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SUMMARY

The features of a 1/50-scale model of the National Full-Scale Aerodynamics Complex (NFAC) are first described. An overview is then given of some results from the various tests conducted with the model to aid in the design of the full-scale facility. It was found that the model tunnel simulated accurately many of the operational characteristics of the full-scale circuits. Some characteristics predicted by the model were, however, noted to differ from previous full-scale results by about 10% .

SYMBOLS

C_p	pressure coefficient = $(p-p_{atm})/q_{ts}$
q	$\rho U^2/2$
x	distance measured along tunnel axis
y	distance measured perpendicular to tunnel axis
z	distance measured in vertical direction
u, v, w	velocity components in x, y, z directions, respectively
U	$[u^2+v^2+w^2]^{1/2}$
ρ	air density

Subscripts:

atm	atmospheric quantity
n	north leg of wind-tunnel circuit
s	south leg of wind-tunnel circuit
ts	test section

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INTRODUCTION

The 1/50-scale model of the National Full-Scale Aerodynamics Complex (NFAC) was built in 1974 to obtain data on the characteristics of various design changes planned for the 40- by 80-Foot Wind Tunnel (referred to herein as the 40 × 80). The papers written about the studies made of the various designs considered, and about some of the uses made of the 1/50-scale model, are listed in references 1-25. The literature notes that most of the modifications of the facility were concerned with the addition of a non-return circuit which has an 80- by 120-ft (80 × 120) test section that angles off the 40 × 80 circuit just upstream of the fan drive (figs. 1, 2).

Subsequent testing of the revised facility in 1982 identified shortcomings that needed to be corrected. The 1/50-scale model (fig. 3) was then taken out of storage in 1982 and again made operational to provide aerodynamic data on not only the nature of the shortcomings that were identified but also to test alternative designs for components that had marginal characteristics. The ease with which the model tunnel could be modified and operated permitted detailed study of a number of design parameters and did much to achieve a better understanding of the characteristics of the full-scale facility. In all cases, the model facility was made to duplicate as closely as possible the two full-scale tunnel circuits in order to simulate the performance of the full-scale facility. This paper describes the model and presents an overview of the tests conducted with it.

DESCRIPTION OF SCALE MODEL

An attempt was made to have the model built as a small-scale version of the full-scale facility (figs. 1-3). As a consequence, the model looks very much like the full-scale facility; it does not, however, duplicate at small scale certain features of the large one (e.g., corregated wall cladding, fasteners). The materials used to construct the model are primarily molded fiberglass, wood, and Lucite, with metal used in a few locations. Since the full-scale facility is made of metal and Transite, a one-to-one correspondence was not retained in the use of construction materials either. Considerable care was taken, however, to have the internal shape of the various components properly scaled and to have the aerodynamic losses properly simulated.

The tunnel circuits consist of several straight segments connected by corners with turning vanes (fig. 1). For example, the 40 × 80 circuit consists of the east, north, west, and south legs; the test section is located approximately in the center of the east leg and the fan drive in about the middle of the west leg. Similarly, the 80 × 120 circuit consists of a diagonal leg which extends to the northwest and of a west leg that includes the drive fans and the exhaust opening located in the southernmost wall of the 40 × 80 circuit.

The model facility (fig. 3) was constructed of various materials. The bellmouth, test section, primary diffuser, and fan-drive areas are made of molded fiberglass. The sidewalls, floors, and some of the ceiling areas are made of plywood on a mahogany frame. The ceiling areas where the sidewalls are wood were composed of clear plastic windows framed in wood in order to allow observation of tufts and other flow-visualization media.

In order to allow observations in the fiberglass sections, one window was located in the ceiling of the bellmouth, one in the 40 $\times$ 80 test section, and four windows in the primary diffuser. (Three windows were added after the photographs in fig. 3 were taken.) The windows and the various sections were all bolted together for ease of disassembly and modifications.

Vane-sets 1, 2, and 8 were made of wood and vane-sets 3, 4, 5, and 7 were made of metal; vane-set 6 was made of wood and metal. All of the vanes were shaped to model the full-scale item. The vane sets are numbered sequentially, beginning downstream of the 40 $\times$ 80 test section. That is, vane-set 1 is the first one downstream of the test section where the airstream makes a 90° turn at the end of the primary diffuser into the north leg of the tunnel (fig. 1(a)). Vane-set 2 is located at the second turn where the flow again turns through 90° from the north leg onto the west leg of the circuit. Vane-sets 3 and 4 serve as doors that direct the flow through one circuit or the other; neither functions as a deflector or turning device for the airstream (figs. 1, 4). For example, when vane-set 3 is open and set 4 is closed (fig. 1), the facility is in the 40 $\times$ 80 mode of operation. Conversely, when vane-set 3 is closed and set 4 is open, the facility is in the 80 $\times$ 120 mode of operation. Vane-set 5 is located just upstream of the fan-drive system at an angle of 67.5° to the centerlines of the two circuits so that it bisects the turning angle made by the air as it comes from the 80 $\times$ 120 test section and turns toward the fan-drive system (fig. 1). The purpose of vane-set 5 is to turn the flow through 45° so that it is headed toward the fan drive system with only small deviations from the centerline direction. In the 40 $\times$ 80 mode, vane-set 5 should have a negligible effect on the airstream, because turning or any other form of processing is not necessary or desirable, and may in fact be detrimental to the performance of the fan-drive system. A ninth vane set (usually referred to as the inlet guide vanes) at the inlet of the 80 $\times$ 120 circuit serves to condition the airstream for entry into the test section.

Table 1 summarizes the characteristics of the nine vanes sets in the model and compares them with the full-scale tunnel. The movable vanes in the model are simulated by replaceable vane sets fixed in either the 40 $\times$ 80 or the 80 $\times$ 120 mode of operation. It is to be noted that vane-sets 1 and 2 are identical because the cross-sectional dimensions and turning angle (90°) of the corner are the same. The vane set shown in fig. 5(a) is the one originally used in the 40 $\times$ 80 for vane-sets 1 and 2. It is also the design used in the model for the first two vane sets. Figure 5(b) presents the cross-section shape of the new vane design (used for vane-sets 1 and 2) which has recently been installed; i.e., the 1986 version. Figure 5(c) illustrates how the vanes and splitters are assembled to achieve the needed strength. Vane-sets 3 and 4 are louver-type vanes that are used only to seal off the unused portions of the circuits (fig. 4). That is, vane-set 3 is closed in the 80 $\times$ 120 mode of operation and opened to correspond to the diffusion angle of 3° on either side of the centerline in the 40 $\times$ 80 mode. Likewise, vane-set 4 is closed in the 40 $\times$ 80 and aligned with the flow in the 80 $\times$ 120 mode. These configurations are simulated in the model by either a solid wall for the vane-closed condition or by flat plates for the vane-open condition. No attempt was made to simulate the truss work on the vanes.

Vane-set 5 is immediately upstream of the drive fans (fig. 4) and is used in the 80 × 120 mode to turn the flow through approximately 45° before it enters the fans. In the 1982 version of the facility, this was accomplished on the full-scale tunnel with a vane set having movable leading-edge flaps (fig. 6a)). When the facility was in the 40 × 80 mode of operation, the flaps were aligned parallel with the sidewalls of the 40 × 80 circuit; that is, half of the vanes were parallel with the east wall and half with the west wall. The angle of attack of the vanes then had about a 6° discontinuity across the centerline of the tunnel. Such a system of splay angles was chosen to assist the airstream in its diffusion down the diverging duct in the vicinity of the fan drive. The model tunnel also used fixed aluminum vanes that were either straight for the 40 × 80 mode or bent at an angle of between 40° and 60° to simulate the flap angles used in various tests in the full-scale device. A change from one mode to another was carried out by slipping out one vane configuration and replacing it with one that had the desired flap angle shape.

After the collapse of vane-set 5 in December 1982, a theoretical and experimental program was undertaken with NASA Lewis Research Center to find a fixed single-element vane (fig. 6(b)) to replace the flat-plate version of vane-set 5 (refs. 13, 14, 17). The new fixed vane set was not tested in the 1/50-scale model of the tunnel. Vane-set 6 is located downstream of the fan drive on the southwest corner of the closed circuit (figs. 1, 7). In the full-scale device, trailing-edge flaps are used to either turn the flow through 90° for the 40 × 80 mode, or, for the 80 × 120 mode, to direct the flow straight toward the south wall where it exhausts through vane-set 7. In the full-scale facility, the nonmoving portions of the vanes are made of acoustical absorbing material on the inside, and the vane shells are made of porous metal. In the model, the fixed part of the vanes is made of wood and the flaps of metal. As with 1982 version of vane-set 5, the flap angle is changed by replacing the entire vane set instead of going to the expense of constructing a movable-flap system. As a consequence, the 1/50-scale tunnel closely models vane-set 6 except for the acoustic surfaces and for the presence of a hinge.

Vane-set 7 comprises the west half of the south wall of the facility (figs. 2, 7, 8). The vanes are doors that when closed provide a relatively smooth wall for operation of the facility in the 40 × 80 mode. When the doors are open (figs. 7(b), 8), the doors become a flat-plate (i.e., not contoured) vane set that allows the airstream from the 80 × 120 circuit to pass through the south wall and that in the process deflects the exhaust airstream upward at an angle of about 38° (refs. 18, 20). Once again the model made use of two separate devices to simulate the two configurations. The solid wall was simulated with a sheet of plywood and the open vane set with a cascade of bent aluminum vanes which approximated the sizes and positions of the open doors of vane-set 7.

In figure 2(b), vane-set 7 is not completely closed for operation in the 40 × 80 mode. The three small dark patches shown in fig. 2(b), in the westernmost (or left hand) column of doors in vane-set 7, are the three permanent openings through which cooling air was allowed to exhaust during the 1982 tests. Since these three openings were used as exits for the air introduced into the wind-tunnel circuits to cool the drive-fan motors (each exhausts 40,000 ft^3/min of cooling air from its tail cone) and for the air introduced to cool the airstream in the tunnel circuit. The flow rate of cooling air for the circuit can be as large as 10% of the airstream flow rate which is brought into the circuit through the air-exchange inlet. During the 1982 Integrated Systems Test (IST), the exhaust system was obtained by leaving three doors off of the westernmost column of doors (fig. 2(b)); that is, from the column next to the southwest corner of the facility. In subsequent tests with the 1/50-scale model, it was found that a larger amount of open area was needed to accommodate the air flow so that the internal air pressure of the tunnel did not exceed the capability of the wall structure. As a consequence, the modified facility has the entire west column of doors fixed in the open position (ref. 19). Estimates then indicated that for certain tests, noise from powered models in the test section that would exceed community guidelines might possibly be transmitted through the larger opening and to the outside. In order to decrease such noise transmission, a wall was constructed between the south wall and vane-set 6 (fig. 9). The purpose of the acoustic wall is to force the sound waves from the test section to pass through the acoustically treated parts of vane-set 6 before leaving the facility and passing to the outside (refs. 17, 23, 24).

Vane-set 8 turns the flow through 90^o at the southeast corner of the 40×80 circuit. The vane shape was not modified during either the 1982 or the 1986 reconstructions, and so it is the same as that of the original shape of vane-sets 1 and 2 but at one-half the size indicated in figure 5. The full-scale vanes are made of wood and sheet metal and the model vanes of wood. After the airstream leaves vane-set 8, it enters the bellmouth contraction that leads to the test section of the 40×80 circuit.

The vanes in the last vane set to be discussed are usually referred to as the inlet guide vanes because they guide and condition the air entering the 80×120 circuit. The vanes used in the 1982 IST (fig. 10(a)) were all placed such that they were parallel to the centerline of the tunnel and aligned horizontally so that their leading and trailing edges were at the same axial station. The inlet of the model tunnel has both vertical and horizontal vanes that are shaped similarly to the 1982 vanes in the full-scale tunnel but with different spacings. The 1986 version of the inlet guide vanes is longer and thinner and the vanes are arranged so that they are splayed (refs. 17, 21, 23) to cause a prescribed loss on the airstream at each lateral station, thereby bringing about a fairly uniform stream in the 80×120 test section. The sidewalls of the full-scale tunnel are also being reshaped, as shown in figures 1 and 11, to alleviate a wall-separation problem on the sidewalls behind the original inlet vane set (refs. 16, 17, 21). Although the model tunnel had an earlier version of inlet guide vanes that did not simulate either of the full-scale vanes, the system used in the model was effective enough to permit various tests on the 80×120 circuit (refs. 17, 20).

FAN-DRIVE SYSTEM

The model and the full-scale tunnel are driven by six fans, each inside its own nacelle. The motors are housed inside a centerbody, which is aligned with the diversion angle of the airstream (figs. 12, 13). Whereas the motors in the full-scale facility are synchronized so that their rotations are locked together, the model motors, although equally powered, are not forced to rotate at exactly the same rate. Hence, a variation between model motors of up to several percent was measured with a stroboscope tachometer. The full-scale motors are air cooled, and the model motors are water cooled. The model motors are three-phase induction-type motors with variable-frequency power input so that the speed can be controlled and changed as desired. The motors are rated at 10 hp at 10,000 rpm and have a maximum speed of 12,000 rpm when the impressed power is at 400 Hz. The motor instrumentation included a tachometer pickup and two thermocouples which monitored bearing temperatures.

Each model motor drives a six-bladed, fixed-pitch fan which has an outside diameter of 9.6 in. and a hub diameter of 4.2 in. (fig. 14). Each blade has a span of 2.7 in., a root chord of 1.4 in., and a tip chord of 1.00 in. The blade root sections are NACA 4420 airfoils, and the tips are NACA 4415 airfoils. The blade-pitch angle is 61° at the root and twists 24° to the tip where the blade has an angle of 37° (fig. 14). The solidity of the fan face is 31% . The fans rotate counterclockwise when looking upstream, which is opposite to the rotational direction of the full-scale fans. The drive fans used in the model also differ from those used in the full-scale tunnel, which has 15 variable-pitch wooden blades and 23 stator blades (ref. 22). The fan blades are tapered and twisted to produce a uniform impulse to the airsteam. Reproduction of the more complex system would have been expensive and was not necessary because the sole purpose of the model fans was to circulate air in the model tunnels and not to test the fan-drive system.

A single row of seven stator blades is located downstream of the fan plane (fig. 12). The blades have a chord of 3 in. and a shape that approximates a 4400-series NACA airfoil. The stators have an angle of about 16° to the tunnel centerline and no twist along their span (fig. 15). As with the fans, the stators do not duplicate at small scale the stator system used in the full-scale tunnel, which has 23 stators with a proportionately much smaller chord than those used in the model (ref. 22).

