



AEROSPACE INFORMATION REPORT

AIR6189™

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Design, Calibration, and Test Methods
for Turbine Engine Icing Test Facilities

RATIONALE

The aim of the document is to assemble and record the current knowledge and test processes for the use of the engine icing test facilities in support of airworthiness certification. There is a particular need to identify and understand the defined test processes that have the greatest influence on the accuracy of the results. The document will address the key concerns and illustrate some of the different types of approach used.

AIR6189 has been reaffirmed to comply with the SAE Five-Year Review policy.

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1. SCOPE

This SAE Aerospace Information Report (AIR) provides descriptions of test procedures and established practices for the application, use, and administration of the conduct of icing testing for all types of turbine engines in conventional supercooled liquid (14 CFR Part 25 Appendix C) environmental conditions in ground test facilities (sea-level and altitude) for icing certification purposes.

1.1 Background

The U.S. Federal Aviation Administration has requested that SAE International establish current practices and guidelines for the acceptable use of engine icing test facilities and test methods to support certification. SAE has already developed a series of Aerospace Recommended Practices (ARP) documents for other icing certification engineering tools. These documents: ARP5903, Droplet Impingement and Ice Accretion Computer Codes, ARP5904, Airborne Icing Tankers, and ARP5905, Calibration and Acceptance of Icing Wind Tunnels were developed to address the calibration and procedures used for icing computer codes, icing tankers, and icing wind tunnels respectively. ARP5905 states that it is not applicable to engine icing test facilities. There was a need to begin the process of identifying the issues associated with engine icing facilities. At this time the industry consensus was that the current facilities and their historical test experiences can be significantly different and there are not a set of common test practices across their use. The SAE committees involved in the development of this document determined that an ARP is not appropriate at this time, so the intention is to create an Aerospace Information Report (AIR) first to identify the methods and equipment currently used.

1.2 Purpose

The purpose of this AIR is to compile, in one definitive source, the currently utilized mature methods and procedures for calibration and acceptance criteria for turbine engine icing test facilities. Facilities that meet these criteria will have icing conditions simulation capability. The scope covers both sea-level and altitude engine icing facilities.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained. SAE Publications

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR4906	Droplet Sizing Instrumentation Used in Icing Facilities
AIR5026A	Test Cell Instrumentation
ARP5305	Structural Design and Construction Considerations for Enclosed Turbofan/Turbojet Engine Test Cells
ARP5624	Aircraft Inflight Icing Terminology
ARP5904	Airborne Icing Tankers
ARP5905	Calibration and Acceptance of Icing Wind Tunnels

2.1.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

Title 14 of the Code of Federal Regulations (14 CFR), Part 25 and Part 33, Federal Aviation Administration

FAA Advisory Circular 20-147A, "Turbojet, Turboprop, Turboshaft, and Turbofan Engine Induction System Icing and Ice Ingestion"

2.1.3 NASA Scientific and Technical Information Program

Copies of these documents are available at <https://www.sti.nasa.gov/>.

NASA Technical Memorandum TM-102447, "Liquid Water Content and Droplet Size Calibration of the NASA Lewis Icing Research Tunnel," Ide, R., January 1990

NASA Technical Memorandum TM-2008-215177, "2006 Icing Cloud Calibration of the NASA Glenn Icing Research Tunnel," Ide, R. and Sheldon, D., May 2008

2.1.4 U.S. Government Publications

Copies of these documents are available at <https://ntrl.ntis.gov/NTRL>.

DOT/FAA/AR-TN06 "Cloud Sampling Instruments for Icing Flight Tests," Jeck, R., 2006

DOT/FAA/AR-07/4, "Advances in the Characterization of Supercooled Clouds for Aircraft Icing Applications", November 2008, Jeck, R., Federal Aviation Administration

2.1.5 U.S. Military Technical Reports

Copies of these documents are available at <http://www.dtic.mil/dtic>.

AEDC Evaporation model paper: "A Kinetic Model for Two-Phase Flow in High Temperature Exhaust Gas Coolers," Pelton and Willbanks, AEDC-TR-72-89, 1972

2.2 Definitions

The following terms are used in this document. The SAE Aircraft Inflight Icing Terminology (ARP5624) is a resource for the definition of additional icing terms.

AMBIENT TEMPERATURE: Ambient temperature is representative of the static temperature at flight ambient condition. This is true for a capture ratio of 1.

"APPENDIX C": The current FAA engineering standard for atmospheric icing, Title 14 of the Code of Federal Regulations (14 CFR), Part 25. Appendix C consists of two envelopes, the continuous maximum and the intermittent maximum, defined by liquid water content, droplet size, static air temperature, and horizontal extent. These curves can be found at the Government Printing Office's website, or at the following link <http://www.gpo.gov/fdsys/pkg/CFR-2011-title14-vol1/pdf/CFR-2011-title14-vol1-part25-appC.pdf>.

"APPENDIX D": A new engineering standard identified for high altitude convective weather ice crystal icing conditions, found in 14 CFR Part 33.

"APPENDIX O": A new engineering standard identified for large droplet icing conditions where the drops exceed the current Appendix C engineering standards. The curves describing these icing conditions can be found in 14 CFR Part 25.

GROUND FOG: Fog is a surface based cloud composed of either water droplets or ice crystals. It is created when radiational cooling at the earth's surface lowers the temperature of the air near the ground to or below its frost dew point. Primarily takes place at night or early morning.

