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Icing Cloud Calibration of the NASA Glenn Icing Research Tunnel

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ICING CLOUD CALIBRATION OF THE NASA GLENN ICING RESEARCH TUNNEL

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Abstract

The icing research tunnel at the NASA Glenn Research Center underwent a major rehabilitation in 1999, necessitating recalibration of the icing clouds. This report describes the methods used in the recalibration, including the procedure used to establish a uniform icing cloud and the use of a standard icing blade technique for measurement of liquid water content. The instruments and methods used to perform the droplet size calibration are also described. The liquid water content/droplet size operating envelopes of the icing tunnel are shown for a range of airspeeds and compared to the FAA icing certification criteria. The capabilities of the IRT to produce large droplet icing clouds is also detailed.

Introduction

The icing research tunnel (IRT) at NASA Glenn Research Center underwent a major rehabilitation in 1999. The leg upstream of the test section, which contains the heat exchanger, was completely removed.

The reconstruction widened this leg from its former 29 feet to 42 feet to allow a flat-faced heat exchanger adequate space to replace the former "W" shaped heat exchanger, which had been operational since 1944. New aerodynamic turning vanes were installed in the corner between the fan and the heat exchanger. These vanes both turn the flow and also expand the flow from the upstream 29-foot width to the new 42-foot width. New vanes were also installed in the corner between the heat exchanger and the contraction. These vanes contract the flow around the corner back to the 29-foot width. Exit guide vanes were also installed downstream of the fan.

These changes to the tunnel were made for two primary reasons. The first was to improve flow quality in the test section. The second was to replace the heat exchanger which was experiencing increased leak rates after it's more than 50 years of service.

Further description of the changes made during the rehabilitation is contained in reference 1. Evaluations of the flow quality improvements realized by these tunnel modifications are contained in reference 2 and 3.

The changes in the icing tunnel necessitated a recalibration of the icing clouds. The recalibration included: (1) establishment of spray nozzle locations in the spray bars to generate a uniform icing cloud in the test section; (2) measurement of the droplet size distributions and of the liquid water content of these clouds to determine the effects of spray air pressure, water flow rate and tunnel airspeed.

This paper describes the methods used in the recalibration of the icing tunnel and presents the results of these calibrations.

Facility Description

A plan view of the former IRT loop and the new IRT are shown in figure 1. The tunnel is of the closed-loop design. The test section is 9 feet wide, 6 feet high and is approximately 20 feet long. The tunnel fan is powered by a 5000 horsepower electric motor, which can generate maximum airspeeds of almost 350 knots. The tunnel now contains a flat-faced heat exchanger, which allows testing over a temperature range of 40°F to –20°F.

The tunnel water spray system consists of 10 spray bars, which are located in the low-speed section of the tunnel just upstream of the contraction. Each spray bar has positions for up to 55 spray nozzles. Each nozzle location is supplied by two independent water manifolds through individually controllable electrically activated solenoid valves. Two different nozzles are used to increase the LWC range of the tunnel. They are referred to as the Standard and Mod 1 nozzles. They are both of the same air-assist configuration, the only difference being the diameter of the water tubes. The Standard nozzles have a water tube diameter of 0.025 inches; the Mod 1 nozzles have a water tube diameter of 0.0155 inches. The nozzles used in the spray system have matched water flow coefficients to within ± 5 percent.

Purpose of Calibration

Calibration of the icing clouds consists of three parts. The first part is to determine the locations of the spray nozzles and the number of nozzles required to generate as uniform an icing cloud as possible in the tunnel test section. The next two parts are to make measurements of the droplet sizes and liquid water contents (LWC) at many different combinations of spray air and water pressures.

The droplet size and LWC data are used to determine the relationship of these parameters to the spray air and water pressures. During actual icing tests the droplet size and LWC are not measured. Instead, the spray air and water pressures are calculated for the desired droplet size and LWC conditions.

The operating ranges of the tunnel are as follows:

Airspeed: 50 to 300 knots
Air Temperature: Ambient, to −20°F
Spray Air Pressure: 10 to 70 psig
Spray ΔP: 5 to 150 psid (Standard nozzles)
5 to 250 psid (Mod 1 nozzles)

The spray ΔP is the water pressure minus the air pressure. This is the parameter that is used for calculations of droplet size and LWC since the water flow rate is proportional to $\Delta P^{0.5}$.

Icing Cloud Uniformity

The term icing cloud uniformity really refers to the degree of liquid water distribution across the tunnel test section. It is desirable that the liquid water within the cloud be uniformly distributed from wall to wall and from floor to ceiling. However, due to limitations in possible nozzle locations within the spray bar system and variations in airflow (wakes, corner vortices, flow angularity, etc.) the icing cloud generated in a tunnel always has variations. The goal of establishing nozzle locations to in turn establish a uniform cloud is to generate as large a cloud as possible with as little variation as possible. The current criteria for a "uniform" icing cloud is that variations in LWC of ± 20 percent are acceptable.

The first step in trying to establish a uniform icing cloud was to determine where the spray from each area of the spray bars ended up in the test section. A six-foot by six-foot stainless steel grid was place in the test section, centered horizontally within the 9-foot wide test section. The grid, a picture of which is shown in figure 2, has six-inch vertical and horizontal spacing. The tunnel was cooled to 0°F and the airspeed was set to 150 knots. Once the tunnel had stabilized at this temperature and airspeed, water spray was initiated from widely spaced spray bars. Ice was allowed to accrete on the grid for several minutes. The peak of the ice accretion as well as the width of the iced band was then documented.

This test was repeated for all of the spray bars. It was also performed for 16 (vertical) columns of nozzles. It was then repeated for the other set of nozzles.

Figure 3 shows the lines of peak ice accretion on the grid for all spray bars. The dashed lines on this figure are the geometric projections of the spray bar locations into the test section. It can be seen in this figure that the spray along the vertical centerline is compressed toward the center of the tunnel. These patterns are similar to the patterns for the previous heat exchanger configuration.

Figure 4 shows the patterns of icing generated from the nozzle column tests. The dashed lines in this figure are the patterns generated from similar tests with the previous heat exchanger. It can be seen that there is considerably less distortion of the spray columns with the new heat exchanger particularly on the left side (inner wall) of the test section. This decrease in distortion is attributable to the elimination of the small heat exchanger section of the old heat exchanger, which severely distorted the flow.

Following this test a uniform pattern of spray nozzles was installed in the spray bars. The tunnel was stabilized at an airspeed of 150 knots and a temperature of 0°F. All nozzles were activated and ice was allowed to accrete on the grid. The ice thickness was then measured at 6-inch vertical intervals, starting 3 inches from the test section ceiling. These data was then ratioed to the average of two values near the center of the test section and were then used to construct a contour plot of the LWC uniformity. This plot along with the results from the single spray bar/single column tests was used to guide the process of adding or changing nozzle locations to improve the cloud uniformity. Approximately 30 iterations of nozzle position changes an acceptable uniformity pattern was established. The process of optimizing the cloud uniformity involved a considerable amount of trial and error and was very time consuming.

During the process of establishing a uniform icing cloud with the Mod 1 nozzles, it was found that the nozzle spacing was much more regular than the nozzle array used with the former heat exchanger. The flow patterns caused by of the former heat exchanger allowed only one set of nozzles to be installed at a time since many of the same nozzle locations were required by both nozzle sets. Given the more uniform pattern of the Mod 1 nozzles, we decided to see if it was feasible to install both the Mod 1 and Standard nozzles in the spray bars at the same time, each set supplied by its own water manifold.

Based on the Mod 1 nozzle locations, the Standard nozzles were positioned between these locations, with somewhat smaller spacing. After about 20 iterations of changes in some Mod 1 and Standard nozzle positions, the final nozzle positions for both nozzle sets were established. The final nozzle arrays contained 150 Standard nozzles and 102 Mod 1 nozzles.

There is a major benefit to being able to have both nozzle sets installed at the same time. Nozzle change-outs are not required to switch between the two nozzle sets, permitting more flexibility is testing. Also the productivity of the tunnel is improved since nozzles changes took approximately four hours.

Figure 5 shows the contour plot of the LWC for the Standard nozzles at an airspeed of 150 knots. The contour intervals on this plot are in 10 percent bands. The blue area represents values within ± 10 percent of the averaged center values. The green areas are low spots and the red areas are high spots. It can be seen from this plot that the cloud covers the whole grid area and that most of the cloud is within the ± 20 percent allowable tolerance.

Figure 6 shows contour plots of the LWC cloud uniformity of the Mod 1 nozzles for several airspeeds. All of these tests were run at spray bar air pressures of 20 psig. At 100 knots (figure 6(a)) the icing cloud is very uniform over the 4.5-foot vertical by 5-foot wide central region of the test section. At 150 knots (figure 6(b)) more high and low spots are present within this same area. As shown in figures 6(c) and 6(d), the 200 and 250 knot clouds have many scattered high and low spots. These high and low areas are a result of insufficient mixing of the spray from individual spray nozzles, which is exasperated by increasing airspeed. Note that in many cases the LWC transitions from a 20 percent high spot to a 20 percent low spot within a distance of only 6 inches.

A test was run to see how higher nozzle air pressure would effect the cloud mixing. The spray bar air pressure was increased to 40 psig while maintaining the same droplet size. The result of this test is shown in figure 7, where it can be seen that when compared to figure 6(b), mixing of the cloud was greatly improved. Almost the whole central region of the cloud is completely uniform.

For comparison with the new data figure 8 shows an LWC uniformity plot generated before the icing tunnel rehabilitation. The airspeed for this test was 217 knots. When compared to figures 6(c) and 6(d) it can be seen that the high and low spots in the new clouds are much smaller than the rather broad areas of the old cloud. This is again an indication that the spray from individual nozzles is not well mixed.

The experiences with establishing a uniform icing cloud point out a reality of icing tunnel work. Improving aerodynamic characteristics can have an adverse effect on the uniformity of the icing cloud.

Droplet Size Calibration

Two droplet sizing instruments were used in the droplet size calibration of the icing research tunnel. These were the Forward Scattering Spectrometer Probe (FSSP) and the Optical Array Cloud Droplet Spectrometer Probes (OAP). These are aircraft type instruments manufactured by Particle Measuring Systems, Inc. of Boulder, Colorado.

The FSSP[4,5] was used to measure droplets with diameters of 2 to 47 μm. In this instrument a laser beam is used to illuminate single particles as they traverse the sample volume. The intensity of the forward scattered light is measured to determine the particle size. Larger particle have greater intensity. The instrument counts each particle passing through the laser beam and places the count in one of 15 size bins. The nominal bin width for the FSSP is 3 μm. Over time a number versus particle size histogram is obtained. A data analysis program is used to convert the number histogram into a volume histogram and to calculate other characteristics of the droplet distribution such as the median volume diameter.