The drive system for the model differs considerably from that of the full-scale system, not only in the blade configuration but also in the fact that the full-scale fan-blade angles can be adjusted from about -18° to 52° and have a speed range capability from 0 to 180 rpm. The inconsistency in drive capacity of the model fans resulted in greater turbulence and less uniformity of the airstream than is to be expected in the full-scale device. There was another difficulty with the small-scale system when the model was in the 40×80 mode of operation. That is, during the start-up of the facility, it was quite often found that one or more fans would stall. The reason was that the fan drive for the 1/50-scale tunnel was designed for the pressure load in the 80×120 circuit, which is slightly lower than that of the 40×80 circuit. Since the fan blades are fixed, the blade design is compromised when the model tunnel is operated in the 40×80 mode. The two fans on the courtyard (inner) side of the wind-tunnel circuit were usually the ones that failed to produce an energetic airstream as the fan system started up. The change to a new air-exchange inlet did much to alleviate the start-up problems. It was also observed that when the back pressure on the fans was lessened by going to the 80×120 mode of operation, the difficulty with start-up of the fans was greatly diminished. It was concluded that the small scale and low Reynolds number of the fan blades made them susceptible to early stall. It was also necessary to clean the blades fairly frequently to remove any accumulated dirt near the leading edges of the blades, which seemed to magnify the stalling problem. The maximum speed of the air through the test sections in the model also differed from the full scale. That is, whereas the full-scale tunnel is designed to operate at 300 knots in the 40 $\times$ 80 test section and at 100 knots in the 80 $\times$ 120 test section, the model can only develop 130 knots ($q = 57$ lb/ft^2) and 55 knots ($q = 10$ lb/ft^2), respectively, in the two test sections.

PRIMARY DIFFUSER

When the NFAC facility was first constructed, the structural members were all located on the outside of the aerodynamic surfaces and were designed to withstand pressure loads imposed by a velocity in the test section of 200 knots. The upgrade of the 40 $\times$ 80 from 200 to 300 knots during the 1980-1982 period made it necessary to place nine vertical struts along the centerline of the primary diffuser to withstand the added loads on that portion of the tunnel. Even though the struts are streamlined, they impede the flow enough that a substantial velocity defect occurred on the centerline at the downstream end of the diffuser (refs. 24, 25). Pressure recovery was also affected adversely by adding an acoustic liner to the test section walls (refs. 17, 23). As a consequence, the pressures in the primary diffuser varied by a sizable fraction of the steady-state values.

In order to reduce the magnitude of these pressure fluctuations and to possibly improve the pressure recovery of the airstream in the diffuser, a research program was undertaken to develop a vortex-generator system to improve the flow field in the primary diffuser; that is, one that would suppress the surging and possibly improve the pressure recovery with a minimum expenditure of power. The chosen vortex-generator system (fig. 16) is located 132 in. downstream of the test section; it has eight elements which produce two regions of swirl in the diffuser. The direction of the angle of attack on the vortex generators is such that the flow along the floor is divided at the centerline and driven upward along the sidewalls and across the ceiling to the centerline where the two rotating flows meet. The flow at the ceiling centerline then descends to the floor. Any lift generated by a model in the test section will then contribute to the swirl and should therefore increase the efficiency of the diffuser-vortex-generator system. Measurements made with the 1/50-scale model and with a 1/10-scale model of the test section and diffuser showed that such an arrangement of generators was optimum. A series of tests was then conducted to determine the optimum size, shape, and location of the vortex generators. The preferred configuration is the one constructed; it is shown in figure 16.

INSTRUMENTATION

A variety of measuring devices were used to diagnose and quantify the flow characteristics of the facility. A number of pressure orifices were located on the sidewalls and ceiling around the circuit for measurement of the local static pressures. Permanently fixed rakes were also built into the device at several stations along the circuit. These rakes were found to not be nearly as useful as a moving probe that continuously recorded the pressures on an x-y plotter as the sensor made its survey across the duct. The traversing mechanism was connected to a potentiometer that drove the recording pen so that a one-to-one record was immediately available for the pressure distribution along a survey path (see, e.g., refs. 19, 24). Both static and total pressures were referenced to atmospheric pressure because the loads on the structure are usually determined by their deviation from their surroundings or from atmospheric pressure. Traverses were taken throughout the circuits with the tunnels configured in various ways to determine the best way to modify the facility and to determine the loads associated with such a change. The pressures were measured with a pressure sensor, as well as with water-tube manometers.

The temperature distribution was also measured in the circuit during the study of the air-exchanger design (ref. 19). The thermocouple probe was designed to be accurate within 1^{o} F and to have a response time of about 1 sec. As with the pressure surveys, the distribution of temperature was recorded automatically on an x-y plotter as the sensor traversed the duct, thereby yielding a continuous record at the various test stations (ref. 19).

During the development of the air-exchange system (ref. 19), a volume flow rate instrument (an Alnor balometer that was designed for and is usually used for air conditioning circuits) was used to determine the amount of air entering or leaving the 1/50-scale model of the 40 $\times$ 80 duct. The readings on the Alnor unit repeated within several percent, and comparison of the Alnor readings with several pressure survey measurements of flow rate indicated that they were accurate to within about 5% . The volume flow rate indicated by the Alnor unit was divided by the volume flow rate through the test section to yield a dimensionless parameter $\dot{m}$ that represents the fraction of air exchanged with the atmosphere per unit time (refs. 19, 24).

The character of the airstream in the ducts was monitored visually by placing yarn tufts on the walls and on wires strung across the tunnel; by nylon microtufts placed on walls, which were illuminated with ultraviolet light; and with a smoke produced by mixing sulfur dioxide and ammonia gases at the tip of a wand held in the airstream. The character of the boundary layer on the walls of the diffuser and the possibility of flow separation were also investigated by painting a thin layer of crankcase oil on the area of interest. The tunnel was then run at high speed for several minutes or until the oil thickness formed a pattern of interest. The oil was then illuminated with ultraviolet light or the flow was stopped and the tunnel opened for inspection or for a photographic record.

The study of the exhaust ramp design for the 80 $\times$ 120 circuit at the south end of the facility made use of a laser velocimeter to accurately determine the affect of various ramp designs on the exhaust airstream (refs. 15, 18). Not only did the instrument give an accurate measurement of the horizontal and vertical velocity components at a precise location, but it also yielded the variation in magnitude of the velocity so that an estimate was available for the magnitude of the unsteadiness and turbulence of the airstream.

A solid-state pressure measuring system was used during the latter part of the research program to measure the characteristics of the 1/50-scale model when configured to represent as closely as possible the 1986 or to-be-built version of the 40 × 80 tunnel (ref. 24). The instrument utilizes a transducer at every measurement port and scans the signals electronically. In order to obtain highly accurate results, periodic on-line calibrations are made using a highly accurate secondary standard. As a consequence, the system can measure up to 1024 pressures at data rates up to 20,000 measurements per second with inaccuracies of no more than 0.1% of full scale. During the tests of reference 24, the system was controlled by an on-line minicomputer which was also used for data reduction and display. The high data rates enabled 88 static pressures around the circuit to be sampled essentially simultaneously with the pressures averaged over a user-specified time period.

OVERVIEW OF TESTS CONDUCTED

A wide variety of tests were carried out with the 1/50-scale model of the NFAC. Many of the tests were run to explore the possibility of certain postulated flow peculiarities that might have occurred and caused the failure of vane-set 5 which led to the damage sustained in the 1982 accident. The ease with which the model facility could be reconfigured and a test conducted made it an ideal device for these kinds of exploratory flow-field studies. Unfortunately, the small scale and low Reynolds number of the aerodynamic components raised doubts about the quantitative accuracy of some of the results. However, the qualitative accuracy of the model tunnel seemed reliable and appeared to yield a true picture of the nature of the flow field.

In this section, an overview will be given of the various tests carried out in the two circuits of the model tunnel. Since most of the detailed test programs are adequately covered in other publications, reference will only be made to the most important results contained in those papers (refs. 19, 20, 24). Worthwhile results not published elsewhere will also be included here for future reference.

Flow Field in the 80 × 120 Test Section

As mentioned previously, the inlet guide vanes of the flow-through facility on the model tunnel are quite different from those on the 1982 and 1986 versions of the inlet. Nevertheless, an estimate was desired of the boundary-layer thickness on the test-section walls and of any steady-state flow angularities in the test-section airstream of the 80 × 120 tunnel. Surveys of the total pressure head were, therefore, made across the channel horizontally and vertically along enough lines to define the flow field. On the basis of yarn-tuft observations and of the fluctuations of the pressure, the flow was found to be quite uniform, but turbulent, in the core region of the airstream throughout the test section. Also, the boundary layer was found to be of uniform thickness on all of the walls at a depth that scaled up to a thickness of between 3 and 4 ft in the full-scale device. Reduction of some of the data from pressure rakes in the full-scale device indicated a boundary layer of about the same thickness. The yarn tufts fluctuated several degrees in direction about zero, showing that the airstream contained some turbulence, but they did not indicate any net or steady-state flow angularity nor any overall cross-section circulation throughout the test section.

Junction of 80 × 120 and 40 × 80 Circuits

After vane-set 5 collapsed, a number of questions were raised about possible sources of excessive loads on the vanes that might have contributed to the destruction of that vane set. As a consequence, the 1/50-scale model was configured in the 80 × 120 mode to measure flow angularity relative to the tunnel centerlines and to measure the flow velocities at various locations around vane-set 5. A cutaway view of the region of interest around vane-set 5 is presented in figure 4. Following the survey of the test section described in the last section, fluorescent nylon microtufts were fastened to the floor area around the ramp junction of the two circuits to find out if the abrupt changes in the floor shape caused any flow separation or flow-direction anomalies. As shown in figure 17, no flow-separation areas were identified, and the streamline directions were roughly as expected from inviscid potential flow.

The inflow directions were then measured by placing thread tufts on music wire strung across the tunnel about 3 chord lengths and 2 chords downstream of vane-set 5. With the tunnel running, the angles of the tufts were measured relative to the centerline of the facility. It was determined that the measurement method yielded results accurate to within about 0.5°. The results for the inflow shown in figure 18 show that the onset flow is within a few degrees of parallel to the centerline except near the floor of the tunnel, where the angularity can deviate considerably. The outflow direction from vane-set 5, however, varied from the ideal or designed value by as much as 5° (fig. 18). The total pressure of the air stream entering vane-set 5 also shows a thick boundary layer, but no large flow anomalies (fig. 19). Subsequent tests with a 1/10-scale tester indicated that flow separation at the hinge of the flap of vane-set 5 causes the flow-turning angle to be erratic (ref. 17). It was then concluded that any inflow angles and/or separated flow regions that were present were neither large enough nor located such that they could have been the primary contributors to the failure of vane-set 5.

Air-Exchange System for the 40 × 80 Tunnel

The 1982 version of the 40 × 80 tunnel incorporated two louver-type openings in the north leg of the circuit for the inlets for the air-exchange system, the purpose of which is to keep the tunnel air temperature below the operating limit (set at 130° F). The cooling air was then exhausted through three openings in vane-set 7 located at the southwest corner of the facility or through a louvered opening on the courtyard wall of the south leg of the tunnel (fig. 2). A study of the air-exchange system (ref. 19) was undertaken primarily because the courtyard inlet, located in the north leg, induced a flow-separation region that extended along the courtyard wall into fans 1 and 4 (fig. 20). The large amount of low-energy air entering the two fans created high inflow distortion, which produced high cyclic loads in the fan blades to an extent such that as the tunnel approached its maximum operating speed, fatigue cracks began to appear in several of the fan blades.

Another reason for undertaking a study of the air-exchange system was to increase the volume of cooling air that could be cycled through the facility without exceeding the design pressure loads on the walls of the tunnel. The design changes, summarized from reference 19, include removal of the old inlet orifices and the construction of a contoured inlet door in the courtyard wall of the north leg (figs. 21-23). Furthermore, the size of the exhaust opening is to be increased from 3 panels to a full column or 11 panels in the westernmost part of vane-set 7. The inlet door was designed so that the incoming jet of cool air is directed downstream and parallel to the duct flow so that it energizes the sluggish flow along the courtyard wall (figs. 21-23). It turned out that the technique was so effective that fan stall was virtually eliminated in the model tunnel. The modifications enabled the maximum air-exchange rates to be increased from 5% to 10% and also improved the flow field in the wind-tunnel channel so that the flow into the fan-drive system is more uniform. Enlargement of the exhaust opening, located in the southwest corner of vane-set 7, so that an entire column of doors is in the open position, was effective in maintaining acceptable pressure levels in the facility at all air-exchange rates planned for operation (ref. 19). An estimate was also made in reference 19 of the power required to support the exchange of air.

Exhaust Deflector Ramp for the 80 × 120 Tunnel

When the 80 × 120 tunnel was implemented in 1982, unacceptably high winds were observed at ground level under the exhaust jet of the flow-through facility. In order to determine the extent of the problem, the wind speeds were measured under the full-scale exhaust jet at an elevation of about 6 ft above the ground by means of a hand-held anemometer. The velocity vectors shown in figure 24 are time-averaged values of the rather unsteady wind field observed in the area. After the model was configured in the 80 × 120 mode of operation, it was first necessary to verify that the model had the same kind of flow characteristics on a ground plane under the jet (ref. 20). A sheet of Plexiglas was therefore placed under the exhaust jet and brushed with a light coating of crankcase oil. The model was then run for about 1 hr to let the air friction develop a streak pattern in the viscous oil surface. A photograph of the resulting pattern indicates that the model and full-scale flow fields are quite similar (fig. 25). Furthermore, measurement with a pitot tube anemometer of the magnitude of the velocity near the ground plane of the model tunnel yielded values in agreement with the full-scale measurements. A complete map of the velocity field was not made because it was difficult to obtain a satisfactory magnitude and direction value in the very unsteady flow field under the jet. Since good agreement had been achieved between the model and full-scale data near ground level, it was assumed that the model would adequately simulate the full-scale device for the design of an exhaust deflector ramp. The study reported in reference 20 was therefore carried out.

The procedure used in the investigation was to select a variety of ramp designs and to then test them to find out how effective they each were in lifting the jet off the ground plane. The variations tried included changes in ramp shape, length, porosity and orientation. The effectiveness of the ramps was determined by observing yarn tufts fastened to the ground plane, by smoke injected into and under the jet itself, and by measuring the vertical and horizontal velocity components in and around the jet with a laser velocimeter (refs. 12, 15, 20). Typical examples of velocity surveys with and without a ramp are presented in figure 26 to illustrate the dramatic difference brought about in the ground wind profiles by a deflector. It was concluded in the study (ref. 20) that the best configuration for a ramp was a flat plate elevated at 45° to the horizontal, with a porosity of about 30% , and a length of about 6 in. (25 ft full scale), and which is located at the base of the opening for vane-set 7 (fig. 27). End plates were added to the ramp because the model tests indicated that unwanted winds at the ends of the ramp were reduced further with the end plates (fig. 28).

Circuit Performance

An effort was made during the test program with the model facility to compare the measured pressures, powers, flow angularities, etc., with any data available from the full-scale facility (refs. 17, 19, 20, 24, 25). In general, quite good agreement was found between the two. However, one parameter was consistently different: the difference in static pressure between the north and south legs of the 40 × 80 tunnel circuit. The model tunnel yielded a pressure difference coefficient $(p_s\text{-}p_n)/q_{ts}$ of about 0.28, whereas in the full-scale tunnel it was at about 0.24. A precise reason for the difference was not found, but is believed to be the slightly higher total head losses through the vane sets brought about by the small scale and low Reynolds number in the model tests. When the total head losses across a number of the vane sets were measured in the model, they were found to be within about 10% or 20% of that estimated for the full-scale tunnel.

