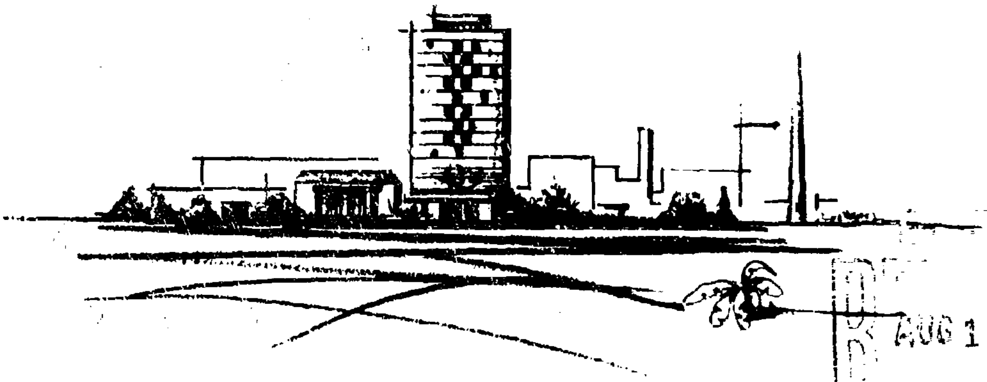
RESEARCH REPORT



BATTELLE MEMORIAL INSTITUTE

COLUMBUS LABORATORIES

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THE SUBSONIC WIND TUNNEL

of

BATTELLE COLUMBUS LABORATORIES

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by

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PREFACE

The Battelle Columbus Subsonic Wind Tunnel was conceived and designed by Battelle staff members and constructed with Battelle funds. The structural design of the wind tunnel was the responsibility of John T. Voedisch of the Mechanical Engineering Department Design Office, who also conceived many of the geometric innovations required to make the facility a useful research tool. Developing the tunnel configuration and performing the aerodynamic design was the responsibility of Vernon O. Hoehne. Valuable technical advice was supplied by many members of the Battelle-Columbus staff.

The wind tunnel and its associated equipment are available for use by both individuals and organizations through Battelle's normal research contracting procedures on a first-come, first-served basis, subject to prior research commitments.

The wind tunnel is managed by the Aerospace Mechanics Research Division of the Mechanical Engineering Department. Robert F. Badertscher is Chief of this Division. Technical manager of the facility is Vernon O. Hoehne, Senior Aerodynamicist in this Division. Either may be contacted for more detailed information, subsequent calibrations, or arrangements for use of the facility.

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ABSTRACT

The Subsonic Wind Tunnel of Battelle Columbus Laboratories has been developed to provide a quality research tool that is economical to operate. It can provide air velocities to 250 fps with a turbulence level of 0.10 percent or less through a 55-inch-high by 38.5-inch-wide test section. Models are mounted directly to the walls, floor, or ceiling of the test section, or on a sting. This report is a description of the tunnel, its management procedures, and cost to users.

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INTRODUCTION

The Subsonic Wind Tunnel of Battelle Columbus Laboratories was conceived and designed as a research tool to support both aeronautical and nonaeronautical studies. It is relatively simple to operate, comparatively inexpensive to use, and with proper operation, it provides quality data. The dominant guidelines for the planning, design, and construction of the facility were that it be capable of providing above-average test conditions at a minimum operating cost.

The purpose in the following pages is to give the potential user of the tunnel a geometric and operational description of the facility as of June, 1967. As with all research tools, the capabilities of the wind tunnel will most assuredly be extended and modified as time goes on. Also, the documentation of the operational characteristics will become more complete as tests are performed and additional equipment is acquired. Because pertinent data about the facility will change, up-to-date information will be made available upon request to interested individuals and organizations.

The tunnel is simple in concept, but fairly broad in application. It is intended to be a tool for studying both detailed aerodynamic phenomena in a precise manner as well as order-of-magnitude examinations of gross air-flow systems. Its open-circuit design not only reduces cost, but also precludes accumulation of contaminants that may be introduced into the test section. The tunnel structure is protectively coated so that a broad spectrum of gases other than air, as well as fire, can be introduced with care into the test stream without danger of destroying the facility. The exit of the tunnel is roughly 40 feet inside the building which houses it, so that space is available for modifying the exit structure to provide a cross-sectionally large test area to suit unusual test requirements.

The discussion of the wind tunnel which follows is divided into several sections. A summary of the contents of these sections follows:

- Geometry and Equipment

  .... physical description of the tunnel and its associated equipment and work areas.

- Operation

  .... description of the operational capabilities of the tunnel including data from both calibration tests and theoretical computations.

- Data Recording and Analysis

  .... list and description of the equipment available for recording and analyzing test data.

- Facility Management

  .... regulations governing the use of the wind tunnel facility.

- Facility Use-Rate Costs

  .... explanation of the costs involved in using the facility.

GEOMETRIC DESCRIPTION

The Battelle Columbus Subsonic Wind Tunnel is of the open-circuit (or NPL) type, drawing its test air directly from the atmosphere. The entrance to the tunnel is located at one end of the building that houses the facility with the exit inside the building as shown on Figure 1. The wind tunnel placement relative to the various work areas in the facility is also indicated. A model assembly area is provided for the assembly, bench test, and modification of test models and instrumentation. Cabinets are located in this room for storing models and specialized instrumentation designed for use with the models. Adjacent to the wind tunnel test section is an 11 x 12-foot platform that provides a floor at a convenient working level relative to the test section (Figure 2). On or adjacent to this platform are the console from which the operator controls the wind tunnel, racks for supporting test instrumentation, and a multitube manometer.

The primary construction material used throughout the wind tunnel is wood. The framework consists of 2 x 4 and 4 x 4 construction lumber. Planar components are cut from 3/4-inch marine plywood and all curved components are fabricated from 1/4-inch tempered Masonite Presdwood. Observation windows in the door and ceiling of the test section are of 3/4-inch Plexiglass. Steel angle sections and tubing are used where necessary for reinforcement. The structure of the wind tunnel was fabricated in eight sections with 1/4-inch hard rubber gaskets at each joint between the sections. In addition to eliminating air leaks, these gaskets help dampen structure-borne vibrations. Wood was used as a construction material because it also can dampen vibrations. The use of wood kept the cost of fabrication comparatively low and made possible a structure that can be easily maintained and modified. The interior and exterior surfaces of all wood components are painted with Albi Fire Retardant intumescent paint which, when exposed to fire, forms an effective insulation to the heat of the fire. This paint serves two purposes: (1) it protects the wood surface during experiments that require high temperatures, and (2) it provides a smooth white surface to reduce tunnel flow losses and enhance the visual observation of test phenomena.

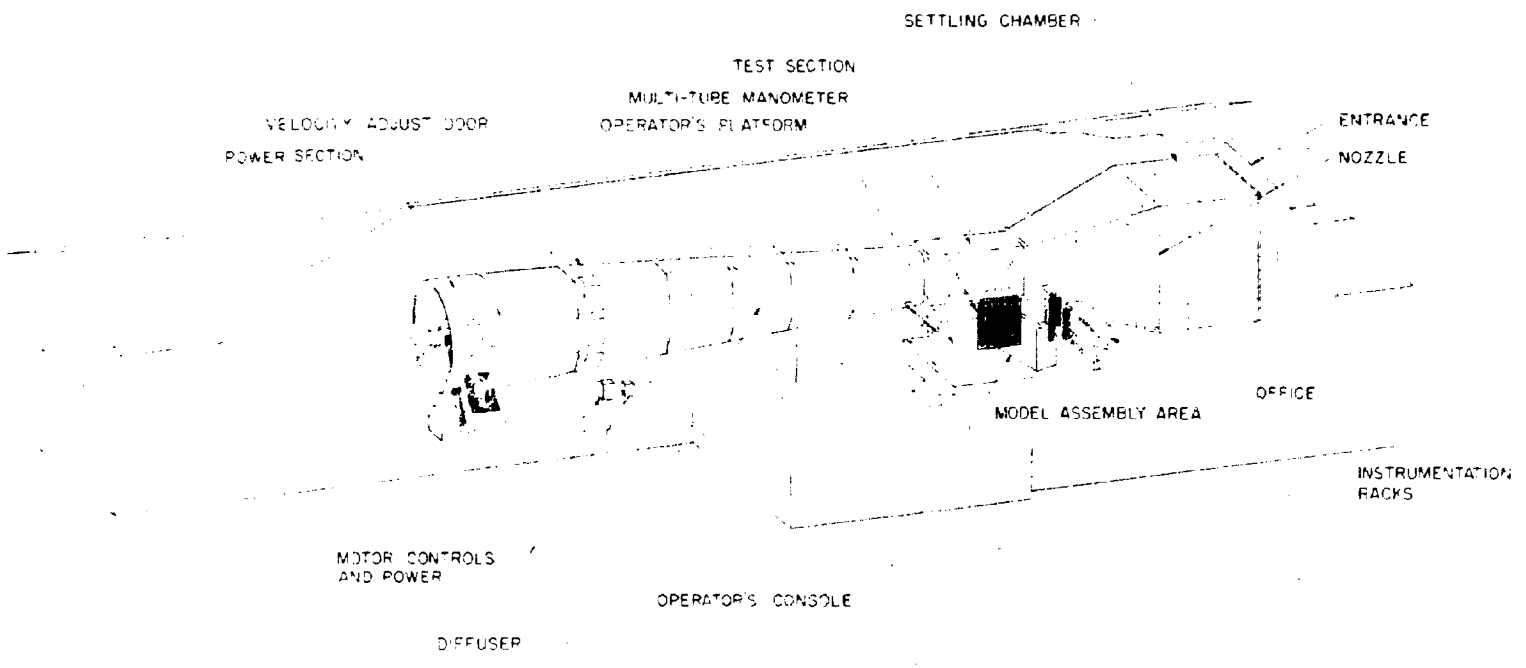

FIGURE 1. THE BATTELLE-COLUMBUS SUBSONIC WIND TUNNEL FACILITY

FIGURE 2. WIND TUNNEL TEST SECTION AND OPERATOR'S PLATFORM

The wind tunnel components, as shown in Figure 3, are: (1) inlet, (2) settling chamber, (3) nozzle, (4) test section, (5) diffuser, and (6) power section. The inlet components consist of quarter-circular fairings mounted to both the building and the closure doors at the tunnel entrance. When the doors are open, these fairings form a transition from the infinite space of the atmosphere to the settling chamber (Figure 4).

The settling chamber provides sufficient space for the installation of six turbulence screens--three have already been installed. These screens are precision woven of 0.0075-inch-diameter stainless steel wire having 24 wires per inch. The wire diameter was chosen on the basis of Reynolds number considerations and the diameter and number per inch was chosen to yield a 67.4 percent projected open area ratio. A ratio having this magnitude, according to tests and theory, is needed for good spanwise flow and for the best reduction in wind tunnel turbulence.(1-7)*

A large contraction ratio helps reduce freestream turbulence and promotes cross-sectionally uniform flow in the test section.(2,7,8) The design geometric contraction ratio of this tunnel is 10:1, a value based on building size restrictions and test section size requirements. The nozzle contraction contour was designed according to the method reported by Smith and Wang.(9) This method is an analytical technique developed to yield maximum pressure recovery or minimum flow losses while funneling the air through the 10:1 contraction. The contour of the nozzle surface was physically formed using 1/4-inch tempered Masonite in such a way that adjustments could be made to achieve a precise contour. The technique for doing this is such that if desired, the cross-sectional size of the test section can be decreased and the nozzle contour changed accordingly. Although this would require a major modification of the tunnel, it would not be nearly as time-consuming as rebuilding the nozzle. This construction technique made possible an exceptionally smooth transition from the settling chamber to the test section.

The test section side walls were designed to diverge from entrance to exit at an angle calculated to be equal to the slope of the increase in the boundary layer displacement thickness with distance at a 200 fps test velocity.

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* Superscript numbers in parentheses refer to references listed at the end of this discussion.