DEW POINT TEMPERATURE: The temperature to which a given air parcel must be cooled at constant pressure and constant water vapor content in order to achieve saturation with respect to water. (ARP5624)

DROPLET: A small spherical particle of any liquid; in meteorology, particularly a water drop. There is no defined size limit separating drops from droplets of water, but it is sometimes convenient to denote two disparate size ranges, such as the oft-used distinction of liquid cloud particles (droplets) from liquid precipitation (drops), thereby implying that a maximum diameter of 0.2 mm is the limit for droplets. (ARP5624)

LANGMUIR DISTRIBUTION: A family of five hypothetical, symmetrical LWC vs. droplet size distributions originally devised for analyzing ROTATING MULTICYLINDER (RMC) measurements. The table gives the droplet diameter as a fraction or multiple of the MEDIAN VOLUMETRIC DIAMETER (MVD) for the center of each of the seven LWC intervals in each column. The table illustrates the distributions in terms of a/a_0 , where a is the average diameter in each group and a_0 is the median volumetric diameter. Distribution “D” or “E” are commonly used for ice accretion computations on airfoils as assumed in 14 CFR-25,29 Appendix C. (ARP5624) Appendix C assumes Distribution “A” which is suitable for accretion, but Distribution “D” or “E” should be used for droplet impingement limits or the calculation of ice limits.

Table 1 - Langmuir distributions

%LWC	a/a_0				
	A	B	C	D	E
5%	1.00	0.56	0.42	0.31	0.23
10%	1.00	0.72	0.61	0.52	0.44
20%	1.00	0.84	0.77	0.71	0.65
30%	1.00	1.00	1.00	1.00	1.00
20%	1.00	1.17	1.26	1.37	1.48
10%	1.00	1.32	1.51	1.74	2.00
5%	1.00	1.49	1.81	2.22	2.71

LIQUID WATER CONTENT (LWC): The mass of water contained in liquid cloud droplets within a unit volume, usually given in units of grams of water per cubic meter of air (g/m^3).

MEAN ARITHMETIC DIAMETER (MAD): A droplet diameter used by the Aviation Register of Russia (MAK).

MEDIAN VOLUMETRIC DIAMETER (MVD) [Also referred to as Median Volume Diameter]: The droplet diameter, usually given in micrometers (10^{-6} m), such that one-half the liquid water volume is contained in droplets smaller than the median volume diameter and one-half the liquid water volume is contained in droplets larger than the median volume diameter. ARP5624 version: The droplet diameter which divides the total LIQUID WATER CONTENT present in the droplet distribution in half, i.e., half the water volume will be in larger droplets and half the volume in smaller droplets.

MEAN EFFECTIVE DROPLET DIAMETER (MEDD) [Also referred to as – a MEAN EFFECTIVE DIAMETER (MED)]: The mean effective droplet diameter is a volume median droplet size, that is, the amount of water in all droplets of diameter greater than the mean-effective diameter is equal to the amount of water in all droplets of smaller diameter (refer to NACA TN 2569).

REFERENCE PLANE: The cloud measurement location in the test facility that is typically one to two engine diameters upstream of the engine inlet.

SUPERCOOLED LARGE DROPS (SLD): Supercooled liquid water that includes freezing rain or freezing drizzle (see “Appendix O”).

STATIC TEMPERATURE: The temperature of a stream of compressible fluid, as measured by a temperature element which is moving with the stream so that there is no relative velocity between the measuring element and the fluid and measured in the absence of radiation (refer to ARP5624).

TOTAL TEMPERATURE: The temperature of a stream of compressible fluid, as measured by a temperature element whose entire surface is subjected to the full DYNAMIC PRESSURE of the fluid stream and measured in the absence of radiation (refer to ARP5624).

TOTAL WATER CONTENT (TWC): The mass of ice and water contained in a mixed phase or fully glaciated cloud particles per unit volume, usually given in units of grams of ice and water per cubic meter (g/m^3).

TURN DOWN RATIO: This is the ratio of maximum/minimum flow condition that a nozzle or valve can operate at properly. This ratio is applicable to both air and water definitions.

VALIDATION: The process that confirms the device or system is functioning as intended, that documentation and version control meet the standards of the validating organization, and that calibration measurements match accepted experimental data in accordance with accepted validation standards within established tolerances.

VERIFICATION: The process of determining that a test accurately represents the facility calibration procedures and known performance values within specified tolerances.

2.3 Abbreviations

CDP: Cloud Droplet Probe

CIP: Cloud Imaging Probe

CFR: Code of Federal Regulations

CPI: Cloud Particle Imager

FAA: Federal Aviation Administration

FOD: Foreign Object Damage

FSPP: Forward Scattering Spectrometer Probe

IWC: Ice Water Content

LWC: Liquid Water Content

MEDD: Mean Effective Droplet Diameter (also referred to as MED – Mean Effective Diameter)

MMD: Median Mass Dimension

MVD: Median Volume Diameter

NPRM: Notice for Proposed Rulemaking

OAP: Optical Array Probe

OAT: Outside Air Temperature

PIP: Precipitation Imaging Probe

PIV: Particle Image Velocimetry

PDPA: Phase Doppler Particle Analyzer

PLIF: Planar Laser-Induced Fluorescence

RTD: Resistance Temperature Device

TAT: Total Air Temperature

TWC: Total Water Content

3. CLARIFICATION OF TERMS

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

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

4. REGULATORY ICING ENVELOPES AND REQUIREMENTS

4.1 Regulatory Icing Envelopes

4.1.1 In-Flight Icing

For over four decades airworthiness regulators worldwide have required turbine engine manufacturers to show acceptable engine operational characteristics when operating in a supercooled droplet icing environment. The FAA defines the supercooled small droplet icing environment within Title 14 CFR Part 25, Appendix C. Other airworthiness authorities have similarly defined icing environments. More recently two other icing environments have been proposed: supercooled large droplets (Title 14 CFR Part 25, Appendix O), and mixed phase and ice crystals (Title 14 CFR Part 33, Appendix D). These three icing environments are described below.

