



NASA Glenn Icing Research Tunnel User Guide

*Waldo J. Acosta, Emily Clapper, Eric Insana, Gretchen Morales-Valle,
Seth Sederholm, and Carolyn Thiemann
Glenn Research Center, Cleveland, Ohio*

*Emily N. Timko and Aaron Johnson
Jacobs Technology, Cleveland, Ohio*

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.**
Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.**
Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain

minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.**
Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.**
Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.**
Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.**
English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>



NASA Glenn Icing Research Tunnel User Guide

*Waldo J. Acosta, Emily Clapper, Eric Insana, Gretchen Morales-Valle,
Seth Sederholm, and Carolyn Thiemann
Glenn Research Center, Cleveland, Ohio*

*Emily N. Timko and Aaron Johnson
Jacobs Technology, Cleveland, Ohio*

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

Acknowledgments

The authors would like to thank NASA's Aerosciences Evaluation and Test Capabilities Portfolio for their continued support to the engineering and technician staff who maintain and operate the IRT. The authors would like to thank members of the Icing Research Branch and Scientific Imaging group, including Andy Broeren, Sam Lee, Jordan Cochran, and Quentin Schwinn for their time and expertise in reviewing and providing comments. The effort to update the IRT user manual began in 2012, and the authors would like to thank the personnel responsible, including Jack Oldenburg, Larry Becks, Dave Sheldon, and Mark Kubiak.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Level of Review: This material has been technically reviewed by technical management.

This report is available in electronic form at <https://www.sti.nasa.gov/> and <https://ntrs.nasa.gov/>

NASA STI Program/Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

Contents

Summary	1
1.0 Introduction	1
2.0 Description of the IRT Facility.....	2
2.1 General Description	2
2.2 Wind Tunnel Performance and Capability	3
2.3 Test Section Details	5
2.4 Main Drive System	7
2.5 Velocity Control	9
2.6 Spray Bars.....	9
2.7 Control Rooms.....	10
3.0 Tunnel Support Service Systems	10
3.1 Heated Air Systems	10
3.2 Steam and Service Air Systems	11
3.3 Model Interface at Tunnel Ceiling.....	11
3.3.1 Pivot Pins	11
3.3.2 Bushings.....	11
3.3.3 Hatch Plate	13
3.4 Engine Inlet Model Exhaust System.....	13
3.5 Model Electrical Power	14
4.0 Instrumentation.....	14
4.1 Temperature Measurements.....	15
4.1.1 Facility Temperature Measurements.....	15
4.1.2 Customer Tunnel User Temperature Measurements.....	15
4.2 Pressure Measurements.....	16
4.2.1 Facility Pressure Measurements.....	16
4.2.2 Tunnel User Pressure Measurements	16
4.3 Model Attitude.....	17
4.4 Scientific Imaging.....	17
4.4.1 Video Imaging.....	17
4.4.2 Still Imaging.....	18
4.4.3 High-Speed Imaging	18
4.4.4 Infrared Imaging	19
4.4.5 3D Ice Shape Scanning	20
5.0 Data Processing	21
5.1 Data Acquisition Hardware	21
5.2 Real-Time Displays	22
5.3 Data Collection	24
5.4 Data Output.....	25
6.0 Pretest Requirements	25
6.1 Pretest Meetings.....	25
6.1.1 Test Objectives and Run Schedule.....	26
6.1.2 Instrumentation	26
6.1.3 Hardware.....	26
6.1.4 Data Acquisition	26
6.1.5 Power Requirements	26

6.1.6	Services Required	26
6.2	Pretest Documentation.....	26
6.3	Model and Equipment Delivery.....	27
7.0	Risk Assessment of Wind Tunnel Model and Test Hardware	27
7.1	Model Systems Report.....	27
7.1.1	Model System Drawings	27
7.1.2	Model Design Loads	28
7.1.3	Model Stress Analysis.....	28
7.1.4	Model Stability Requirements	28
7.1.5	Inspection Report	28
7.1.6	Structural Test Report	29
7.1.7	Hazard Analysis	29
7.2	Design Criteria for Model and Support Structures	29
7.2.1	Material Selection	29
7.2.2	Structural Joints.....	29
7.2.3	Pressure Systems.....	29
7.2.4	Pressure Piping.....	30
7.2.5	Electrical Equipment Components.....	30
7.3	Model Fabrication Requirements.....	30
7.4	Model Installation Procedures	30
8.0	General Information	30
8.1	Logistical Support.....	31
8.1.1	Model Buildup	31
8.1.2	Space Assignment.....	31
8.1.3	User Personnel Responsibilities.....	31
8.1.4	Operation of Government Equipment.....	31
8.1.5	Tunnel Safety	31
8.1.6	Aerodynamic Test for Model Checkout.....	31
8.1.7	Support During Tests	31
8.1.8	Personnel Safety Briefings.....	31
8.2	Operations.....	32
8.2.1	Normal Operating Days and Shift Hours	32
8.2.2	Off-Shift Access.....	32
8.3	Planning.....	32
8.3.1	Safety Permit Request.....	32
8.3.2	Test Time	32
8.3.3	NASA Debriefing	33
8.4	Security Notification Requirements.....	33
8.4.1	Nonclassified Test by U.S. Citizen	33
8.4.2	Nonclassified Test by Non-U.S. Citizen	33
8.4.3	Sensitive Test by U.S. Citizen	34
9.0	Personnel Safety	34
9.1	Hazards	34
9.2	Protective Equipment.....	35
9.3	Emergency Procedures	35
9.4	Working Alone	35

10.0 Contact and Shipping Information.....	35
10.1 Facility Manager.....	36
10.2 Technical Lead.....	36
10.3 Shipping Information.....	36
11.0 Concluding Remarks	36
Appendix A.—Nomenclature	39
Appendix B.—Example of Exported COBRA Output Sheet	41
References.....	42

List of Figures

Figure 1.—Icing Research Tunnel schematic.	2
Figure 2.—IRT balance chamber first floor. All dimensions are in feet.	2
Figure 3.—Aircraft models and experiments installed in IRT test section. (a) Wing section. (b) Rotorcraft. (c) Icing instruments. (3) Engine inlet.....	3
Figure 4.—Estimated maximum test airspeed in IRT based on relative area blockage and assembly drag coefficient. (a) Test model with streamlined afterbodies. (b) Test model with squared-off afterbodies.	4
Figure 5.—Downstream view of test section through IRT spray bars.....	5
Figure 6.—IRT turntable and model mounting plate. All dimensions are in inches.	6
Figure 7.—IRT model mounting plate. Note: Tunnel is 6 ft by 9 ft wide. If model extends beyond turntable, leave 1/2-in. clearance above top or below bottom of model. All dimensions are in inches.	6
Figure 8.—Access to IRT test section from overhead hatch. All dimensions are in inches.	7
Figure 9.—Isometric view of test section.	8
Figure 10.—Dimensions of control room walls against test section. All dimensions are in inches. (a) South control room. (b) North control room.	8
Figure 11.—IRT icing envelope at 100 knots.....	9
Figure 12.—IRT icing envelope at 250 knots.....	10
Figure 13.—Pivot pin details. All dimensions are in inches.....	12
Figure 14.—Bushing details. All dimensions are in inches; typ. is typical.	12
Figure 15.—Hatch plate details. All dimensions are in inches; typ. is typical.	13
Figure 16.—Altitude exhaust attachment detail; standard steel flanges and elbow for connecting inlet models to exhaust system.	14
Figure 17.—Ice accumulation. (a) Scallop ice shape. (b) Postprocessed 3D laser scan of scallop ice shape. (c) Rime ice shape. (d) Postprocessed 3D laser scan of rime ice shape.....	20
Figure 18.—COBRA architecture.....	21
Figure 19.—Tunnel overview display.	22
Figure 20.—Test section overview display.....	23
Figure 21.—Spray bar overview display.	23
Figure 22.—Example real-time C_p plot.	23
Figure 23.—Example model temperature and pressure plot.....	24

NASA Glenn Icing Research Tunnel User Guide

Waldo J. Acosta, Emily Clapper, Eric Insana, Gretchen Morales-Valle,
Seth Sederholm, and Carolyn Thiemann
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Emily N. Timko and Aaron Johnson
Jacobs Technology
Cleveland, Ohio 44114

Summary

This user guide describes the capabilities of the Icing Research Tunnel (IRT) at the NASA Glenn Research Center in Cleveland, Ohio, and provides information for users who wish to conduct experiments in the facility. The IRT is a closed-loop atmospheric tunnel with a test section that is 6 ft high, 9 ft wide, and 20 ft long. The facility is designed to support a testing environment simulating natural icing conditions. The icing cloud envelope and characteristics referenced are for test section velocities ranging from 50 to 300 knots. The facility test support systems described herein include heated air, low-pressure steam, compressed air, engine inlet bypass air (altitude exhaust), and electrical power systems. Data acquisition systems include parameters of temperature, pressure, and test article angle of attack. The facility supports video and photographic documentation of the test article as well as 2D and 3D ice shape documentation. Specific capabilities and information for the IRT are described throughout this document.

1.0 Introduction

This user guide describes the capabilities of the Icing Research Tunnel (IRT) at the NASA Glenn Research Center at Lewis Field, located adjacent to Cleveland Hopkins International Airport in Cleveland, Ohio. This guide provides information for users who wish to conduct experiments in the IRT facility. The goal of the IRT is to replicate the Federal Aviation Administration (FAA) aircraft icing certification standards contained in 14 Code of Federal Regulations (CFR) Part 25, Appendix C and limited Appendix O.

Tunnel users desiring to test at the IRT should contact the IRT facility manager 1 year in advance. This allows time for (1) the tunnel user's test to be entered on the IRT schedule, (2) a Space Act Agreement (SAA) to be completed, and (3) IRT personnel to review instrumentation, documentation, designs, and test plans for a successful entry.

A model can be delivered to the IRT by any commercial service as well as by private means (with approval). The delivery address is provided in Section 10.0 with additional IRT contact information. A diagram of the tunnel loop is shown in Figure 1.

The facility can accommodate testing for commercial, Government, and academic personnel. IRT security capability can be adjusted to suit open, company-proprietary, and Government sensitive test programs. Personnel access to the shop, balance chamber, test section, and control room can be controlled. Security requirements must be discussed with IRT personnel in the initial planning stages. Pretest meetings are held to clarify requirements and answer questions.

2.0 Description of the IRT Facility

2.1 General Description

The IRT is a closed-loop atmospheric tunnel with a test section measuring 6 ft high, 9 ft wide, and 20 ft long (see Figure 1). The IRT balance chamber is a three-story structure that encloses the test section and control rooms.

The first floor of the balance chamber is shown in Figure 2. Models are brought into the balance chamber through the 9-ft-wide by 8.25-ft-high access door. The shop is located outside of the balance chamber and is used for model buildup and support. Shipping crates for the models are brought into the shop through a 10.5-ft-wide by 10.67-ft-high overhead rollup door.

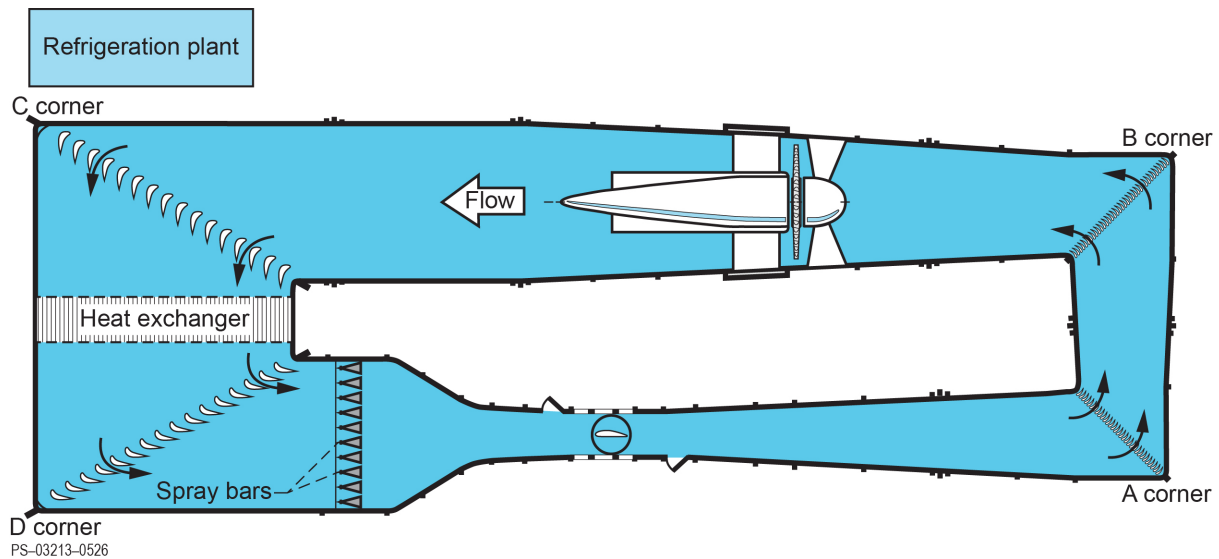


Figure 1.—Icing Research Tunnel schematic.

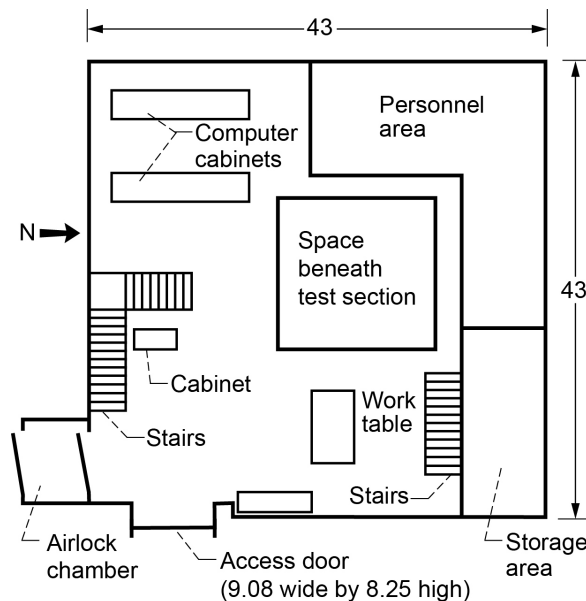


Figure 2.—IRT balance chamber first floor. All dimensions are in feet.



Figure 3.—Aircraft models and experiments installed in IRT test section. (a) Wing section. (b) Rotorcraft. (c) Icing instruments. (3) Engine inlet.

A test section access hatch is located on the third floor of the balance chamber to allow for model installation through the ceiling of the test section and plumbing for the engine inlet bypass air (altitude exhaust) duct. The access hatch measures 11.66 ft long by 4 ft wide. For models that are too large for the test section access hatch, a model access door is located downstream of the test section at the end of the diffuser in corner A (see Figure 1). The corner A model access door is 8 ft high by 10 ft wide.

The IRT is designed to simulate the FAA icing envelope for different cases of liquid water content (LWC) and median volumetric diameter (MVD). A refrigeration plant and spray-bar system generate a cloud of microscopic supercooled droplets using deionized water to simulate the icing environment inside the tunnel. Examples of IRT models are shown in Figure 3, and more information is provided in the reports on icing research and tunnel capabilities listed in References 1 to 20.

2.2 Wind Tunnel Performance and Capability

The maximum calibrated airspeed achievable in an empty IRT test section is 300 knots. The maximum speed for each model will vary depending on the size, shape, and different configurations of the test article and the associated test section blockage. The larger the model, the blunter the shape, and

the larger the projected frontal cross-sectional area, the lower the maximum speed. Figure 4 shows two plots estimating maximum tunnel speed based on test article blockage. As ice accretes on the model and throughout the tunnel loop during the daily test run, the achievable maximum speed will decrease due to blockage. As the ice accretion increases during the test run, the revolutions per minute (RPM) will increase to maintain the target airspeed. Discussions can occur prior to testing on how to approach test conditions that will reach near the tunnel RPM maximum.

