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Development of the Cox Icing Research Facility

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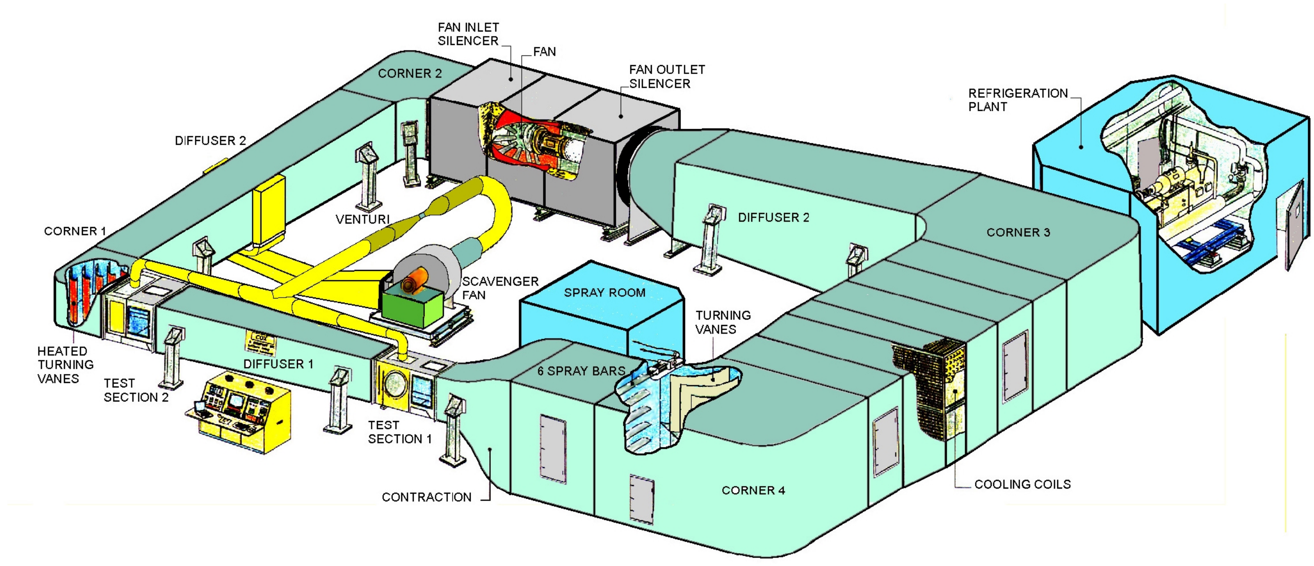

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DEVELOPMENT OF THE COX ICING RESEARCH FACILITY

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ABSTRACT

The LeClerc Icing Research Laboratory was designed and constructed at Cox & Company in downtown New York City (Manhattan). The facility was engineered to meet a number of design criteria in addition to being environmentally non-intrusive to the surroundings. It consists of a closed-loop refrigerated wind tunnel with the capability to simulate a cloud of supercooled water droplets as specified in the FAR's Part 25-C. Two test sections are provided with an airspeed up to 220 mph in the main test section and 120 mph in the secondary one. Provision for testing engine inlet nacelles is provided with a scavenge system that is capable of simulating engine core air flows of up to 15 lb/sec. The tunnel air temperature can be controlled down to –22 °F at the maximum heat load conditions.

I. Introduction

EXTENSIVE testing, in-flight and ground, is normally required in the design and evaluation of ice protection systems. The cost involved can be somewhat prohibitive. Flight testing requires searching for natural icing conditions or flying behind an icing tanker which is time consuming and very costly. Furthermore, natural icing conditions tend to be short and uncontrollable. The cost and development period involved can be reduced by testing in ground facilities that can reliably produce controlled icing environments. Additionally, experimental data (ice shapes and ice protection system performance) in conjunction with icing simulation computer codes may be utilized in the certification process to shorten the required flight testing matrix, once approved by the FAA.

The LeClerc Icing Research Laboratory (LIRL) was constructed in Cox's plant, in a business district of downtown New York City. It is completely enclosed, engineered and constructed to be quiet and non-intrusive to the surroundings. It was designed to meet the company's need for its own product development, to support the certification process of these products, and to provide industry with an efficient and cost effective tool to promote the safety of flight worldwide.

