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Federal Aviation Administration
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Aviation Research Division
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# Technical Report From the Engine Icing Working Group on Liquid Water Content for Ground Operations in Icing Below -18° Celsius

November 2015

Final Report



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16. Abstract

In response to several in-service engine damage events that occurred during airplane ground taxi operations in freezing fog at very cold temperatures, the European Aviation Safety Agency developed a Certification Review Item that requires new engines to be tested to colder temperatures than had previously been required. The Engine Harmonization Working Group of the Aviation Rulemaking Advisory Committee proposed to adopt this test requirement in the Notice of Proposed Rulemaking 10-10, with the final rule expected in 2015. The test is required to be conducted between -9°C and -18°C at a liquid water content (LWC) of 0.3 $gm^{-3}$ for 30 minutes duration. The proposed rules require that the conditions tested, in terms of time and temperature, be considered as operational limitations necessary for safe operation in freezing fog and be included in the Airplane Flight Manual. This would effectively prevent new airplanes certified to these rules from operating at temperatures below -18°C in freezing fog, whereas previously they were certified to operate at temperatures as low as -62°C.

It is undesirable for airplane operations to be limited by the engine test temperature, because there are practical limits on the lowest temperature at which supercooled droplets can be reliably produced for engine testing. An alternative is for the applicant to demonstrate capability below the tested temperature using an analytical approach. If such an approach is taken, a relationship of LWC to temperature for temperatures below -18°C that are appropriate to use for analysis is needed.

The Engine Icing Working Group undertook the task of developing a relationship of LWC to temperature appropriate for use in critical point analysis to assess the criticality of engine ground rime test points for freezing fog at temperatures less than -18°C. It was decided to use a relationship expressing LWC as a function of visibility based on an extensive ground-fog study conducted by Environment Canada. Using the Gultepe equation and the visibilities from an airport database, the working group developed a function of LWC versus temperature for use in critical point analysis in determining the most critical test point for freezing ground fog.

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## LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| $N_d$ | Number density, number of drops per cubic centimeter |
| CFR | Code of Federal Regulations |
| EASA | European Aviation Safety Agency |
| EIWG | Engine Icing Working Group |
| FAA | Federal Aviation Administration |
| ISD | Integrated Surface Database |
| LWC | Liquid water content, in g $m^{-3}$ |
| NPRM | Notice of Proposed Rulemaking |
| OAG | Official Airline Guide |
| RVR | Runway visual range |
| WMO | World Meteorological Organization |

## EXECUTIVE SUMMARY

In response to several in-service engine damage events that occurred during airplane ground taxi operations in freezing fog at very cold temperatures, the European Aviation Safety Agency (EASA) developed a Certification Review Item that requires new engines to be tested at colder temperatures than had previously been required. The Engine Harmonization Working Group of the Aviation Rulemaking Advisory Committee in 2005 proposed to adopt this test requirement in the Notice of Proposed Rulemaking 10-10 [1], with the final rule expected in 2015. The test is required to be conducted between -9°C and -18°C at a liquid water content (LWC) of 0.3 $gm^{-3}$ for 30 minutes.

The proposed rule requires that the conditions tested, in terms of time and temperature, be considered as operational limitations necessary for safe operation in freezing fog and be included in the Airplane Flight Manual. This would effectively prevent new airplanes certified to these rules from operating at temperatures below -18°C in freezing fog, whereas previously they were certified to operate at temperatures as low as -62°C (a limit is not based on icing considerations).

It is undesirable for airplane operations to be limited by the engine test temperature because there are practical limits on the lowest temperature at which supercooled droplets can be reliably produced for engine testing. An alternative approach is for the applicant to demonstrate capability below that tested using an analytical approach. If an analytical approach is taken, an appropriate relationship of LWC to temperature, for temperatures below -18°C, is needed. EASA and the Federal Aviation Administration have agreed to consider an analytical approach if it achieves an equivalent level of safety.

The Engine Icing Working Group, which consists of engine manufacturers, airframe manufacturers, regulators, and researchers, undertook the task of developing a relationship of LWC to temperature appropriate for use in critical point analysis to assess the criticality of engine ground rime test points for freezing fog at temperatures lower than -18°C.

The working group consulted with a number of meteorological experts and, following their guidance, examined the relevant research literature. Different approaches were assessed, both individually and in comparison to one another, to determine the consistency of different approaches. It was decided to use a relationship expressing LWC as a function of visibility (referred to here as the Gultepe equation, after its discoverer) based on an extensive ground fog study conducted by Environment Canada.

The working group identified an extensive database of global airport weather observations, known as the Integrated Surface Database (ISD). Using the ISD as a source, an observation database for airports with runways greater than 9000 feet was extracted, followed by a larger database of airports with runways greater than 3000 feet. Using the Gultepe equation and the visibilities from the airport databases, the working group developed a function of LWC versus temperature for use in critical point analysis to determine the most critical test point for freezing ground fog.

# 1. INTRODUCTION

## 1.1 BACKGROUND

### 1.1.1 Origins and Composition of the Engine Icing Working Group

In response to National Transportation Safety Board recommendations A-96-54, A-96-56, and A-96-58, the joint Engine Harmonization Working Group and Power Plant Installation Harmonization Working Group were assembled by the Ice Protection Harmonization Working Group to make recommendations for rulemaking on supercooled large droplet and mixed-phase icing. The joint working group found that mixed-phase and ice crystals in deep convection at high altitudes are the cause of the majority of engine-icing-related events. It also identified a large technology gap that required continued work after the joint working group had made its recommendations for rules. The Engine Icing Working Group (EIWG), sponsored by the Aerospace Industries Association, was created in 2007 primarily to continue to determine the needs for and motivate the research on engine ice crystal icing. The working group is comprised of experts in the field of engine icing from industry and government bodies and is able to address all engine icing issues (not just ice crystal icing) affecting the industry as they arise. Therefore, the topic of engine icing due to supercooled droplets at the ground at very cold temperatures was studied by the working group.

The EIWG is currently chaired by an engineer from The Boeing Company. Representatives from the following entities also serve on this committee: General Electric, Pratt & Whitney, Pratt & Whitney Canada, Rolls-Royce, SNECMA, Cessna, Hawker-Beechcraft, Airbus, Honeywell Engines, Transport Canada, the Federal Aviation Administration (FAA), the European Aviation Safety Agency (EASA), Environment Canada, National Research Council of Canada, Aerospace Industries Association, Williams International, Gulfstream, Embraer, NASA, and Dassault-Aviation.

### 1.1.2 Problem Statement and Approach

The FAA Notice of Proposed Rulemaking (NPRM) 10-10 [1] includes a new engine ground rime ice test point for freezing fog at -9°C to -18°C with a liquid water content (LWC) of 0.3 $gm^{-3}$. A similar EASA Certification Review Item written for new engines also requires testing below -9°C. In addition, these proposed rules require that the conditions tested, in terms of time and temperature, be considered as operational limitations necessary for safe operation in freezing fog and be included in the Airplane Flight Manual.

This would effectively prevent new airplanes certified to these rules from operating at temperatures below -18°C in freezing fog; previously, they were certified to operate at temperatures as low as -62°C (a limit not based on icing considerations).

The working group felt that it was undesirable for airplane operations to be limited by the engine test temperature because there are practical limits on the lowest temperature at which supercooled droplets can be reliably produced for engine testing. An alternative is for the applicant to demonstrate capability below that tested using an analytical approach. If such an approach is taken, a relationship of LWC-to-temperature is needed that is appropriate for analysis of temperatures below -18°C.

Engine companies use critical point analysis to develop proposed test points for FAA certification [2]. This analysis takes into account many of the key factors needed to assess engine capability in icing at colder temperatures: ice mass for a given water content, adhesion strength changes with temperature (ice could shed at a higher engine power), location of ice formation (ice may form further aft at colder temperatures), surge and flameout margin, and damage tolerance. Critical point analysis tools can be used to determine if a colder temperature is less critical than the point required to be tested.

Therefore, the primary goal of the working group was to develop a relationship of LWC-to-temperature appropriate for use in critical point analysis to assess the criticality of engine ground rime test points for freezing fog at temperatures lower than -18°C. The relationship would have to be acceptable to the FAA, EASA, and Transport Canada, and would be exclusively for Appendix C icing conditions; snow and supercooled large drops would not be included.

The working group decided to use only existing historical weather data; no new weather measurements were collected. Initially, the working group consulted experts familiar with the research literature to determine what relevant data were currently available. Next, the working group reviewed the data and evaluated each source as to its applicability and accuracy. The available historical data on icing conditions were evaluated and an agreement was reached in the working group on how the data could be used to formulate a statistically significant and conservative relationship between LWC and temperature at the cold temperatures required. Because it was necessary to use visibility data, and the correlation between visibility and LWC is known to contain significant scatter, a conservative approach was necessary.

## 2. ENGINE ICING EVENTS RELATED TO THE NEED FOR COLDER TESTING

The members reported four engine core damage events to the working group. These events had provided motivation for the new proposed ground rime icing test point for freezing fog. All of the events occurred at Oslo Airport. The weather observations on the event days showed that the temperature was between -9°C and -18°C. If supercooled liquid exists in very cold temperatures, ice can form further aft in the engine; behind the fan; and on the splitter, core inlet guide vanes, and downstream blades. This core ice has the potential for shedding on throttle-up, causing damage or engine instability. In the cases considered by the working group, engine blade damage occurred. The following are the four reported engine core damage events:

- Event 1: January 14–16, 2001. The observed weather was freezing fog (weather code 49—see appendix A, table A-1) with visibility as low as 100 m for two nonconsecutive hours in a 5-hour period, and later, 200 m for 6 consecutive hours, during which time the temperature was -12°C. The taxi time is not available.

- Event 2: December 12, 2002. The observed weather was freezing fog (weather code 48) with 100 m visibility and a temperature of -16°C. The combined taxi-in and taxi-out time was 72 minutes.

- Event 3: December 21, 2005. The observed weather was freezing fog (weather code 49) with 300 m visibility and temperatures as low as -12°C. The combined taxi-in and taxi-out time was 44 minutes, though the exact time of taxi is not available.

- Event 4: January 23, 2007. Analysis of the aircraft operation indicates that an engine parameter shift indicative of damage most probably occurred on departure from Oslo at approximately 0900 UTC. Airport data show freezing fog (weather code 49) with a visibility of 200 m at -14.7°C. The departure taxi-out time was approximately 24 minutes.