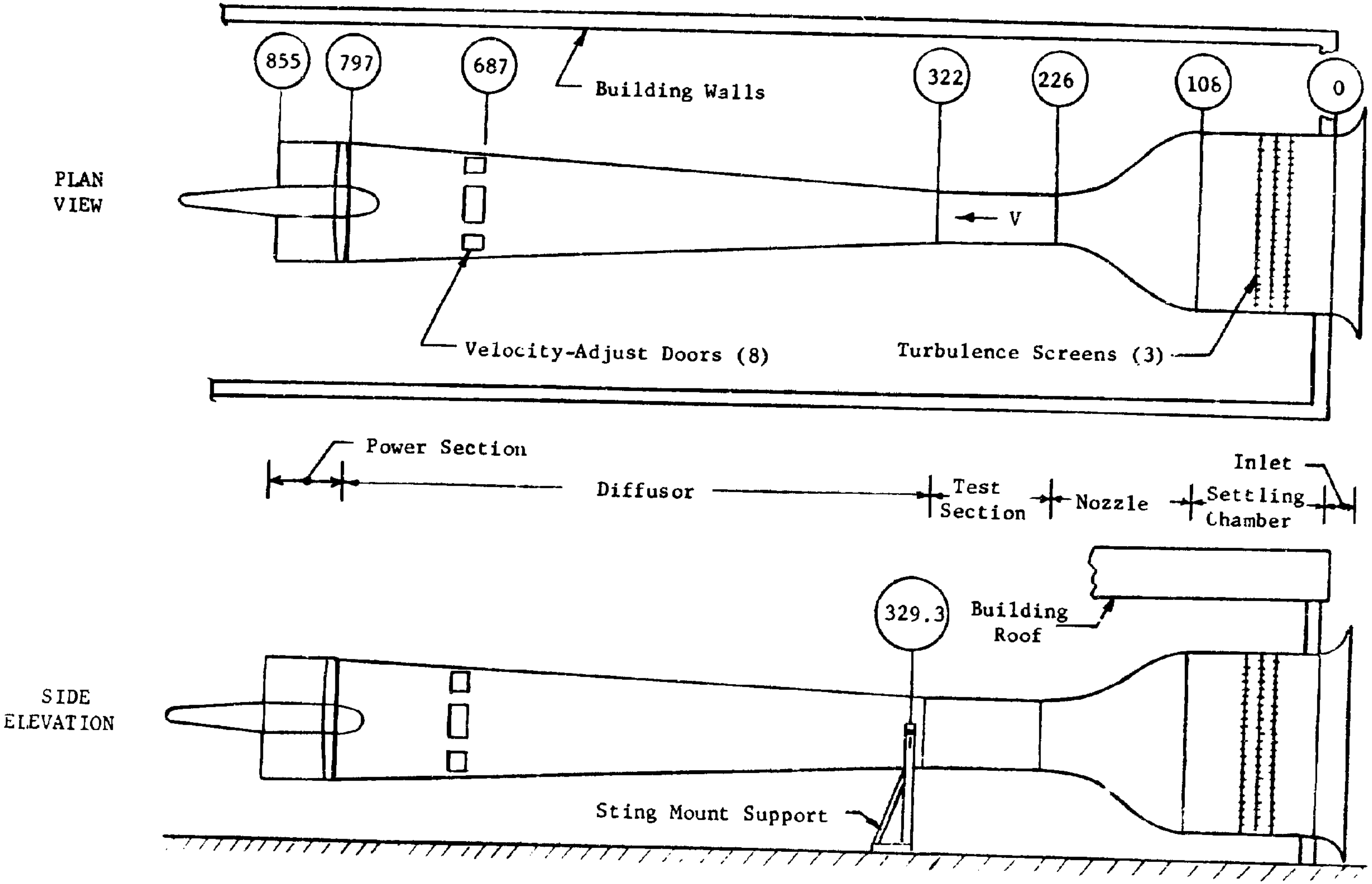


FIGURE 3. SCHEMATIC OF INTERNAL CONTOUR OF THE WIND TUNNEL

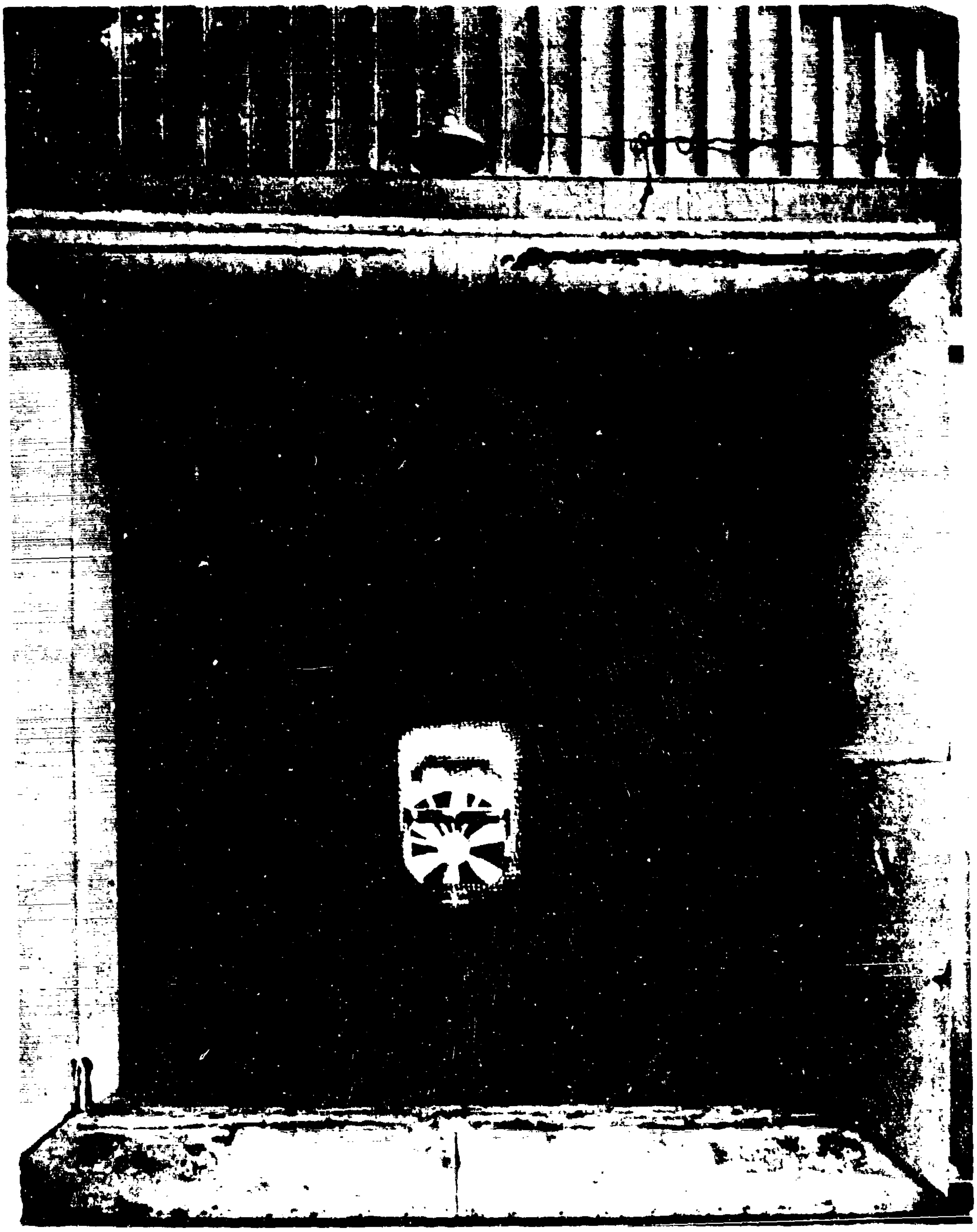
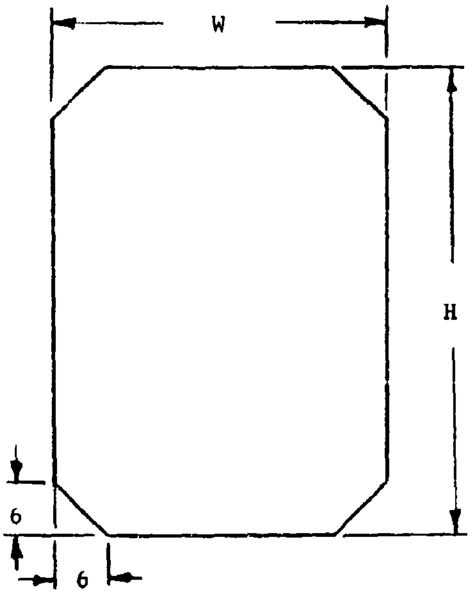


FIGURE 4. FLOW INLET AND SETTLING CHAMBER SHOWING TURBULENCE SCREENS

The actual cross-sectional dimensions at both the entrance and exit of the test section are shown in Figure 5. The walls are planar between these stations. Windows for visually observing tests, admitting light, and photographically recording data are provided in the door side and the top of the test section. There are four 17 x 33-inch windows in the door and one 16 x 72-inch window in the ceiling. Each of these windows can be easily removed for access to the test section. The test section access door opens the entire side of the section providing an opening 43 x 84 inches to facilitate model installation and removal. An adjustment mechanism on the door provides for preloading the door such that the pressure differential between the inside and outside of the test section causes the door to deflect to a flat surface rather than being curved inward. This adjustment mechanism can be varied to account for any test pressure differential or can be stowed for tests during which door deflections are not detrimental to the test environment.



Station	Location	W	H
226	Entrance	38.73	55.00
322	Exit	39.09	55.53

FIGURE 5. DETAILS OF TEST SECTION CROSS SECTION

Models can be mounted to the side walls, the ceiling, or the floor of the test section. The more usual locations for mounting are backed by steel channels for reinforcement. In addition, a sting model support is attached through steel channels directly to a concrete foundation that is separate from the tunnel structure to isolate vibrations from the sting mount.

The diffuser of the wind tunnel extends from Station 322 to Station 797 (Figure 3). The cross-sectional shape of the diffuser varies from the test section shape (Figure 5) to very nearly an octagon--and then to an 8-foot-diameter circle. The diffusion angle in the horizontal plane is 7 degrees; in the vertical plane, 5.04 degrees. This yields an overall diffusion angle (based on a pseudo-diffuser shape that is a truncated right circular cone having the same end cross-sectional areas as the diffuser inlet and outlet) of 5.26 degrees--a value well below the 7-degree angle considered to be the stall angle.(10) The 5-degree diffusion angle in the vertical plane permits enough latitude for changing the test section cross-section to a square with the resulting vertical diffusion angle not exceeding 7 degrees. An internal view of the diffuser is shown in Figure 6.

At Station 687, eight remote-controlled 14 x 24-inch doors are located about the periphery of the diffuser to facilitate adjusting the test section velocity to a desired value (Figures 3, 6, and 7). Each door is controlled through a positive linkage by a gear motor synchronized to the other seven motors. These doors bleed air to the wind tunnel propeller, by-passing the test section and thereby reducing the mass flow drawn through the test section. Because of the conservation of mass, the velocity in the test section decreases as these doors are adjusted toward full open (45-degree angle to the diffuser side wall). An indicator at the operator's console indicates the door position in percent of total door angular travel.

The power section of the wind tunnel consists of an 8-foot-diameter, -bladed, adjustable-pitch propeller mounted in a 58-inch-long steel tube. A fan tip clearance with the tube of 0.25 inch or less is maintained at all circumferential stations. Seven flow-straightener vanes are located downstream of the propeller. These serve the dual purposes of converting rotational energy in the airstream to a pressure rise and providing support for the propeller assembly (Figure 8). The vanes were designed to have a radially

