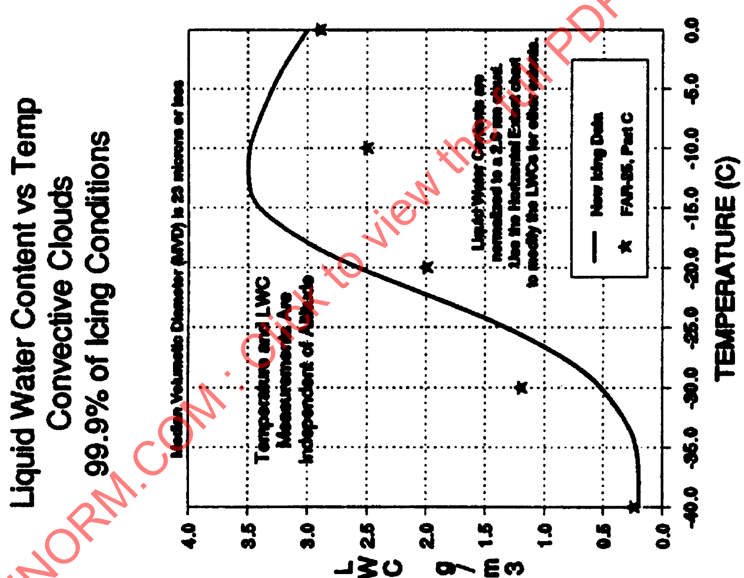


Figure B2B

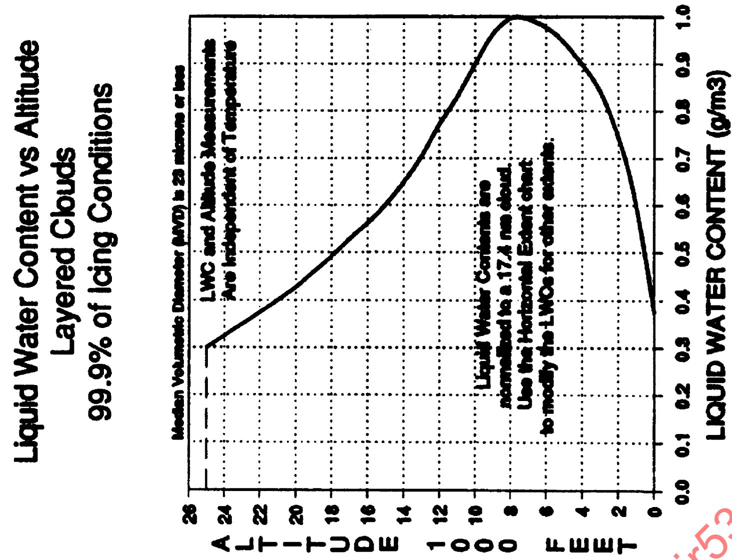


Figure B3A

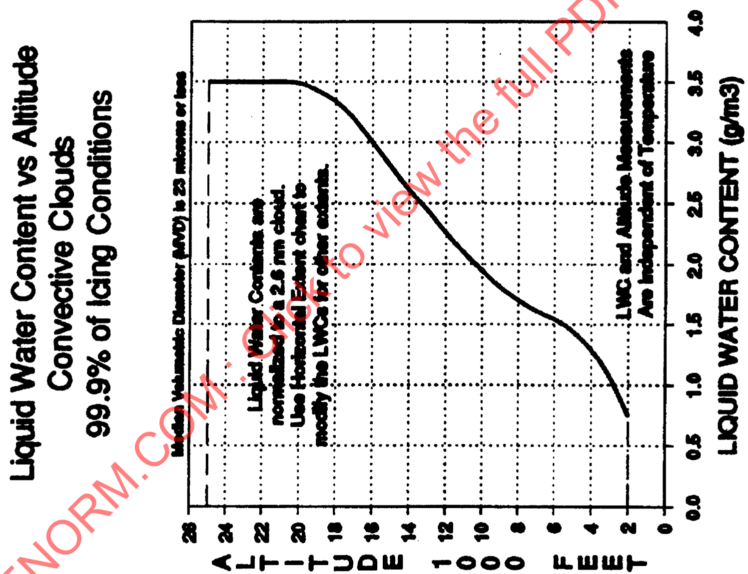


Figure B3B

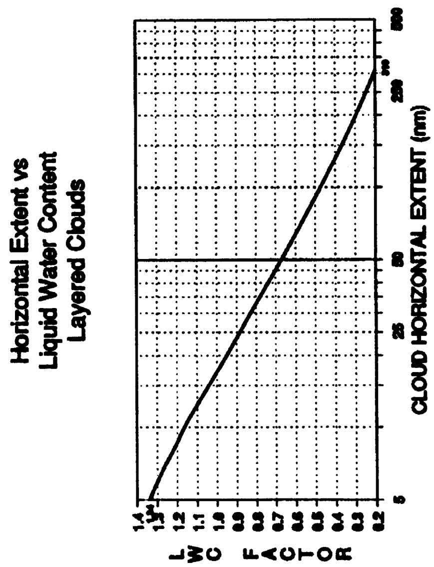


Figure B4A

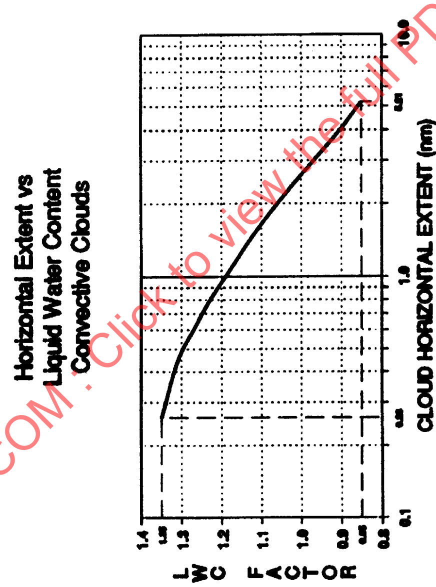


Figure B4B

APPENDIX C - FIGURES FOR DISTANCE-BASED ENVELOPES
(CONTRIBUTED BY RICHARD K. JECK)