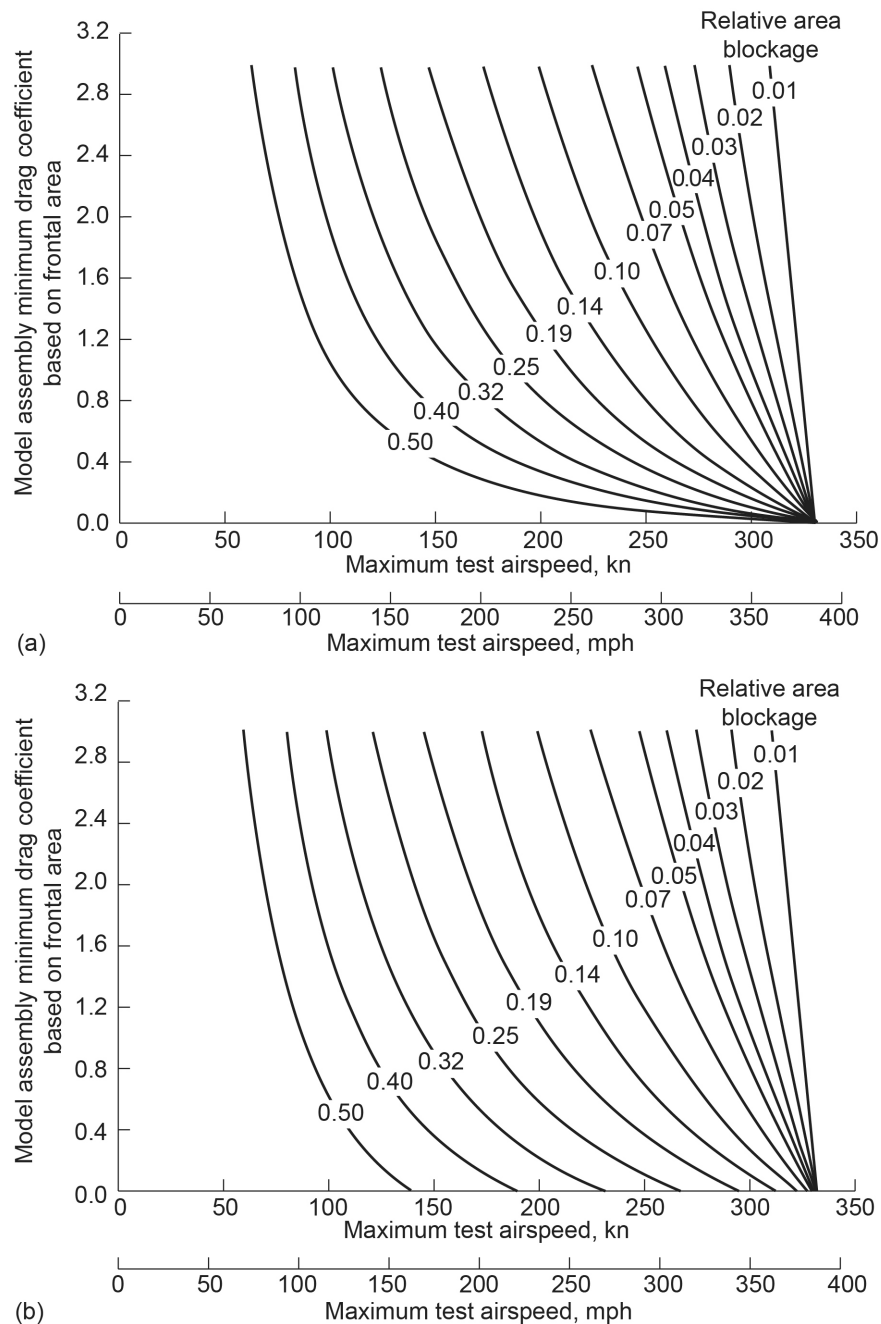


Figure 4.—Estimated maximum test airspeed in IRT based on relative area blockage and assembly drag coefficient. (a) Test model with streamlined afterbodies. (b) Test model with squared-off afterbodies.

The tunnel circuit operates at or below atmospheric pressure. The static temperature range for the test section can be controlled between -40 and 10 °C for the majority of the IRT speed range. Specialized high-speed cases have a maximum total temperature of 5 °C. Detailed statistical information on total pressure, static pressure, Mach number, test section velocity, flow angle, and total temperature are available in Reference 13.

2.3 Test Section Details

The view of the bellmouth inlet to the IRT test section through the spray bars is shown in Figure 5. This view is from the settling chamber (corner D) looking downstream into the test section.

The balance chamber that surrounds the test section (Figure 1) is at approximately the same static pressure as the test section. Therefore, no pressure bulkhead fittings or hermetically sealed connections are required for instrumentation leads and service air hoses entering the test section ceiling or floor. Personnel access to the test section from the balance chamber is through a 4.5-ft-wide by 5.25-ft-high door in the south tunnel wall.

The center of the 8.67-ft-diameter turntable is 106.5 in. from the inlet of the test section. The turntable can be rotated $\pm 20^\circ$ in the horizontal plane. A plan view of the turntable and model floorplate is shown in Figure 6. Tunnel users must supply a mounting plate to interface with the turntable floorplate. This interface must meet the specifications shown in Figure 7. The mounting plate must contain the mounting holes as detailed in Figure 7 for bolting the plate to the turntable. The model mounting plate may need additional holes for attaching the model to the floor plate, routing of instrumentation, wiring for electrical systems, and tubing for air systems. The model profile in the vertical plane is restricted to 71.5 in. A model that spans the full height of the tunnel can be attached to the test section ceiling.



Figure 5.—Downstream view of test section through IRT spray bars.

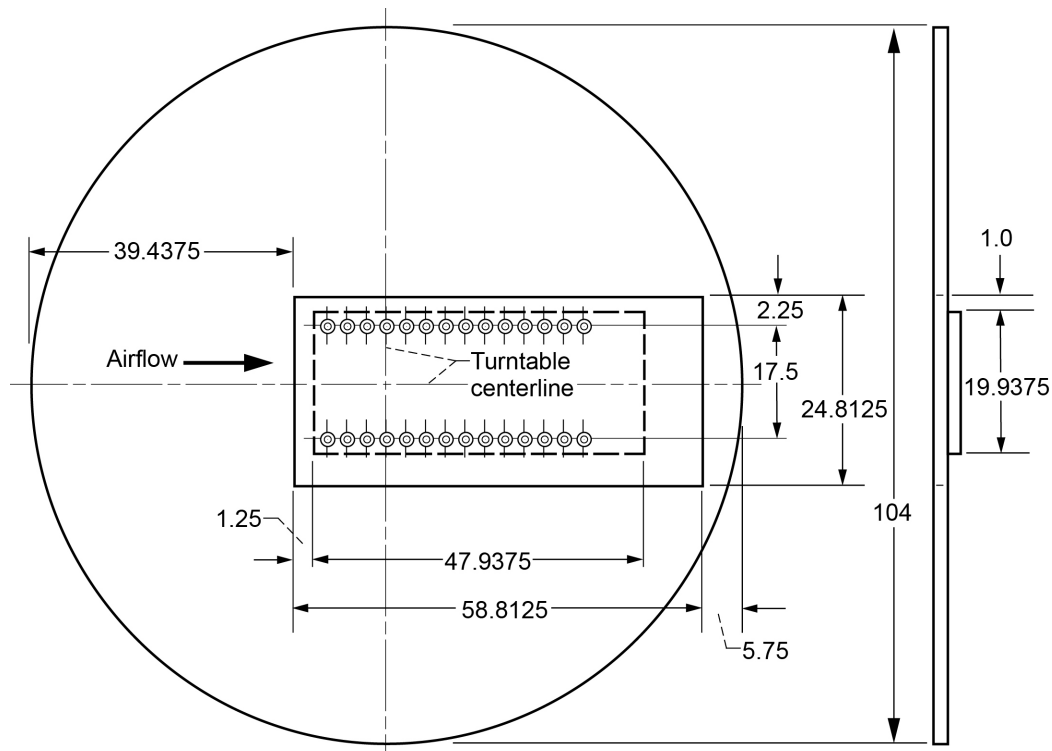


Figure 6.—IRT turntable and model mounting plate. All dimensions are in inches.

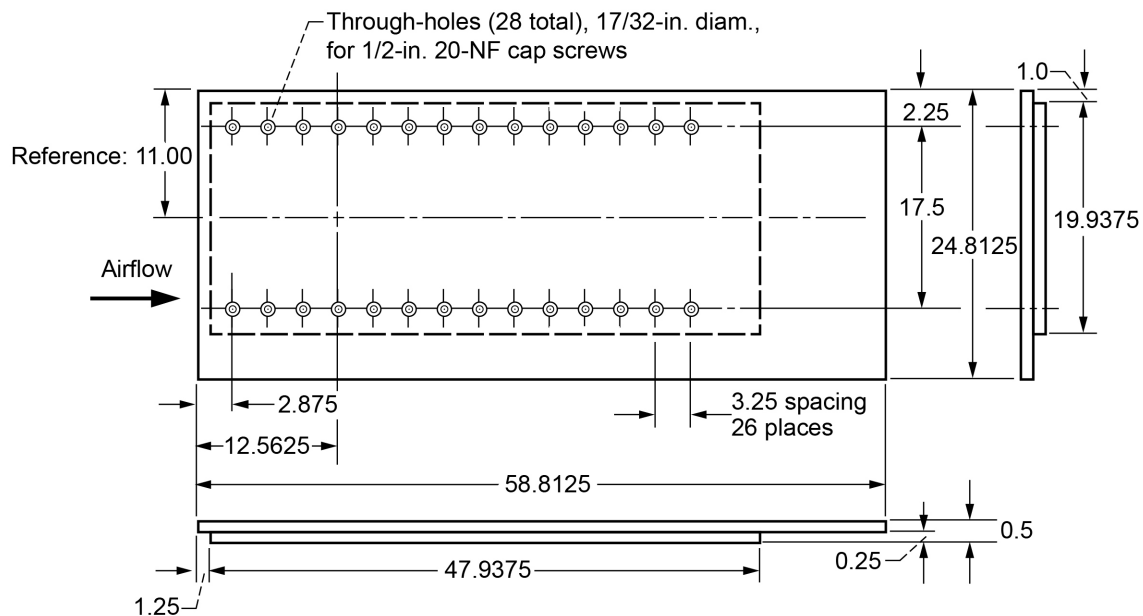


Figure 7.—IRT model mounting plate. Note: Tunnel is 6 ft by 9 ft wide. If model extends beyond turntable, leave 1/2-in. clearance above top or below bottom of model. All dimensions are in inches.

All forward-facing surfaces will accrete ice. This factor must be taken into consideration when designing a model and its attachments for test in the IRT.

The test section ceiling has an access hatch that is 4 ft wide by 11.66 ft long. Test articles and equipment can move into and out of the test section through the access hatch or test section door. A 2-ton overhead electric crane located on the third floor of the balance chamber is available to lift models and equipment from the first floor to the second or third floors. The model should have a hard lifting point(s) that will balance the model at the center of gravity to reduce the amount of rigging required. Openings in the hatch cover can be fitted with aluminum inserts or with acrylic windows for observation of the model from above. The support bars between the hatch openings can be removed and reset at 2-in. increments to make any size windows, with the exception of the small windows across the tunnel. Openings of 54 by 43 in. can be subdivided into smaller sections in 2-in. increments. The hatch windows are unheated. Users may supply panels of transparent material other than acrylic if required. The user-supplied panels must meet IRT safety requirements and conform to the orientation and dimensions shown in Figure 8. The thickness of these panels should be 1 in., which includes a 3/8-in. step. A drawing is available upon request.

In Figure 9, an isometric view of the IRT test section walls shows the tunnel's observation windows in relation to the turntable. The south control room (Figure 10(a)) contains four windows for observing the model during testing. Three windows are 29 in. wide by 44 in. high, and one window is 24 in. wide by 40 in. high. These four windows are electrically heated to prevent frost and fogging. The north control room (Figure 10(b)) contains a test section access door and three electrically heated windows. All three windows are 24 in. wide by 40 in. high.

2.4 Main Drive System

The major components of the main drive system are the drive motor, fan blades, fan inlet guide vanes, and fan outlet guide vanes. The synchronous motor is rated at 5,000 hp and is air cooled. The drive motor is installed inside a nacelle. The main drive motor is directly coupled to a fixed-pitch, 12-bladed fan fabricated from laminated Sitka spruce. The fan outer diameter is 25.17 ft, and the maximum rotational speed is 460 rpm. Fan control is via an operator station in the south control room. Start, stop, and motor speed (RPM) are adjusted throughout a given test run. Test section speed is derived from controlling the RPM of the motor. As ice accretes around the tunnel loop, the RPM of the fan must increase to maintain constant velocity in the test section.

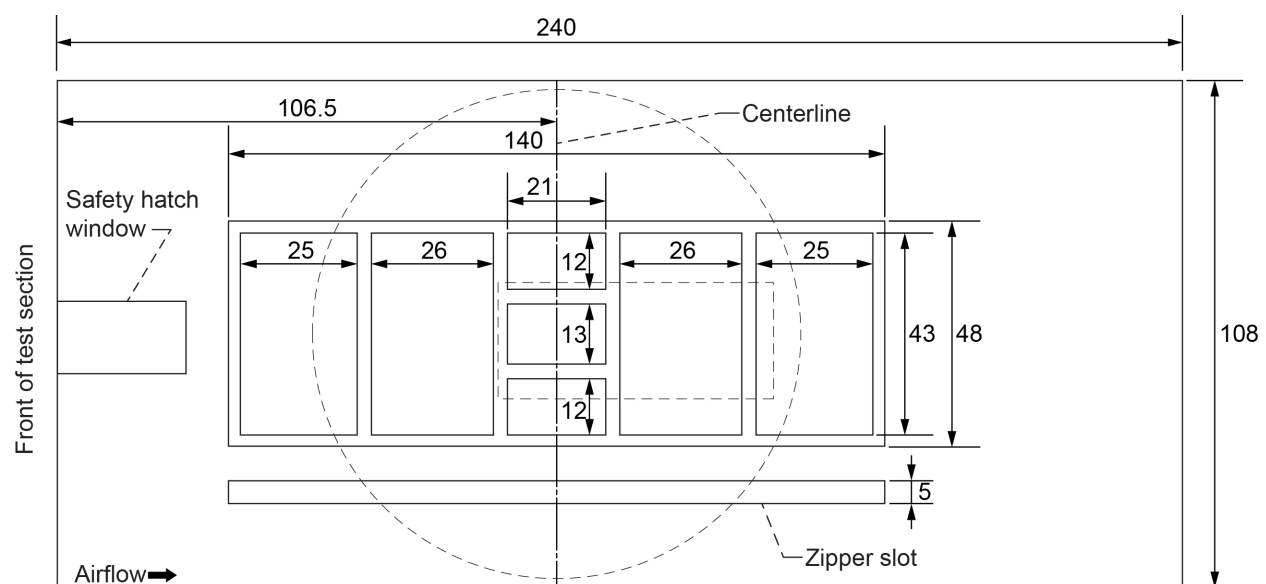


Figure 8.—Access to IRT test section from overhead hatch. All dimensions are in inches.

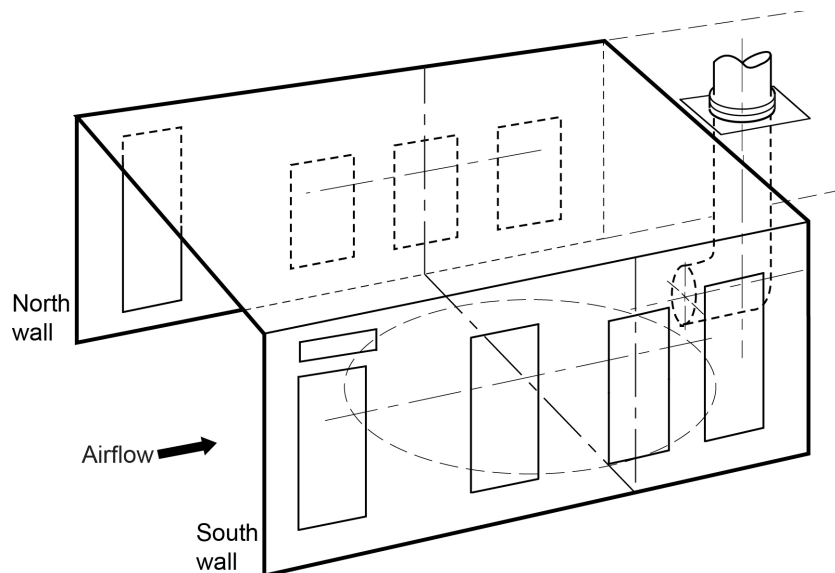


Figure 9.—Isometric view of test section.