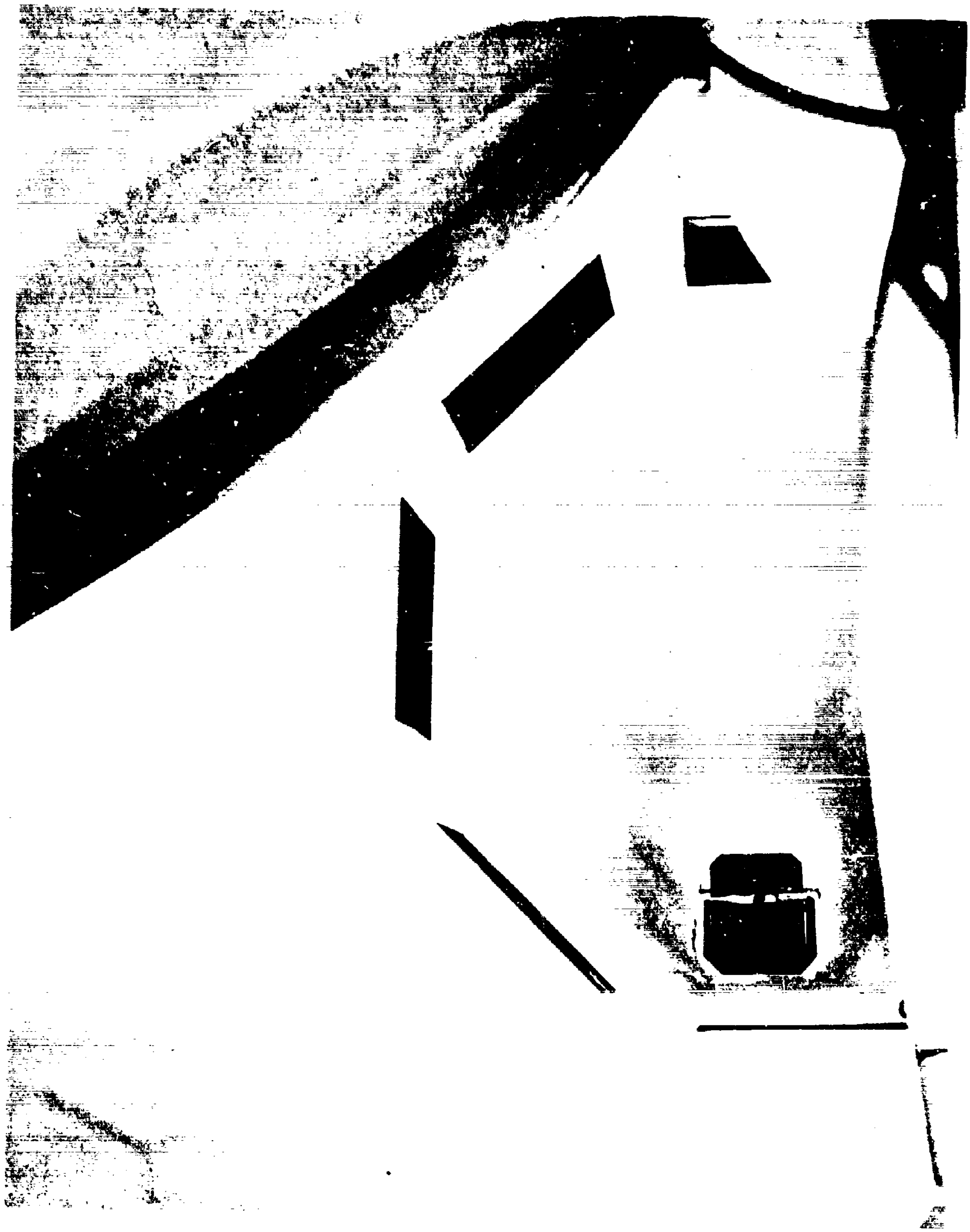


FIGURE 6. INTERNAL VIEW OF THE DIFFUSER LOOKING FROM THE POWER SECTION

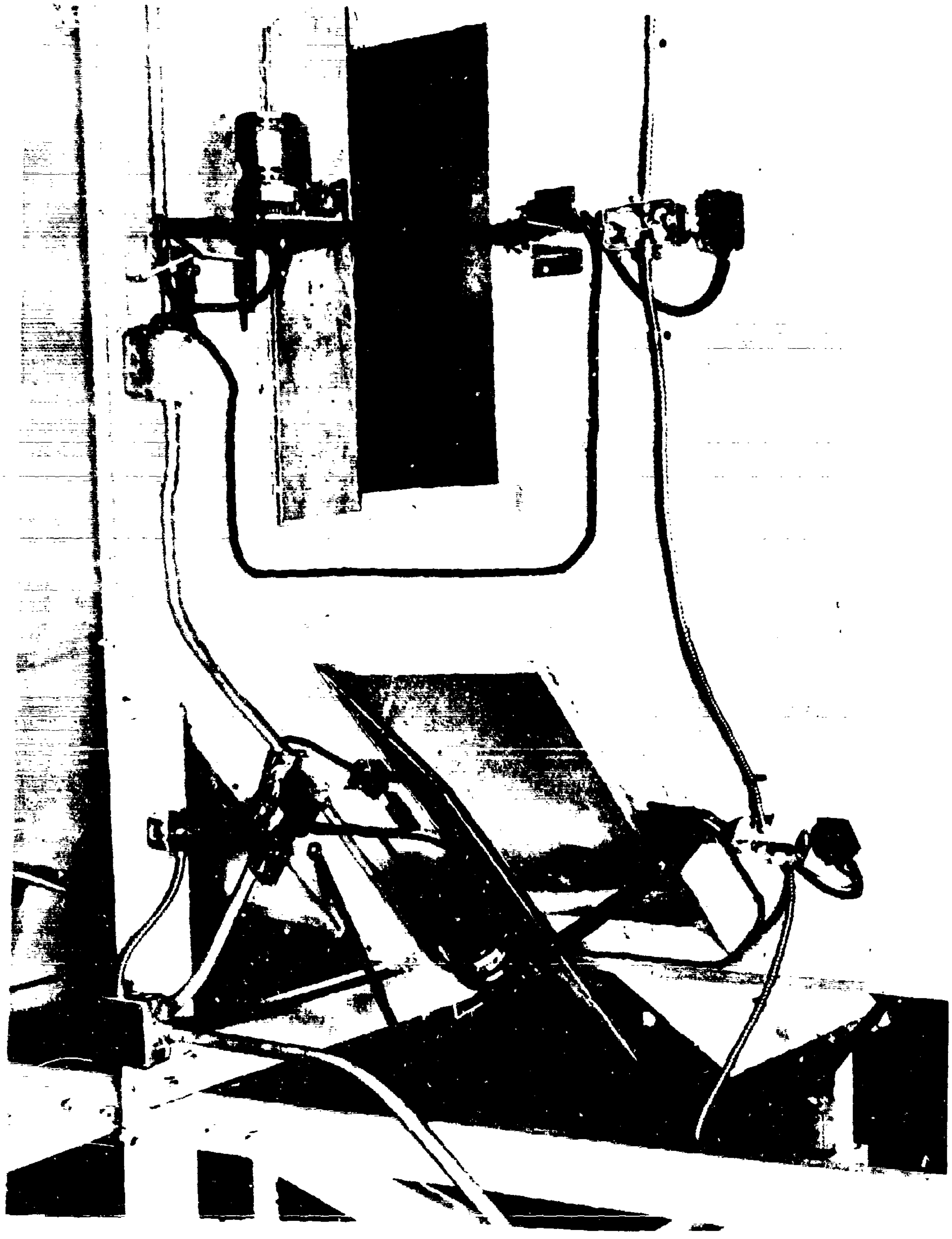


FIGURE 7. VELOCITY-ADJUST DOOR AND DOOR MECHANISM WITH ELECTRICAL COMPONENTS EXPOSED

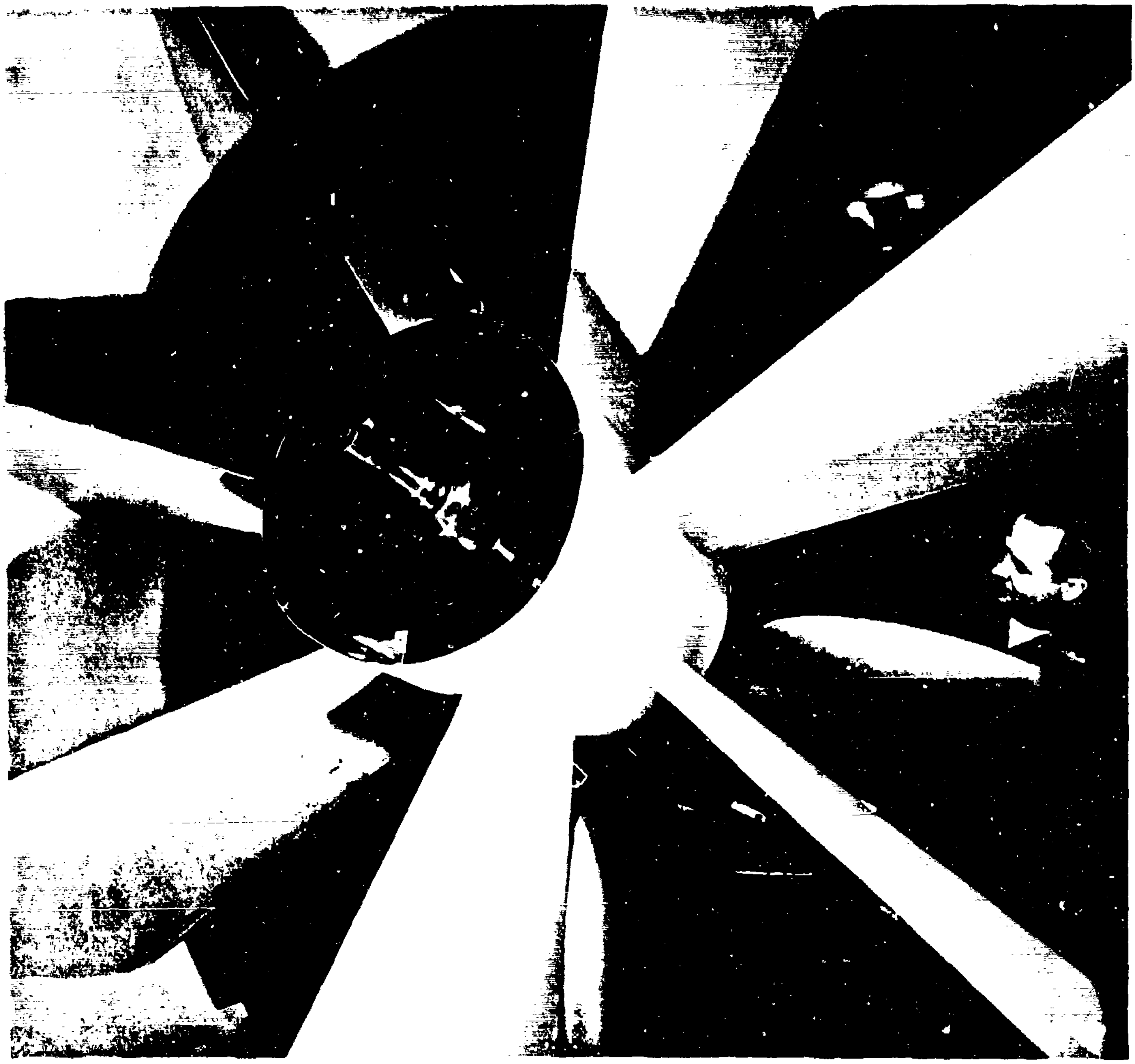


FIGURE 8. INTERNAL VIEW OF THE POWER SECTION WITH THE PROPELLER DRIVE SHEAVE AND FAIRING REMOVED

varying chord to yield a solidity ratio equal to one.(11) The support structure within the vanes has provisions for adjusting the alignment of the propeller axis of rotation to the wind tunnel centerline.

A commercially available Hartzell MP96-6 cooling tower fan is used to pump the air through the tunnel. The fan blades are fabricated of fiberglass, which would facilitate blade chord modifications to improve undesirable test flow conditions if needed. The pitch angle of each blade is adjusted individually with tooling that is designed specially for this purpose. The performance of the fan is shown in Figure 9. The available pressure rise through the fan indicates the capability of the fan to recover the flow losses caused by both the presence of a model and model support mechanism, and the wind tunnel walls, screens, etc., in the flow stream when the test velocity is as indicated. The flow losses due to the survey rake used for calibrating the tunnel and the calculated losses due to tunnel wall boundary layers, turbulence screens, etc., are shown plotted in the figure for reference.

The wind tunnel fan is driven by a Star 125-hp squirrel-cage induction motor through a system of eight V-belts and sheaves that reduce the rotational speed from roughly 1175 to 700 rpm. The motor uses 3-phase, 60-cycle, 440-volt electrical power. Although the motor is rated at 125 hp, higher power values can be achieved when necessary without damage if winding temperature is controlled. Cooling slots and openings in the motor case make it possible to cool the motor by an auxiliary blower when necessary. A general view of the power end of the wind tunnel is shown in Figure 10.

The successful performance of wind tunnel tests often requires the use of energy sources external to the tunnel itself. These sources can be electrical, pressure, or vacuum. Electrical sources of energy in the wind tunnel building consist of:

(1) Single-phase, 110-volt, 60-cycle, a.c.

(2) Three-phase, 220- or 440-volt, 60-cycle, a.c. with up to 600-ampere capacity.

(3) Direct current power from batteries only.

Many combinations of d.c. voltage and amperage can be supplied using equipment that is available on a use-rate basis from the Battelle-Columbus Instrument Laboratory.

