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# ANALYTICAL AND PHYSICAL MODELING PROGRAM FOR THE NASA LEWIS RESEARCH CENTER'S ALTITUDE WIND TUNNEL (AWT)

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## Abstract

An effort is currently underway at the NASA Lewis Research Center to rehabilitate and extend the capabilities of the Altitude Wind Tunnel (AWT). This extended capability will include a maximum test section Mach number of about 0.9 at an altitude of 55 000 ft and a -20 °F stagnation temperature (octagonal test section, 20 ft across the flats). In addition, the AWT will include an icing and acoustic research capability. In order to insure a technically sound design, an AWT modeling program (both analytical and physical) was initiated to provide essential input to the AWT final design process. This paper describes the modeling program, including the rationale and criteria used in program definition, and presents some early program results.

## Introduction

An effort is currently underway at the NASA Lewis Research Center to rehabilitate and extend the capabilities of the Altitude Wind Tunnel (AWT) to meet anticipated future needs for aeropropulsion research. The AWT was first brought on line in 1944 and was utilized for aeropropulsion research until 1958 when it was converted into a series of altitude test chambers for space research. As originally configured, the AWT had a maximum Mach number of 0.6 at 30 000 ft of altitude with temperature capability down to -65 °F. A photograph of AWT in its original (and current) configuration is shown in Fig. 1.

The current AWT program involves not only rehabilitating the facility to make it an operational wind tunnel again, but also extending its capability. A schematic of the planned rehabilitated configuration is shown in Fig. 2, with the major components identified, and with a tabulation of the major facility capabilities. (Currently the facility is empty of any of its original components - the only portion remaining is the basic insulated shell and structure.) In addition to the expanded Mach number capability of 0.9+ and the altitude pressure (up to 55 000 ft) and low temperature (down to -40 °F) capability, the facility will also provide for an adverse weather test environment (icing, freezing rain, heavy rain, and snow), and will be designed to permit acoustical measurements to be made in the test section. The test section itself is octagonal in cross section with a 20 ft span across the flats. The test section walls are acoustically treated, slotted, and surrounded by a 40 ft diam plenum that is tied into a plenum evacuation system (PES) to provide for high quality test section airflow with large blockage models. Downstream of the test section, in the high speed diffuser, is an engine exhaust removal scoop that provides the capability for testing fuel-burning engines in the test section. Four new sets of turning vanes are required. A two-stage fan drive system will be installed downstream of the second corner, followed by an air reentry area (PES air and additional makeup air for altitude control) and a rapid diffusion into the heat exchanger. Located upstream of the test section are the flow conditioners (honeycomb and screens) that provide good flow quality in the test section, as well as a removable spray bar system required to generate the icing cloud when the tunnel is being used for icing research.

When operational, AWT will provide for all of the capabilities listed in Fig. 3. It will provide for actual altitude pressure up to 55 000 ft, and actual altitude temperature over much of its operating range (down to a minimum total temp. of -40 °F). Because of the large test section size, either full or large scale models can be tested at Mach nos. extending over the full subsonic speed range and actual fuel burning engines can be operated. Acoustic measurements can be made on the test articles in the test section and the facility will be capable of providing an adverse weather test capability (ice, rain, snow). A more detailed discussion of the AWT components and features, as well as a more complete description of its capabilities, can be found in Ref. 1. Additional information relative to its role as an all weather test facility can be found in Ref. 2.

Because of the extensiveness of the AWT rehabilitation and the significant extensions to its original capability (higher Mach number, adverse weather, acoustics), it was determined to be imperative that a modeling program (both analytical and experimental) be undertaken to insure the technical soundness of the aerodynamic, thermodynamic, acoustic, adverse weather, and system dynamics design. The purpose of this paper is to describe this modeling program and discuss some preliminary results of the program.

## Modeling Program Overview

The AWT modeling program was established in early 1984 and has been structured to effectively utilize the Lewis Research Center's experience in internal fluid mechanics, icing, acoustics, dynamics and controls and wind tunnel testing. Being NASA's propulsion research center, Lewis has been involved in both the experimental and analytical aspects of air-breathing propulsion systems for many years. Expertise in cascade design, fan and compressor design, and the internal fluid mechanics of inlets and nozzles has been directly applied to the aerothermodynamic modeling aspects of the AWT circuit components. Experience in the design of acoustical treatment for turbofan noise reduction, and the prediction of fan and jet noise levels has been applied directly to the acoustical aspects of the modeling effort. Lewis has an on-going program in aircraft and propulsion system icing research which has provided significant expertise for the adverse weather aspects of the modeling program. In the dynamics and controls area, Lewis has had considerable involvement in the dynamic performance and control of air-breathing propulsion systems which is being directly applied to the development of an AWT mathematical model for dynamic studies and control system evaluation. In terms of wind tunnel testing experience, Lewis has a number of operational wind tunnels being used for propulsion research including the 10 by 10 ft Supersonic, 8 by 6 ft Supersonic, 9 by 15 ft Subsonic, and 6 by 9 ft Icing Wind Tunnels. All-in-all, the AWT modeling program has benefitted significantly from the in-house propulsion system expertise that was already in place at the Lewis Research Center.

In addition, a considerable amount of valuable information and insight into the scope and magnitude of a large facility modeling program has been provided by various other organizations who have had recent involvement in such a project. In particular, both NASA Ames and NASA Langley, as well as AEDC and the Boeing Company have been extremely cooperative and helpful.

The modeling program has been organized into the four distinct groups shown in Fig. 4 - aerothermodynamics, icing, acoustics, and system dynamics. In each group, both experimental and analytical modeling efforts are underway. The elements of responsibility in each of the four groups are indicated in the figure. Briefly, the aerothermodynamics group is responsible for determining the aerothermodynamic performance, as well as the aerodynamic loads, of all the various components within the AWT circuit (test section, high speed diffuser, engine exhaust removal scoop, all four corners, drive fan, rapid diffuser, heat exchanger, acoustic silencer, flow conditioning devices, contraction, etc.). In addition this group is responsible for the overall steady state performance of the entire AWT circuit. The icing group is responsible for two basic aspects of the all weather capability for AWT. First is the development of the adverse weather generation systems for AWT (icing spray, snow, etc.), and second is the ice protection of the various components around the circuit that are sensitive to the adverse weather environment (e.g., icing build-up on the turning vanes, heat exchanger, and fan blades). The acoustics group has two basic responsibilities, also. The first is to provide an anechoic test section to permit the measurement of test article directional noise characteristics, and the second is to insure that the acoustic background level in the test section, as determined by the various noise generating sources around the circuit, is below the level of the test article. The system dynamics group is responsible for developing a dynamic math model of the AWT circuit and then using that model to assess the tunnel control concepts. The model will also eventually be used to develop a real-time digital simulator of the facility to be used for pre-run checkout of controls and for operator training.

The AWT modeling program is being driven by the need to have modeling results in a timely way so they can feed into the facility final design and construction process. The overall schedule for the various aspects of the AWT project is shown in Fig. 5. The Preliminary Engineering Report (PER) for AWT was completed in November of 1984. The intent of this effort was to complete a detailed enough preliminary design to establish the cost of the facility modification within a certainty of 90 percent. The final design is scheduled to begin in April of 1985 and will run for about two years with completion scheduled for about mid FY1987. The actual construction of the facility is planned to begin in mid FY1986 and run for about four years, ending in mid FY1990. In order to provide timely input to this entire process, the modeling program has been structured to deliver its major results by the end of calendar year 1985, which is about eight months into the final design. The final design and construction are being structured, as much as possible, with the modeling schedule being an important consideration. As Fig. 5 indicates, the modeling activities will be most intense through mid FY1987 and will then taper off to some lower level for the remainder of the construction period. It is fully expected, however, that some elements of the modeling program will continue even after the facility is operational, as an aid in solving any facility problems that may occur and as a means for evaluating any proposed modifications or extensions to the AWT capability.

With this general overview of the AWT modeling program in mind, a more specific description of the modeling activities will now be presented for each of the four groups - aerothermodynamics, icing, acoustics, and system dynamics.

## Aerothermodynamic Modeling

The aerothermodynamic modeling effort will be described in two parts. The first relates to the experimental modeling and the second, to the analytical modeling. In practice, of course, these two parts are closely related with the analytical modeling giving a first, early look at how the components might be expected to perform, and the experimental results providing ultimate confirmation of the performance levels and information for modification and validation of the analytical methods.