Table 1 shows the lowest visibility reported and associated temperature on the event days. As shown in table 1, LWC can be conservatively estimated using the Gultepe equation with number density $(N_d)$ = 100. The estimate is included in table 1.

**Table 1. The four engine damage events at Oslo Airport**

| Date | Temperature (C) | Visibility (m) | LWC ($gm^{-3}$) |
|---|---|---|---|
| 14 Jan. 01 to 16 Jan. 01 | -12° | 200 | 0.12 |
| 12 Dec. 02 | -16° | 100 | 0.35 |
| 21 Dec. 05 | -12° | 300 | 0.06 |
| 23 Jan. 07 | -14.7° | 200 | 0.12 |

## 3. SOURCES OF ICING DATA CONSIDERED

### 3.1 PAUCITY OF LWC MEASUREMENTS AT GROUND LEVEL; CORRELATIONS BETWEEN LWC AND VISIBILITY

The weather observations sought by the working group were LWC and temperature at ground level. It was determined that few actual measurements of LWC at ground level are made globally and not enough to construct a statistically significant database to support a certification standard. Flight campaigns [3–6] that collected observations of LWC at cold temperatures in flight have been conducted. However, the working group considered these observations to be overly conservative for defining ground icing conditions because supercooled water is more likely to glaciate near the ground than it is higher in the atmosphere because of the greater concentration of ice nuclei and the presence of cold surfaces near the ground.

Standard weather observations from ground stations do, however, include visibility as a parameter. Researchers have developed correlations between LWC and visibility at the surface. Because the correlations between visibility and LWC have significant scatter, conservative use of these data is necessary (note that care must be taken in the use of these relationships for the following reason: if the relationship is developed from conditions consisting of liquid water exclusively, then it should not be applied to conditions consisting of liquid water mixed with ice crystals, snow, or other solid hydrometeors).

Based upon these findings, the working group decided to use visibility data to estimate LWC in supercooled fog.

Many scientists have conducted work to establish a relationship of LWC to visibility. Tables and graphs of these relationships were compiled to facilitate review and comparison by the working group (see table 2 and figure 1). Figure 1 shows a comparison of equations from table 1 expressing LWC as a function of visibility. Figure 1 also shows that the Gultepe function with an $N_d$ of 50 has the highest LWC as a function of visibility.

## Table 2. Summary of literature presenting correlations of LWC with visibility (General Electric summary for working group [7–17])

| Author (Series) | LWC vs. VIS | Measuring System | Droplets radius | Comments |
|---|---|---|---|---|
| Eldridge (A) | $LWC = \left(0.024/VIS\right)^{\frac{1}{0.65}}$ | Inferred from measured spectral transmission through fog with aid of Mie scattering theory | 0.3µm–10µm | Limited data inferred vs measured (“spider web”, Arnulf) |
| Eldridge (B) | $LWC = \left(0.043/VIS\right)^{\frac{1}{0.65}}$ | Composite data from Eldridge ’66 and Houghton. Houghton collected fog droplets on coated slides. | .03µm–70µm | Stable fogs<br>Ground fog for Houghton data. |
| Pinnick (C) | $LWC = \left(0.027/VIS\right)^{\frac{1}{0.63}}$ | PMS Classical Scattering Aerosol Spectrometer mounted on a tethered balloon, different heights. | 0.24µm–16µm | Fixed ranges<br>Fog up to 250m alt |
| Tomasi<br>(D & E) | $LWC = \left(0.0602/VIS\right)^{\frac{3}{2}}$ | Modified gamma size distribution models. | Mode radius around 9µm (large droplets) | Dist. characteristic of wet and warm fogs (Platt nomenclature) |
| | $LWC = \left(0.034/VIS\right)^{\frac{3}{2}}$ | | Mode radius around 3µm (small droplets) | Dist. characteristic of dry and warm fogs (Platt nomenclature) |
| Kunkel<br>(F, G, & H) | $LWC = \left(0.027/VIS\right)^{\frac{1}{0.88}}$ | PMS Forward Scatter Spectrometer Probes FSSP- 100 at two different heights (5m and 30m). | 0.25µm–23.5µm | Universal relationship<br>Ground fog data |
| | $LWC = \left(0.024/VIS\right)^{\frac{1}{0.84}}$ | | 3.4µm (30m, mean radius)<br>3.05µm (5m, mean radius) | Polluted environment<br>Ground fog data |
| | $LWC = \left(0.0395/VIS\right)^{\frac{1}{0.92}}$ | | 4.9µm (30m, mean radius)<br>7.3µm (5m, mean radius) | Clean environment<br>Ground fog data |
| Fišák (I &J) | $LWC = 0.0152 * VIS^{-0.8582}$ | Particle Volume Meter PVM-100; active sampling device Rotary Arm Collector, PWD 21 for visibility | N/A | Polluted environment<br>Ground fog data |
| | $LWC = 0.0324 * VIS^{-0.9021}$ | Particle Volume Meter PVM-100; active fog water sampling device NES 210; FD12P for visibility | N/A | Clean environment<br>Ground fog data |
| Dui (K) | $LWC = 37.216 * VIS^{-1.2302}$ | Triple-use drop-size meter for fog water content and fog droplet spectra; hot-wire LWC meter. | 3.75µm–6.65µm<br>Arithmetic mean radius | Input VIS in meters<br>Ground fog data |
| Gultepe | $LWC = \dfrac{\left(1.002/VIS\right)^{1/0.6473}}{Nd}$ | FSSP with two size ranges, Particle Cavity Axial Spectrometer Probe, King Probe, among others. | 2.1µm–48.4µm FSSP-96<br>4.6µm–88.7µm FSSP-124 | VIS=f(LWC, Nd)<br>In-flight data sets |
| Stoelinga | NCAR mesoscale model version 5 (MM5), Kunkel Univ. | Experimental design: DIMIX (12-hr. initialization, mixed); DISIMP (12-hr. initialization, simple); NDIMIX (static initialization, mixed). | Model validated against SAO observations and NWS forecasts | Model for visibility forecasting |

VIS = Visibility

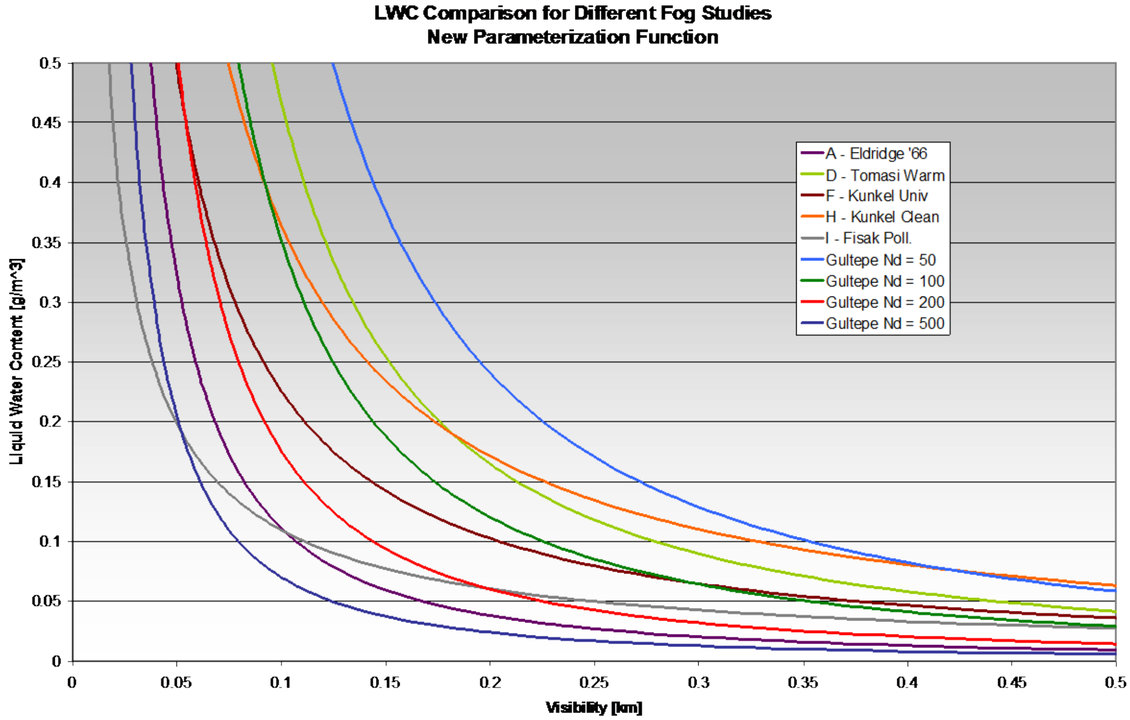


**Figure 1. Some of the correlations in the literature compared at various LWC and visibilities (General Electric summary)**

Given the variation of the different methods reviewed in figure 1, especially at low visibility, the working group consulted with a leading icing meteorology expert, Dr. Ismail Gultepe of Environment Canada, seeking his recommendation for a conservative choice of number density ($N_d$) in his equation. From that discussion, the following important points relative to the choice of $N_d$ were established:

- Freezing fog data in Dr. Gultepe's study were gathered at approximately 0°C; however, he believes it is valid to -7°C
- Fog observations with temperature less than -10°C are likely to be ice fog (composed of solid hydrometeors), not freezing fog (liquid)
- Values for $N_d$ over continental areas with typical concentrations of ice nuclei are approximately 200, but can be as low as 100 in clean air
- Values of $N_d$ over the ocean are typically 100
- Salt provides nuclei, and wind increases their concentration and the rate of nucleation

As a result of the discussion, an $N_d$ value of 100 was chosen as a conservative choice for the working group study. It should be noted that Dr. Gultepe advised that fog is likely to be composed of solid particles below -10°C; therefore, the condition the working group was trying to quantify—supercooled water at temperatures below -18°C—is rare.

Repeated here is the Gultepe equation [18] used for the working group study, using $N_d$ =100 (note that visibility units should be km to have LWC in units of g m$^{-3}$),

$$LWC = \frac{\left(1.002/VIS\right)^{1/0.6473}}{N_d} \quad (1)$$

The various papers relating visibility to LWC typically use an instrument to measure visibility or a parameter, which can then be used to directly compute visibility. For example, in the work discussed by Kunkel, extinction coefficient was measured, from which visibility was computed.

Visibility is commonly reported; historically, it has not always been measured by an instrument but instead has been estimated by human observers.