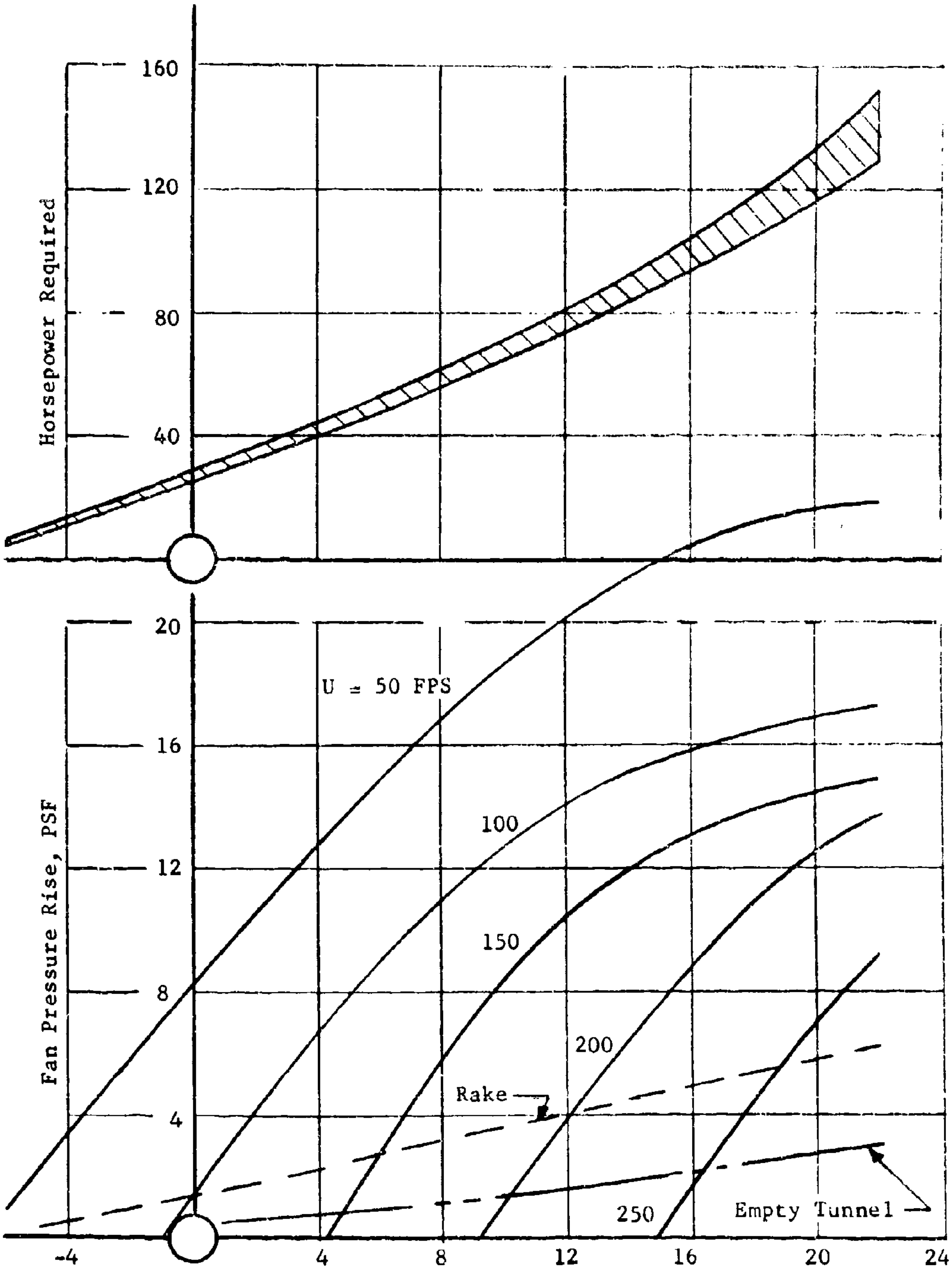


FIGURE 9. WIND TUNNEL FAN PERFORMANCE CHARACTERISTICS

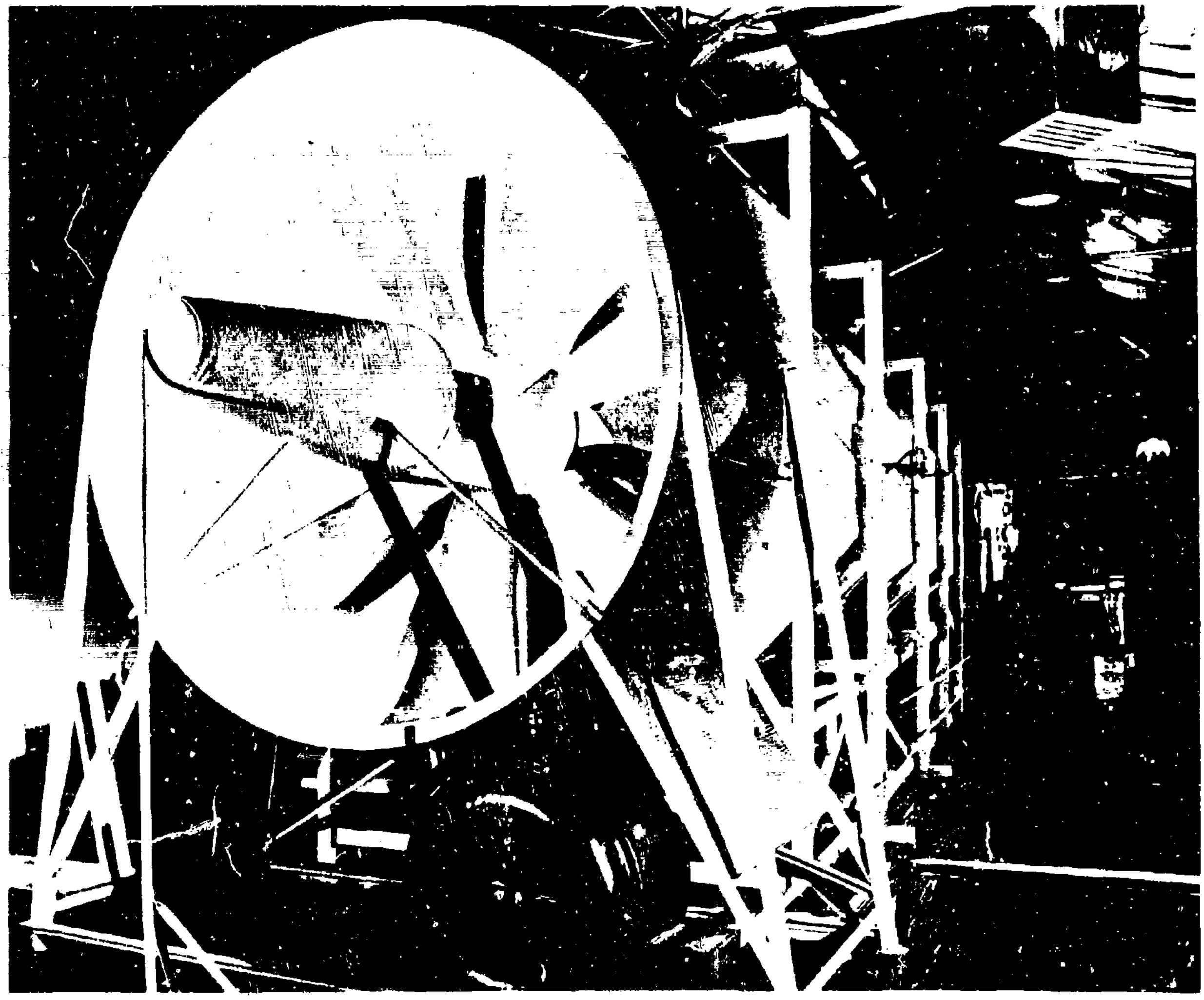


FIGURE 10. VIEW OF THE WIND TUNNEL FROM THE FLOW EXIT END

Any reasonable supply of auxiliary air and/or service vacuum can be provided as needed.

OPERATIONAL DESCRIPTION

The operational characteristics of the Battelle Columbus Subsonic Wind Tunnel consist essentially of the flow characteristics that can be achieved in the test section during operation. In the following discussion, comparisons of the actual characteristics to those estimated by theory during design are made where applicable to indicate tunnel capabilities. Subjects covered are: test velocity, flow turbulence, buoyancy, and effects of atmospheric conditions.

Air Velocity in Test Section

The operational characteristics of most concern to the planner of a test program for a subsonic wind tunnel is the range of air velocities achievable in the facility. Figure 11 shows the variation of air velocity with fan-blade pitch angle and with position of the velocity-adjust doors. These data depict flow conditions with the test section empty. Any model in the test section would decrease the velocity capability at that pitch angle by an amount proportional to the drag of the model. The maximum velocity-change performance of the velocity-adjust doors is a function of doors-closed test section velocity as shown in Figure 12. In Figures 11 and 12 the data recorded during calibration tests are plotted as a solid line with extrapolations to the practical test boundaries based on both the design of the tunnel and its data-recording capabilities which are shown as dashed lines. The calibration data will be extended to include this entire range.

Figure 13 shows tunnel velocity and Reynolds number as functions of tunnel dynamic pressure and temperature. The liquid used in the tunnel dynamic pressure indicating manometer is Meriam fluid, which has a specific gravity of 0.82--a value approximately equal to that of alcohol. Therefore, throughout this discussion, dynamic pressures are noted in units of "inches of alcohol". Figure 13 also shows Mach number variation with indicated dynamic pressure.

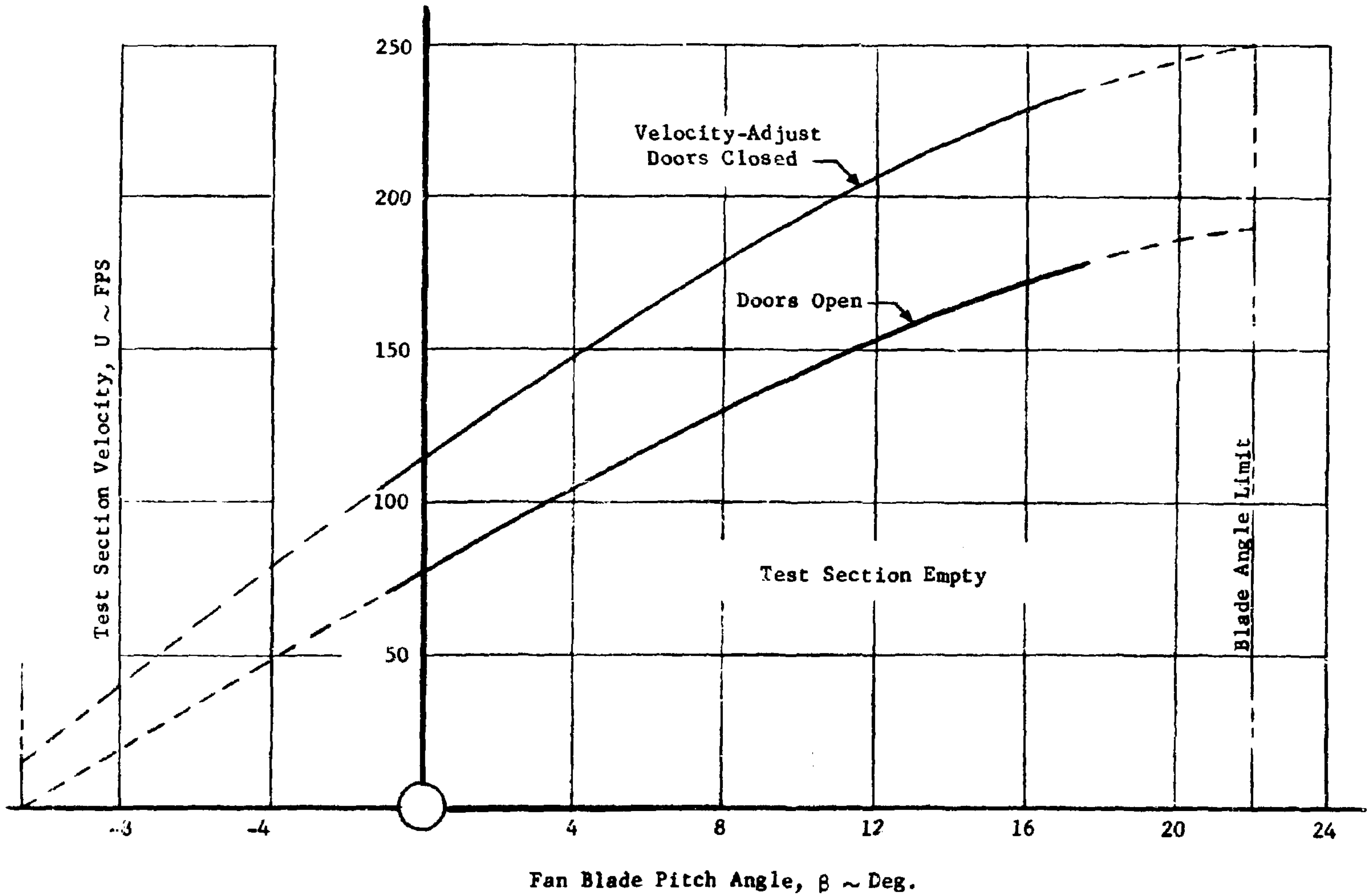


FIGURE 11. VELOCITY VARIATION WITH FAN BLADE PITCH ANGLE AND VELOCITY-ADJUST DOOR POSITION

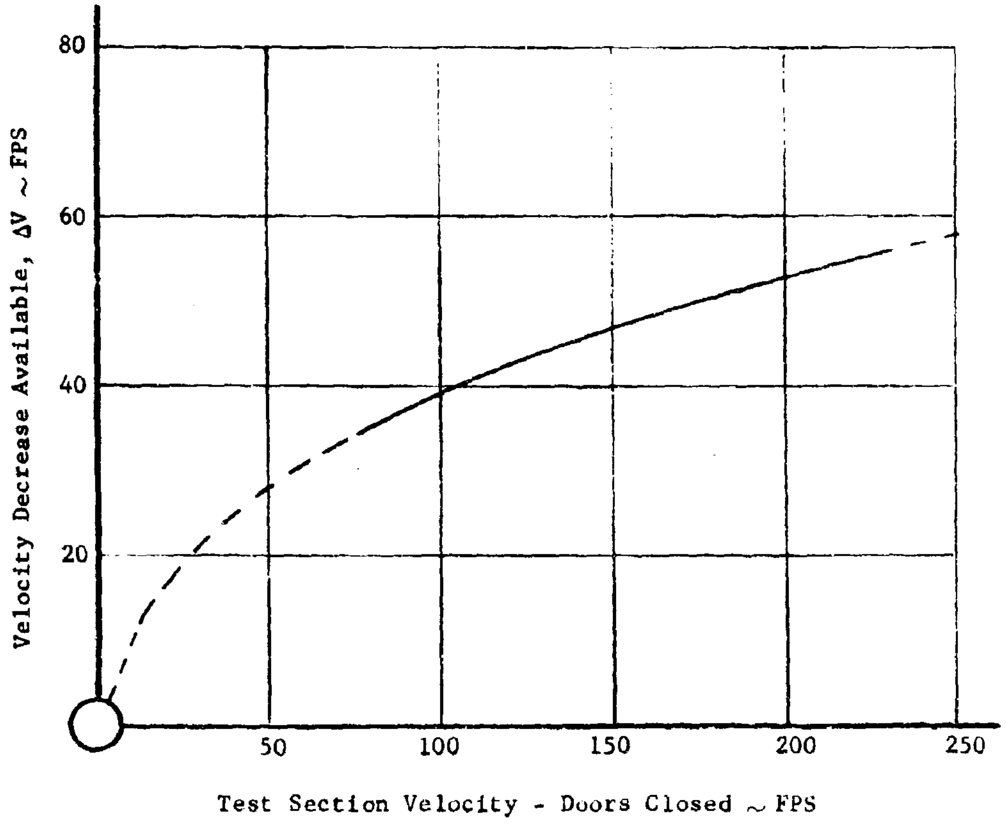


FIGURE 12. EFFECT OF VELOCITY-ADJUST DOORS ON TEST VELOCITY

The flow through the tunnel test section was surveyed using a pitot-static tube rake and wall and floor boundary layer rakes located as shown in Figure 14. Pressure leads from these rakes were attached to one side of the U-tube manometer shown in Figure 2. During calibration, the fluid level in each tube was read visually while the tunnel was operating; any slight unsteadiness of the rake or of the flow caused the manometer fluid level to fluctuate. As a result of these fluctuations, there was a maximum possible estimated reading error of 0.05 inch of alcohol in each leg of the U-tube during any manometer reading. This could lead to maximum overall pressure reading errors of 0.10 inch of alcohol.