### Experimental

The primary experimental models for determination of the aerodynamic performance and loading of the various AWT components are the 1/10-scale models shown in Fig. 6. Four basic models have been built, or are being built, at this scale - the high speed leg model, the corner model, the fan model, and the complete loop model formed by combining these three individual models. The 1/10-scale model size was selected because of past facility modeling experience at this scale,[3,4] and because it represents the upper limit on size that can utilize the exhaust flow capability available at Lewis for providing model airflow. (In reality, because the model testing is being done at atmospheric conditions as opposed to altitude conditions, the actual Reynolds number scale of the models is somewhat greater than 1/10.) Each of these models will now be discussed in a bit more detail.

A detailed schematic of the high speed leg model is shown in Fig. 7. The model is shown installed within the walls of its test facility. The phase 1 configuration, shown in the top of the figure, will be tested first and is made up of the tunnel stilling chamber with flow conditioning devices, the contraction, the slotted test section with surrounding plenum evacuation system (PES), the high speed diffuser with engine exhaust scoop, and corner number 1. Both the PES and the engine exhaust scoop are tied into the exhaust system so that these systems can actually be operated. Dry air is supplied to the large plenum tank (containing its own set of flow conditioning devices and also acoustic attenuators), and then pulled through the model by a connection to the low pressure exhaust system located downstream of corner number 1. With the high speed leg model in this configuration, the basic aerodynamic performance will be determined for the contraction, test section, and high speed diffuser. In addition, tests will be run with a variety of flow conditioning devices in the stilling chamber to assess their influence on the quality of the airflow in the test section (turbulence level and Mach number distribution - axial and radial).

For phase 2 testing, corners number 3 and 4 are added to the model, upstream of the stilling chamber, to permit an assessment of the influence of those corners on the downstream components. As the figure indicates, the plenum tank and its tie in to the air supply system have to be relocated within the facility.

The current status of the high speed leg model is that all of the hardware has been designed and fabricated and is currently being installed in the facility for phase 1 tests to begin shortly. The model will be switched over to the phase 2 configuration about mid-year with testing continuing until the end of calendar 1985. (In addition to the aerodynamic testing being discussed here, the model is also used during this time for acoustic testing as will be discussed later.)

A photograph of the 1/10-scale corner test model is shown in Fig. 8. This model has been on test since about August of 1984. As indicated, the corner itself is located downstream of an inlet bellmouth and a flow conditioning section used to provide uniform inflow. Downstream of the corner, the flow is exhausted to the laboratory exhaust system. Many of the components of this model, as well as the other 1/10-scale models, are constructed of transparent plastic materials to permit flow visualization studies. An extensive amount of total and static pressure instrumentation (including traversing probes) is located both upstream and downstream of the turning vanes in order to make an accurate assessment of the performance of this fairly complicated geometry.

Thus far, tests have been completed with two different turning vane designs installed in corner number 1, without the scoop penetrating the corner. Additional tests have been completed with the best of the two turning vane designs, with the scoop penetrating design. Detailed analysis of the results is underway. Tests with corner number 2 are currently being conducted (including the drive shaft penetrating the corner). When completed, both corners number 1 and 2 will be tested together, with the connecting crossleg, to assess interaction effects and to get an indication of the character of the flow likely to be introduced into the drive fan.

The 1/10-scale fan model, shown in Fig. 6, is scheduled to become operational in mid-1985. As indicated, it will have both corners number 1 and 2 installed upstream and the various elements of the tunnel geometry installed downstream, including the low speed conical diffuser, the rapid diffuser, the heat exchanger blister (including a series of screens to simulate the heat exchanger pressure drop), and the acoustic silencer. The flow then exhausts into the laboratory exhaust system to provide the variable fan back pressure required for complete mapping of the fan performance. This model will be used to determine the operating characteristics of the fan including its limitations of stall and choke.

After the individual tests have been completed with the high speed leg, the corner model, and the fan model, each of these models are then combined together to form the complete loop model shown in Fig. 6. The complete loop model provides a more complete picture of how the various components work together as a system. The model will be installed in the same facility that housed the high speed leg model, with provisions to use a heat exchanger with refrigeration system in order to remove the fan heat of compression. The model will operate at atmospheric pressure and temperature. The model will become operational during the first quarter of 1986. Models of test articles (including rotating machinery) will be installed in the test section and tested to determine their influence on tunnel performance and component aerodynamic loads. As indicated earlier, it is fully expected that this model will continue to be used throughout the final design and construction of AWT and probably even after the facility becomes operational. It will be of significant value in determining the causes of and fixes for any problems that may occur in the actual tunnel and also useful for evaluating any future AWT modifications or enhancements.

In addition to the 1/10-scale aerothermodynamic modeling effort, there are a number of other experimental modeling efforts being undertaken in support of AWT. One of these involves a test of a 3 by 3-ft panel of the actual full scale AWT heat exchanger. A photograph of the panel is shown in Fig. 9. The panel has been installed in a flow duct attached to a fan drive system to pull airflow at the proper velocity through the coils. The panel has been tested to determine the pressure drop across the coils and also with refrigerant flowing through the tubes and in an icing environment, to determine the change in performance as ice collects on the coils. (More will be said about this in the icing discussion.)

## Analytical

The analytical modeling effort in AWT aerothermodynamics involves the steady state analysis of the entire system and also the analysis of specific components. The steady state system analysis is being accomplished by use of a modified version of the one-dimensional code described in Ref. 5. The code contains a series of loss models for each of the tunnel components, and uses those models to determine the overall circuit loss (for specified tunnel operating conditions), which in turn, leads to specification of the drive fan pressure ratio and the horsepower requirements (and ultimately the majority of the heat exchanger cooling requirements). As results are provided from the experimental modeling program, and also the component analytical modeling, they are used to adjust the component loss models in this one-dimensional code to provide updated fan pressure ratio and horsepower requirements.

As indicated earlier, the component analytical effort, in most cases, is based on the application of analytical methods that had already been developed for internal fluid mechanics studies of various air-breathing propulsion system components (inlets, nozzles, diffusers, turboprops, cascades, fans and compressors, mixers, etc.). In some case, the codes have been applied directly, but in most cases, at least some modifications were required. A more complete discussion of some of the aspects of the aerothermodynamic analytical modeling effort can be found in Ref. 6. As an example of the kind of results being provided by the analyses, Fig. 10 shows results from a three-dimensional, viscous method that was originally developed for analyzing aeropropulsion flow ducts (inlets, nozzles, etc.). The method has been applied to the AWT contraction and test section to evaluate the performance of the contraction in terms of boundary layer behavior and test section flow quality delivered by the contraction. In this particular case, the contraction geometry was not exact, in that it was modeled as being circular in cross section (but with the proper axial area distribution) as opposed to including the transition from circular to octagonal. (Since these initial calculations were made, the method has been modified to handle the actual transitioning three-dimensional geometry of the contraction.) The figure shows the development of the streamwise velocity profile through the contraction and then into the test section at a test section Mach number of 0.8. In addition to these profiles, the figure also shows the velocity distortion (maximum velocity, minimum velocity, average velocity) at the exit of the contraction (solid line) and 10 ft downstream of the end of the contraction (dashed line). These results indicate the considerable amount of flow development and "smoothing-out" that occurs in the front part of the test section.

Another example of aerothermodynamic analytical modeling results is shown in Fig. 11. This figure shows surface Mach number distributions on two different turning vane designs for corners number 1 and 2. The simple vane design is a traditional double circular arc design. The results indicate a Mach number "spike" near the leading edge of the simple vane design followed by a rather rapid diffusion to a lower Mach number along the suction side. Although the calculations indicate the airflow is staying attached, it may well be that with some distortion into the vanes, caused by a model in the test section, the flow may separate from the vane suction surface. The other vane design shown in the figure is termed the complex design, and its shape is the result of specifying the desired surface Mach number distribution (an inverse method). In this case the suction side Mach number distribution was selected to be "flat" over the initial length of the vane in order to avoid the "spike" encountered with the simple vane design. The intent is to provide the vane with more tolerance to inflow angle-of-attack variations and thereby minimize any sudden increases in corner losses as a result of distortions generated by models in the test section. The current plan is to use the complex vane design in corners number 1 and 2 where the Mach number are highest but to use the more conventional design in corners number 3 and 4 where the Mach number is considerably lower and the flow more uniform (downstream of the flow-smoothing heat exchanger).

## Icing Modeling

The icing modeling effort will also be described in two parts, experimental and analytical. Although referred to as the "icing modeling", the term "icing" is being used to refer to all aspects of providing an adverse weather environment in AWT (i.e., icing, freezing rain, heavy rain, and snow).