4.1.2 Icing Environments

1. "Appendix C" - supercooled small droplet

The FAA defines the certification standard supercooled small droplet icing environment in 14 CFR Part 25, Appendix C, and 14 CFR Part 29, Appendix C. See Sections 3 and 4 for clarification of MEDD and MVD terms. This small droplet environment includes both stratiform and cumuliform clouds in the following range of conditions:

- a. LWC range: up to 2.9 g/m³
- b. MVD (MEDD) range: 15 to 50 micrometers
- c. Ambient temperature: -40 to 0 °C (includes extended envelope)

2. "Appendix D" - ice crystals

- a. TWC range: from 1 g/m³ to 5.1 g/m³
- b. MMD range and ice particle size: ice crystal size median mass dimension (MMD) range is 50 to 200 micrometers (equivalent spherical size)
- c. Ambient temperature range: -4 to -60 °C
- d. Portion that is LWC: less than 1 g/m³ depending on temperature and cloud extent

3. "Appendix O" - supercooled large drop (freezing rain and drizzle)

- a. LWC range:
 - (1) Freezing rain: up to 0.31 g/m³
 - (2) Freezing drizzle: up to 0.44 g/m³

- b. MVD range: greater or less than 40 micrometers
 - (1) Freezing rain: containing some drops greater than 500 micrometers
 - (2) Freezing drizzle: containing some drops between 100 to 500 micrometers
- c. Ambient temperature range:
 - (1) Freezing rain: 0 to -13 °C
 - (2) Freezing drizzle: 0 to -25 °C

4.1.3 Test Requirements for Simulated In-Flight Icing Conditions

The FAA airworthiness certification icing requirements for turbine engines are defined within 14 CFR Part 33, paragraph 33.68, titled Induction System Icing. It requires a demonstration of acceptable operation for various flight scenarios. There are some prescribed conditions, as well as a requirement for a critical point analysis. The prescribed conditions are defined in terms of both a specific atmospheric icing condition as well as a specific engine operating condition. The time duration for each condition is dependent upon the power level being simulated. These standard test practices have been developed over many years. Refer to FAA Advisory Circular 20-147A for more detailed test guidance.

4.1.4 Application to Engine Test Operating Conditions

For freejet facilities, the velocity in the reference plane upstream of the engine is typically low enough that the total and static air temperatures are considered to be equal. For direct connect facilities, either sea-level or altitude, the static temperature could be lower than the total, depending on the engine power setting. For testing purposes, the temperature is chosen to match the condition stated in the test plan.

4.1.5 Ground Operations Icing Conditions

Under the airworthiness standards, there are separate ground operation icing conditions. Each prescribed set of conditions must be demonstrated to show that the engine operates acceptably (refer to 14 CFR Part 33, paragraph 33.68(a)); the set of conditions is dependent on agreement between the regulatory authority and manufacturer. Ground based icing conditions include freezing fog icing. The standards require a demonstration of acceptable prolonged operation for at least 30 minutes in freezing fog conditions. Both glaze icing conditions above -9 °C and rime icing conditions below -9 °C are evaluated. The atmospheric icing content of 0.3 g of super cooled liquid per cubic meter of air is evaluated down to -18 °C. Below -18 °C a diminished atmospheric icing content is evaluated. Unlike the simulated in-flight icing compliance testing, periodic engine speed run-ups are allowed for ground simulated conditions to shed ice during the demonstrations. The MVD is defined as 15 to 25 micrometers. Typically engine manufacturers show long duration test demonstrations, depending on the engine application. Refer to FAA Advisory Circular 20-147A for more detailed test guidance.

5. COMMENTS ON USE OF REGULATIONS

Icing facilities are designed to meet the requirements described in Section 5. However, not all of the cloud characteristics may be suitable for an engine installation in a particular icing facility for an icing certification test. The cloud characteristics are given explicitly in the regulatory requirements such as LWC, MVD and temperature. Not explicitly stated are the size of the icing cloud, uniformity, droplet freeze out, and droplet distribution. It is recommended to discuss the facility icing cloud characteristics and test conduct for a particular engine installation with the regulatory authority well in advance of acquiring any certification data.

5.1 Icing Facility Cloud Characteristics

To determine the icing conditions of the facility, the cloud must be calibrated. This calibration varies for different types of icing facilities and is described in Section 10. Each cloud characteristic must be determined to be acceptable to acquire certification data and the acceptance criteria must be discussed with the regulatory authority. The icing facility cloud characteristics are:

- LWC,
- MVD,
- droplet freeze out,
- droplet distribution,
- droplet temperature or acceptable droplet transit time in the cloud,
- extent of the cloud entering the engine, and
- cloud uniformity.

LWC and MVD will typically use calibration curves as discussed in Section 10 to conduct the test points, since measuring equipment will typically not be installed ahead of, or near the engine. The LWC and MVD presented to the engine may vary from point to point and thus cloud uniformity must be taken into account when reporting the LWC and MVD to the regulatory authority. LWC and MVD acceptance criteria are simply that the required test plan conditions must be achieved. Droplet freeze out, distribution and temperature should be determined during calibration and testing of the spray system. These characteristics must be available to the facility users and may need to be supplied to any regulatory authority responsible for projects using data from the facility. The acceptance of these cloud characteristics will vary from facility to facility and company to company and must be discussed with the regulatory authority. Icing testing is typically a test of the entire engine; therefore, all of the air entering the engine should be conditioned. However, reduced cloud uniformity may be used when agreed with the regulatory authority if it can be shown that a sufficient amount of conditioned airflow enters the appropriate parts of the engine. The simplest cloud uniformity acceptance criteria are to assure that the cloud enters the entire engine inlet for the tested engine power levels. Cloud uniformity should be determined during calibration and testing of the spray system.