It would be preferable to use an instrument-measured parameter to remove the potential for human observational error and bias. However, the only parameter related to visibility that is consistently measured at airports by an instrument is runway visual range (RVR).

It was determined that RVR poses too many problems for it to be used in this study. It is difficult to obtain on a broad, global scale as desired for this analysis, whereas visibility is widely reported. More importantly, it does not make a good proxy for visibility because visibility is a function of only the extinction coefficient, whereas RVR is a function of both the extinction coefficient and light intensity.

Figure 2 shows how poorly RVR correlates to visibility. There were a number of airports for which the working group was able to obtain both visibility and RVR data. These observations were plotted as a scatter plot, as shown in figure 2. There are 2,999,967 data points plotted in figure 2. If there is any correlation, it should be readily apparent that it is extremely weak.

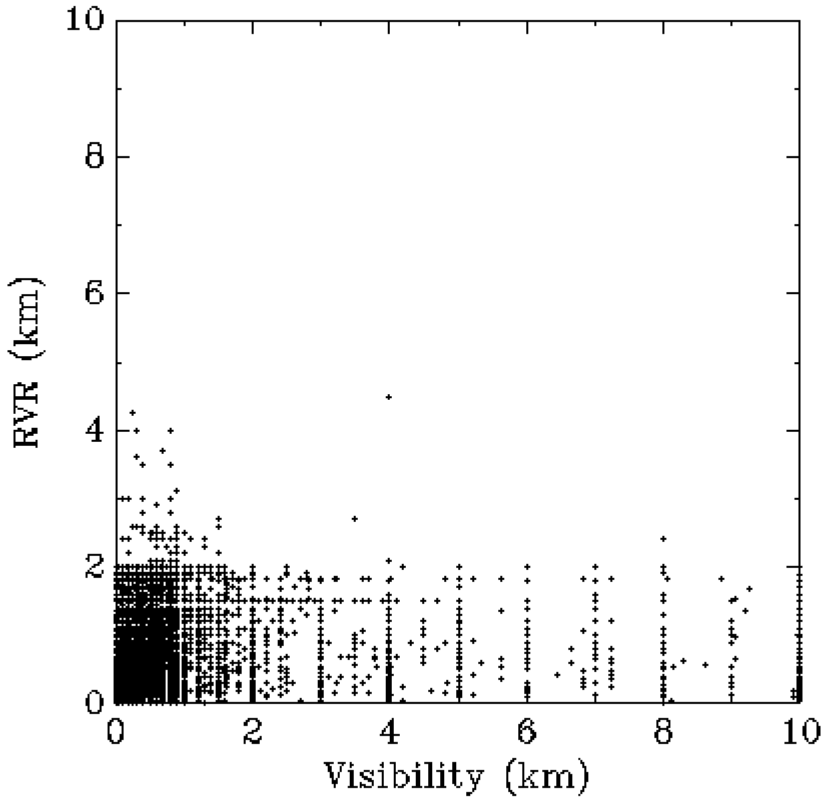


**Figure 2. Scatter plot of RVR versus visibility**

3.2 AIRPORT OBSERVATIONS DATABASE

The working group identified an extensive database of global airport weather observations, the Integrated Surface Database (ISD)[1], to use in its study. The observation sites in ISD, most of which are airports, are referenced by their World Meteorological Organization (WMO) numbers. Boeing had previously identified airports with runways at least 9000 feet long and 150 feet wide, considered suitable for large commercial transport aircraft, matching the airport codes to WMO numbers for 1031 of the airports. To evaluate the feasibility of using airport observational visibility data in developing a relationship of LWC to temperatures below -18°C, the existing set of weather stations at these 1031 airports was used. Data were limited to the most recent 30 years for each airport, yielding a total of 221,779,180 total observations.

The ISD codes distribute present weather into 100 categories, of which at least 10 can, to some degree, be construed as indicating fog. However, for this study, only two of the fog codes (those indicating rime depositing) were used. The expectation is that supercooled fog droplets accrete ice on surfaces, which is consistent with rime depositing. A total of 342,480 reports over the most recent 30 years of data for these airports had freezing fog with rime depositing. This represents approximately 0.15% of the total observations. Note that only 12,551 observations are

[1] The ISD website is located at https://www.ncdc.noaa.gov/isd.

at -18°C or below (3.66% of the total rime fog observations, 0.0057% of total observations). A histogram of all the reports of freezing fog with rime depositing is shown in figure 3.

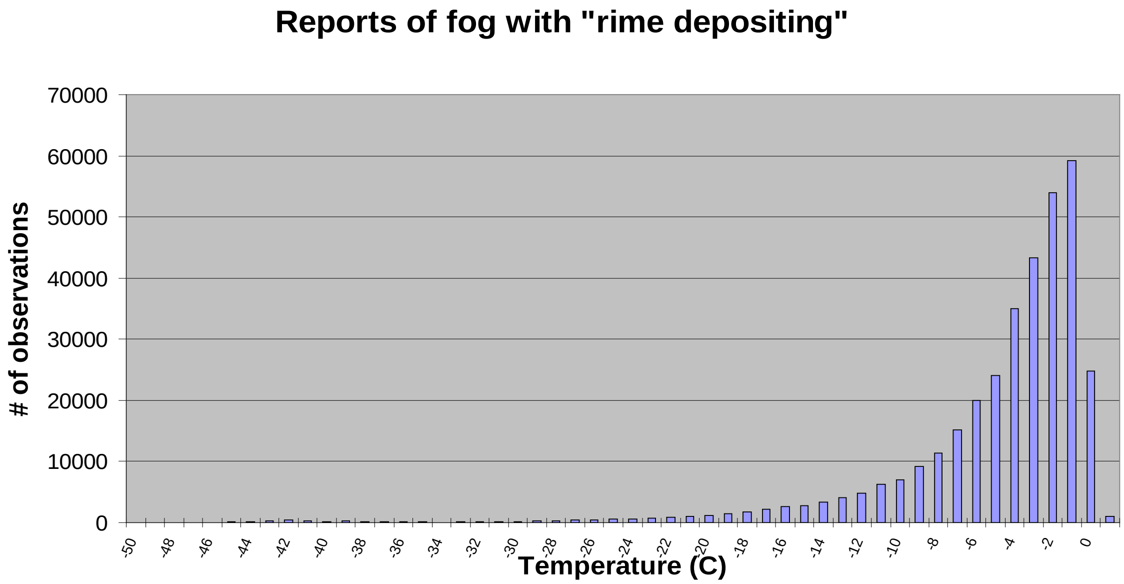


**Figure 3. Histogram of all reports for which data are available regarding fog with rime depositing from the 1031 airports with runways at least 9000 feet long and 150 feet wide**

The average visibility versus temperature for the observations is shown in figure 4. It shows the visibility rising slightly as the temperature decreases in the range between 0°C and -22°C. Visibility then rises sharply as the temperature decreases between -22°C and -33°C, then decreases sharply as the temperature decreases between -33°C and -40°C. The explanation for the peak at temperatures colder than -30°C is hypothesized to be the deposition of water vapor at very cold temperatures (i.e., ice deposits on surfaces without going through the liquid stage). Average LWC versus temperature for the observation is shown in figure 5. Data below -30°C are not included in figure 5 and not used in this analysis because icing is considered to be negligible below -30°C (see FAA Aircraft Icing Handbook [19]).