### Experimental

The experimental icing effort involves two distinct areas. The first is the development of the systems for providing the adverse conditions and the second is the development of protection methods for the various tunnel components that need such protection. The development of adverse weather generating systems is currently focused on providing the systems for generating the icing cloud. One important aspect of this effort is the development of the spray nozzles required to generate the cloud in the stilling chamber upstream of the test section. Because of the large variation in water droplet size and liquid water content that the nozzles must provide, it has been necessary to engage in a spray nozzle development program. Both NASA-designed nozzles and commercial nozzles are being evaluated for AWT. Not only has it been necessary to engage in a spray nozzle development program, it has also been necessary to engage in a droplet measurement instrument development program. There are a number of instruments available to measure droplet sizes, but they all use different techniques and the measurements tend to disagree from one instrument to another. Hence, in order to develop both the spray nozzles and the droplet measuring systems, a new facility has been developed and is shown in Fig. 12. The facility is referred to as the Single Nozzle Spray Test Facility. It consists of an air supply system that provides air of a specified velocity, humidity, and temperature to a location in a flow duct where a single spray nozzle is installed and operated. The characteristics of the spray are then measured in a transparent test section where either external or in-the-stream droplet sizing instruments are located. Initially, the spray facility will be used for developing icing nozzles and then later for developing heavy rain and freezing rain nozzles.

In addition to this spray nozzle and instrument development work, there are also activities underway to determine droplet spreading and mixing characteristics. Some of this work is being done in the Single Nozzle Spray Test Facility and additional work is being done in Lewis' Icing Research Tunnel (IRT). The IRT is a low speed tunnel (maximum Mach number = 0.4), having a 6 by 9-ft test section. In IRT, spray from a single nozzle is being examined to determine the behavior of the spray in terms of mixing and spreading as it moves downstream of the spray bar, through the contraction, and into the test section. These IRT measurements are then being compared with analytical predictions (to be discussed shortly) for verification of the analytical methods. The analytical methods will then be applied to the AWT configuration to assist in determining the proper number of spray nozzles and the spacing required to attain a given spray cloud uniformity in the AWT test section.

The second aspect of the experimental icing modeling involves experiments in the IRT to determine the effects of the icing environment on the various components within an icing research tunnel like the IRT and the AWT. An example is shown in Fig. 13, where the ice build up on the first set of turning vanes downstream of the test section in IRT is shown. In a similar manner, ice built up on the various other components in the IRT, was collected and weighed, and the results of these tests are summarized in Fig. 14. The figure shows the percent of the icing cloud that accumulates on the various components around the IRT circuit. As indicated, the ice accumulation on any given component is a function of the size of the water droplets - the smaller droplets tend to follow the airflow and hence are less likely to accumulate on the turning vanes and fan blades. Clearly, the majority of the icing cloud accumulates on the very cold surfaces of the heat exchanger, with the percentage becoming larger as the droplet size decreases. This type of IRT data is currently being used to estimate the ice buildup on the various components in AWT, taking into account the difference in operating conditions and component geometries. The information is needed for the mechanical design of the components (they must be able to withstand the higher drag and weight loads caused by the accumulated ice) and for the design of an appropriate ice protection system (if needed). Additional experiments being run in the IRT include a test of a number of turning vane deicing methods, tests of flow conditioning devices (screens and honeycombs) to determine their icing characteristics, and icing tests on the 3 by 3-ft AWT heat exchanger panel already discussed. In each of these cases, the heat exchanger in particular, an important result of the tests is the degradation in performance of the given component as ice accumulates. As ice builds up on a set of turning vanes, a fan blade or a heat exchanger coil, the question becomes: How long can the facility operate before the aerodynamic performance (loss) of the iced-up components increases to the point where a facility operating limit of some sort is reached

In addition to these two near-term aspects of the icing experimental program just described, there are also plans to develop a 1/10-scale AWT high speed leg icing model. This model is scheduled to come on-line in 1987 and will look much like the aerodynamic high speed leg model discussed earlier (Fig. 6). It will be installed in one of Lewis' engine test tanks where low temperature air can be used to provide an icing research capability. The purpose of using this model is to begin to gain experience in high speed icing research and identify early any problems that may be encountered in the actual AWT (e.g., the effect of icing on the test section slots).

### Analytical

The analytical icing effort involves the modification and application of methods developed for the analysis of icing spray systems as well as for combustor spray systems and turbine blade cooling. The icing and combustor spray methods are being used to predict the behavior of the spray in terms of spray mixing, spreading, and droplet trajectories. An example of the results obtained from a droplet trajectory code is shown in Fig. 15. The figure shows the predicted trajectories of various sized droplets injected at various angles into a moving airstream. In this particular case, the calculations were done for a spray being injected into the Single Nozzle Spray Test Facility described earlier. The results indicate that the smaller drops align themselves more quickly with the airstream, and that there is a spray injection angle above which the droplet will hit the flow duct wall. These same methods will be used to predict the trajectories of the droplets within the actual AWT geometry and will also be used, in combination with turning vane and fan/stator blade aerodynamic codes, to predict droplet impingement characteristics.

Heat transfer analytical methods, developed for ice protection system studies and turbine blade cooling studies, are being applied to understand the details of both turning vane and fan blade ice protection schemes. In particular, the use of both steam and electrothermal systems is being analyzed using these methods.

## Acoustic Modeling

Again, the acoustic modeling program will be described in two parts - experimental and analytical.

### Experimental

There are several activities planned and underway for the acoustical modeling effort. First, a considerable amount of acoustical data will be gathered from the 1/10-scale high speed leg, fan, and complete loop models. These models have been designed to include the necessary acoustical features (acoustically treated test section walls, acoustic choke downstream of the test section to prevent downstream generated noise from propagating upstream, acoustic silencer downstream of the heat exchanger, etc.), and appropriate noise sources and measuring systems to evaluate acoustical performance. In addition special care has been taken to insure that extraneous noise sources (valves, air supply lines, etc.) do not interfere with the actual model noise levels by incorporating mufflers and flow choking as needed. Acoustical test objectives for these models include the measurement of noise levels generated within the circuit by the various components (fan, air injection systems, tunnel wall slots, turning vanes, high speed diffuser, etc.), and the evaluation of the effectiveness of the test section acoustical treatment for absorbing test article generated noise.

The design of the test section wall treatment is particularly challenging because of the high test section Mach nos. and the wall boundary layer.

Upstream of the test article, the boundary layer has a tendency to refract the incoming acoustical energy away from the treated wall and thereby reduce the treatment effectiveness. In order to develop effective treatment designs, a series of tests have been conducted (and more are planned) in Lewis' 8 by 6-Ft Supersonic Wind Tunnel to assess full-scale treatment performance. Photographs of this test setup in the tunnel are shown in Fig. 16. One of the test section viewing windows has been replaced by a round canister containing acoustical treatment covered by a porous face sheet. On the opposite wall of the test section, a noise generating source was installed, and a microphone system located within the test section. Several treatment designs (and treatment depths) were evaluated over a range in test section Mach number up to 0.8. The data system used (time delay spectrometry) permitted a measurement of the incoming acoustical energy and the energy contained in the first reflection from the treated canister, thereby allowing a determination of the acoustical effectiveness of the treatment. Results from the first series of tests are currently being analyzed.

Another acoustical experiment was conducted to determine the acoustical attenuation characteristics of the 8 by 6-Ft Supersonic Wind Tunnel heat exchanger. Although this particular heat exchanger is not an exact match to the AWT configuration, it was close enough to provide useful results. A photograph of the test setup is shown in Fig. 17. A test stand was positioned upstream of the heat exchanger, with noise sources positioned on the stand to beam acoustical energy into the heat exchanger at a number of incidence angles. Microphones were positioned upstream and downstream of the heat exchanger to measure the attenuation of the incoming acoustical energy. Preliminary results of this test indicated significant attenuations across this particular heat exchanger configuration, but when the results are extrapolated to the AWT heat exchanger configuration, the attenuation appears to be minimal. There is no heat exchanger attenuation "credit" currently being assumed in the acoustical design of AWT, and the data analyzed to date do not warrant a change in this assumption.

### Analytical

The analytical acoustic modeling effort involves the application of methods developed for the prediction of turbofan fan noise levels, jet noise levels and the analytical design of tubofan duct treatment. The source noise prediction methods have been used to estimate the AWT fan noise levels and specifically to select the proper ratio of fan-to-stator blade number in order to insure acoustical cutoff of the fan/stator interaction fundamental tone. Jet noise prediction methods have been used to predict the acoustic levels of the reinjected PES and make-up air supplies.

