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New Icing Cloud Simulation System at the NASA Glenn Research Center Icing Research Tunnel

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SUMMARY

A new spray bar system was designed, fabricated, and installed in the NASA Glenn Research Center's Icing Research Tunnel (IRT). This system is key to the IRT's ability to do aircraft in-flight icing cloud simulation. The performance goals and requirements levied on the design of the new spray bar system included increased size of the uniform icing cloud in the IRT test section, faster system response time, and increased coverage of icing conditions as defined in Appendix C of the Federal Aviation Regulation (FAR), Part 25 and Part 29. Through significant changes to the mechanical and electrical designs of the previous-generation spray bar system, the performance goals and requirements were realized. Postinstallation aerodynamic and icing cloud calibrations were performed to quantify the changes and improvements made to the IRT test section flow quality and icing cloud characteristics. The new and improved capability to simulate aircraft encounters with in-flight icing clouds ensures that the IRT will continue to provide a satisfactory icing ground-test simulation method to the aeronautics community.

INTRODUCTION

A new icing cloud simulation system, or spray bar system, was designed and installed in the Icing Research Tunnel (IRT) at the NASA Glenn Research Center. The spray bar system creates an artificial icing cloud by injecting microscopic droplets of water into the wind tunnel airstream just upstream of the test section. The previous spray bar system had limited ability to control important IRT performance characteristics, such as the size and shape of the test section icing cloud. The response time of the old system was also limited in terms of achieving steady-state spray conditions. The performance goals set for the new spray bar system were increased size of the uniform icing cloud, faster system response time, and expanded coverage of icing conditions as defined in Appendix C of the Federal Aviation Regulation (FAR), Part 25 and Part 29. To meet the technical requirements and performance-related goals, the spray bar system, including the spray bars and the supporting mechanical and electrical systems, were replaced in their entirety. The design team did not use any analytical tools to perform flow solution and/or droplet trajectory studies of candidate improvements and designs. Instead, relying upon empirical data from the old system, they concluded that the addition of two spray bars, bringing the number in the system to 10, would result in a larger test section icing cloud. The two additional spray bars are located within 4 ft of the IRT settling chamber ceiling and floor, which is 2 ft closer than in the old system.

The spray bar control system was tuned and settling times required to achieve steady-state conditions are an order of magnitude less than those of the previous system.

The calibration of the test section aerodynamics and icing cloud was completed following installation of the new spray bar system. The results of the aerodynamic calibration indicate that the flow quality in the IRT test section is approximately the same as that previously recorded. A decrease of approximately 0.5 percent in the turbulence intensity was measured and is attributed to the aerodynamically shaped cover fairings of the spray bars. The previous spray bar system had a uniform icing cloud that was approximately 30 percent of the test section cross-sectional area whereas that of the new system covers greater than 60 percent.

The goal to expand coverage of icing conditions as defined in Appendix C of the FAR, Parts 25 and 29 included the capability to cycle between continuous maximum and intermittent maximum icing conditions, but this capability was not fully realized because of hardware and time constraints.

GOALS AND REQUIREMENTS

The performance goals of the IRT new spray bar system were increased size of the uniform icing cloud passing through the IRT test section, faster system response time, and expanded coverage of icing conditions as defined in Appendix C of FAR, Parts 25 and 29, which included the capability to cycle between continuous maximum and intermittent maximum conditions as defined therein.

The performance and design requirements of a spray bar system for an icing ground simulation test facility were well documented by Bartlett (ref. 1). Key performance requirements include the ability of the spray bar system to create a cloud of liquid water content and droplet diameter distribution consistent with icing conditions as defined in Appendix C of FAR, Parts 25 and 29 and to do so while achieving the desired icing cloud spatial uniformity. Key design requirements include flow rates and pressures of water and air systems, spacing of spray nozzles, geometry of the spray bar, and freeze protection.

For this project, it was necessary to distinguish between requirements and goals. Requirements were levied on the spray bar electrical and mechanical designs when meeting the requirement was a function only of the spray bar design and/or operation. Goals were established for performance parameters when the spray bar system performance and the performance of another IRT system both had a first-order effect upon achieving the stated goal.

The key design requirements for the spray bar physical and functional characteristics, including air and water system temperatures, pressures, and flow rates, are listed in table I.

FACILITY DESCRIPTION

The Icing Research Tunnel is the world's largest refrigerated low-speed wind tunnel dedicated to the study of aircraft in-flight icing phenomena (ref. 2). Icing conditions encountered by aircraft are duplicated by controlling liquid water content (LWC), droplet size, and air temperature in the wind tunnel. The IRT refrigeration plant and spray bar system combine with the low-speed wind tunnel to generate a cloud of supercooled microscopic water droplets. The new spray bar system recently installed in the IRT's settling chamber is the subject of this report (fig. 1).

The IRT is a closed-loop, atmospheric, low-speed wind tunnel. The test section is 6 ft high, 9 ft wide, and 20 ft long. The air velocity in the empty test section can be controlled from 43.4 to 373.4 kn. Model blockage and the model assembly drag coefficient can significantly reduce the maximum airspeed. The tunnel circuit operates at or below atmospheric pressure and the test section total temperature range for chilled air is controlled between –22 and +33 °F. The tunnel temperature is determined arithmetically by averaging measurements from the 11 thermocouples mounted on the turning vanes just downstream of the heat exchanger.

SPRAY BAR SYSTEM

Mechanical Design

The previous 8-spray-bar system was replaced with a 10-spray-bar system in the wind tunnel settling chamber (insert of fig. 1). The settling chamber dimensions are 29.17 ft wide by 26.17 ft high. The spray bars span the width of the settling chamber and are each equally spaced (2 ft apart) centerline to centerline. The spray bars together are spaced about the heightwise midspan (horizontal centerline) so that bars 5 and 6 are equidistant from that centerline. Water nozzle holders are spaced every 6 in. on each bar, a total of 54 possible water nozzle locations per bar. The first and last water nozzle locations on each bar are 12 in. from the settling chamber sidewalls. Each nozzle holder is connected to one air line and two water lines. The water line headers are plumbed to the nozzle holders via flex hoses. Isolation between the header and nozzle holder is via a solenoid valve. The two water headers installed in each spray bar are required to provide the different water pressures necessary to cycle between continuous maximum and intermittent maximum icing conditions.

The construction is identical for each of the 10 spray bars. They are fixed on the south tunnel sidewall and are free on the north sidewall to minimize induced stresses from thermal expansion and contraction. At the center point (midspan), the spray bars are supported by an aerodynamically shaped column, which is an NACA 0024 airfoil section with a chord dimension of 12.525 in. The selection of an aerodynamic shape for the spray bar was based upon Boeing's experience in the Boeing Research Aerodynamic Icing Tunnel (BRAIT, ref. 3). The flow quality in the

BRAIT compared favorably with that of the IRT with the old spray bar system, indicating successful operation with the aerodynamically shaped spray bars. The new spray bar in the IRT is a modified NACA 0024 airfoil shape. Modification was necessary to accommodate the air line, two water supply and return lines, solenoid valves at each water supply to nozzle holder location, steam lines, and electrical wiring. The spray bar chord length is 19.4 in. and the chord thickness is 5.68 in. Figure 2 shows a schematic of the spray bar system showing the internal components to be described next.

The construction of the spray bars is as follows. All metal structural and nonstructural components are made from anodized aluminum to maximize useful life. The main structure, or spar, of the spray bar is a D-shaped leading edge. The secondary support is a trailing edge that houses the nozzle block assembly, the holder for the water spray nozzle. The leading and trailing edges are connected via ribs with 2 ft between adjacent ribs. Aluminum skin covers the spray bar assembly to complete the airfoil shape. The spray bar structural members were sized for a live load of 250 lb as might occur during maintenance activities.

Located inside the leading edge spar, the air manifold is a 2.5-in. stainless-steel tube sized for flowing air to 25 of the possible 54 nozzles per bar at a maximum pressure of 80 psig. The pressure drop across the entire length of the air manifold is less than 1 psi. The two water manifolds are located in the center area of the spray bar. Each manifold is a 1-in. stainless-steel tube sized for flowing water to 18 of the possible 54 nozzles at a maximum pressure of 230 psig. The pressure drop across the entire length of the manifold is less than 1 psi.

The spray bar freeze protection is via 3/8-in., stainless-steel-tube steam lines that are charged when air and water are not flowing through them. The steam pressure is maintained at 20 psig and is turned on when the temperature inside the spray bar drops below 40 °F. In addition to the freeze protection provided by the internal steam lines, 0.5-in.-thick, closed-cell foam insulation is attached to the inside of the spray bar skins. The heated airline in the leading edge is wrapped with the closed-cell foam insulation.

Water Spray Nozzles

The IRT spray bar system design is based on the water spray nozzle performance and specifically on the nozzle water and airflow rates (coefficients). The minimum and maximum water flow rates for the Standard and Mod-1 nozzles were shown in table I.

Figure 3 shows a cross section of the IRT water spray nozzles. They are identical except for the water tube nominal diameter and are designated Standard and Mod (modified) -1. The Standard nozzle diameter is 0.025 in. and the Mod-1, 0.0155 in. These are air-assist, atomizing nozzles, an airstream being used to break up or atomize the water stream. The nozzles spray a plume of atomized (microscopic) droplets when the water pressure minus the air pressure (delta pressure) is positive. The smaller water tube of Mod-1 nozzles reduces the water flow and, hence, lowers the liquid water content that can be achieved in the icing cloud.