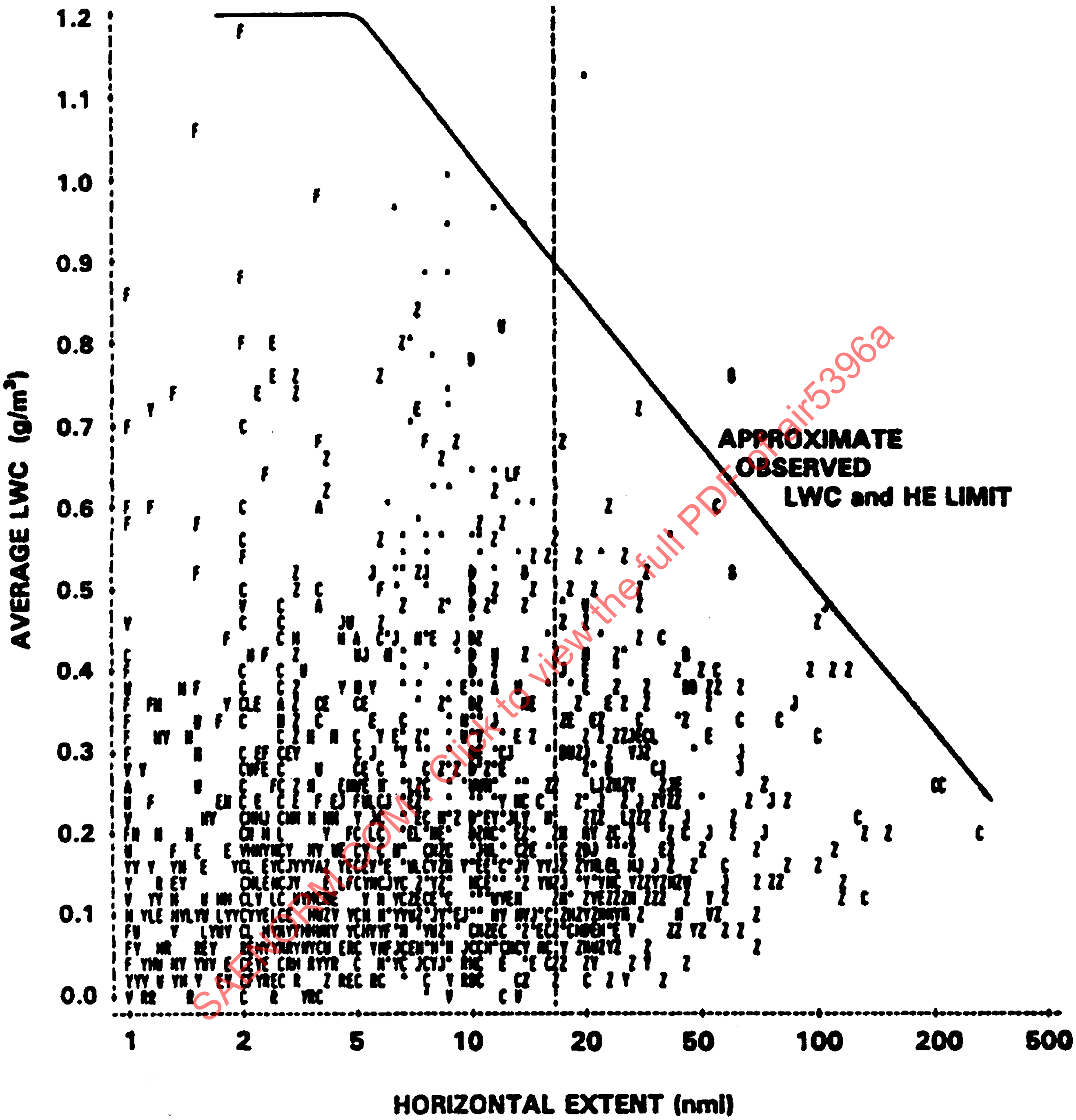


Figure C1 - The supercooled layer cloud database plotted in LWC versus HE format plotting symbols indicate data source