5.2 Conducting an Icing Test

The procedures for conducting an icing test, where the data will be acquired for engine icing certification, should be clearly defined to the regulatory authority. These procedures must clearly define:

- the state of the engine at its required set point and any additional throttle procedures,
- the state of the cloud at its required set point (determine length of time needed to stabilize the cloud such that it is within its calibration limits),
- the length of time in the icing cloud.

Acquiring icing data can be expensive and take significant amounts of time. Therefore, the test plan should address the use of data acquired during testing for conditions that fall outside of the range defined in the test plan or the range of calibration data. This plan should take into account how to use data acquired outside of limits or when to abort the test points. At times, it may be easier to abort a test point and retest rather than to continue to acquire data that will not be acceptable. Obviously, this process will vary from company to company and should be discussed with the regulating authority.

5.3 Facility Requirements

5.3.1 Minimum Facility Capabilities to Meet Regulatory Test Requirements

The facility must be capable of determining engine performance, including thrust, pressures, temperatures, speeds, vibration, fuel flow, etc., to within sufficient accuracy to detect changes resulting from potential ice damage to the engine components, or changes to engine operability. In addition, the facility must be able to provide droplet sizes, LWC and inlet temperatures which cover the range specified in the airworthiness documents.

5.3.2 Anti-Ice for the Inlet System

For freejet facilities, there should be hot air, steam or electricity available to heat the inlet cowls to prevent ice buildup, or the potential for ice shedding that might damage an engine. The anti-ice system is usually fully evaporative over the entire operating range of the icing test, to prevent runback ice formation. Excessive heat on the inlet may adversely affect the temperature of the air entering the engine.

6. FACILITIES DESCRIPTION

There are only a handful of engine icing test facilities throughout the entire world. Most of these facilities have developed their own icing equipment and test methodologies over a period of many years, in relative isolation from each other. The evolution of engine icing facilities has produced two major facility types which can be configured in either sea level or altitude modes: freejet and direct connect, as well as a less common bypass facility. A description of these facility types is given below.

6.1 Freejet

6.1.1 General Description of Functional Capabilities and Performance Range

The freejet (open jet) icing facility is defined as a wind tunnel and a spray rig nozzle array that produces an icing cloud which envelops the inlet of the engine being tested. The engine is positioned downstream of the wind tunnel exit, typically with a flight style inlet. With the wind tunnel velocity constant, a constant/uniform cloud condition can be set at the reference plane. As the engine operates, it pulls in the amount of airflow and cloud that is based on engine airflow/speed and the rest of the cloud bypasses the engine, very similar to aircraft in-flight and ground operations. The facility wind tunnel airflow is sized for at least the maximum engine airflow (plus excess to assure complete and uniform inlet coverage) to ensure that all engine components are subjected to the proper icing cloud conditions being set. Figure 1 shows a typical engine installation in a freejet facility. The spray rig nozzle array can be installed at the exit of the wind tunnel or incorporated within the tunnel structure itself.

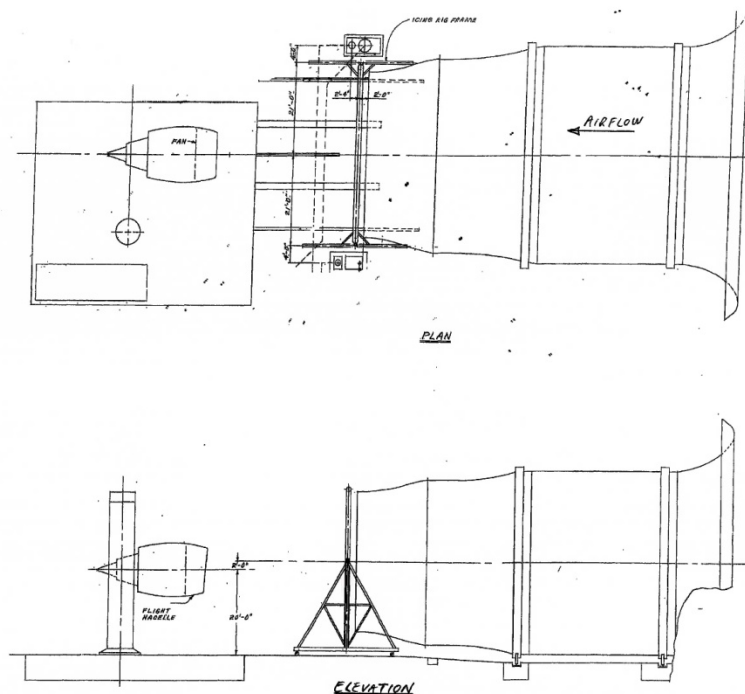


Figure 1 - Freejet Facility

6.1.2 Design Considerations

- The spray rig nozzle array should have a spacing so that the cloud at the engine inlet plane is uniform. Spray nozzle spacing should be based on nozzle plume size to ensure good mixing and cloud uniformity.
- The tunnel uniform velocity flow field deteriorates typically by a cone angle of 6 to 7°, as shown in Figure 2. This deterioration should be considered when setting the distance from the tunnel exit to the engine inlet, so that the engine will see a full velocity/cloud profile at all power settings. The engine airflow stream tube capture volume needs to be smaller than the tunnel total airflow.