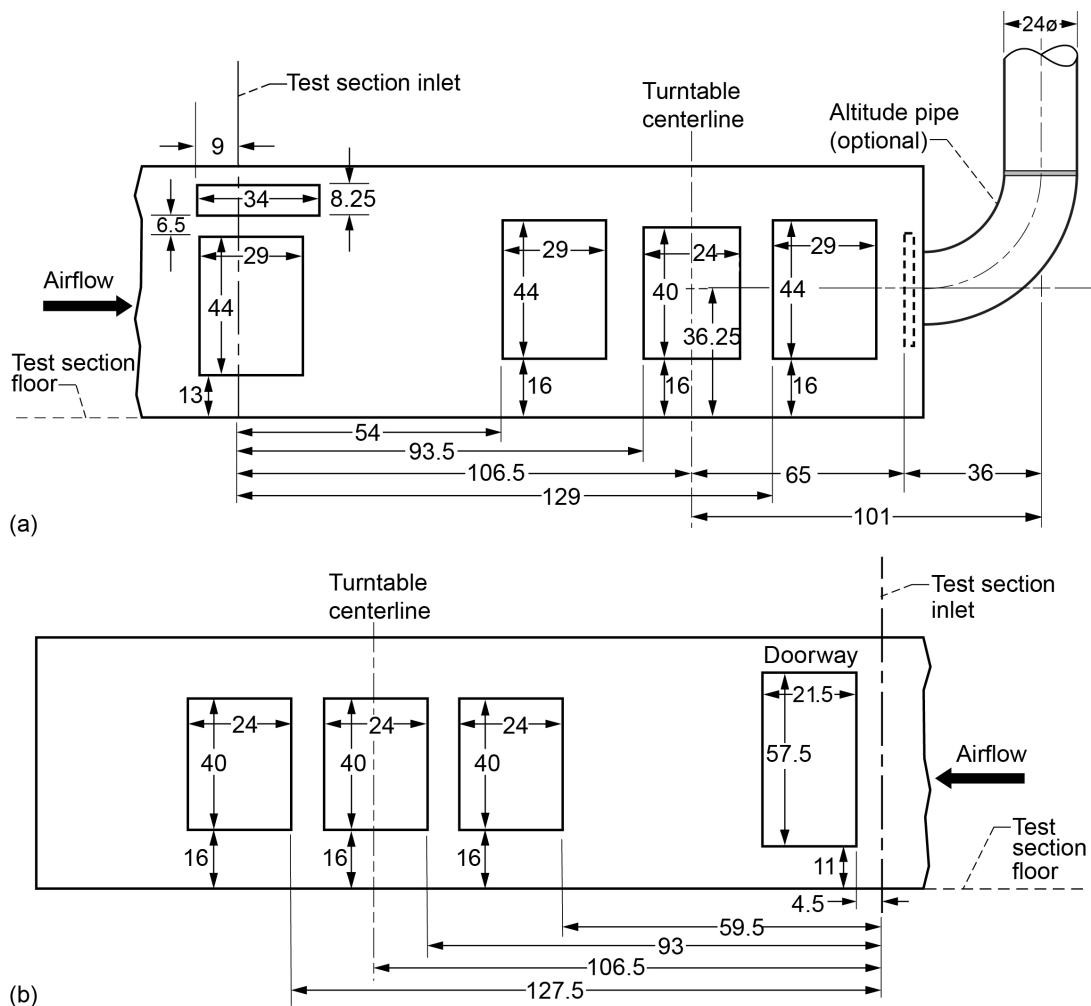


Figure 10.—Dimensions of control room walls against test section. All dimensions are in inches. (a) South control room. (b) North control room.

2.5 Velocity Control

At the test section entrance are two electrically heated pitot-static probes that are used to measure the total and static pressures required to compute the free-stream velocity. Once a model is installed, an aerodynamic checkout test is run. This run is used to verify the structural integrity and stability of the test article. Additionally, it establishes the base, clean relationship between fan RPM and test section airspeed. The goal is to reach 110% of the test article maximum airspeed for each configuration and/or the maximum tunnel conditions achievable. If the model experiences excessive flutter or other instability during the aerodynamic checkout, the allowable maximum velocity will be reduced. If the model causes excessive blockage, the maximum desired airspeeds might not be achieved. If there are known flutter concerns, a separate aeroelasticity analysis is required in addition to the model stress report.

2.6 Spray Bars

Air-assisted water spray nozzles are used to produce the distribution of drop sizes (MVD) and liquid water content (LWC) in the icing cloud envelope. Ten spray bars produce the uniform icing cloud in the test section. Two types of nozzles are installed in the spray system. They are labeled as Mod1 or STD (standard), with the only difference being the diameter of the water tube. The STD nozzles are used to produce a high LWC in the test section, and the Mod1 nozzles are used to produce a low LWC. The spray system is controlled by a dedicated programmable logic controller (PLC) integrated with the IRT control system. Each nozzle set is connected to a separate water manifold with a common air manifold. Both nozzle sets are used simultaneously to achieve the highest LWC conditions.

The goal of the IRT is to replicate the FAA aircraft icing certification standards contained in 14 CFR Part 25, Appendix C and Appendix O. The IRT operating envelope, with Appendix C and limited Appendix O conditions, is provided to tunnel users for test matrix creation. It is created from data acquired during the most current icing cloud calibration (Ref. 14).

Figures 11 and 12 show the IRT icing envelope at 100 and 250 knots with the FAA Appendix C envelopes.

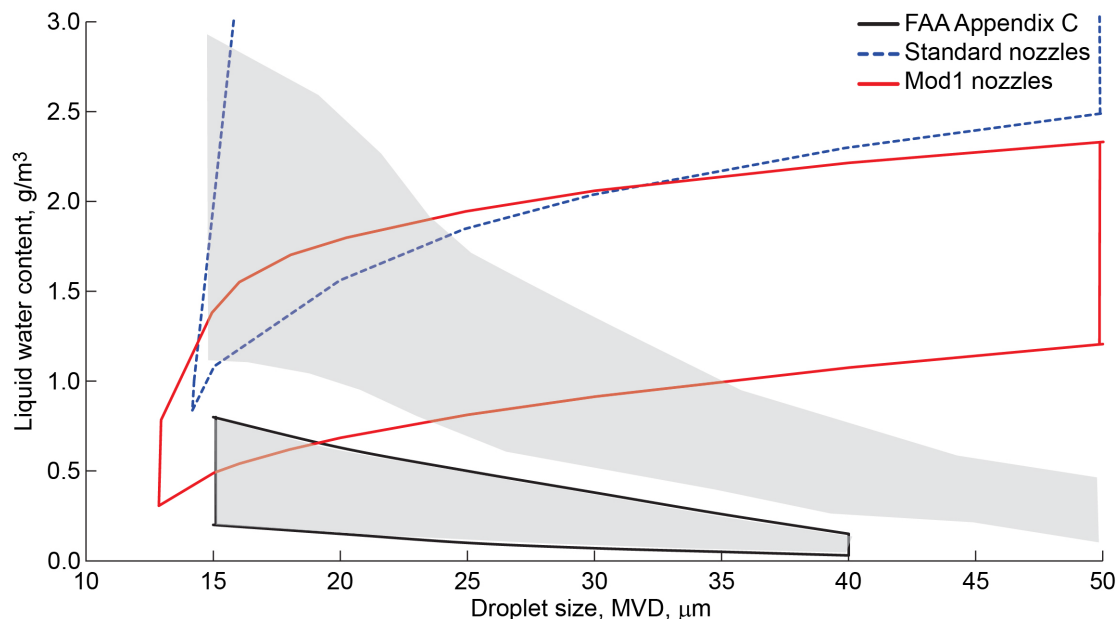


Figure 11.—IRT icing envelope at 100 knots.

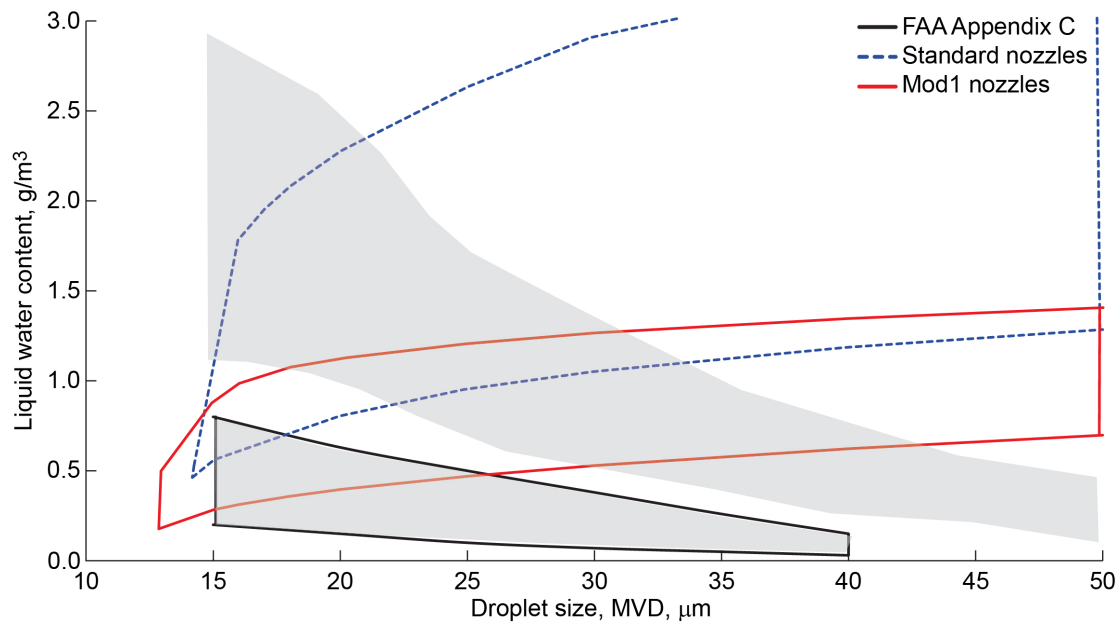


Figure 12.—IRT icing envelope at 250 knots.

2.7 Control Rooms

The control rooms, the balance chamber, and the facility test section are all at the same static pressure. Two control rooms, primary and secondary, are located on the second floor of the balance chamber adjacent to the test section. Specific details of control room equipment function and location are discussed in pretest meetings.

The primary (south) control room is for the IRT operators, engineers, and tunnel user personnel. The tunnel is operated from an interactive distributed control system. There are three operator stations for setting and monitoring the facility's operations. From these consoles, operators control tunnel fan speed, spray-bar air and water pressures, spray duration, turntable position, tunnel temperature (refrigeration system), and other auxiliary systems as required. A broadcast-quality video station and the COBRA (Collect Observe Broadcast Record and Analyze) data acquisition interface station are also located in the south control room. The north control room acts as an overflow area to the south control room.

3.0 Tunnel Support Service Systems

3.1 Heated Air Systems

The IRT has a heated air system for models that require bleed air simulation: a Stahl natural gas burner and an inline 110-kW, 440-V electric heater. The gas heater is located outside in the tunnel courtyard. The burner is supplied by 150-psig combustion air or 125-psig service air with 60-psig natural gas. The burner specifications are presented in Table I.

A 2-in. supply line that feeds off the main 4-in. line enters the electric heater located inside the balance chamber underneath the test section. Heated air is transported to the model through a 2-in. flex line with a Swagelok® (Swagelok Co.) fitting that can be downsized to meet model requirements. The electric heater performance is presented in Table II.

TABLE I.—BURNER DETAILS

Operating condition	Combustion air	Service air
Pressure, psig	150	125
Flow rate, lb _m /s	1.0	1.0
Temperature, °F	500	700

TABLE II.—ELECTRIC HEATER DETAILS

Flow rate, lb _m /s	Up to 1.0
Temperature, °F	700

Two valves in the system isolate heated air flow to the model and direct it through a vent. The gas burner and the electric heater can be used independently or in series. When the gas burner and the electric heater are used simultaneously, the gas burner acts as a preheater. The configuration of the heated air system is decided in pretest meetings.

3.2 Steam and Service Air Systems

A 3/4-in.-diameter line provides 40-psig steam, which may be used for model and/or instrumentation deicing. Service or shop air, nominally at 125 psig, is available for systems that require compressed air, such as ejector valves or pneumatic tools that may be needed to install the model in the test section.

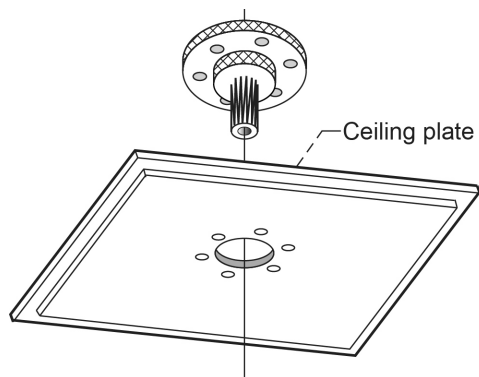
3.3 Model Interface at Tunnel Ceiling

3.3.1 Pivot Pins

Six types of pivot pins are available to support models at the hatch (ceiling) of the IRT test section. The pin material is 7075-T6 aluminum. The outside diameters of these pins vary from 1.0 to 3.0 in. As shown in Figure 13, the selected pin is inserted through an opening in a test section hatch plate and into a user-supplied bushing or spherical bearing located at the top of the model. The pivot pin is fastened to the test section hatch bushing plate located in the ceiling hatch. This configuration adds stability to the model. The table in Figure 13 lists the six types of pivot pins available for use at the IRT. The hollow core of the pivot pin can be used to bring instrumentation lines from the model through the IRT test section hatch to user/facility data acquisition systems.

3.3.2 Bushings

Seven types of bushings are available for model support at the hatch of the IRT test section (Figure 14). The inside diameters of these bushings vary from 0.530 to 2.530 in. (see the table in Figure 14 for details). The bushing material is 7075-T6 aluminum. The bushing selected is inserted through an IRT hatch plate and onto a user-supplied pin mounted at the top of the model. The bushing is fastened to the hatch plate. The addition of the bushing adds stability at the top of the model.



Pivot pin details

Item	D1, ± 0.005	D2, ± 0.005
A	3.000	2.000
B	2.500	1.500
C	2.000	1.000
D	1.500	0.750
E	1.250	0.500
F	1.000	0.000

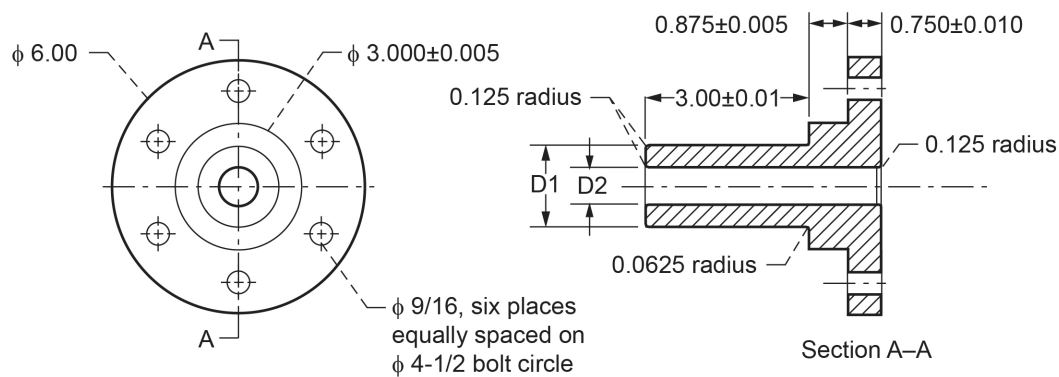
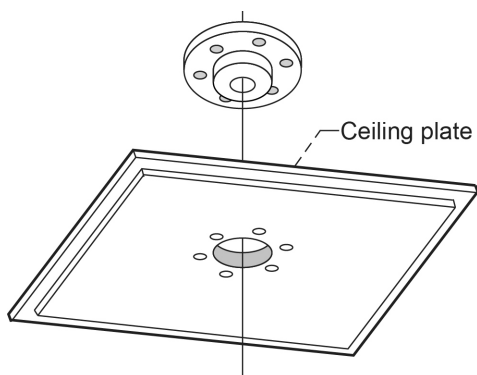


Figure 13.—Pivot pin details. All dimensions are in inches.



Bushing details

Item	D1, ± 0.005
A	2.530
B	2.030
C	1.530
D	1.280
E	1.030
F	0.780
G	0.530

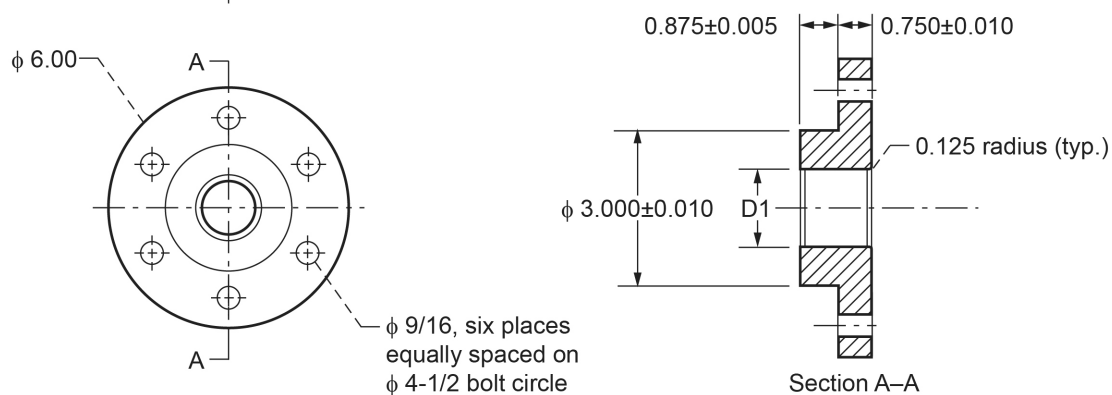


Figure 14.—Bushing details. All dimensions are in inches; typ. is typical.