Electrical Control System

The IRT subsystems, including the spray bar, low-speed wind tunnel, and refrigeration subsystems, are operated through the Westinghouse Distributed Processing Family (WDPF), interactive, distributive control system. Operator consoles located in the IRT main control room are used to set and monitor the facility operation, which includes tunnel fan speed, spray bar air and water pressures, icing spray duration, turntable position, and miscellaneous auxiliary systems. The control of the spray bar system as described herein is accomplished by the WDPF controller. Addressing and correcting problems associated with the previous spray bar system was a priority in the design of the new system. The old system's primary problem was the transition between spray-off and spray-on conditions. The settling time (required for the air and delta pressures in the eight bars to stabilize at the set point pressures) was 30 to 90 sec, and the pressure overshoot was typically 10 to 15 percent of the set point pressures. The settling time was unacceptable, especially for short-duration icing sprays. The pressure overshoot was undesirable but acceptable.

With the new system, each spray bar has an air header and two water headers that feed air and/or water to 54 nozzle holders per bar. A solenoid valve at each water nozzle location controls the flow from each water header. When not spraying, the solenoid valves are in the closed position and the water in the header recirculates to a holding tank. A block diagram of the spray bar system is shown in figure 4. Air from the air header flows continuously through the water nozzles because there is no shutoff valve in the air headers. Blanks are installed at nozzle locations not in use during

icing sprays to effectively manage the airflow rate and pressure requirements. The nozzle positions in each spray bar are different for the Standard and Mod–1 nozzle sets; the position is determined during the time that the icing cloud uniformity is established (see the section Liquid Water Content (Icing Cloud) Uniformity).

A computer-driven switching system controls the individual solenoid valves at the nozzle holders. Software to monitor and control the switching system runs on a dedicated control computer. The set of nozzles to be used for a given spray, or the spray configuration, is preselected and stored in the control computer. Closing a relay and completing the circuit to one side of the solenoid valve coil enables the solenoid valves to be selected as part of the spray configuration. The location of the nozzles in the Standard and Mod–1 nozzle sets does not vary as a function of icing test set points or spray conditions.

The WDPF controller is used to command spray-on conditions, at which point power is supplied to the valve power bus and all selected valves in the spray configuration are opened simultaneously. Verification that individual valve coils have been energized is done by measuring the electrical current to the entire power bus and comparing the value of the measured with the expected current. An alarm is activated if the measured and expected values differ by an amount greater than the current of one valve.

A 125-psig compressed air system supplies air to the spray bar system. A steam-to-air heat exchanger increases the compressed air temperature to 180 °F. The air pressure in the spray bar is controlled by a dome-loaded pressure regulator, and the pressure in the dome is controlled by a current-to-pressure (I/P) converter that converts a 4- to 20-mA control signal to a 0- to 120-psig pressure. The pressure is regulated using a typical proportional-integral-derivative (PID) control loop. The stability is ±0.1 psi over the operating range of 2 to 80 psig.

The spray bar water is supplied from a 500-gal holding tank of deionized water by up to three 25-hp centrifugal pumps. For typical required flow rates, one pump is sufficient. A dome-loaded backpressure regulator controls the pressure to the main water supply line. Pressure in the dome is controlled by an I/P converter with an output range of 0 to 400 psig. The main water line pressure is controlled by allowing water to bleed back into the holding tank. A steam-to-water heat exchanger increases the spray bar water temperature to 180 °F. The main water line splits out of the heat exchanger into the two water circuits. A control valve reduces the pressure in each of the two circuits. A flowmeter is installed to measure flow to the spray bars. Vertical manifolds supply the two water headers in each spray bar. A globe valve at the inlet to each spray bar controls the water pressure in the spray bar. Another valve controls the backpressure that governs the flow resistance in the water manifold. A quarter-turn ball valve shuts off the return water flow.

The goal of the control scheme is to set the water pressure and flow rate in each spray bar before initiating a spray so that the valve is at the correct position and the water pressure set points can be obtained quickly. The water pressure is set using a typical PID closed-loop control. Although the use of flowmeters was considered to provide feedback to the closed-loop control to set spray bar water flow rates, the cost associated with 20 flowmeters was prohibitive and a more cost-effective strategy was implemented.

The backpressure valve is used to simulate the flow resistance of the spray nozzles, thereby matching water flow rates between the spray mode and the recirculation mode. This is accomplished by calculating the required valve flow coefficient C_v based on the water and air pressure set points and the number of spray nozzles in the spray bar. Calibration curves were generated for each backpressure valve to relate C_v to a valve opening. This valve opening is then set in an open-loop control scheme to prevent interactions between it and the inlet valve. The only valve in closed-loop control is the inlet valve to each spray bar, which has resulted in a very stable water spray system.

As seen in figure 5, the steady-state stability of water pressure is ±0.25 psi. When the spray is started, a transition error occurs because of small flow rate differences between recirculation and spray conditions. Typically, the pressure overshoot is ≤3 psi at the spray-on command. Steady-state stability is said to be achieved when the deviation drops to ±0.25 psi, which occurs within the first 10 sec for most test conditions.

The response time required to achieve steady-state water pressure in the spray bars is a marked improvement over the old system, in which there were 8 spray bars with 10 to 15 nozzles per bar. Also, the heated air in the spray bar flowed one way and was deadheaded at the end of the bar and the heated water was recirculated. The water pressure was controlled in each bar by a gage transmitter at a pressure set point of 10 psi less than the air pressure (in nonspray or recirculation mode). A by-product of the water pressure being held lower than the air pressure was that air entered the water system, causing two-phase flow problems. Moreover, each spray bar had its own delta pressure transducer, which caused additional problems with the transition between the recirculation and spray-on modes. As seen in figure 6, the settling time after spray-on was commanded until steady-state pressure was achieved in all eight bars was 30 to 90 sec. The pressure overshoot was approximately 10 to 15 percent of the set point.

AERODYNAMIC CALIBRATION

Instrumentation and Test Conditions

Following installation of the new spray bar system, a test section aerodynamic calibration was performed to determine the test section total pressure, static pressure, velocity, and temperature. A detailed flow quality study of the IRT was completed in 1994 (ref. 4) for the purpose of identifying potential flow quality improvements. The test section calibration performed recently documents changes from the test section flow characteristics recorded in 1994. The objectives of the aerodynamic calibration were to quantify the following:

Total pressure recovery	Total temperature recovery	Flow angularity
Static pressure recovery	Axial turbulence intensity	

All measurements were taken at the test section turntable vertical centerline location. The new 9-ft horizontal rake built for the IRT test section was fitted with 11 pitot-static, flow-angle pressure probes spaced 9 in. apart and 11 T-type total temperature probes spaced 9 in. apart. The pressure probes measure pitch (vertical) flow angle, yaw (horizontal) flow angle, total pressure, and static pressure. The IRT electronically scanned pressure (ESP) system measures all pressures from the rake. The pressure probes were calibrated for flow angle, total pressure recovery, and static pressure recovery in a free-jet calibration rig at the NASA Glenn Research Center. The temperature probes were calibrated in a temperature bath in the in-house flow lab and were calibrated for total temperature recovery in the free-jet calibration rig. A single-sensor, hot-wire anemometer mounted at the midspan of the survey rake measured axial turbulence intensity.

The 9-ft survey rake was mounted to the test section sidewalls at 11 discrete vertical locations, starting 6-in. from the test section floor and then at every 6 in. to a final height of 66 in. (the test section height is 72 in.). The brackets used to mount the rake to the walls were designed to account for thermal expansion and contraction of the rake. A vertical centerline support was located at the midspan of the rake to minimize the possibility of rake flutter.

Data were taken at test section velocities between 50 and 350 mph in increments of 50 mph. At the vertical centerline (36-in. height) only, measurements were taken in 25-mph increments. Data were taken at 40 °F except at the vertical centerline location where they were also taken at 20, 0, and –20 °F. Also recorded at the vertical centerline was the effect of the spray bar air being on.

Results

The results of the postinstallation aerodynamic calibration are reported in reference 5, which gives the full details of the flow quality in the IRT test section. The results taken at 200 mph for static and total pressure recovery, total temperature, Mach number recovery, and flow angularity are described herein.

The IRT test section flow quality goals, modified to account for the IRT's uniqueness, are presented in table II and are consistent with the flow quality requirements for low-speed wind tunnels established at the NASA Wind Tunnel Calibration Workshop held in 1989 (ref. 6). For comparison, the table also lists the generic low-speed wind tunnel requirements.

To fully establish the effect of the new spray bar system, the flow quality is compared with the test section flow quality measurements taken in 1994.

The total and static pressure and Mach number data are normalized by the bellmouth conditions as measured using the facility pitot-static probes, which are permanently mounted on the sidewalls at the test section inlet. Flow angularity, or flow pitch and yaw, data are plotted as directional vectors at every probe location on the 9-ft rake and at every vertical rake position. The direction of the vector indicates flow angle, and the length as plotted represents magnitude.