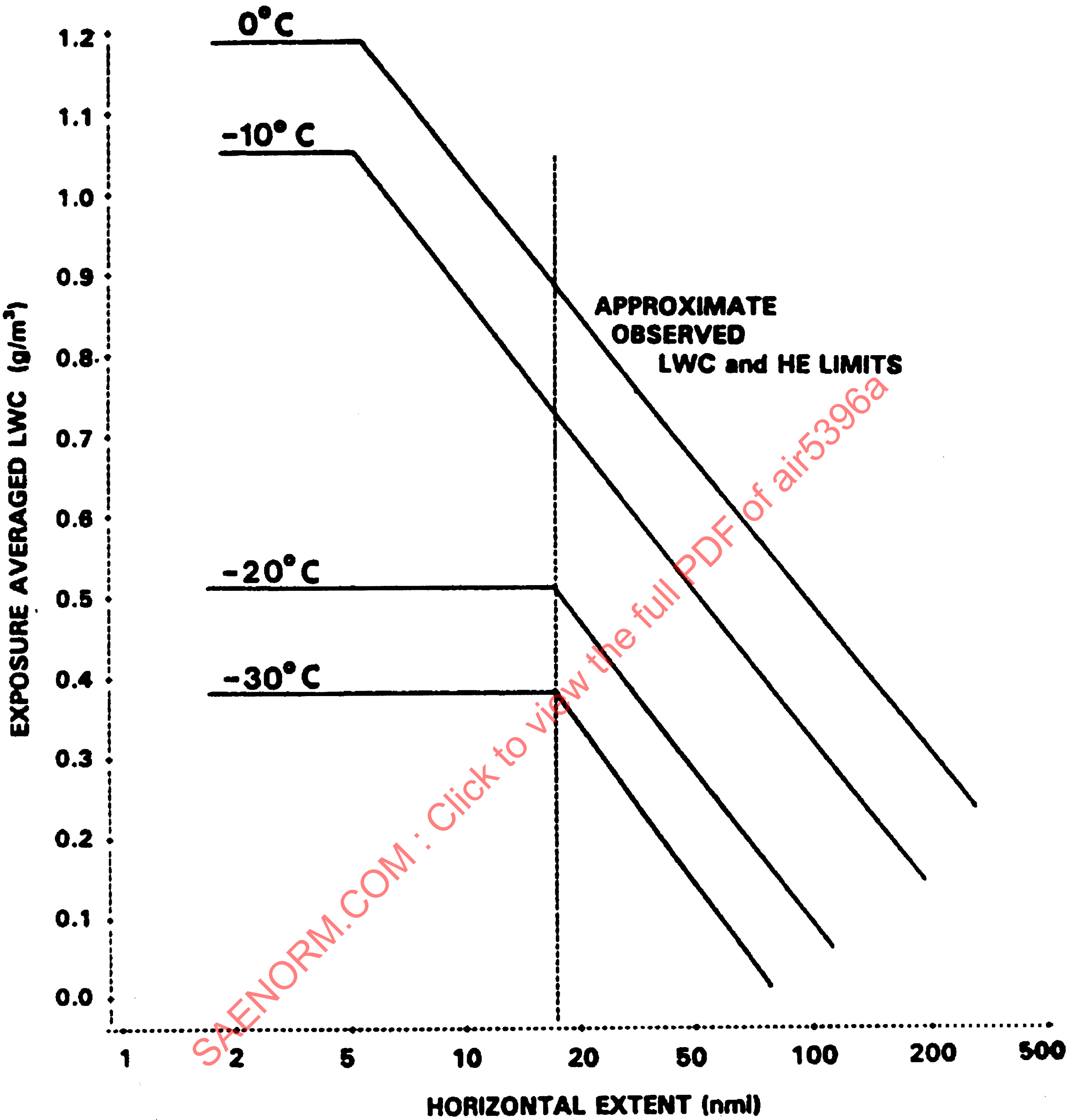


Figure C2 - Overlay of observed temperature limits to LWC and HE for layer clouds