Another aspect of the model and full-scale comparison that deserves special attention was the finding that an improper turning magnitude by a vane set at a corner would propagate around the circuit (refs. 17, 24). The particular case studied in detail was the flow-turning capability of vane-set 6 as regulated by the trailing-edge flaps. The 1982 configuration employed a 3-ft-long flap that was deflected at 90°. Because of flow separation on the aft part of vane-set 6, the flow was turned less than 90°, so that it was underturned. As a consequence, the energetic part of the airstream, or the core flow, appeared to have migrated toward the outside of the circuit. When the flap length on vane-set 6 was doubled and set at an angle of 80°, tests in a model tunnel designed to test vane sets at 1/10-scale showed that the airstream would be turned the proper 90°. This result was then confirmed in the 1/50-scale model tunnel (ref. 24). If the rest of the vanes were also set to turn the airstream properly, the energetic core lined up with the tunnel centerline as it should (ref. 17). This experience reminds the wind-tunnel designer that a satisfactory facility requires that all components perform the task assigned and that there be no room for marginal or submarginal performance of any component.

CONCLUDING REMARKS

The 1/50-scale model has proved to be a useful and quite reliable tool for design studies of the NFAC facility. In the tests conducted and reported herein, the model always yielded qualitative results that could be relied upon. Quantitatively, it was found that the model results differed from those of other tests by only about 10% on the circuit pressure losses. In other cases, such as turning angles and cross-stream pressure distributions, the small scale and low Reynolds number of the model did not seem to affect the results appreciably.

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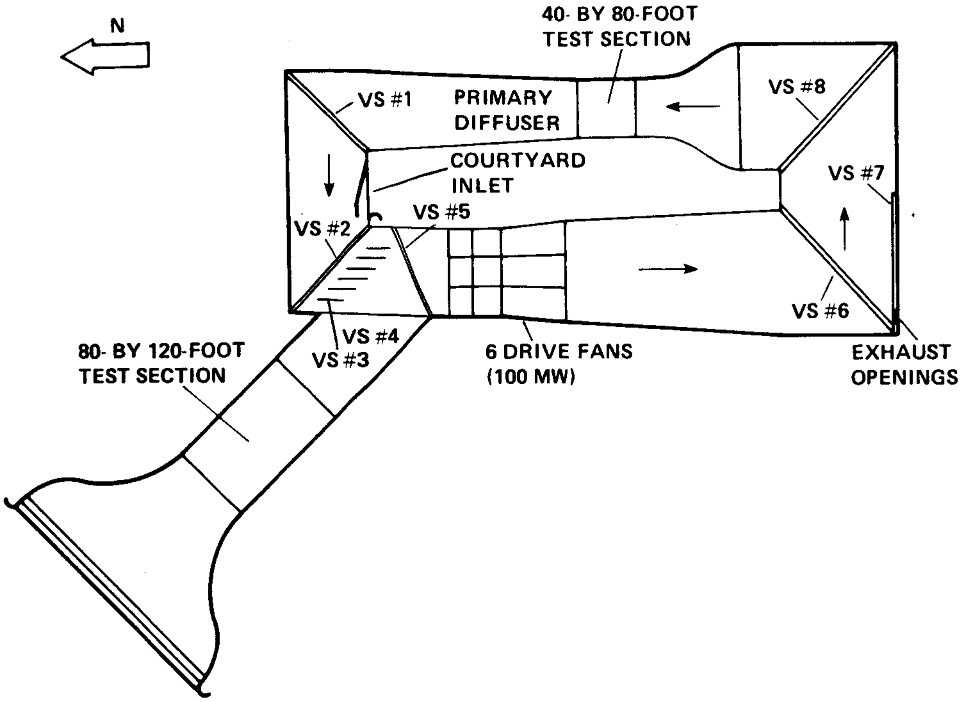
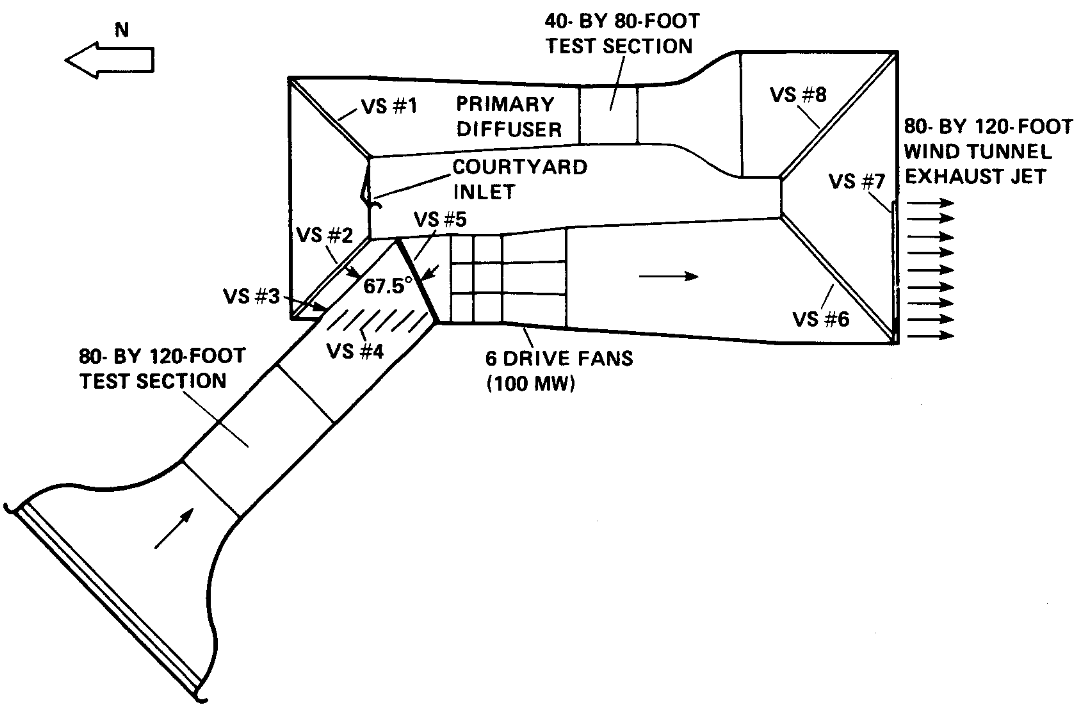
TABLE 1.– CHARACTERISTICS OF MODEL VANE SETS

Vane set	Tunnel dimensions, height/width, in.	Vane-set length, in.	Number of vanes in airstream	Number of splitter plates	Chord-to-gap ratio
1	16.5/26.1	37	50	1	1.97
2	16.5/26.1	37	50	1	1.97
3	16.7[a]/28.7	37.5	7		1.4
4	17.7[a]/28.9	39.4	5		1.4
5	19.5[a]/28.3	31.0	37	7	1.95
6	31.8/41.4	58.5	57	0	5.8
7	31.8/47.9	31.8	12		1.4
8	31.8/41.4	58.5	78	2	1.97
Inlet guide	31.8/86.9	86.9	20	10	2

[a]Averaged values over tapered sections.



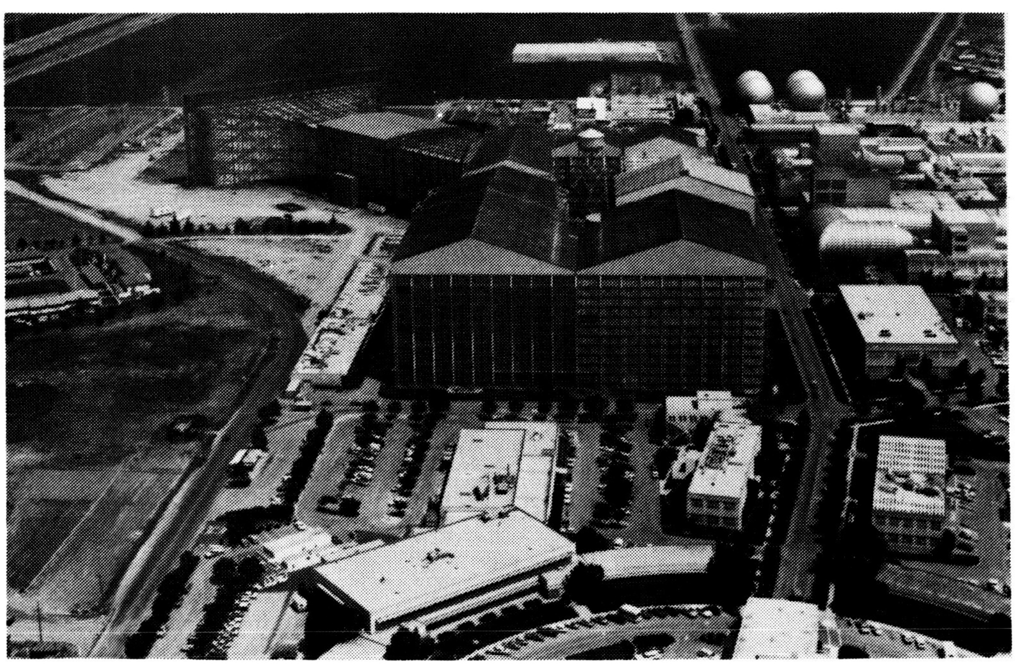
(a) 40 × 80 circuit.



(b) 80 × 120 circuit.

Figure 1.- Plan view of NFAC at Ames Research Center.

(a) Looking into the entrance of the 80 × 120 tunnel from the northwest.

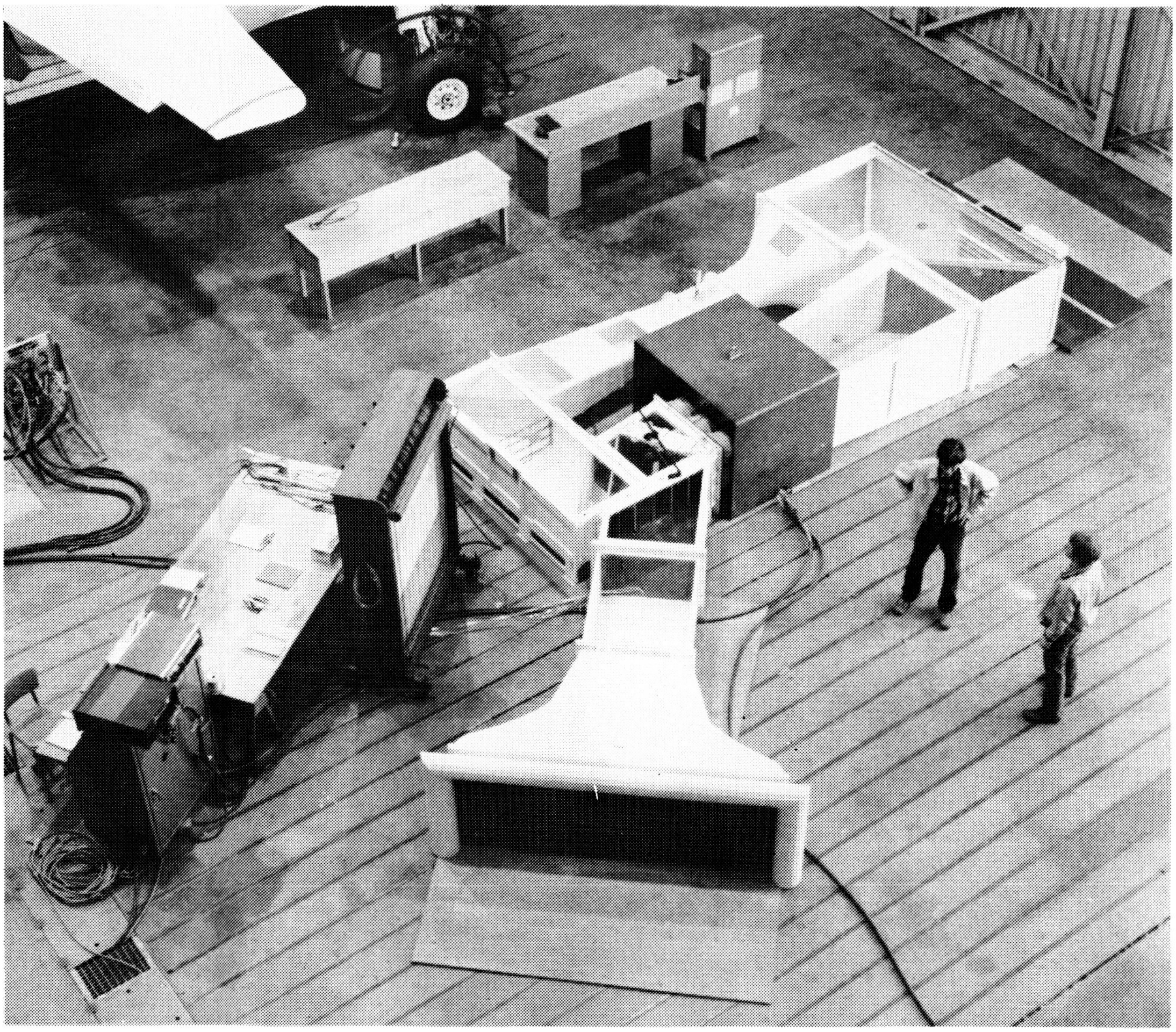


(b) Looking at south wall of the 40 × 80 tunnel.

Figure 2.- The NFAC (1982).

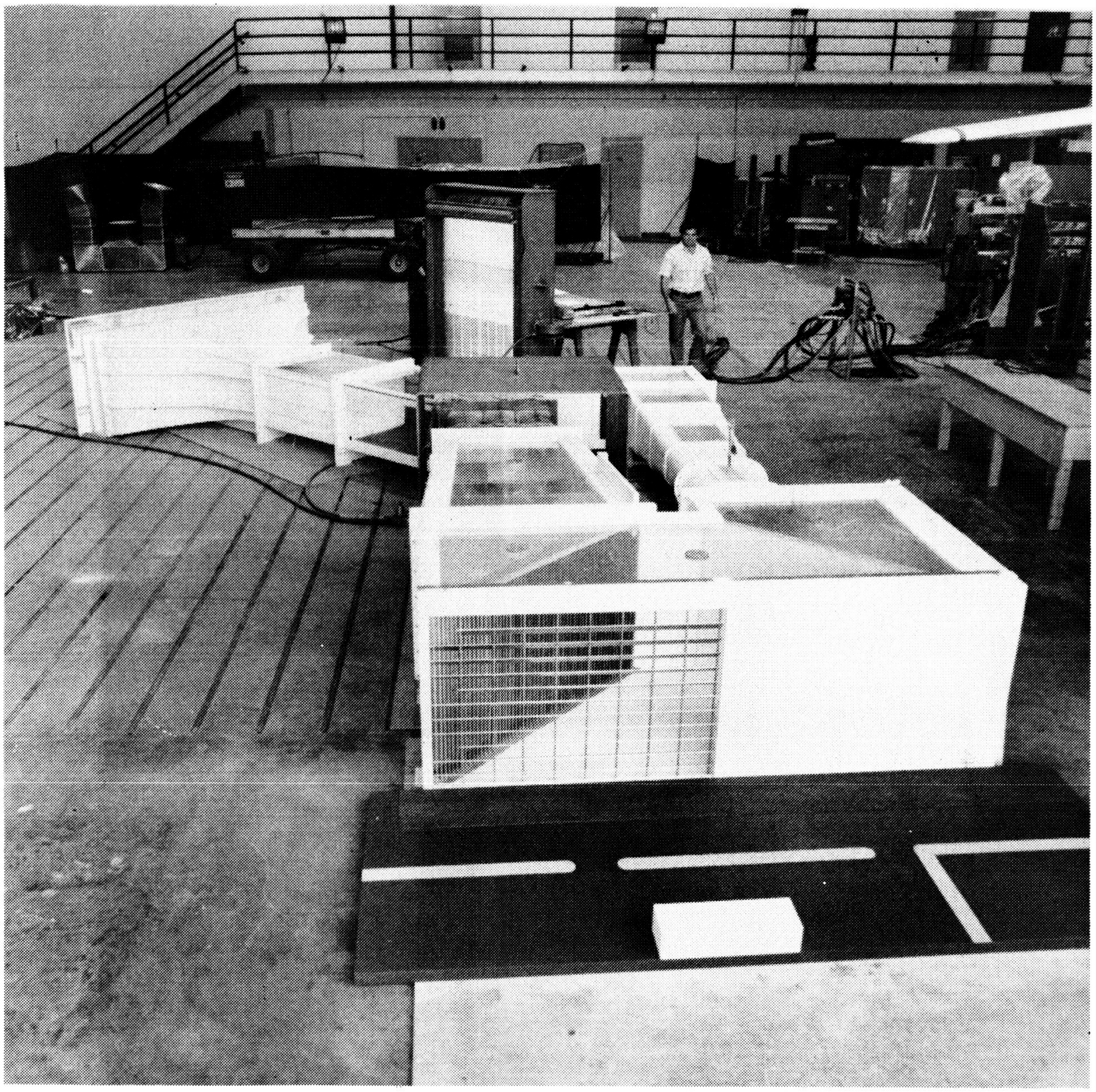
(a) Overhead view (two windows were added to top of primary diffuser after photograph was taken).