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II. Facility Design and Description

Several issues were involved in the decision process to build the facility. First was the selection of the construction site. Due to the noise level expected from the operation of all subsystems, initial consideration was given to build the facility off-site (not in Manhattan) of the company's plant. However, the inconvenience and the additional cost involved to operate a totally separate facility overruled that consideration. It was decided to build the facility within the existing company space. In order to do so, the following criteria had to be met:

- All tunnel components must fit through a 3rd floor window of our downtown Manhattan commercial office building
- Power must not exceed 800 kW
- A minimum of 200 mph airspeed in the main test section
- The air temperature must be controllable from –22 ˚F to 32 ˚F
- Noise levels had to be non-intrusive to offices within the building as well as within the Cox facility (3 adjacent floors) outside the icing research lab area.
- The largest possible test section that meets the above requirements and constraints in addition to the space assigned to the laboratory.

There were three main challenges: (1) noise issues within and surrounding the building; (2) size of the tunnel components and access to the building; and (3) power supply to the building in New York City is limited to 3-phase, 208 volts. The following sections discuss the design features of the major sub-systems.

II.1 Structural Design and Acoustics

The LeClerc Icing Research Laboratory is an indoor closed-loop refrigerated tunnel measuring approximately 72 ft x 44 ft, in plan view. Figure 1 is an illustration of the tunnel layout. Its basic structure consists of 0.165 inch thick steel walls with reinforcing ribs. The rib size and location depends on the particular tunnel section and the natural frequency of the panel to be reinforced. The total tunnel structure weighs about 80,000 lbs.

The first challenge to be resolved was the noise and vibration issue. Cox's facility is located in one of three buildings in New York City constructed to handle an average floor loading of 250 lb/ft^2. While extremely robust, its 8.5 inch thick solid concrete floors permit vibration and noise to be easily transmitted to other floors within the 12-story building. Consequently, all components with moving parts have been mounted on floating concrete platforms which were isolated from the building structure using Super Waffle pads and appropriately designed coil springs. The entire tunnel structure and non-moving parts were isolated from the building structure using concrete platforms and waffle pads. Moreover, the main axial fan and the scavenge system centrifugal blower were designed with efficient acoustic silencers on their inlets and outlets.

The tunnel walls were covered with insulation material for two reasons: (1) minimize the heat load on the refrigeration system, and (2) reduce the transmission of "white" noise from inside the tunnel loop to the laboratory surroundings. The insulation consisted of a combination of closed-cell foam, fiber glass, and air gaps. The overall acoustic treatment was so effective that no noise is heard in adjacent floors or offices nearby the laboratory area. Also, normal conversation is possible within the lab area.

II.2 Test Sections

The tunnel is designed to support testing of lifting surfaces, engine inlets, and large subsystems such as aircraft potable water systems and components that do not require a high airspeed environment. It is a closed-loop system and features two test areas with the following capabilities:

- ❄ A high speed main test area (Test Section 1)
- ❄ A low speed test area with larger cross-section (Test Section 2).

Additionally, an adjacent large cold chamber is provided to support full scale testing and development of systems at low temperature and very low airspeeds.

The bellmouth between the spray bars (see Fig. 1) and Test Section 1 provides a contraction ratio of 9:1. Test section 1 shown in Figure 2 is the main test area for high speed simulation and angle of attack variation. It has the following properties:

- ❄ Dimensions: 28" wide, 46" high, 6.5' long with 6" fillets that extend from the bellmouth inlet down to the end of Test Section 2.
- ❄ Maximum speed: 220 mph.
- ❄ Rotating side mounts to vary the angle of attack of airfoil sections.
- ❄ 4 heated viewing windows (sides at 28" x 22", top and bottom at 19" x 13").

Left and right side mounts are provided with synchronized gearing mechanism driven by a single stepper motor. A Baldor SmartMotor™ with a programmable keypad is used to rotate the side mounts at variable speeds a full 360º.

A diffuser section, 18.75 ft long, following Test Section 1 has a 5º total included expansion angle. This expansion is fairly modest allowing for larger models in Test Section 1 and a reasonably good flow qualities and uniform icing cloud in Test Section 2. This secondary test area is provided for testing large models at lower speeds where a convenient variation of the angle of attack is not required. This section has the following properties:

- ❄ Dimensions: 48" wide, 48" high, 5' long with 6" fillets.
- ❄ Maximum Speed: 120 mph.
- ❄ 4 Heated Viewing Windows (sides at 28" x 22", top and bottom at 19" x 13").