The OAP[5] was used to measure droplets with diameters of 9.5 to 457.5 μm. This instrument uses a collimated laser beam to illuminate particles creating a shadow, which is magnified and projected onto a linear photodiode array. The number of diodes shadowed determines into which particle size bin the particle will be placed. The diode spacing and the system magnification determine the size definition of each size bin. The nominal bin width for this OAP is 15 μm.

The particle sizing instruments were mounted in the tunnel on the centerline of the test section one at a time. The FSSP is shown in Figure 9. Each spray condition (i.e., air pressure and water pressure) was set and allowed to stabilize before a measurement was started. The sample time used for the FSSP was 50 seconds and the sample time for the OAP was 100 seconds. Measurements were made with the FSSP first for all the spray conditions, which covered the air pressure and water pressure range of the facility. The OAP was then used for those spray conditions where it appeared that the FSSP had not captured the complete droplet size distribution. Approximately 100 test conditions were measured for the Standard nozzles and 150 test conditions were measured for the Mod 1 nozzles.

Data Processing of Droplet Size Distributions

The median volume diameter (MVD) is used to characterize the droplet size distribution. The MVD is defined as the diameter where half of the volume of water is contained in droplets with diameters smaller (or larger) than this diameter. To calculate a meaningful median volume diameter (MVD), it is often necessary to combine the droplet size distributions from more then one instrument. The procedure used to calculate the total volume was to calculate the total volume of the droplets from the FSSP and to add to this the additional volume of the droplets from the OAP that exceed the range of the FSSP. Thus in the overlap size region of the FSSP and OAP the FSSP measurements are used. This provides an effective droplet size range for the OAP of 47 to 457.5 μm. Figure 10 shows an example of the combined distributions from the FSSP and OAP. This distribution is a droplet number distribution versus droplet size that has been normalized by the instruments' bin widths and sample volumes. The square symbols are from the FSSP and the triangle symbols are from the OAP. The two filled triangles are the data from the OAP in the overlap region that are discarded In this example, the two instruments combine to produce a smooth continuous curve from 2 to 300 μm with a large dynamic range in number density of $1e^2$ to $1e^{-5}$.

Figure 11 shows examples of cumulative volume distributions for MVD values from 15 to 40 μm. These curves are generated by calculating the percentage of the total droplet volume contained in each size bin of each instrument and then summing them. It can be seen from these curves that as the MVD increases the droplet size distribution becomes broader. Note that the 40 μm MVD distribution has droplet diameters exceeding 200 μm.

Droplet Size Equations

The MVD data from the droplet size calibrations were fit to an equation for each nozzle type so that the tunnel cloud MVD can be directly calculated for any pair of spray bar air pressure and water pressure settings. These equations are valid over a range of air pressures from 10 to 70 psig; ΔP range of 10 to 150 psid for the Standard nozzles and 10 to 250 psid for the Mod 1 nozzles. The calculation of MVD is valid for MVD values up to 50 μm.

For each nozzle type (Mod 1 and Standard) the MVD data was tabulated as a function of spray bar P_{air} and ΔP. A commercially available software program[6] was used to fit these data using least-squares procedures to a large number of candidate equations. These equations were then ranked based on the root mean square error (MSE). The top several ranked equations were reviewed for both nozzle types in order to select the best equation that could be used for both the Mod 1 and Standard nozzle types. The equation has the following form:

$$MVD = EXP(a + bx + cy + dx^2 + ey^2 + fyx + gx^3 + hy^3 + iy^2x + jyx^2)$$

where x is the natural log of the air pressure in psig, and y is the ΔP in psid. The coefficients a thru j for the Mod 1 and Standard are listed in Table 1. Figures 12 and 13 show these equations plotted as a function of MVD versus ΔP for constant air pressure lines between 10 and 70 psig for the Standard and Mod 1 nozzles.

Liquid Water Content Calibration

A standard icing blade[7] was used to measure the liquid water content in the center of the test section. The blade is made of stainless steel and is 6-inches long, three-fourths of an inch deep and one-eighth of an inch thick. All tests were run at an air temperature of 0°F to insure that the ice that formed on the thin eighth inch face would have minimal width so that the blade collection efficiency would not have to be adjusted.

The collection efficiency, E_b, of the blade was calculated for the full range of airspeeds and droplet sizes used for this testing. The computer code used, the FWG two-dimensional droplet trajectory code,[8] uses a Hess-Smith panel code for the flowfield prediction and a C. W. Gear stiff equation scheme to integrate particle trajectories.

After the tunnel temperature and desired airspeed were stabilized the water spray was turned on at the desired air and water pressure for a predetermined time. The thickness of ice on the blade was measured using a chilled micrometer. The measured ice thickness, exposure time and airspeed were used in the equation below to calculate the liquid water content.

$$LWC = \frac{C \times \rho_{ice} \times \Delta S}{E_b \times V \times t} = \frac{4.34 \times 10^4 \times \Delta S}{E_b \times V \times t}$$

In this equation C is a unit conversion constant, ρ_{ice} is the density of ice which is assumed to be constant (i.e., $\rho_{ice} = 0.88$), ΔS is the thickness of ice in inches, E_b is the blade collection efficiency, V is the free-stream airspeed in knots and t is the spray time in seconds.

The icing blade was used to measure liquid water content values over a range of spray air pressures from 10 to 70 psig, airspeeds from 50 to 300 knots and droplet sizes from 14 to 50 μm. It was known from past experience that the liquid water content calibration is a function of both air pressure and airspeed, that is:

$$LWC = K(f(P_{air}, V) \times \frac{\sqrt{\Delta P}}{V}$$

where ΔP is the spray bar water pressure minus the air pressure and is proportional to the water flow rate.

The first series of tests involved varying the spray bar air pressure while holding the airspeed and droplet size constant. The results of these tests are shown in figure 14 for both nozzle sets. It can be seen from this plot that the liquid water content decreases as the air pressure increases. There are two possible causes for this decrease—droplet freeze-out and evaporation. Droplet freeze-out is caused by the temperature decrease of the compressed air as it undergoes an isentropic expansion at the exit of the nozzles.[9,10] Evaporation of some of the water is also very possible since the air used in the spray system is very dry, having a dew point of approximately –50°F and is heated to a temperature between 165 and 190°F. And since the airflow increases with air pressure an increase in evaporation would be expected with increasing air pressure.

The next series of tests involved varying the airspeed from 50 to 300 knots while holding the air and water pressures and the droplet size constant. Figure 15 shows the results of these tests, where it can be seen that a natural log function generates a reasonable fit to the data.

The effect of droplet size was also investigated, but no significant effects were found within the droplet size (i.e., MVD) range of 14 to 50 μm.

The two equations for "K" generated from the air pressure and airspeed tests were combined to generate the calibration equations for each nozzle set. The final equations are:

Standard Nozzles:

$$LWC = (14.2 \times LnV - 0.30 \times P_{air} - 13.0) \times \frac{\sqrt{\Delta P}}{V}$$

Mod 1 Nozzles:

$$LWC = (4.45 \times LnV - 0.0475 \times P_{air} - 4.8) \times \frac{\sqrt{\Delta P}}{V}$$

Figure 16 shows a comparison of the LWC data taken with the icing blade to the values calculated from the equations above. Almost all of the data is within a ± 10 percent band, indicating a reasonable fit of the data by the equations.

Icing Cloud Operating Range

The results of the liquid water content and droplet size calibrations were combined to establish the operating envelopes of the spray system. Since the liquid water content is a function of airspeed in the tunnel, these operating envelopes are also a function of airspeed.

The goal of any icing tunnel is to be able to duplicate as fully as possible the Federal Aviation Administration (FAA) aircraft icing certification standards contained in FAR Part 25, Appendix C. These icing envelopes are shown in figure 17. The upper envelope is called the maximum intermittent envelope applicable to flight in cumulous clouds while the lower envelope, the continuous maximum envelope, is applicable to flight in stratus-type clouds.

Figure 18 shows the capabilities of the IRT at an airspeed of 100 knots compared to the FAA icing criteria. The figure illustrates that the IRT has the capability to cover much of the higher LWC conditions of the intermittent maximum envelope at the smaller droplet size end but does a poor job of covering the lower LWC range of the intermittent maximum envelope at droplet sizes above 35 μm. The IRT at this speed can duplicate very little of the continuos maximum envelope.

Figure 19 shows the capabilities of the IRT at an airspeed of 300 knots. At this airspeed it can be seen that the IRT does a better job of duplicating the lower LWC values of the continuous maximum envelope but cannot duplicate the higher LWC values at smaller droplet sizes of the intermittent maximum criteria.

The number of nozzles in the spray bars could be adjusted to expand the amount of overlap between the tunnel capabilities and the FAA criteria. However, any changes in the nozzle array would require additional liquid water content calibrations. Substantial changes in the number of nozzles could have a detrimental effect on the cloud uniformity. The number of different nozzle arrays must also be balanced against the impact of the productivity of the tunnel.

Another possible approach of increasing the amount of overlap between tunnel capability and the FAA criteria is to use a different type of spray nozzle. However, no nozzle that is clearly superior to the NASA nozzles has been found.

Large Droplet Icing Clouds

The crash of an ATR-72 at Roselawn, Indiana in 1994 initiated a lot of interest in icing clouds not normally considered in aircraft icing certification. These include freezing drizzle and freezing rain. Customers have requested NASA to generate icing clouds with much larger droplets than previously required. In response to customer demand, and lacking guidance from the FAA, a small number of large droplet conditions were established in the IRT.

The calibration methods for these conditions were similar to those already described for the "normal" icing conditions. The LWC of these large droplet clouds was measured using a 1.5-inch diameter rotating cylinder instead of the icing blade. It was felt that large droplets might splash off the surface of the blade, resulting in an under-estimation of the true LWC, and that this was much more unlikely with a the rotating cylinder.

Also an additional droplet-sizing instrument was used. The operation of this instrument is the same as the OAP previously described but measures droplets with diameters from 50 to 1500μm.

Table 2 lists the large droplet conditions calibrated in the IRT. Five large droplet conditions have been established. The cloud uniformity and LWC were determined for these 5 conditions at 3 airspeeds. It can be seen from this table that as the airspeed is increased the LWC decreases as expected. The cloud size also decreases with increasing airspeed.