3.3.3 Hatch Plate

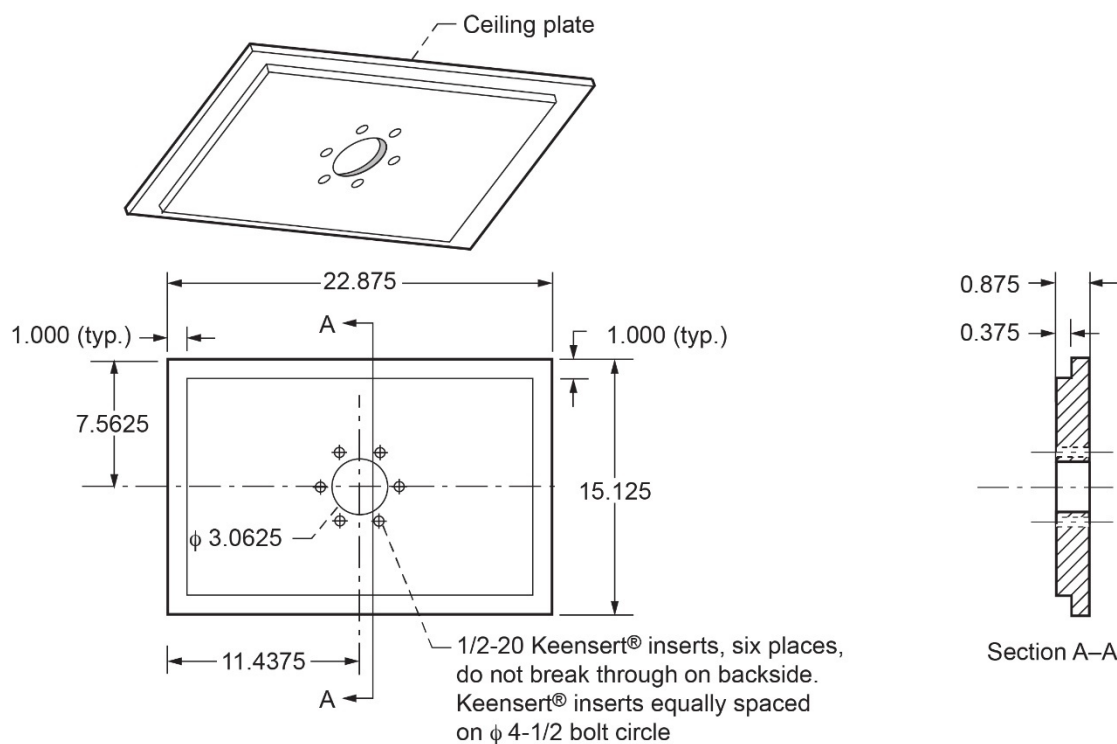
The ceiling plate presented in Figure 15 is used to retain a pivot pin (Section 3.3.1) or a bushing (Section 3.3.2). The hatch plate is made of 6061-T6 aluminum and is inserted in the test section access hatch of the IRT. The hatch plates are held in place by clamping devices.

3.4 Engine Inlet Model Exhaust System

The IRT altitude exhaust system is used to simulate internal flows for inlet or engine models. It consists of a series of duct expansions and contractions that vary in diameter from 24 to 36 in. The geometrical relationship between the test section turntable and the altitude exhaust piping is presented in Figure 16. The exhaust flow rate is measured by a venturi installed in the facility ducting and located on the roof of the IRT. Three venturi diameters are available (small, medium, and large) with calibrated ranges of 0.1 to 3 lb_m/s, 3 to 20 lb_m/s, and 15 to 85 lb_m/s. Changing between the medium and large venturis requires a day of downtime and favorable weather.

The flow is controlled by an electric butterfly valve integrated into the facility control system. The exhaust pipe flange is skewed in the vertical plane (see Figure 16) and requires custom connection between the model exhaust and the inlet to the steel elbow. Tunnel users who decline or cannot use the existing IRT exhaust connectors will need to procure applicable components. Specific details for an applicable test entry will be discussed in pretest meetings.

The altitude exhausters (large vacuum pumps) that provide the flow are a laboratory-wide service for use by several Glenn facilities. They are located within the central process system facilities and are a shared resource that is scheduled weekly. Demands for this service are variable and may require different test shifts for any given test. Tunnel users must request this service from the facility manager so the associated power costs can be included in the estimated price.



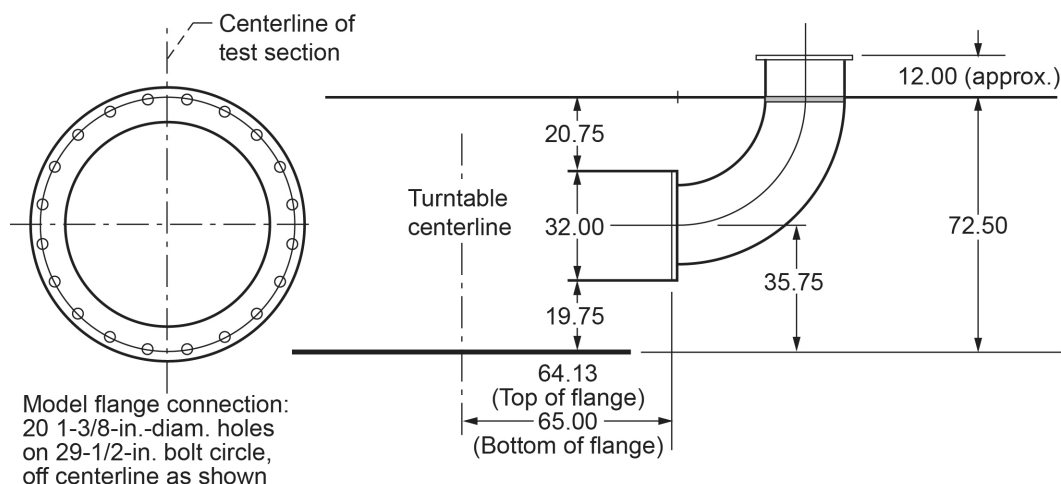


Figure 16.—Altitude exhaust attachment detail; standard steel flanges and elbow for connecting inlet models to exhaust system.

TABLE III.—POWER AVAILABILITY FOR TUNNEL USERS

Voltage, V	Phase	Frequency, Hz	Current, A	Circuits available, no.
0 to 120 VAC	Single	60	20	6
480 VAC	Three	60	20/3	2
0 to 40 VDC	---	---	100	3
0 to 400 VDC ¹ or 0 to 300 VAC ¹	DC or Single, Three	DC or 16-819 Hz	0 to 100 A (DC) ¹ or 0 to 100 A (AC) ¹	Up to 6 single phase, 2 three-phase, depending on configuration

¹Configurable using California Instruments® MX-45 (AMETEK Inc.). Maximum capabilities differ by usage.

3.5 Model Electrical Power

The descriptions and maximum capacities of the power systems available to tunnel users are listed in Table III.

Special requests are handled on a case-by-case basis and addressed in pretest meetings.

4.0 Instrumentation

Instrumentation in the IRT is categorized as either facility instrumentation or model instrumentation. Facility instrumentation consists of sensors and instruments necessary to monitor and control the tunnel safely and effectively. The data from these instruments display on Ovation™ (Emerson Electric Co.) control system operators' stations. Most of the facility instrumentation measurements are duplicated in the COBRA data acquisition system via an Ethernet link between Ovation™ and COBRA. Detailed information on the uncertainty analysis of facility measurements can be found in Reference 20.

Model and facility instrumentation calculations are handled by the COBRA data acquisition system, which is capable of compiling the following:

- Facility parameters: Velocity (UTSK), motor RPM, average tunnel temperature, model angle of attack, spray-bar control parameters, heated air flow, heated air temperature, altitude exhaust flow, and other auxiliary systems.

- Temperature (Bustec® ProDAQ® 6150 (Bustec Production Ltd.)): 144 Type K and 144 Type T thermocouples.
- Temperature (resistance temperature detector (RTD)): 64 100-Ω four-wire channels available.
- Pressure (NetScanner™ (TE Connectivity)): 176 0-to-5-psid channels and 64 0-to-100-psid channels available. Further module modifications can be discussed with IRT electrical engineers to accommodate additional 0-to-5-psid channels.
- Analog: 128 ±10V channels available with configurable gain, sensitivity, and sample rate.

4.1 Temperature Measurements

4.1.1 Facility Temperature Measurements

Tunnel total air temperatures are measured at corners C and D, upstream of the test section (see Figure 1) by probes mounted on the leading edges of the turning vanes. Corner C uses an array of 16 Type T thermocouples that are mathematically averaged to present the total temperature in corner C at the entrance of the heat exchanger. Corner D utilizes an array of 24 100-Ω platinum RTDs, which are averaged to represent the total air temperature at the exit of the heat exchanger and upstream of the spray bars and test section. The aerothermal calibration of the IRT derives the test section total temperature, correcting for the effect of the spray-bar air injection. These data points are available in both the facility control system and the COBRA data system.

4.1.2 Customer Tunnel User Temperature Measurements

The model temperature measurement system utilizes six Bustec® ProDAQ® 6150 isolated precision thermocouple LXI instruments. (LXI stands for LAN (local area network) eXtensions for Instrumentation.) The units accept two-prong mini connectors and are located in a cabinet underneath the turntable. There are 288 thermocouple channels (144 Type K and 144 Type T) available for tunnel users' models, as shown in Table IV. One Bustec® ProDAQ® 6150 unit has 48 channels. Users must terminate their instrumentation with connectors. This significantly reduces model installation time.

For measurements from –100 to 100 °C, the typical error of the Bustec® ProDAQ® 6150 system using Type K and Type T thermocouples is between ±0.07 and ±0.05 °C. The maximum error of the system for measurements from –100 to 100 °C is between ±0.6 and ±0.3 °C using Type K thermocouples and between ±0.45 and ±0.3 °C using Type T thermocouples. Note that these errors are for a sample rate of 1 sample per second. Each channel can be sampled up to 1,000 samples per second with a resolution of 1 sample per second.

The Bustec® system communicates to the data system via Ethernet connection and has a 24-bit sigma-delta analog-to-digital (A/D) converter. Each channel has its own cold junction compensation circuit with an internal thermistor that measures the cold junction temperature. The channels are also electrically isolated between channels and between channel and ground and are rated for common-mode voltages up to 350 VRMS. The calibration interval of the Bustec® ProDAQ® 6150 units is 12 months.

TABLE IV.—TEMPERATURE CHANNELS AVAILABLE

Measurement device	Thermocouple type	Max. no.	Connection style
Bustec® ProDAQ® 6150 LXI	K	144	Connector
Bustec® ProDAQ® 6150 LXI	T	144	Connector
RTD	Pt, 100 Ω	56	Bare wire

The IRT can accommodate up to 56 RTDs for users requiring precision temperature measurement. The facility instrumentation is limited to 100- Ω platinum RTDs ($\alpha = 0.00385$). However, any resistive device ranging from 0 to 500 Ω can be accurately measured and scaled with a user-supplied curve fit.

4.2 Pressure Measurements

The IRT acquires pressure data with a NetScanner™ distributed pressure data acquisition system employing a dedicated intelligent pressure transducer per input. The IRT NetScanner™ system is composed of three rackmount chassis, each of which can house up to eight 16-channel pressure scanner modules (model 9816). Each 9816 pressure scanner module includes 16 silicon piezoresistive pressure sensors and an integrated four-way pneumatic calibration manifold. This automatic manifold provides online re-zero, span check/calibration, purge, and leak-check functions. Each pressure sensor includes an integral temperature monitor and EEPROM (electrically erasable programmable read-only memory) chip for storage of pressure and temperature calibration data unique to that sensor. An onboard 32-bit microprocessor acquires the sensor data and generates temperature-compensated engineering unit (EU) data output via the Ethernet interface.

Each chassis provides electrical power, pneumatic supply connections, supply pressure data, hardware trigger, and Ethernet communication to each of the model 9816 pressure scanners. The IRT system uses two pressure controllers (model 9034) that automatically generate validation and re-zero pressures for the pressure scanner modules. The two-pressure controller full-scale ranges at IRT are 23 psia and 100 psia for the ± 5 -psid and ± 100 -psid scanner ranges, respectively. All modules use a buffered atmospheric pressure reference for every channel and a precision pressure standard within the 23-psia 9034 unit to enable conversion from psid to psia, used in the COBRA data system. The IRT configuration provides support for the purge feature on each module with a dry instrument air source capable of maintaining constant pressure while all ports are simultaneously purged. The purge feature prevents liquid water from forming and/or accumulating inside the model pressure tubing, where it can cause measurement errors.

4.2.1 Facility Pressure Measurements

The two pitot-static probes inside the test section use the facility NetScanner™ system. These pressure measurements are displayed in the facility control system and COBRA system. Together with the test section temperature, these pressures are used to calculate the tunnel test section airspeed.

The facility spray-bar air pressure and the differential pressure (air minus water, or ΔP) are displayed in both the facility control and COBRA systems. These pressures are measured with Honeywell® pressure transducers. The air pressure is maintained to ± 0.2 psig, and the differential pressure is controlled to ± 0.5 psig in the steady-state spray mode.

4.2.2 Tunnel User Pressure Measurements

There are 240 NetScanner™ channels available for test article pressure measurements. Table V shows the breakdown of pressure ranges. The ± 5 -psid range is typically used for model surface pressures. The ± 100 -psid pressure range is used for internal pressure bays, piccolo tubes, and any other measurement above 5 psid.

TABLE V.—PRESSURE MEASUREMENT RANGES

Pressure range	Ports available
± 5 psid	176 (adjustable)
± 100 psid	64

4.3 Model Attitude

A model mounted on the test section turntable can be rotated $\pm 20^\circ$ about the test section vertical centerline. Angular data can be recorded on both the IRT control and COBRA systems. The measurement is via a shaft-mounted encoder with a precision of $\pm 0.1^\circ$. Turntable rotation of more than $\pm 20^\circ$ can be accommodated if the requirements are within tunnel capabilities, as determined during pretest meetings.

4.4 Scientific Imaging

Video and still imaging equipment are used to document test setup and visuals during a test run. Photographic equipment may be mounted in or on the tunnel ceiling hatch panels or in the control room windows. Photographic equipment may also be carried into the test section between runs. If required, the acrylic windows may be replaced with other materials; specific options can be discussed with the facility engineer. Alterations to the hatch cover must be discussed with the facility engineer as far in advance of the test as possible. Lighting is provided by three light-emitting diode (LED) floodlights flush-mounted on the south wall and four LED mobile light panels. Glenn's Imaging Technology Center (ITC) has the expertise, equipment, and experience to meet the imaging needs of tunnel users. Scientific imaging specialists use a variety of imaging technologies for data acquisition and analysis.

The following services are performed by Glenn's ITC personnel and are at additional cost to a standard test. Tunnel users must request this service from the facility manager so it can be included in the estimated price. The ITC recommends that imaging requirements be discussed early in the project-planning process to ensure the availability of expertise and equipment. The following sections provide an overview of video imaging (4.4.1), still photography (4.4.2), high-speed video (4.4.3), infrared imaging (4.4.4), and 3D ice shape scanning (4.4.5).

4.4.1 Video Imaging

The IRT has a broadcast-quality digital video system. The major components of the system are as follows:

- High-definition (HD) cameras: Three Panasonic® AW-120KPJ cameras (Panasonic Holdings Corp.) and two InterTest box cameras
- Digital recorders: Six AJA® Ki Pro® Rack digital recorders (AJA Video Systems, Inc.), ProRes 422® (Apple Inc.) encoding
- Teranex® video processors (Teranex Systems, Inc.): Two available
- Data system overlay: Six channels available
- Video router: Allows routing of video to various monitors
- Monitors: Primary (65 in.), secondary (70 in.), and various-sized monitors to display test video

Three primary video cameras are available. These views are of the test section from each control room and a forward-looking-aft (FLA) view from a hatch at the test section entrance. These views are hardwired through the COBRA data overlay to digital video recorders (DVRs) 1 to 3. All three views are remote pan, tilt, zoom, focus, and iris controllable. The auxiliary cameras are remote zoom, focus, and iris controllable. They must be tripod mounted or otherwise hard mounted, but they are mobile for specific views not seen by the standard fixed primary cameras.