The results of the present and 1994 calibration tests are shown graphically in figures 7 and 8, respectively. Several significant features of the flow quality are worth noting. The Mach number variation in the test section remains at about the same level as that with the old spray bar system. The majority of the test section cross-sectional area is within the Mach number variation goal of less than 0.005. The pressure recovery contours indicate a more uniform pressure recovery than that previously recorded, which should ensure a more uniform Mach number profile.

The flow angularity plot shows the pronounced swirl patterns in the flow in all four corners of the test section. This swirl was also present with the old spray bar system and is attributable to other causes or IRT design features, such as the heat exchanger and contraction section. The general trend of the flow to pitch (in the vertical direction) and yaw (in the horizontal direction) towards the test section axial centerline is also still present.

Significant temperature variation was measured near the inside (north) wall of the test section (fig. 9). However, at the vertical centerline where most models are installed, the temperature variation is no more than 2 °F, which meets the operational goal for the IRT.

Axial turbulence intensity measurements were taken at the center point of the test section with the spray bar air both on and off. Results indicate that for airspeeds greater than 100 mph, the turbulence intensity is less than 1 percent. Turning on the spray bar air does increase the turbulence intensity in the test section but by much less than 0.5 percent for airspeeds greater than 100 mph. In an icing wind tunnel, axial turbulence aids water droplet mixing and does make a positive contribution to the icing cloud uniformity in the test section.

ICING CLOUD CALIBRATION

The methodology for calibrating the IRT icing cloud is described in detail by Ide (ref. 7). A thorough description of the water nozzle flow calibration, the establishment of liquid water content uniformity, the liquid water content calibration, the droplet size calibration, and the establishment of the IRT icing cloud operating envelopes is contained therein.

Nozzle Performance Curves

The water nozzle design was modified to facilitate installation: the location of the threaded connection to the nozzle holder was changed, and the water tube within the nozzle was designed to be removable whereas it had previously been fixed to the nozzle body. The functional performance of the nozzle remained the same.

For the new spray bar system, 250 Standard and 250 Mod–1 nozzle water tubes were fabricated. The flow coefficient (the water flow rate divided by the square root of the differential pressure between the water and air supplied to the nozzle) of each nozzle was measured. Nozzles selected for use had flow coefficients within ±5 percent of the average flow coefficient of the entire set. This variation in nozzle water flow coefficient has historically proven to be acceptable for ice accretion tests.

Three droplet-sizing instruments are used to perform the droplet size calibration: the forward scattering spectrometer probe (FSSP) and two optical array probes, the OAP–1DC and the OAP–1DP. The latter is an extended range OAP that can measure droplets up to a diameter of 1500 μm. The FSSP can accurately measure drops from 2 to 47 μm. The OAP can measure drops from 15 to 450 μm. For both sets of nozzles, the instrumentation is installed one instrument at a time in the center of the test section. Tests are performed at 20 °F and at 150 mph. To reduce the droplet number density to measurable levels by the FSSP, only half of the spray bars are turned on during droplet size calibration. Tests are run at 12 air pressures and over a range of delta pressures from 5 to 150 psid for the standard nozzles and 5 to 250 psid for the Mod–1 nozzles. After measurements are completed with the FSSP, the OAP is installed in the center of the test section. Test points are repeated for spray bar settings where the median volumetric diameter (MVD) as measured by the FSSP exceeded 16 mm.

The measured performance of the Standard and Mod–1 nozzles is shown in figures 10 and 11, respectively. The IRT nozzles perform over a wide range of air pressure and delta pressure (water pressure minus air pressure) conditions. This is illustrated graphically in the figures where droplet size or median volumetric diameter (MVD) is plotted as a function of air and delta pressure. As seen from the plots, the water nozzle performance is characterized by increasing MVD with increasing delta pressure and increasing MVD with decreasing air pressure.

Liquid Water Content (Icing Cloud) Uniformity

To establish liquid water content uniformity in the test section, a two-step process is followed. The first is to determine the relationship between water nozzle location in the spray bar and the final water droplet location in the test section. The second step is to determine the location of the nozzles to establish a uniform icing cloud. The procedures described next are repeated for the Standard and Mod–1 nozzle sets.

Mapping the relationship between the location of the nozzle in the spray bars and the resulting location of the spray in the test section is necessary to efficiently guide the development or establishment of the uniform cloud. Sixteen spray nozzles are installed at the same horizontal-dimension locations in each of the 10 spray bars. A 6- by 6-ft stainless-steel grid with 6- by 6-in. spacing is installed in the test section to collect ice. The leading edge of the grid members is approximately 3/8 in. thick. An icing spray is made using only 1 of the 10 spray bars and the ice accretion on the grid is measured. The vertical locations of the maximum ice thickness, moving horizontally or laterally, are recorded. The spread of the spray is also recorded. This test is repeated until the spray from all 10 individual bars has been mapped. The same procedure is repeated using vertical "columns" of water nozzles. Here, 1 nozzle in each of the 10 spray bars is activated. After each icing spray, the horizontal location of the maximum ice thickness and the spread corresponding to that location are recorded.

The information obtained from the single bar and "column" sprays is utilized to systematically set up the initial water nozzle positions so that the process of establishing the overall cloud uniformity can be started. The 6- by 6-ft grid is again used for a trial-and-error iterative process, during which nozzle locations are changed to lessen ice accretion in areas of relatively high concentration and to increase ice accretion in areas of low concentration (voids). The icing cloud is considered uniform when spatial uniformity is achieved; that is, when the measured ice accretion thickness on the grid is within ±20 percent of the test section center point ice accretion thickness.

The LWC uniformity contour plots for the old spray bar system using Standard and Mod-1 nozzles are shown in figure 12 for a test section airspeed of 180 mph. The new spray bar system LWC uniformity contour plots taken at 200 mph are shown in figures 13 and 14 for the Standard and Mod-1 nozzles, respectively. The LWC uniformity contour plots shown in figures 12 to 14 are normalized by the value of the LWC at the center of the test section. As can be seen from the figures, the size of the uniform cloud in the IRT test section for both nozzle sets has increased. For the Standard nozzle set, the uniform cloud was approximately 3 ft high by 4 ft wide. For the Mod-1 nozzle set, the uniform cloud was approximately 2 ft high by 3 ft wide. With the new spray bar system, the uniform icing cloud for both nozzle sets is approximately 5 ft high by 5 ft wide. There are a few discrete locations of high or low LWC concentration within the 5- by 5- ft zones, but on the vertical centerline (X = 0 in the figures), the variation in LWC is minimal. The vertical centerline corresponds to the location where most wing (airfoil) models are mounted for testing and is therefore a critical region or zone with regard to LWC uniformity.

The greater than 100-percent increase in the size of the uniform icing cloud is attributed to the addition of spray bars 1 and 10. Droplet trajectory results from the single spray bar tests indicate that the increased liquid water content in the icing cloud near the floor and ceiling of the test section results directly from spray emanating from these bars. Similarly, the increase in cloud uniformity in the horizontal direction is attributed to the new spray bar design that locates the water spray nozzles closer to the sidewalls than they were in the previous system.

Liquid Water Content Calibration

An icing blade is used to establish the liquid water content calibration. The icing blade, an aluminum coupon 6 in. long, 3/4 in. wide, and 1/8 in. thick, is positioned at the center of the test section with the edge of the length-by-width side facing into the airstream, and consequently, into the icing spray. During spray startup, the position of the blade behind a hydraulically actuated shield is necessary to avoid the test section LWC transient associated with the initiation of spraying. The measured ice accretion thickness on the blade and the exposure time of the blade to the icing spray are then used to calculate the liquid water content. All LWC tests are run at 0 °F.

Operating Envelopes

The results of both the droplet size and the LWC calibrations are combined to define the operating envelopes of the IRT spray bar system for the Standard and Mod-1 nozzle sets. Because the LWC in an icing wind tunnel is a function of airspeed, the operating envelopes are defined for various airspeeds. No attempt is made here to graphically represent the entire range of IRT operating conditions; rather, the operating envelopes at 200 mph are shown in figure 15 superimposed on the FAA icing criteria as found in Appendix C of FAR, Parts 25 and 29. From this plot, the limitations of the IRT to duplicate the regulatory criteria are evident. Also seen from the figure is that the IRT is limited in its ability to reproduce high LWC and small droplets (MVD) and, conversely, low LWC and large droplets.

With the new spray bar system, researchers have the flexibility (new capability) of adding and/or removing nozzles from the spray bar system to extend the overlap of the FAR icing criteria. However, such a change would require establishing LWC uniformity, calibration of the liquid water content, and confirmation of droplet sizes. To date, the amount of time required to extend the IRT operating envelopes has not been available.

SUMMARY OF RESULTS

A new spray bar system was installed in the Icing Research Tunnel (IRT) at the NASA Glenn Research Center. The new capability offered by this system enhances the IRT's ability to reproduce an artificial icing cloud in a wind tunnel environment. Key performance goals were realized: increased size of the uniform cloud, faster system response time, and extended coverage of icing conditions as defined in Appendix C of Federal Aviation Regulations (FAR), Parts 25 and 29. The IRT is the world's largest refrigerated wind tunnel dedicated to the study of aircraft in-flight icing, and this state-of-the-art spray system ensures its usefulness to investigate the important areas of icing physics, icing prediction (computer code) validation, ice protection system development, and ice protection system certification.