Figure 20 shows a contour plot of the cloud uniformity of the 120 μm cloud at 200 knots. Note that the scale for this plot differs from the contour plots previously shown. The scale for this plot is in intervals of 20 percent, not 10 percent as previously used. It can be seen from this plot that there exists a reasonably uniform area around the center of the test section with an approximate size of 4-feet high by 2.7-feet wide.

The droplet size distributions, in the form of cumulative percent LWC curves, are shown in figure 21. These curves indicate the very wide range of droplet diameters that exit in these distributions. Note that the maximum droplet diameters in these distributions are approaching 1000 μm or 1 mm.

Conclusions

A complete calibration of the IRT was performed following the rehabilitation of the leg between the fan and the test section. This calibration included establishing nozzle locations to optimize the icing cloud uniformity and performing extensive droplet size and LWC measurements to generate a calibration relating these measurements to the spray air and water pressures.

It was shown that, although the flow qualities of the tunnel were greatly improved, the uniformity of the icing clouds did not show similar improvement and may have been degraded somewhat as a result of reduced mixing.

A major advancement in tunnel capabilities was attained as a result of the improved flow qualities. Both the Standard and Mod 1 nozzles are now installed in the spray bars at the same time, each set operated off separate water manifolds. This results in much more flexibility in running icing tests and increases the productivity of the facility.

The large droplet icing capabilities of the IRT were documented through measurement of the cloud uniformity, droplet sizes and LWC values at several airspeeds. It was shown that some very large droplets, on the order of almost 1000 μm, can be generated and delivered to the test section, although the uniform cloud shrinks with increasing droplet size and airspeed.

Recommendations

Methods of increasing the amount of mixing of the icing sprays to improve the LWC uniformity in the test section at high airspeeds and low spray air pressures should be investigated. A method to generate more mixing without adversely affecting the maximum airspeed of the tunnel is desired.

Methods of increasing the LWC/MVD coverage of the FAA icing test criteria contained in FAR Part 25 Appendix C should be investigated. This should include considering the use of other types of spray nozzles.

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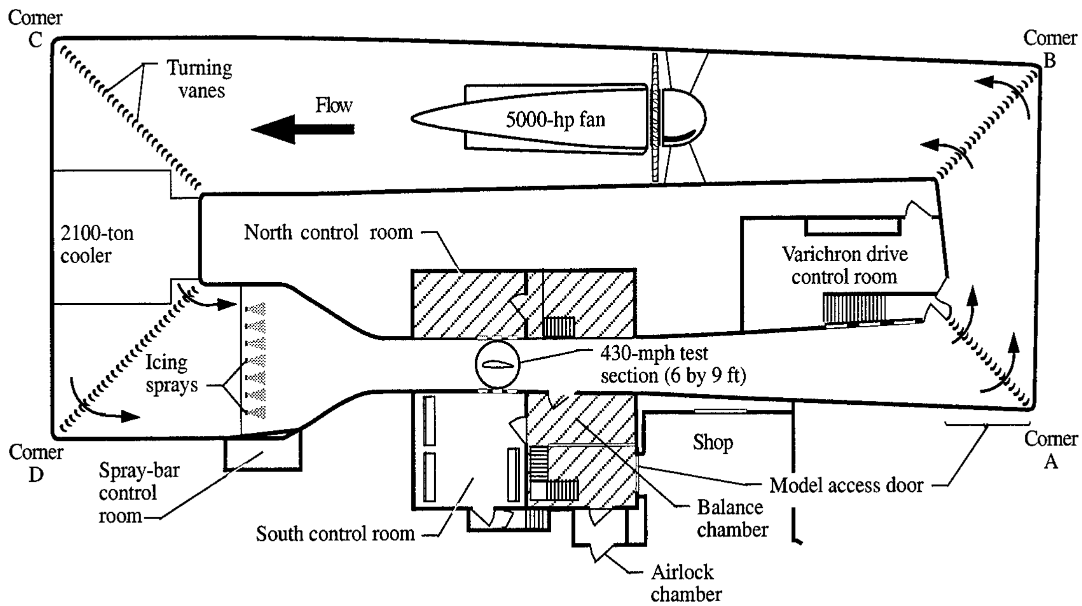
Table 1.—Values for coefficients in droplet size equations.

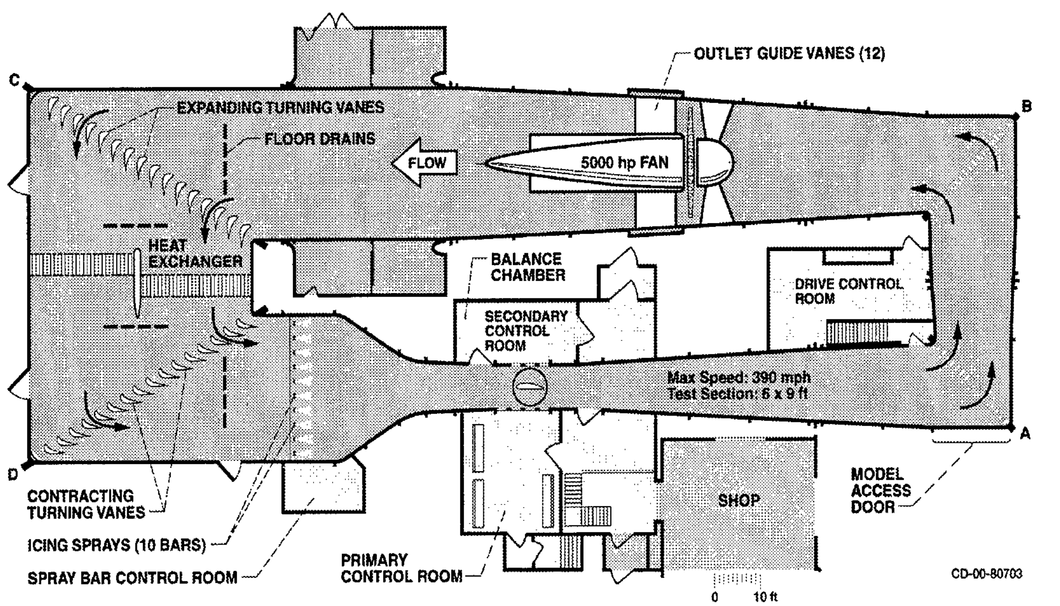
COEFFICIENT	MOD 1 NOZZLES	STANDARD NOZZLES
a	8.748044966	15.86986874
b	–5.758889866	–13.19240311
c	0.138821237	0.972293768
d	1.698096143	4.129785202
e	4.86192E-05	0.001586357
f	–0.067544202	–0.49291007
g	–0.165992209	–0.416788168
h	8.85362E-08	1.70613E-07
I	–2.14547E-05	–3.86283E-04
j	0.008648964	0.062787444

Table 2.—Super-cooled large droplet test conditions.

AIRSPEED [kts]	MVD [um]	LWC (+6 in)	LWC center	LWC (-6 in)	LWC (AVERAGE)	CLOUD SIZE H x W (ft)
100	70	0.86	0.84	0.80	0.84	4.8 x 5.5
100	100	0.95	1.01	0.92	0.96	4.2 x 5.5
100	120	0.98	1.08	0.97	1.01	4.2 x 5.3
100	175	1.52	1.76	1.76	1.68	4.0 x 5.2
100	270	0.99	1.46	1.46	1.30	2.8 x 4.5
150	70	0.63	0.60	0.57	0.60	4.5 x 4.5
150	100	0.67	0.69	0.67	0.68	4.3 x 3.5
150	120	0.65	0.70	0.72	0.69	4.3 x 3.5
150	175	0.96	1.01	1.01	0.99	4.0 x 3.0
150	270	0.87	0.97	0.97	0.94	2.5 x 2.3
200	70	0.43	0.45	0.37	0.42	4.5 x 2.5
200	100	0.47	0.50	0.40	0.46	4.3 x 2.5
200	120	0.46	0.50	0.42	0.46	4.0 x 2.7
200	175	0.63	0.65	0.55	0.61	3.5 x 2.7
200	270	0.45	0.55	0.37	0.46	3.0 x 3.0



(a) Icing tunnel loop before rehabilitation.



(b) Icing tunnel loop after rehabilitation.

Figure 1.—Illustrations of the NASA Glenn icing research tunnel before and after the recent rehabilitation.

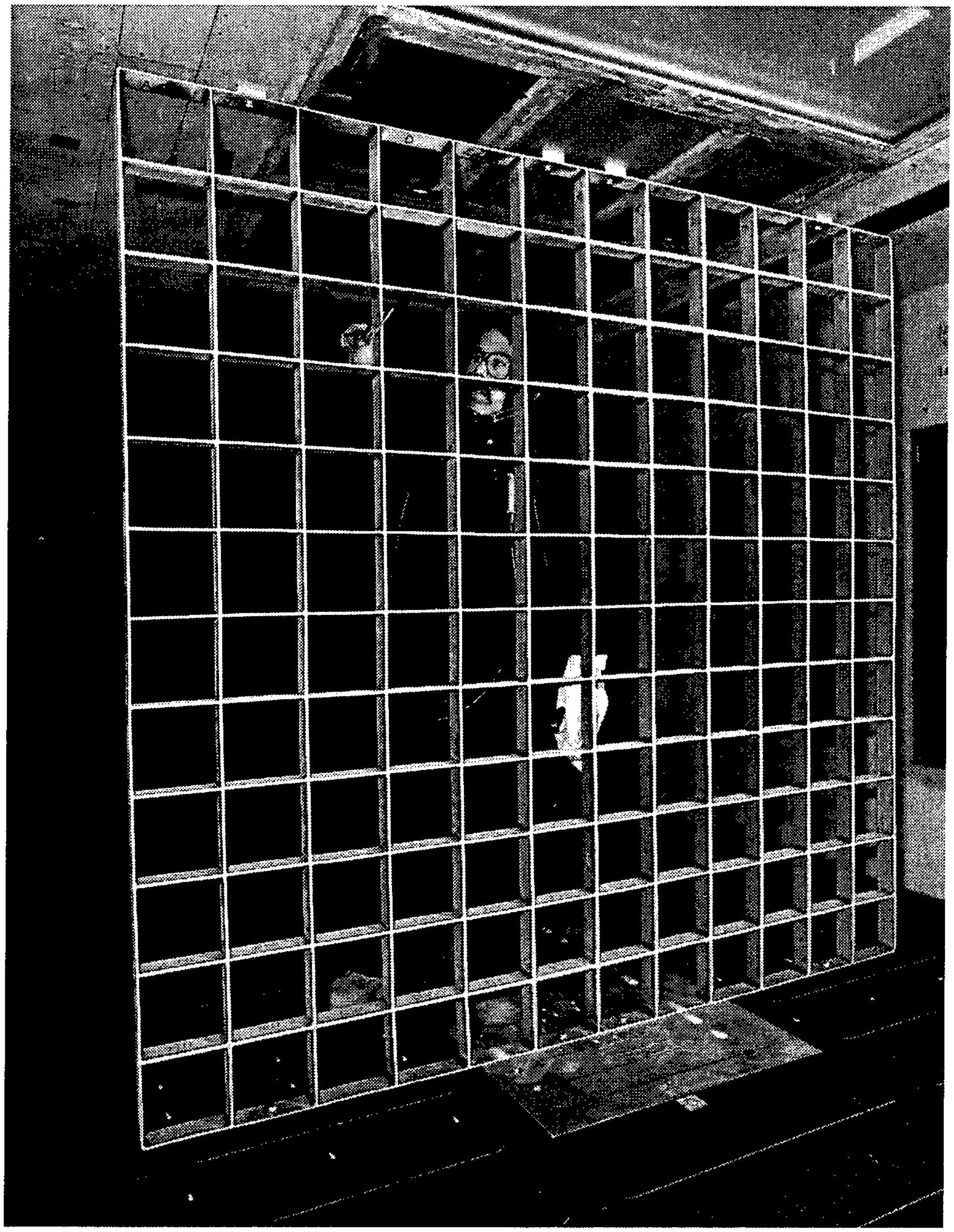


Figure 2.—The icing grid used for cloud uniformity measurement.