Figure 3.- One-fiftieth-scale model of NFAC used in the investigation.



(b) Looking along entry and test section parts of 80 × 120 circuit.

Figure 3.- Continued.



(c) Looking at south end of model with vane-set 7 in open position.

Figure 3.- Concluded.

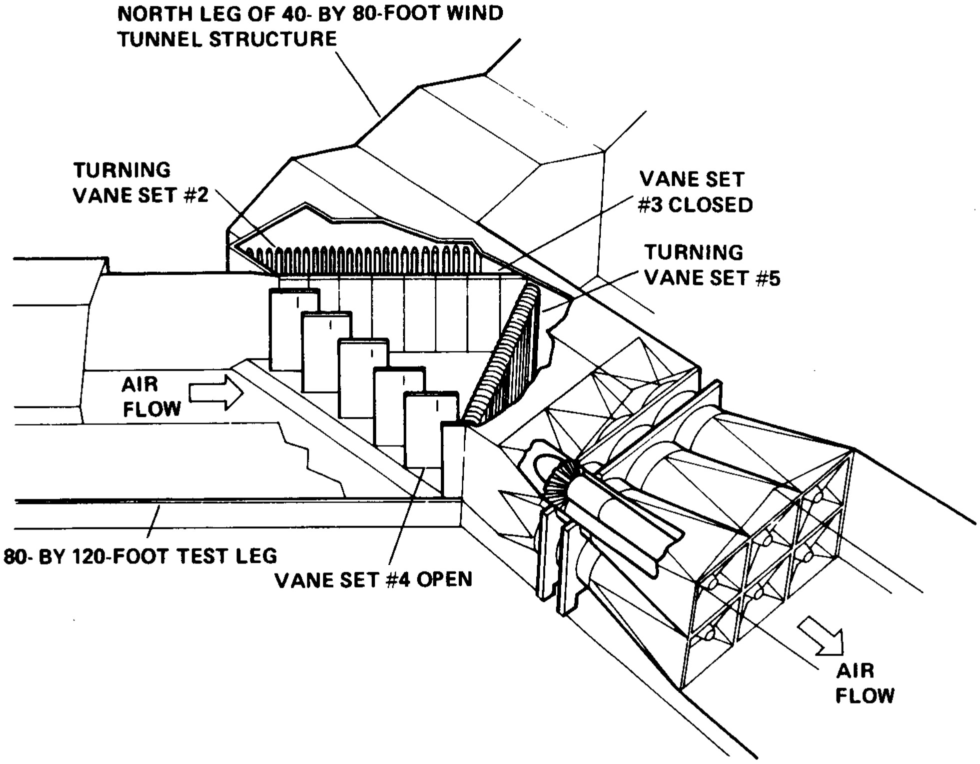
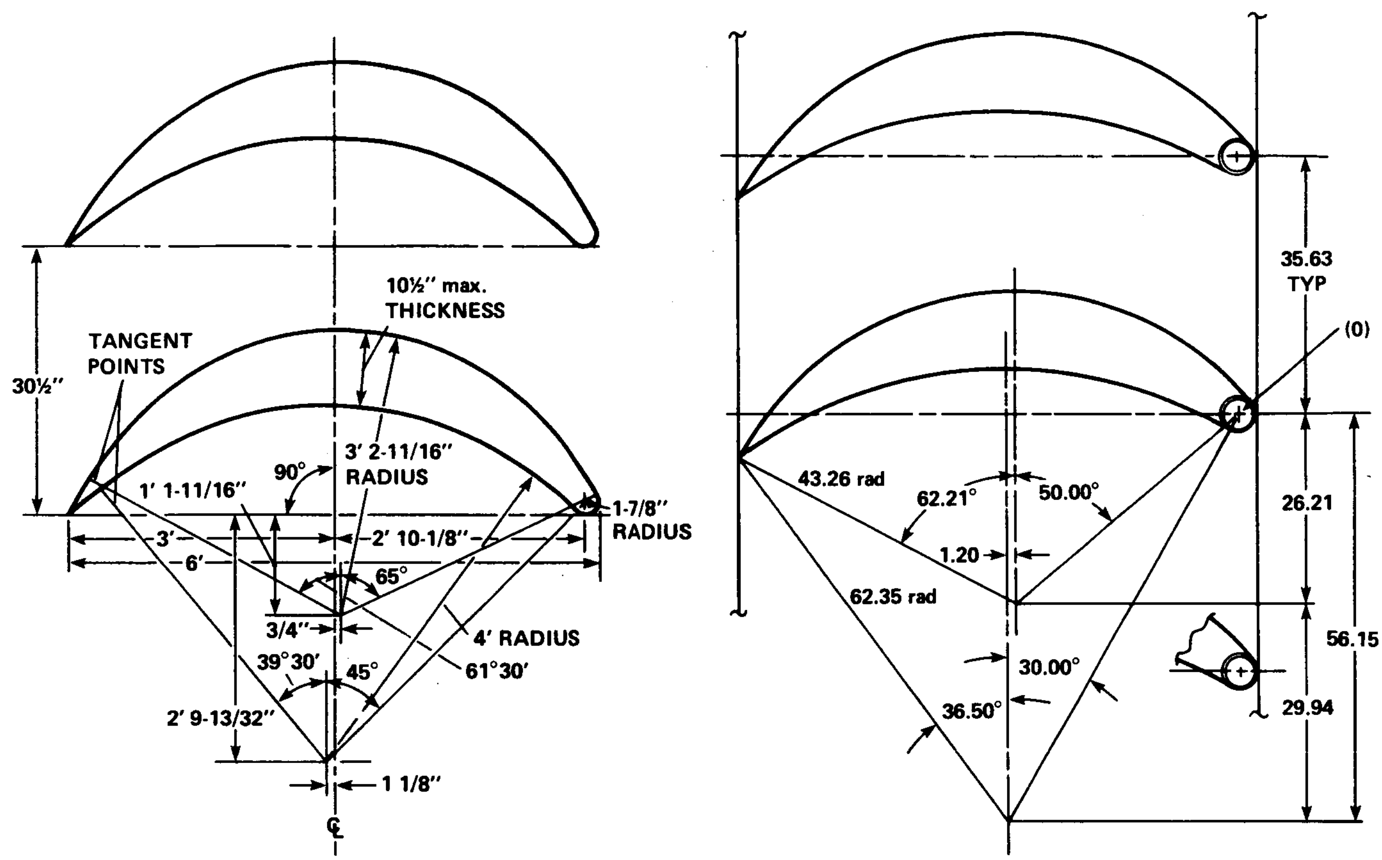


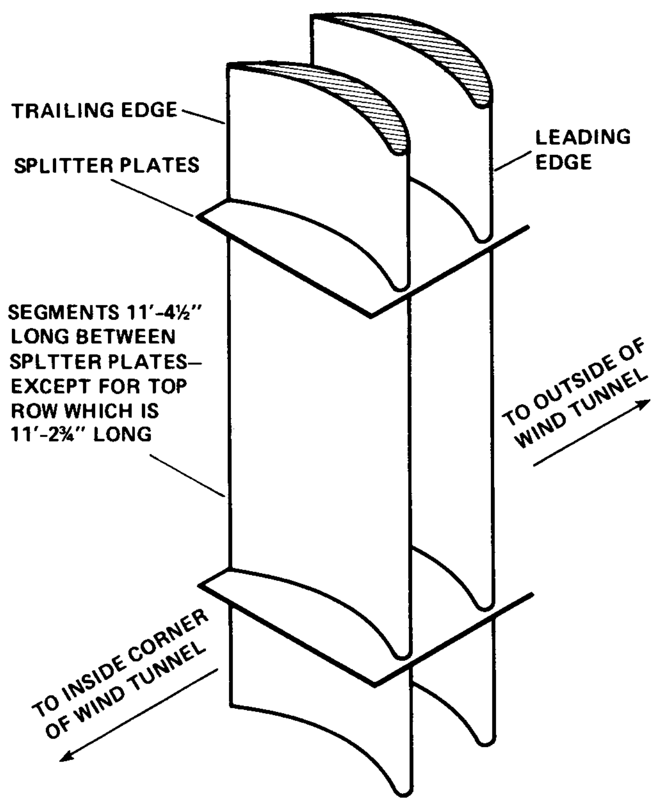
Figure 4.- Vane arrangement for operation of the 80 × 120 circuit at junction with the 40 × 80 circuit.



(a) 1943-1982 version of vane-sets 1 and 2; present version of vane-set 8 is one-half dimensions shown, and model vanes are 1/50 of the dimensions shown (chord = 1.44 in., gap = 0.73 in.).

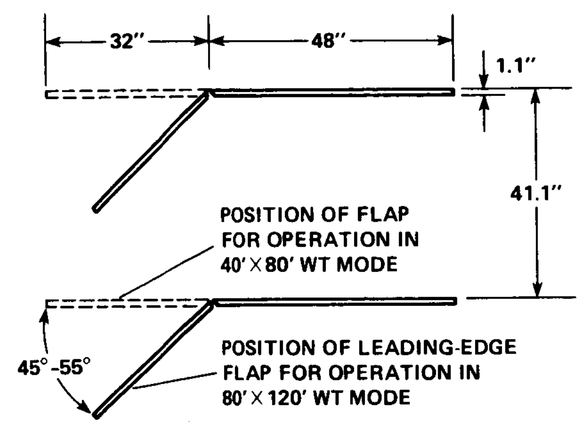
(b) 1986 version of vane-sets 1 and 2; all linear dimensions are in inches.

Figure 5.- Section profiles of vanes used in vane-sets 1, 2, and 8.

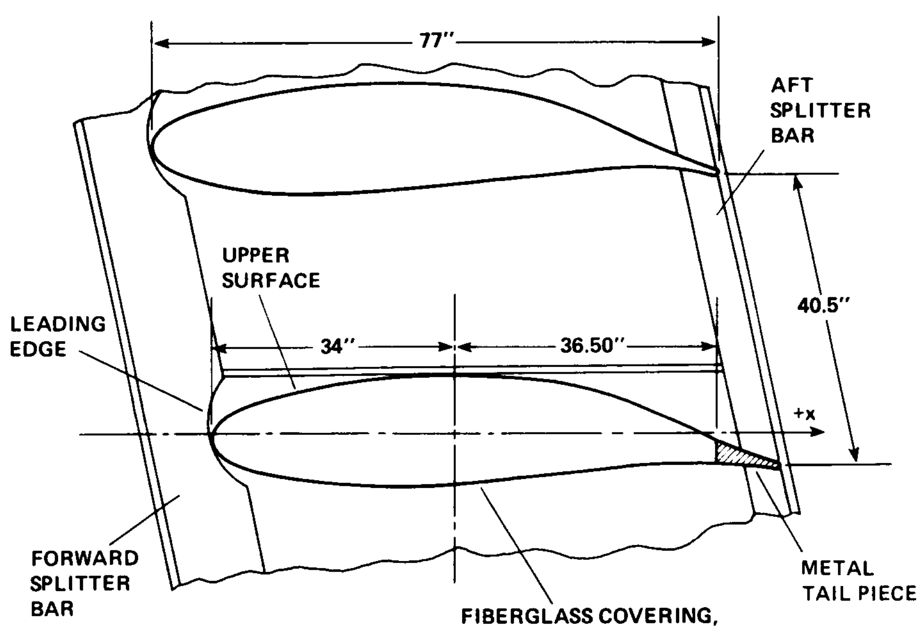


(c) Portion of vane-sets 1 and 2 showing how splitter plates and vanes fit together for 1986 version of the vane sets.

Figure 5.- Concluded.

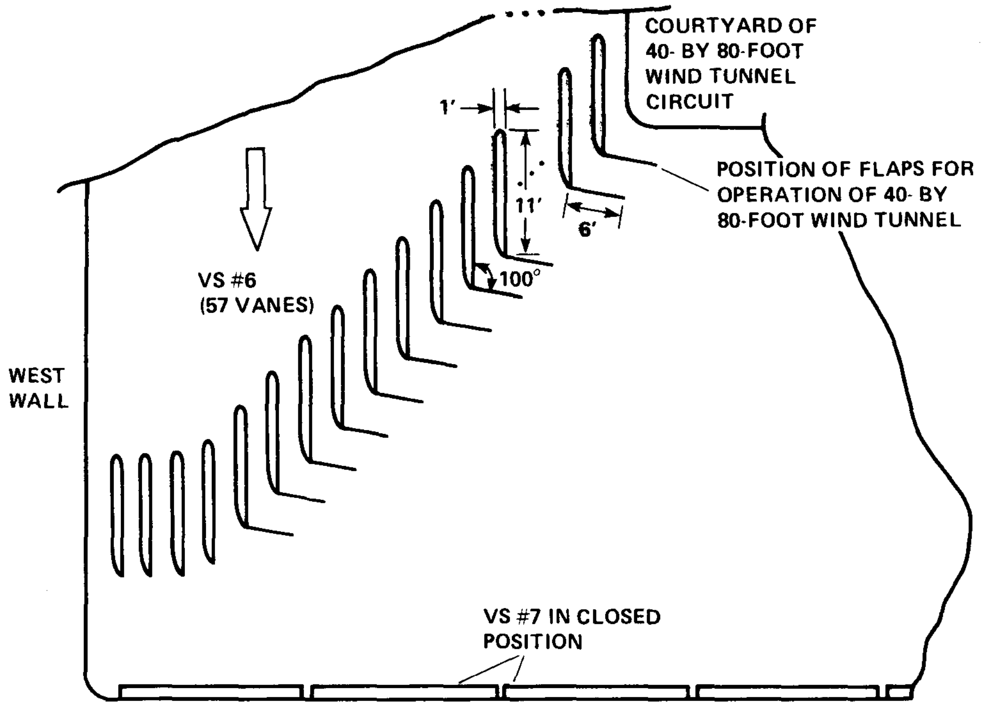


(a) 1982 version of vane-set 5 (38 vanes); the horizontal splitter plates extended across the tunnel over the length of the fixed part of the vanes.