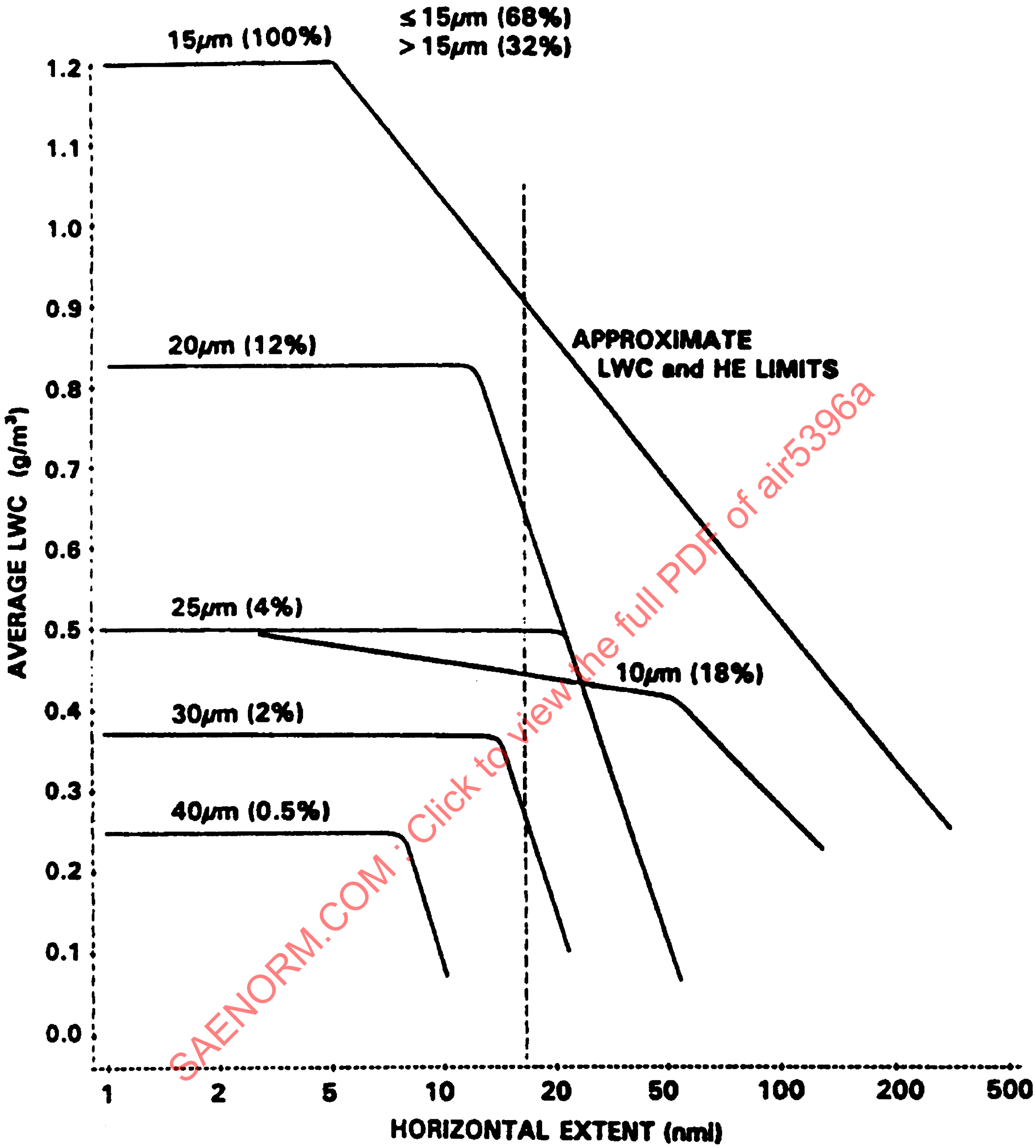


Figure C3 - Overlay of observed MVD limits to LWC and HE for layer clouds percentages give the relative number of data miles recorded under each curve

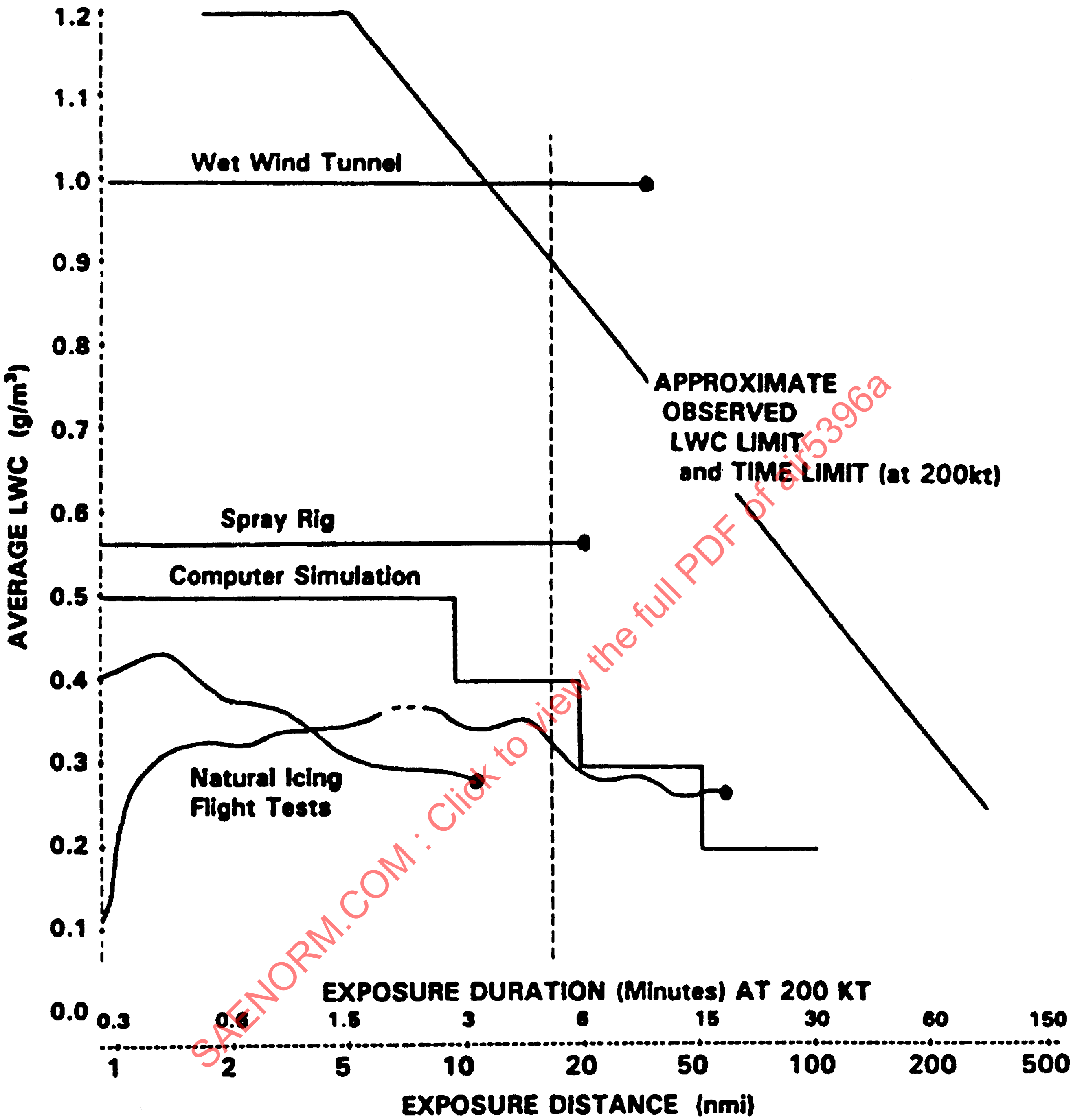


Figure C4 - Plotting LWC histories in addition to conventional test "points"