Both test sections are provided with slots for venting to the ambient air and for setting the reference ambient pressure in either test section. The large heated windows in the main and secondary test sections are provided for direct clear viewing, video recording, and still photography of the test article. Lighting is provided by 6 halogen lights in the fillets of each test section. Lights are rated at 500 Watts each with individual switches for better illumination control.

II.3 Main Drive

An axial flow fan provides air speeds up to 220 mph in the main test section and is completely contained within inlet and outlet silencers for noise control. Additionally, acoustic center-bodies are installed on both sides of the fan. The drive motor is rated at 200 hp 3-phase 208 volts A/C running at constant RPM. The fan consists of 16 variable pitch blades at 72" diameter. Airspeed is controlled by an external pneumatic actuator that sets the appropriate blade tip angle up to 18.5 degrees. Settings are established in a closed-loop using airspeed feedback and an analog signal output from a PID controller. With little model blockage, up to 160,000 scfm air flow can be attained at the maximum blade settings.

II.4 Scavenge System for Engine Inlets

A realistic simulation of the icing process of an engine inlet nacelle requires a good representation of the flowfield, and, consequently, of the stagnation line. The latter affects the locations where supercooled water droplets impinge on the surface. In addition, the variation of air flow in and around the inlet is largely dependent on the the flight envelope, for example, during take-off (full power) and approach (slightly above idle speed).

The tunnel is equipped with an independent scavenging system to simulate the engine inlet flowrate. This system, shown in Figure 3, consists of air ducts just downstream of each test section (either or both can be blocked) where air is ingested and then ducted back into the tunnel loop at the second diffuser. This air flow is provided by a centrifugal fan driven by a 75 hp A/C motor. A Variable Frequency Drive (VFD) is provided for engine flowrate variation. The motor/fan assembly is capable of simulating inlet air flows up to 15 lb/sec.

Measurement of the flowrate is accomplished using a venturi. The flowmeter has an inlet diameter of 20 inches, throat diameter of 8.13 inches, and a total length of 110 inches. Two pressure transducers are used to measure the static and differential pressures in the venturi to compute the flowrate and provide closed-loop control of the inlet air flow.

II.5 Refrigeration System

The refrigeration system was designed to meet the tunnel cooling requirements. The system, shown in Figure 4, includes a user-friendly microprocessor controlled compressor from MYCOM. This unit consists of a single stage rotary screw compressor driven by a 250 hp motor. The system was designed to provide a cooling capacity of 80 tons at –22 ˚F air temperature leaving the evaporator coils. The compressor and condenser units are isolated in a fully enclosed room. Waste heat is exhausted to Cox's water cooling tower on the roof of the building.

The refrigerant fluid used is R-22. Two identical evaporators with a total face area of about 141 ft^2 are located between Corner 3 and Corner 4 in the tunnel. This arrangement was selected based on the maximum space available between the ceiling and the floor, and between building structural columns. Air temperature control is achieved with a PID controller that communicates with the compressor unit's microprocessor.

Due to the heat generated by the compressor motor in the enclosed room, cooling was provided by direct exchange with outdoor air. Special ducts equipped with acoustic silencers were required in order to meet city codes on noise transmission to nearby residences.

II.6 Spray System

A spray system was designed to support testing over the largest possible range of Liquid Water Content (LWC) and Mean Volume droplet Diameters (MVD) as specified by the FAA in Appendix C of FAR-25. Most of the spray system support components, including the water pump, are isolated in an enclosed room, adjacent to the spray bars, for noise control. The spray system relies on compressed air and water to generate a cloud in the tunnel. These subsystems are described in the following paragraphs.

II.6.1 Spray Bars

Cloud formation is achieved by atomizing liquid water in nozzles distributed on six horizontal spray bars. Figure 5 illustrates a downstream view of the spray bars. Each spray bar consists of two concentric tubes, the outer one for air supply and the inner for water supply. These bars were obtained from the NASA Lewis Icing Research Tunnel (IRT) during the major upgrade to their individually controlled nozzle system in early 1997. Some modifications were required to accommodate them to the tunnel due to size differences and control requirements. Each spray bar can hold as many as 17 nozzles at 6" spacing. However, cloud uniformity and normal LWC range require only three or four nozzles per bar, for a total of 18 to 24 nozzles. Location of these nozzles is being determined through cloud uniformity calibration. This effort is in progress.