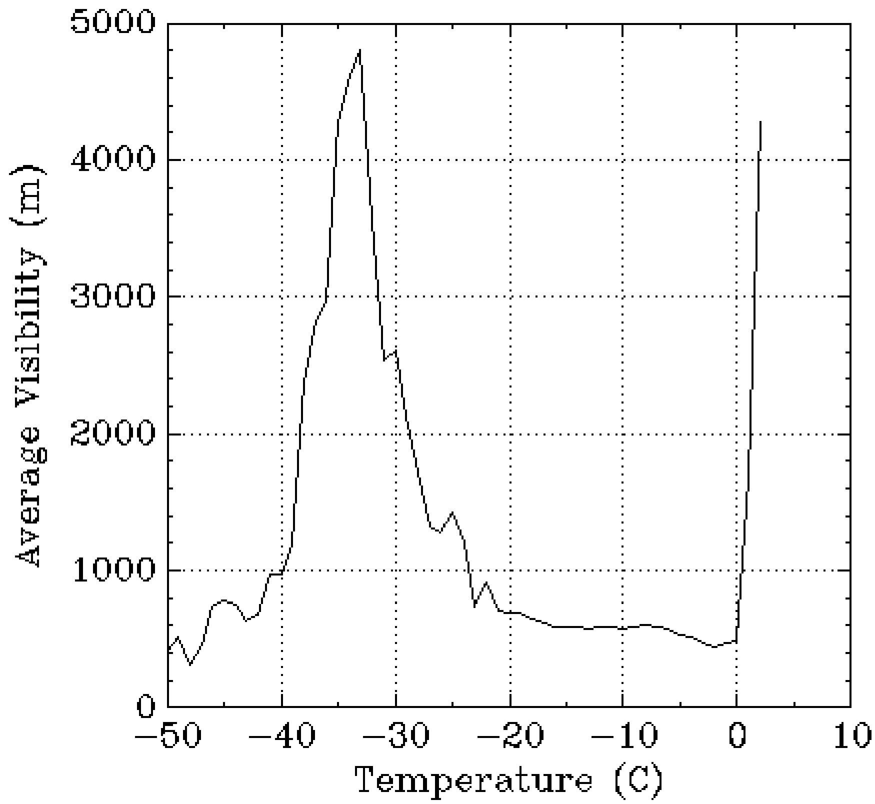


**Figure 4. Average visibility versus temperature for the observations shown in figure 3**

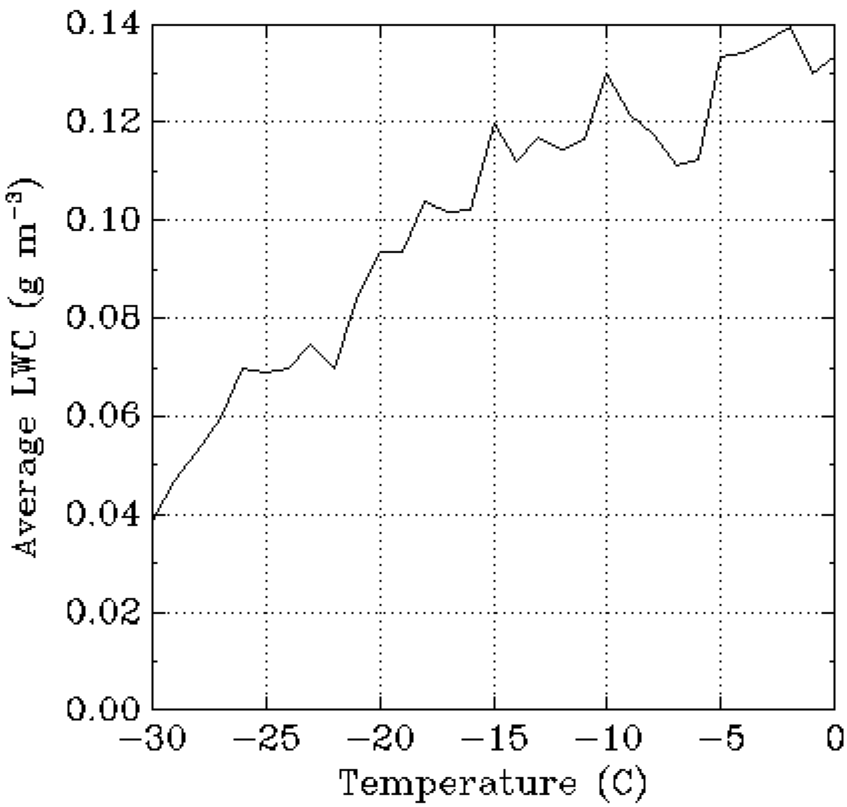


**Figure 5. Average LWC versus temperature for the observations shown in figure 3**

3.3 COMPARISON OF AIRPORT OBSERVATIONS TO IN-FLIGHT OBSERVATIONS

To explain the validity of using the ground-based observations and the visibility-to-LWC correlation, a comparison of the LWCs derived from the ground observations to LWCs for flight data was undertaken. Dr. George Isaac of Environment Canada provided 3 km-averaged LWC measurements taken off the East coast of Canada; in central Ontario and the Arctic during the Canadian Freezing Drizzle Experiment I and III; the Alliance Icing Research Study; and the FIRE Arctic Cloud Experiment [16 and 17]. The LWC in-flight values at seven different temperatures are provided in table 3. The data were originally published in g $kg^{-1}$; however, one of the authors, Dr. Stewart Cober, converted the data to g $m^{-3}$ for this comparison.

**Table 3. Percentile LWC for different temperatures**

| Temperature (C) | C25 (g m$^{-3}$) | C50 (g m$^{-3}$) | C75 (g m$^{-3}$) | C95 (g m$^{-3}$) | Mean (g m$^{-3}$) |
|---|---|---|---|---|---|
| -2° | 0.0435 | 0.1078 | 0.2057 | 0.3802 | 0.1406 |
| -6° | 0.0458 | 0.1111 | 0.2106 | 0.4028 | 0.1464 |
| -10° | 0.0448 | 0.1204 | 0.2493 | 0.4689 | 0.1672 |
| -14° | 0.0331 | 0.0743 | 0.1849 | 0.4665 | 0.1360 |
| -18° | 0.0205 | 0.0502 | 0.1041 | 0.2228 | 0.0752 |
| -22° | 0.0316 | 0.0600 | 0.1014 | 0.2892 | 0.0888 |
| -26° | 0.0182 | 0.0290 | 0.0819 | 0.2518 | 0.0716 |

Figure 6 shows the LWC and temperature for a given percentile of total observations. Solid lines represent Environment Canada in-flight measurements of LWC in grams per cubic meter versus temperature in degrees Celsius, and dashed lines represent LWCs derived from visibility values in the airport data using the Gultepe equation. The flight data are expected to be conservative because supercooled water is more likely to glaciate near the ground than higher in the atmosphere, so the fairly close agreement of the two datasets at the higher percentile probabilities was encouraging and provided further support for use of LWC derived from airport visibility data using the Gultepe equation.

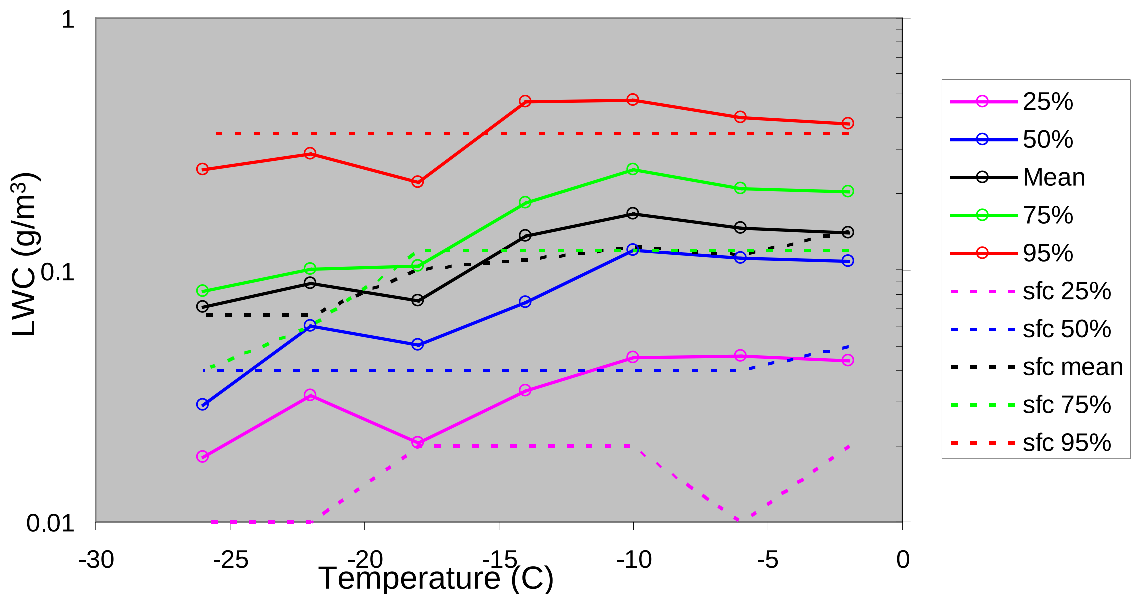


**Figure 6. LWC versus temperature for a given percentile of total observations (solid lines are in-flight, whereas dashed lines represent LWC derived from airport observations of visibility using the Gultepe equation with an $N_d$ of 100)**

## 3.4 COMPARISONS OF AIRPORT OBSERVATIONS AND OSLO EVENTS

Because all four of the engine damage events occurred at Oslo Airport, it was speculated that Oslo may have some unique environmental conditions. The Oslo Airport is noted for freezing fog in the winter thought to be due to the presence of a large fjord adjacent to the airport.

To assure that the weather conditions associated with the four events of concern at Oslo are not unique to Oslo, a search was conducted for similar conditions elsewhere. Using the airport database described in section 3.2, all the observations meeting the following criteria were extracted: temperature between -40°C and -15°C with visibility of 200 m or less and all fog-related weather codes (see appendix A, table A-1). To ensure the resulting observations were from relevant airports (i.e., from airports in which airplanes certificated to the FAA Title 14 Code of Federal Regulations [CFR] Part 25 operate), the frequency of commercial air traffic landings per day was obtained for those airports with high numbers of observations meeting the weather criteria described above.

The airport air traffic landing frequency was obtained from a query of the Official Airline Guide (OAG) database for one week in February 2011, thought to be representative of current wintertime utilization. Flights per week for any of the aircraft in table 4 were included (OAG processes and distributes flight schedules data; live and historical flight status information; travel planners; flight timetables; flight network mapping software; business travel planning products; aviation market reports; and flight schedules analysis tools for the air passenger and air cargo markets).

**Table 4. Aircraft considered in the airport landing frequency study of section 3.4**

| Manufacturer | Model |
|---|---|
| AIRBUS INDUSTRIE | A300 |
| AIRBUS INDUSTRIE | A300 |
| AIRBUS INDUSTRIE | A300–600 |
| AIRBUS INDUSTRIE | A310 |
| AIRBUS INDUSTRIE | A310–300 |
| AIRBUS INDUSTRIE | A310–300 |
| AIRBUS INDUSTRIE | A318 |
| AIRBUS INDUSTRIE | A318/319/320/321 |
| AIRBUS INDUSTRIE | A319 |
| AIRBUS INDUSTRIE | A320 |
| AIRBUS INDUSTRIE | A321 |
| AIRBUS INDUSTRIE | A330 |
| AIRBUS INDUSTRIE | A330–200 |
| AIRBUS INDUSTRIE | A330–300 |
| AIRBUS INDUSTRIE | A340 |
| AIRBUS INDUSTRIE | A340–300 |
| AIRBUS INDUSTRIE | A340–600 |
| AIRBUS INDUSTRIE | A380–800 |
| AIRBUS INDUSTRIE | A380–800 |
| ANTONOV | AN-12 |
| ANTONOV | AN-124 |
| ANTONOV | AN-140 |
| ANTONOV | AN148-100 RUSLAN |
| ANTONOV | AN-24 |
| ANTONOV | AN-26/30/32 |
| ATR | 72 |
| ATR | 42–300/320 |
| ATR | 45–500 |
| ATR42/ATR72 | |
| AVRO | RJ100 |
| AVRO | RJ70/RJ85/RJ100 |
| AVRO | RJ85 |
| BEECHCRAFT | 1900 |
| BEECHCRAFT | RJ70/RJ85/RJ100 |

**Table 4. Aircraft considered in the airport landing frequency study of section 3.4 (continued)**

| Manufacturer | Model |
|---|---|
| BEECHCRAFT | 1900C |
| BEECHCRAFT | 1900D |
| BEECHCRAFT-LIGHT | AIRCRAFT-TWIN |
| BOEING | 727 |
| BOEING | 727 |
| BOEING | 737 |
| BOEING | 737 |
| BOEING | 747 |
| BOEING | 747 |
| BOEING | 757 |
| BOEING | 767 |
| BOEING | 767 |
| BOEING | 777 |
| BOEING | 777 |
| BOEING | 717–200 |
| BOEING | 727–200 |
| BOEING | 737 (MIXED CONFIGURATION) |
| BOEING | 737–200 |
| BOEING | 737–200 |
| BOEING | 737–300 |
| BOEING | 737–300 |
| BOEING | 737–300 (WINGLETS) |
| BOEING | 737–400 |
| BOEING | 737–400 |
| BOEING | 737–400 (MIXED CONFIGURATION) |
| BOEING | 737–500 |
| BOEING | 737–500 (WINGLETS) |
| BOEING | 737–600 |
| BOEING | 737–700 |

The frequency of conditions meeting the criteria discussed above is plotted in figure 7 for the 25 airports with the highest frequency of flights per week.