The acoustical treatment in various areas of the tunnel, including the test section walls, has been designed using methods developed for noise suppressing treatment in turbofan inlets and exhaust ducts. As indicated earlier, a particularly difficult aspect of this problem is the design of effective treatment for the case where a high subsonic Mach number and a boundary layer are present on the treatment face.

### System Dynamics

The fourth aspect of the AWT modeling program is system dynamics. In order to understand the role of this element of the modeling program, the operation of the facility will be first briefly described. The operation of AWT will require closed-loop control of pressure, temp., and Mach number in the test section. Tunnel pressure is to be controlled by balancing the airflows in and out of the tunnel. Tunnel temperature is controlled by an elaborate refrigeration system that will regulate the flow of refrigerant through the coils of the tunnel heat exchanger. Test section Mach number is controlled by adjusting the fan drive motor speed with "fine tuning" being provided by variable inlet guide vanes. In addition to these major tunnel control functions, the proper flow quality must be maintained over a model in the test section by use of the plenum evacuation system (PES) and a series of "finger flaps" located at the exit of the test section that control the amount of air that flows out through the test section slots and then back in through the finger flaps. The operation of all of the AWT controls must be coordinated in such a way that the desired tunnel operating conditions can be maintained and that changes from one condition to another can be made in a safe and efficient way.

The design of the AWT control system hardware (e.g., valves, drive motor, sensors, controllers) and software (e.g., algorithms, controller gains) depends on having an a priori understanding of the transient behavior of the tunnel processes and the dynamic interactions that can exist between those processes. It is highly desirable to be able to predict the transient response of the tunnel and to be able to assess proposed control system designs prior to finalizing the control design and building the hardware. This requires the development of a mathematical model and computer simulation of the AWT system. As shown in Fig. 18, plans call for the development of such a mathematical simulation that will run on the Lewis mainframe computer. That program will serve as the primary analytical tool for studying the AWT system dynamics and control system performance.

However, there are many aspects of the AWT control system design that cannot be evaluated using the type of simulation just described. For example, because of the expected parallel control system logic, a single serial simulation of the tunnel and its controls will not provide insight into potential problems with control timing and inter-computer communications. To gain these insights, a real-time simulation of the AWT processes and controls that includes a parallel-processor simulation of the control computers is needed. As shown in Fig. 18, the hybrid computer systems at Lewis that are used for propulsion system simulation, will be used to simulate the AWT processes in real-time. A digital, parallel-processor computer system is also available to simulate the distributed controls in real time. The parallel-processor and hybrid computer simulations will be tied together to allow closed-loop evaluations of proposed control system designs. This real time capability will also allow selected operating scenarios, component failures, etc. to be evaluated in a timely fashion.

Long-term planning for the initial checkout tests is currently underway. As part of this, it is recognized that an on-site, real-time simulation capability would facilitate the checkout of control hardware and software prior to actual tunnel running. An on-site simulator would also allow for training of tunnel operators prior to the startup of the tunnel. While the design of a real-time, digital simulator for AWT has not been finalized yet, the technology for such a simulator exists. The final portion of Fig. 18 shows an experimental simulator system that has been developed at Lewis for jet engine simulation.

## Summary

This paper has described an extensive effort that is underway at the NASA Lewis Research Center to model the various aspects of the proposed rehabilitated and modified Altitude Wind Tunnel (AWT) in order to insure it has a technically sound basis for design. The modeling program consists of four basic elements: aerothermodynamics, icing, acoustics, and system dynamics. In each case both experimental and analytical work is underway. The program is targeted to provide input in a timely fashion to the AWT final design and construction process.

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6. Towne, C.E., Povinelli, L.A., Kunik, W.G., Muramoto, K.R., McClallin, K.L., Hughes, C.E., and Levy, R., "Analytical Modeling of Circuit Aerodynamics in the New NASA Lewis Altitude Wind Tunnel," AIAA Paper 85-0380, Jan. 1985.

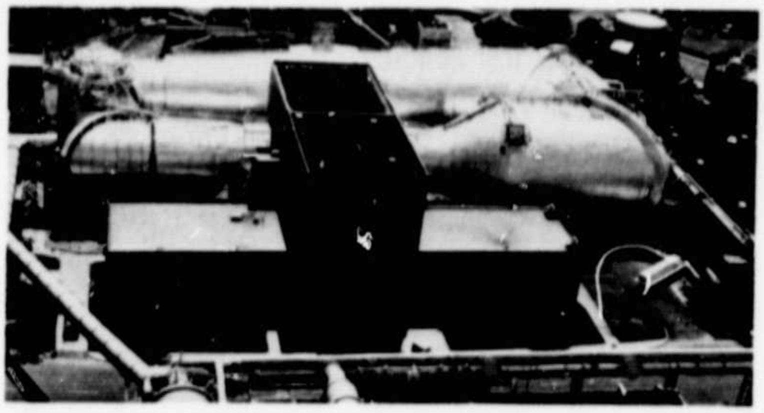
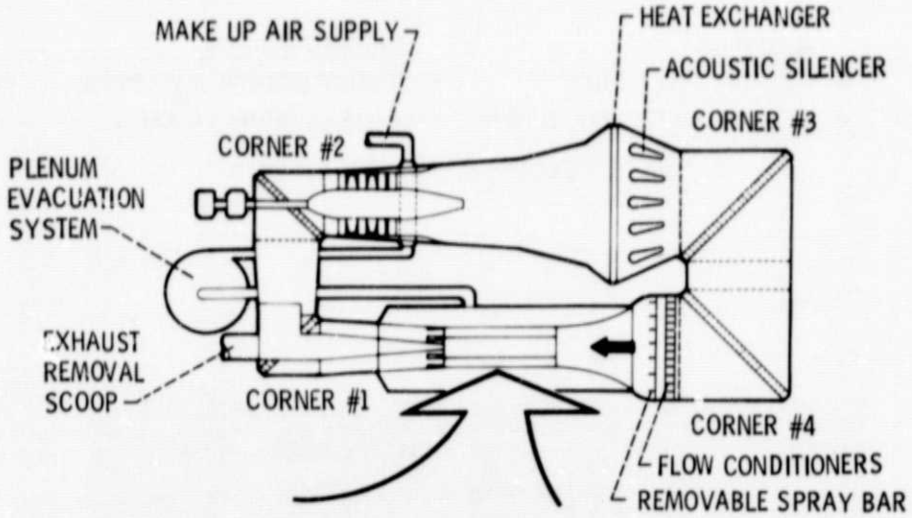
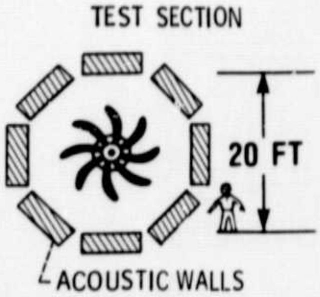


Figure 1. - Current configuration of the Lewis Research Center's Altitude Wind Tunnel (AWT).





| CAPABILITIES | |
|---|---|
| MACH NUMBER | 0 TO 0.9 + |
| ALTITUDE | 0 TO 55 000 FT + |
| TOTAL TEMPERATURE | -40° TO 60 °F |
| TEST SECTION ACOUSTIC LEVEL | 120 dB (OASPL) |

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Figure 2. - Capabilities of modified and rehabilitated AWT.

- CONCURRENT PRESSURE AND TEMPERATURE SIMULATION OF ALTITUDE
- LARGE SCALE TEST ARTICLES
- FULL SUBSONIC SPEED RANGE
- PROPULSION SYSTEM OPERATION/SIMULATION
- ACOUSTIC MEASUREMENT CAPABILITY
- ICING, HEAVY RAIN CAPABILITY

Figure 3. - New test facility requirements satisfied by AWT.

AEROTHERMODYNAMICS

- COMPONENT AERODYNAMIC AND THERMODYNAMIC PERFORMANCE
- COMPONENT AERODYNAMIC LOADS
- OVERALL SYSTEM PERFORMANCE - STEADY STATE

ACOUSTICS

- ANECHOIC TEST SECTION
- BACKGROUND ACOUSTIC LEVELS

ICING

- TUNNEL SYSTEMS FOR PROVIDING ICING/HEAVY RAIN/FREEZING RAIN/SNOW
- EFFECT OF ICING ON TUNNEL COMPONENTS

SYSTEM DYNAMICS

- DEVELOP DYNAMIC MATH MODEL
- ASSESS CONTROL CONCEPTS

Figure 4. - Elements of AWT modeling program.