II.6.2 Water Supply

The water system consists of the following:

- Three water filters (5 microns).
- A de-ionizing system with one activated carbon tank followed by two mixed bed tanks. This combination yields a water resistance as high as 18 Mohm-cm. A meter indicates the actual resistance and an alarm light provides an

indication of when de-ionizing tank replacement is required.

- A 100 gal water storage tank with heater.
- A 5 hp water pump provides more than 4 gpm at 360 psig.
- Two high accuracy 0-400 psig pressure transducers for control feedback.
- Two pneumatically actuated control valves.

II.6.3 Air Supply

The compressed air supply consists of the following:

- Water cooled 60 hp air compressor with a total capacity of 300 scfm at 100 psig. Additional air is available through other pre-existing company compressors.
- A 240 gal receiving tank.
- Air dryer/chiller.
- A 30 kW air heater.
- One 0-100 psig high accuracy pressure transducer for control feedback.
- A pneumatically actuated control valve.

II.6.4 Atomizing Nozzles

Air assisted atomizing nozzles are used to create the water droplets. These are of the NASA Lewis IRT design, namely the MOD-1 and Standard (STD) nozzles. The difference between the two is that the latter yield higher water flow rates for the high LWC cases to be simulated.

The supply air pressure primarily controls the size of atomized water droplets. The water flowrate through each nozzle is determined by the difference between the water and the air supply pressures. This is given by the following equation:

$$C_f = \frac{m}{\sqrt{P_{water} - P_{air}}}$$

where,

C_f = nozzle flow coefficient
m = water mass flowrate, gal/min
P = supply pressure, psig

The flow coefficient is almost a constant for the range of normal pressures. In order to extend the range of LWC while maintaining a high level of controllability and cloud uniformity, Cox produced a variation of the NASA nozzles designated MODC nozzles. With these three sets of nozzles, the LWC range from 0.25 to 3.0 g/m^3 is covered for more than 85% of either test section. The flow coefficient of some of these nozzles is shown in Table 1. Once the entire set of nozzles is calibrated, the best selection will be made for use in the tunnel. Three percent or less nozzle flow coefficient deviation from the nominal value is considered acceptable.

Table 1: Typical Measured Flow Coefficients of a Random Number of Nozzles

Nozzle ID	Flow Coefficient	% Deviation from average
STD-35	0.01290	-0.70
STD-36	0.01340	3.20
STD-37	0.01310	0.80
STD-39	0.01340	3.22
STD-40	0.01310	0.80
STD-45	0.01330	2.40
MOD-400	0.00482	1.69
MOD-411	0.00476	0.42
MOD-414	0.00465	-1.90
MOD-429	0.00473	-0.21
MOD-441	0.00476	0.42
MOD-520	0.00467	-1.48
MODC-1	0.00327	-1.21
MODC-3	0.00332	0.30
MODC-4	0.00333	0.60
MODC-5	0.00333	0.60
MODC-6	0.00333	0.60
MODC-7	0.00325	-1.81
MODC-8	0.00326	-1.51
MODC-10	0.00326	-1.51

II.7 Instrumentation and Control System

Control of all tunnel subsystems is achieved by a single operator from the Master Control Console shown in Figure 6. The console houses a personal computer (PC) which includes a high speed analog and digital I/O card that communicates with six data acquisition and control signal conditioners.

Direct control is achieved by 10 individual PID controllers that communicate to the PC via RS-485 multi-drop serial communication modules. This built-in redundancy permits control through the stand-alone PID controllers or through software by serial communication between the PC and the individual controllers. Process and control values are continuously monitored by the computer and written to data files for record keeping and future reference.

III. Present Activities

Preliminary flow calibration was performed to assess the air flow quality and uniformity in the main test section. A 16-channel digital pressure scanner was used for that purpose. Typical results are shown in Figure 7 where the average airspeed was 226.7 mph. The maximum deviation from the average was 0.65% near the wall.

Temperature uniformity in the test section is directly related to uniform cooling of the air by the refrigeration evaporator coils. To investigate this matter, eight evenly distributed type-T thermocouples were installed, four on the upper coils and four on the lower one, one foot downstream of the coils. The resulting measurements are given in Table 2. This indicates a very uniform air temperature distribution within the sensors' accuracy. Moreover, the additional mixing through corner 4 and the contraction further improves that uniformity.