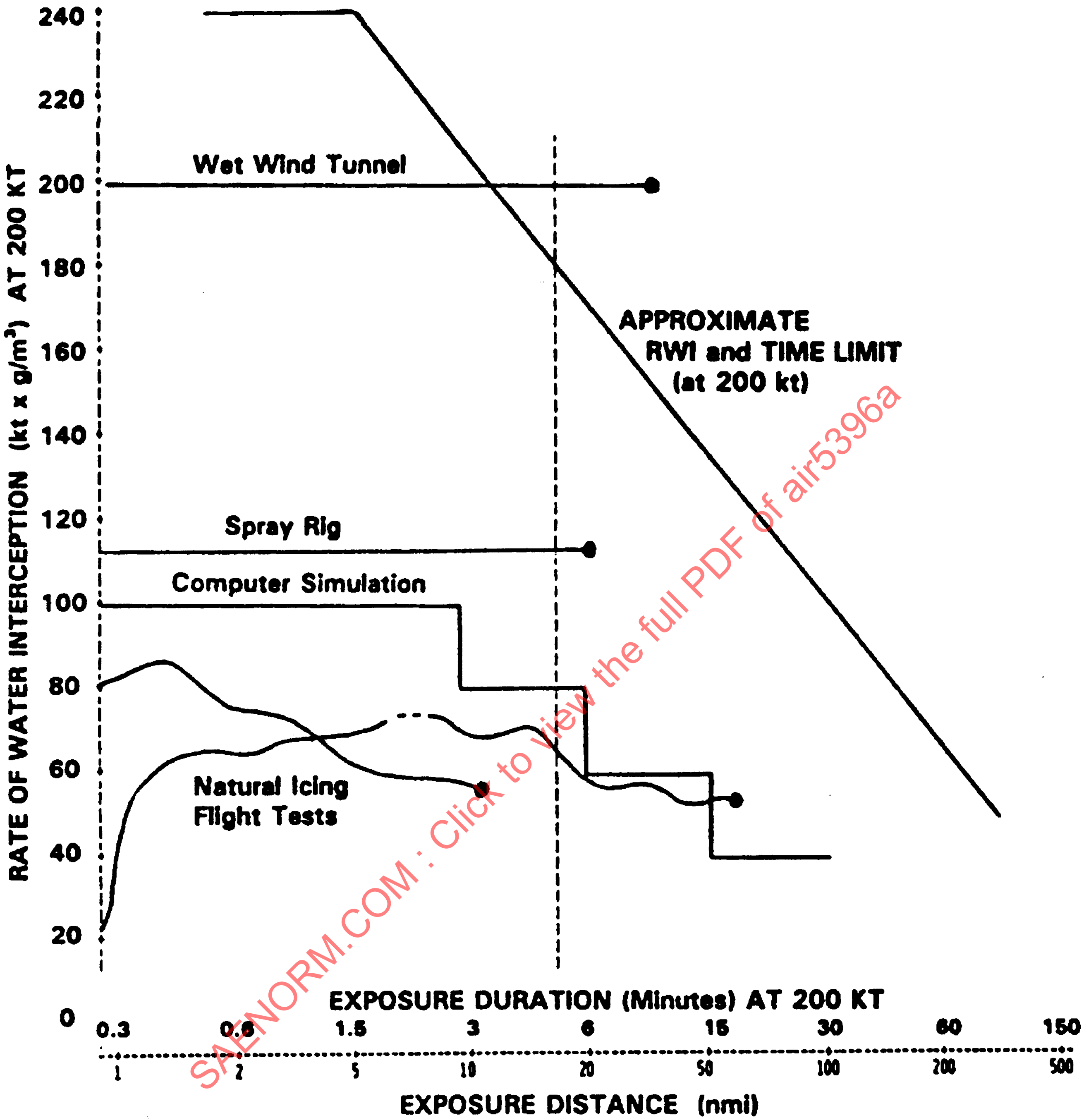


Figure C5 - Example of converting the LWC axis to rate of water interception (RWI)