Key physical characteristics of the new spray bar system are 10 spray bars (the old system had 8), solenoid valves at each water nozzle location to control water flow to individual nozzles, and aerodynamically shaped fairings on the spray bars and on a center vertical support column. Key functional characteristics of the new system are an improved system response time so that steady-state pressure stability is achieved in both air and water supply pressures in ≤10 sec from spray initiation (spray-on condition), and an expanded test section uniform icing cloud.

Postinstallation aerodynamic and icing cloud calibrations were completed. The test section aerodynamic flow quality is not measurably different from that of the previous spray bar system, with the exception of an overall decrease in the turbulence intensity. This decrease would indicate that other IRT design features are strong contributors to the flow quality; these features include the fan, the heat exchanger, and the contraction section shape. The icing cloud calibration resulted in a set of calibration curves used by the wind tunnel operators to set spray bar conditions to achieve the desired icing cloud characteristics. The operating envelopes that define the range of liquid water content and median droplet diameter of the icing cloud as a function of airspeed were also established.

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TABLE I.—SPRAY BAR AIR AND WATER SYSTEM KEY REQUIREMENTS

Design requirement	Standard nozzles		Mod–1 nozzles	
	Minimum	Maximum	Minimum	Maximum
Working nozzles per bar (max)	18	18	18	18
Water temperature, °F_____	165 to 185	165 to 185	165 to 185	165 to 185
Water flow rates				
Delta pressure, psi_____	5	150	5	250
Nozzle flow, gal/min_____	0.027	0.147	0.01	0.071
Spray bar flow, gal/min_____	0.21 to 0.4	1.18 to 2.64	0.08 to 0.1	0.57 to 1.28
Air pressure, psi_____	5 to 80	5 to 80	5 to 80	5 to 80
Pressure setpoint settling time, sec at psi	2 at ±1	2 at ±1	2 at ±1	2 at ±1
Pressure setpoint overshoot, percent___	10	10	10	10

TABLE II.—TEST SECTION FLOW QUALITY GOALS FOR ICING RESEARCH
TUNNEL AND NASA LOW-SPEED WIND TUNNELS

Flow quality parameter	Icing Research Tunnel	NASA Low-Speed Wind Tunnel
Mach number variation	0.005	0.001
Flow angularity, deg	.25	.1
Turbulence intensity, percent	.50	.10
Total temperature variation, °F	2	1 to 2
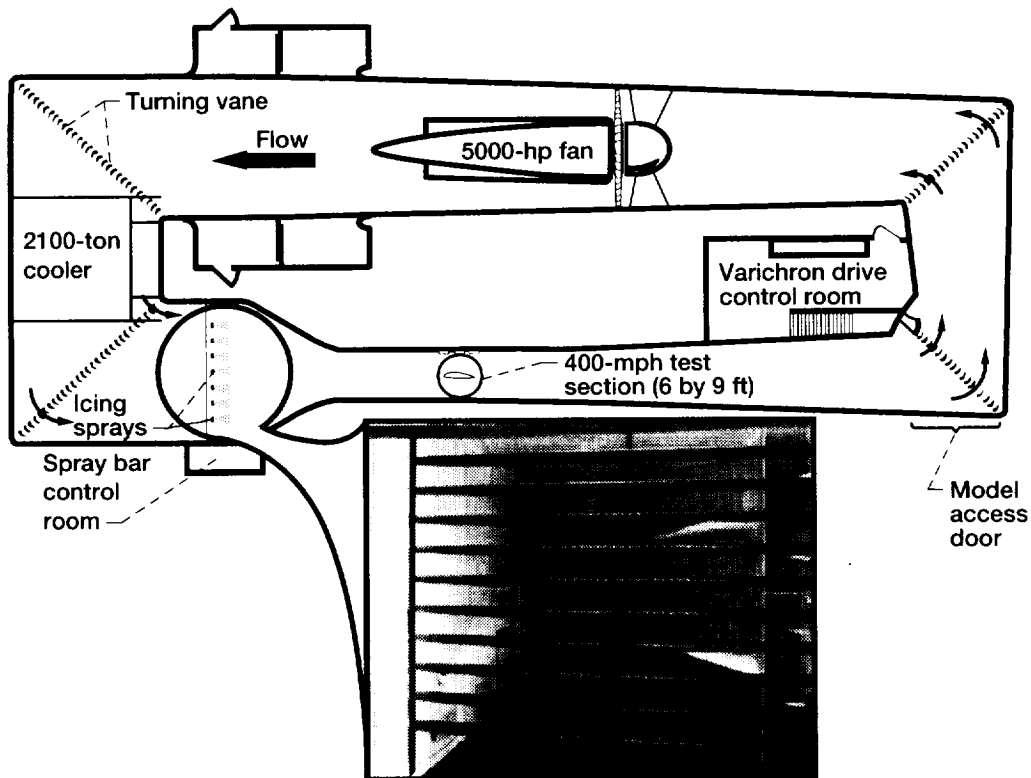
Figure 1.—Icing Research Tunnel (IRT).
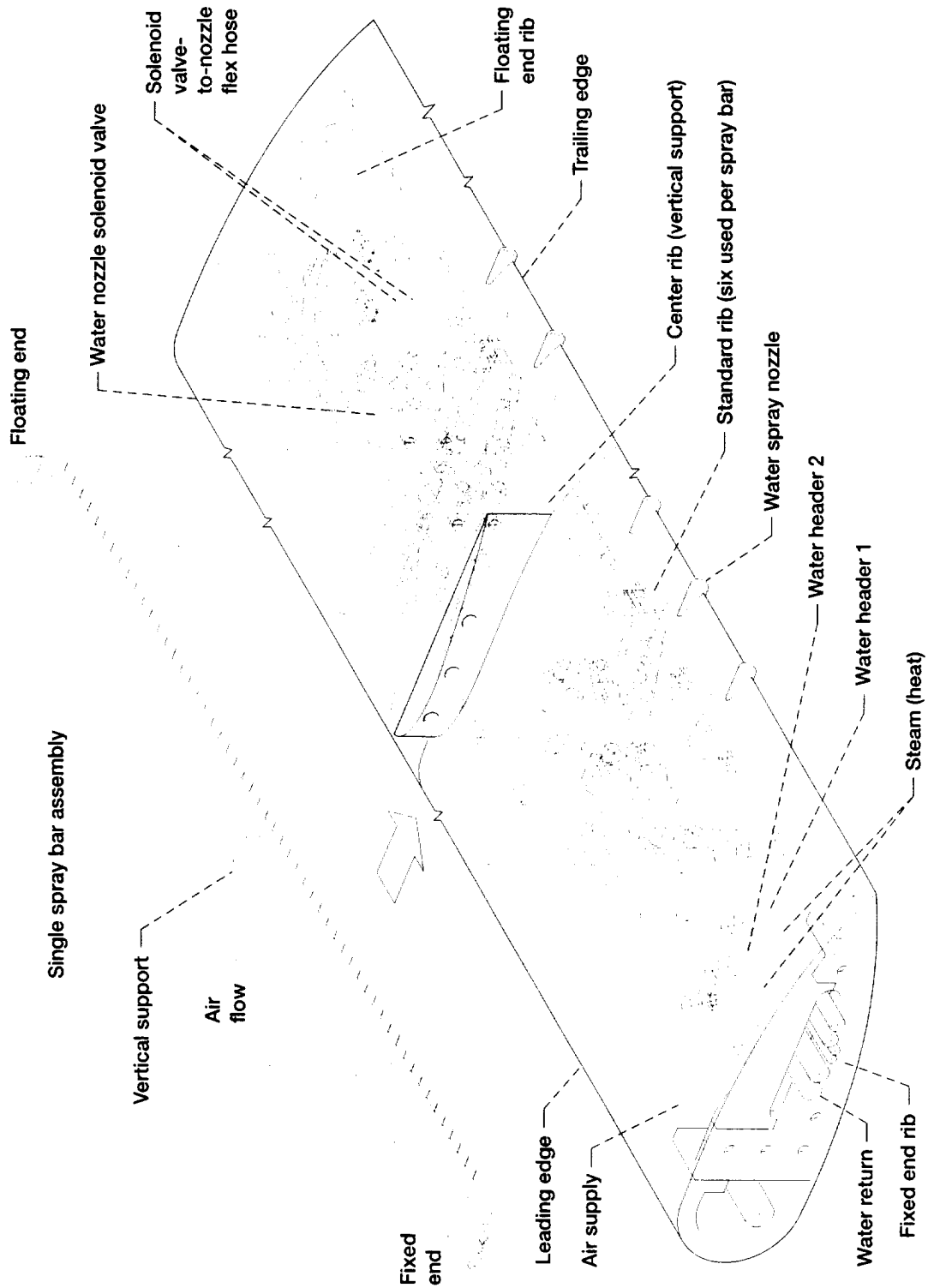
Figure 2.—New spray bar system cutaway showing internal components and plumbing.