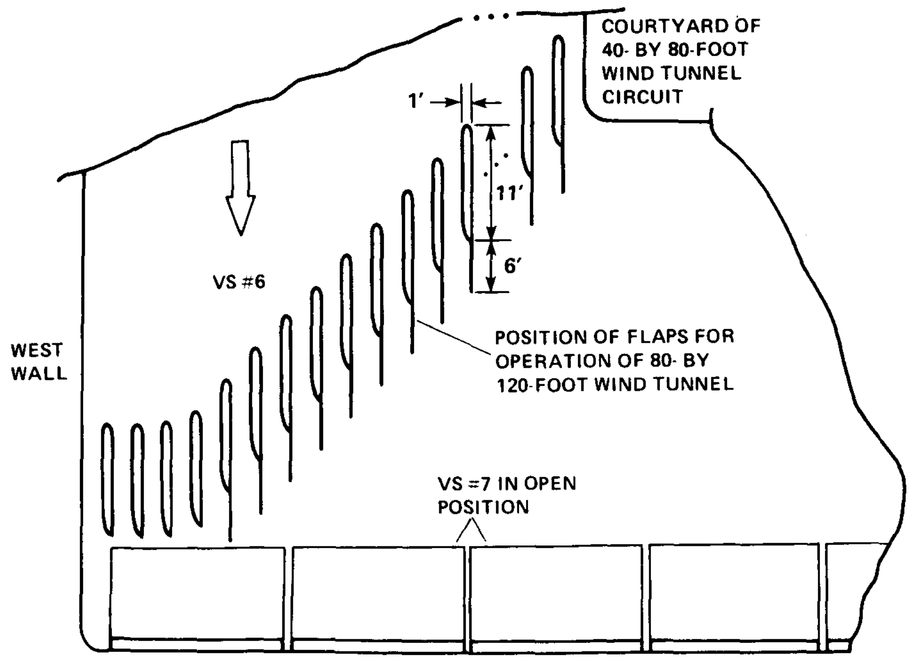


(b) 1986 version of vane-set 5 with splitter plate.

Figure 6.- Section profiles used for vane-set 5.



(a) 40 X 80 mode of operation.



(b) 80 X 120 mode of operation illustrating offset of three corner vanes and removal of four flaps to accommodate the inward swing of vane-set 7 as it opens.

Figure 7.- Southwest corner of NFAC facility illustrating disposition of vane-sets 6 and 7 during operation of the two circuits; debris screen and structure on outside of building are not shown.

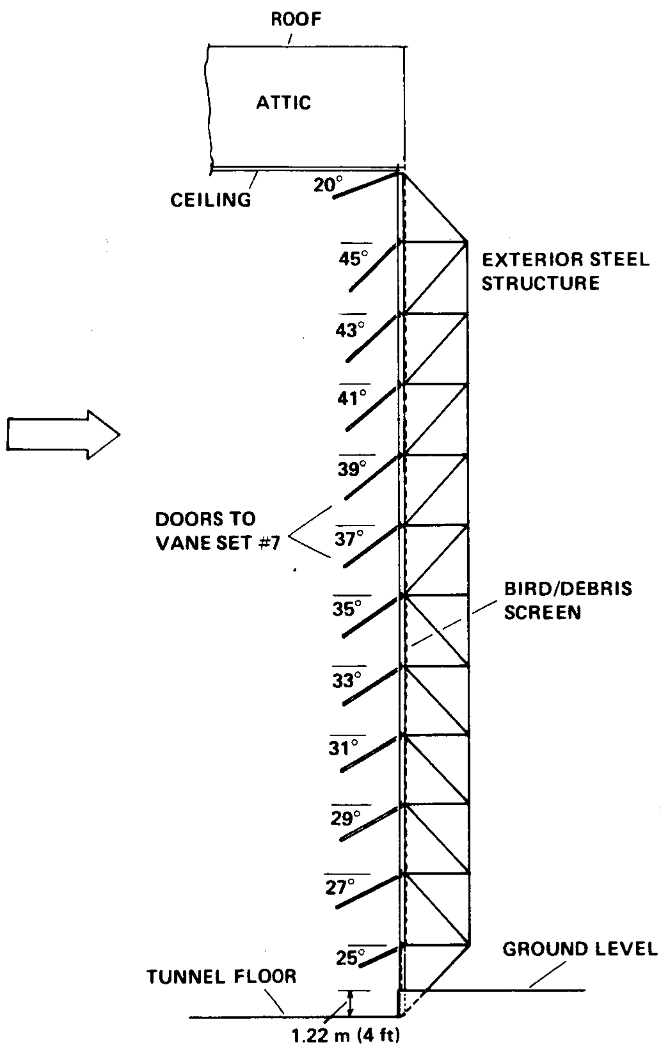


Figure 8.- Cross section of vane-set 7 and exhaust opening which illustrates splay angles of doors and offset of tunnel floor from ground level.

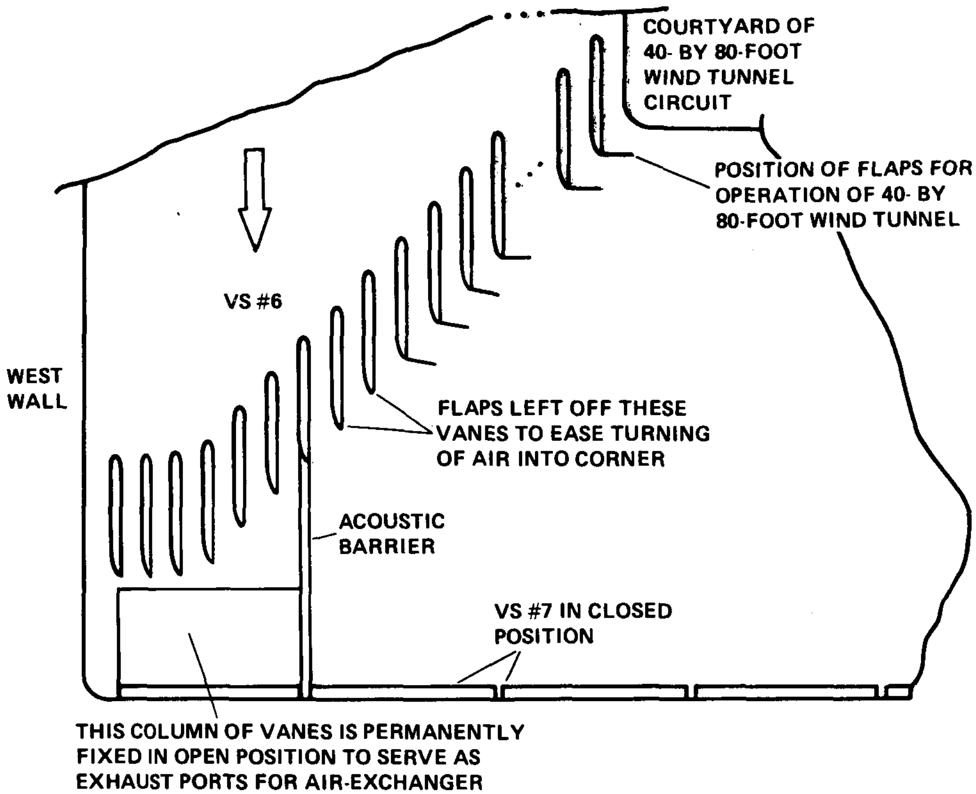
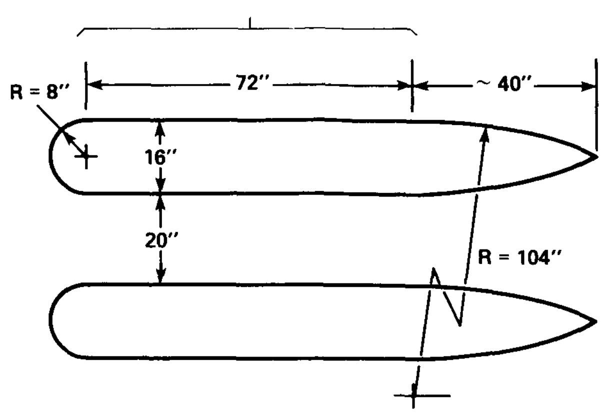
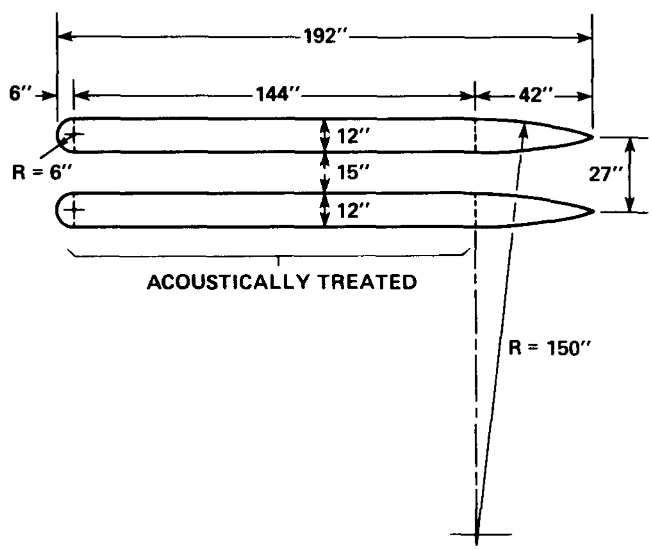


Figure 9.- Aerodynamic surfaces located near southwest corner of facility which illustrates relationship of acoustic barrier to vane-sets 6 and 7.



(a) 1982 version: vanes have no splay and same spacing.



(b) 1986 version: spacing of vanes varies with splay angle from value shown above which corresponds to center line arrangement.

Figure 10.- Shape of inlet guide vanes for 80 X 120 tunnel.

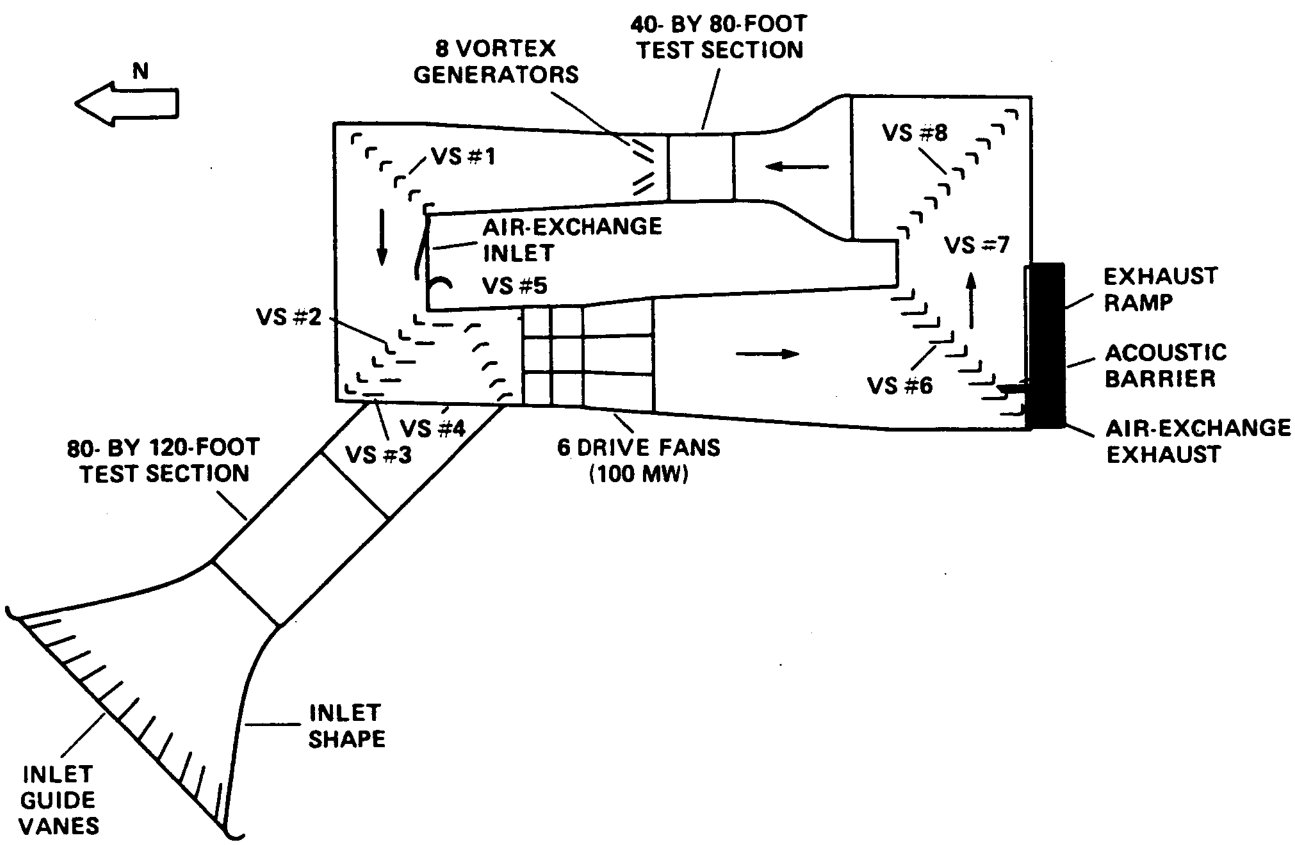
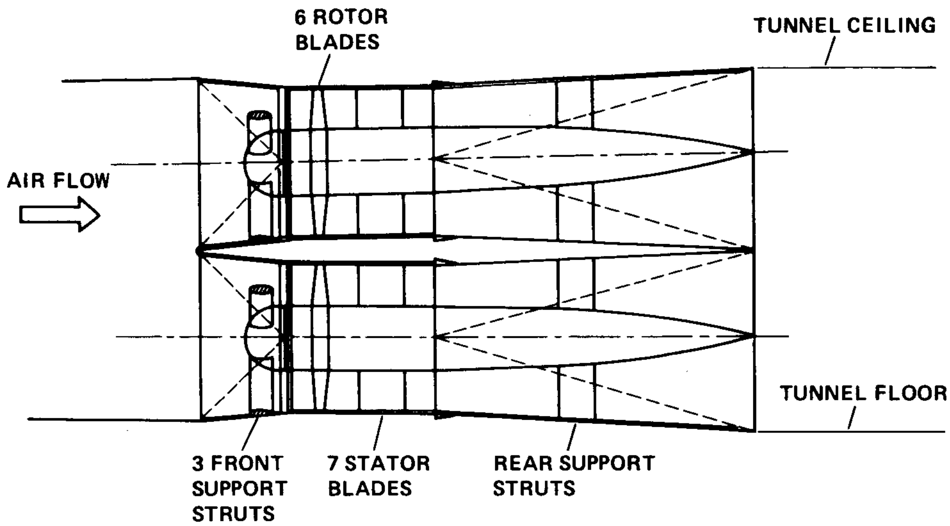
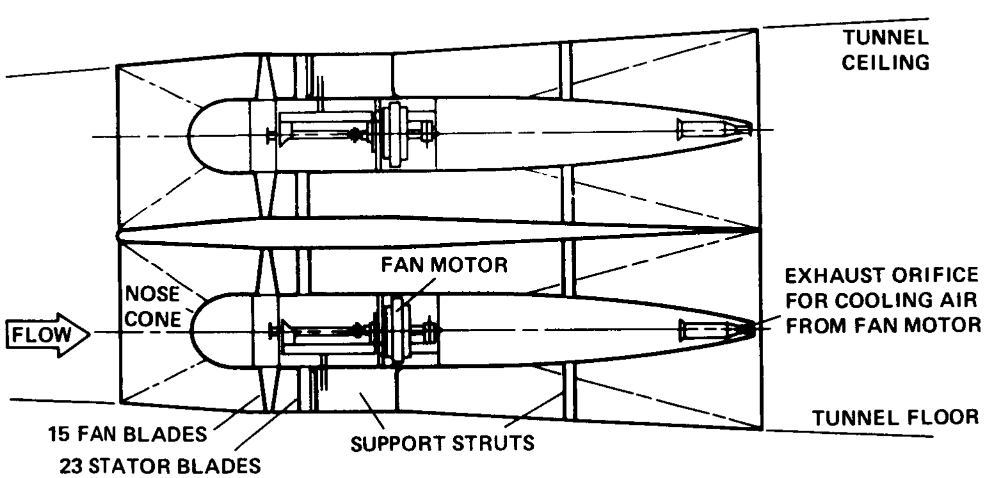


Figure 11.- NFAC complex after 1986 modifications.