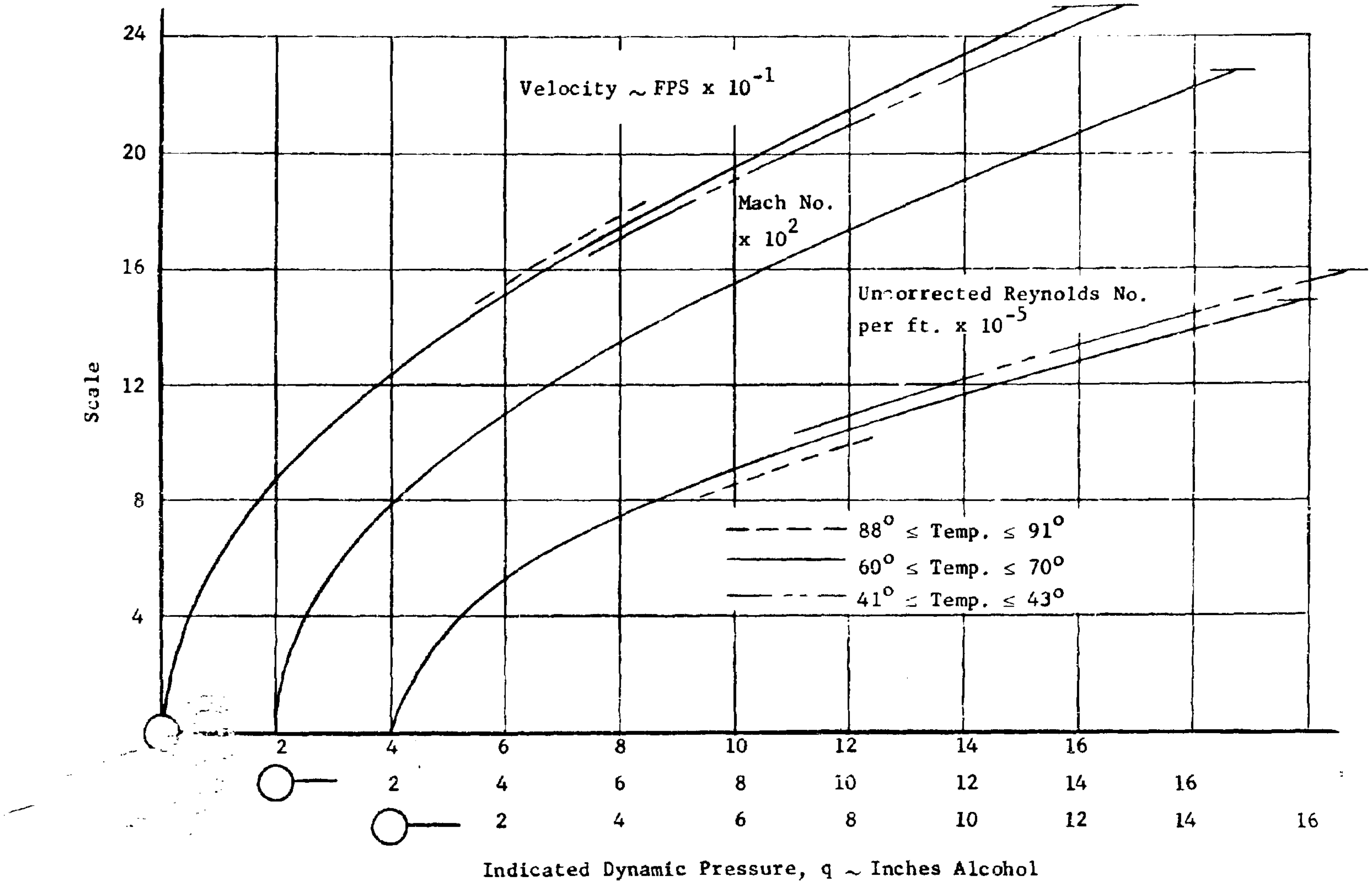


FIGURE 13. VARIATION OF TEST VELOCITY, REYNOLDS NUMBER, AND MACH NUMBER WITH INDICATED DYNAMIC PRESSURE

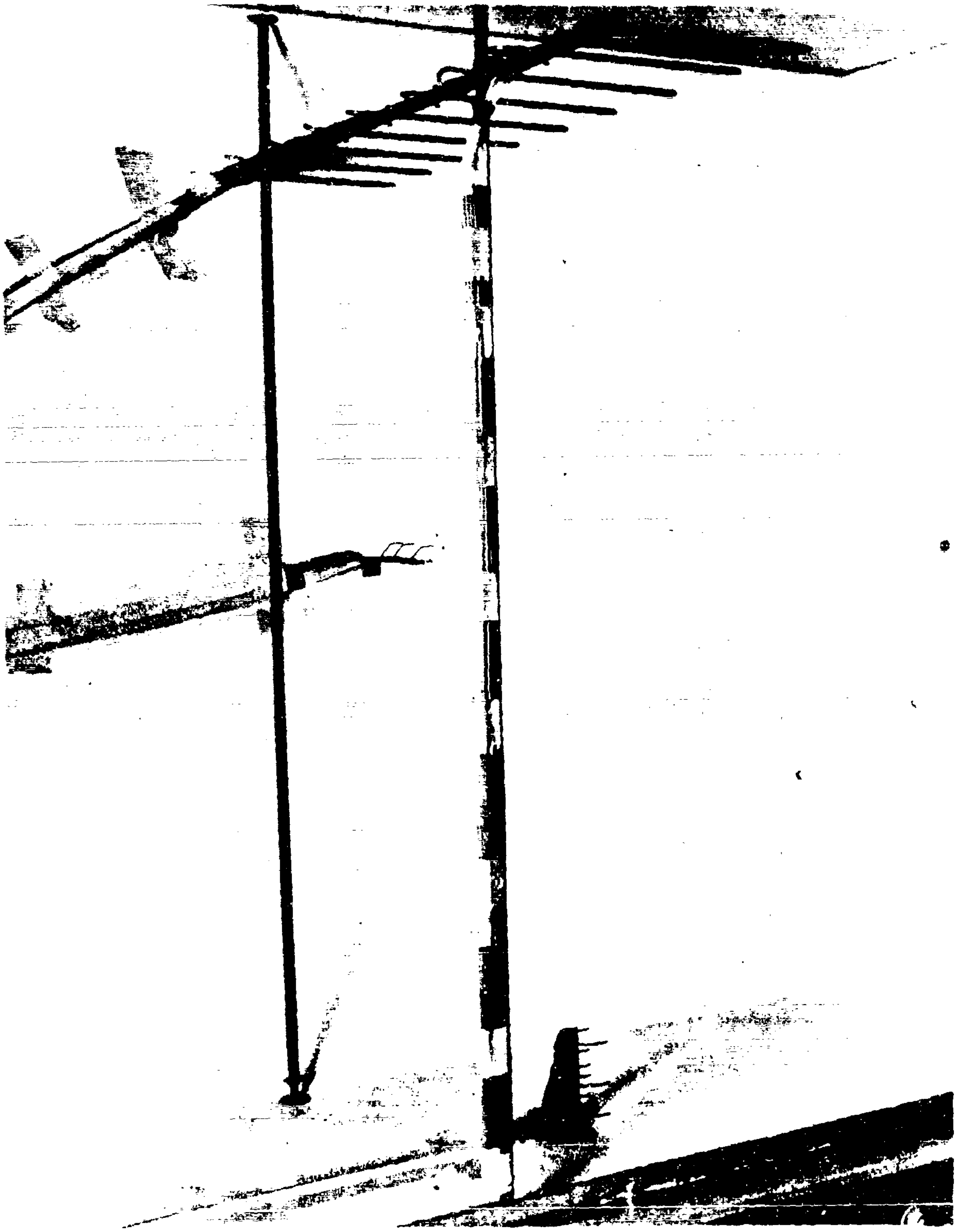


FIGURE 14. FLOW SURVEY INSTRUMENTATION INSTALLED IN THE WIND TUNNEL TEST SECTION

Since a knowledge of the accuracy of experimental data is very important to the user of data, a brief analysis of pressure errors during the calibration was performed with the results presented in Figure 15. The results indicate that if the range of reading errors is between 0.05 to 0.10 inch of alcohol, then inaccuracies as high as 4 to 5 percent can exist in the data taken at the lowest recorded test dynamic pressures of 1.75 inches of alcohol. The use of inclined manometers and extra care at low test dynamic pressures restricted the maximum error to an estimated value of 3 percent as shown. Subsequent modifications to the tunnel pressure indicating system have reduced the possibilities of errors to an overall value of between 0.025 and 0.050 inch of alcohol. At the other velocity extreme, inaccuracies to significantly less than one percent at the maximum test dynamic pressure of 14.7 inches result.

Based on the above, the method of surveying the flow was not sufficiently accurate to indicate the uniformity of test section velocity since variations in dynamic pressure of less than 0.50 percent indicate desirable uniformity.(11) In many instances, the recorded data show variations less than this, but, as indicated by Figure 15, no credibility can be placed on these results. Sufficient survey-data runs were made, however, to permit the calibration of the dynamic pressure indicating system and the measurement of wall boundary layers at two tunnel stations. A detailed survey of flow uniformity is planned with hot-wire anemometer equipment.

Flow survey tests were made using the 9-tube rake shown in Figure 14 positioned at five vertical locations at tunnel Station 263.6 in the test section. The velocities at which these data were recorded varied from roughly 80 fps to 220 fps. A representative plot (a total of 30 such plots were made) of dynamic pressure versus percentage of test section width throughout the range of test dynamic pressures is shown in Figure 16.

The tunnel operator's dynamic pressure indicating manometer depicts in fluid-column height the difference in static pressure between the tunnel settling chamber and the entrance to the test section.(11) The accuracy of this system in depicting test dynamic pressure is based on the assumptions that there are no losses in the tunnel nozzle, that the velocity at the static pressure measuring station in the settling chamber is exactly zero, and that there are no losses in the pressure-indicating system. These assumptions are

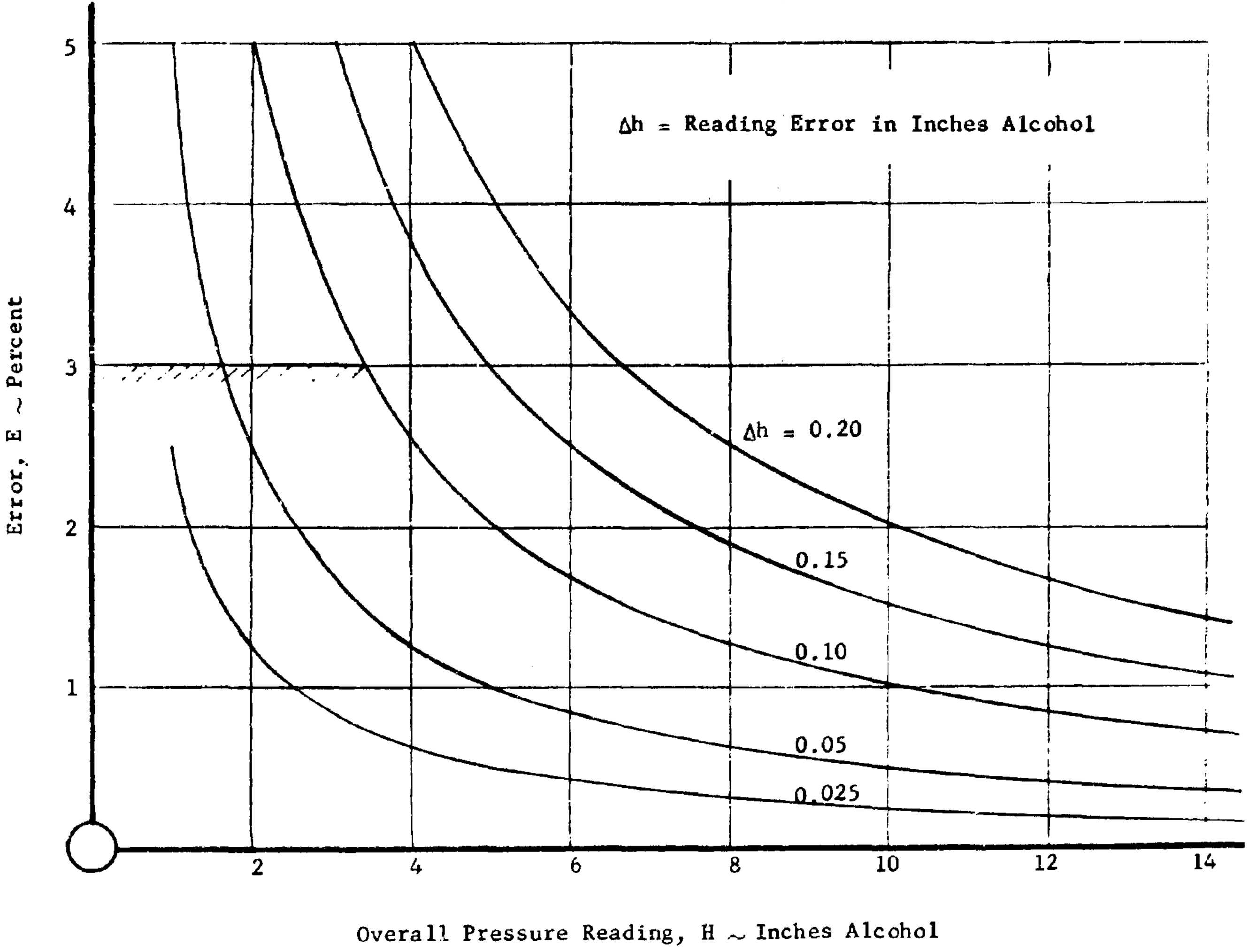


FIGURE 15. ANALYSIS OF U-TUBE MANOMETER PRESSURE READING ERRORS

Note: Data measured at horizontal centerline of test section.