Floating end

Solenoid valve-to-nozzle flex hose

Water nozzle solenoid valve

Floating end rib

Trailing edge

Center rib (vertical support)

Standard rib (six used per spray bar)

Water spray nozzle

Water header 2

Water header 1

Steam (heat)

Water return

Fixed end rib

Air supply

Leading edge

Air flow

Vertical support

Single spray bar assembly

Fixed end
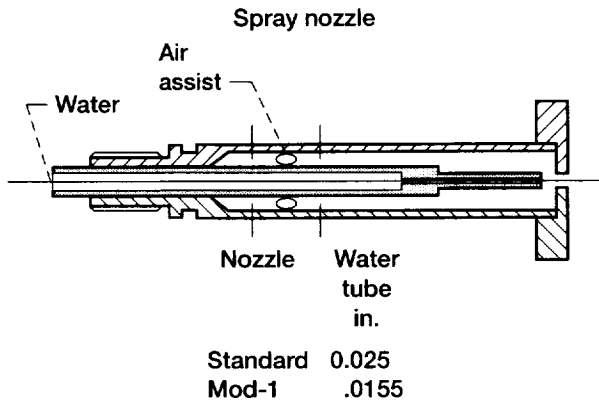
Figure 3.—IRT water spray nozzle.

Standard 0.025
Mod-1 .0155
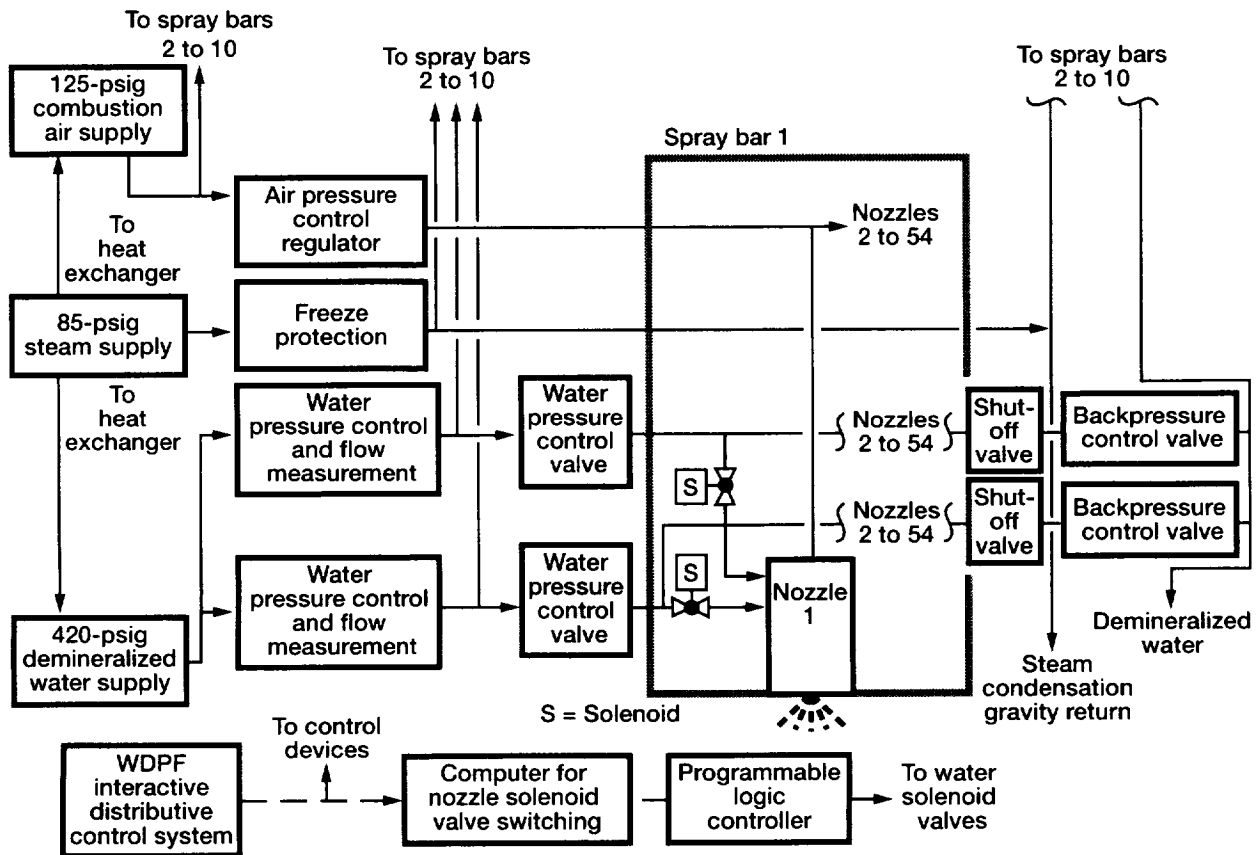
Figure 4.—IRT spray bar system.
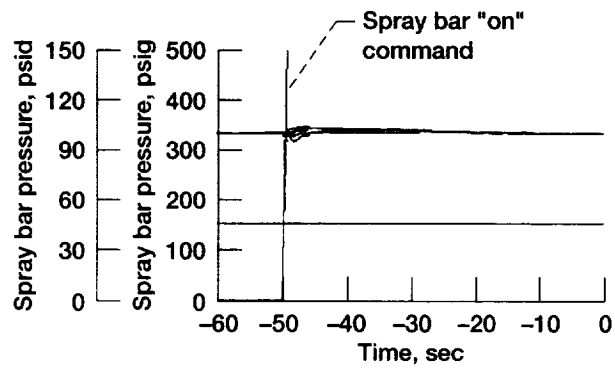
Figure 5.—New spray bar system delta pressure
response and stability curves.
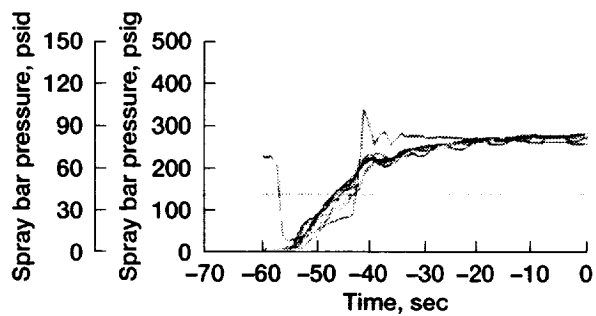
Figure 6.—Old spray bar system delta pressure
response and stability curves.
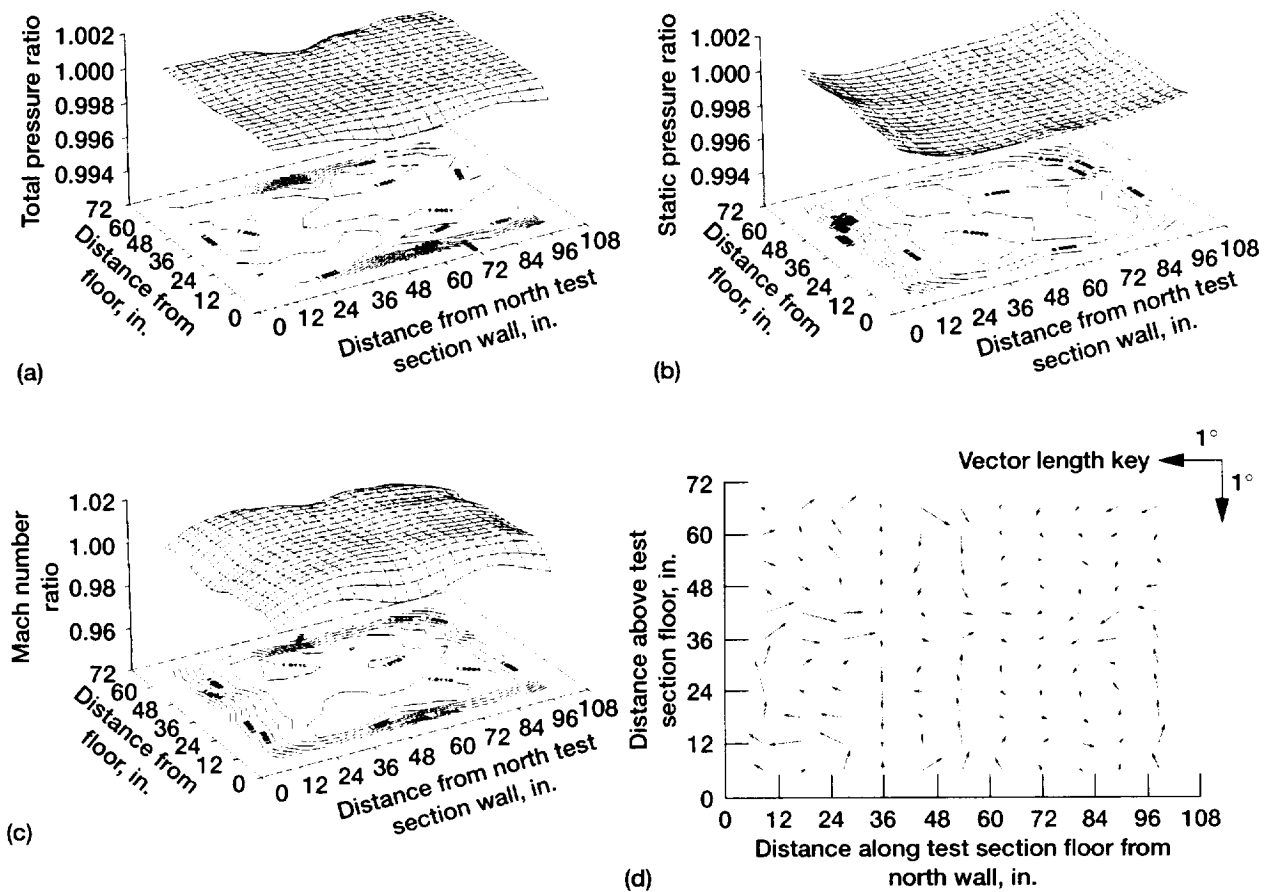
Figure 7.—New spray bar system test section flow-field survey data at turntable vertical centerline location for test section velocity of 200 mph. (a) Total pressure ratio. (b) Static pressure ratio. (c) Mach number ratio. (d) Flow angularity vectors.
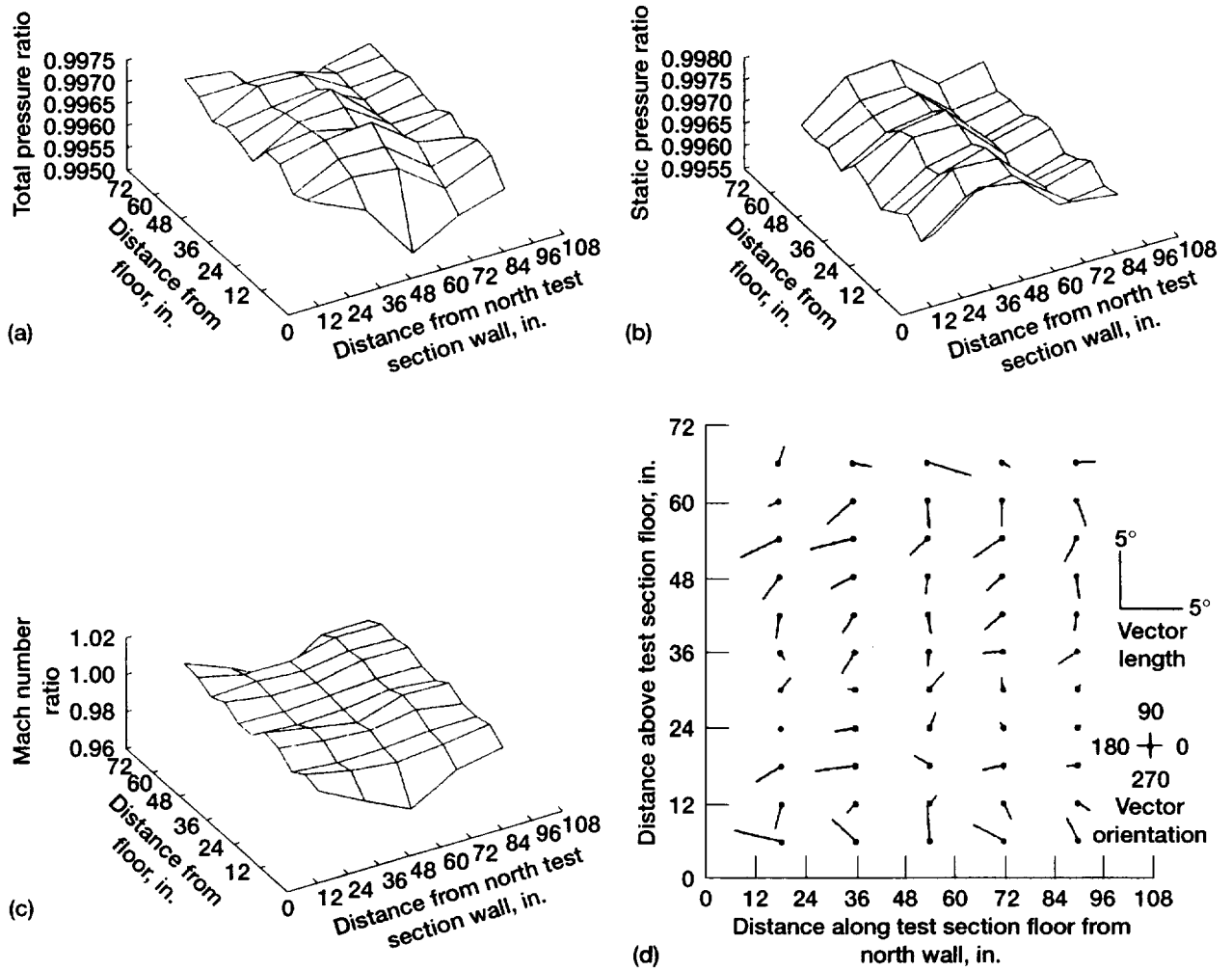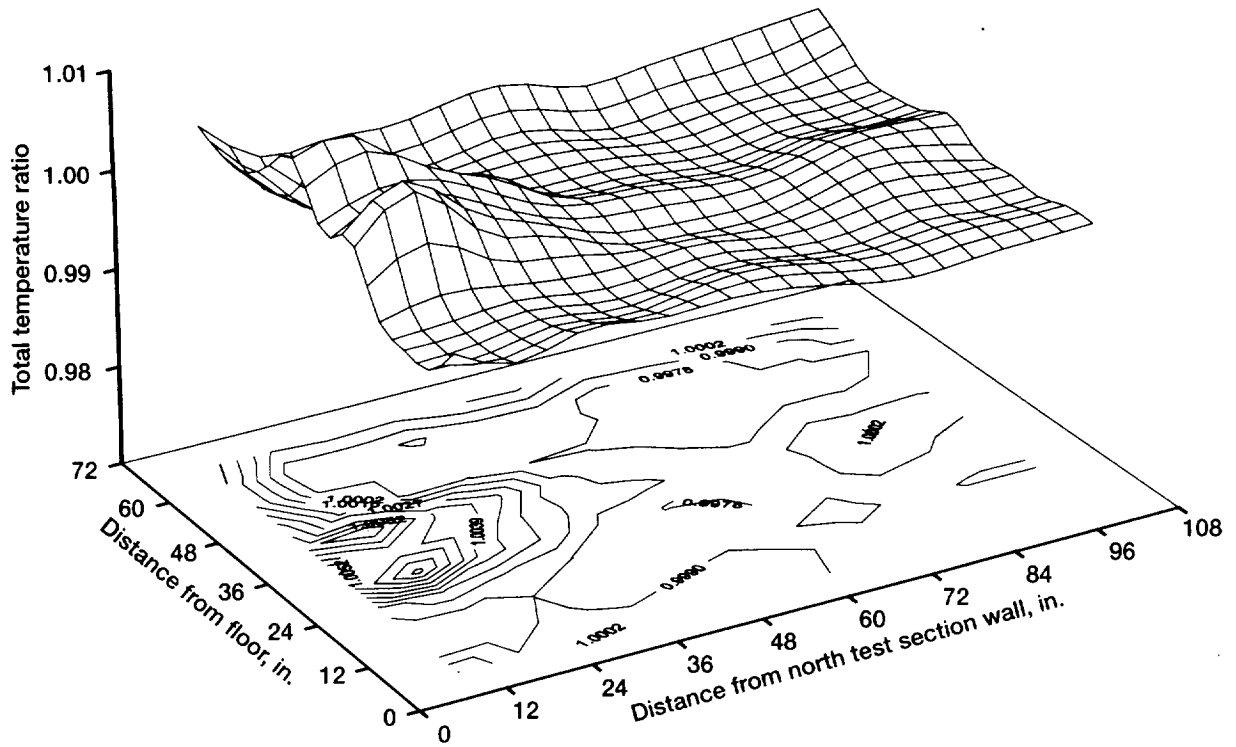
Figure 8.—Old spray bar system test section flow-field survey data at test plane survey station for test section velocity of 200 mph. (a) Total pressure ratio. (b) Static pressure ratio. (c) Mach number ratio. (d) Flow angularity vectors.