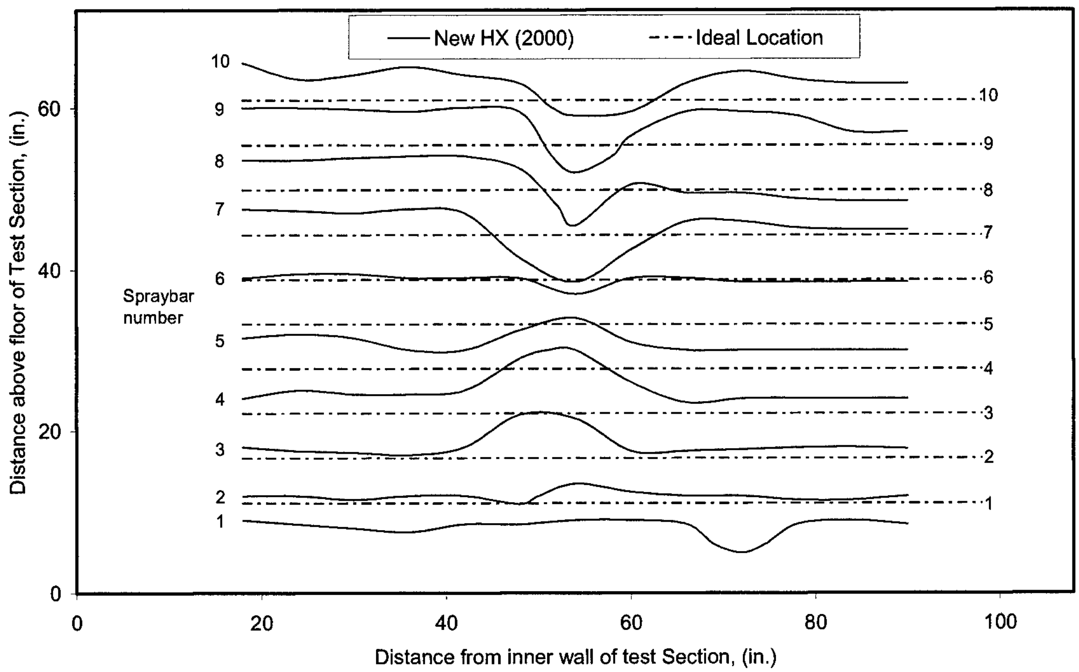


Figure 3.—Results from single spray bar test showing where the peak ice accretion occurs compared to the geometric projection of the spray bar locations into the test section.

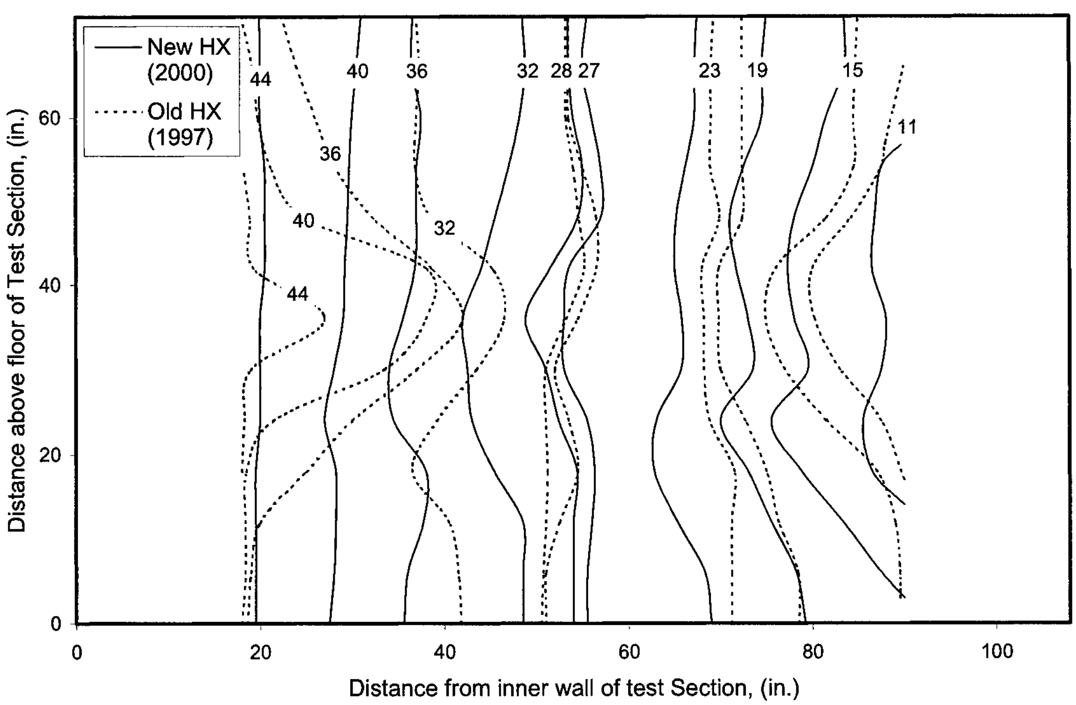


Figure 4.—Results from single columns of spray nozzles showing where the peak ice accretion occurs compared to a similar test with the previous heat exchanger.

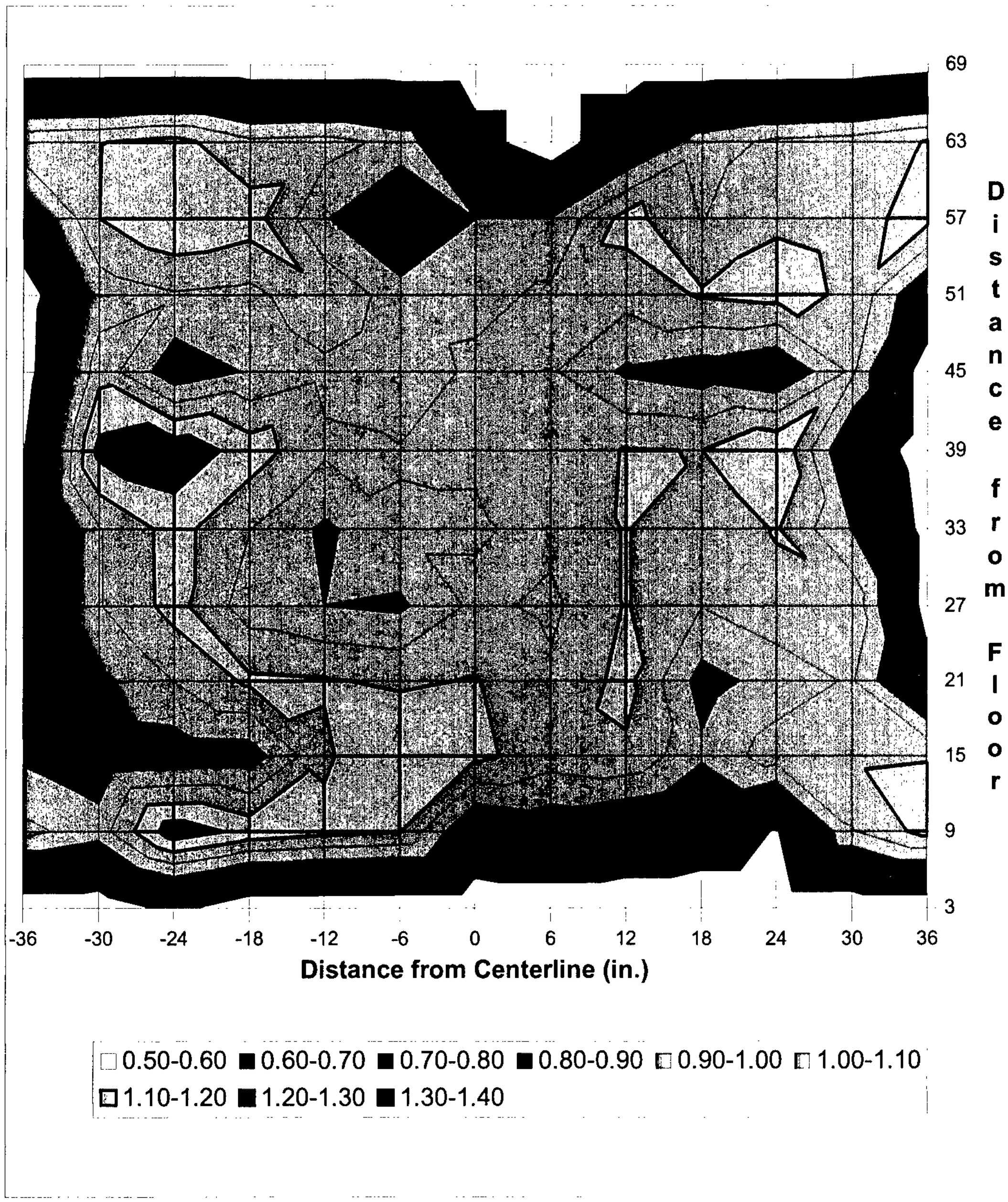
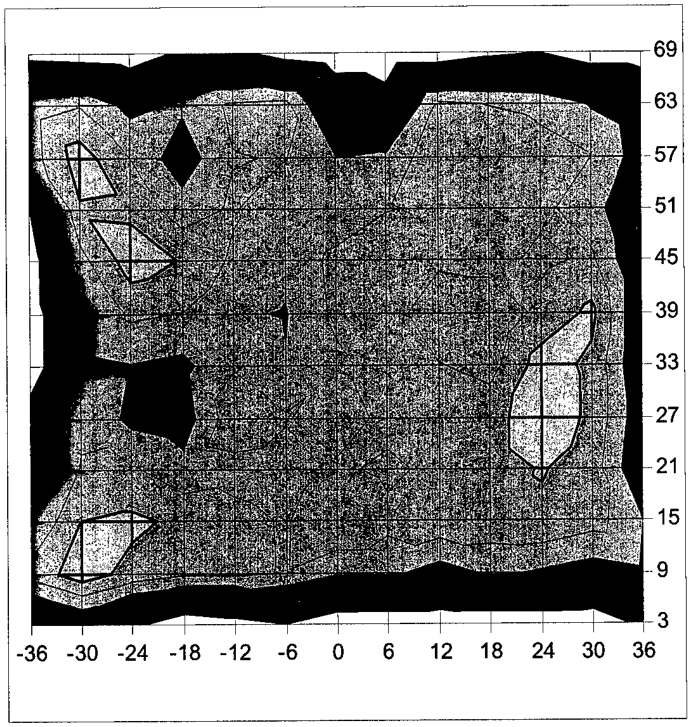
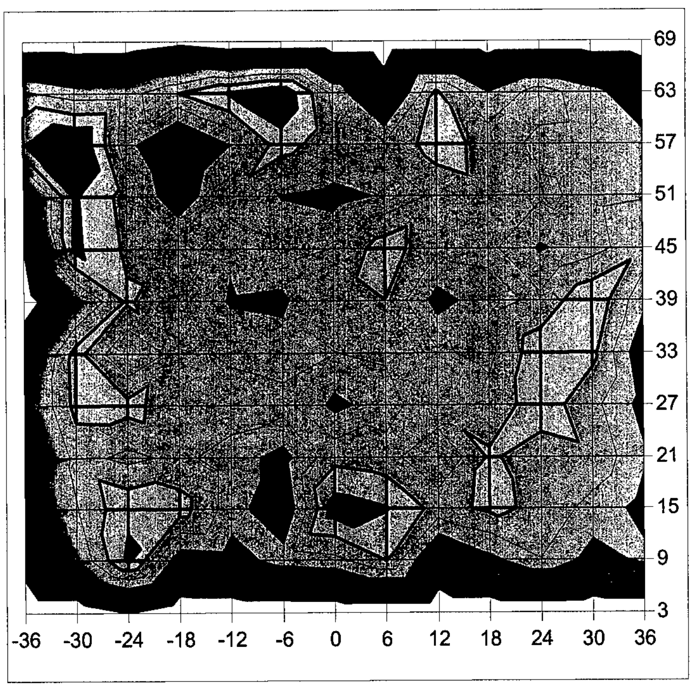