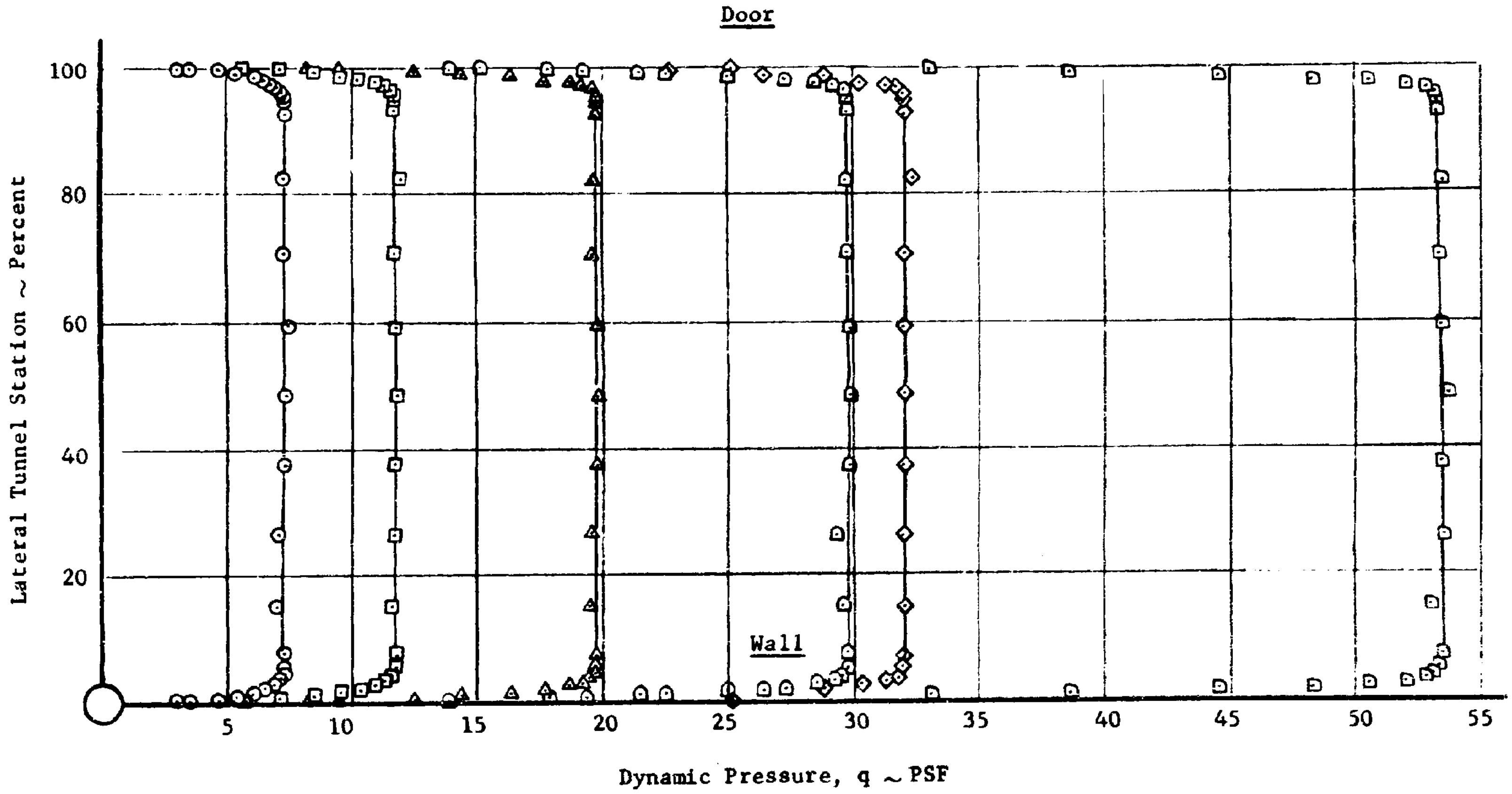


FIGURE 16. SPANWISE VARIATION OF DYNAMIC PRESSURE AT STATION 263.6

not completely valid; consequently, the indicating system required calibration. For this calibration, the mean dynamic pressure between the outer edge of the wall boundary layers for the tests at all stations and at each dynamic pressure setting (one station shown in Figure 16) was used as the value of the exact dynamic pressure. Figure 17 shows a comparison of this value to the indicated dynamic pressure through the equation:

$$q_m = Kq_i \quad ,$$

where K = calibration factor

q_m = mean dynamic pressure at each station

q_i = indicated dynamic pressure.

This figure shows that a maximum error of 1.5 percent or less occurs in the indicated dynamic pressure data if the calibration factor K is ignored over the entire range indicated. Also shown in Figure 17 is the theoretical variation in calibration factor. The general shapes of the two curves agree; only the slopes disagree. This is probably attributable to the fact that the change in flow area due to the displacement boundary layer thickness in the nozzle was ignored during the theoretical calculation of K. Logic shows that closer agreement does exist when this thickness is used to reduce the flow area at each nozzle station.

Flow Turbulence

The turbulence factor of the wind tunnel was measured using the NACA technique of relating the change of pressure difference on a sphere to the Reynolds number of the test.(12) The pressures whose differences are measured are the pressures at the front and the rear stagnation points of the sphere. The variation of this pressure difference divided by the free-stream dynamic pressure with Reynolds number is shown in Figure 18 for the wind tunnel with both two and three turbulence-reducing screens installed.

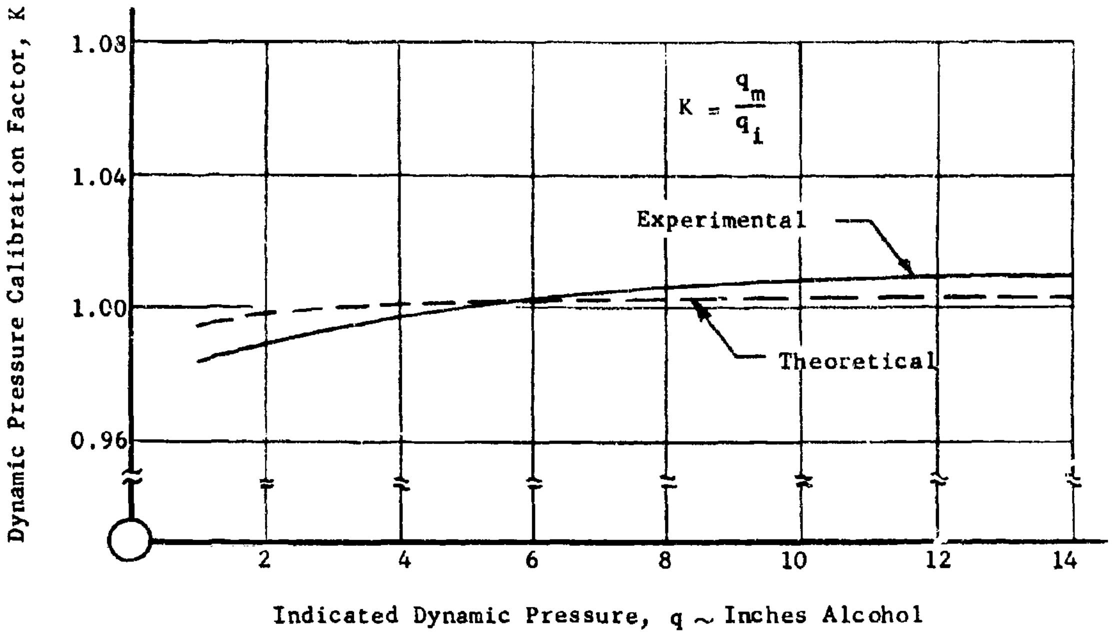


FIGURE 17. WIND TUNNEL DYNAMIC PRESSURE INDICATING SYSTEM CALIBRATION FACTOR

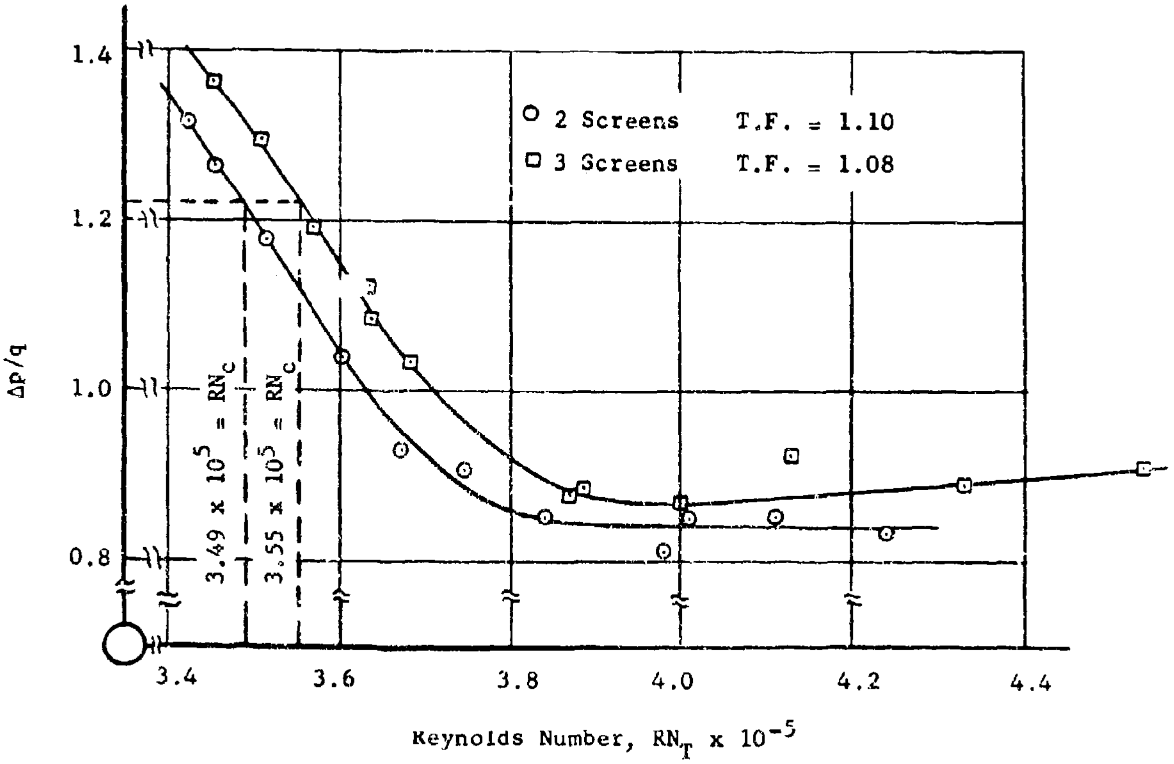


FIGURE 18. DETERMINATION OF TUNNEL FREESTREAM TURBULENCE FACTOR

The test sphere used to measure turbulence was five inches in diameter. Additional tests with both smaller and larger diameter spheres are planned to measure turbulence at both higher and lower test velocities. If additional reductions in turbulence levels are required, the geometry of the tunnel is such that the installation of up to three additional screens to reduce the turbulence perturbation velocity level to the desired level of 0.10 percent of the freestream velocity throughout the test range can be achieved.

The test conditions existing when the data in Figure 18 were recorded with three turbulence screens installed were achieved at two fan blade-pitch angle settings (8 and 10 degrees). This suggests that pitch angle effects on turbulence within this range of variation are negligible. Further tests with spheres will be made, but wide ranges of pitch angle are impossible because the dependence of the critical Reynolds on sphere diameter limits the velocity range and, therefore, the blade pitch range. Tests with hot-wire anemometer equipment circumvent this problem so that the use of this equipment for measuring turbulence is planned.