Figure 9.—Total temperature variation in IRT test section at turntable vertical centerline location.
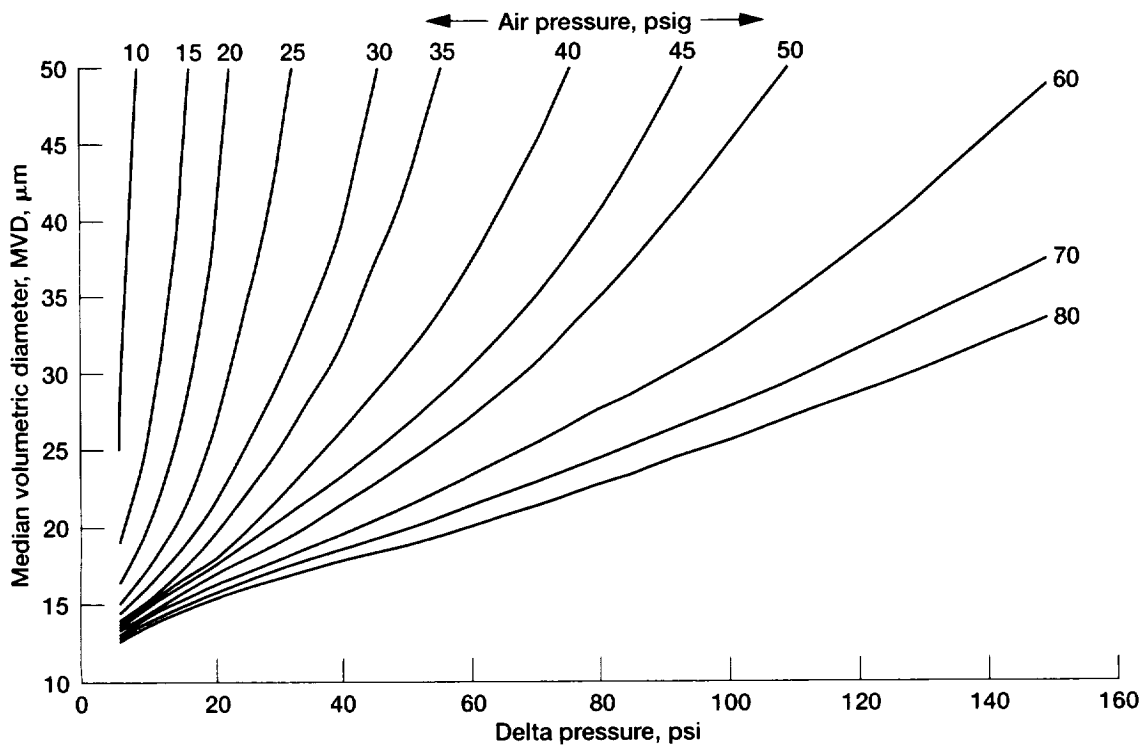
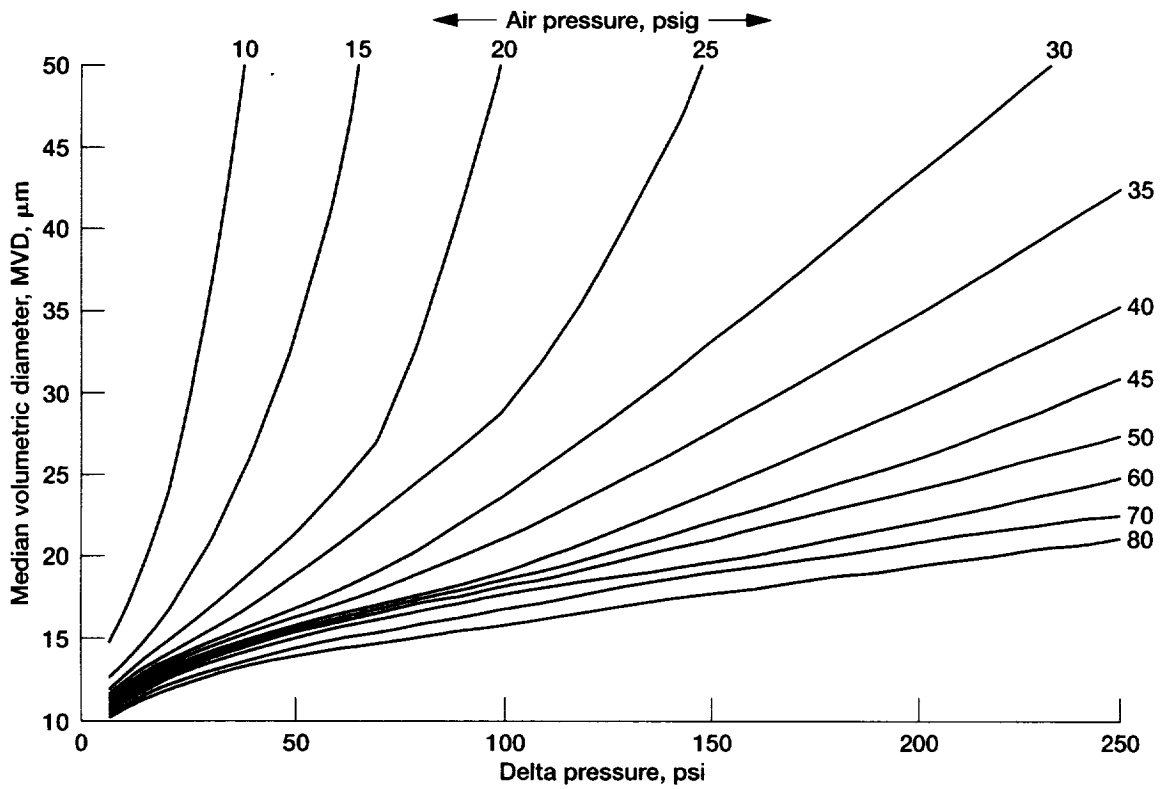Figure 10.—IRT standard nozzle operating performance curves.
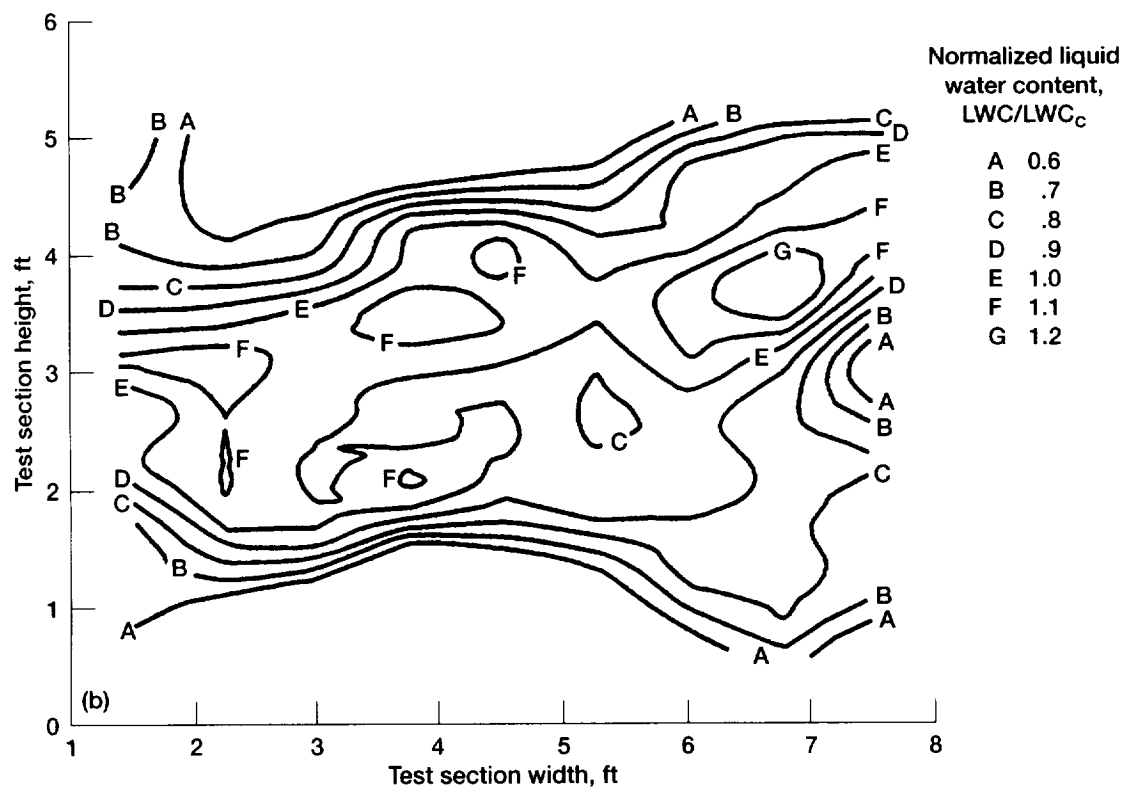
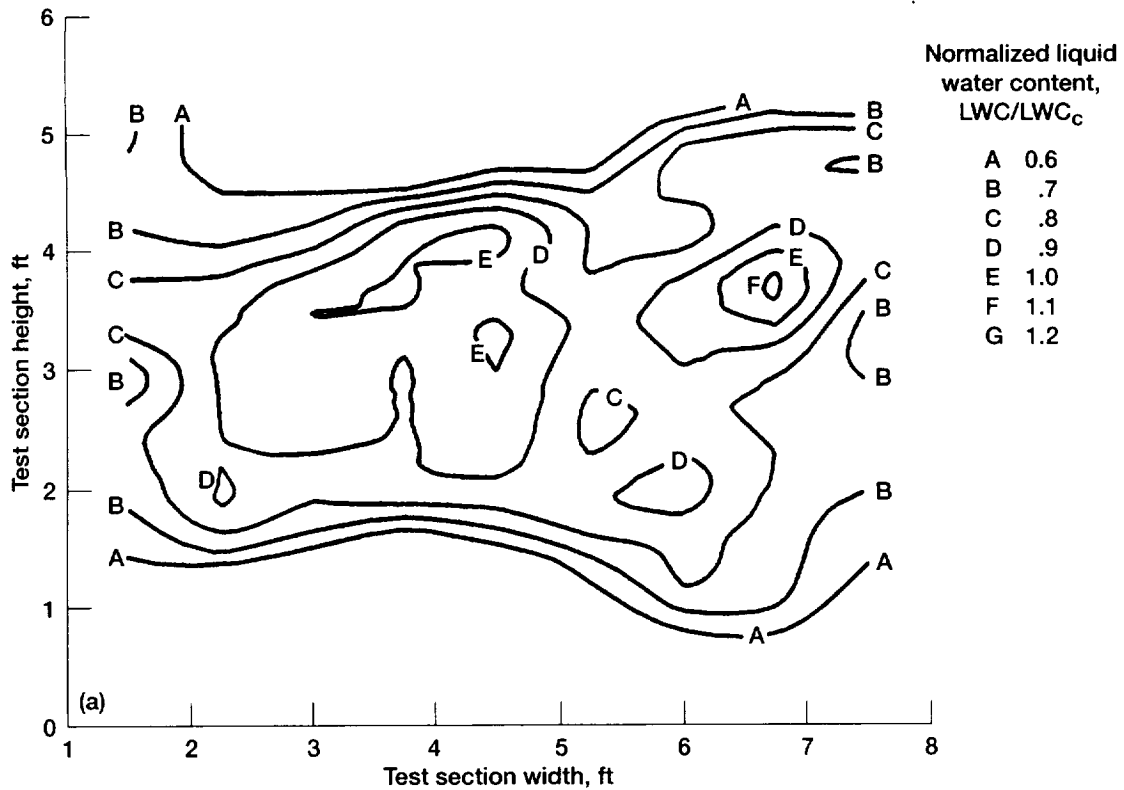Figure 11.—IRT Mod–1 nozzle operating performance curves.