Tunnel Velocity Deterioration

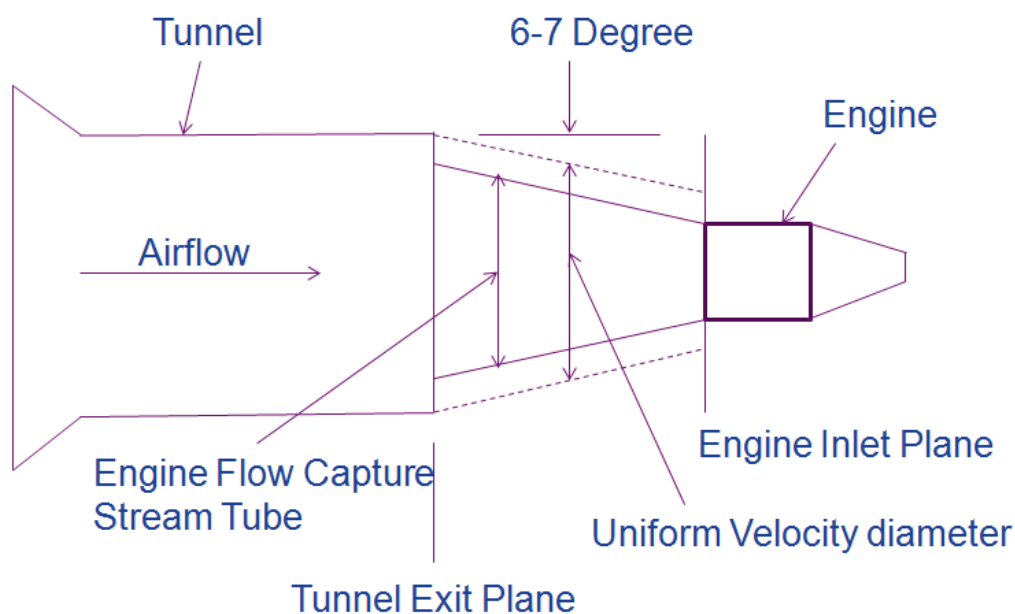


Figure 2 - Schematic of Freejet Facility

6.1.3 Advantages and Limitations of Configuration

Advantages:

- Since an engine is not required to pull airflow through the tunnel, an icing cloud calibration can be performed prior to an engine installation. This calibration will be completed for a full array of nozzles, rather than on a single nozzle lab calibration. The cloud water droplet size is a function of water flow and air pressure. The cloud conditions are then measured at the reference plane after full mixing and evaporation occurs so the cloud conditions at the engine inlet during engine testing will be more accurately determined. This calibration is then good for any equivalently sized or smaller engine. This calibration is a periodic facility calibration and is not engine specific. Each engine is subjected to an icing cloud environment similar to in-flight conditions. The engine airflow sets the percentage of the cloud that enters the engine inlet.
- The tunnel exit velocity is calibrated prior to engine testing and thus the airflow remains constant at a constant velocity and a given tunnel exit area and facility fan speed.
- The flow measurements of the water flow system, nozzle air supply system and the spray rig atomizing nozzle are on the order of 10:1 (turn down ratio) by setting constant tunnel exit velocity and airflow. This reduces the number of nozzle sets and simplifies instrumentation required over higher turn down ratios.

- A freejet setup eliminates installation and fabrication of custom duct work to connect to the engine forward flange.
- It is easier to more accurately measure the change in engine scale force (thrust) as ice accretes on engine components because there is no interaction between the tunnel exit and the engine inlet.
- It is possible to access the engine inlet immediately after the test point is concluded to measure ice accretions.
- This setup provides the ability to perform nacelle inlet evaluation testing, allowing the checkout of the engine inlet anti-ice system.

Limitations:

- The freejet has to produce the drive air with tunnel blower fans. Therefore, initial facility investment costs will be higher than engine-driven direct connect because of the wind tunnel fan and drive system. These tunnel drive systems will also increase operating and maintenance costs.
- There will almost always be cloud overspray since a freejet facility is sized based on the maximum engine airflow. This overspray means that the engine exterior components, the engine inlet highlight and the test stand facility structure will be subjected to ice accretion while testing. Special care should be taken to minimize the effect of such accretion and the inlet highlight should be heated to prevent accretion. In cases where the full engine cowling is part of the test, the overspray can be an advantage.
- Accurate steady state thrust measurements are more difficult to obtain because the cloud impinges on facility and engine mount systems. The cloud impingement effect on thrust can be determined by running an engine performance/thrust calibration with and without the wind tunnel.
- Additional inlet instrumentation is required to determine the steady state engine airflow.
- The inlet air temperature can be affected by the heated (anti-iced) engine inlet. However, this experimental setup can better represent actual flight conditions.

6.2 Direct Connect

6.2.1 General Description of Functional Capabilities and Performance Range

The direct connect icing facility is defined as an icing tunnel which interfaces directly to the front flange of the engine being tested. There are two types of direct connect facilities: one type that delivers externally compressed air into the engine and a second type where the test engine draws atmospheric air through a bellmouth. The direct connect method has been used in both altitude and sea-level test facilities.