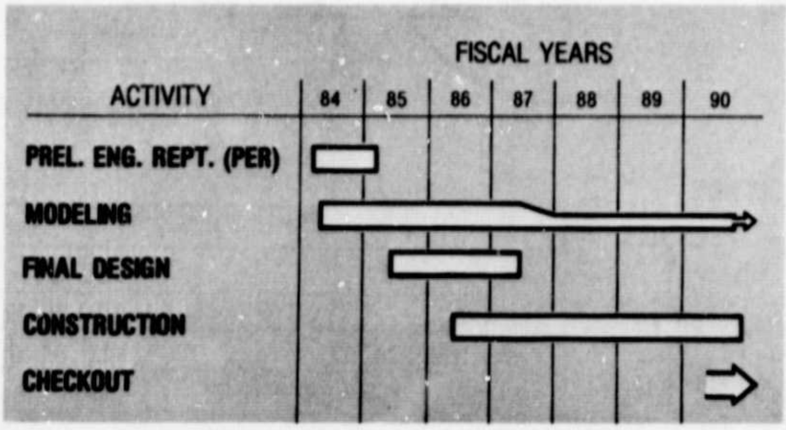

Figure 5. - Relationship of modeling program to other aspects of the AWT project.

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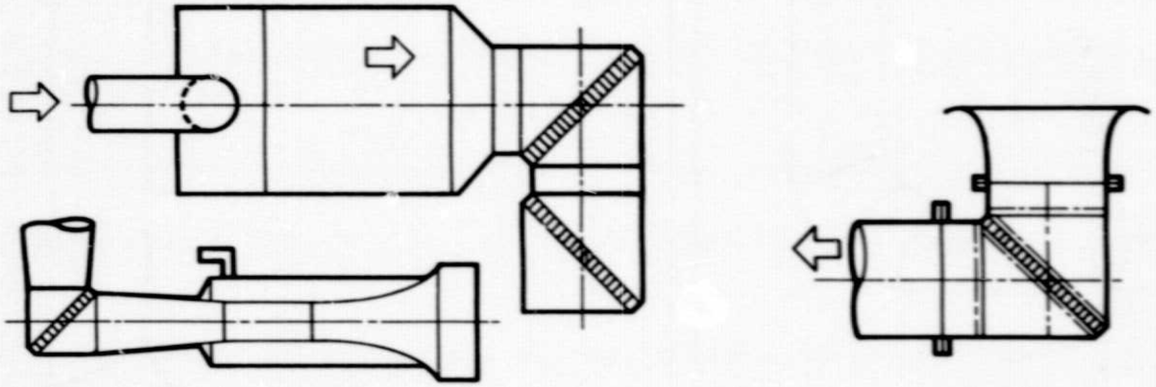
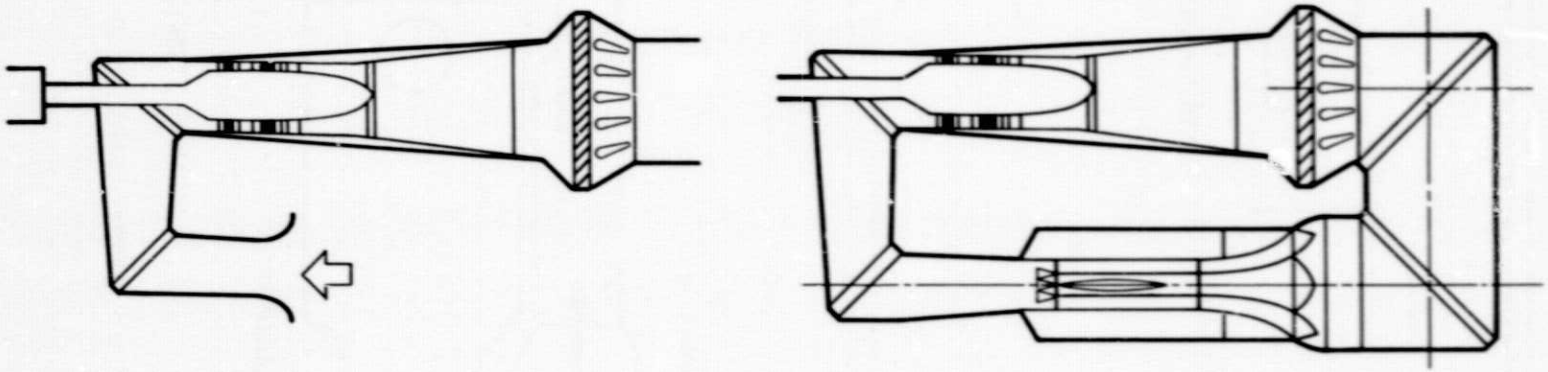


HIGH SPEED LEG

CORNERS



FAN

COMPLETE LOOP

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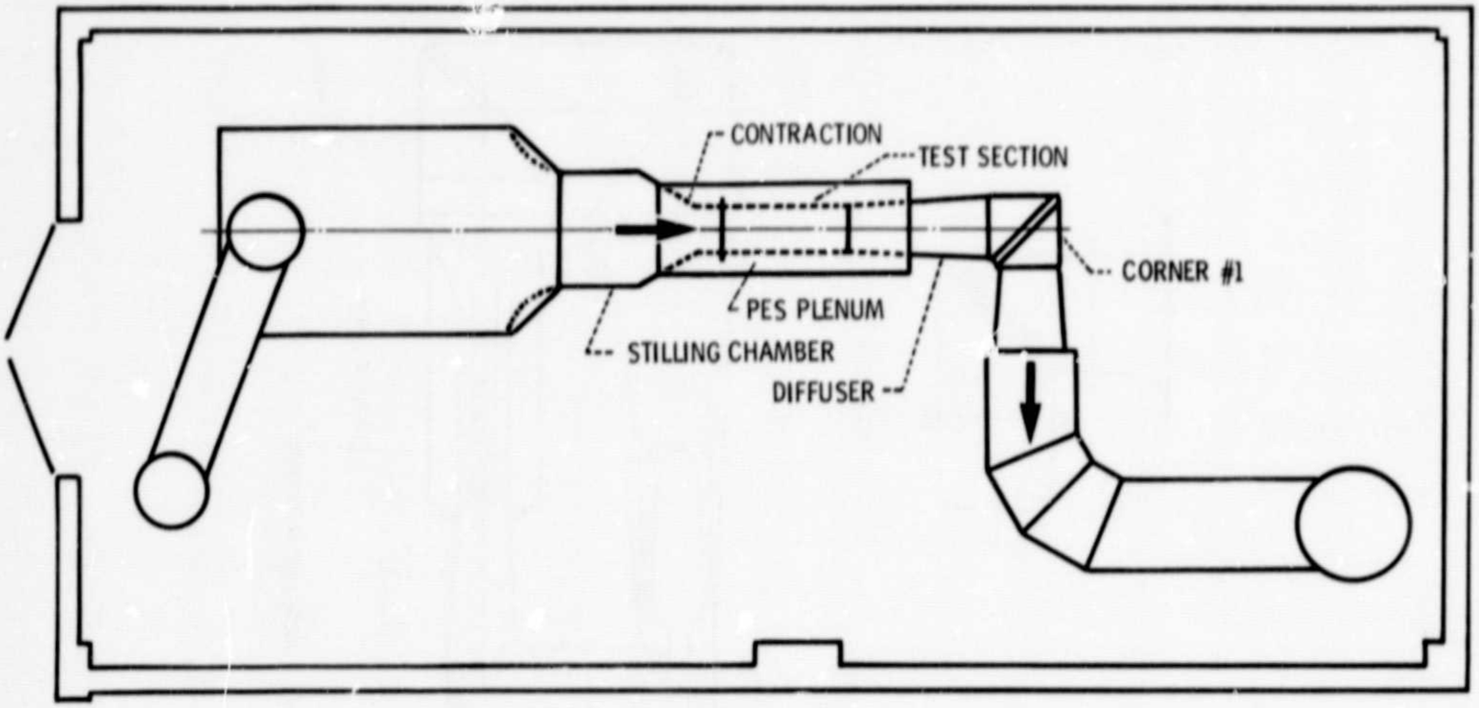
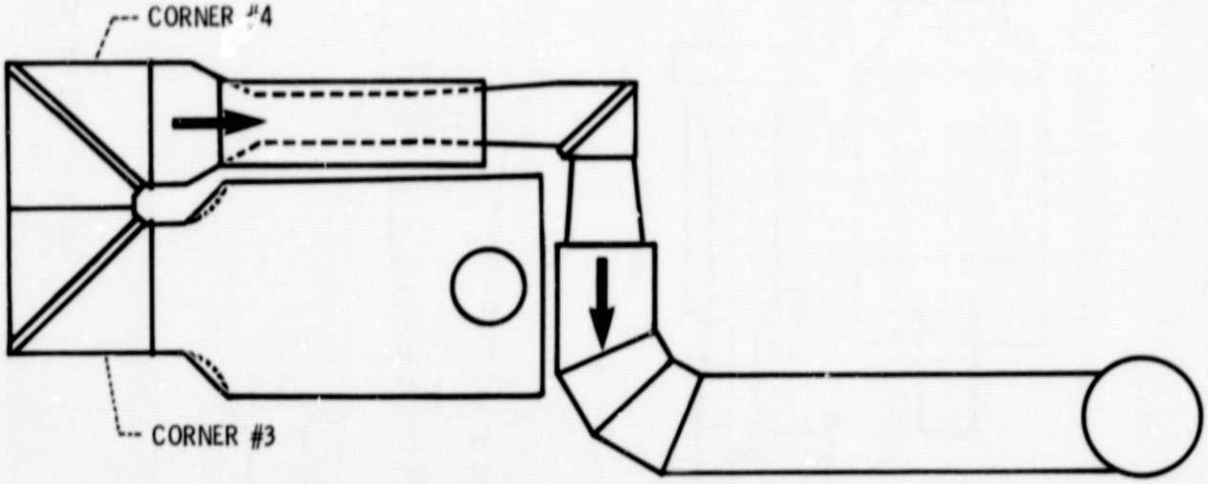
Figure 6. - AWT 1/10-scale experimental aerodynamic models.