With the three turbulence screens that are presently installed, the turbulence factor (T.F.) of the tunnel is 1.08 at a freestream velocity of 140 fps. The turbulence perturbation velocity measured with the 5-inch sphere is 0.098 percent of freestream velocity. Using this value, the corrected value of any test Reynolds number resulting from velocities near 140 fps is:

$$RN = T.F. \times RN_u \quad ,$$

where RN_u = Reynolds number uncorrected for turbulence (T.F.).

Buoyancy

According to Pope$^{(11)}$, buoyancy is the tendency of a model to be "drawn" downstream by the longitudinal decrease in pressure through a parallel-sided wind tunnel test section. The build-up of the boundary layer displacement thickness through such a test section configuration effectively reduces the flow area causing an increase in velocity and a corresponding decrease in pressure.

This pressure decrease, acting over the length of the model, causes a pressure drag force which acts in the direction of the velocity. The width and height of the test section of this wind tunnel increase linearly with test section length to offset this displacement thickness build-up and, thereby, yield zero buoyancy at or near a test velocity of 200 fps.

As a check on the adequacy of these measures to eliminate buoyancy, two flow quantities were measured in the wind tunnel:

(1) Boundary layer profile at two stations
(2) Longitudinal pressure variation.

Figure 19 shows example boundary layer profiles at wind tunnel test section Stations 263.6 and 311.6. Other profiles were measured at test velocities from 80 to 215 fps for Station 263.6 and from 175 to 233 fps for Station 311.6. Analysis of these data, including a recognition and accounting for the data recording errors discussed earlier, gave the boundary layer displacement thickness data shown in Figure 20. The decrease in boundary layer displacement thickness with an increase in freestream velocity, as indicated by these data, agrees with observations made by J. Nikuradse(10) in his experiments on a flat plate. The difference in displacement thickness from Station 263.6 to Station 311.6 at 200 fps indicates that the test section walls should have a slope of 0.001603 rather than the slope of 0.001875 that has been built in. Additional tests are needed to validate this comparison.

The variation of static pressure at the wall of the wind tunnel from Station 90 to Station 366 is shown compared with that calculated by theoretical methods in Figure 21. In lieu of pressure orifices drilled through the tunnel side walls, orifices were drilled into the individual plastic pressure tubes at one-foot intervals in two lengths of 10-tube Strip-A-Tube. The tubes were plugged at one end with the other ends connected to the U-tube manometer. Since the pressure holes were drilled in plastic, some pressure-recording inaccuracies could occur because of imperfect orifices. The pressure variations through the final 35 percent of the test section length are consistent from test to test and, therefore, may not be the result of this type of error. These observed variations have not yet been investigated in sufficient detail to identify their cause and indicate a cure.

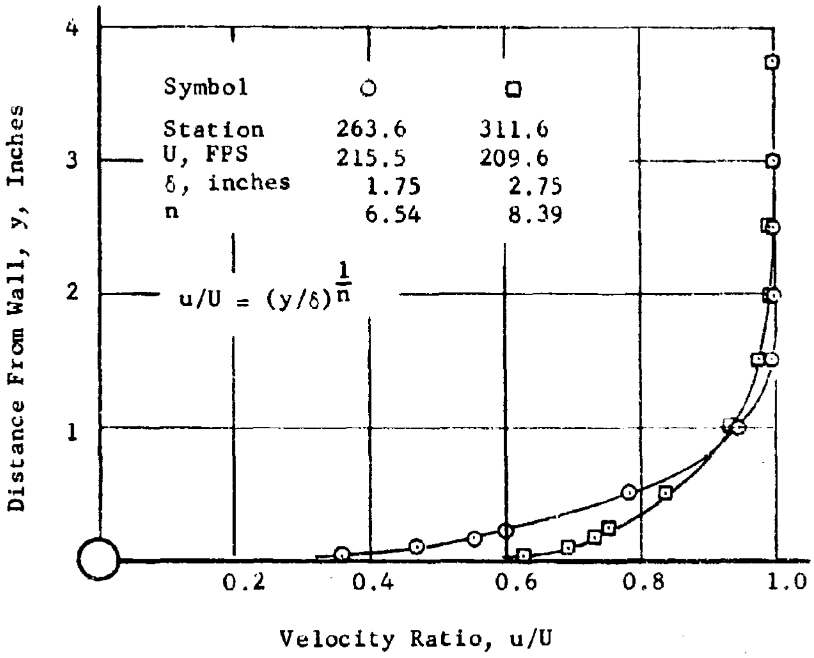


FIGURE 19. EXAMPLE BOUNDARY LAYER PROFILES ON THE WALL OF THE WIND TUNNEL TEST SECTION AT TUNNEL STATIONS 263.6 AND 311.6

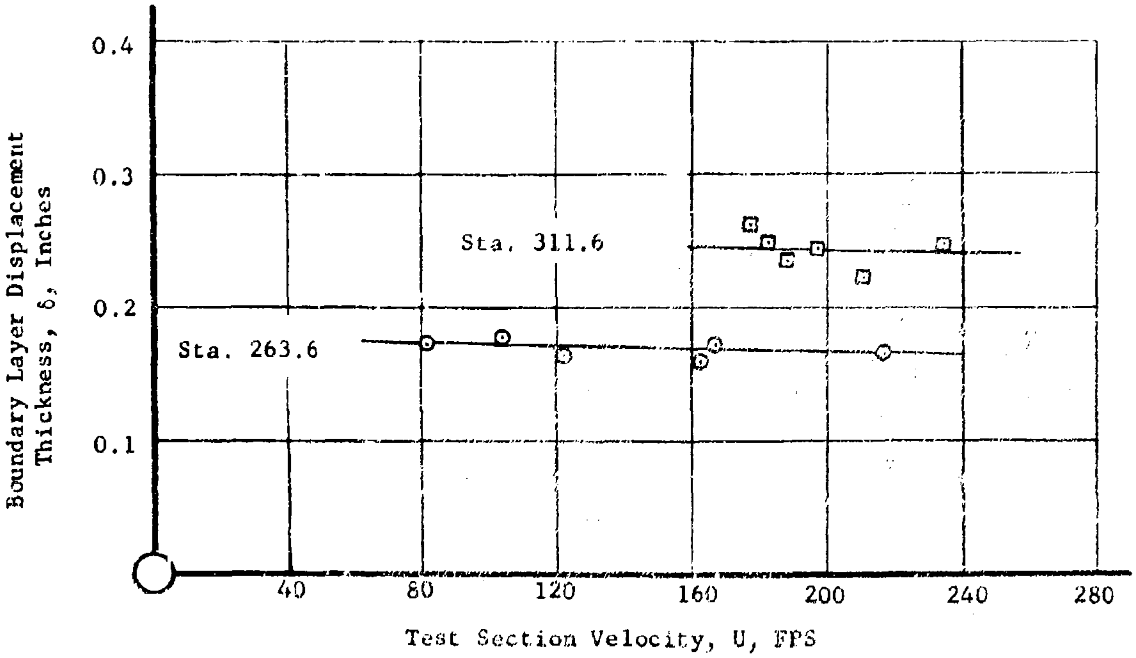


FIGURE 20. BOUNDARY LAYER DISPLACEMENT THICKNESS VARIATION WITH VELOCITY

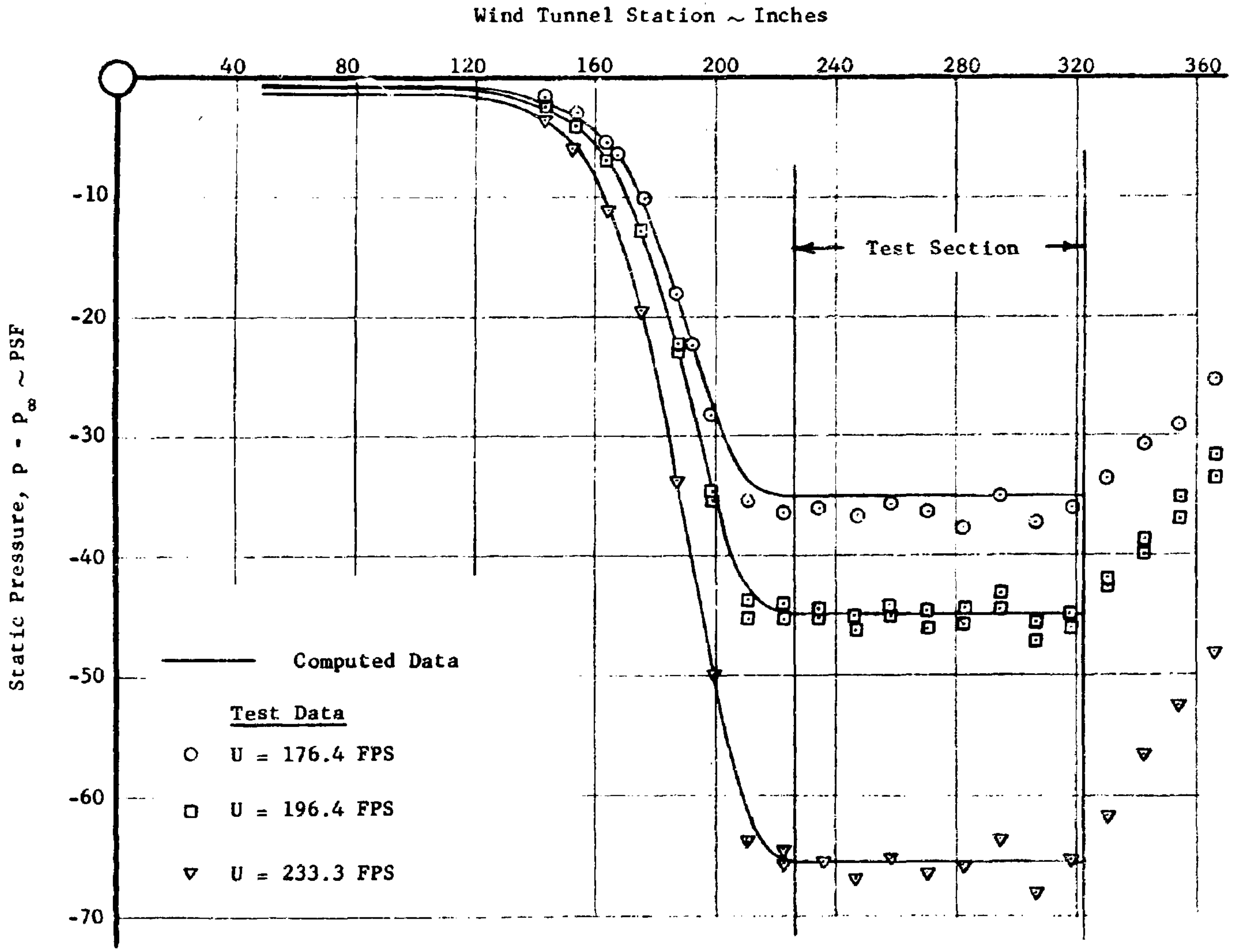


FIGURE 21. LONGITUDINAL STATIC PRESSURE VARIATION IN THE WIND TUNNEL NOZZLE, TEST SECTION, AND DIFFUSER

Effects of Atmospheric Conditions

The wind tunnel draws its test air directly from the atmosphere. Consequently, the conditions in the test section are affected by atmospheric conditions. The conditions that have the greatest effect on the test environment are wind direction and gustiness, humidity, precipitation, and temperature. An overall discussion of the problems encountered in an open-circuit wind tunnel is presented by Pope in the first chapter of his book, Low-Speed Wind Tunnel Testing.(11) Additional comments pertinent to this wind tunnel are included in the following paragraphs.

The entrance to the wind tunnel is protected by 30- to 40-foot tall trees located roughly 80 feet from the entrance. These trees shield the entrance from low-velocity ground winds. Winds of high magnitudes are seldom experienced in Central Ohio and, therefore, are not a serious detriment to testing in this tunnel.

The wind tunnel flow is much less susceptible to winds directed toward its entrance than those directed toward its exit. Winds directed toward the air-exit door of the building have produced a maximum of 18 psf (0.4 inch alcohol) fluctuation in tunnel test section dynamic pressure while wind gusts directed at an angle to the entrance have produced a maximum dynamic pressure variation of only 4 psf (0.10 inch alcohol). These fluctuations occur infrequently and can be easily recognized by the tunnel operator. If necessary, testing can be terminated, or if perturbation frequency is low enough, data can be recorded only when the fluctuations do not occur.

The addition of instrumentation for indicating the magnitude and direction of winds in the vicinity of the wind tunnel building is planned.

The density of air increases as the humidity of the air decreases so that it is necessary to measure the humidity of the test air to precisely establish test conditions. A simple wet-bulb/dry-bulb system is installed in the side wall of the entrance to the tunnel settling chamber. This system consists of two precision thermometers, one with a wetted wick shield covering the mercury bulb and the other exposed directly to the air flow entering the tunnel.