Figure 5.—LWC uniformity contour plot for the Standard nozzles. Airspeed = 150 knots, MVD = 21 um, nozzle air pressure = 20 psig. The legend and axis titles apply to all plots in figures 6 through 8.

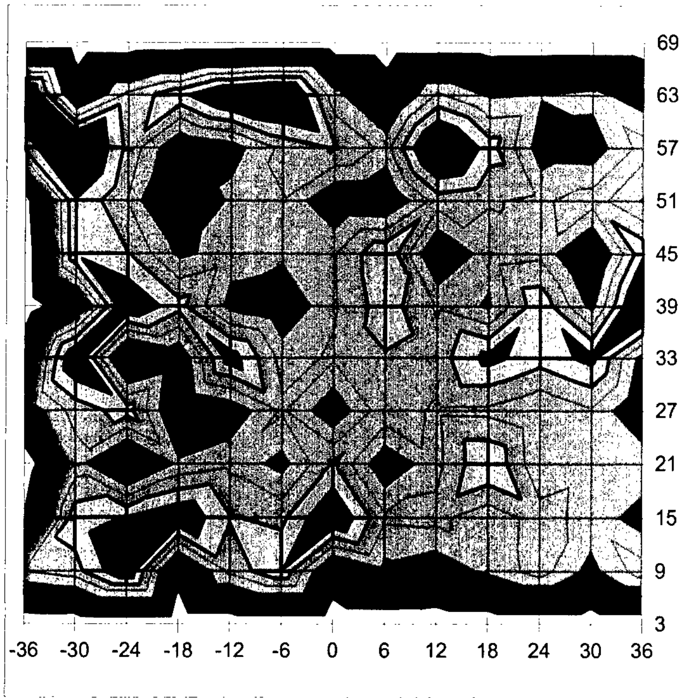


(a) Airspeed = 100 knots

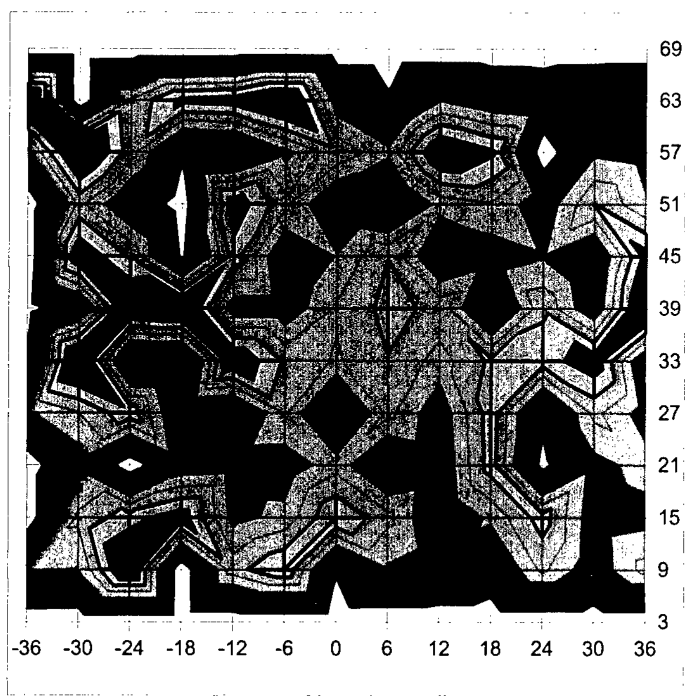


(b) Airspeed = 150 knots

Figure 6.—Mod 1 nozzle LWC uniformity plots for airspeeds of 100, 150, 200 and 250 knots. MVD=21 um, nozzle air pressure=20 psig.



(c) Airspeed = 200 knots



(d) Airspeed = 250 knots

Figure 6.—Concluded.

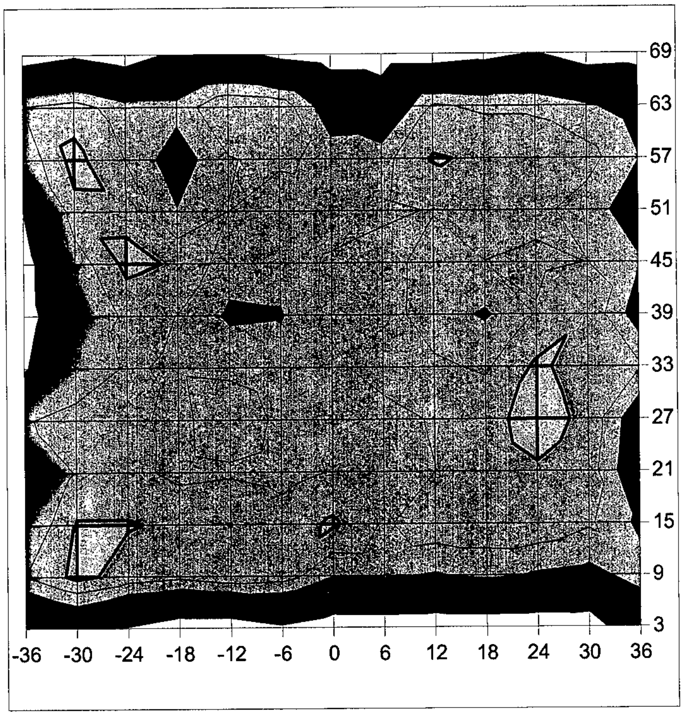


Figure 7.—Mod 1 nozzle LWC uniformity plot for a nozzle air pressure of 40 psig.
Airspeed = 150 knots, MVD=21 um.

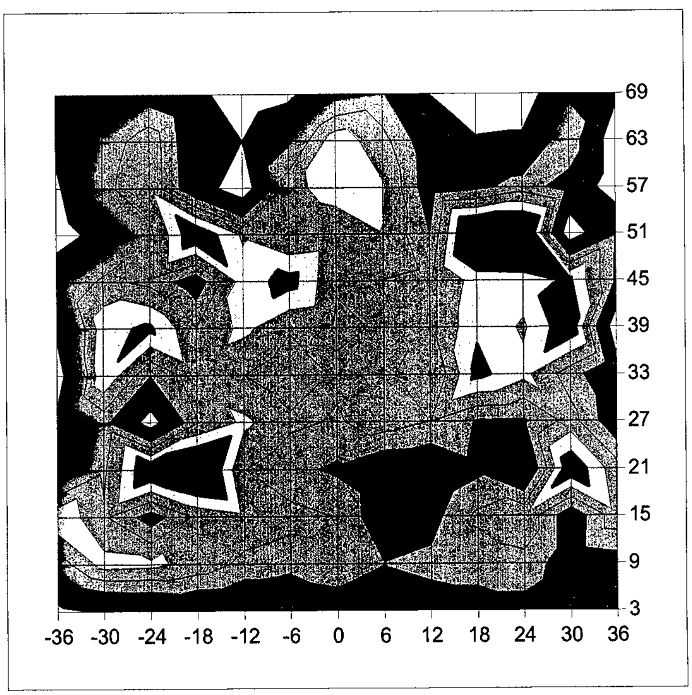


Figure 8.—Mod 1 nozzle LWC uniformity plot from before the tunnel rehabilitation.
Airspeed = 217 knots, MVD=21 um, air pressure = 20 psig.

Figure 9.—Picture of the FSSP droplet sizing instrument mounted in the test section of the IRT.