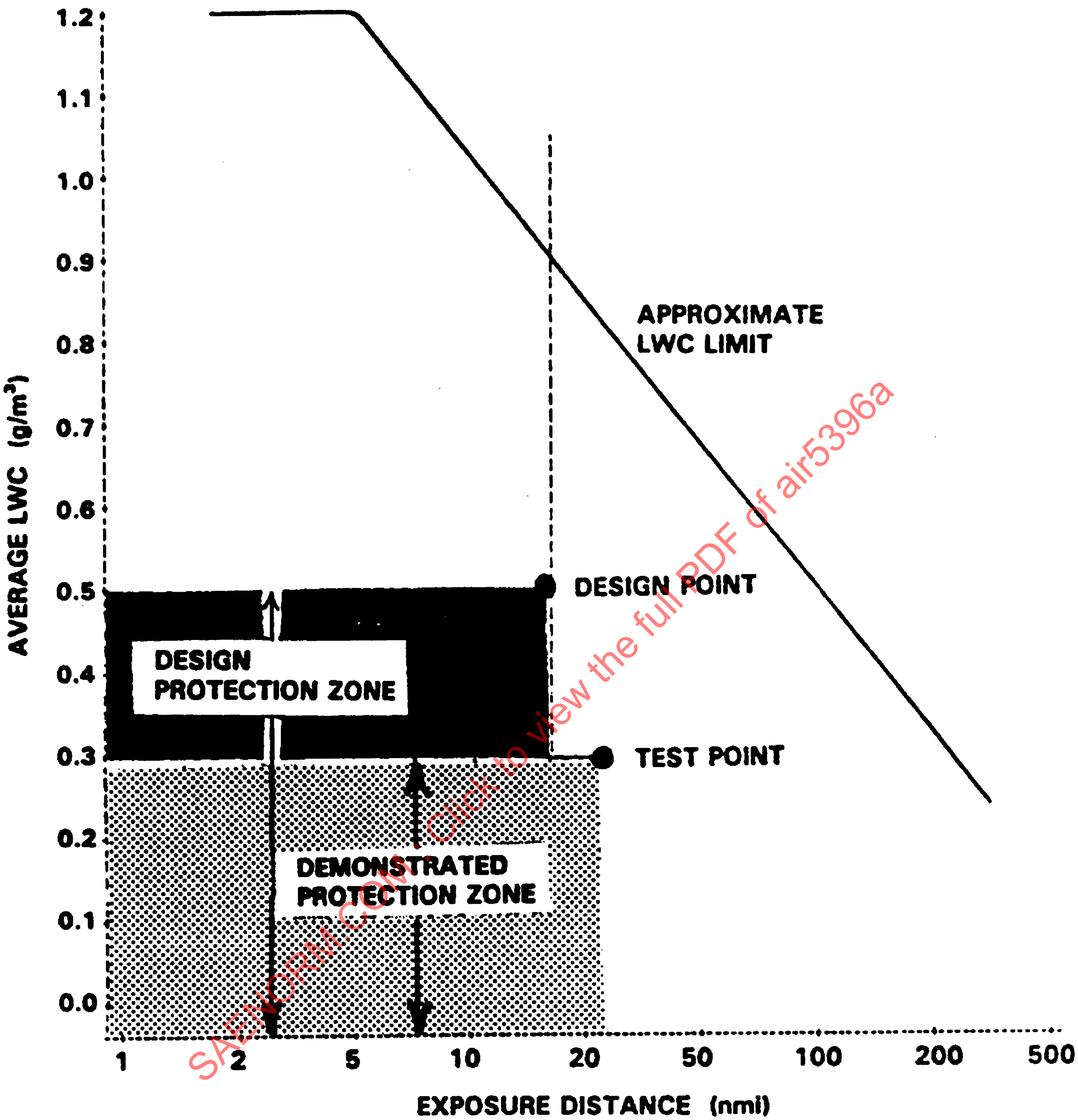


Figure C6 - Examples of "protection zones" assignable to design and test points

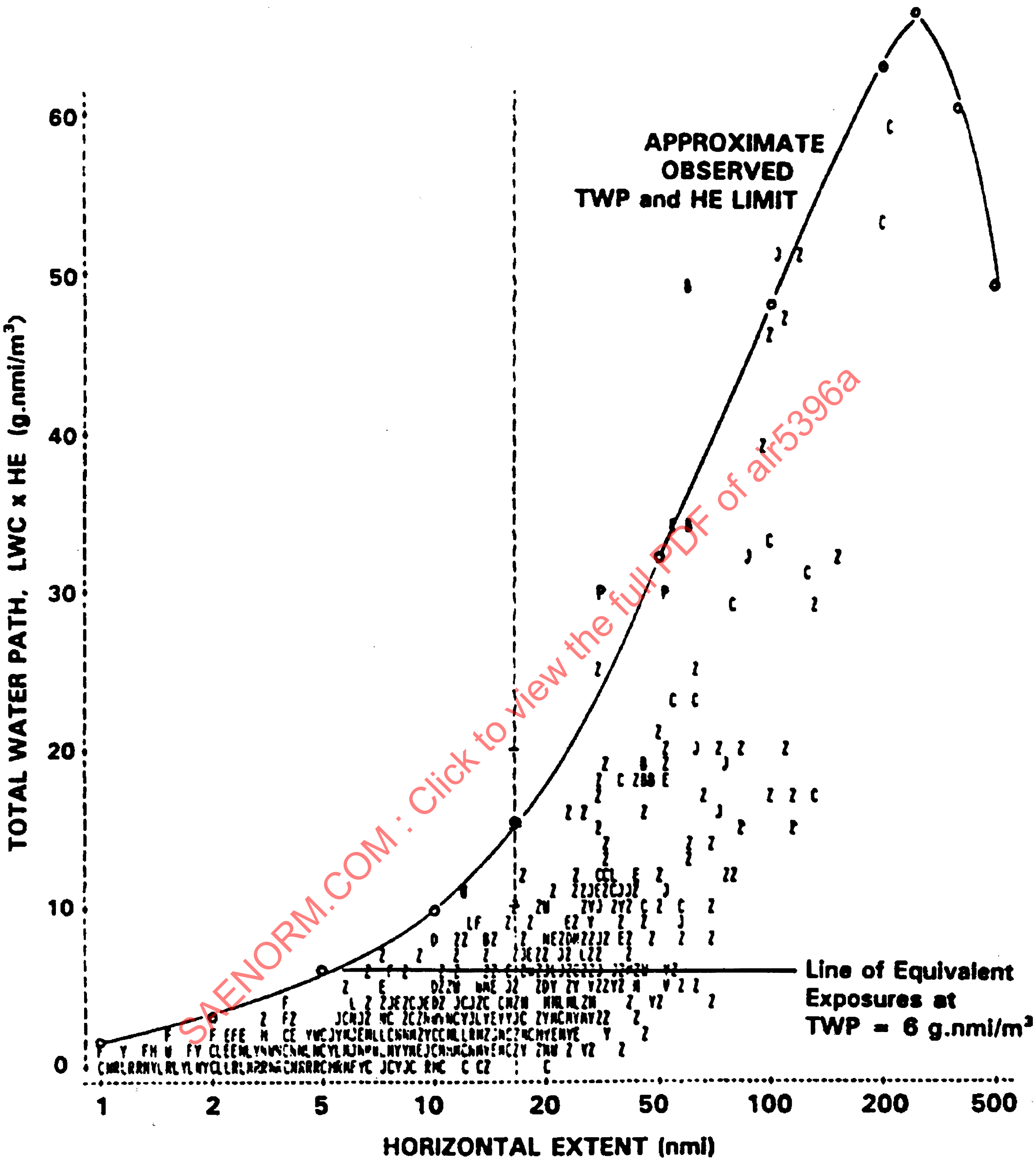


Figure C7 - The supercooled layer cloud database plotted in the TWP versus HE format