DVRs 1 to 3 are fixed to the primary camera inputs. DVRs 4 to 6 are user defined for input. The auxiliary cameras may be routed to any of DVRs 4 to 6. Any internal model cameras may be routed to DVRs 4 to 6 only. User-supplied cameras must have HD-SDI (high-definition serial digital interface)

BNC connectors for connection to the IRT video system. The DVRs' file size is approximately 1 GB/min. They have the capability to perform interval recording from 1 fps (frames per second) to the full 60 fps. Using interval recording at a lower frame rate can greatly reduce the file size but potentially reduces the capture of any intermittent events during testing. The IRT standard procedure is full frame-rate recording, with interval recording available on request.

Each video view records to hard drives on the AJA® Ki Pro® DVRs. There is one hard drive per view. The DVRs have a dedicated output to confidence monitors. The view displayed on the confidence monitor is what is being recorded. The video is copied to a hard drive(s) that contains all tunnel user data deliverables (video, photographs, high-speed images, infrared images, and COBRA data). This hard drive(s) is shipped after the test to an address provided by the user. Tunnel users must assess the delivered hard drive to ensure they received and can access all files.

All deliverables are stored on a local system for 4 weeks after the test or until additional space is required. The files are then deleted, with the exception of the COBRA data files, which are stored in the data systems archives.

4.4.2 Still Imaging

Two cameras are available for tunnel users. Memory cards, external flash, spare batteries, and chargers are available for use with these cameras. In most cases, flash use is recommended. Photographs captured are copied to the tunnel user's hard drive. The photographs are not archived; they are stored temporarily and deleted on the same interval as the video files (Section 4.4.1). The following cameras are available for use:

- Nikon® D850 DSLR (digital single-lens reflex): 45.7-megapixel CMOS (complementary metal-oxide-semiconductor), 3.2 tilting touch-sensitive LCD (liquid crystal display)
- Olympus® Tough TG-5: 12 megapixel BSI (backside-illuminated) CMOS, F2.0 lens, IP8X rated

4.4.3 High-Speed Imaging

For tunnel users requiring high-speed video imaging, the IRT has access to the following cameras:

- Phantom® v7.3 (Vision Research, Inc.)
- Phantom® v9.0
- Phantom® v10
- Phantom® v2640: 4K resolution
- Photron® SA5 (Photron Ltd.): Excellent low-light performance with 1K resolution

System setup consists of a high-speed camera connection to a dedicated laptop via Ethernet. For a multi-camera setup, each camera requires a dedicated laptop. Event triggering is done from the laptop via a coaxial cable. Multiple camera triggering is accomplished from one trigger box attached to a laptop. The trigger can be input by the camera operator upon visual detection of an event, or the input can be triggered by an event in the picture frame. In the IRT, an operator-entered trigger is the most reliable.

The trigger input can either stop the recording or start the recording. It can also be timed to occur at any point during the recording. Example: The camera is in record mode and is continually recording. An event is detected, and the camera operator triggers the camera. The record time is 10 s, as defined by the RAM in the camera and the other defining parameters. The operator has set the trigger to be at 5 s. The resulting recording will show the 5-s period preceding the trigger input and the 5-s period following the trigger input.

While the recording is captured to the dedicated laptop, another monitor displays a live view of the event via an external video-out signal. The cameras record in a continuous mode in their volatile memory.

The cameras will start re-recording once the internal memory is full, overwriting the previous recording, and will repeat this until a trigger input is detected. Once the camera is triggered and the recording is completed, the recording can be played and trimmed to a specific moment of the event.

The length of each recording depends on several factors: the size of the internal volatile memory of the camera; the size, in pixel area (total number of pixels), of the picture being recorded; the frame rate; and, to a lesser extent, the exposure time. Nonvolatile memory options are not currently available without hardware purchase. Downloading of the selected portion of the recording is done from the camera to the laptop via the Ethernet cable. Downloading must be completed before the camera is ready for another recording session.

4.4.4 Infrared Imaging

For tunnel users requiring infrared (I/R) imaging, the IRT has access to the following I/R cameras:

- FLIR® SA640 (Teledyne FLIR, LLC): Handheld, 640 by 480 resolution, calibrated for cold temperatures
- FLIR® A8500: Tripod mount, 4K resolution, calibrated for cold temperatures, 50-mm and 100-mm lenses available

The I/R cameras can only be used from the north control room. Normal window glass is opaque to I/R cameras, so an acrylic window with an infrared window insert is used. The infrared window insert is specifically made for the type of camera used. Only one camera is available at a time.

The I/R camera is connected to a laptop via Ethernet. FLIR® licensed software is used to view and record the event. The frame rate for recording videos can be varied (30 Hz and slower). This allows for recording of events that are longer in duration. The camera can output a video signal via HD-SDI, and this output can be routed to the IRT video system for viewing. The thermographic file containing the I/R data is recorded and processed on the laptop connected via Ethernet. Any computer that has the correct software can be used to view thermographic files.

Each recording is saved to the laptop or connected device in real time and is available for review as soon as recording ends. Every parameter of the recording can be changed postrecording except for temperature range and focus. Temperature range is set to the temperatures expected during a test run (e.g., 5 to -25 °C).

Parameters that can be altered postrecording include emissivity, color scale, span, spread, reflected infrared, environment temperature, lens temperature, window transmissivity, and humidity. Emissivity indicates an object's efficiency in emitting infrared energy in values ranging from 1.0 (perfect) to 0.3 (very bad). Standard black electrical tape has a known emissivity of 0.97 and is often used to gauge the emissivity of an unknown object.

Variables that cannot be measured or controlled can add to the uncertainty of the temperature readings. Known variables, such as test article emissivity and reflected temperature, can yield more accurate temperature readings, which are considered quantitative data. Otherwise, the recorded thermographic data is considered qualitative.

Examples of I/R imaging use include measuring the temperature change associated with the impingement, runback, and freezing of water on an airfoil; monitoring deicing heater zone warming; and detecting the transition between laminar and turbulent air flow.

4.4.5 3D Ice Shape Scanning

Glenn's Icing Research Branch has developed a process to use a 3D laser scanner to digitize an accreted ice shape (Refs. 16 to 19). The process involves using a ROMER® Absolute Arm™ SI (integrated scanner) articulating arm with Geomagic® software (Hexagon Mfg. Intelligence, Inc.) to acquire the data. The arm projects a laser line on the surface and a charge-coupled device (CCD) camera uses triangulation to determine the surface location. The maximum line resolution is 0.002 in. Reference points (#6-32 countersink) must be placed on the model on orthogonal flat surfaces and/or other points with known coordinates. The ROMER® arm has a reference point probe to measure point data at these locations. This translates the scanned data to the model coordinate system. The model must be able to withstand a titanium oxide-based "ice paint" (TiO₂ suspension) and 99.9% isopropyl alcohol (IPA) cleaning. The ice paint coats the ice shape, allowing for reflection of the laser into the CCD camera.

The process can be reduced to the following base steps:

1. Accrete ice on the test article.
2. Spray ice shape with ice paint (~2 to 5 min).
3. Install and prepare the scanner arm and computer (~2 min).
4. Scan the ice shape (~10 to 25 min, depending on ice shape size and complexity).
5. Remove scanner arm (~2 min).
6. Clean model with IPA (~5 to 10 min, depending on model size and complexity).

The laser scanner can capture most of the features on a swept-wing scallop ice shape except for the deep gaps between the scallop shapes. The laser scanner cannot scan into holes or deep crevasses. The process will not capture every feature of an ice shape, but the resulting 3D laser scan is aerodynamically equivalent to a cast-produced ice shape. Aerodynamic tests with both laser-scanner-created and cast ice shapes illustrate that the NASA-developed process is capable of digitizing aerodynamically equivalent ice shapes. Figure 17 shows real ice shapes side-by-side with postprocessed 3D laser scans of the ice shapes. Figures 17(a) and 17(b) show a scallop ice shape and 3D laser scan, and Figure 17(c) and 17(d) show a rime ice shape and 3D laser scan.

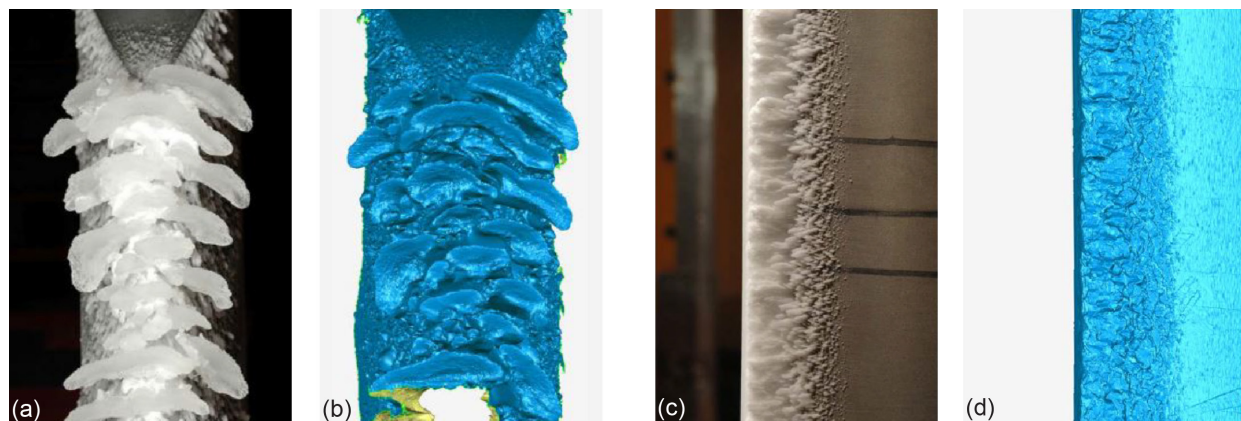


Figure 17.—Ice accumulation. (a) Scallop ice shape. (b) Postprocessed 3D laser scan of scallop ice shape. (c) Rime ice shape. (d) Postprocessed 3D laser scan of rime ice shape.

5.0 Data Processing

5.1 Data Acquisition Hardware

COBRA (Collect Observe Broadcast Record and Analyze) is Glenn's standardized low-speed (under 800 samples per second per channel) data acquisition system. The system uses commercial off-the-shelf (COTS) hardware and operating systems coupled with NASA-developed data acquisition and application hardware/software modules. It has a flexible and scalable design that utilizes a distributed network architecture approach (Figure 18). This design allows the attachment of measurement devices from a wide range of vendors. This approach allows the system to evolve over time and permits use of the latest technology that meets Glenn's measurement requirements.

The COBRA system consists of distributed servers, data acquisition systems, display stations, an operator station, and output devices all connected via a network switch. The data acquisition systems and nodes within the COBRA system utilize a synchronized time generator that provides Network Time Protocol (NTP), Precision Time Protocol (PTP), IRIG (Inter-Range Instrumentation Group) signals, and frequency outputs. The generator is synchronized to GPS/USNO (Global Positioning System/United States Naval Observatory) time via the Glenn central time source.

The Universal Data Server (UDS) runs the data processing engine (DPE) and the COBRA Calculation Processor (CCP). The DPE is responsible for collecting and aggregating data from one or more data acquisition systems and recording the data. These raw data are then available to the CCP to perform real-time calculations, including EU conversions as well as more complex variable calculations.

The display stations run the data viewer software. The data viewer receives data from the UDS across the COBRA network. The data viewer software allows the user to view real-time data in numerical and graphical representations (Figures 19 to 23). The data viewer screens can be customized for each test as well as reconfigured during a test.

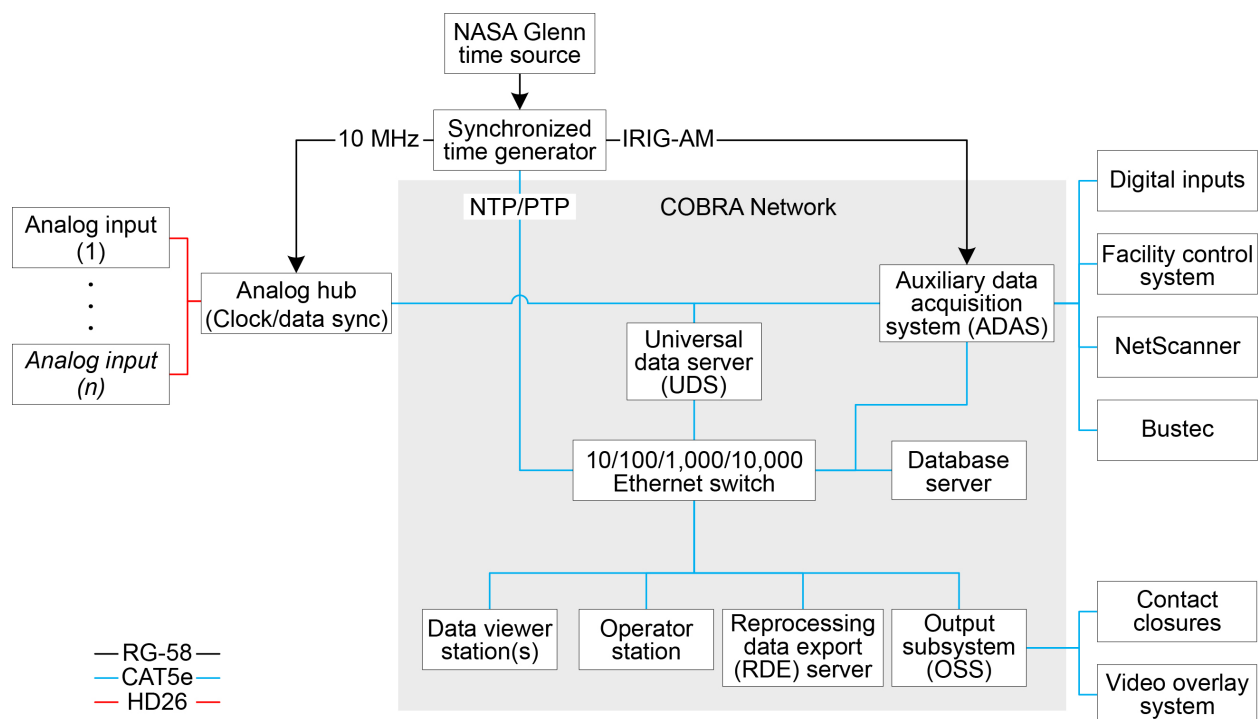


Figure 18.—COBRA architecture.

The operator station is used to configure and manage the COBRA system. It runs the user operator interface, configuration tool, device and channel run-time reconfiguration interface, data viewer, and reprocessing and data export interface. The data engineer uses the COBRA Configuration Tool (CCT) to create a COBRA project for each test. The test project contains all the setup information, channel definitions, and user calculations. Standard facility calculations are prebuilt using facility parameters and reference measurements such as test section speeds and pressures. For a list of facility calculations available, please contact the IRT project engineer and the IRT data engineer.

The IRT COBRA data acquisition system consists of the following:

- Analog input system: DSPCon® PodLink P4-PLS (DSPCon, Inc.)
- Electromechanical pressure measurement system: TE Connectivity's NetScanner™ 9816 scanners and 9034 calibrators
- Temperature measurement system: Bustec® ProDAQ® 6150
- Facility control system interface
- Resistance temperature detector (RTD) channels

5.2 Real-Time Displays

Six monitors are available for real-time data display. Three are generally reserved for tunnel parameters. Figures 19 to 21 show the standard facility display and custom test displays. The additional three monitors are available for tunnel users (e.g., for real-time plotting). The plots requested most by tunnel users are measured C_p (pressure coefficient) versus x/c (airfoil thickness/chord length) superimposed on a plot of theoretical C_p versus x/c . The desired theoretical data is supplied by the user, preferably in a Microsoft® Excel® (Microsoft Corp.) spreadsheet format. Other variables, such as temperatures, can also be plotted versus time. Plots and displays can also be newly created or modified in the control room with the assistance of the IRT data engineer(s). Figures 22 and 23 show examples of real-time C_p plots and thermocouple measurements.

Analog data (voltages) from an experiment are acquired by a DSPCon® system located beneath the test section. These analog channels can be used for ± 10 -V signals, with appropriate conversions to EUs for use on display screens and for exporting the data to an output file.

