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SUBJECT

REPORT OF A VISIT TO THE UNITED STATES TO DISCUSS HIGH-SPEED WIND TUNNEL DESIGN MARCH 3 TO MARCH 7, 1952

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ISSUED TO Internal

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SUMMARY

This note describes a visit made by the authors to the N.A.C.A. Laboratories at Cleveland, Ohio, and Langley Field, Virginia, to N.A.C.A. headquarters in Washington, and to Cornell Aeronautical Laboratories Incorporated at Buffalo, from March 3 to March 7, 1952. The purpose of the visit was to discuss high-speed wind tunnel design. Particular attention was paid to methods of obtaining transonic test velocities. Several large transonic and supersonic wind tunnels were visited, and opinions were obtained on a number of questions which have arisen or will arise in connection with the design of the proposed N.A.E. high-speed tunnel.

1.0 INTRODUCTION

A proposal to design and construct a high-speed tunnel of the continuous type has been under consideration by the National Aeronautical Establishment for some time. To date, the following specifications have been decided upon, at least tentatively:

Working section size: 6 ft. x 6 ft.
Drive power: 20,000 h.p.
Pressurization: up to 4 atmospheres,
down to vacuum.
Maximum Mach Number: 2.0.

In the past two or three years, information has been received from the N.A.C.A. concerning a new method of obtaining blockage-free transonic velocities in high-speed wind tunnels, and it has been proposed that this development be incorporated in the N.A.E. tunnel.

In order to obtain more information concerning this and other questions related to high-speed tunnel design, a visit was made by the authors to the Lewis Flight Propulsion Laboratories in Cleveland, to the Cornell Aero. Labs. in Buffalo, to N.A.C.A. headquarters in Washington and to the Langley Aeronautical Laboratories at Langley Field, Virginia.

During the visit several large high-speed wind tunnels were seen, and these are separately described below, in the order in which they were visited. Much information was gathered concerning wind tunnel design in general, and this is also recorded. It had been proposed in the past that an economical alternative to a continuous tunnel would be a blowdown tunnel of very short running time, and some discussion was held with members of the staff at Langley Field concerning the relative merits of the two schemes, since both are in existence there.

The tentative specifications as listed above for the N.A.E. tunnel were also discussed.

As a result of the visit, a number of conclusions have been drawn which have a bearing on the proposed tunnel specifications.

2.0 LEWIS FLIGHT PROPULSION LABORATORIES, CLEVELAND, OHIO

2.1 8 ft. x 6 ft. Supersonic Tunnel

This tunnel was originally proposed as a continuous tunnel with provisions for operation as a straight-through tunnel for ram-jet tests. After the money was obtained on the original estimates it became apparent that the job would exceed the appropriation and the design was modified to the present straight-through configuration. The general tunnel layout is shown in Figure 1.

The tunnel has a rectangular working section 8 feet high and 6 feet wide. Flexible walls in the nozzle section are on the 8 foot dimension. A three-component Toledo balance is available (See Figure 4) but strain-gauge balances are used for most tests.

The drive unit for the compressor consists of three 27,000 HP wound-rotor induction motors mounted on a common shaft. The speed of the drive may be varied btween 700 and 880 RPM by liquid rheostats in the motor rotor circuits. A small cooling tower is used to cool the water from the motor air and rheostat cooling system.

An air drying tower about 40 feet square on its base and 40 feet high contains beds of powdered alumina. Large paper filters are fixed at the inlet air and at the exit to remove alumina particles which could cause wear in the compressor blading.

The reactivation machinery for the drier is located in the basement of this tower.

The compressor is a 7-stage axial-flow compressor with about 960 blades (total stator plus rotor). The design compression ratio is 1.8. This compressor is about 18 feet in diameter.

Dry air is drawn into the compressor through a bell-mouth entry from a plenum chamber connected to the drying tower.

The flexible wall system in the nozzle section is an extremely sound bit of engineering. The two flexible walls are controlled independently from the tunnel control room by push-buttons. Each wall is entirely independent mechanically and electrically with positions controlled to produce working section Mach Numbers of from 1.4 to 2.0 in 0.1 M intervals.

The stainless steel walls are fixed along the downstream edge to remain parallel to the tunnel axis and permitted to rotate while restrained to move parallel to the tunnel axis at the upstream edge. An inflateable rubber seal is used to seal the flexible wall - fixed wall joints while the tunnel is running and is deflated to permit motion of the flexible wall while changing nozzle position. Each wall has 14 jacking stations each of which is controlled by a special cam and has the general details as shown in Figures 2 and 3.