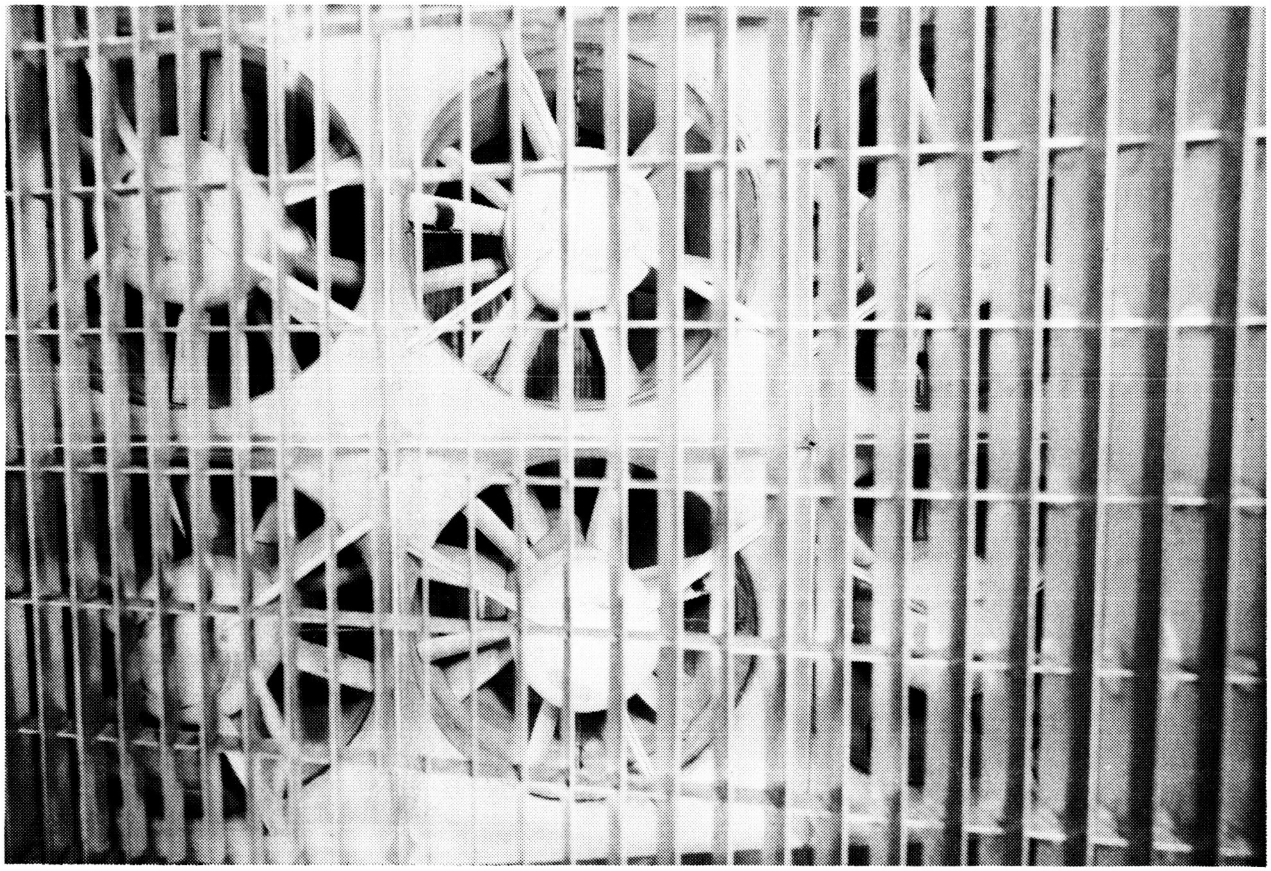


(a) One-fiftieth-scale model: fan diameter = 9.6 in.; nacelle length = 37 in.



(b) Full-scale wind tunnel: fan diameter = 40 ft; nacelle length = 150 ft.

Figure 12.- Vertical sections through drive-fan systems.

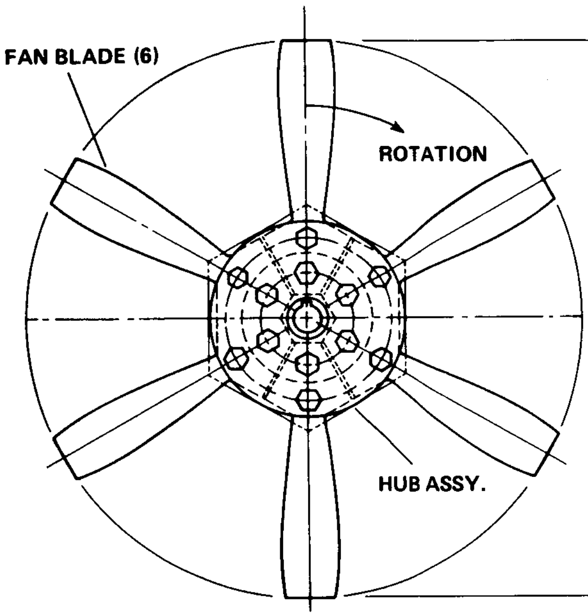


(a) One-fiftieth-scale model fan system as viewed through vane-set 5.

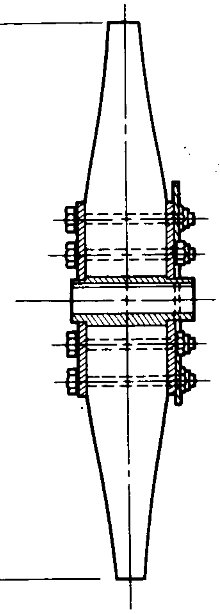
Figure 13.- Fan-drive systems.

(b) Full-scale wind tunnel as viewed through vane-set 5.

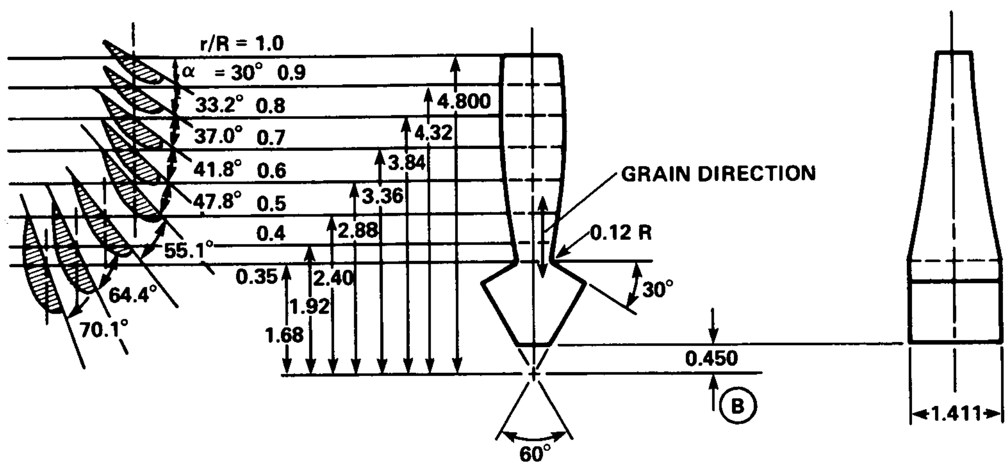
Figure 13.- Concluded.



(a) Front view.

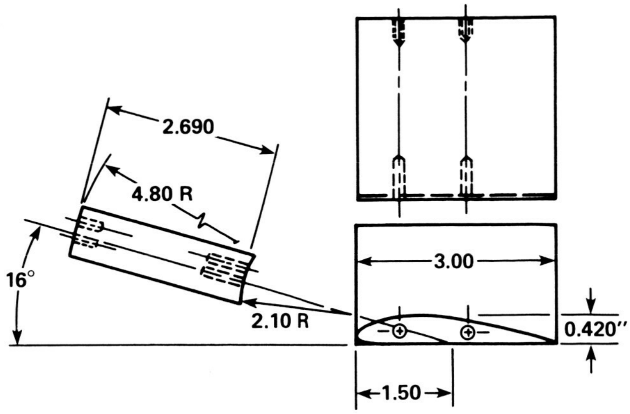


(b) Side view.

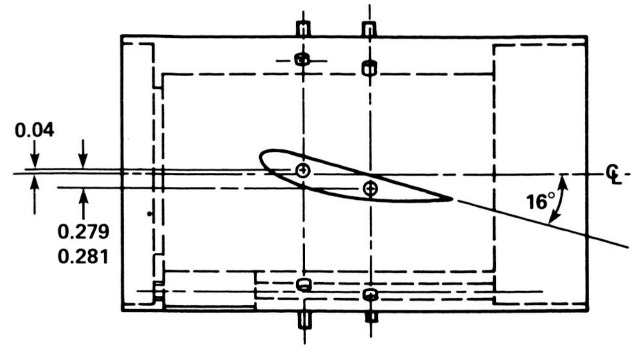


(c) Characteristics of blades.

Figure 14.- Details of fans for 1/50-scale model.

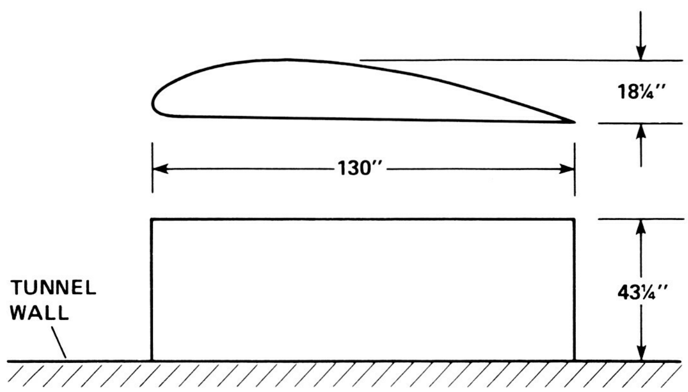


(a) Shape of stator blades.

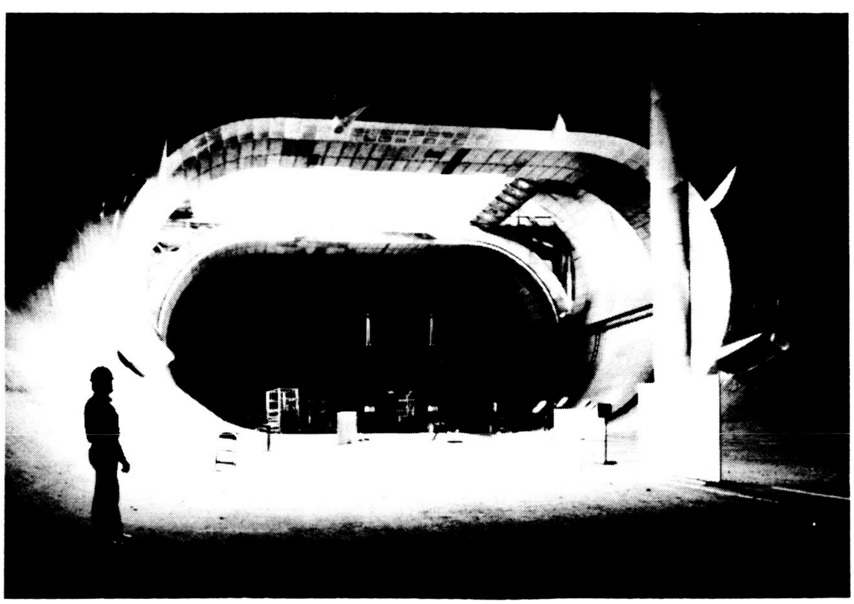


(b) Mounting alignment on motor housing.

Figure 15.- Details of stators for 1/50-scale model fan-drive system.



(a) Shape of vortex generators.



(b) Vortex generators as installed at an angle of attack α of 15° at a distance of 134 in. downstream of test section.

Figure 16.- Characteristics of eight vortex generators for primary diffuser of full-scale 40 × 80 tunnel.