Table 2: Temperature Uniformity Data Downstream of Cooling Coils (ºF)

-22.1	-21.8	-22.5	-22.7
-20.3	-20.9	-21.7	-22.0

Cloud uniformity studies are still in progress. A grid of about 5 inch spacing was built and installed Test Section 1. Atomized water was released from individual rows and columns of nozzles to map their location on the grid in the test section as described in Reference [1] for the NASA IRT calibration. Analysis of the results will be used to predict the location and number of individual nozzles on the spray bars that yield the most uniform cloud in the test section. Figure 8 is an example illustration showing the ice accretion on the grid resulting from a straight column of six nozzles installed near the middle of the spray bars. This data can be used to relocate some of the nozzles in order to obtain an even vertical ice accretion within the NASA acceptable limits of 20% overall uniformity [1]. The grid was also installed in Test Section 2 where cloud uniformity is even better due to the additional mixing in Diffuser 1.

In an effort to accelerate current product development schedules, testing of ice protection and ice detection systems by Cox and its partners has already been initiated. Until actual calibration of the cloud droplet distribution is completed, pre-existing NASA IRT calibration data are being used in the LIRL. It is expected that slightly higher air pressures are required for the same MDV. This is related to the shorter distance between the spray bars and the model in test at LIRL, and subsequently less evaporation from the droplets. Figure 9 illustrates a section of a horizontal stabilizer with a hybrid ice protection system (thermal & low power electro-expulsive) being tested [2].

IV. Future Activities

The following is a list of future activities:

- ❄ Perform MVD calibration for MOD-1, STD, and Cox MODC nozzles by NASA Lewis engineers.
- ❄ Perform a thorough aerodynamic calibration that includes flow angularity studies using a 5-hole probe, and measure the turbulence intensity with and without spray air using hot wire anemometers.
- ❄ Complete LWC calibration and documentation.
- ❄ Conduct ice accretion on standard geometries including a NACA0012 airfoil and a cylinder to compare results with the NASA Lewis IRT.
- ❄ Experiment with other types of nozzles to explore the possibility of improving on the normally accepted 20% cloud uniformity.
- ❄ Investigate methods to simulate mixed icing and snow environments as required by the JAR.

V. Concluding Remarks

The LeClerc Icing Research Laboratory was designed and constructed at *Cox & Company* facility in downtown New York City. It consists of a large static cold chamber and a closed-loop refrigerated wind tunnel to simulate environmental icing conditions in two test sections. Airspeeds as high as 220 mph can be attained in the main test section at temperatures as low as –22 ˚F. A scavenge system is included to simulate engine inlet air flow and allow an accurate representation of the flowfield in and around the inlet nacelle.

Preliminary aerodynamic calibration, cloud and temperature uniformity studies have been very promising. Further calibration will include droplet size.

The facility will be used mainly for development of Cox ice protection and detection products, and to provide industry with an efficient and cost effective tool for systems testing under simulated icing environments.

Acknowledgments

The support provided by the technical and operations members of the IRT and the Icing Technology Branch at the *NASA Lewis Research Center* throughout the project is well appreciated and recognized.

References

[1]Ide, Robert, "Liquid Water Content and Droplet Size Calibration of the NASA Lewis Icing Research Tunnel," *AIAA 28th Aerospace Sciences Meeting*, Jan 90, AIAA Paper 90-0669, NASA TM-89-C-014

[2]Al-Khalil, K., Ferguson, T., and Phillips, D., "A Hybrid Anti-icing Ice Protection System," *AIAA 35th Aerospace Sciences Meeting*, Reno, NV, Jan. 6-10, 1997, AIAA Paper 97-0302.