Light rain or snow has little effect on the operation of the wind tunnel. Some moisture is drawn into the tunnel entrance at high test velocities, but not enough to hamper the tests. As the quantity of moisture increases, however, a combination of droplet size and velocity is reached such that the moisture enters the nozzle and clogs the pressure orifices used to indicate tunnel-test dynamic pressure. Further increases in either moisture quantity or test velocity can block openings in pressure instrumentation mounted in the test section causing unreliable or erroneous data indication. Tests during periods of heavy rain or snow are terminated at the judgment of the tunnel operator.

Temperature variations, by themselves, are no detriment to tests being performed in the wind tunnel. Only rarely does temperature near freezing couple with a dew point near freezing such that there is condensation and freezing of moisture in the test section. The humidity-indicating system described above becomes ineffective below freezing, but this is of little consequence since the effect of humidity on density becomes insignificant as temperature is decreased to freezing.

Probably the greatest effect that atmospheric temperature has on tests is its effect on Reynolds number (Figure 13). A series of constant Reynolds number tests would require that the tunnel dynamic pressure be varied according to changes in atmospheric temperature. Generally, the slight changes are insignificant, but day-to-day changes can be significant.

The effect of atmospheric variations on the test conditions in the Battelle Columbus open-circuit wind tunnel are generally detrimental to the tests being performed. However, planning and experience can mitigate all but the most extreme of these variations. The added cost of building a tunnel having a closed circuit to prevent these atmospheric effects could cause the price of the type of tests planned for this tunnel to be a greater burden to the performance of a research program than does these atmospheric variations. Inexpensive modifications to the tunnel to further mitigate the effects of weather can be initiated when and if weather variations become significantly detrimental to warrant the necessary expenditures.

DATA RECORDING AND ANALYSIS

As stated earlier, the Battelle Columbus Subsonic Wind Tunnel was built to provide a facility in which good-quality aerodynamic data can be obtained at low cost. A very significant portion of the initial cost of a wind tunnel is the cost of the instrumentation and the force balance system. The size and operational range of the Battelle Columbus wind tunnel tends to direct its use toward fundamental aerodynamic studies in which costly all-inclusive permanent equipment often does not serve as well as more specialized equipment. Because of these considerations, the tunnel has been equipped with only the equipment needed to yield basic test data. These basic test data include:

(1) Pressure distribution
(2) Flow distribution (using flow rakes)
(3) Flow visualization (using tufts and surface films).

Specialized strain-gage balance systems for measuring one-, two-, or three-component force and moment data can be provided through the design and fabrication facilities available at Battelle Columbus. The acquisition of a three-component, sting-mounted balance system is planned and will be installed when the need arises.

Because the tunnel instrumentation is limited to the essential minimum, each user of the facility need pay "use-rate" only on the equipment that is built, purchased, or rented to fulfill his needs. Items of instrumentation are being added to the tunnel stock as they are needed with their cost being distributed in "use-rate" charge only to those who use them. This policy assures that a more careful selection of instrumentation items is made at the time of purchase because both a definite purpose has been identified and more experience with the tunnel facility has been accrued.

Data Recording Capabilities

A representative list of equipment that is available to the user of the Battelle Columbus wind tunnel is as follows:

Inclined U-tube manometers

Single-tube, well-type manometers of assorted lengths

Precision 30-inch, well-type manometer by Hass Brothers Instrument Company

38-tube U-tube manometer board

Kiel tube

Yawhead flow-direction indicator

Pilot-static tubes

Boundary layer rakes

Impact probe with remote traversing system

Miniature dynamic pressure transducers for ± 2 psi differential.

Additional equipment and instrumentation are available through the loan services of the Battelle Columbus Instrument Laboratory.

The Battelle Columbus photographic laboratory provides to users of the wind tunnel the staff and equipment necessary to record data by either still photographs or motion pictures. In addition to the more conventional framing rates, photographic and lighting equipment are available to record data at framing rates up to 4,000 frames per second.

Data Analysis Capabilities

Mathematical analysis must be applied to wind tunnel data for the purpose of correcting the data to a free-air unbounded-flow condition. Not all test data need be corrected; however, the purpose and desired results of each test must be evaluated to determine if corrections are needed and which correction procedures should be used. The nominal cross-sectional dimensions of the Battelle Columbus wind tunnel test section have a 7-to-10 ratio to take advantage of the abundance of correction procedures available for tunnels having this cross-sectional shape. Standard correction procedures are used to analyze test data with data from several reports and texts being used as guidelines.(11,13-18)

The facilities of the Battelle Columbus Computation Center are available to users of the wind tunnel for the analysis of data and the computation of comparison theoretical information. These facilities include a Control Data 6400 computer and associated peripheral equipment. This computer has 65,536 60-bit words of core memory, a 75-million-character disk file, three IBM compatible tape units, and associated card readers and printers. Apart from these facilities are three separate consoles of Electronic Associates, Inc., Precision Analog Computing Equipment (PACE). This equipment includes 180 amplifiers, 310 coefficient potentiometers, and an assortment of multipliers, resolvers, etc. Output equipment includes digital voltmeters, X-Y plotters, and hot-wire recorders. A staff of trained and experienced computer specialists is available to assist the user of this equipment.

FACILITY MANAGEMENT

A number of regulations have been established to guide the user of the wind tunnel toward proper use of the facility. Included in this section are explanations of pretest requirements, security restrictions, and other items that can be considered as part of the overall management of the facility. These regulations have been established to assure that the users of the wind tunnel receive the most accurate test data with the least expenditure of funds possible. They are designed to protect the financial investment in the facility and to assure that Battelle's standards for research are maintained. In some particular cases, adherence to these rules will lessen the possibility of injury to both the contractor's personnel and the wind tunnel staff.

Pretest Planning

It is recommended that tunnel test time be scheduled as far in advance of the desired test dates as possible to increase the likelihood that the desired dates will be available. Often, considerable time and funds can be saved if the entire test program as visualized is discussed with the Battelle-Columbus wind tunnel staff during the formative stages of planning. Their experience with this facility (and with other tunnel facilities) can often be most beneficial if it is integrated early into the program.

Estimates of time and costs will be prepared by the wind tunnel staff upon request. The degree of accuracy of these estimates depends on the uniqueness of the test program and on the completeness of the information describing the test that is supplied as a basis for the estimates. There is no charge for preparing these estimates.

To protect the wind tunnel and its associated equipment and the model being tested, the structural integrity of the model and its mounting structure must be assured. On the other hand, mounting systems that assure structural integrity by using excessive attachments to the tunnel structure are undesirable because excessive attachment holes reduce the life of the tunnel structure. Therefore, at a time that is sufficiently far in advance of the model installation date to be practical, one of the following requirements must be met by the user of the wind tunnel:

(1) Engineering drawings of the model mounting system and that portion of the model that structurally ties to the mounting system must be furnished to the Battelle Columbus engineer responsible for the wind tunnel. These drawings must be accompanied by an analysis of the loads and stresses resulting from testing at the conditions specified. Proof of the capability of the model and model mounting to withstand these stresses must also be included. The cost of the review of this information will be charged to the project.

(2) Engineering drawings of the model and model mounting system, with a statement of model weight and test variables must be furnished to the wind tunnel engineer. The cost of analyzing this information to determine the capability of the model and its mounting system to withstand the loads resulting from the test variables will be charged to the project. Recommendations for model and mounting revisions to benefit the test program will be made when applicable.

(3) Sufficiently detailed information about the objectives of the test must be furnished to the engineer responsible for the wind tunnel to permit the design of the model and mounting system by Battelle designers. The lead time necessary for this service depends on the availability of qualified Battelle Columbus staff and on the complexity of the model and test arrangement. Fabrication of the resulting test components can be done by the Battelle Columbus model shop, by subcontract, or by any organization designated by the contractor. The cost of providing these services will be added to the cost of the project.

The Battelle Columbus engineering staff that is responsible for the wind tunnel reserves the right to reject any test component or configuration on the basis of lack of sufficient structural integrity to fulfill the requirements of the test program. Or, when deemed advisable, the range of test conditions and/or variables will be restricted to preclude exceeding the design strength of either the test components, the assembly, or the wind tunnel.

Test Personnel

The training and experience of the personnel performing the wind tunnel tests are very important to the success of the test program both from the standpoint of results achieved and total costs. Also, the precision and care with which attachments to and modifications of the tunnel structure are made are important to the continued availability of this facility for research. Therefore, the Battelle Columbus wind tunnel engineer and/or laboratory technician(s) assigned to the wind tunnel facility will be responsible for all modifications or attachments to the wind tunnel or its associated equipment. The pretest inspection of the facility, the physical starting and stopping of the wind tunnel, and the monitoring of the tunnel operation are the exclusive responsibility of wind tunnel personnel.

The operation of equipment used with the particular test configuration and the recording of test data may be performed by contractor personnel or by wind tunnel personnel as decided by the contractor. Personnel for hand computing and plotting of data are available from the Battelle staff. An electronic computer and qualified staff are available for the purpose of programming and operating data analysis computer programs.

The wind tunnel facility is located in a building that is comparatively isolated from other buildings and other personnel. Therefore, for reasons of safety, it is advisable that no less than two people be working in the wind tunnel facility during any time that tests are being performed or potentially dangerous equipment is being used.

Facility Hours

The normal operating hours of the wind tunnel facility are from 8:00 a.m. to 5:00 p.m., five days per week. Hours other than this can be arranged to suit specific test requirements or to take advantage of particular weather conditions, since the tunnel design makes its operation partially dependent on the weather. No premium charge for either wind tunnel occupancy time, operational time, or blockage time (see the following section for definitions of these times) will be made for overtime hours.

Security

General plant protection and security requirements dictate that all personnel not in the employ of Battelle Memorial Institute be either accompanied by an employee of the Institute at all times or be cleared by appropriate security procedures while in other than designated areas of the Institute buildings. Although the building in which the wind tunnel is housed is not one of these designated areas, access to the wind tunnel facility for wind tunnel business can be authorized by a member of the Battelle staff in charge of the wind tunnel. Since cognizant plant protection personnel must be notified of visits to the wind tunnel building during other than normal operating hours, a request for access should be made to the wind tunnel engineer by noon of the day just preceding an evening visit or by Friday noon just prior to a weekend visit.

FACILITY USE-RATE COSTS

Charges to the users of the Battelle Columbus wind tunnel are based on occupancy time, operational time, and blockage time. The definitions of these times as well as the changes pertaining to them are explained in the following paragraphs. Also explained are the labor charges associated with using the wind tunnel and use-rate charges for instruments and equipment obtained through the Battelle-Columbus Instrument Loan service.

Prices to users of the wind tunnel facility are subject to change without prior notification before the start of any test program.

Occupancy Time

Occupancy time is a unit of time during which the wind tunnel is used by a specific project. It is charged to the project in units defined as a standard 8-hour working shift. If a project requires activities during more than one shift per day, occupancy time will be charged for each unit. The occupancy time includes time for modifying the tunnel to accept a particular test configuration, model installation and calibration, model changes, testing, model removal, occupying the tunnel test area with test apparatus, and restoration of the tunnel to its original configuration. Occupancy time for a project commences at the beginning of the shift on the first day that is allotted to it and stops at the end of the shift on the day that the tunnel is returned to its original condition.

The charges for occupancy time are $15 per 8-hour unit or fraction thereof.

Operational Time

Operational time is the time that the wind tunnel fan is turning--commonly referred to as "fan-on" time. This time includes all "fan-on" time required by the project, whether test data are recorded or not.

Operational time charges are based on the total "fan-on" time that is accumulated during a project This total is the sum of all "fan-on" times recorded by the tunnel operator in the wind tunnel log. The unit of operational time is the hour.

The charges for each operational hour or fraction thereof are $15. No premium is charged for operational hours outside the normal working shift, which is from 8 a.m. to 5 p.m.

Blockage Time

Blockage time is defined as that period of time during which a test program that is being charged occupancy prevents another program from using the wind tunnel facilities.

The unit of blockage time is four (4) hours or one-half shift. A minimum charge of $30 per unit or fraction thereof is made to the program that is blocking the tunnel facility. If the sum of occupancy and operational charges exceeds the blockage charge, the large amount will be assigned, not both.

No charge for blockage time will be made without prior notification of this fact to the program causing the blockage.

Labor Charges

The specific operation of the tunnel, including model installation and removal and tunnel modification, must be handled by staff members of the Battelle Columbus Aerospace Mechanics Division. Other activities such as planning, stress analysis, design, model construction or modification, and data collection, reduction, and analysis, need not be done by staff members. If they are, however, they must be arranged for through the Aerospace Mechanics Division. All staff-time charges are in addition to the other charges described.

Equipment and Material Charges

Charges will be made for all use-rate items of special equipment both belonging to the wind tunnel and borrowed from the Battelle Columbus Instrument Laboratory for use by a test program. Charges for the basic instruments and and equipment that are a part of the normal operational configuration of the tunnel are included in the basic facility use-rate charges.

Expendable materials required for the fabrication of models, model supports, or specialized instrumentation will be invoiced at actual cost.

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13. ABSTRACT

The Subsonic Wind Tunnel of Battelle Columbus Laboratories has been developed to provide a quality research tool that is economical to operate. It can provide air velocities to 250 fps with a turbulence level of 0.10 percent or less through a 55-inch-high by 38.5-inch-wide test section. Models are mounted directly to the walls, floor, or ceiling of the test section, or on a sting. This report is a description of the tunnel, its management procedures, and cost to users.

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