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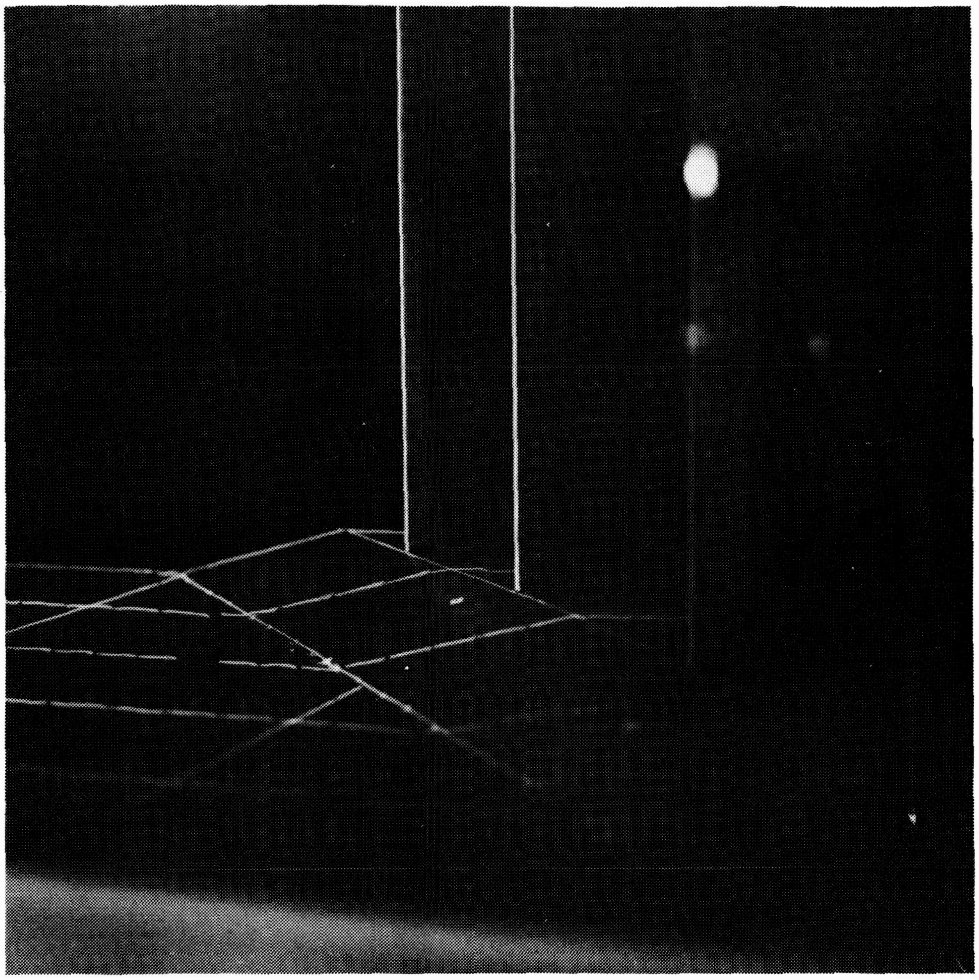
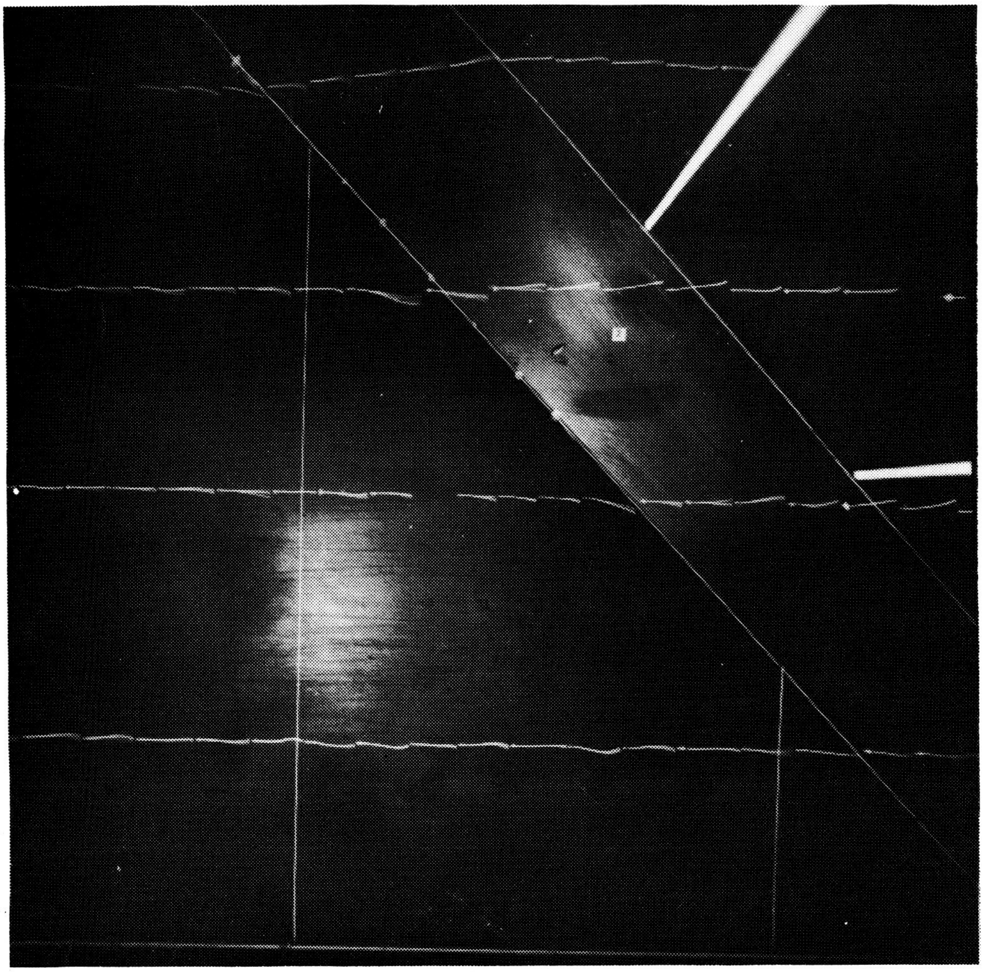


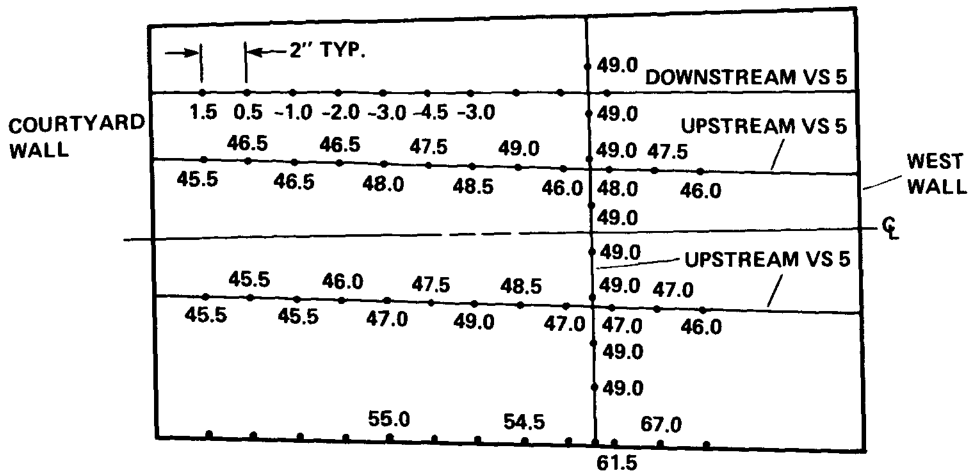
(a) Oblique view.

Figure 17.- Fluorescent mircrotufts in ramp region of junction of 40 × 80 and 80 × 120 tunnels as taken in 1/50-scale model.

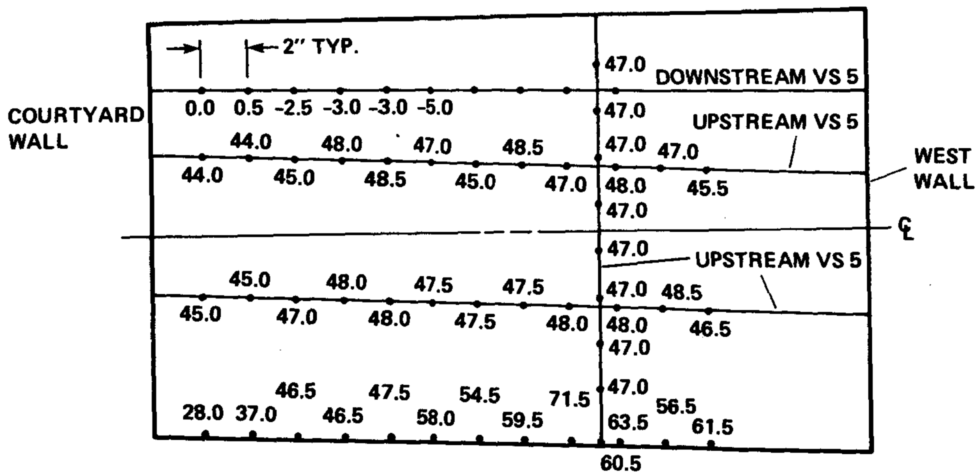


(b) Plan view of floor. Blur or appearance of multiple filaments is caused by their motion during exposure.

Figure 17.– Concluded.



(a) Leading-edge flaps set at 45°.



(b) Leading-edge flaps set at 55°.

Figure 18.- Flow angularity into and out of vane-set 5 as measured in 1;50-scale model with 1982 version of vanes. Inflow measured at 3 chord lengths upstream and outflow at 2 chord lengths downstream of vane-set 5 with thread-type tufts on wires. Numbers denote flow angularity in degrees relative to centerline of 40 X 80 circuit.

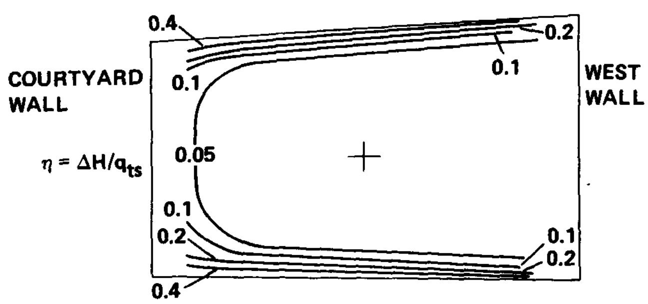


Figure 19.- Contours of constant total pressure head 2 chord lengths upstream of vane-set 5 when leading-edge flaps are set at 45°.

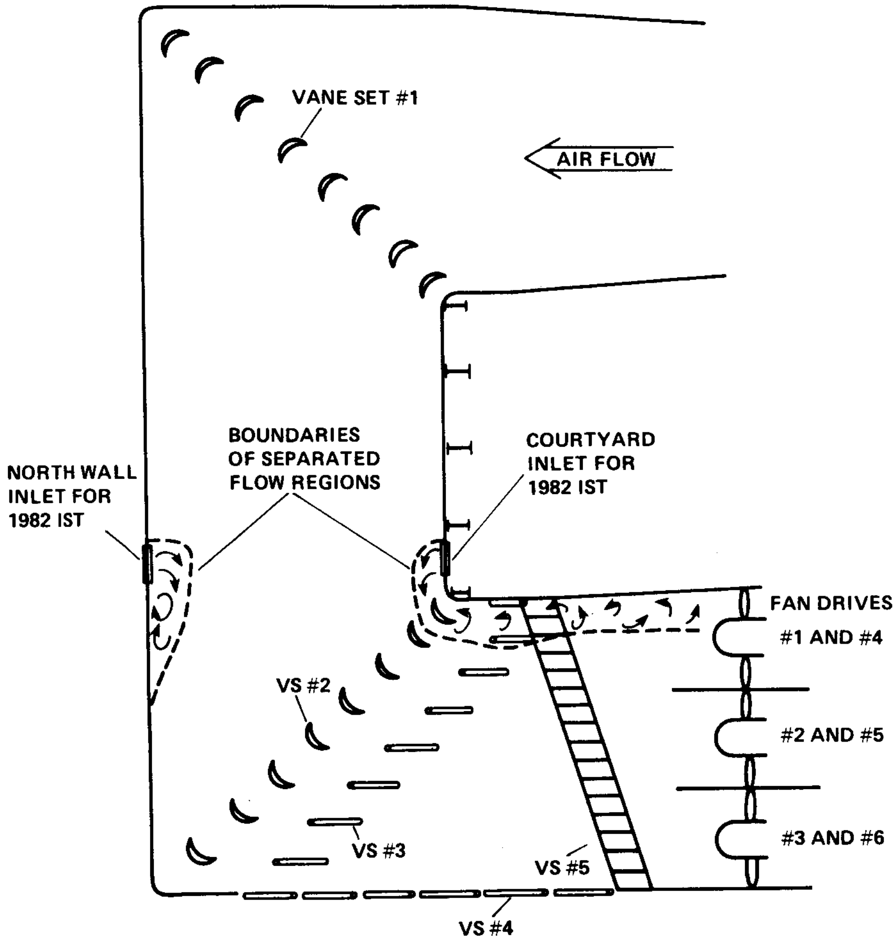


Figure 20.- Diagram of northern part of the 40 × 80 circuit illustrating separated flow regions instigated by inflow through louvered air-exchanger inlets used during 1982 Integrated Systems Test.

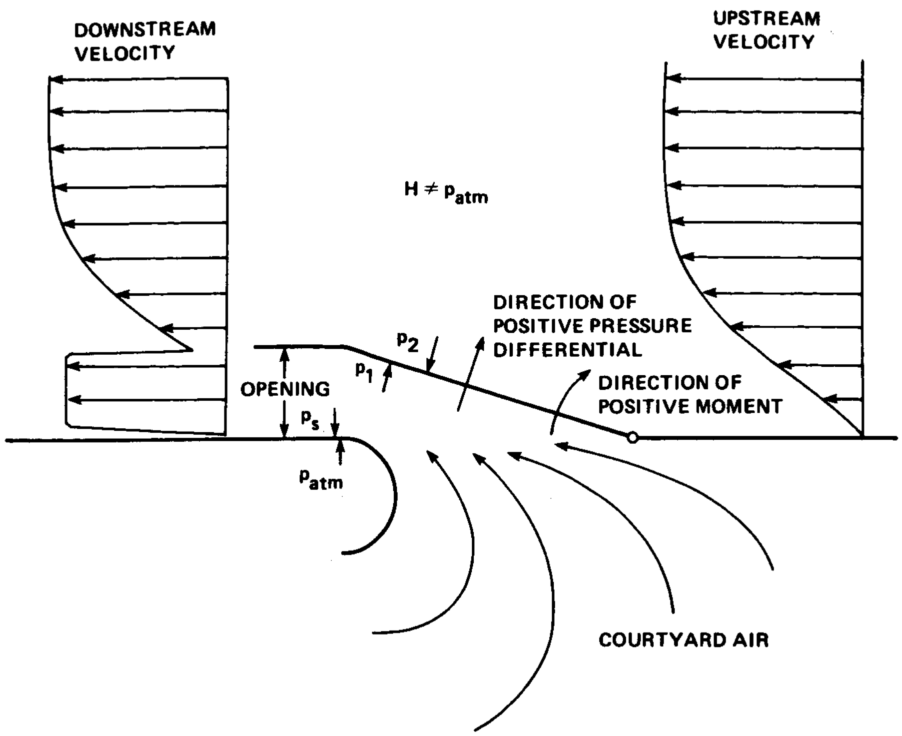


Figure 21.- Flow field in tunnel near air-exchanger inlet door.

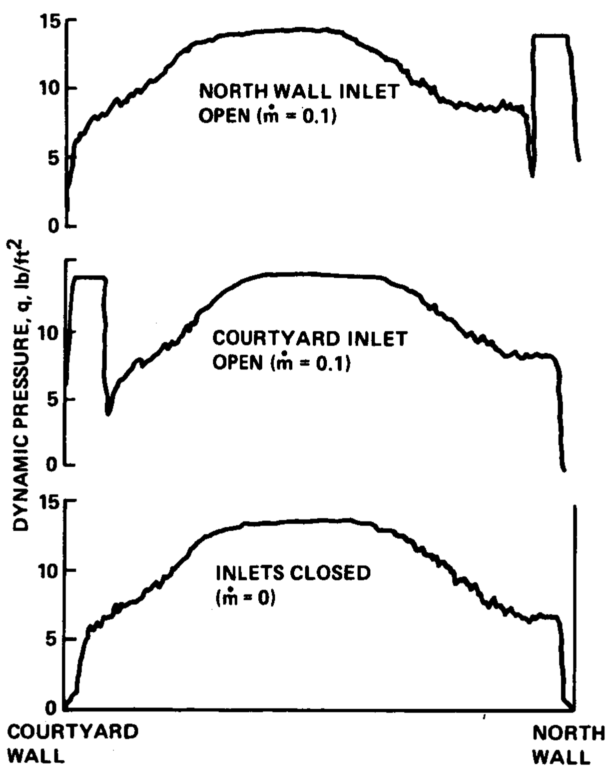


Figure 22.- Profiles of dynamic pressure across tunnel on horizontal plane through centerline of tunnel 1 in. downstream of inlets; $q_{ts} = 57$ lb/ft^2. No screens or superstructure over contoured inlets. Records are offset to clarify changes in curve shapes.