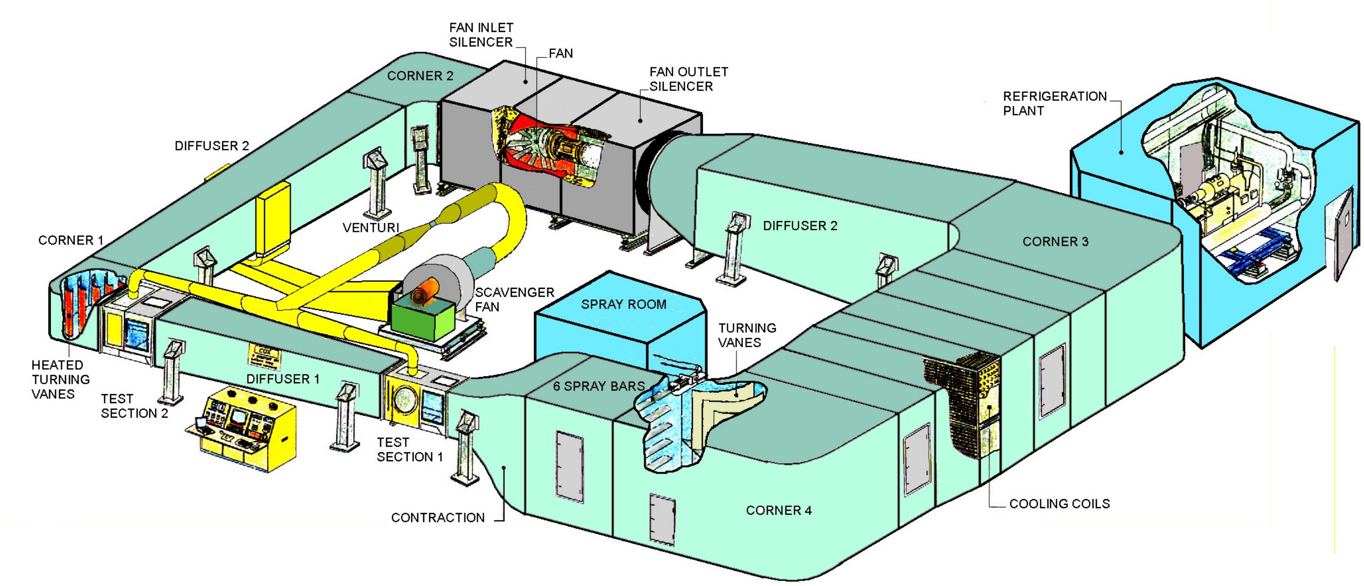

Figure 1: Layout of The LeClerc Icing Research Laboratory

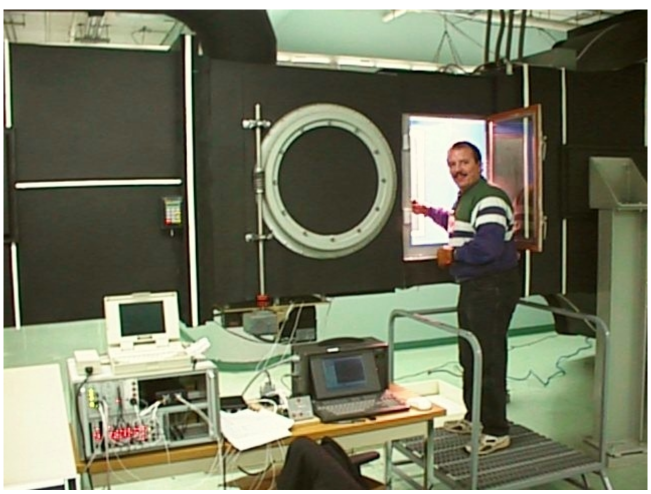

Figure 2: Main Test Section

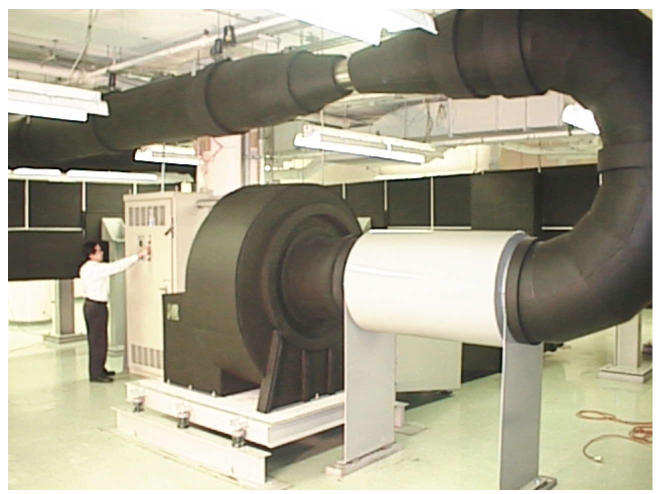

Figure 3: Engine Inlets Scavenging System

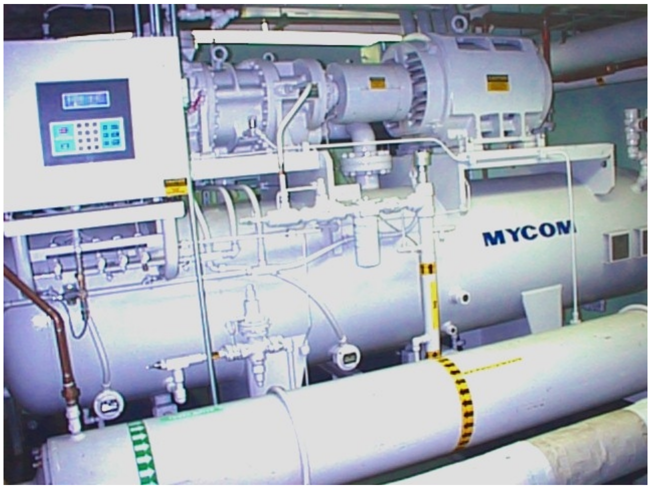

Figure 4: Refrigeration Compressor System

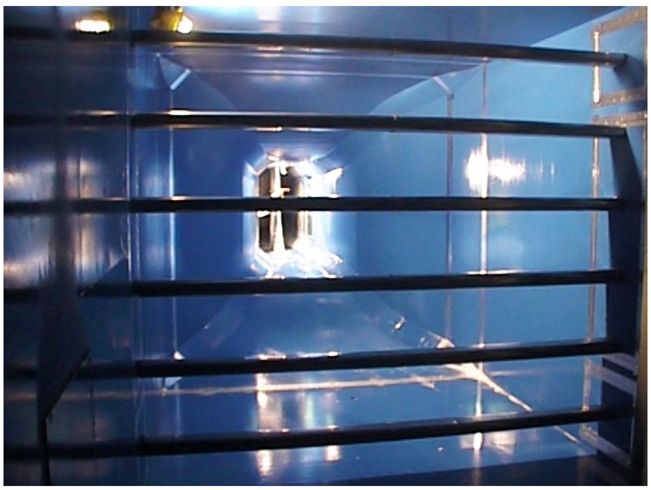