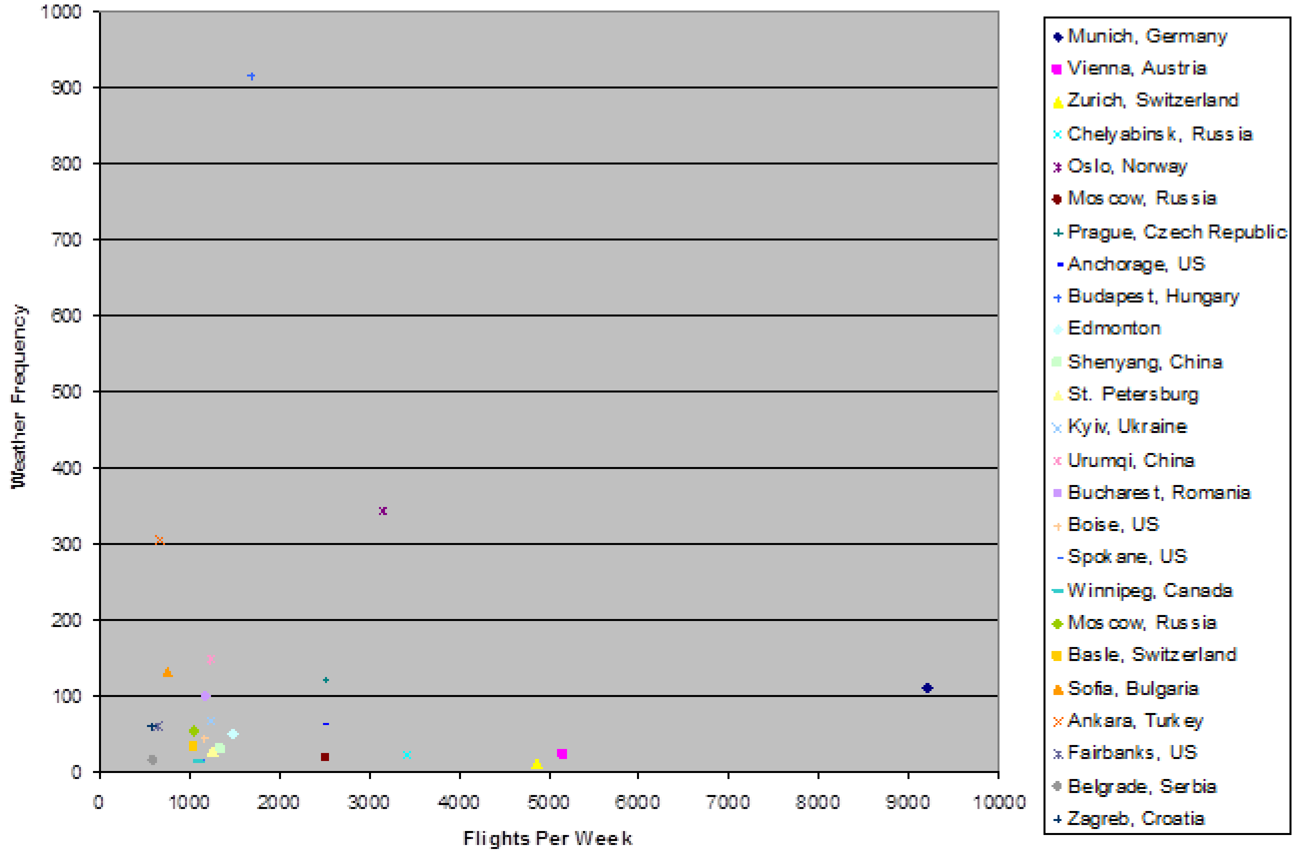


**Figure 7. The 25 airports with the highest frequency of flights per week (for February 2011), and the number of weather observations meeting the criteria: temperature between -40°C and -15°C with visibility of 200 m or less, and fog, using the airport observation database described in section 3.2**

Note from figure 7 that Budapest, Hungary far exceeds Oslo for the number of observations meeting the weather criteria; however, Budapest has no recorded engine damage events. The working group concluded from this data that there are many other airports with observed weather similar to those that caused engine damage events in Oslo and with sufficient air traffic to be relevant to this study.

## 4. PROBABILITY OF GROUND ICING FREEZING FOG CONDITIONS USING OBSERVATION DATABASE FOR AIRPORTS WITH RUNWAYS LONGER THAN 9000 FEET

The goal of the working group—to determine a relationship of LWC to temperature for supercooled ground fog at extremely cold temperatures—requires agreement on an appropriate probability of occurrence. The current engine icing means of compliance outlined in AC 20-147 [2] includes table points, which are used as reliable demonstrations of an engine's icing capability. For ground icing, the AC 20-147 (Table 1: "Icing Conditions for Engine Certification Testing," Test Point 3: "ground fog icing") requires a supercooled LWC of 0.3 g $m^{-3}$, an inlet temperature of 15°F–30°F (-9°C to -1°C), and a mean effective water droplet diameter of 20 microns, minimum (hereafter, this test point will be referred to as the "ground icing freezing fog table point"). The history of the weather observations, which led to the development of the ground icing freezing fog table point, is not well documented, but it is believed to have resulted from a 1977 Aircraft Engine Regulatory Review Conference for which recorded meteorological data were evaluated. A search of the FAA rulemaking records indicates that an earlier version of the ground icing freezing fog table point was revised in 1983, and from that time onward, engines were certified to an LWC of 0.3 $gm^{-3}$ rather than 0.6 $gm^{-3}$, as had been done previously. The NPRM Notice No. 80-21[20], issued on November 10, 1980, further stated as explanation that the then existing 14 CFR 33.68 was unnecessarily severe and would be changed "by reducing the prescribed LWC and drop diameter to values that are more representative of actual ground fog conditions in that temperature range." The engine experience since 1983 shows the test to be effective in that some engines are challenged to pass the test, and those that pass go on to have excellent service experience when operating in freezing fog within the test temperature range.

Because there is a lack of records regarding the meteorological origins of the ground icing freezing fog table point, it also has an unknown probability of occurrence. The working group considered that if the new threat level for temperatures below -18°C could be made with the same probability of occurrence, it too would lead to good service experience. Therefore, the probability of 0.3 g $m^{-3}$ at -9°C was estimated from the airport observation database. The temperature of -9°C was chosen because it is expected that the colder temperature for the ground icing freezing fog table point would be more conservative than -1°C, because LWC decreases with the temperature.

Using the Gultepe equation with an $N_d$ of 100 and using the airport observation database resulted in an estimated probability of 23.2% of occurrence of the ground icing freezing fog table point of 0.3 g $m^{-3}$ at -9°C. Subsequently, for temperatures below -9°C, the LWC with the same probability (23.2%) of occurrence was calculated, resulting in the curve shown in figure 8. The LWC versus temperature representation in figure 8 is stepped because the visibility observations are reported in discrete distances (i.e., 400, 300, 250, 200, 150, and 100 meters).

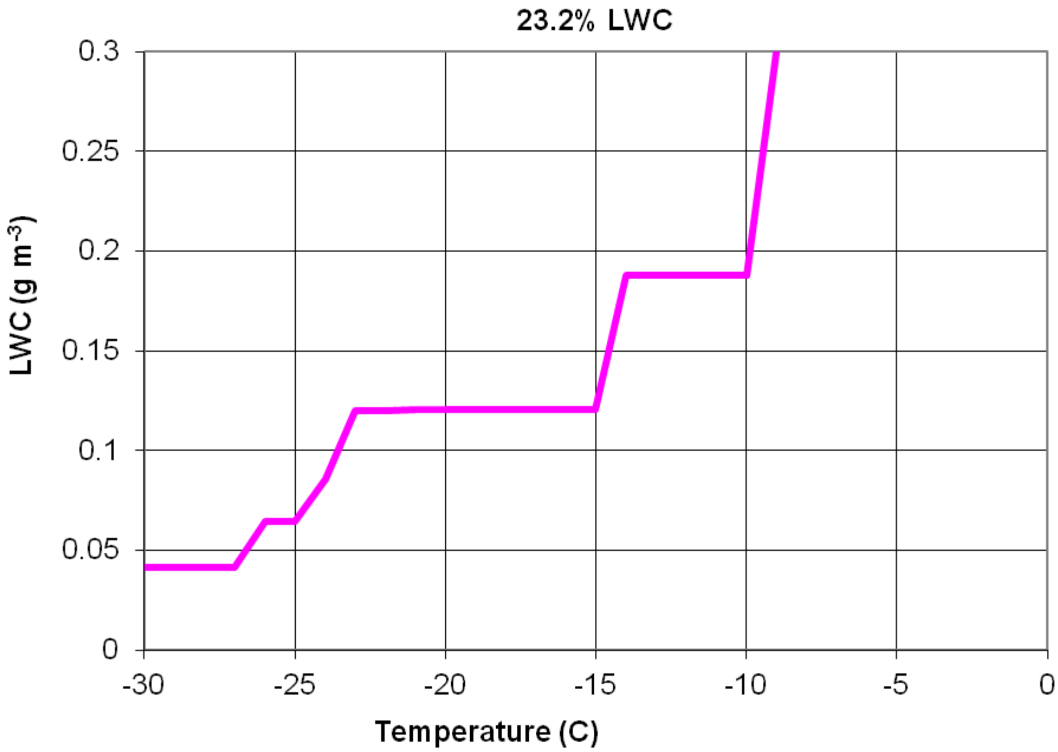


**Figure 8. For temperatures below -9°C, an LWC representing the 23.2% probability of occurrence**

## 5. EXPANSION OF THE AIRPORT OBSERVATION DATABASE TO INCLUDE AIRPORTS WITH RUNWAYS LONGER THAN 3000 FEET

The airport data discussed above were compiled using a previously developed airport list, which was created specifically for research using data from airports used by large transport aircraft, and included only airports with runways greater than 9000 feet in length. To ensure that the findings using these airports are representative of all airports used by aircraft certificated to FAA 14 CFR 23 and 25, the working group decided to expand the database to include all airports with runways greater than 3000 feet in length. The expansion required a manual process of connecting the airport observation database with the list of airports having runways greater than 3000 feet in length because they had two different airport code nomenclatures. In some cases, there was no connection, and the airport was not used. The resulting database includes 4511 airports. The most recent data, provided they were not older than 30 years, were used for each airport.