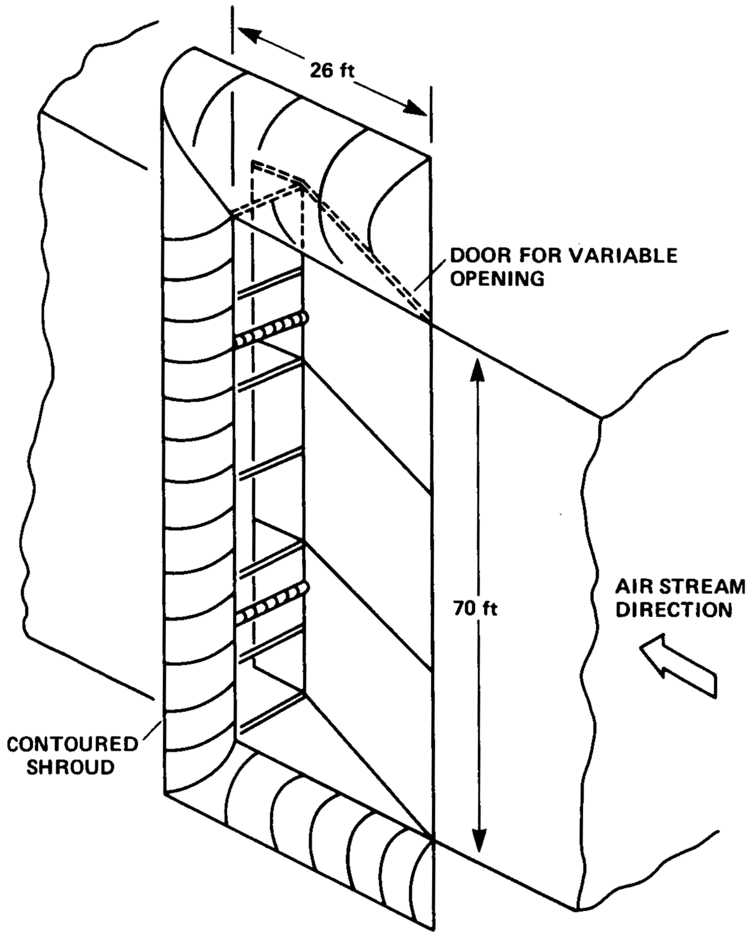


Figure 23.- Region around inlet door for cooling air exchange; debris screen and its supporting structure are not shown for clarity.

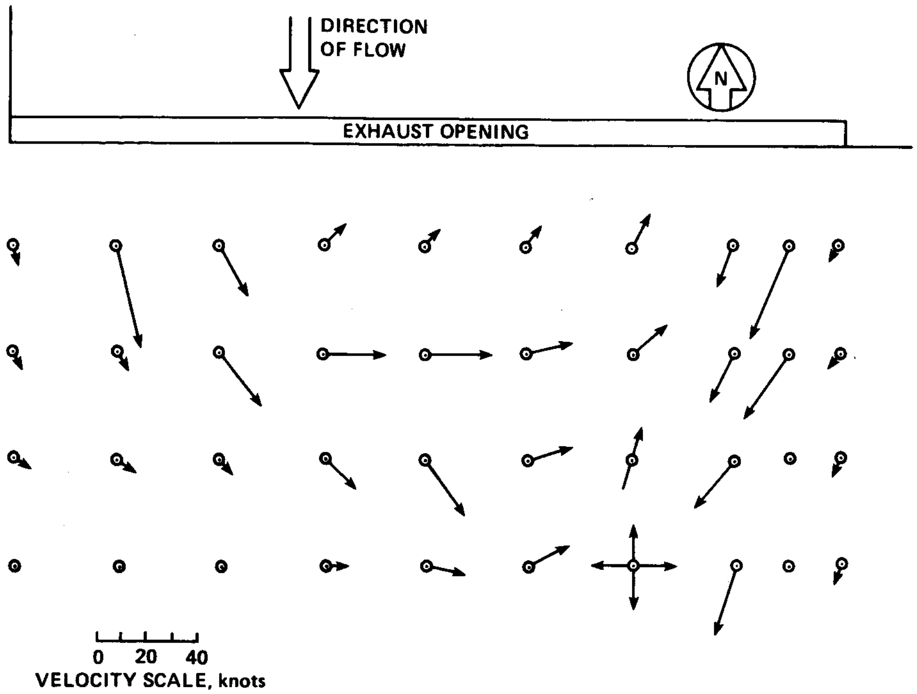


Figure 24.- Wind vectors measured with a hand-held wind anemometer on the ground under the exhaust jet during the 1982 tests of the full-scale facility. (Run 12, fan-drive blade angle = 44^o (on 12-9-82); V_{ts} = 86 knots, V_{jet} = 40 knots, P = 77.7 MW.)

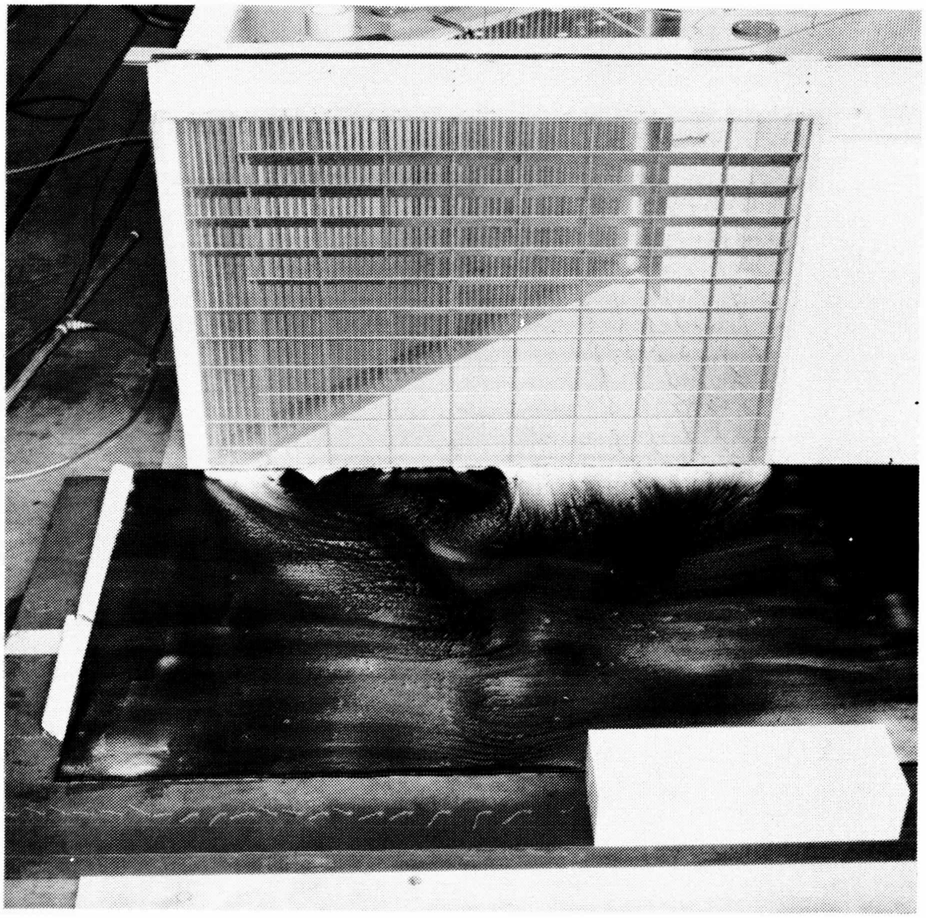
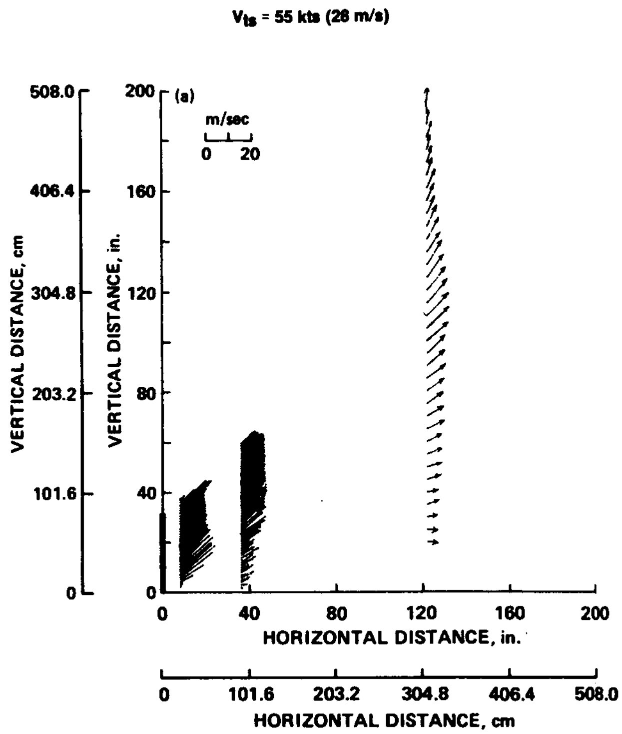
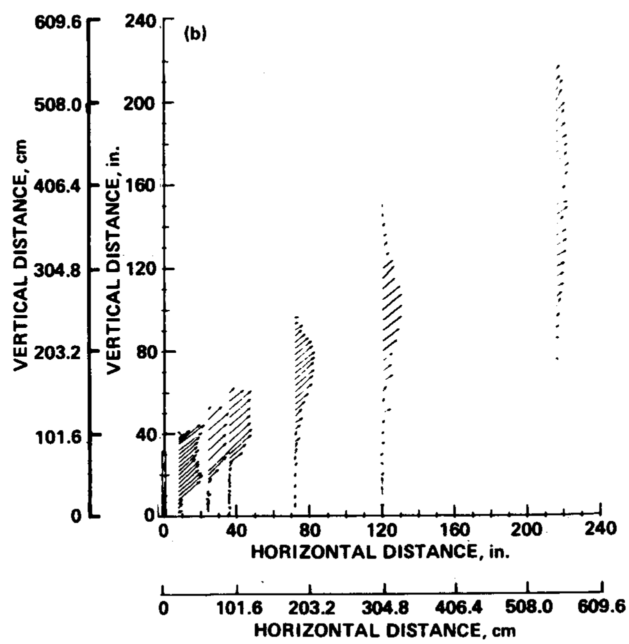


Figure 25.- Streaks scrubbed in an oil smear by winds on ground plane under exhaust jet of 1/50-scale model. Note similarity with velocity pattern measured full-scale and shown in figure 24.



(a) Without a ramp.



(b) With a ramp 6 in. long at 45° elevation and with 30% porosity created by 0.125-in. holes uniformly spaced.

Figure 26.- Vector representation of velocity in flow field downstream of exhaust opening of 80 X 120 tunnel.

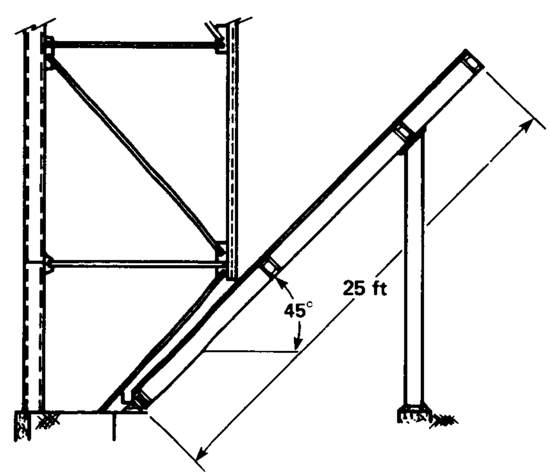


Figure 27.- Location of ramp relative to superstructure on outside of facility.

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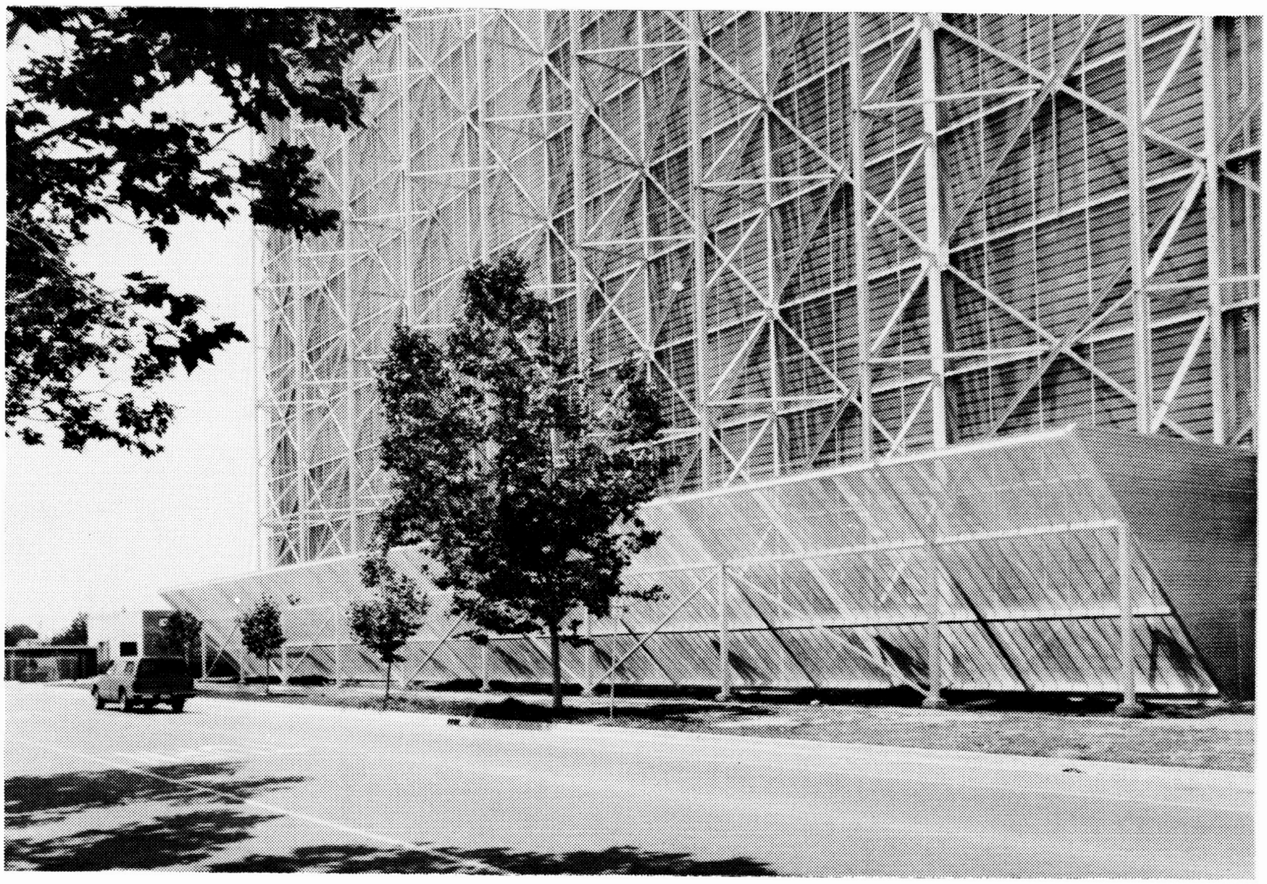

Figure 28.- Ramp area illustrating how end plates are to be made.

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16. Abstract

The features of a 1/50-scale model of the National Full-Scale Aerodynamics Complex are first described. An overview is then given of some results from the various tests conducted with the model to aid in the design of the full-scale facility. It was found that the model tunnel simulated accurately many of the operational characteristics of the full-scale circuits. Some characteristics predicted by the model were, however, noted to differ from previous full-scale results by about 10%.

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