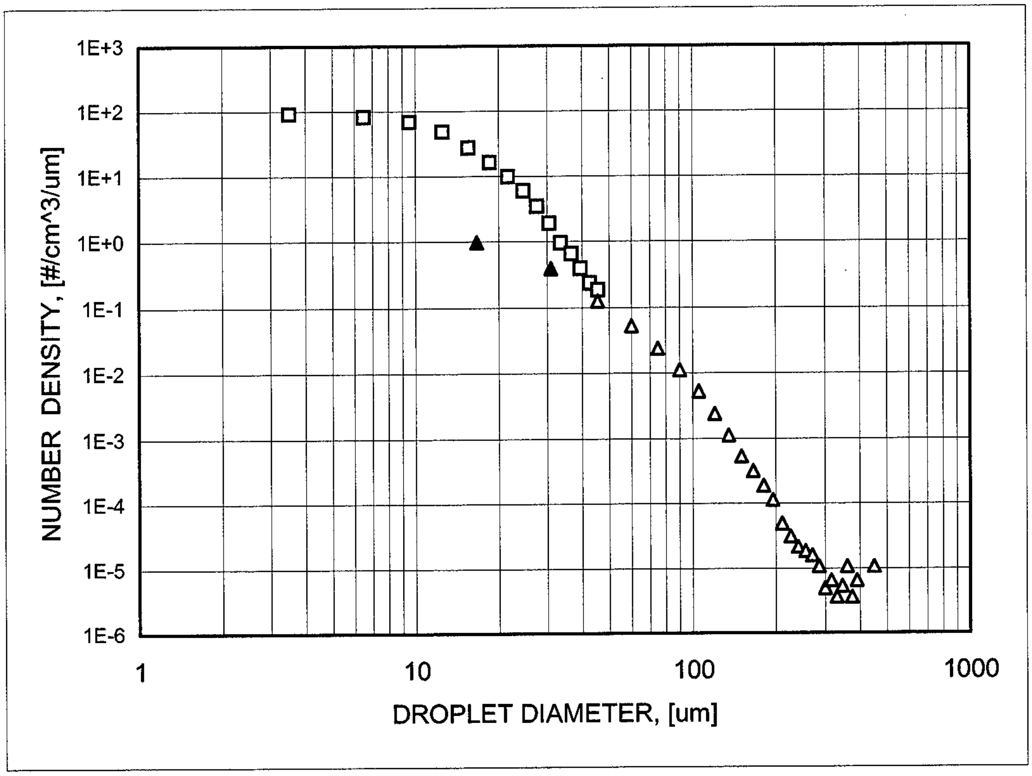


Figure 10.—Number density drop distribution measured by the FSSP and OAP. MVD = 25 μm.

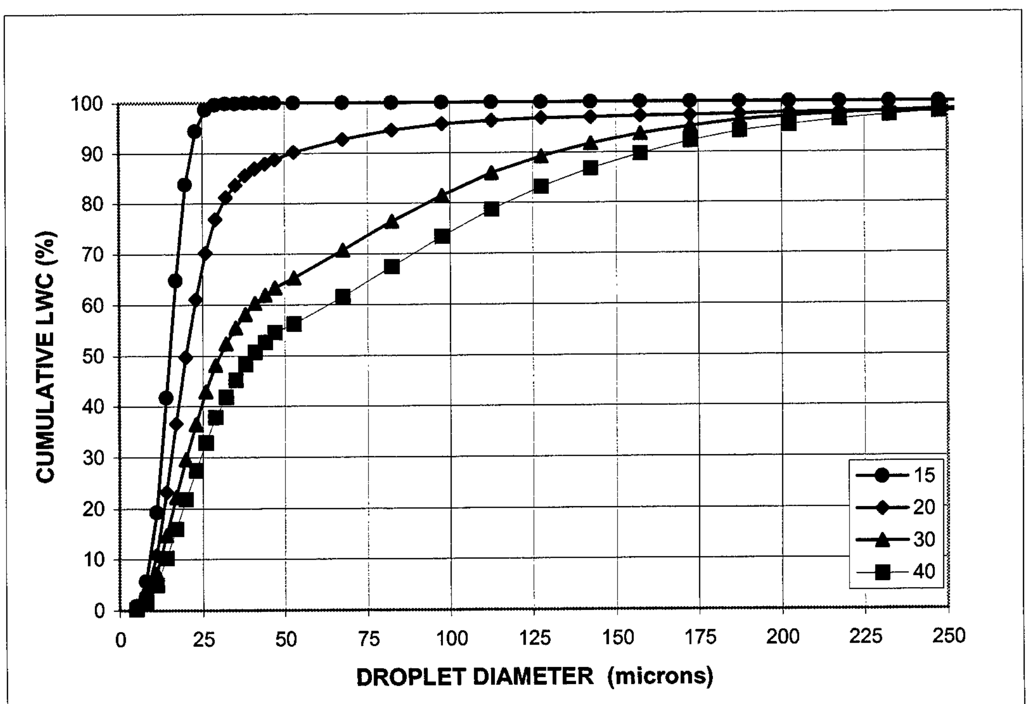


Figure 11.—Cumulative percent LWC droplet distributions for MVD values of 15, 20 30 and 40 μm. These distributions are from measurements of the Mod 1 nozzles.

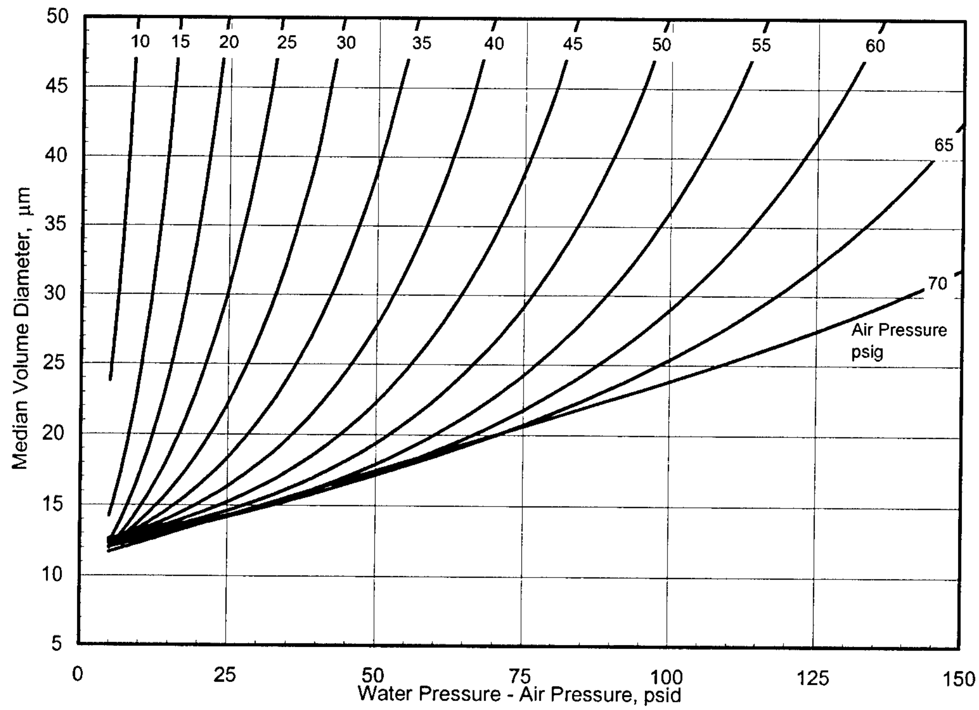


Figure 12.—The droplet size calibration curves for the Standard nozzles plotted as MVD versus ΔP for the complete range of air pressures.

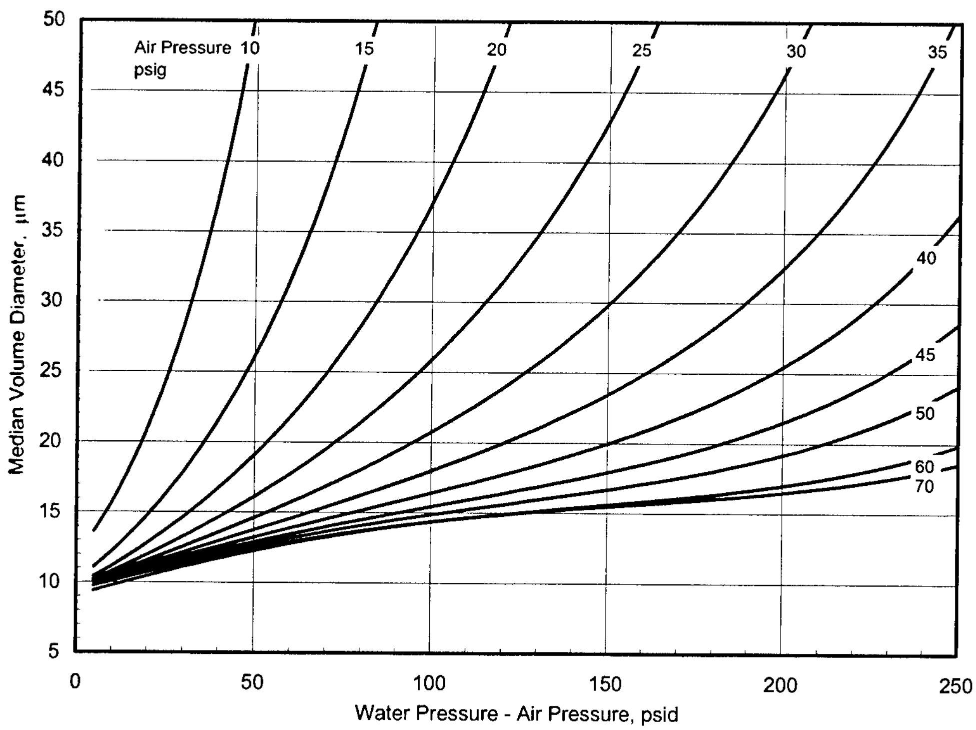


Figure 13.—The droplet size calibration curves for the Mod 1 nozzles plotted as MVD versus ΔP for the complete range of air pressures.