Figure 12.—Contour maps of liquid water content distribution in IRT test section with old spray bar system at airspeed of 180 mph. (a) Standard nozzles. (b) Mod–1 nozzles.
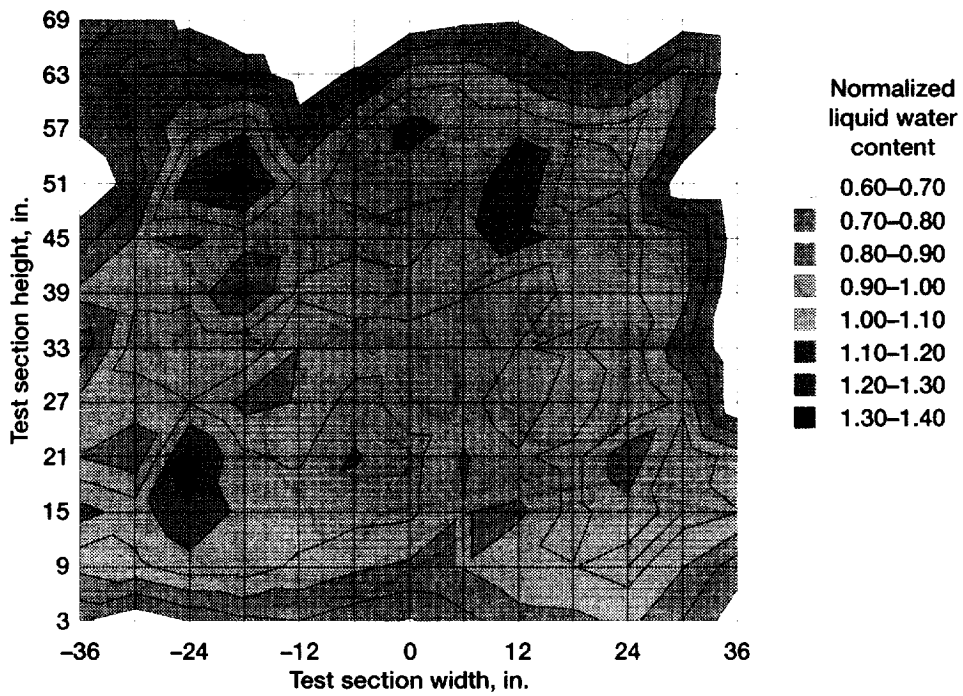
Figure 13.—Contour map of liquid water content distribution in IRT test section for new spray bar system with Standard nozzles at airspeed of 200 mph.
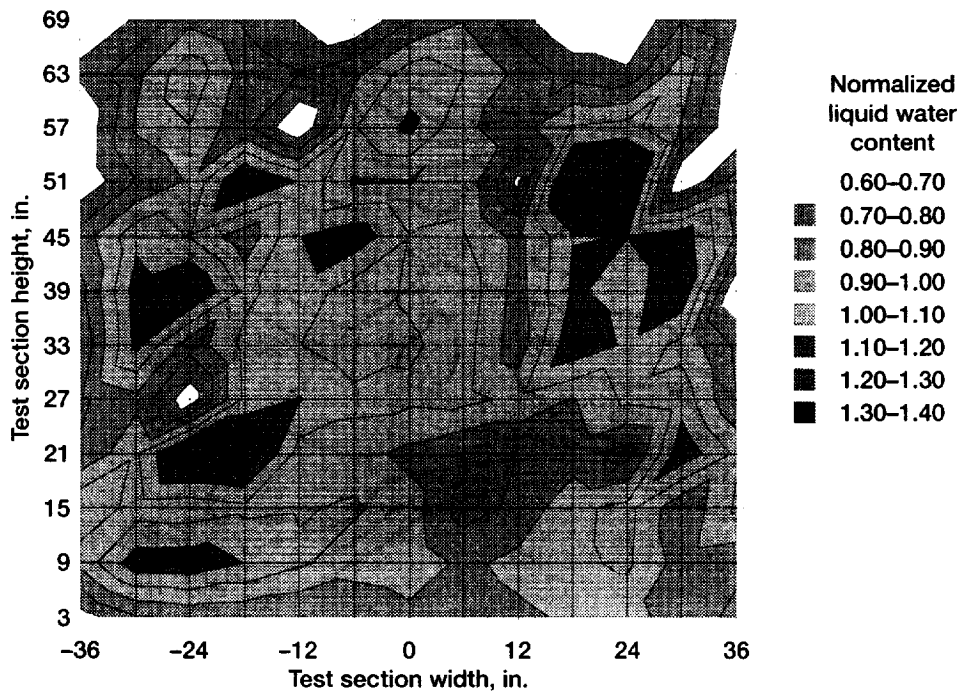