The general operating sequence is as follows:

1. The operator in the control room pushes the button to deflect the nozzle. This closes the circuit which operates the motor driving the camshaft;

2. As the cam rotates it deflects the tracer element, which is a standard profile miller or planer element;

3. The deflection of the tracer regulates oil flow from hydraulic pumps to a hydraulic motor connected to the two jacks. The jacks move the wall to relieve the cam pressure on the tracer element.

The jack system at each station is arranged so that the jacks will always deflect to compensate for the rotation of the wall as it assumes a new profile and never introduce excess bending stresses in the wall plate or an overturning moment on the vertical T-bar. The whole structure is braced externally by bridge channels roughly 18 inches wide and 10 inches deep. Due to errors in the cam system resulting from mounting the camshaft bearings on the channels carrying the jack mechanism, all the cam equipment was later mounted on separate channels fitted inside the jack channels (see Figure 2) and anchored to the roof trusses.

The whole system is equipped with safety devices to prevent damage to the walls and cam system. Strain indicators mounted on the operating panel in the control room are connected to strain gauges at various points on the flexible walls to record maximum bending stresses. If the T-bar supports have an excessive deflection, the cam drive system is stopped automatically; and the system also stops if the tracer leaves the cam or exerts too high a pressure on it.

The position of the cam shaft (and hence the profile of the nozzle) is indicated in the control room by a counter which is operated by an autosyn driven by the cam motor. The nozzle system is checked each day before running the tunnel. This nozzle arrangement cost approximately $1,000,000 but was the most efficient one seen during the trip.

The operators claimed profile accuracy of ±0.005 inches for the system over the whole deflection range with excellent reliability.

The control room for the tunnel was very well designed with ample space for operators and equipment. One feature of interest was an interchangeable panel system where recording equipment could be mounted for specialized tests. These panels could be made up in the shops and installed in the tunnel. One corner of the control room was used for racks of brush recorders for use with strain gauges on the models or Statham pressure transducers. A periscope system from the working section chamber provided schlieren pictures for the operators on a screen which could be changed for a camera assembly for photography. The schlieren mirrors in the working chamber were 42 inches in diameter and mounted on a track which permitted them to be moved to either one of two longitudinal positions. The diameter of the schlieren mirrors was equal to the diameter of large steel blanking plates in the walls of the working section. Windows of a diameter slightly larger than the radius of these steel discs were mounted in the discs on the tunnel wall. By rotating these discs the whole mirror area could be exposed without providing an excessive glass area or having to move the schlieren mirrors.

A large manometer room is located below the working section of the tunnel containing many banks of tubes about 12 feet high. Photographic equipment is set up to record manometer readings and is controlled by an operator who is in communication with the control room by telephone.

This tunnel is fitted with a large acoustic damping chamber at the outlet end of the diffuser. This feature was added after completion of the tunnel as a result of public complaints on the noise level - especially during tunnel tests of ram-jet engines.

This tunnel cost approximately $10,000,000. to build and required a staff of from 40 to 50 engineers and assistants to work on the design and coordination of the project. The time from start of design to completion of the job with first tunnel run was about 4 yrs.

2.2 10 ft. x 10 ft. Unitary Plan Tunnel

A short time was spent discussing the details of a proposed 10 ft. by 10 ft. supersonic tunnel which will be built on the N.A.C.A. site at Cleveland. A considerable amount of design work has already been done on this proposal.

This design is for a very versatile supersonic tunnel with a maximum speed of Mach 3.5 in a working section 10 feet square. A general plan of the tunnel, as nearly as could be determined from the discussion, is shown in Figure 5. Two drives are planned; one of 150,000 HP and one of 100,000 HP, with one drive in a tunnel leg which may be separated from the tunnel circuit. This method of compressor selection was considered to be a better solution to the compressor problem than alternatives such as free wheeling compressor stages, blade pitch changes, one large compressor operating at low efficiency under some load conditions, and dismountable compressor section (Bedford). The tunnel may be operated with available powers of 150,000 HP (single) or 250,000 HP (series) and as either a closed circuit or a straight-through tunnel.

The tunnel will have coolers placed in an onion with a cooling tower-fin and tube radiator cooling system. Corner vanes will be of rolled ½-inch plate.

The contract for the drive system has been let to General Electric and the speed control will be liquid-rheostat as in the case of the existing 8 ft. x 6 ft. tunnel.