APPENDIX D - FIGURES FOR A NOMOGRAM AND STATISTICAL APPROACH
(CONTRIBUTED BY DAVID J. YURKANIN)

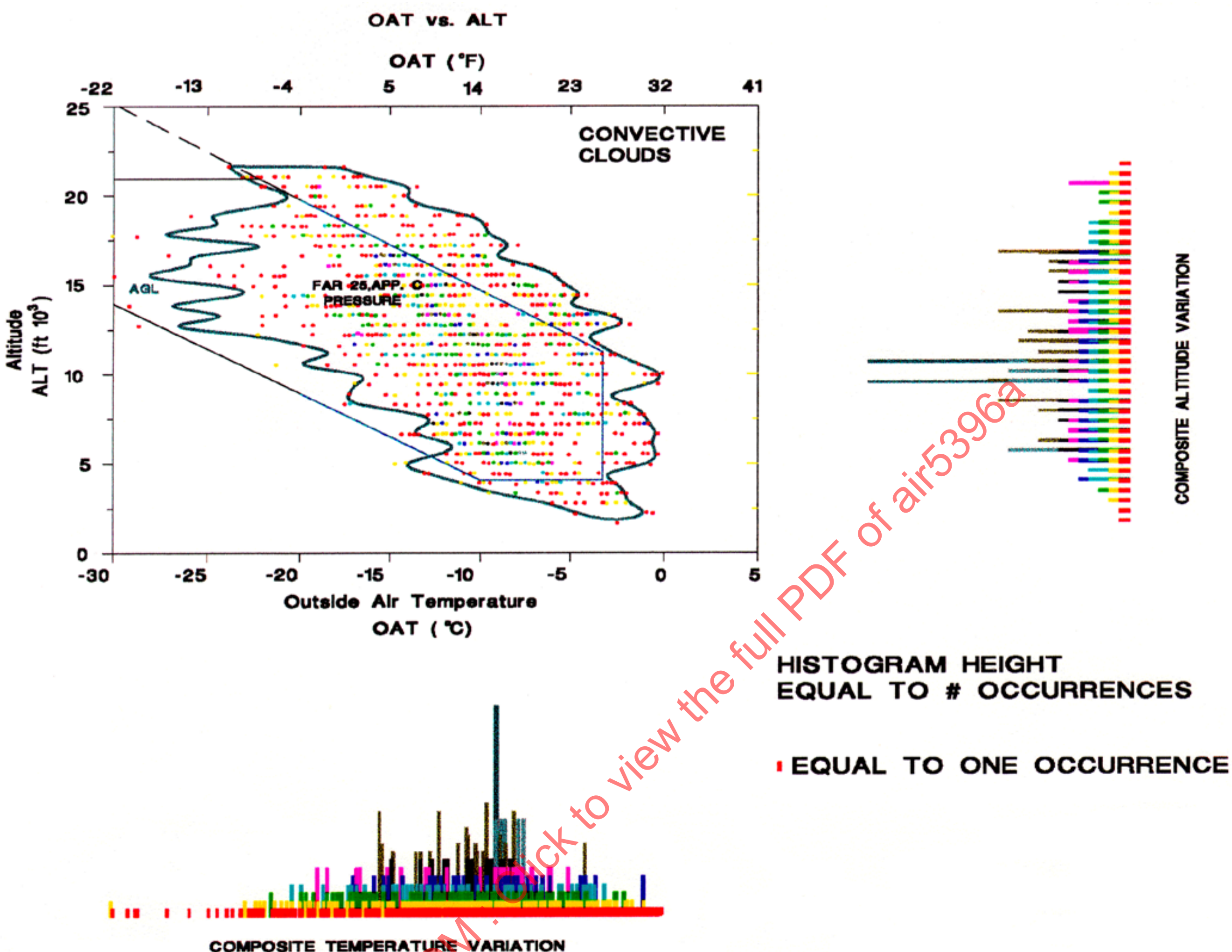


Figure D1 - Altitude versus outside air temperature (OAT) icing envelope with scatter graph and histograms