- a. Externally compressed air for direct connect facilities is usually used for altitude simulation. It consists of pressurized air supplied to the inlet of the engine to simulate forward flight Mach number and an exhaust system to draw down the test chamber to simulate the flight pressure altitude.
 1. The inlet pressurized air system typically is supplied by compressors which utilize atmospheric air pressurized through several stage compressors to increase the pressure to a known set point. From this set point the air pressure is then regulated to set the required flight condition. The inlet air should be run through a heat exchanger after compression to return it to near ambient temperature. Before the temperature of the inlet air can be reduced, the air must be dried to lower the dew point so that saturation does not occur. This may be done through desiccant dryer beds. The inlet air may then be temperature conditioned to simulate the lower temperature experienced at altitude. Typically, this is done through turbo-expanders. Once the inlet air temperature is set, the inlet pressure of the air is reduced using pressure control valves. The set pressure is determined by the required Mach number for the given pressure altitude and is a ratio of PT_1/PS_0 with PT_1 being inlet plenum total pressure and PS_0 being the tank pressure. In engine icing testing total pressure rakes are usually removed from station 1 and because total pressure is conserved, the inlet plenum total pressure is used.

2. The facility pressure altitude is set by an exhaust system. This is typically exhausters which draw the pressure of the exhaust line down. The system usually runs at a constant vacuum pressure and the pressure is then set by pressure control valves in the exhaust line. Exhaust gas temperature may need to be reduced through water spray quench and/or heat exchanger to not exceed inlet temperature limits for the exhaust equipment.
 3. Both inlet and exhaust may have primary control legs and smaller control legs in parallel for finer control. Typically, the required set points are roughed in with the primary control legs and then final set point is achieved through the smaller control legs. The systems may also have automatic pressure controls through control loops which maintain set point pressures.
 4. Spray bars are usually located in the inlet plenum where velocities are low. Flowing through a transition section with a contraction will drop the static pressure and temperature and avoid droplet freeze out. FOD screens are removed from the plenum but flow straightening devices to assist with airflow uniformity are usually included just upstream of the spray bars.
- b. For test engine driven type direct connect facilities, the icing tunnel may be hard mounted to the engine flange, or a slip joint or soft seal is used to connect to the tunnel. This allows the engine to move ahead slightly, allowing for the measurement of thrust while the engine is running. In hard mount applications, the thrust of the engine has to be calculated from other parameters such as airflow and pressure. A typical sea-level direct connect system is shown in Figure 3.

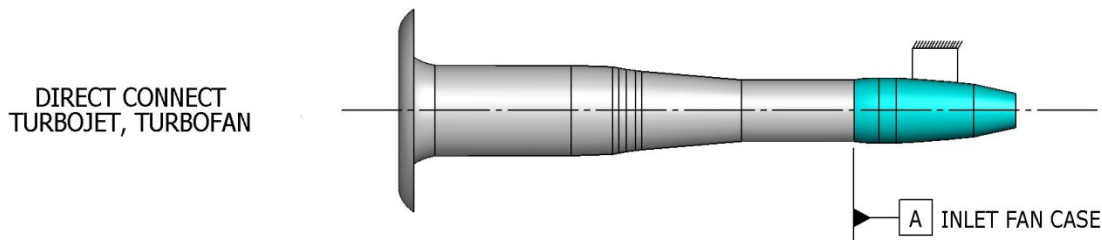


Figure 3 - Typical setup for an engine driven direct connect system

In the engine driven direct connect mode, the engine draws the airflow through the tunnel. The entire icing cloud will pass through the engine. This means the airflow must be continuously measured to make sure the correct test conditions are being met. The airflow through the tunnel is measured in what is referred to as the reference section, a straight cylindrical section located close to the inlet of the engine. The reference section has a known effective flow area from a prior section calibration, and a series of static pressure taps mounted on the wall at several circumferential locations. The airflow is used to compute how much water will be added to provide the required LWC as specified in the test plan.

The engine-driven direct connect icing tunnel usually consists of the following components in this order:

1. Tunnel bellmouth
2. Spray rig section
3. Straight section
4. Conical reducer section(s)
5. Reference section
6. Viewing section

c. Tunnel construction

The tunnel sections should be made of a noncorrosive material to prevent rusting of internal surfaces. All sections generally remain unpainted. Roundness and concentricity are important for all tunnel sections. For the reference and viewing sections, these parameters, as well as surface finish, are critical for accurate performance measurements and stable engine operation.

As the tunnel will expand or contract in length with ambient temperature, provision must be made for axial movement with the fixed end located toward the engine end of the tunnel. The reference and viewing sections of the tunnel will experience differential pressures generated by the maximum tunnel air velocity which could be Mach 0.5 or higher, and thus should be strengthened or stiffened to prevent distortion during testing.

Tunnel sections are required to be moved out of position for engine installation and removal. For this reason, the tunnel sections should be strengthened or supported externally to allow them to be moved

The tunnel must be designed to withstand the thrust generated by the airflow passing through it. The amount of thrust generated on the tunnel is typically up to 30% of the gross thrust of the engine tested.

1. Reference sections (engine specific)

The reference section should have a minimum length of half the fan diameter, and is located between the last conical tunnel section and the viewing section (see Figure 3). There shall be a minimum of 4 static pressure taps (preferably 8) mounted in a plane 50% along the length of this section. There should not be a static port located at the 6 o'clock position to avoid liquid contamination of the pressure port.

2. Distribution screen (engine specific)

A distribution screen should be designed for the purpose of determining spray uniformity in icing conditions. In the case of engine driven airflow facility, the reference section should include the provision for a frame to support a distribution screen (i.e., uniformity grid) to be mounted at the interface with the viewing section. When the screen is removed for icing tests, an insert is slid into the frame to provide a smooth transition across the gap. In the compressed air driven airflow facility, the screen is mounted in place of the engine itself.

The porosity of the screen is normally determined for each icing test program depending on engine size and liquid water concentration to be tested. For large tunnel cross-sections, a motorized or hydraulic system may be needed to move the screen in and out of the flowpath.