2.3 Slotted Walls

The people at the Cleveland Laboratories have had no experience to date with slotted wall transonic tunnels. In a brief discussion with the head aerodynamicist for the 8 ft. x 6 ft. tunnel, he mentioned that a system of slotted walls was being tested at the Ames Laboratories where the slots are fitted with an arrangement of zig-zag baffles to prevent the pressure-rise behind a shock from being transmitted to the stream immediately ahead of the shock through the slots. This method distributes the effects of the shock pressure-rise farther upstream, reduces the effect of the shock on boundary-layer growth, and results in a shock reflection which is only 1/8 to 1/4 of the strength of the incident shock.

At present slotted walls are being considered at Cleveland for some of their future tunnel designs.

3.0 CORNELL AERO. LABS. INC., BUFFALO, NEW YORK

3.1 Perforated Wall Experiments

Under a U.S.A.F. contract the Cornell Aero Labs some time ago began an investigation into a method of producing transonic flow in wind tunnels. It can evidently be shown theoretically that if part of the working section flow, just after emerging from the contraction section, is sucked away through porous walls the remainder of the flow will expand to supersonic speeds if the tunnel drive system is producing enough power, and furthermore the Mach Number distribution may reach a steady value appropriate to the suction chamber pressure after travelling only a short distance into the working section.

The Aerodynamic Research Group carried out experiments on a small tunnel (4 inches x 2½ inches) equipped with porous walls made of various materials. Suction through the walls was provided by an auxiliary compressor. In some cases suction was applied only to the upper and lower walls (2½ inches wide) and schlieren photographs were taken through the side walls with a biconvex aerofoil mounted in the tunnel. Pressure distributions were also measured on a body of revolution (the so-called NACA RM-12 body) and were compared with N.A.C.A. dropped body results.

The results of these experiments are described in two Cornell reports:

CAL No. AD-706-A-5, and CAL No. AD-706-A-6, An Experimental Investigation of the Perforated Wall Transonic Wind Tunnel, Phases I and II.

Briefly, the results were claimed to be as follows: In most cases supersonic flow was established in the tunnel working section after about two or three inches, beyond which the Mach Number remained steady. In other words nearly all the outward flow through the walls took place in the first two or three inches.

The pressure distribution measurements on the body of revolution were in reasonable agreement with N.A.C.A. results, but the scale of the graphs on which the comparison was made was very small.

Schlieren photographs were seen which were intended to show that shock waves from the nose of a body or aerofoil were not being reflected from the walls. The quality of the photographs was not good, however, and the tunnel flow was criss-crossed with waves originating at the wall perforations.

A variety of porous wall materials such as sintered metals, screens, and perforated plates were tried in the experiments, and perforated plates were finally chosen for further tests in the 8½ x 12 ft. tunnel. Screens were too difficult to handle structurally, and the sintered materials tended to clog with dust.

A preliminary investigation was carried out in the 8½ x 12 foot tunnel after a new working section had been built with perforated walls. The walls were constructed of steel plates punched with ¼-inch holes on ½-inch centres and suction was provided by a J-35 axial compressor driven electrically through an aircraft engine reduction gear turned backwards. The compressor discharge was fed back into the tunnel circuit through slots at the downstream end of the working section.

Evidently the tunnel measurements were confined to a comparison of the Mach Number distribution with and without suction. No transonic speeds were attained. In fact no speeds were obtained with suction on, which were higher than the tunnel could achieve with solid walls. This was because the suction plant was very much smaller than that which will be required eventually, and was scarcely making up for the extra losses due to the perforated walls themselves.

These experiments in the 8½ x 12 foot tunnel are described in detail in a Cornell report:

CAL No. AB-625-W-4, Preliminary Tests of a Perforated-Wall Transonic Throat in the Cornell Aero Lab Inc. 12 ft. Variable Density Wind Tunnel.

From the results of the small scale experiments and , those in the 12 ft. tunnel, an estimate was made of the power and suction requirements to produce transonic working section conditions and a modification to the large tunnel is now in progress.

The authors were not greatly impressed by the description of these experiments or by the perforated wall scheme in general. In the first place the design of the modification to the large tunnel (described in more detail below) represents an extrapolation from very meager results. The extra power requirements to drive the tunnel and to provide suction appear to be very large. Furthermore, the perforated walls, unlike the N.A.C.A. slots, provide no very obvious means of adjustment to obtain satisfactory flow conditions. Structurally it is difficult to support the thin perforated plates in the manner in which the N.A.C.A. has found it necessary to support the slotted walls. It seems probable that the decision to proceed with methods different from those of the N.A.C.A. was influenced by the fact that the work is being carried out under Air Force contract.