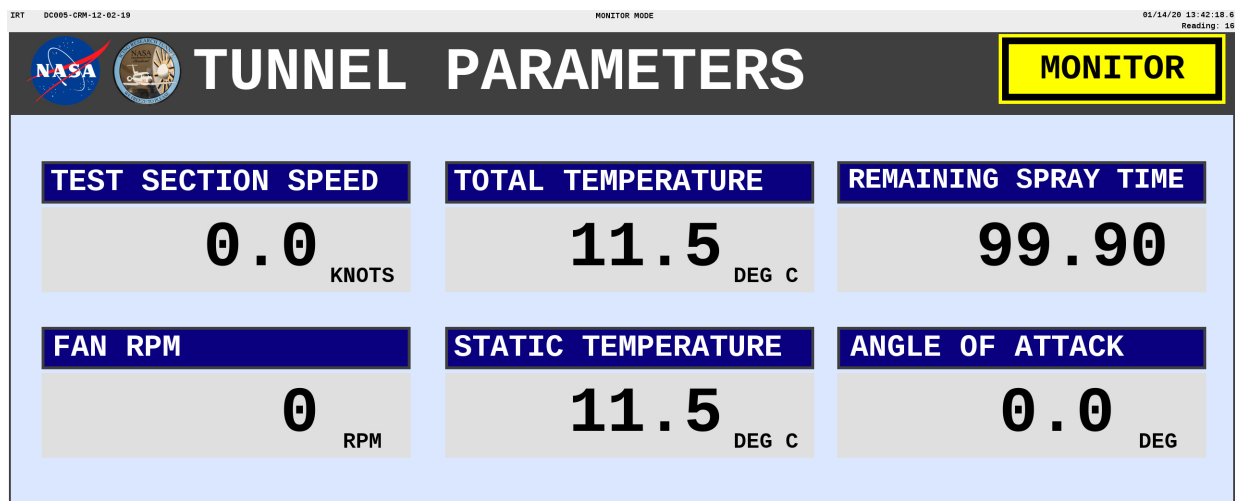


Figure 19.—Tunnel overview display.

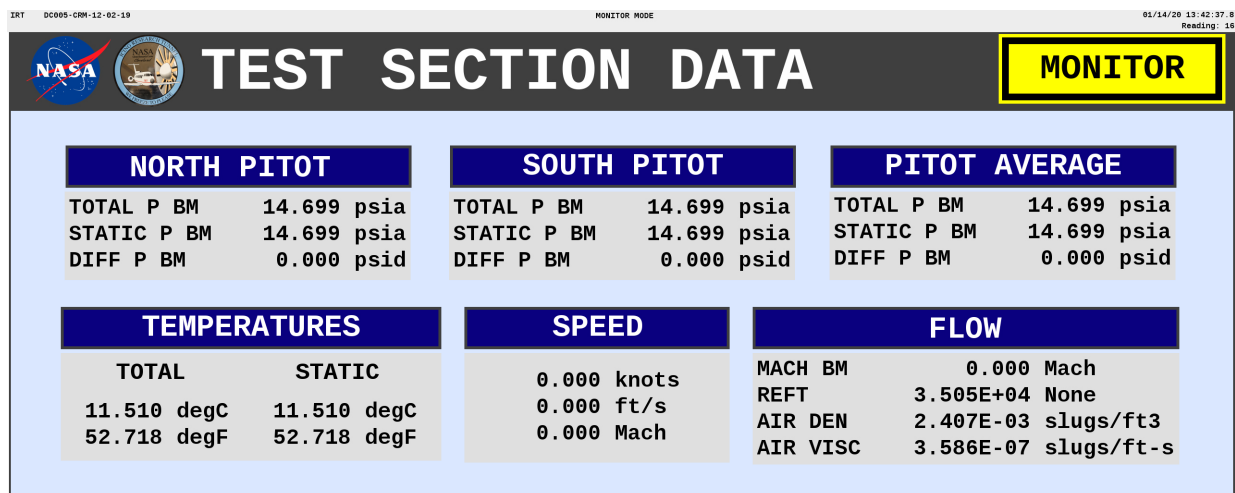


Figure 20.—Test section overview display.

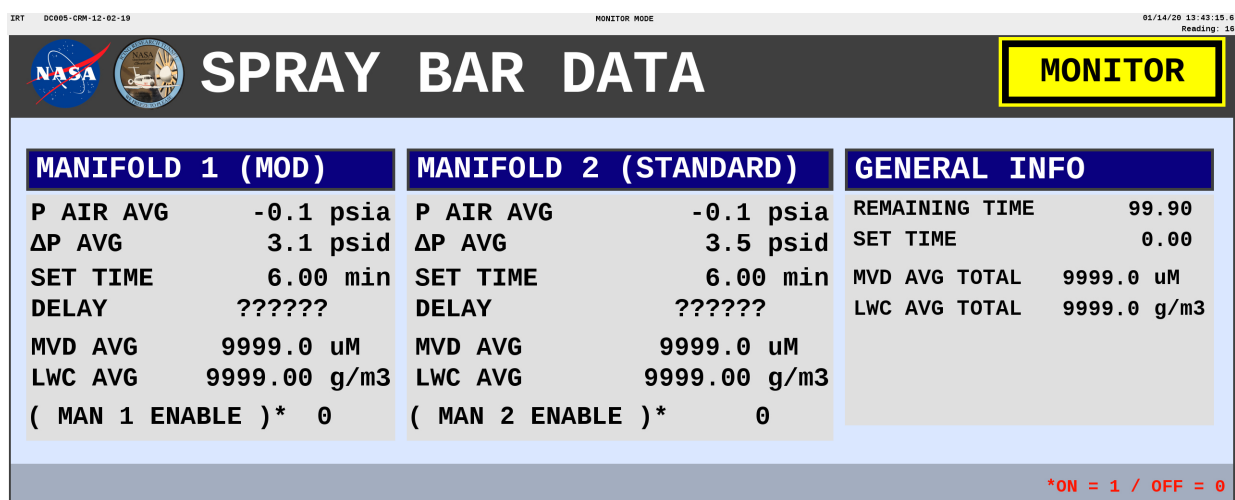


Figure 21.—Spray bar overview display.

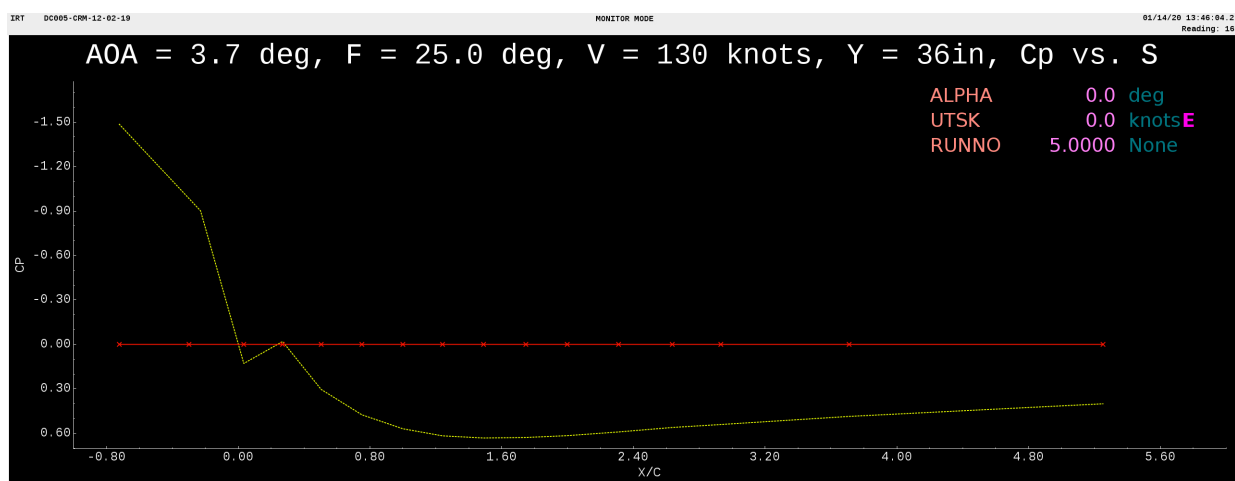


Figure 22.—Example real-time C_p plot.

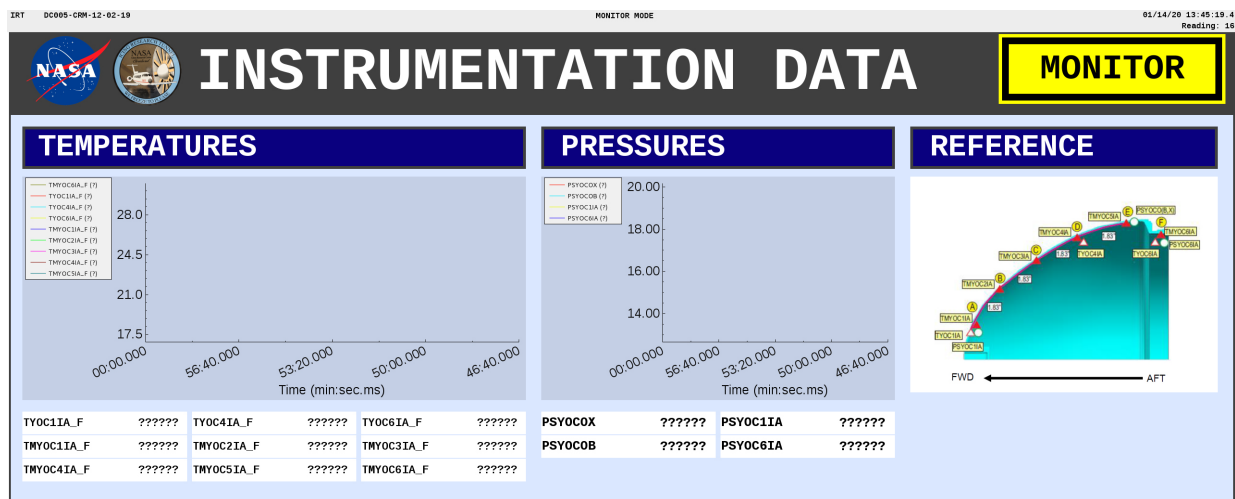


Figure 23.—Example model temperature and pressure plot.

Tunnel users have the option of furnishing their own data acquisition and data processing equipment or providing model instrumentation compatible with the COBRA system. A single IRIG-B signal is available and can be provided using a BNC cable, allowing timestamps to be synchronized between facility and user data and control systems. If more than one source requires the signal, it would need to be split. Data acquisition needs should be specified during a pretest meeting between the tunnel user, the IRT facility manager, the IRT project engineer, the IRT electrical engineer, and the IRT data engineer.

5.3 Data Collection

When COBRA data are recorded, all data channels are scanned, saved, and assigned a unique reading number. Recordings can be manually triggered for a specified length of time or begun as an open-ended recording that is then manually ended when desired. There are two sources to initiate a recording:

1. General Purpose Panel (GPP): This source is a physical panel of buttons, each programmed with different functions, including a Record button to start an indefinite recording, a Monitor button to end any recording and return to monitor mode, and a Single Point button to trigger a predefined length of recording. The time interval of the Single Point button can be changed to meet the tunnel user's needs. COBRA recordings triggered from the GPP will not automatically trigger video recordings.
2. Ovation™ Record: This source is a manual or automatic triggering of a recording through the tunnel control system, Ovation™. COBRA recordings triggered through Ovation™ will automatically trigger video recordings to start as well.
 - a. Spray Record/Spray Delay: This recording method automatically triggers a COBRA recording based on tunnel Spray On/Spray Off. As an additional feature, Spray Delay mode enables the recording but then delays the start of the spray by a user-defined interval. This allows for data acquisition in dry air prior to spray on. For example, if the spray delay is 5 s, the data recording will start 5 s before the spray will initiate. When the spray is complete, the data recording will continue for 5 s after.
 - b. Single Point: Similar to the Single Point GPP button, Single Point recordings through Ovation™ will trigger a COBRA recording of a predefined length.

All data are stored as both raw instrumentation data and with EUs obtained with appropriate conversion calculations. When the data are batched and exported, either or both can be included upon request.

5.4 Data Output

All data collected are stored on COBRA's Reprocessing and Data Export (RDE) server, from which the data can be exported for the tunnel user. The user may require only specific output parameters from all the data channels that are automatically being recorded. The data can also be exported as either a cyclic or an average recording. A cyclic export will contain every individual scan collected; an average export will average all the scans into a single value for a given recording.

A customized output file can be generated based on the tunnel user's requirements and input. The standard output file format is .CSV (comma-separated value), but if other file formats are required, this can be discussed with the IRT project engineer and IRT data engineer. The name of the file can be customized to include the date, time, test name, and recording identification number. The file contains header rows with user-defined names or descriptions and EUs, followed by the values of recorded data. The first few columns show the reading number, date, time of day, and scan number, followed by user-defined channels. Appendix B presents a sample of a customized COBRA output file and a symbols list of parameters that are listed in the table.

Typically, the output file is generated at the end of each spray cycle. From the COBRA workstation, all data can be copied to a Universal Serial Bus (USB) or tunnel user hard drive. Output files can also be copied directly from the COBRA file server by the tunnel user using a local network connection.

6.0 Pretest Requirements

The IRT is scheduled for continuous testing throughout the year except for a summer and winter shutdown for laboratory-wide maintenance. Tunnel users are advised to contact the IRT facility manager (see Section 10.0) at least 1 year in advance of the desired tunnel test entry. Early notification will allow the facility manager and appropriate IRT personnel to review the proposed model design and to ensure compatibility with the tunnel test section. Non-NASA users should contact the IRT facility manager at Glenn Research Center for the IRT Test Request Form.

On receipt of a completed IRT Test Request Form, a cost estimate will be prepared and sent to the tunnel user. If the user is in concurrence with the proposed test cost, Glenn Research Center's reimbursable test process for initiation of a Space Act Agreement (SAA) will be started. The SAA is a legal contract between NASA and the customer that covers responsibilities, schedule, financial obligations, liabilities, and data rights. A signed SAA will be required prior to the start of any testing and active throughout the duration of the facility occupancy period.

The tunnel user is also requested to prepare an IRT model systems report for the IRT project engineer prior to the first pretest meeting held at Glenn. The IRT project engineer will specify the content of the IRT model systems report. A general description of the contents of this document is presented in Section 7.1.

6.1 Pretest Meetings

A series of pretest meetings are held at Glenn to discuss the test plan, instrumentation, tunnel hardware, data requirements, power requirements, and other miscellaneous services described in the following paragraphs. The number of pretest meetings required is a function of the complexity of the test. The attendees at these meetings are the requester/user personnel (e.g., the lead engineer plus key test personnel), IRT facility manager, IRT project engineer, IRT electrical engineer, and key IRT personnel.

6.1.1 Test Objectives and Run Schedule

The requester should provide a statement indicating the test objectives and goals. The statement should thoroughly explain any special test requirements. A prioritized run schedule compatible with the available test window should also be provided.

6.1.2 Instrumentation

The tunnel user should provide the IRT project engineer with a list of requested instrumentation. If the COBRA system is to be used, the tunnel user's instrumentation must be adapted to the IRT data system (see Sections 4.0 and 5.0). If the tunnel user's data system is to be used, this should be discussed with the IRT project engineer and the IRT electrical engineer at the first pretest meeting.

6.1.3 Hardware

The tunnel user is required to submit drawings of the model and support hardware as installed in the test section. The tunnel user must provide (1) the mounting plate to attach the model to the test section turntable (see Section 2.3); (2) any hardware necessary to fasten the model to the tunnel, other than that shown in Figures 6 to 8 and Figures 13 to 16; and (3) guidelines to handle hardware security.

6.1.4 Data Acquisition

Tunnel users may choose to bring a self-contained computer system onsite for data processing. Such arrangements can be discussed with the IRT project engineer and the IRT electrical engineer to ensure compatibility.

6.1.5 Power Requirements

The power requirements for the model should be stated by the tunnel user at the pretest meeting. The power available is discussed in Section 3.5.

6.1.6 Services Required

At the pretest meeting, tunnel users should specify which facility services will be required for their tests. The services available are heated air systems (Section 3.1), engine inlet model exhaust system (Section 3.4), and model attitude (turntable positioning) system (Section 4.3).

6.2 Pretest Documentation

The tunnel user must supply the IRT project engineer with the following information at least 8 weeks before the scheduled tunnel test:

1. Test matrix for the model
2. Model system drawings (see Section 7.1.1)
3. IRT model systems report (the IRT project engineer establishes the content of this report; the outline of this report is presented in Section 7.1)
4. All calibration information required of the tunnel user
5. A list of all tunnel-user-supplied equipment, with block diagrams and wiring schematics of the equipment
6. Model assembly and installation procedures (see Section 7.4)
7. Data acquisition instructions (see Section 6.1.4)

If a model is identical or very similar to a previously installed model, and if the test conditions do not exceed those of previous tests, the requirement to submit load and stress reports may be waived because of the similarity. If the tunnel user and Glenn Research Center agree to a cooperative publication of the data, the tunnel user may be asked to supply selected model drawings and/or photographs for reproduction in NASA technical papers.