In the same manner as explained above for the observation database for airports with runways longer than 9000 feet, a probability of occurrence was calculated for the ground icing freezing fog table point for -9°C for the expanded database. The probability was determined to be 15.2%.

Next, the LWCs at the colder temperatures having this same 15.2% probability of occurrence were determined and are presented in figure 9, along with the data plotted in figure 8.

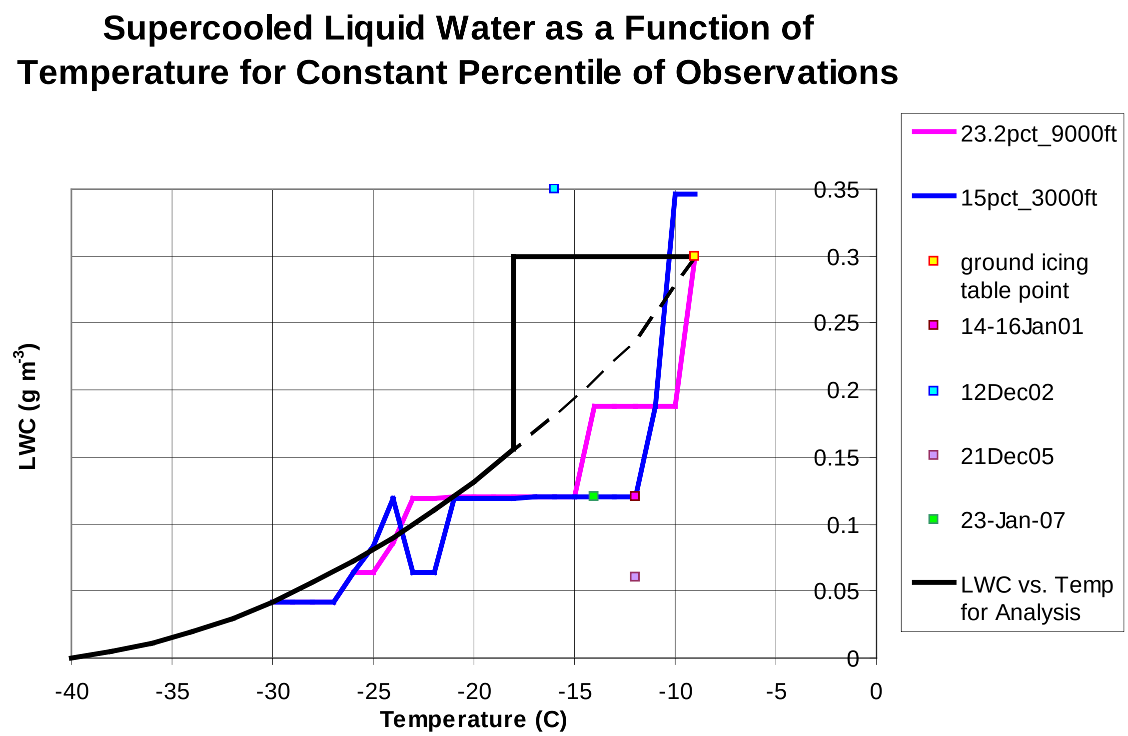


**Figure 9. Comparison of the airport database with runways greater than 9000 feet (pink) and 3000 feet (blue)**

For both sets of data, the LWC versus temperature curves (see figure 9) are stepped because the visibility observations are reported in discrete distances (i.e., 400, 300, 250, 200, 150, and 100 meters; note that this also explains why the 15.2% LWC value of the 3000-foot runway database is larger than 0.3 g $m^{-3}$; the 15.2% visibility is 100 m, and the next visibility in the cumulative frequency curve is 120 m). A second degree polynomial, depicted with a solid black curve, was fit to the coldest points for selected LWCs (i.e., (-9°C, 0.3), (-14°C, 0.19), (-23°C, 0.12), (-30°C, 0.04)) for the 9000-foot runway data). In addition, the polynomial for LWC was fit to the point of (-40°C, 0).

The proposed LWC versus temperature curve for engine critical point analysis follows the solid black curve on figure 9. From -9°C to -18°C, the LWC to be used for analysis will be 0.3 g $m^{-3}$, consistent with the engine test requirements. Below -18°C, the black polynomial curve is proposed. The algebraic definition of the LWC versus temperature curve proposed for use by engine manufacturers in a critical point analysis is:

- Between -9$^{o}$C and -18$^{o}$C:
  $LWC = 0.30$

- Below -18$^{o}$C:
  $LWC = 0.000242 * Temp^2 + 0.0211 * Temp + 0.4571$

(where *LWC* is in grams per cubic meter and *Temp* is in degrees Celsius)

Figure 9 also shows the four engine damage events, the worst visibility, and the associated temperature from table 1. Notably, the observation from the engine damage event in Oslo on December 12, 2002 is slightly above the proposed LWC versus temperature curve. The weather was variable that day and the low visibility of 100 meters was reported for only one observation; the 30-minute observations preceding and following this observation were 200 and 1000 meters, respectively. The NPRM 10-10 [1] test point for freezing fog below -9°C was derived from the engine damage events in Oslo and based on 4 days of observations. The NPRM 10-10 requires a minimum test duration of 30 minutes between -9°C and -18°C, therefore adding the requisite element of severity beyond the single observations on the event days. It is proposed that the engine company use their critical point analysis to find the most critical point between -9°C and -40°C using the LWC versus temperature curve, then test that point. Following this procedure, it will be shown that no point at a colder temperature is more critical than that tested.

It can be concluded from figure 9 that the two datasets using airports with over 9000-foot and 3000-foot runways achieve consistent estimates of LWC with temperature based on the methodology presented here.

When assessing the results presented here (a comparison to 14 CFR 25), Appendix C is appropriate. The envelope of LWC, temperature, and median volume diameter defined by 14 CFR 25 Appendix C are understood to have a probability of 1/1000 [21] over a distance of 17.4 nautical miles. This probability does not translate to ground taxi operations over small distances. The Advisory Circular test points result in good service experience because an extended exposure to icing constitutes a more severe encounter.

## 6. CONCLUSION

The results presented in this report are not proposed to take the place of existing engine test requirements; therefore, any engine certified will be demonstrated by test to meet the requirements in the current Advisory Circular and, later, the new rule. The liquid water content versus temperature relationship presented here is proposed to be used with analytical methods to determine if the proposed engine freezing test point is more critical than any point at a lower temperature.

## 7. REFERENCES

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APPENDIX A—Weather Codes Used and Weather Data Observed During the Oslo Airport Aircraft Engine Damage Events

Table A-1 shows the World Meteorological Organization's present weather codes used in the analysis of airport observations.

**Table A-1. Weather codes used in the analysis of airport observations (see section 3.2)**

| WX Codes | Description |
|---|---|
| 2 | State of sky on the whole unchanged |
| 10 | Mist |
| 12 | More or less continuous shallow fog or ice fog at the station not deeper than about 2 meters |
| 28 | Fog or ice fog |
| 40 | Fog or ice fog at a distance at the time of observation, but not at the station during the preceding hour, the fog or ice fog extending to a level above that of the observer |
| 41 | Fog or ice fog in patches |
| 44 | Fog or ice fog, sky visible, no appreciable change during the preceding hour |
| 45 | Fog or ice fog, sky invisible, no appreciable change during the preceding hour |
| 46 | Fog or ice fog, sky invisible, has begun or has become thicker during the preceding hour |
| 47 | Fog or ice fog, sky invisible, has begun or has become thicker during the preceding hour |
| 48 | Fog, depositing rime, sky visible |
| 49 | Fog, depositing rime, sky invisible |
| 56 | Drizzle, freezing, slight |
| 76 | Diamond dust (with or without fog) |

Tables A-2–A-5 show weather observations from Oslo during the engine damage event days presented in section 2 of the main document. The asterisks represent missing data. The liquid water content (LWC) is calculated with the Gultepe equation with number density ($N_d$) = 100.

**Table A-2. Weather observations for Oslo, Norway Airport (ENGM) January 14–16, 2001**

| Date/Time (UTC) | T (deg C) | Vis (m) | LWC (g/m^3) | WX |
|---|---|---|---|---|
| 1/14/2001 0:00 | -11.1 | 2500 | 0.00 | 41 |
| 1/14/2001 0:50 | -13.0 | 2500 | 0.00 | 41 |
| 1/14/2001 1:50 | -14.0 | 900 | 0.01 | 48 |
| 1/14/2001 2:50 | -14.0 | 1300 | 0.01 | 41 |
| 1/14/2001 3:00 | -13.1 | 1300 | 0.01 | 41 |
| 1/14/2001 3:50 | -14.0 | 800 | 0.01 | 49 |
| 1/14/2001 4:50 | -14.0 | 800 | 0.01 | 49 |
| 1/14/2001 5:50 | -14.0 | 800 | 0.01 | 49 |
| 1/14/2001 6:00 | -11.9 | 800 | 0.01 | 44 |
| 1/14/2001 6:50 | -14.0 | 800 | 0.01 | 49 |
| 1/14/2001 7:50 | -14.0 | 200 | 0.12 | 49 |
| 1/14/2001 8:50 | -13.0 | 600 | 0.02 | 49 |
| 1/14/2001 9:00 | -11.5 | 600 | 0.02 | 45 |
| 1/14/2001 9:50 | -12.0 | 100 | 0.35 | 49 |
| 1/14/2001 10:50 | -11.0 | 200 | 0.12 | 49 |
| 1/14/2001 11:50 | -11.0 | 300 | 0.06 | 49 |
| 1/14/2001 12:00 | -9.8 | 300 | 0.06 | 45 |
| 1/14/2001 12:50 | -10.0 | 100 | 0.35 | 49 |
| 1/14/2001 13:50 | -11.0 | 1000 | 0.01 | 41 |
| 1/14/2001 14:50 | -10.0 | 600 | 0.02 | 49 |
| 1/14/2001 15:00 | -10.4 | 600 | 0.02 | 47 |
| 1/14/2001 15:50 | -11.0 | 350 | 0.05 | 49 |
| 1/14/2001 16:50 | -10.0 | 400 | 0.04 | 49 |
| 1/14/2001 17:50 | -10.0 | 600 | 0.02 | 49 |
| 1/14/2001 18:00 | -9.8 | 600 | 0.02 | 45 |
| 1/14/2001 18:50 | -10.0 | 1200 | 0.01 | 41 |
| 1/14/2001 19:50 | -10.0 | 1200 | 0.01 | 41 |
| 1/14/2001 20:50 | -10.0 | 700 | 0.02 | 49 |
| 1/14/2001 21:00 | -9.8 | 700 | 0.02 | 47 |
| 1/14/2001 21:50 | -10.0 | 2700 | 0.00 | 10 |
| 1/14/2001 22:50 | -12.0 | 800 | 0.01 | 49 |
| 1/14/2001 23:50 | -13.0 | 500 | 0.03 | 49 |
| 1/15/2001 0:00 | -12.3 | 600 | 0.02 | 44 |
| 1/15/2001 0:50 | -14.0 | 2500 | 0.00 | 41 |
| 1/15/2001 1:50 | -14.0 | 1000 | 0.01 | 41 |
| 1/15/2001 2:50 | -14.0 | 3000 | 0.00 | 41 |
| 1/15/2001 3:00 | -12.0 | 4000 | 0.00 | 40 |
| 1/15/2001 3:50 | -14.0 | 500 | 0.03 | 49 |
| 1/15/2001 4:50 | -14.0 | 1200 | 0.01 | 41 |