Figure 5: Downstream View of the Spray Bars

Figure 6: Master Control Console

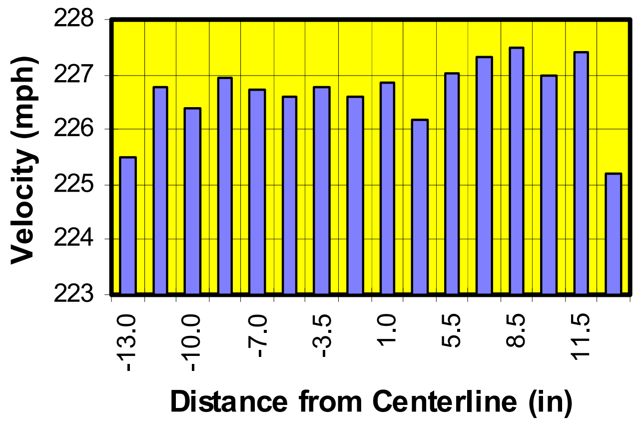

Figure 7: Typical Velocity Distribution in the Main Test Section

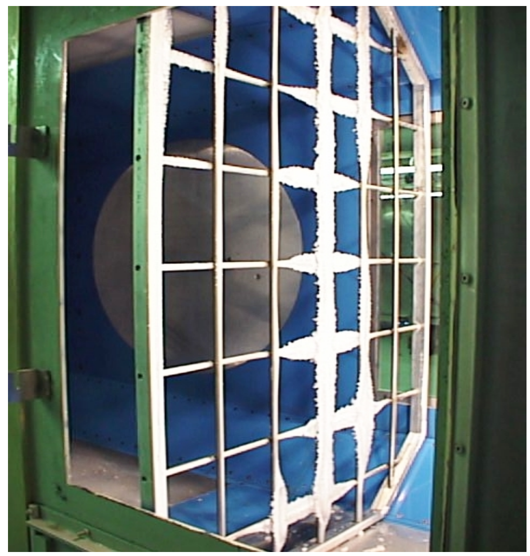

Figure 8: Cloud Uniformity Calibration Grid (one column of nozzles in this case)

Figure 9: An Ice Protected Horizontal Stabilizer under Testing