3. Viewing section (engine specific)

The viewing section should have a minimum length of one fan diameter, and is located immediately in front of the engine. It normally has multiple viewing ports or windows to allow for lighting, and camera access. The ports or windows should be made of a non-breakable material, and must be retained to prevent them from blowing out in case of an engine surge or being sucked into the tunnel during engine operation. Camera selection (locations, frame speed, etc.) are engine test specific. Camera ports should be available for multiple camera views, redundant images, and a "one-per-rev" synchronization with the fan speed coordinated with the facility and manufacturer. An example of the viewing section coupled to the distribution screen and reference section is shown in Figure 4.

4. Slip joint section (may be engine specific)

Slip joints are included in the inlet ducting to allow for thrust measurement, thermal expansion, and axial movement of the engine. For test engine driven direct connect facilities, the slip joint is usually attached to the engine forward flange.

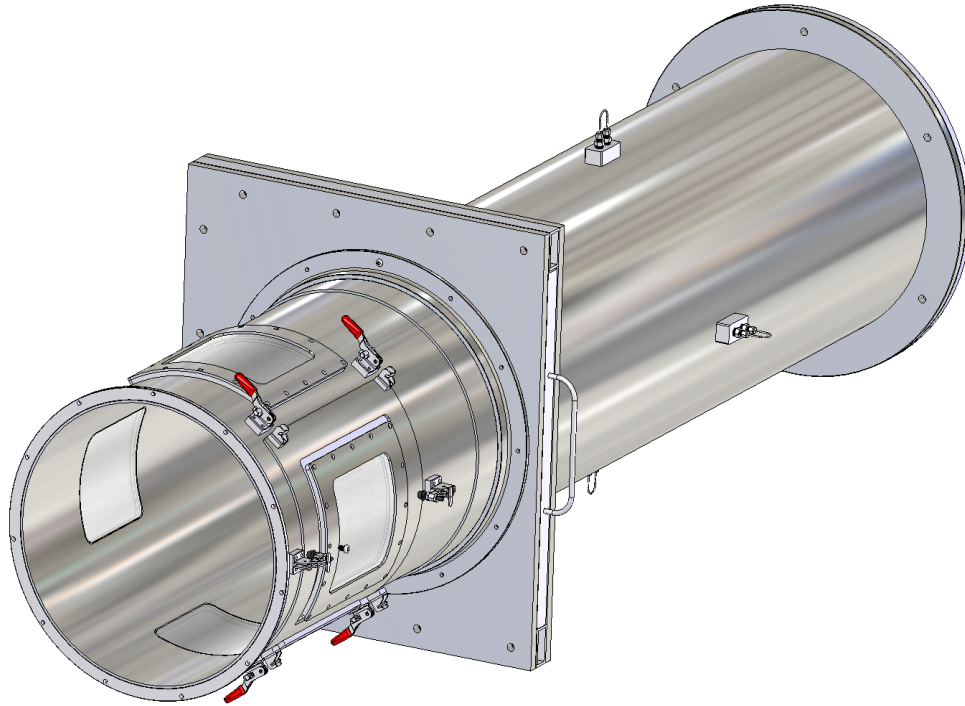


Figure 4 - Slip joint section and viewing area

6.2.2 Advantages and Limitations of Configuration

Advantages:

- Direct connect is generally cheaper to build and operate.
- All of the icing cloud goes into the engine; there is no spillage over the engine. There is no possibility of unconditioned airflow into the engine other than the boundary layer effect.
- The external compressed air-driven direct connect offers the capability to test at simulated altitude conditions which can address more representative fan-module performance.
- In this configuration, engine performance can be more easily determined through the direct measurement of engine total airflow. Care must be exercised to account for the interaction of the engine and facility duct work.

Limitations:

- Specific duct work is needed for each engine size.
- Spray uniformity may be compromised at low engine power settings. Multiple spray configurations may need to be set up and calibrated to cover the entire engine operating range.
- For test engine driven direct connect systems, the cloud uniformity checks can only be done with the engine running
- For test engine driven direct connect systems, direct measurement of droplet size and LWC is difficult due to the size of instrumentation which would need to be placed in front of the running engine (FOD hazard). Therefore, the true cloud properties can be questioned unless measurements are made at every engine airflow, for a given test sequence. Small diameter ducts (>1 m) can utilize a remote real-time measuring system, as laser measurement systems are usually limited to 1 m distance between the transmitter and receiver.

- There is a potential to form frost on the tunnel convergent sections due to either high LWC or high humidity.
- For direct connect facilities a tunnel airflow measurement has to be made at every test condition. This airflow measurement then becomes critical to setting the right cloud conditions to the engine. Also in a direct connect facility as the engine accretes ice at a given power setting, the total engine airflow typically goes down. As this engine airflow changes, the spray rig water flow and air pressure will have to be adjusted to keep a constant cloud condition at the engine inlet plane.
- For a direct connect configuration the water turndown ratio is on the order of 50:1. This can result in a compromise of uniformity of spray, or a multiple nozzle configuration to accommodate the higher turndown ratio.
- For direct connect configurations, access through a removable panel is required to access the engine inlet immediately after the test point is concluded to measure ice accretions.
- For direct connect systems care must be taken to account for boundary layer effects on the cloud in the contraction section.

6.3 Bypass

6.3.1 General Description of Functional Capabilities and Performance Range

The bypass icing configuration is a combination of direct connect and freejet icing test modes. The engine is mounted in a proper flight nacelle, and the nacelle is mounted on a pylon inside a tunnel which is directly connected to the icing tunnel and spray mast, as shown in Figure 5. The tunnel section around the nacelle is designed to match the streamline contour related to the Mach Number for a specific flight condition, thus providing the correct location of the stagnation point on the forward lip of the nacelle. If multiple flight conditions need to be tested, then separate duct contour sections need to be fabricated and installed for each test. The flight speed in the plane of the engine inlet is controlled by an ejector drive or exhaustor system mounted at the exit of the bypass tunnel downstream of the nacelle.