3.2 Proposed Modifications to 12-foot Tunnel

Extensive modifications to the 12-foot tunnel are in the process of design by the Cornell staff to permit the use of perforated walls in the working section. Since the power required by this method appears to be very large, the present A.C. tunnel drive motor (9000 HP) is to be replaced by a 28,000 horsepower motor, and the present motor is to be used to drive three suction pumps. These pumps will be grouped in a series-parallel arrangement giving a delivery of 600,000 cu. ft./min. with a pressure ratio of 3. This volume flow is about 5 percent of the working section flow. The working section of this tunnel is at present surrounded by a pressure sphere, and when the perforated walls are installed it is intended that the sphere will be used as a suction chamber.

The air which is drawn through the working section walls into the sphere is carried to the compressors through a 7-foot pipe connected to the sump at the bottom of the sphere. After passing through the compressors it is delivered to the pressure chamber which surrounds the first diffuser of the tunnel. It is proposed to let the air back into the tunnel through openings in the diffuser wall, a scheme which they admit may spoil the diffuser flow characteristics.

The new tunnel drive is to be a synchronous motor, started by the present DC motor, with the fan blades set at zero pitch. Speed control will be by blade angle adjustment only. The increased power necessitates an increase in the cooler installation and a new cooling tower. A new transformer (rated at 12000 HP and equipped with forced cooling to allow overload) is also to be installed.

It is estimated that approximately 9000 to 10,000 man-hours will be required to design the modifications, not including the details of the perforated walls, and about 12,000 man-hours will be required to supervise the installation of the equipment.

4.0 N.A.C.A. HEADQUARTERS, WASHINGTON

A short discussion was held at N.A.C.A. Headquarters with Dr. Dryden and Mr. Ira Abbott, concerning the design of high-speed wind tunnels, and in particular the transonic technique.

The security aspects of the "ventilated wall" transonic technique were brought up by Dr. Dryden who took the stand that the N.A.C.A. was not particularly anxious to give away the details of a discovery which it had taken them several years to develop.

This development is still continuing and not a great deal of progress has been made in reducing the power requirements with slotted walls. He thought that the design of a large new tunnel using the technique would have to allow provision for fairly extensive modifications to the working section.

At Moffat Field the N.A.C.A. is mainly interested in the use of slots for interference-free flow rather than the production of transonic conditions. Some work has been done using a simple one-jack nozzle for producing supersonic flow in a working section fitted with slots. Some slot configurations use a large number of longitudinal slots as an approach to a porous wall. They have not been able to get rid of shock reflections completely.

The Cornell type of approach to the porous wall was discussed and was criticized on the grounds that the tunnel velocity distribution will probably not be acceptable and the perforated walls do not provide an easy means of adjustment. In Dr. Dryden's opinion the maximum Mach Number to which a transonic tunnel can be run depends on the degree of velocity uniformity that the operator is prepared to accept and he believes that Cornell is optimistic about their scheme because they are not being realistic about what is acceptable.

The subject of blow-down tunnels was brought up and Dr. Dryden mentioned the proposed Swedish scheme of using a rock reservoir as a storage capacity. The proposal is to hollow out a large reservoir in the rock to serve as air storage space. The air in the reservoir (which has small vertical dimensions) is kept at constant pressure by connecting it to a source of water at a higher level. When the tunnel is run, the reservoir still remains at constant pressure as it fills up with water. To recharge the reservoir, dry air is pumped back and the water is, of course, forced out. To keep the air dry it is proposed to maintain an oil film on the water surface inside the reservoir. How far this scheme has got beyond the proposal stage is not known, although it is understood that the decision has been made to carry on with it.

5.0 LANGLEY FIELD, VIRGINIA

5.1 8-foot Tunnel with Slotted Walls

A visit was paid to the 8-foot tunnel at Langley Field. This tunnel was originally designed and built as a high-speed subsonic tunnel with one atmosphere stagnation pressure. The original power was 10,000 HP which was stepped up to 14,000 HP by forced cooling of the motor and by installing a modification to the Kramen control system. This modification is described in a later paragraph, 6.11. It was the first large tunnel to be equipped with a transonic working section.

Originally the working section was of circular cross-section but has been modified to a 12-sided regular polygon with longitudinal slots at the vertices. A great deal of work was carried out in this tunnel to find the optimum slot shape from the point of view of flow uniformity. This work is described in N.A.C.A. RM L51H10, and so will be described only briefly here.