6.3 Model and Equipment Delivery

All models, instrumentation, and support hardware should be delivered to Glenn to the attention of the IRT project engineer (the IRT facility manager will supply the name of this engineer to the tunnel user). To reduce installation delays (see Section 7.2), all model parts, model internal instrumentation, and tunnel-user support hardware should be assembled prior to shipment to Glenn. Large shipping crates must have skids so they can be handled by forklift trucks. The maximum weight of the model plus the shipping crate should not exceed 4,000 lb. The delivery date of equipment and models prior to testing will vary according to the complexity of the model installation and the amount of instrumentation to be hooked up to the data system. The tunnel user and the IRT project engineer should agree upon an appropriate delivery time.

When shipments leave the tunnel user's plant, the IRT project engineer should be notified of the scheduled arrival date and identifying shipping numbers. Deliveries are normally accepted at Glenn from 8:00 a.m. to 3:00 p.m. eastern time, Monday through Friday, excluding Federal Government holidays. Off-hour delivery can usually be accommodated by prior arrangement with the IRT facility manager or the IRT project engineer.

7.0 Risk Assessment of Wind Tunnel Model and Test Hardware

The following sections discuss permissible model design criteria pertaining to loads and allowable stresses, which are presented in the IRT model systems report, and model fabrication and quality assurance requirements. The information within Sections 7.1 and 7.2 is summarized from the NASA Technical Standard document NASA-STD-8719.28, "Wind Tunnel Model Systems Criteria."

7.1 Model Systems Report

An IRT model systems report prepared by the tunnel user is required for all model systems to be tested at Glenn. The IRT model systems report is to be a complete, comprehensive stand-alone document. The user must submit this report to the IRT project engineer at least 8 weeks prior to tunnel entry, but the IRT project engineer may request an earlier delivery date for the report. The IRT project engineer establishes the content of the IRT model systems report from the information outlined in Sections 7.1.1 to 7.1.7.

7.1.1 Model System Drawings

The model system drawings should include the as-built drawings of the model system configuration to be tested and (where applicable) assembly drawings, installation drawings, electrical sketches, and wiring diagrams. Detailed drawings of the cross-sectional area distribution of the model should also be provided to assist in checking blockage and air load calculations.

7.1.2 Model Design Loads

The model design load calculations must consider model specifications and requirements. Derived loads must consider aerodynamic, mechanical, and thermal effects. Life-cycle requirements must also be addressed (if applicable).

7.1.3 Model Stress Analysis

The models tested in the IRT are usually flight-type hardware, so the allowable stresses must be adjusted to reflect this fact.

Thermal stresses that could occur in the model because of the IRT experiments should be subtracted from the ultimate tensile strength and the tensile yield strength before safety factors for the allowable stresses are applied. The material properties used in calculations should be the expected minimum values.

The stress analysis should include (1) dynamic factors that may result from flow separation, (2) thermal stresses due to cold-air experiments, (3) stress concentration factors, and (4) cyclic thermal loads. The calculations should show that the worst-case load does not exceed the allowable stresses.

For each section of the model analyzed, there should be a sketch showing the forces and moments acting on that section. The analysis of each section should list approximations, assumptions, model section properties, and the heat-treatment conditions of the material. All general equations should be listed before the numerical values are substituted. The number of axial stations selected should be based on an axial cross-sectional model change of at least +5%. Detailed shear and moment diagrams for the model should be presented along with the stress analysis for a worst-case loads scenario.

The model stress analysis must summarize all safety factors that are used in model design calculations. General equation sets, terms, and computer programs must be referenced. Any assumptions used in equation set development must be properly noted. The model stress analysis should also specify material data for all components that comprise the model system as well as for fasteners that are used to secure model components together. The material data should include standard and minimum properties within the complete range of environments to which the model will be exposed (i.e., pressure, temperature, or other environmental effects).

A structural analysis for the model system components must be performed if applicable. This analysis considers bolted, welded, brazed, and bonded joints. A model system component analysis must be performed for pressurized systems, hydrostatic systems, and specialized model systems that are subjected to fatigue and thermal effects.

7.1.4 Model Stability Requirements

The IRT model systems report should have a section dedicated to model stability. The information presented should show that the model, mounting points, and restraints are statically and dynamically stable (i.e., there is at least a 15% margin between the natural frequencies of the model and its restraints and the model and model restraint frequencies that occur due to the test conditions) within the model test matrix. It should also discuss the effects of Reynolds number, Mach number, surface conditions, and so forth in the development of equations noted in the analysis. The range of such parameters as mass and inertia and the stiffness coefficients used in the dynamic analysis should be noted.

7.1.5 Inspection Report

The user may be required to supply the IRT project engineer with an inspection report. The IRT project engineer initiates this request and specifies the content of the inspection report. The inspection report may contain information on fabrication planning, material information, or nonconforming hardware control information.

7.1.6 Structural Test Report

The IRT project engineer initiates the request for a structural test report if required. This test report may include material properties, model load information, static and dynamic balancing, and model runup tests.

7.1.7 Hazard Analysis

A hazard analysis may have to be developed for some tests in the IRT test section. The decision to develop this analysis should be made at the first pretest meeting of the user, the IRT facility manager, and the IRT project engineer (at least 1 year before the actual tunnel test time). The IRT project engineer will decide if such an analysis is required and what the hazard report should contain. The hazard report can discuss possible damage to the model and the facility if a model failure occurs due to stress, thermal effects, fatigue, instrumentation malfunction, facility power loss, chemicals, or some other factor. This report is the joint effort of the IRT project engineer and the user. It is included as part of the IRT model systems report.

7.2 Design Criteria for Model and Support Structures

The following sections discuss model and support structure material selection, structural joints, pressure systems, pressure piping, and electrical equipment components.

7.2.1 Material Selection

Materials for the model and support structures are to be selected and sized based on the applicable physical and mechanical properties listed in one or more of the following standards:

1. American Society for Testing Materials (ASTM)
2. American Society of Mechanical Engineers (ASME)
3. SAE International
4. Aerospace Structural Metals Handbook (Department of Defense)

All material properties used in the model structural and hazard analyses shall be the minimum values for the complete range of environments to which the model will be exposed.

7.2.2 Structural Joints

All counterbores, spot faces, and countersinks in the model, mounting plate (Section 2.3), and other support structures must be aligned to keep the fasteners from bending due to torquing.

Information on the design of bolted joints and gaskets is presented in References 21 to 23. All structural bolted or screwed connections must have positive mechanical locks such as locking inserts, self-locking nuts, cotter pins, or safety wiring.

All welded joints should be designed and fabricated in compliance with the code of the American Welding Society (AWS).

7.2.3 Pressure Systems

Model systems and test equipment using hydraulic, pneumatic, or other systems with operating pressures above 15 psig shall be designed, fabricated, inspected, tested, and installed in accordance with ASME B31.3, Process Piping.

Pressure-relief devices may be required in a hydraulic or pneumatic system but not necessarily in the model. These devices should be able to relieve the overpressure by discharging a sufficient flow from the pressure source under the conditions causing a malfunction.

The IRT facility manager and the IRT project engineer should be given the following information about all components of a pressure system: volume capacity, temperature range, working pressure, and proof pressure. All components of a pressure system should be stored in clean, dry, and sealed conditions after proof testing and before delivery to the IRT.

7.2.4 Pressure Piping

All piping shall be designed, fabricated, inspected, tested, and installed in compliance with ASME B31.3. Allowances for thinning of the pipe wall due to bending and/or threading of the pipe should be in accordance with ASME B31.3. Threaded joints, seal welding of threaded joints, and flange joints must also comply with this code.

7.2.5 Electrical Equipment Components

Because of the harsh environment in the IRT test section, the hardware, equipment, and material to be used must conform to the National Electrical Code. Each set of wires on all pressure transducers, strain gauges, vibration pickups, and other low-voltage devices must be shielded. Details regarding user-supplied control panels and/or control boxes and the associated wiring to the facility control room should be discussed with the IRT electrical engineer at one of the pretest meetings. The format for user-supplied electrical schematics, wiring diagrams, and connectors to interfaces at control panels, control boxes, and/or the model should be also discussed with the IRT electrical engineer.

7.3 Model Fabrication Requirements

Models should be completely assembled at the manufacturer's plant, and any discrepancies should be corrected at that time. All model parts must be inspected to ensure proper fit and must be certified for the loads and deflections to be encountered during testing. In addition, all remotely controlled model functions must be checked out and all position indicators should be calibrated before shipment to Glenn.

All electrical leads and pressure lines from the model should be clearly identified. The pressure lines must be clean and free of oil and debris and must have been checked for leaks at operating pressures.

7.4 Model Installation Procedures

Written procedures for model assembly, installation, and configuration changes in the IRT are required for quality assurance. They should be submitted to the IRT project engineer at least 8 weeks before the scheduled test. These procedures should list sequentially the steps to be taken to mount the model in the tunnel test section. They should also indicate the model's alignment in the test section and the bolt torquing values for fastening the model to the mounting plate. The assembly, installation, and checkout of user-supplied hardware should also be addressed. The model installation procedures should be supplemented with the necessary drawings and/or sketches.

8.0 General Information

The following information is provided to familiarize the tunnel user with the services available and the standard operating procedures of the IRT.

8.1 Logistical Support

8.1.1 Model Buildup

In most instances, the designs of the models tested in the IRT vary from simple to moderately complex, and the degree of difficulty of installation in the tunnel varies accordingly. The lead time by which the model must arrive at the IRT before testing should be agreed upon with the IRT project engineer.

8.1.2 Space Assignment

The primary control room is used for tunnel operations, and space in it for tunnel users is limited. Most of the space in the secondary control room is generally available for tunnel users.

8.1.3 User Personnel Responsibilities

It is recommended, but not required, for the tunnel user to provide mechanics and technicians familiar with the model during installation. The user's personnel must set up any custom data systems, along with the required instrumentation. Any specialty and/or unique tools, spare parts, equipment, and supplies necessary to work on the model and its ancillary systems must be provided by the tunnel user. It is recommended that a tunnel-user aerodynamicist familiar with the model and the test objectives be present during testing.

8.1.4 Operation of Government Equipment

Tunnel-user personnel may not operate Government-furnished equipment or make connections to this equipment without the approval of a Glenn representative.

8.1.5 Tunnel Safety

Tunnel users may enter the tunnel test section only after they are given permission by the IRT project engineer or a qualified IRT tunnel operator. Care must be taken while examining the model in the test section to preclude injury from sharp edges on the model due to ice accretion or from instrumentation probes and/or rakes that may be positioned in the tunnel test section (see Section 9.1). The test section floor is slippery after a run, so caution must be exercised when entering the test section (see Section 9.1). All persons entering the tunnel for an extended period after a test run must wear the proper protective cold-weather clothing (see Section 9.2).

8.1.6 Aerodynamic Test for Model Checkout

The IRT project engineer will direct IRT personnel in the steps that are outlined in the Aerodynamic Test Record sheet. Step V on the sheet discusses the procedure to increase tunnel speed in 10% increments to 110% of the maximum test velocity. A copy of the Model Qualification Procedures sheet is available to IRT personnel from the IRT project engineer.

8.1.7 Support During Tests

All tunnel-user requests for worker assistance and shop or facility services should be submitted by the tunnel user to the IRT project engineer.

8.1.8 Personnel Safety Briefings

Prior to the start of the test program, the IRT project engineer will call a meeting to be attended by user and IRT facility personnel to discuss potential hazards and the methods of operations during the test.

8.2 Operations

8.2.1 Normal Operating Days and Shift Hours

The facility is staffed Monday through Friday for a two-shift operation. The first shift, 0700 to 1530 (7 a.m. to 3:30 p.m.), is reserved for model work and facility checkout. During the second shift, 1530 to 2300 (3:30 p.m. to 11:30 p.m.), tests are run between 1530 and 2200 (3:30 p.m. and 10 p.m.), after which the icing capabilities at the tunnel are shut off, and the fan is turned off at 2230 (10:30 p.m.) to allow for post-run tunnel checkouts. This test window can be expanded for an ambitious test schedule by requesting an early start. Tunnel users should discuss extending the test time with the IRT facility manager and the IRT project engineer as early in the pretest planning as possible.

8.2.2 Off-Shift Access

Access to the IRT at times other than operating shifts must be with the permission of the IRT project engineer.

8.3 Planning

8.3.1 Safety Permit Request

The IRT project engineer will prepare a Safety Permit Request package for each model. This package describes the safety aspects of the tests as well as the test objectives, run schedule, instrumentation, and hardware. The Safety Permit Request package is submitted to the Glenn Safety and Health Division (SHeD) via the Electronic Safety Permit System. The Safety Permit Request should be completed and available for review at least 12 weeks prior to the start of testing.

The following is a list of conditions that would require special action by the IRT Facility Safety Committee:

1. Use of radioactive materials or gases
2. Use of high-speed rotating model parts without suitable shrouds
3. Ejection into the tunnel circuit of material or gases that may cause an explosion
4. Use of hazardous materials

At one of the pretest meetings, the IRT project engineer can advise the tunnel user about the acceptability of toxic model materials. A Safety Data Sheet (SDS) is required for all hazardous materials.

8.3.2 Test Time

The tunnel test time charged to a non-NASA user will include the total time the facility is available to the user, that is, time for model and instrumentation installation and removal, experiment time, and time for returning the tunnel and associated areas to their pretest condition. The time required to uncrate the user's model and equipment and to crate them for shipment must also be included. Extensions to a test window may be granted. Extensions are negotiable between the tunnel user's lead engineer and the IRT facility manager. Discussions with Glenn personnel who have experience with the facility should enable the tunnel user to make a fairly accurate estimation of the time required to complete the test program.

8.3.3 NASA Debriefing

Prior to completion of the test program, the tunnel user's lead engineer shall meet with the IRT facility manager to evaluate the test support received by the tunnel user during the test program. The IRT facility manager will plan for the meeting.

8.4 Security Notification Requirements

The amount of advance notice required to obtain access to the IRT at the NASA Glenn Research Center depends on the classification of the test program and characterization of the non-NASA visitor. Access to Glenn is initiated by IRT personnel through the Enterprise Visitor Access Management System (EVAMS) Agency tool.

8.4.1 Nonclassified Test by U.S. Citizen

For nonclassified test programs, the IRT project engineer will notify the Glenn Office of Protective Services (OPS) through EVAMS at least 3 business days prior to the arrival of a non-NASA visitor who is a U.S. citizen. The following visitor information is required: (1) the name of the visitor, (2) the visitor's place of employment, (3) the business email of the visitor, (4) the purpose of the visit and the associated dates, and (5) the Glenn contact person and escort.

8.4.2 Nonclassified Test by Non-U.S. Citizen

All foreign national visitors must be sponsored. A foreign national is any person who is not a U.S. citizen or lawful permanent resident (LPR, also known as Permanent Resident Alien (PRA) or green card holder). A list of foreign national visitors must be provided to the NASA test lead at least 4 weeks prior to the visit to initiate the approval process. Visit requests for foreign nationals are initiated via IdMAX, NASA's centralized identity/access management system. The NASA test lead or designated sponsor enters the visitor's details and triggers the vetting/access workflow through IdMAX. The visitor will receive an email with a link requesting the following information:

1. Full legal name as it appears on passport
2. Date of birth
3. Country of birth
4. Citizenship(s)
5. Copy of passport – required to be uploaded
6. Copy of visa or visa waiver (also known as ESTA, Electronic System for Travel Authorization) – required to be uploaded

Note: Individuals from Visa Waiver Countries will be required to provide an I-94 document prior to admission to Glenn. This document is obtained upon entry to the United States and can be uploaded using the same link provided in the original email or by the NASA Identity Requester. More information about this document can be found on the U.S. Customs and Border Protection I-94/I-95 website at <https://i94.cbp.dhs.gov/home>.

Providing this information in advance of the visit is required. The review and identity vetting is performed by the international visitor coordinator (IVC) of OPS at Glenn.

On the first day of the visit, upon arrival at the NASA Glenn Main Gate, the visitor will be required to provide two forms of identification, typically a passport and a visa, and to have their photo taken. The visitor will be issued a foreign national visitor badge, and the NASA sponsor or assigned escort will meet

them at the gate and remain with them during the visit. Escort ratios are 1 escort to 5 foreign nationals from nondesignated countries, and 1 escort to 1 foreign national from designated countries.