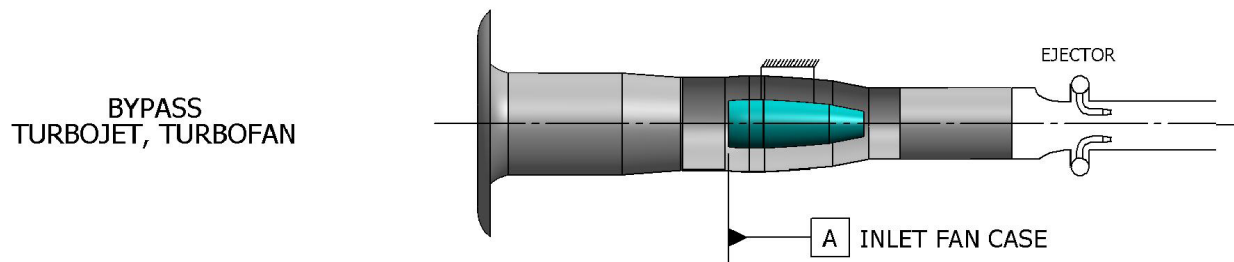


Figure 5 - Bypass configuration

6.3.2 Advantages and Limitations of the Bypass Configuration

Advantages:

- Each engine is subjected to an icing cloud environment similar to in-flight forward speed conditions.
- Since an engine is not required to pull airflow through the tunnel, an icing cloud calibration can be performed prior to an engine installation. This calibration will then be completed for a full array of nozzles, rather than based on a single nozzle lab calibration. The cloud water droplet size is a function of water flow and air pressure. The droplet is then measured after full mixing and evaporation occurs so the cloud conditions that the engine will see during testing can be more accurately determined. The engine airflow sets the percentage of the cloud that enters the engine inlet.
- Provides ability to simultaneously perform nacelle inlet evaluation testing. This allows the checkout of the engine inlet anti-ice system.

Limitations:

- Bypass facility has to produce the drive air. Therefore, initial facility investment costs will be higher than engine-driven direct connect because of the ejector or exhaustor drive system. These tunnel drive systems will also increase operating and maintenance costs.
- There will almost always be cloud overspray since a bypass facility is sized based on the maximum tunnel airflow. This overspray means that the engine exterior nacelle components and the engine inlet highlight will be subjected to ice accretion while testing. Special care should be taken to minimize the effect of such accretion and the inlet highlight should be heated to prevent accretion. True actual steady state thrust measurements are more difficult to obtain because the cloud impinges on facility and engine mount systems. Additional inlet instrumentation is required to determine the steady state engine airflow.
- The inlet air temperature can be affected by the heated (anti-iced) engine inlet. However, this experimental setup can better represent actual flight conditions.

6.4 Additional Facility Requirements

6.4.1 Steady State and Rapid Power Changes and the Ability to Deliver Conditioned Air

The altitude facility supplies conditioned air to the engine using compressors and refrigeration systems at the facility inlet, and an exhaustor at the facility outlet. As the engine power demand changes, these facility components must increase or decrease the airflow through the test chamber to match the engine inlet and exhaust conditions. This air processing equipment uses many megawatts of power, and cannot react as quickly as the gas turbine engine to meet the airflow demand without the incorporation of a bypass around the test cell. This means that snap acceleration of the engine can be limited in an altitude facility without a bypass system. With the advent of the newer larger turbofan engines, the airflow capacity of the engine has significantly exceeded the flow capacity of the air processing equipment of even the largest altitude facility in the world. This means that the engine cannot be tested at its highest power setting at near sea-level conditions. To overcome this shortfall, the facility is operated at a significantly higher altitude (as the engine airflow requirements drop significantly with altitude). For example, a ground fog test might be done at idle power at near sea-level conditions, and then the facility will raise the altitude to 20,000 feet prior to accelerating the engine to takeoff power.

6.4.2 Humidity Control

Altitude test facilities generally have the capability of controlling the humidity of the incoming air upstream of the icing spray mast. This is usually done by injecting steam into the air stream. Controlling the humidity will provide a repeatable evaporation rate for water droplets between the spray mast and the engine face for a given test condition. Controlling the humidity to fully saturated conditions is usually not desirable.

6.4.3 Turboshift/Turboprop Engine Test Considerations

Turboshift engines require some unique icing test considerations. They may be tested with or without a load absorbing device (e.g., water brake dynamometer). If the load is not absorbed, the output shaft is removed, and an exhaust nozzle must be mounted to the back of the engine and the engine is tested as a jet. Thrust measurements can be made to confirm any loss of performance related to ice ingestion. If the load is being absorbed, the load absorber must be small enough in diameter as to not block the icing cloud from entering the engine. It is also not acceptable to have ice accretion on the load absorber which could break off and be ingested into the engine. It may be possible to use a right-angle drive to allow the load absorber to be mounted away from the engine inlet. If the icing test is done in a freejet mode, the bellmouth needs to be heated to prevent ice accretion. Often the turboshift engine is tested with a flight intake with a built in bypass duct or particle separator to centrifuge ice away from the compressor inlet.

Turboprop engines are usually not iced with the propeller attached, due to the very large airflow requirements of the propeller. The engine is treated as a turboshift engine, and tested as described above. For small turboprop engines with a propeller, a freejet facility must be used.