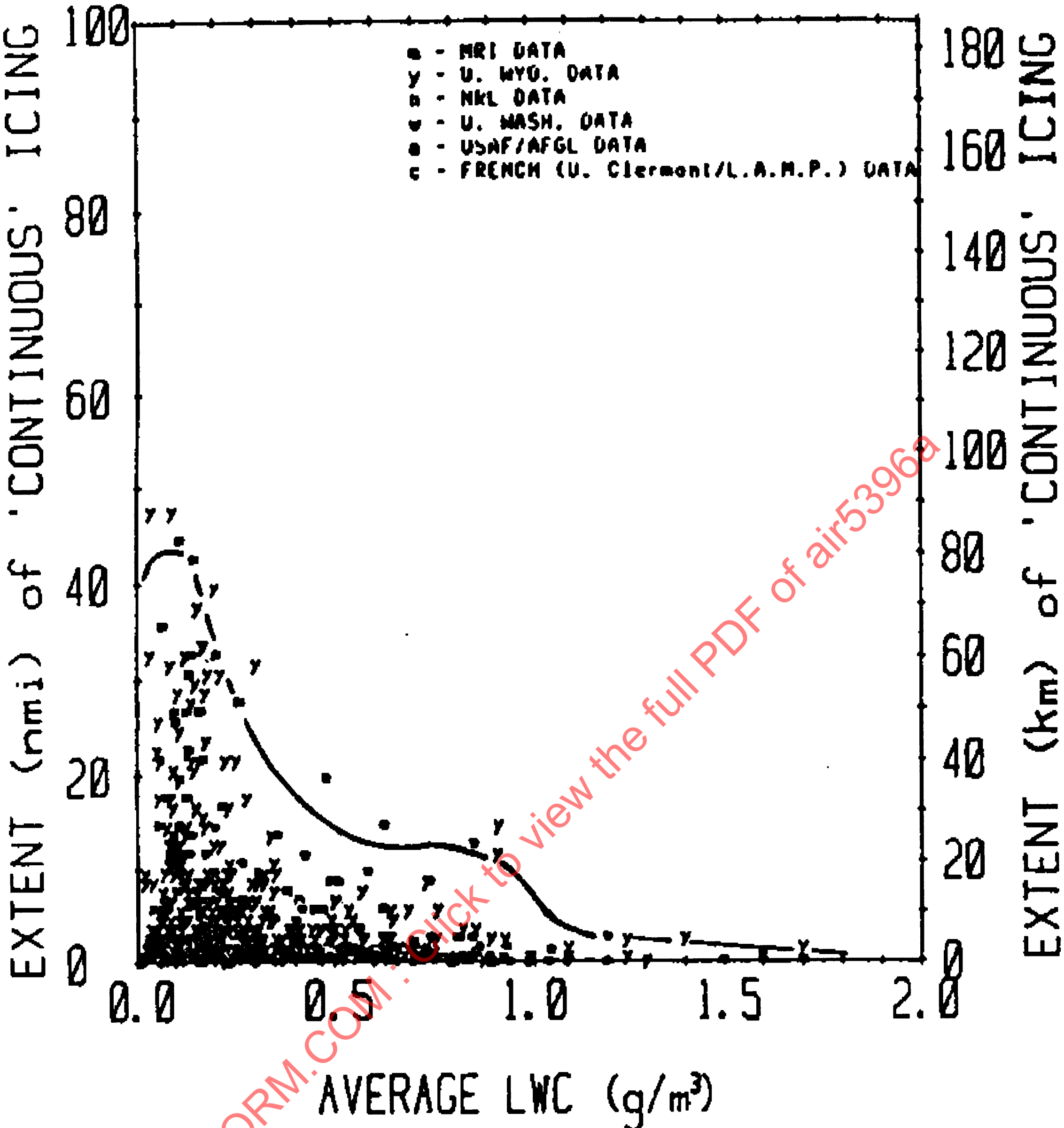
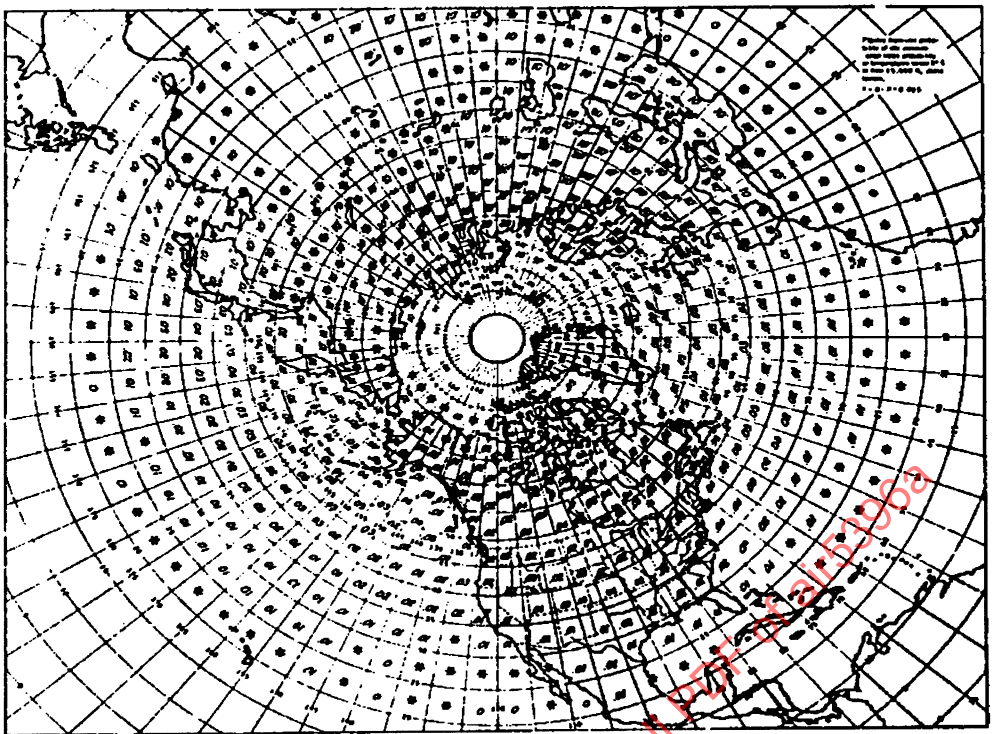


Figure D2 - Liquid water content versus horizontal extent with scatter graph showing data source symbols (from reference 2.1.27)



Low Altitude Icing Probabilities for the Northern Hemisphere — January
From WADC TN-55-225

Figure D3 - Icing probability polar projection at low altitudes by sector