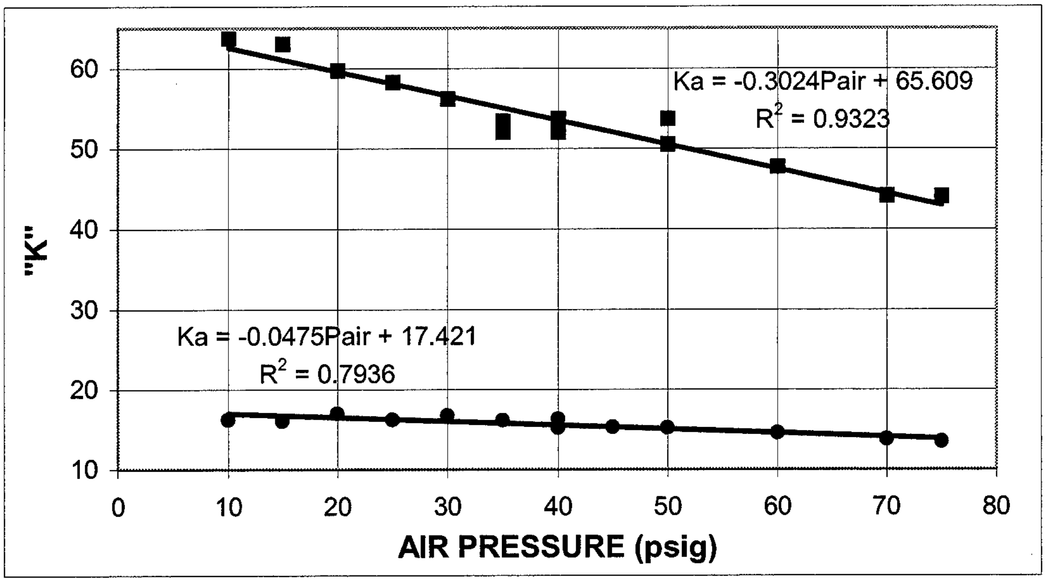


Figure 14.—Effect of nozzle air pressure on "K" for the Standard (upper curve) and Mod 1 (lower curve) nozzles.

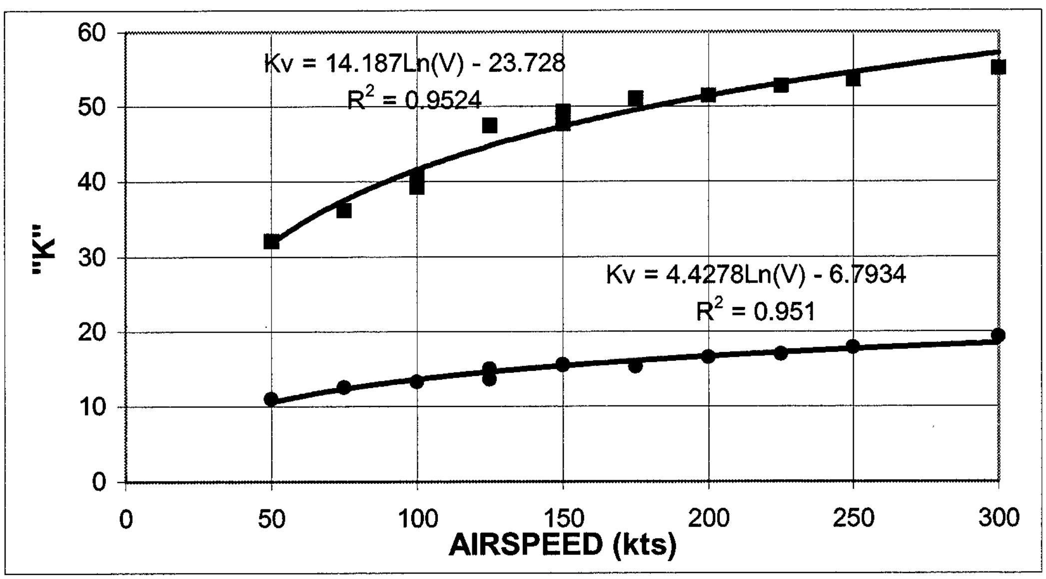


Figure 15.—Effect of tunnel airspeed on "K" for the Standard (upper curve) and Mod 1 (lower curve) nozzles.

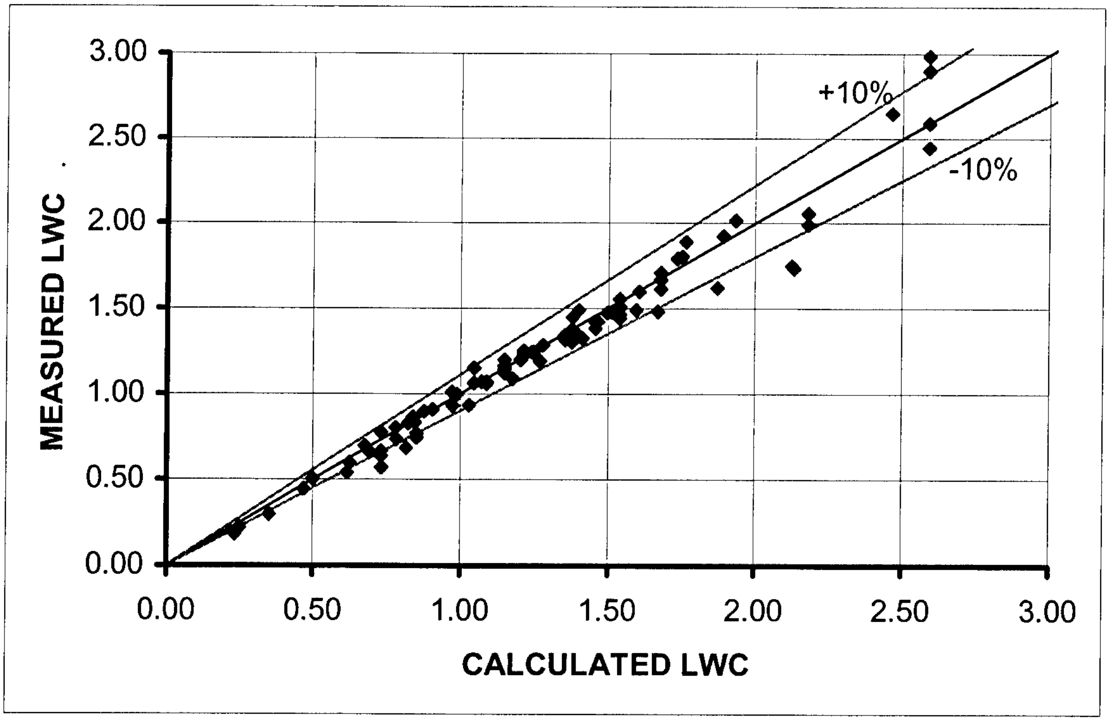


Figure 16.—A comparison of the LWC measured by the icing blade to the LWC calculated from the calibration equations.

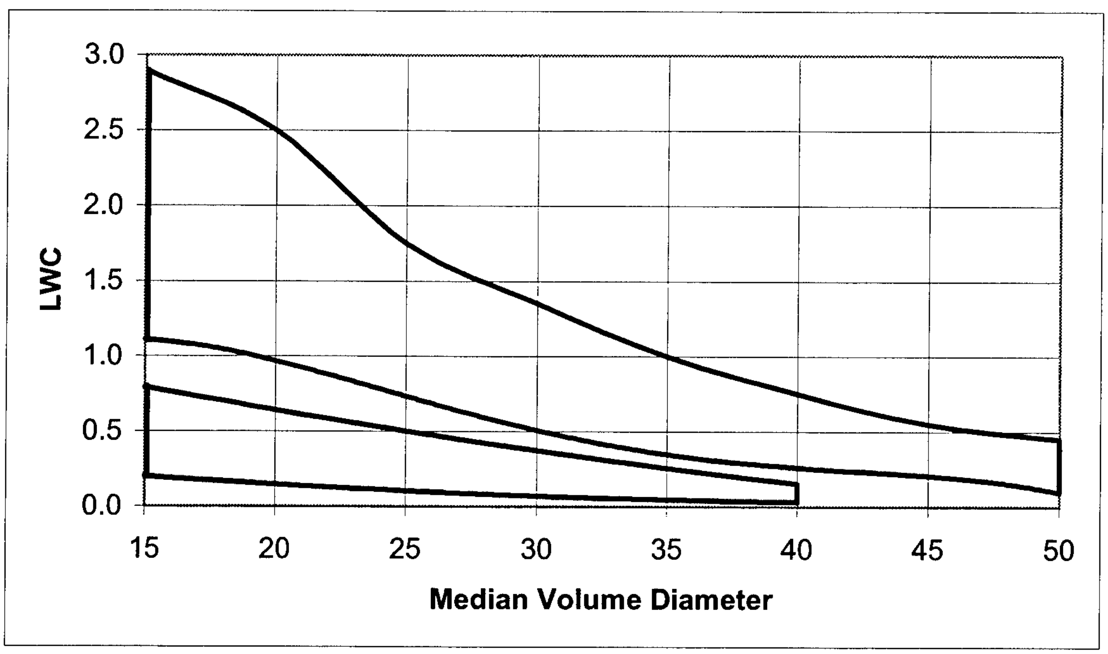


Figure 17.—The LWC/MVD icing certification criteria from FAA FAR Part 25, Appendix C.

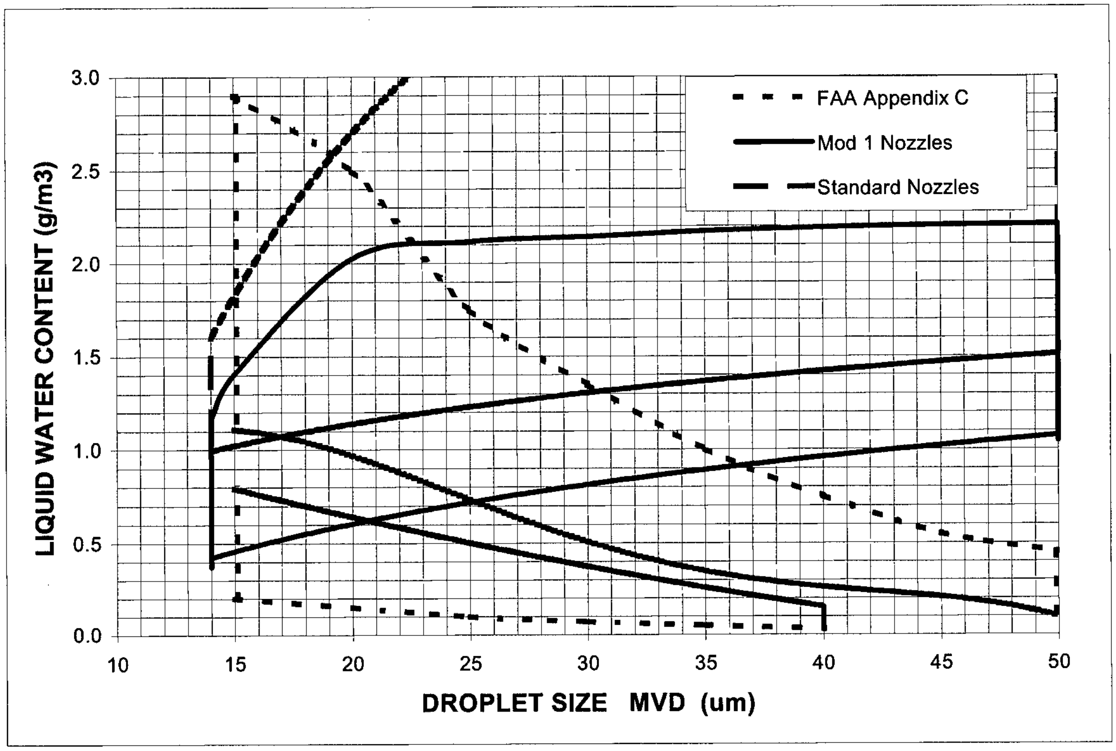


Figure 18.—Comparison of the LWC/MVD operating envelopes for the IRT to the FAA icing certification criteria for an airspeed of 100 knots.