The idea of using slots first grew out of considerations of model blockage at high subsonic speeds. It was shown theoretically that zero-blockage conditions should be possible with slots having a certain ratio of slot width to total tunnel perimeter, and this ratio would depend on the number of slots used. For a 12-sided working section the ratio is about one-ninth. Subsequent experiments in a small tunnel gave good results and when the tunnel power was increased, the working section Mach Number increased through the transonic regime with no evidence of choking. Accordingly the first slots fitted to the 8-foot tunnel could be operated transonically merely by increasing the power but velocity traverses down the tunnel centre-line showed a non- uniform Mach Number distribution. It was realized that this effect was probably magnified by the near-circular shape of the working section, which tends to focus any disturbances along the tunnel centre-line at supersonic speeds. It was also felt that the flow in the first few feet of the working section was overexpanding through the slots so that the Mach Number overshot the steady value and had to decrease again, thus giving rise to a cyclic variation along the tunnel. These considerations gave rise to the use of tapered slots which have zero width at the beginning of the working section. The present slots were developed more or less by trial and error and it was stated that the Mach Number distribution in the test section is constant to within ±0.005 across any cross section and also longitudinally. In order to determine the optimum slot, the slot edges were constructed first of wood so that modifications were comparatively easy, and the final shape was copied in steel.

Some attention was paid to the problem of reducing the power required. At first it appeared that the use of slots doubled the requirements, but without too much trouble improved re-entry lips were developed to take the slot flow back into the tunnel diffuser entrance, and it was stated that the pressure ratio required (and hence also the power required) is approximately 50 percent above the solid wall value for the same Mach Number. It was claimed that further power savings should still be possible but that the transonic tunnels have so many obvious problems to work on that there hasn't been time to go into the matter further. At present the maximum Mach Number in the tunnel is 1.10, and the fan pressure ratio is 1.09.

The cooling of this wind tunnel is by air exchange and humidity troubles are avoided merely by allowing the stagnation temperature to reach high values (about 170° at M = 1.1). The air exchanger lets in cold air around an annular slot in the return section, and by the time the flow reaches the working section there is still a large temperature gradient from the centre line to the walls. The flow near the walls is cool and hence wet. During a run vapour trails can be seen in the slots.

It was claimed that the slots greatly reduce the strength of reflected waves from the tunnel walls. In the range of Mach Number for which shock reflections might be expected to rebound back to the model (M = 1.04 to 1.08 approximately) some evidence of this can be found in pressure distribution measurements, but the effects have been much reduced by the slots. It was felt also that in a tunnel not having a nearly circular working section, the effects of shock reflection would be very small because of the lack of "focusing", and in fact some tests on a body mounted off-centre in the 8-foot tunnel had given excellent results.

The reasons for the effectiveness of the slots in absorbing incident waves are still not clearly understood.

It is not yet certain what will be the maximum permissible model size in transonic tunnels. In practice the 8-foot tunnel is not used for models of more than about two feet span. The reason was said to be that the N.A.C.A. wanted to be sure that the first results were good and could be used for future comparisons. It will not be long before other establishments will have smaller transonic tunnels and will try to put the largest possible models into them and so there will be a need for good conservative results. At Langley Field the transonic tunnel results have been compared with dropped body tests and with rocket firings and excellent agreement has been found. The same was true with comparisons between tunnel and flight tests on the X-1. It is not known what is the effect of the slotted walls on the standard subsonic wall interference effects, but so far no attention has been paid to this because the model sizes are such that these corrections would be very small.

The type of slotted walls built into the 8-foot tunnel make possible schlieren observations through windows approximately one foot square set into the wall panels. The final slot shape (a so-called trumpet shape) is given in RM L51H10, Figure 16. A sketch showing a cross-section through one part of the working section wall is shown in Figure 6 of the present note. It will be noted that the supporting structure has been designed for rigidity. The divergence of the wall panels has been found to be of importance in adjusting the velocity distribution and in this tunnel the divergence is 5 minutes on each panel. The fact that such small angles have a physical significance is an indication of the dimensional tolerances which must be held throughout the structure. The inside surfaces of all the wall panels are machined and great care is taken to prevent any discontinuities in the surface such as at the junction of the contraction section and working section and around windows. Provision should also be made for adjustment of the divergence angle of the walls.

The 8-foot tunnel is constructed of reinforced concrete with a steel liner. The working section is enclosed by a concrete igloo-shaped chamber which required no modification when the transonic working section was installed early in 1950. Windows in the igloo allow direct observation of the working section, but the schlieren system is normally mounted inside the igloo.

It was quite apparent that the operating staff of this tunnel consider that it is one of the best. The operating procedure is similar to that of a low-speed tunnel since the speed depends only on the fan r.p.m. The velocity distribution in the working section is actually better than most low-speed tunnels, to say nothing of supersonic tunnels. There is no blockage, negligible shock reflection, and no nozzle blocks. The tunnel is on a 24-hour operating schedule and there seems to be absolute confidence in the results. At the time of the visit the model in the tunnel appeared to be the fuselage and tail of the Douglas D-558 transonic aircraft.