PHASE 1 CONFIGURATION



PHASE 2 CONFIGURATION

Figure 7. - AWT 1/10-scale high speed leg model.

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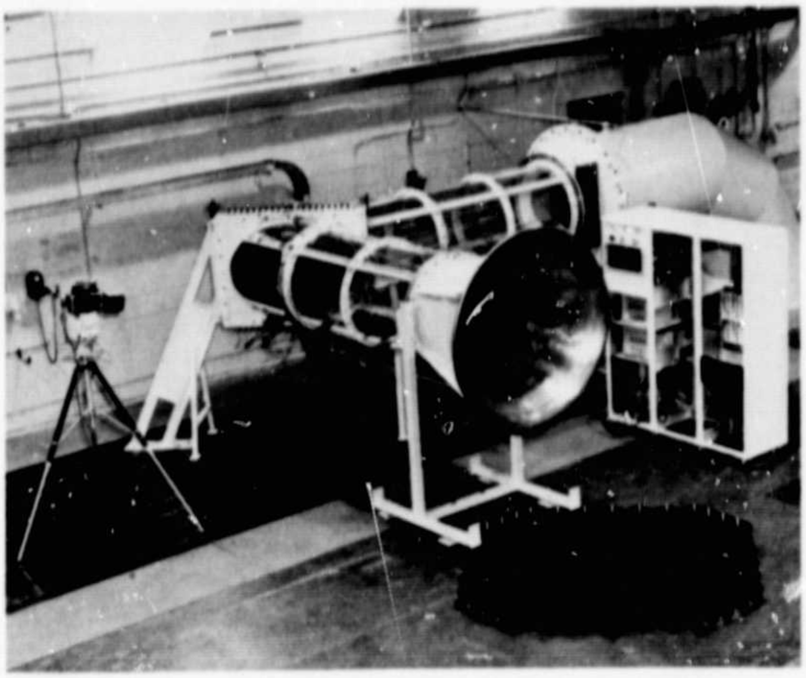

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Figure 8. - AWT 1/10 - scale corner model.

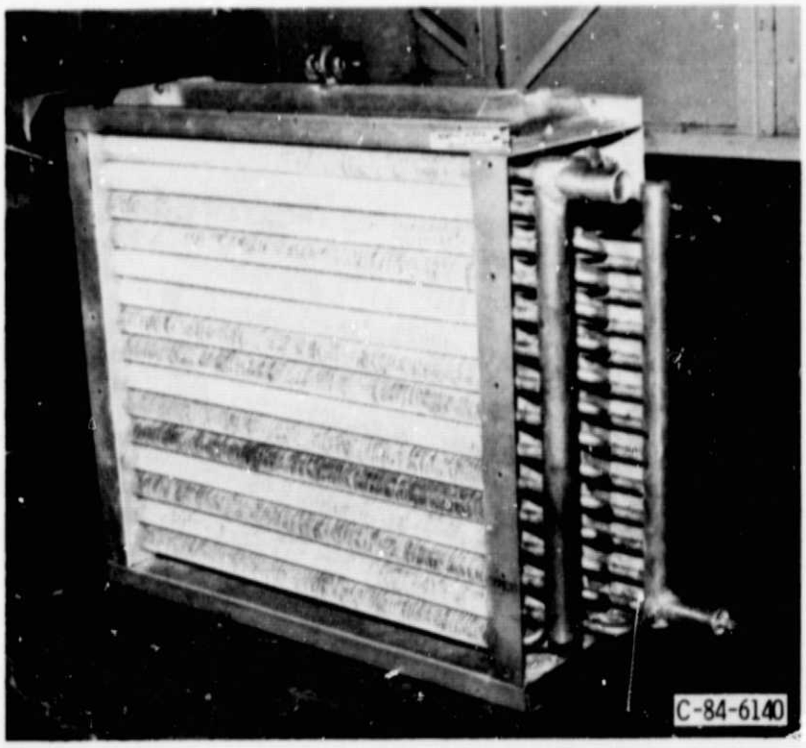

Figure 9. - AWT heat exchanger model - 3 foot X 3 foot panel of full size configuration.

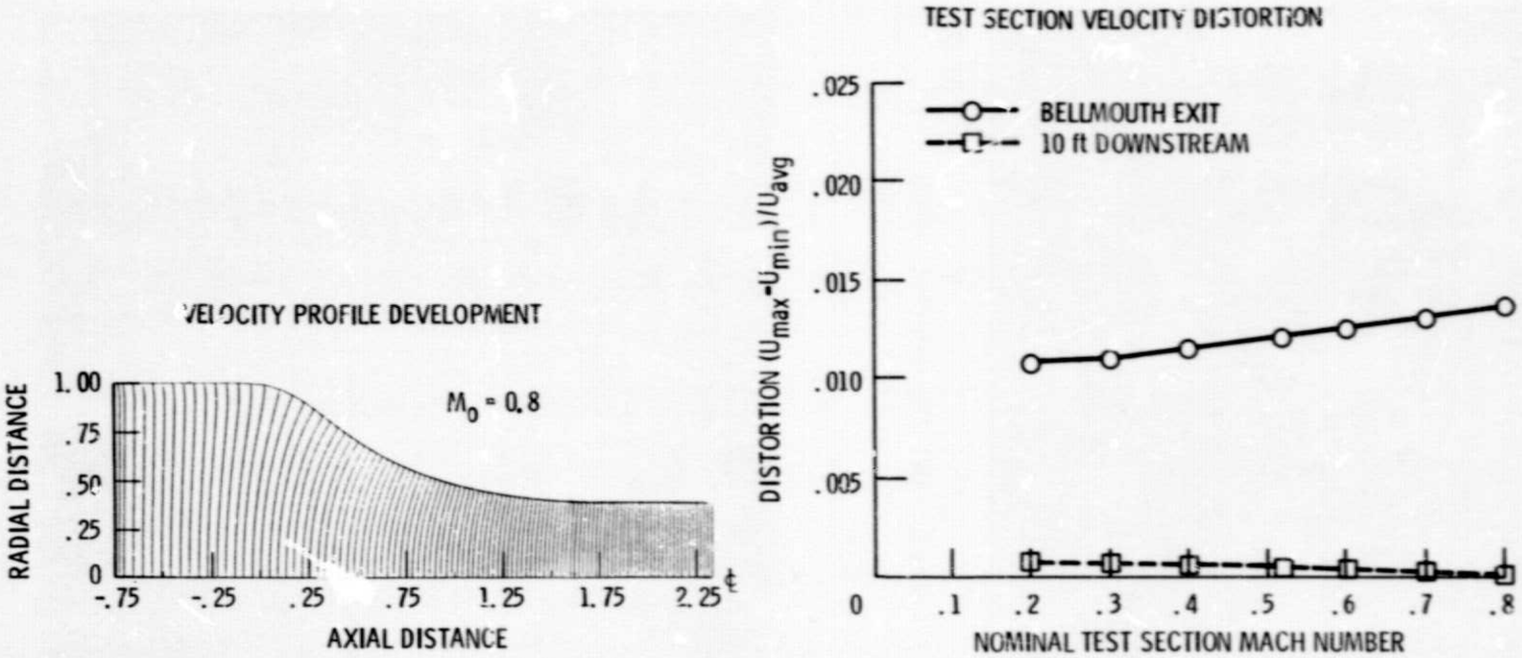

Figure 10. - AWT analytical modeling results. Variation of velocity in contraction and test section. Axisymmetric, viscous calculation (VISTA code).