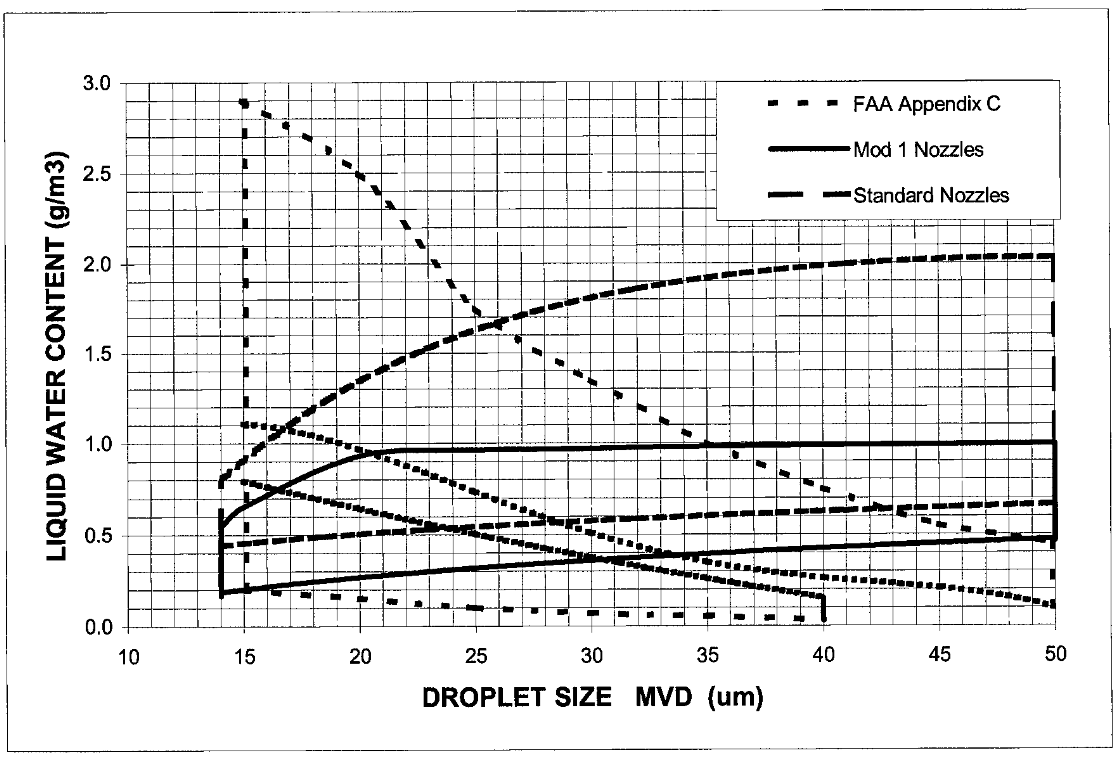


Figure 19.—Comparison of the LWC/MVD operating envelopes for the IRT to the FAA icing certification criteria for an airspeed of 300 knots.

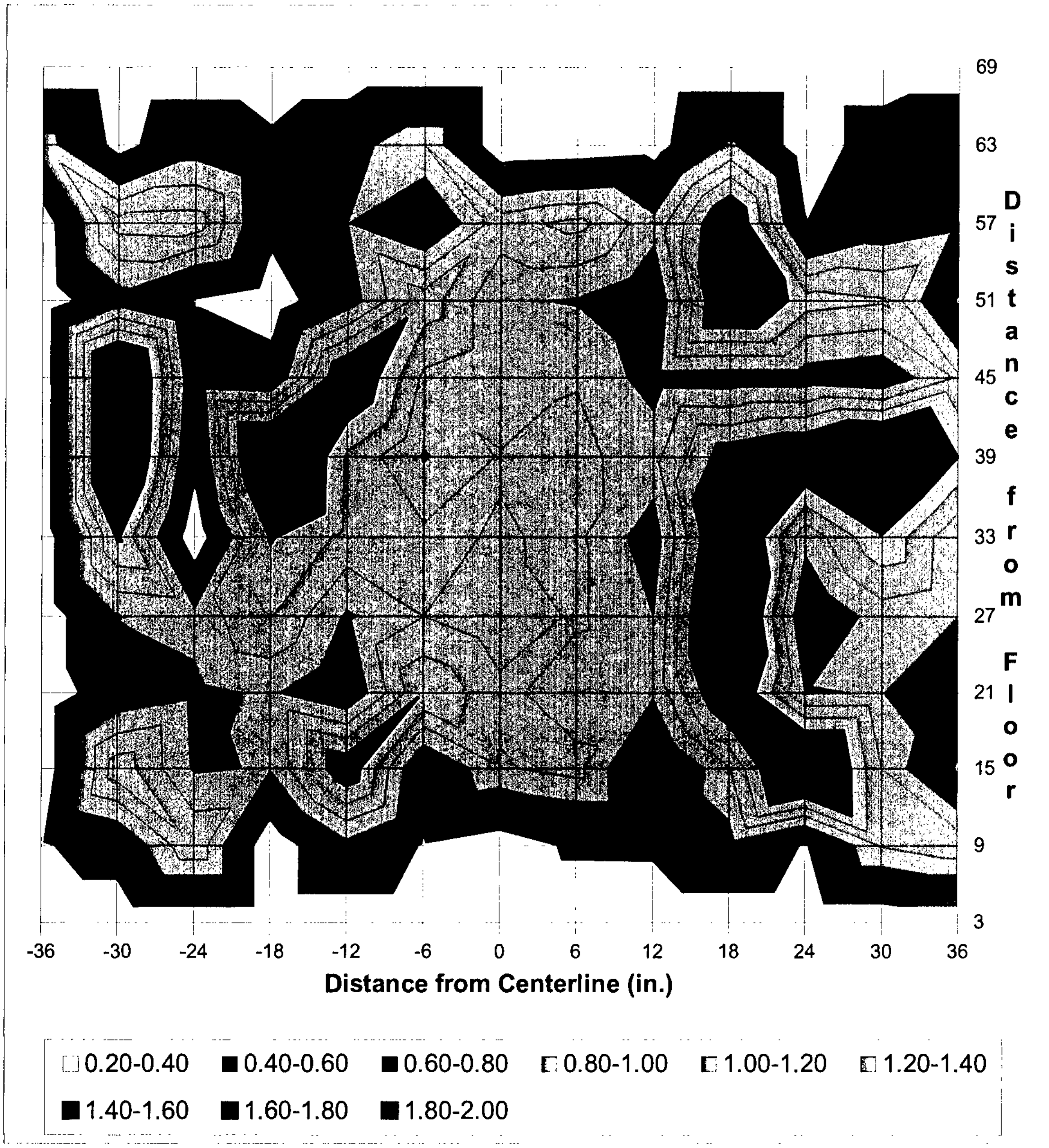


Figure 20.—The LWC uniformity contour plot for an MVD of 120 μm and an airspeed of 200 knots.

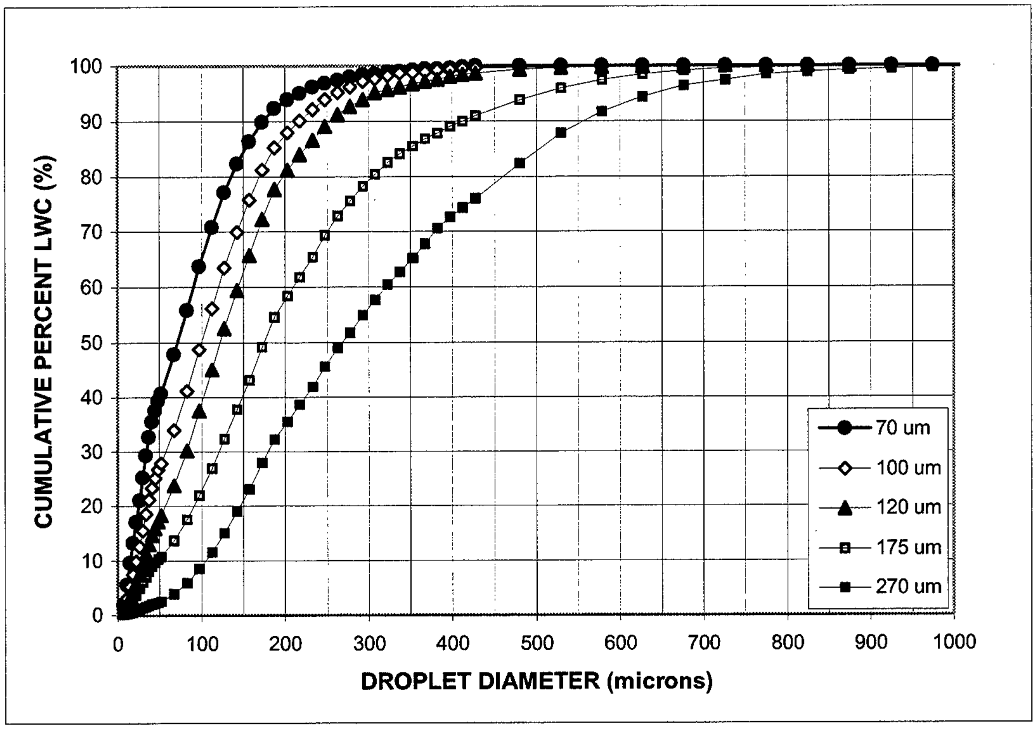


Figure 21.—Cumulative percent LWC distributions for the large droplet test conditions of the IRT.

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13. ABSTRACT ***(Maximum 200 words)***

The icing research tunnel at the NASA Glenn Research Center underwent a major rehabilitation in 1999, necessitating recalibration of the icing clouds. This report describes the methods used in the recalibration, including the procedure used to establish a uniform icing cloud and the use of a standard icing blade technique for measurement of liquid water content. The instruments and methods used to perform the droplet size calibration are also described. The liquid water content/droplet size operating envelopes of the icing tunnel are shown for a range of airspeeds and compared to the FAA icing certification criteria. The capabilities of the IRT to produce large droplet icing clouds is also detailed.

14. SUBJECT TERMS
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