5.2 New 8 ft. x 8 ft. Transonic Tunnel

During the tour of the tunnels at Langley Field, some time was spent inspecting the new 8 ft. by 8 ft. transonic tunnel which is at present well along in the construction stages with an estimated date of completion in July of this year (design started in fall of 1949). This tunnel was of special interest since it is roughly of the size, configuration, and power of our proposal. A plan of the tunnel is shown in Figure 7.

The tunnel is mounted horizontally with its centreline about 30 feet above the ground. The fan station is fixed on a reinforced concrete base and all other support points are designed to deflect along a radial line through this fixed point. As shown in dotted outline in Figure 7, the building will fit inside the tunnel circuit and house the pressure chamber around the working section.

The tunnel contraction ratio is fairly high - 19:1 - which ratio, we were informed, was determined by the cooler design arequirements. The cooler is placed in an onion section in the third leg of the circuit.

The drive unit is mounted on a separate reinforced concrete tower which contains the motor forced-cooling equipment. Provision has been made to install 25,000 HP in a single motor for the first stage and an additional 25,000 HP unit as a second stage development. Speed regulation on the drive is by the new modified Kramer system which is a combination of the Kramer and the liquid-rheostat control. The drive motor is connected to the fan shaft through a flexible coupling.

The fan for this tunnel is a single-stage wood-bladed fan designed from cascade theory for a design pressure ratio of 1.19 with an estimated working section Mach Number of 1.2+.

The fan tip diameter is 17 feet, the hub diameter is about 12 feet, and blade twist is of the order of 32 degrees. On installation the fan tip clearance was 1/16 of an inch. There was some doubt during the fan design stage that laminated wooden blades could hold a twist of 32 degrees under load but whirling tests of sample blades showed a twist change of only 1 degree. The blades are made up of sitka spruce with the laminations placed with 5 degrees between grain directions on succeeding layers. The tunnel shell is enlarged at the fan station to permit a trough of reinforced concrete to be placed in the tunnel wall and the shell thickness at this station is 2½ inches.

The tunnel was designed for pressurization to 2 atmospheres. This limit was chosen as the maximum pressure to which the tunnel could be operated and be proof-tested by pressurization alone. Under the ASA code, pressure vessels for pressures up to 37 p.s.i. may be proven pneumatically. Any design pressures in excess of this figure require hydraulic proof tests and in cases such as this tunnel, the requirement of hydraulic proof-tests would have had a considerable effect on the support design and general tunnel cost.

The thickness of the shell necessary to withstand two atmospheres was not an important factor in the choice of a minimum shell thickness of 1 inch. The general opinion of the designers at Langley Field was that a minimum shell thickness of 1 inch was necessary from considerations of noise and vibration.

The entire exposed shell was being insulated with a mastic material and an external layer of gunite as shown in Figure 9. This insulation is intended to act both as a protective coating for the tunnel, a noise and vibration damper, and as a heat seal to permit a standard tunnel operating temperature independent of ambient conditions. This latter point of temperature standardization was considered important from considerations of reliability of model strain-gauge balance systems. The maximum design stagnation temperature is to be 125°F, this figure being considered as one at which a room temperature strain-gauge balance calibration is still reliable.

At the time of our visit, the working-section for this tunnel had not been completed since this element was being delayed until the last possible moment to incorporate the latest developments in slotted wall design. The working section in this case will only have slots in the roof and floor to permit the installation of schlieren windows on the sides.

A general view of the pressure chamber is shown in Figure 8. In this design, the accent was on flexibility. A large crane was built in to this chamber to handle the working-section or working-sections which can be unbolted from the contraction cone and diffuser and dropped out of the chamber through large doors in the lower part of the shell onto a truck for removal. It is the intention of the designers to make working sections which have removable slots and variable-divergence walls.

A second lighter crane runs on the same tramways as the heavy crane to carry the schlieren apparatus. A very complicated schlieren and periscope system has been developed which will permit automatic movement of the schlieren system longitudinally, vertically, and in yaw while presenting the schlieren pictures on a screen in front of the operator. It appears that there may be some consideration being given to stereoscopic viewing of schlieren pictures although this is a conclusion of the authors. A manual control is also provided to permit motion of the schlieren system in roll if required. Industrial television had been considered but, while the quality of the pictures obtained was deemed acceptable, it was decided that it would not be used on the grounds of complication, lack of dependability, and servicing difficulties.