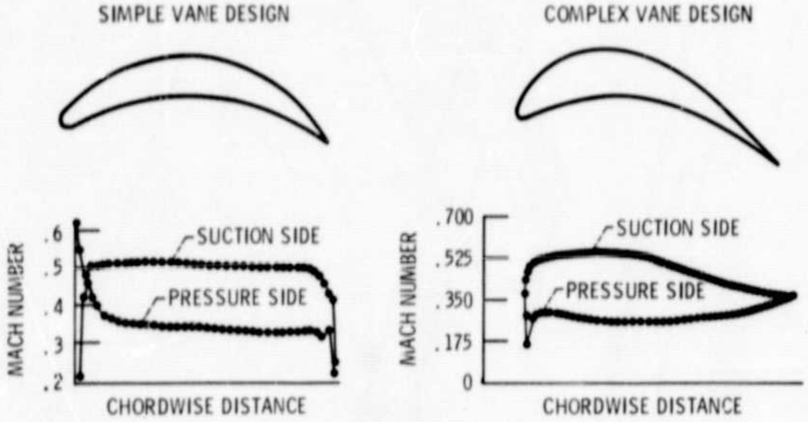

Figure 11. - AWT analytical modeling results. Design of turning vanes for corners 1 and 2.

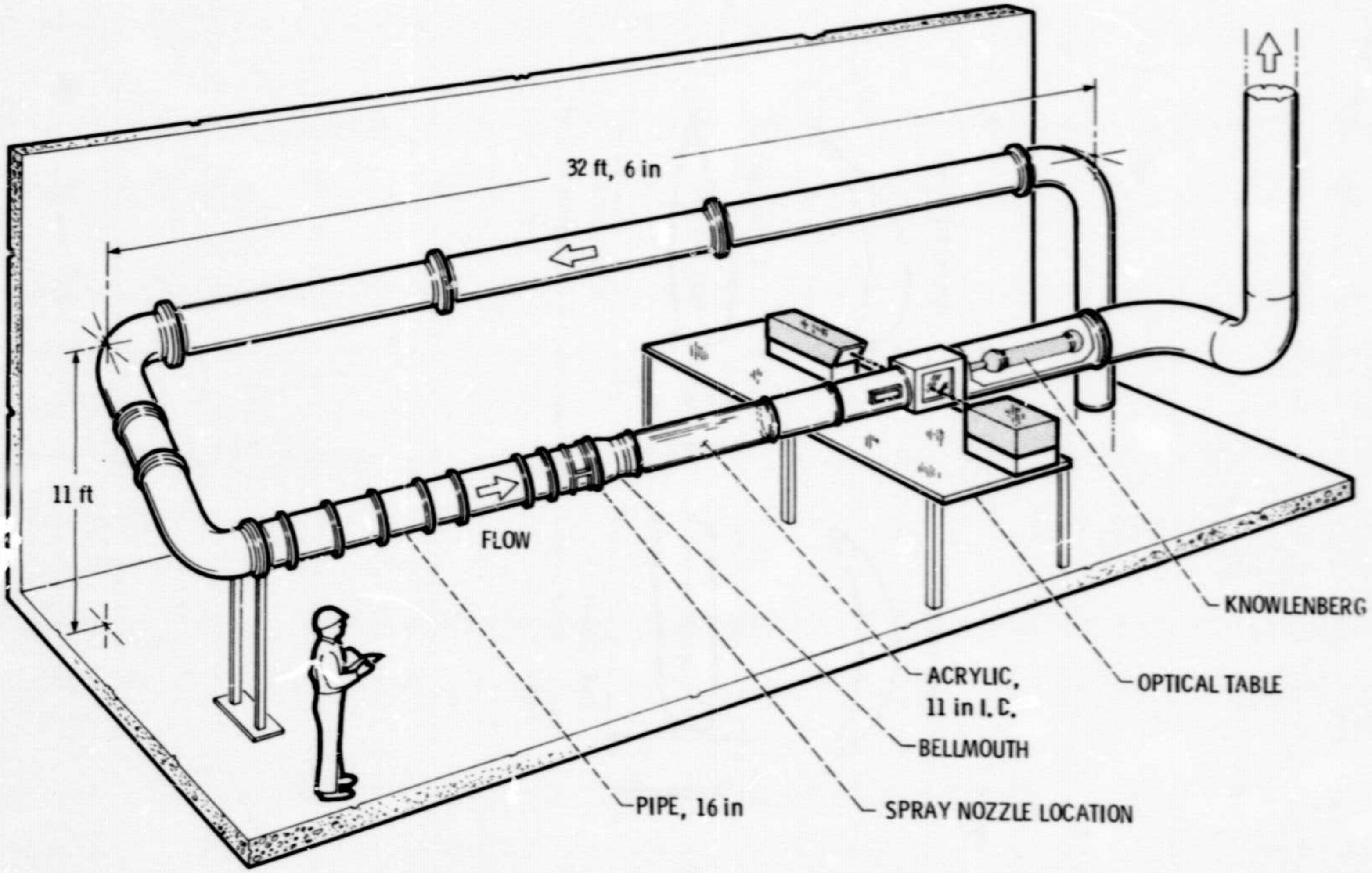

Figure 12. - Single nozzle spray test facility.

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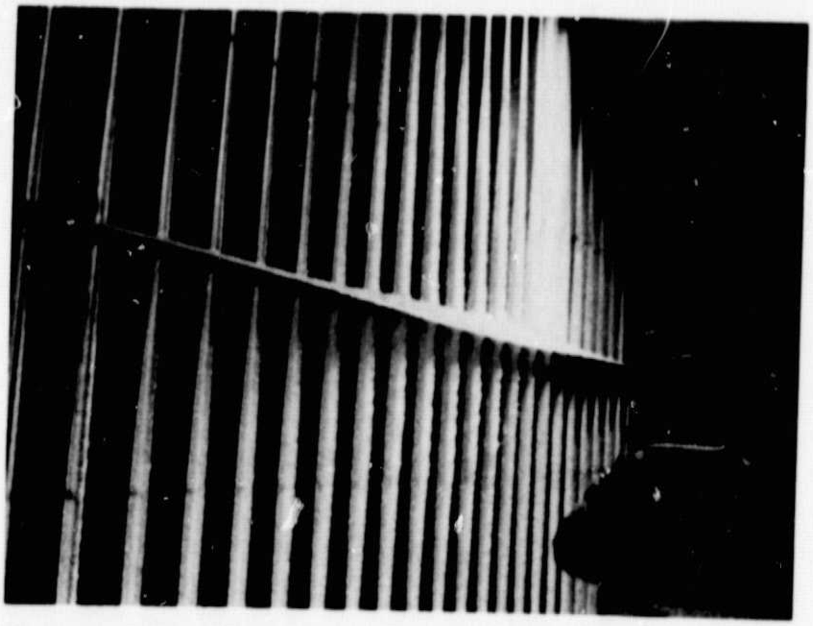


Figure 13. - Ice accretion tests in Lewis' icing research tunnel. First turning vane set downstream of test section after extended operation.