Figure 14.—Contour map of liquid water content distribution in IRT test section for new spray bar system with Mod–1 nozzles at airspeed of 200 mph.
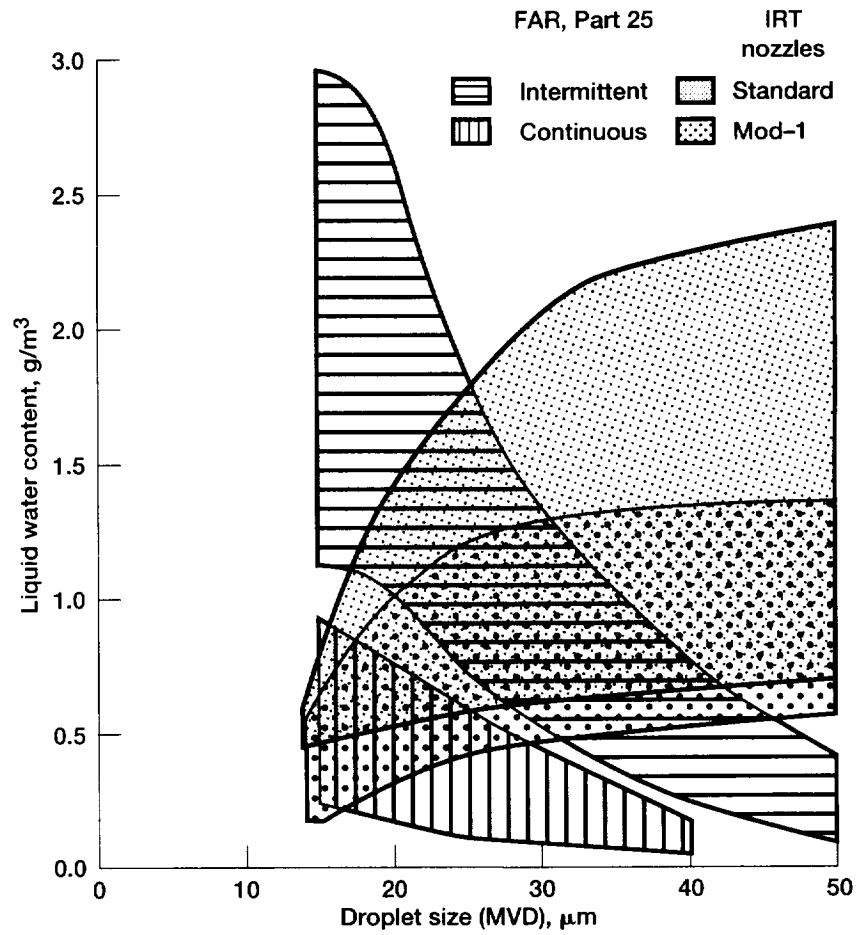
Figure 15.—Comparison of IRT operating envelopes at 200 mph with icing
conditions as defined in Federal Aviation Regulations FAR, Part 25 and
Part 29.

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13. ABSTRACT (Maximum 200 words)

A new spray bar system was designed, fabricated, and installed in the NASA Glenn Research Center's Icing Research Tunnel (IRT). This system is key to the IRT's ability to do aircraft in-flight icing cloud simulation. The performance goals and requirements levied on the design of the new spray bar system included increased size of the uniform icing cloud in the IRT test section, faster system response time, and increased coverage of icing conditions as defined in Appendix C of the Federal Aviation Regulation (FAR), Part 25 and Part 29. Through significant changes to the mechanical and electrical designs of the previous-generation spray bar system, the performance goals and requirements were realized. Postinstallation aerodynamic and icing cloud calibrations were performed to quantify the changes and improvements made to the IRT test section flow quality and icing cloud characteristics. The new and improved capability to simulate aircraft encounters with in-flight icing clouds ensures that the IRT will continue to provide a satisfactory icing ground-test simulation method to the aeronautics community.

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