About 400 fixed pressure pickups are being permanently installed in the working section region. A window in the wall of the pressure chamber about 5 ft. long and 2½ ft. wide, made up of four panes of glass roughly 2 inches thick permits the working section to be observed from the control room.

A unique future of this tunnel is the turning-vanes in the first corner. All other corners have solid rolled plate vanes but this corner is fitted with hollow vanes inside an annular header chamber as shown in Figure 9. The hollow vanes have a ¼-inch slot along their trailing edge to discharge air from the header into the tunnel circuit. At present this system will be used to supply the tunnel with dry air but the design was arranged originally to provide a means to return air to the circuit that has been sucked from the slots by compressors, if the developments in slotted-wall techniques go in this direction. This is another example of design flexibility in this project.

The air drying system for this tunnel will be similar to that to be described under the discussion of the 4 ft. x 4 ft. supersonic tunnel.

5.3 <u>16-Foot Tunnel with Slotted Walls</u>

This wind tunnel, like the 8-foot tunnel, was originally designed and built for high-speed subsonic operation. Its general construction, except for size, was much like that of the No. 3 horizontal wind tunnel of the N.A.E.: the steel plate thickness is about 3/8 inch with a circular cross-section in most of the duct. External bulkhead rings stiffen the structure at intervals. When the tunnel was modified for transonic operation, a 60,000 HP drive was installed and after some operation many troubles due to vibration developed. In the working section, where much of the steel plating was 1/4 inch thick, the steel actually began to tear, and there are still visible several welded patches. The tunnel noise level was also high.

The stiffness of the whole tunnel was increased by adding built-up truss work from angle iron and concrete reinforcing rod over the entire external surface of the tunnel shell. A diagram of this is shown in Figure 10. The amount of work required to do this must have been enormous. There are so many short lengths of reinforcing rod involved that one gets the impression from a distance that the tunnel has grown hair.

The transonic working section is a copy of that in the 8-foot tunnel except that in this case provision is made for changing the wall divergence angle by means of jacks. The downstream expanding portion of the wall panels is flexible to maintain a smooth fairing when the wall angle is changed. The re-entry fairings are also similar to those on the 8-foot tunnel. The upper part of the working section can be completely removed by an overhead crane; the splitting line is along the slots at the upper edge of the vertical side panels.

During the visit, the upper part of the working section had been lifted and work was in progress on the installation of a 6000 HP propeller dynamometer for tests on a supersonic propeller. The propeller was not seen, but was understood to be of more or less conventional plan form with very thin blades. A diagram of the dynamometer set-up is shown in Figure 11. The dynamometer was supported near its upstream end by large struts projecting through the transonic slots from the outer tunnel structure. These struts were said to produce little or no effect on the operation of the slots. Also shown in Figure 11 is a feature in which this tunnel differs from the 8-foot tunnel: large circular fairings connect the slot re-entry lips with the tunnel outer shell, presumably to cut down losses in the circulatory flow outside the working section. The propeller dynamometer fairing is longer than the working section, and extends beyond it at both ends. The portion of it that is within the test section is a circular cylinder about 2 or 3 feet in diameter.

Figure 12 shows a general view of the control room for this wind tunnel. The N.A.C.A. designs its own control layouts, making most of the panels removable from in front for easy servicing. Of particular interest in this case are the provisions made for handling the results of pressure plotting. The usual manometer banks are set up at the far end of the room and can be photographed for record purposes by cameras remotely operated from the control panel. In most cases, however, there is no need to go through the tedious procedure of reading the films since other means are provided for recording and partially reducing the results. For example, a device was built by the N.A.C.A. which permits pressures of strain gauge readings to be recorded by a standard IBM Summary Card Punch. This device has, outside the case, plugboards for fastening pressure tubes or strain gauge leads and its output goes directly to the IBM card punch, which merely records the date and does no further computing. If further computing is required, the cards are simply sent to a computing centre nearby and in most cases it was said that the results can be obtained in an hour, or at any rate before the next night. (The 16-foot tunnel does most of its running at night). For ordinary wing pressure-plotting, however, the pressure measurements are reduced by still another means. In this wind tunnel such measurements have been standardized at seven spanwise stations with 40 chordwise pressure holes at fixed percentage of the chord at each station (making 280 pressure readings in all). The pressure tubes, as well as being fed to the manometer banks, are connected directly to two "pressure integrators" on the control panel. One of these integrators computes the total normal force for each spanwise station and prints the seven results when the operator pushes a button. The other integrator is similar except that it computes and prints the seven local values of pitching moment.