When required, Access Control Plans (ACPs) should be submitted as soon as possible to OPS after IdMAX initiation. Policies for the use and creation of ACPs can be found in NASA Procedural Requirements (NPR) 2190.1, NASA Export Control Program. Additional information regarding ACPs can be found in NASA Advisory Implementing Instructions (NAII) 2190.1, Export Control Program Operations Manual. Foreign nationals are not authorized access to NASA IT assets at Glenn.

8.4.3 Sensitive Test by U.S. Citizen

A sensitive test program at Glenn may be conducted only by a U.S. citizen. For such tests, the proper security clearance must be in place prior to the arrival at Glenn of a non-NASA U.S. citizen. OPS must receive a visit notification letter from the visitor's place of employment. This letter is to include the following information for each visitor:

1. Social Security number
2. Full name
3. Date and place of birth
4. Security clearance level
5. Date clearance was granted
6. Who granted the clearance
7. Date and duration of visit
8. NASA contact

Visit notification letters are to be sent to the following address:

NASA Glenn Research Center
Attn: Office of Protective Services
Mail Stop 14-140G
21000 Brookpark Road
Cleveland, OH 44135
Phone: 216-433-7488
FAX: 216-433-6664

9.0 Personnel Safety

The following information is provided to acquaint the tunnel user with tunnel test section and facility control room safety requirements. However, tunnel users are responsible for understanding all the potential hazards associated with the operation of the IRT and protecting all user personnel from injury. User personnel are also responsible for any actions that may endanger Glenn personnel.

9.1 Hazards

All first-time tunnel users and/or visitors must take the mandatory safety briefing given by the IRT project engineer or the IRT crew chief. Additional hazards associated with a particular test will be discussed with tunnel users by the IRT facility manager and the IRT project engineer at one of the pretest meetings.

Tunnel-user personnel should be aware of the following hazards:

1. The facility control rooms are located within the facility balance chamber. Because noise levels in the balance chamber may be high during tunnel testing, noise levels in the control rooms may exceed acceptable levels. In such cases, hearing protectors (provided by Glenn) may be required.
2. Models installed in the tunnel test section may have sharp edges due to their design and fabrication and/or the accretion of ice during testing. The tunnel users and the IRT project engineer should discuss tunnel test section safety associated with the model at one of the pretest meetings.
3. The test section floor is often wet and slippery due to melting ice, condensation, and/or the use of spray bars during a tunnel test. Tunnel users should not enter the test section to examine the model after a test run until they have the permission of the IRT project engineer or a qualified tunnel operator. Tunnel users entering the test section after a test run must wear appropriate shoes and be careful of their footing.
4. Barometric pressures in the balance chamber may be as low as 3.3 psi below atmospheric under extreme conditions, which is equivalent to an altitude of approximately 7,200 ft. Abrupt airspeed changes during normal and emergency tunnel operation will cause the pressure in the balance chamber and in both control rooms to change quickly and may cause some discomfort to personnel.

The tunnel user's lead test engineer is responsible for ensuring that all members of the user team are accounted for prior to closing the access hatch to the tunnel test section.

9.2 Protective Equipment

Users may require protective hearing equipment while working in the balance chamber when the tunnel is operating. When the model is being examined between runs, users should wear cold-weather clothing and gloves (both supplied by Glenn).

9.3 Emergency Procedures

The IRT facility has specific operating procedures to protect tunnel personnel, the facility, and computing equipment in case of emergency. The IRT project engineer will discuss these procedures with tunnel users at the pretest meeting on Day 1 of the test entry.

9.4 Working Alone

Inside the tunnel, users should always work in groups of at least two people. Working alone is not permitted unless specific, limited approval is obtained in advance from the IRT project engineer. Working alone is defined as working out of audio or visual contact with a coworker for more than 5 min.

10.0 Contact and Shipping Information

Contact information was current at the time of publication but is subject to change. Visit the IRT website at <https://www.nasa.gov/centers-and-facilities/glenn/icing-research-tunnel/> for current information.

10.1 Facility Manager

The facility manager is the key contact person at the IRT. The facility manager may be contacted in any of the following ways:

- Email: dennis.g.eck@nasa.gov
- IRT website: <https://www.nasa.gov/centers-and-facilities/glenn/icing-research-tunnel/>
- Phone: 216-554-7474
- Mailing address:

NASA Glenn Research Center at Lewis Field
Attn: Dennis Eck
Mail Stop 6-8
21000 Brookpark Road
Cleveland, OH 44135

10.2 Technical Lead

The technical lead may be contacted in any of the following ways:

- Email: waldo.j.acosta@nasa.gov
- IRT website: <https://www.nasa.gov/centers-and-facilities/glenn/icing-research-tunnel/>
- Phone: 216-433-2979
- Mailing address:

NASA Glenn Research Center at Lewis Field
Attn: Waldo Acosta
Mail Stop 11-1
21000 Brookpark Road
Cleveland, Ohio 44135

10.3 Shipping Information

Tunnel users' models and equipment can be shipped to the following address:

NASA Glenn Research Center
Attn: Waldo Acosta
Mail Stop 11-SHOP
21000 Brookpark Road
Cleveland, Ohio 44135

11.0 Concluding Remarks

The NASA Glenn Research Center's Icing Research Tunnel (IRT) is located in Cleveland, Ohio. The IRT is a closed-loop atmospheric tunnel with a test section that is 6 ft high, 9 ft wide, and 20 ft long. The facility is designed to support a testing environment simulating natural icing conditions. This user guide was created to provide common technical information and details typically exchanged with IRT tunnel

users for a test program. The structure of this guide has been developed to provide a high-level, general introduction for potential test tunnel users. Upon request to the IRT facility manager, tunnel users are provided a more detailed description of the test facility and its capabilities to address specific test program requirements. The IRT staff intends for this document to facilitate tunnel user understanding of the IRT's capabilities and the process of conducting a test in this world-class test facility.

Appendix A.—Nomenclature

2D, 3D	two-dimensional, three-dimensional
A/D	analog to digital
ACP	Access Control Plan
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
AWS	American Welding Society
BSI	backside illuminated
C_p	pressure coefficient
CCD	charge-coupled device
CCP	COBRA Calculation Processor
CCT	COBRA Configuration Tool
CFR	Code of Federal Regulations
CMOS	complementary metal-oxide-semiconductor
COBRA	Collect Observe Broadcast Record and Analyze
COTS	commercial off-the-shelf
CSV	comma-separated value
DPE	data processing engine
DSLR	digital single-lens reflex
DVR	digital video recorder
EEPROM	electrically erasable programmable read-only memory
ESTA	Electronic System for Travel Authorization
EU	engineering unit
FAA	Federal Aviation Administration
FLA	forward looking aft
GPS	Global Positioning System
HD	high definition
I/R	infrared
IPA	isopropyl alcohol
IRIG	Inter Range Instrumentation Group
IRT	Icing Research Tunnel
IVC	international visitor coordinator
LCD	liquid crystal display
LED	light emitting diode
LPR	lawful permanent resident
LWC	liquid water content
MVD	median volumetric diameter
NAII	NASA Advisory Implementing Instructions
NTP	Network Time Protocol
OPS	Office of Protective Services
PLC	programmable logic controller
PRA	Permanent Resident Alien

PSIA	pounds per square inch absolute
PSID	pounds per square inch differential
PSIG	pounds per square inch gauge
PTP	Precision Time Protocol
RAM	random access memory
RDE	Reprocessing and Data Export
RPM	revolutions per minute
RTD	resistance temperature detector
SAA	Space Act Agreement
SDI	serial digital interface
SDS	Safety Data Sheet
STD	standard
UDS	Universal Data Server
USB	Universal Serial Bus
USNO	United States Naval Observatory
UTSK	test section velocity
VAC	volts alternating current
VDC	volts direct current
VRMS	voltage, root-mean-square

Appendix B.—Example of Exported COBRA Output Sheet

This appendix shows an example of a COBRA output file from a recording taken during a test run. Each recording is generally stored as a comma-separated value (.CSV) file. An export file can contain the contents of a single recording or multiple recordings from the same test program taken over several weeks of testing.

Because COBRA is a distributed system, most inputs do not begin recording data simultaneously; instead, data inputs at different sources can begin within a few milliseconds of one another, yielding invalid readings before each system acquires the signal. As a result, exports are typically configured to trim each invalid datapoint before and after the recording period, although they can easily be reconfigured to display all acquired data, regardless of input initialization.

	A	B	C	D	E	F	G	H	I	J
1	Reading	Date	Time	Scan#	C1_ANEMOMETER	C1_ANEMOMETER_DIRECTION	C2_ANEMOMETER	C2_ANEMOMETER_DIRECTION	D3_ANEMOMETER	D3_ANEMOMETER_DIRECTION
2					None	None	None	None	None	None
3	205	2023-Mar-15	49:02.8	1	5.963791	2.452829	4.539088	0.212022	6.188889	4.969801
4	205	2023-Mar-15	49:02.8	2	5.846146	2.537266	4.517728	0.042581	6.140337	4.940872
5	205	2023-Mar-15	49:02.8	3	5.820222	2.540817	4.457022	0.024017	6.083123	4.80151
6	205	2023-Mar-15	49:02.8	4	5.842056	2.522748	4.436045	0.085464	6.035074	4.744063
7	205	2023-Mar-15	49:02.8	5	5.883327	2.495073	4.4185	0.08662	6.142913	4.912442
8	205	2023-Mar-15	49:02.8	6	5.927462	2.465756	4.436721	0.107288	6.203202	4.960961
9	205	2023-Mar-15	49:02.8	7	5.982147	2.431711	4.443455	0.15771	6.201349	4.982916
10	205	2023-Mar-15	49:02.8	8	6.011091	2.415349	4.469407	0.216535	6.265062	5.063029
11	205	2023-Mar-15	49:02.8	9	6.028018	2.404529	4.483801	0.232089	6.14699	4.898504
12	205	2023-Mar-15	49:02.8	10	6.09412	2.35707	4.501175	0.269473	6.182875	4.963472
13	205	2023-Mar-15	49:02.8	11	6.085553	2.36318	4.540457	0.273181	6.249365	5.068728
14	205	2023-Mar-15	49:02.8	12	6.0472	2.390003	4.536571	0.27828	6.236569	5.031843
15	205	2023-Mar-15	49:02.8	13	6.014417	2.413993	4.533162	0.240225	6.2659	5.057076
16	205	2023-Mar-15	49:02.8	14	5.982207	2.435689	4.530378	0.215521	6.202244	4.985177
17	205	2023-Mar-15	49:02.8	15	5.885722	2.512494	4.50046	0.1136	6.125458	4.894407
18	205	2023-Mar-15	49:02.8	16	5.818636	2.549672	4.467069	0.000002	6.101355	4.882086
19	205	2023-Mar-15	49:02.8	17	5.828668	2.518827	4.450098	0.067367	6.107974	4.891825
20	205	2023-Mar-15	49:02.8	18	5.857456	2.488759	4.428083	0.079179	6.13603	4.919578
21	205	2023-Mar-15	49:02.8	19	5.91477	2.456419	4.425803	0.100497	6.19787	4.991764
22	205	2023-Mar-15	49:02.8	20	5.960612	2.445216	4.432309	0.154923	6.228783	5.005429
23	205	2023-Mar-15	49:02.8	21	6.006191	2.419116	4.449541	0.213687	6.204537	4.961295
24	205	2023-Mar-15	49:02.9	22	6.034043	2.400678	4.453926	0.248095	6.128714	4.891767
25	205	2023-Mar-15	49:02.9	23	6.057042	2.363702	4.471605	0.265973	6.213034	5.01344
26	205	2023-Mar-15	49:02.9	24	6.067277	2.368161	4.504649	0.272093	6.276977	5.090762
27	205	2023-Mar-15	49:02.9	25	6.058658	2.382585	4.528917	0.277197	6.202601	5.001902
28	205	2023-Mar-15	49:02.9	26	6.033931	2.392074	4.502893	0.274067	6.160868	4.953565
29	205	2023-Mar-15	49:02.9	27	6.010273	2.412558	4.520217	0.264732	6.199068	4.991428

References

1. Addy, Harold E., Jr.; Potapczuk, Mark G.; and Sheldon, David W.: Modern Airfoil Ice Accretions. NASA TM-107423 (AIAA Paper 97-0174), 1997.
2. Addy, Harold E., Jr.; Miller, Dean R.; and Ide, Robert F.: A Study of Large Droplet Ice Accretion in the NASA Lewis IRT at Near-Freezing Conditions; Part 2. NASA TM-107424, 1997.
3. Addy, Harold E., Jr.: Ice Accretions and Icing Effects for Modern Airfoils. NASA/TP-2000-210031, 2000.
4. Miller, Dean R.; Addy, Harold E., Jr.; and Ide, Robert F.: A Study of Large Droplet Ice Accretions in the NASA-Lewis IRT at Near-Freezing Conditions. NASA TM-107142 (AIAA Paper 96-0934), 1996.
5. Ratvasky, Thomas P.; Van Zante, Judith Foss; and Riley, James T.: NASA/FAA Tailplane Icing Program Overview. NASA/TM-1999-208901 (AIAA Paper 99-0370), 1999.
6. Reehorst, A., et al.: An Experimental and Numerical Study of Icing Effects on the Performance and Controllability of a Twin Engine Aircraft. NASA/TM-1999-208896 (AIAA-99-0374), 1999.
7. Vargas, Mario; and Reshotko, Eli: LWC and Temperature Effects on Ice Accretion Formation on Swept Wings at Glaze Ice Conditions. NASA/TM-2000-209777 (AIAA Paper 2000-0483), 2000.
8. Vargas, Mario; and Reshotko, Eli: Physical Mechanisms of Glaze Ice Scallop Formations on Swept Wings. NASA/TM-1998-206616 (AIAA Paper 98-0491), 1998.
9. Wright, William B.; and Rutkowski, Adam: Validation Results for LEWICE 2.0. NASA/CR-1999-208690, 1999.
10. Miller, Dean, et al.: Validation of NASA Thermal Ice Protection Computer Codes Part 1—Program Overview. NASA TM-107397 (AIAA-97-0049), 1996.
11. Irvine, Thomas B., et al.: Overview of the Icing and Flow Quality Improvements Program for the NASA-Glenn Icing Research Tunnel. NASA/TM-2001-210686 (AIAA Paper 2001-0229), 2001.
12. Sheldon, David W., et al.: Lessons Learned From the Construction of Upgrades to the NASA Glenn Icing Research Tunnel and Re-Activation Testing. NASA/TM-2001-210688 (AIAA Paper 2001-0231), 2001.
13. Rinehart, David A.; Johnson, Aaron M.: Full Aerothermal Characterization of the 6- by 9-Foot Icing Research Tunnel (2019 Test). NASA/CR-20205005811, 2020.
14. Timko, Emily N.; King-Steen, Laura E.; Van Zante, Judith F.; and Acosta, Waldo J.: NASA Glenn Icing Research Tunnel: 2019 Cloud Calibration Procedure and Results. NASA/TM-20205009045, 2021.
15. Slater, Howard; Owens, Jay; and Shin, Jaiwon: Applied High-Speed Imaging for the Icing Research Program at NASA Lewis Research Center. NASA TM-104415, 1991.
16. Lee, Sam; Broeren, Andy; Kreeger, Richard; Potapczuk, Mark; Utt, Lloyd: Implementation and Validation of 3-D Ice Accretion Measurement Methodology (AIAA Paper 20150000868, 2014).
17. Lee, Sam; Broeren, Andy P.; Addy, Harold E., Jr.; Sills, Robert; and Pifer, Ellen M.: Development of 3-D Ice Accretion Measurement Method. NASA/TM-2012-217702 (AIAA Paper 2012-2938), 2012.
18. Lee, Sam; Broeren, Andy P.; Kreeger, Richard E.; Potapczuk, Mark G.; and Utt, Lloyd: Implementation and Validation of 3-D Ice Accretion Measurement Methodology. AIAA Paper 2014-2613, 2014.
19. Broeren, Andy P.; Addy, Harold E., Jr.; Lee, Sam; and Monastero, Marianne C.: Validation of 3-D Ice Accretion Measurement Methodology for Experimental Aerodynamic Simulation. NASA/TM-2015-218724, 2015.

20. Kelsey, Nathan: Measurement Uncertainty Analysis of 6×9 Icing Research Tunnel (IRT). NASA/CR-20210023627, 2021.
21. Chambers, Jeffrey A.: Preloaded Joint Analysis Methodology for Space Flight Systems. NASA TM-106943, 1995.
22. Bickford, John H.: An Introduction to the Design and Behavior of Bolted Joints. Third ed., Marcel Dekker, New York, NY, 1995.
23. Bickford, John H.: Gaskets and Gasketed Joints. Marcel Dekker, New York, NY, 1998.