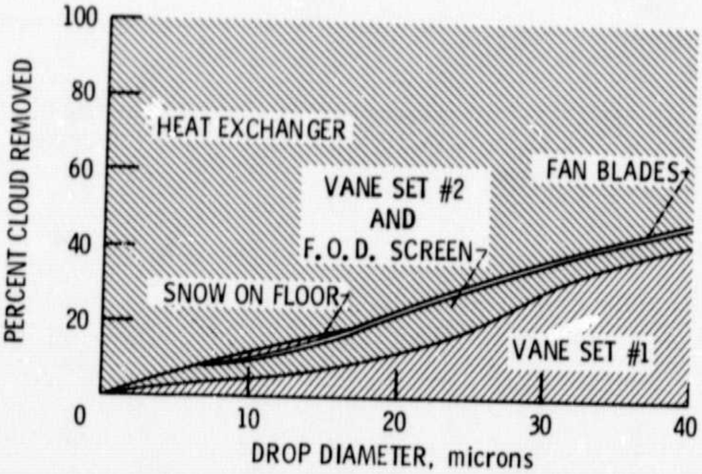


Figure 14. - Results of ice accretion tests in Lewis' icing research tunnel.

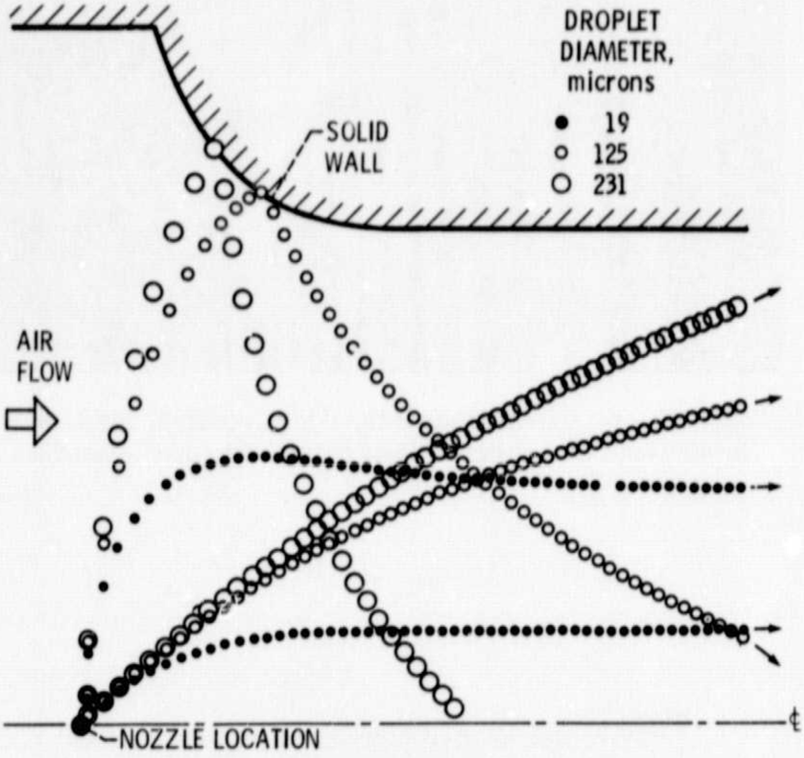
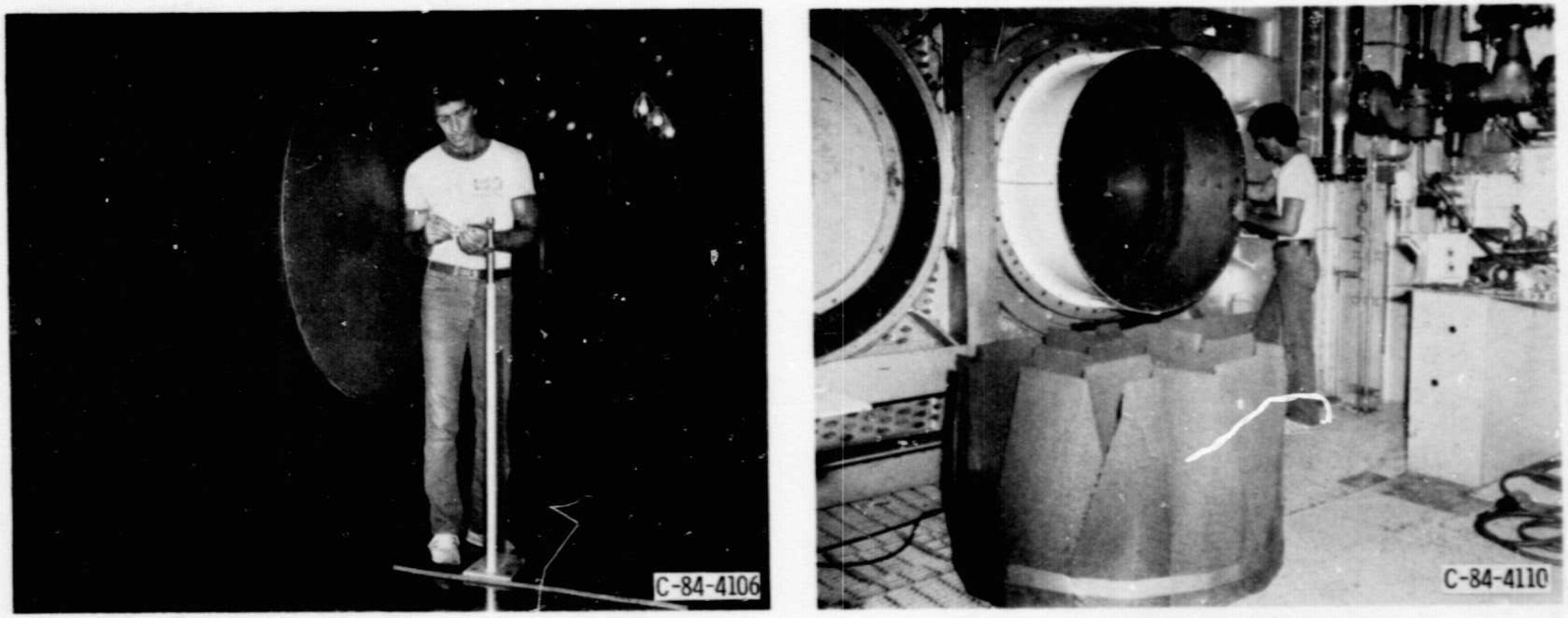


Figure 15. - AWT analytical modeling results. Trajectories of water droplets of various sizes, injected at various angles in the single nozzle spray test facility.



View from inside test section

View from outside test section

Figure 16. - AWT acoustic treatment tests in the Lewis 8X6 foot wind tunnel

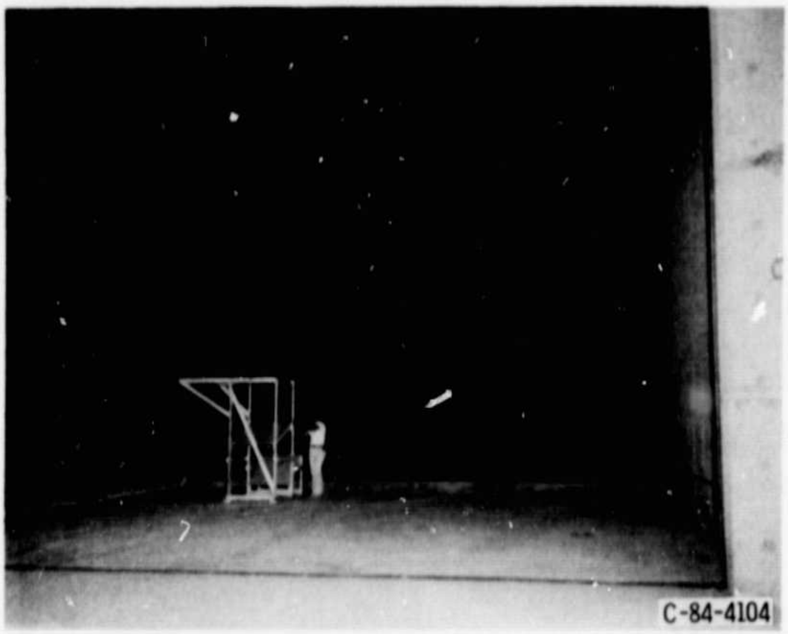


Figure 17. - Heat exchanger acoustic attenuation tests in Lewis 8X6 foot wind tunnel.

**SYSTEMS SIMULATION**

- IBM 370/FORTRAN MODEL OF AWT SYSTEM
- ANALYSIS OF TRANSIENT RESPONSE AND SYSTEM INTERACTIONS

**CONTROLS**

- REAL-TIME SIMULATION USING HYBRID COMPUTER
- EVALUATION OF PROPOSED CONTROL DESIGNS

**REAL-TIME DIGITAL SIMULATOR**

- FACILITY SIMULATOR FOR PRE-RUN CHECKOUT OF CONTROLS AND OPERATOR TRAINING

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Figure 18. - System dynamics analysis.