**Table A-2. Weather observations for Oslo, Norway Airport (ENGM) January 14–16, 2001 (continued)**

| Date/Time (UTC) | T (deg C) | Vis (m) | LWC (g/m^3) | WX |
|---|---|---|---|---|
| 1/15/2001 5:50 | -13.0 | 300 | 0.06 | 49 |
| 1/15/2001 6:00 | -11.2 | 400 | 0.04 | 45 |
| 1/15/2001 6:50 | -13.0 | 200 | 0.12 | 49 |
| 1/15/2001 7:50 | -12.0 | 200 | 0.12 | 49 |
| 1/15/2001 8:50 | -12.0 | 300 | 0.06 | 49 |
| 1/15/2001 9:00 | -11.5 | 600 | 0.02 | 45 |
| 1/15/2001 9:50 | -12.0 | 300 | 0.06 | 49 |
| 1/15/2001 10:50 | -11.0 | 700 | 0.02 | 49 |
| 1/15/2001 11:50 | -10.0 | 700 | 0.02 | 49 |
| 1/15/2001 12:00 | -9.5 | 700 | 0.02 | 45 |
| 1/15/2001 12:50 | -10.0 | 300 | 0.06 | 49 |
| 1/15/2001 13:50 | -10.0 | 300 | 0.06 | 49 |
| 1/15/2001 14:50 | -10.0 | 400 | 0.04 | 49 |
| 1/15/2001 15:00 | -10.1 | 400 | 0.04 | 45 |
| 1/15/2001 15:50 | -10.0 | 400 | 0.04 | 49 |
| 1/15/2001 16:50 | -11.0 | 300 | 0.06 | 49 |
| 1/15/2001 17:50 | -11.0 | 400 | 0.04 | 49 |
| 1/15/2001 18:00 | -11.4 | 400 | 0.04 | 45 |
| 1/15/2001 18:50 | -12.0 | 1000 | 0.01 | 41 |
| 1/15/2001 19:50 | -12.0 | 600 | 0.02 | 49 |
| 1/15/2001 20:10 | -11.0 | 300 | 0.06 | 49 |
| 1/15/2001 21:00 | -10.8 | 300 | 0.06 | 45 |
| 1/15/2001 21:50 | -11.0 | 600 | 0.02 | 49 |
| 1/15/2001 22:50 | -11.0 | 200 | 0.12 | 49 |
| 1/15/2001 23:50 | -11.0 | 300 | 0.06 | 49 |
| 1/16/2001 0:00 | -10.7 | 300 | 0.06 | 45 |
| 1/16/2001 0:50 | -11.0 | 200 | 0.12 | 49 |
| 1/16/2001 1:50 | -12.0 | 200 | 0.12 | 49 |
| 1/16/2001 2:50 | -12.0 | 200 | 0.12 | 49 |
| 1/16/2001 3:00 | -11.0 | 200 | 0.12 | 45 |
| 1/16/2001 3:50 | -11.0 | 200 | 0.12 | 49 |
| 1/16/2001 4:50 | -11.0 | 200 | 0.12 | 49 |

**Table A-3. Weather observations for Oslo, Norway Airport (ENGM) December 12, 2002**

| Date/Time (UTC) | T (deg C) | Vis (m) | LWC (g/m^3) | WX |
|---|---|---|---|---|
| 12/12/2002 0:00 | -17.3 | 300 | 0.06 | 48 |
| 12/12/2002 0:20 | -17.0 | 1000 | 0.01 | 48 |
| 12/12/2002 0:50 | -17.0 | 300 | 0.06 | 48 |
| 12/12/2002 1:00 | -17.0 | 300 | 0.06 | 48 |
| 12/12/2002 1:20 | -17.0 | 300 | 0.06 | 49 |
| 12/12/2002 1:50 | -17.0 | 800 | 0.01 | 48 |
| 12/12/2002 2:00 | -17.0 | 800 | 0.01 | 48 |
| 12/12/2002 2:20 | -17.0 | 800 | 0.01 | 48 |
| 12/12/2002 2:50 | -17.0 | 300 | 0.06 | 49 |
| 12/12/2002 3:00 | -15.9 | 300 | 0.06 | 49 |
| 12/12/2002 3:20 | -16.0 | 200 | 0.12 | 49 |
| 12/12/2002 3:50 | -16.0 | 200 | 0.12 | 49 |
| 12/12/2002 4:00 | -15.9 | 200 | 0.12 | 49 |
| 12/12/2002 4:20 | -16.0 | 400 | 0.04 | 49 |
| 12/12/2002 4:50 | -16.0 | 300 | 0.06 | 48 |
| 12/12/2002 5:00 | -15.2 | 300 | 0.06 | 48 |
| 12/12/2002 5:20 | ***** | 300 | 0.06 | ** |
| 12/12/2002 5:50 | -17.0 | 900 | 0.01 | 48 |
| 12/12/2002 6:00 | -15.4 | 900 | 0.01 | 48 |
| 12/12/2002 6:20 | -18.0 | 1500 | 0.01 | 41 |
| 12/12/2002 6:50 | -18.0 | 1300 | 0.01 | 41 |
| 12/12/2002 7:00 | -16.4 | 1300 | 0.01 | 41 |
| 12/12/2002 7:20 | -17.0 | 300 | 0.06 | 48 |
| 12/12/2002 7:50 | -18.0 | 600 | 0.02 | 48 |
| 12/12/2002 8:00 | -15.8 | 600 | 0.02 | 48 |
| 12/12/2002 8:20 | -18.0 | 600 | 0.02 | 48 |
| 12/12/2002 8:50 | -18.0 | 600 | 0.02 | 48 |
| 12/12/2002 9:00 | -15.7 | 6600 | 0.02 | 48 |
| 12/12/2002 9:20 | -17.0 | 200 | 0.12 | 48 |
| 12/12/2002 9:50 | -16.0 | 100 | 0.35 | 48 |
| 12/12/2002 10:20 | -16.0 | 1000 | 0.01 | 41 |
| 12/12/2002 10:50 | -17.0 | 1000 | 0.01 | 41 |
| 12/12/2002 11:20 | -17.0 | 800 | 0.01 | 48 |
| 12/12/2002 11:50 | -16.0 | 200 | 0.12 | 48 |
| 12/12/2002 12:00 | -14.2 | 200 | 0.12 | 77 |
| 12/12/2002 12:20 | -16.0 | 200 | 0.12 | 48 |
| 12/12/2002 12:00 | -14.2 | 200 | 0.12 | 77 |
| 12/12/2002 12:20 | -16.0 | 1200 | 0.01 | 41 |

**Table A-3. Weather observations for Oslo, Norway Airport (ENGM) December 12, 2002 (continued)**

| Date/Time (UTC) | T (deg C) | Vis (m) | LWC (g/m^3) | WX |
|---|---|---|---|---|
| 12/12/2002 12:50 | -16.0 | 700 | 0.02 | 48 |
| 12/12/2002 13:00 | -14.9 | 700 | 0.02 | 48 |
| 12/12/2002 13:20 | ***** | 700 | 0.02 | ** |
| 12/12/2002 13:50 | -16.0 | 100 | 0.35 | 49 |
| 12/12/2002 14:00 | -14.7 | 100 | 0.35 | 49 |
| 12/12/2002 14:50 | -17.0 | 500 | 0.03 | 48 |
| 12/12/2002 15:00 | -14.9 | 500 | 0.03 | 48 |
| 12/12/2002 15:20 | -17.0 | 1200 | 0.01 | ** |
| 12/12/2002 15:50 | -16.0 | 800 | 0.01 | ** |
| 12/12/2002 16:20 | -16.0 | 1500 | 0.01 | ** |
| 12/12/2002 16:50 | -17.0 | 300 | 0.06 | 48 |
| 12/12/2002 17:20 | -16.0 | 500 | 0.03 | 48 |
| 12/12/2002 17:50 | -16.0 | 800 | 0.01 | 48 |
| 12/12/2002 18:00 | -14.5 | 800 | 0.01 | 48 |
| 12/12/2002 18:20 | -16.0 | 1700 | 0.00 | 41 |
| 12/12/2002 18:50 | -16.0 | 2000 | 0.00 | 10 |
| 12/12/2002 19:00 | -13.6 | 2000 | 0.00 | 28 |
| 12/12/2002 19:20 | -15.0 | 1300 | 0.01 | 41 |
| 12/12/2002 19:50 | -15.0 | 3000 | 0.00 | 41 |
| 12/12/2002 20:00 | -14.4 | 3000 | 0.00 | 10 |
| 12/12/2002 20:20 | -15.0 | 6000 | 0.00 | 10 |
| 12/12/2002 20:50 | -16.0 | 6000 | 0.00 | 41 |
| 12/12/2002 21:00 | -16.5 | 6000 | 0.00 | 40 |
| 12/12/2002 21:20 | -17.0 | 5000 | 0.00 | 41 |
| 12/12/2002 21:50 | -16.0 | 5000 | 0.00 | 41 |
| 12/12/2002 22:20 | -15.0 | 11265 | 0.00 | 41 |
| 12/12/2002 22:50 | -17.0 | 11265 | 0.00 | 41 |
| 12/12/2002 23:00 | -14.9 | 12000 | 0.00 | 40 |
| 12/12/2002 23:20 | -16.0 | 11265 | 0.00 | 41 |
| 12/12/2002 23:50 | -15.0 | 11265 | 0.00 | 41 |

**Table A-4. Weather observations for Oslo, Norway Airport (ENGM) December 21, 2005**

| Date/Time (UTC) | T (deg C) | Vis (m) | LWC (g/m^3) | WX |
|---|---|---|---|---|
| 12/21/2005 0:00 | -12.7 | 5000 | 0.00 | 10 |
| 12/21/2005 0:50 | -13.0 | 3000 | 0.00 | 10 |
| 12/21/2005 1:20 | ***** | 350 | 0.05 | ** |
| 12/21/2005 1:50 | -12.0 | 450 | 0.03 | 49 |
| 12/21/2005 2:20 | -12.0 | 500 | 0.03 | 49 |
| 12/21/2005 2:50 | -12.0 | 500 | 0.03 | 49 |
| 12/21/2005 3:00 | -10.5 | 500 | 0.03 | 47 |
| 12/21/2005 3:20 | -11.0 | 500 | 0.03 | 49 |
| 12/21/2005 3:50 | ***** | 600 | 0.02 | ** |
| 12/21/2005 4:20 | -11.0 | 900 | 0.01 | 49 |
| 12/21/2005 4:50 | -11.0 | 500 | 0.03 | 49 |
| 12/21/2005 5:20 | -11.0 | 300 | 0.06 | 49 |
| 12/21/2005 5:50 | -10.0 | 400 | 0.04 | 49 |
| 12/21/2005 6:00 | -9.9 | 500 | 0.03 | 47 |
| 12/21/2005 6:20 | ***** | 1200 | 0.01 | ** |
| 12/21/2005 6:50 | -10.0 | 2000 | 0.00 | 10 |
| 12/21/2005 7:20 | -10.0 | 2200 | 0.00 | 10 |
| 12/21/2005 7:50 | -9.0 | 500 | 0.03 | 49 |
| 12/21/2005 8:20 | -0.0 | 900 | 0.01 | ** |
| 12/21/2005 8:50 | -9.0 | 900 | 0.01 | 49 |
| 12/21/2005 9:00 | -8.3 | 900 | 0.01 | 49 |
| 12/21/2005 9:20 | -9.0 | 400 | 0.04 | 49 |
| 12/21/2005 9:50 | -9.0 | 350 | 0.05 | 49 |
| 12/21/2005 10:20 | -9.0 | 350 | 0.05 | 49 |
| 12/21/2005 10:50 | -8.0 | 300 | 0.06 | 49 |
| 12/21/2005 11:20 | -8.0 | 300 | 0.06 | 49 |
| 12/21/2005 11:50 | -0.0 | 400 | 0.04 | ** |
| 12/21/2005 12:00 | -7.6 | 400 | 0.04 | 49 |
| 12/21/2005 12:20 | -8.0 | 600 | 0.02 | 49 |
| 12/21/2005 12:50 | ***** | 550 | 0.03 | ** |
| 12/21/2005 13:20 | -8.0 | 500 | 0.03 | 49 |
| 12/21/2005 13:50 | -8.0 | 650 | 0.02 | 49 |
| 12/21/2005 14:20 | -8.0 | 700 | 0.02 | 49 |
| 12/21/2005 14:50 | -8.0 | 700 | 0.02 | 49 |
| 12/21/2005 15:00 | -7.9 | 700 | 0.02 | 49 |
| 12/21/2005 15:20 | -8.0 | 2000 | 0.00 | 10 |
| 12/21/2005 15:50 | -8.0 | 4000 | 0.00 | 10 |
| 12/21/2005 16:20 | -8.0 | 3000 | 0.00 | 10 |

**Table A-4. Weather observations for Oslo, Norway Airport (ENGM) December 21, 2005 (continued)**

| Date/Time (UTC) | T (deg C) | Vis (m) | LWC (g/m^3) | WX |
|---|---|---|---|---|
| 12/21/2005 16:50 | -8.0 | 2900 | 0.00 | 10 |
| 12/21/2005 17:20 | -7.0 | 2300 | 0.00 | 10 |
| 12/21/2005 17:50 | -7.0 | 3000 | 0.00 | 10 |
| 12/21/2005 18:00 | -6.8 | 3000 | 0.00 | 56 |
| 12/21/2005 18:20 | -7.0 | 4000 | 0.00 | 10 |
| 12/21/2005 18:50 | -6.0 | 3400 | 0.00 | 10 |
| 12/21/2005 19:20 | -4.0 | 4900 | 0.00 | 10 |
| 12/21/2005 19:50 | -5.0 | 7000 | 0.00 | ** |
| 12/21/2005 20:20 | -5.0 | 7000 | 0.00 | ** |
| 12/21/2005 20:50 | -4.0 | 6000 | 0.00 | ** |
| 12/21/2005 21:00 | -4.3 | 6000 | 0.00 | 10 |
| 12/21/2005 21:20 | -4.0 | 6000 | 0.00 | ** |
| 12/21/2005 21:50 | -4.0 | 4000 | 0.00 | 10 |
| 12/21/2005 22:20 | ***** | 1200 | 0.01 | ** |
| 12/21/2005 22:50 | ***** | 800 | 0.01 | ** |
| 12/21/2005 23:20 | -4.0 | 500 | 0.03 | 49 |
| 12/21/2005 23:50 | ***** | 500 | 0.03 | ** |

**Table A-5. Weather observations for Oslo, Norway Airport (ENGM)**
**January 23, 2007**

| Date/Time (UTC) | T (deg C) | Vis (m) | LWC (g/m^3) | WX |
|---|---|---|---|---|
| 1/23/2007 0:00 | -14.5 | 65000 | 0.00 | 2 |
| 1/23/2007 0:15 | -15.0 | 9900 | 0.00 | ** |
| 1/23/2007 0:40 | -15.0 | 9900 | 0.00 | ** |
| 1/23/2007 1:13 | -15.0 | 9900 | 0.00 | ** |
| 1/23/2007 1:40 | -15.0 | 9900 | 0.00 | ** |
| 1/23/2007 2:11 | -16.0 | 9900 | 0.00 | ** |
| 1/23/2007 2:42 | -16.0 | 9900 | 0.00 | ** |
| 1/23/2007 3:00 | -17.0 | 20000 | 0.00 | 2 |
| 1/23/2007 3:14 | -16.0 | 9900 | 0.00 | ** |
| 1/23/2007 3:41 | -17.0 | 11265 | 0.00 | 12 |
| 1/23/2007 4:10 | ***** | 500 | 0.03 | ** |
| 1/23/2007 4:42 | -15.0 | 900 | 0.01 | 49 |
| 1/23/2007 5:12 | ***** | 300 | 0.06 | ** |
| 1/23/2007 5:41 | -16.0 | 300 | 0.06 | 49 |
| 1/23/2007 6:00 | -16.9 | 300 | 0.06 | 44 |
| 1/23/2007 6:12 | -16.0 | 550 | 0.03 | 49 |
| 1/23/2007 6:42 | -16.0 | 700 | 0.02 | 49 |
| 1/23/2007 7:12 | -16.0 | 2200 | 0.00 | 49 |
| 1/23/2007 7:44 | ***** | 700 | 0.02 | ** |
| 1/23/2007 8:15 | -15.0 | 350 | 0.05 | 49 |
| 1/23/2007 8:42 | -15.0 | 200 | 0.12 | 49 |
| 1/23/2007 9:00 | -14.7 | 200 | 0.12 | 49 |
| 1/23/2007 9:11 | ***** | 300 | 0.06 | ** |
| 1/23/2007 9:40 | -15.0 | 500 | 0.03 | 49 |
| 1/23/2007 10:18 | -14.0 | 6000 | 0.00 | 41 |
| 1/23/2007 10:42 | -14.0 | 4100 | 0.00 | 41 |
| 1/23/2007 12:00 | -11.1 | 200 | 0.12 | 49 |
| 1/23/2007 12:12 | ***** | 600 | 0.02 | ** |
| 1/23/2007 12:41 | -13.0 | 650 | 0.02 | 49 |
| 1/23/2007 13:15 | -12.0 | 2500 | 0.00 | 41 |
| 1/23/2007 13:43 | -12.0 | 1000 | 0.01 | 49 |
| 1/23/2007 14:12 | ***** | 300 | 0.06 | ** |
| 1/23/2007 14:41 | ***** | 350 | 0.05 | ** |
| 1/23/2007 15:00 | -12.3 | 300 | 0.06 | 49 |
| 1/23/2007 15:10 | -13.0 | 500 | 0.03 | 49 |
| 1/23/2007 15:42 | -13.0 | 2000 | 0.00 | 41 |
| 1/23/2007 16:17 | -14.0 | 2500 | 0.00 | 41 |
| 1/23/2007 16:43 | ***** | 900 | 0.01 | ** |

**Table A-5. Weather observations for Oslo, Norway Airport (ENGM)**
**January 23, 2007 (continued)**

| Date/Time (UTC) | T (deg C) | Vis (m) | LWC (g/m^3) | WX |
|---|---|---|---|---|
| 1/23/2007 17:14 | ***** | 2500 | 0.00 | ** |
| 1/23/2007 17:44 | -16.0 | 7000 | 0.00 | 40 |
| 1/23/2007 19:16 | ***** | 2000 | 0.00 | ** |
| 1/23/2007 19:43 | ***** | 7000 | 0.00 | ** |
| 1/23/2007 20:14 | -18.0 | 9000 | 0.00 | 40 |
| 1/23/2007 20:44 | -18.0 | 5000 | 0.00 | 41 |
| 1/23/2007 21:00 | -17.2 | 5000 | 0.00 | 46 |
| 1/23/2007 21:12 | -18.0 | 4500 | 0.00 | 41 |
| 1/23/2007 21:45 | ***** | 500 | 0.03 | ** |
| 1/23/2007 22:14 | -18.0 | 1500 | 0.01 | 41 |
| 1/23/2007 22:40 | ***** | 2000 | 0.00 | ** |
| 1/23/2007 23:14 | ***** | 3000 | 0.00 | ** |
| 1/23/2007 23:45 | -19.0 | 3000 | 0.00 | 41 |