The tunnel is equipped with a six-component balance with Toledo scales. A half-model technique is at present under development, using a reflection plane near one side of the working section. It was stated that Reynolds Numbers equal to full scale values will be obtained on fighter models at transonic speeds.

The cooling of this wind tunnel is by an annular air exchange, and since there is no drying, the tunnel must be operated at high stagnation temperatures, as is the case for the 8-foot tunnel. Since the cold air enters the tunnel at the outside edge of the stream, trouble was encountered with velocity and temperature distribution in the working section. The transonic working section maintains a very uniform Mach Number distribution, and thus a temperature variation necessitates a velocity variation also. The situation was cured by closing off all but six of the cold air entrance flaps. The remaining six were equally spaced around the annulus and in order to provide enough cooling they had to be opened to 45°.

This wide angle caused adequate mixing of the intake air with the tunnel air and the maximum temperature variation in the working section is now about 10°F (as compared with 100°F previously).

The tunnel is driven by two 30,000 HP motors (Kramer system) driving two separate fans. The fans are counter-rotating and are located close together in the short leg of the tunnel just after the first corner downstream of the working section. The two drive shafts enter the tunnel at two opposite corners. The fan blades are constructed of Sitka spruce with fabric covering on the leading edges only. The fan hub fairing downstream of the fans is too long to be contained in the short leg of the tunnel and so it carries through the next corner with a mitred, 90° turn through the corner vanes and projects another 50 feet or more along the next leg of the tunnel circuit. Due to the wooden construction of the fan blades, a complete new set can be manufactured in three weeks if necessary.

The corner vanes are built of steel plate about ½-inch thick, with no aerofoil-shaped fairing. At the lower end they are fixed to the tunnel structure, but at the upper end they are free to slide longitudinally to allow for expansion. The vanes are stiffened laterally by horizontal steel plates spanning the duct and spaced about 10 feet apart. The vanes are spaced too closely to permit walking through and to provide access through a corner, the lower extremities of two of the vanes are hung on hinges from the lowest lateral stiffener and can be unfastened at the bottom and swung apart. Just upstream of the first set of vanes after the working section is a heavy wire mesh screen to catch broken models. Originally this screen was merely fastened to the leading edges of the vanes, but as part of the vibration troubles in the tunnel, the grid wires began to cut their way into the vanes. These grooves are still visible and in some cases are about ¼-inch deep. The screen was then moved about 3 inches ahead of the vanes and some stiffness is provided by widely spaced spring connectors joining the screen to the vanes.

The impression was gained during the visit to this tunnel, that it, like the 8-ft. tunnel, is now essentially trouble-free and is operating at maximum utilization.

5.4 4-Ft. Supersonic Tunnel

The general layout of this tunnel is fairly well known by this time, having been described in several NACA reports, so a view of the complete tunnel has not been given here. This tunnel is powered by a 60,000 HP drive utilizing a Kramer variable-frequency supply station in common with the 16 ft. tunnel. The motors drive the compressor through a step-up gear box with the ratio 2:3. To date no trouble has been experienced with this gear system. The motors have a closed-circuit forced cooling system which has independent cooling water pumps and circuit to the cooling tower.

The compressor shaft is driven through the gear box and a flexible joint, and has a large oil seal where the shaft passes through the tunnel shell. Of the whole drive system, this oil seal is the one which has given the most trouble. The sealing problem is severe due to possible eccentricity of the shaft from tunnel deflections, the pressure ratio across the seal, and the important requirement that absolutely no oil may be permitted to leak into the tunnel. A small oil leak results in an oil coating on the cooling coil fins which cuts down the cooler effectiveness.

The tunnel auxiliaries are housed in a separate building as shown in Figure 13. A total of 1200HP in centrifugal pumps are installed to handle the tunnel cooling water with a small additional unit for the motor cooling system. Three evacuating pumps with a total drive of 7,000 HP are needed to handle tunnel air. These pumps (two reciprocating and one vane type) could evacuate the tunnel to a minimum of 0.1 atmospheres and evacuate the tunnel to $\frac{1}{4}$-atmosphere in 15 minutes. It was felt that this latter evacuation requirement was a good design figure.

The air drying equipment consists of a compressor, which compresses the air to 10 atmospheres;

a small Freon cooler, which cools the compressed air to 40F; and a small alumina dehumidifying unit which dries the air further before it is passed to storage tanks. The dry air is stored at 10 atmospheres in two large tanks situated outside the auxiliary building. These tanks are standard boiler-type pressure vessels roughly 12 ft. in diameter and 40 ft. long with a capacity of 5,000 cu. ft. of dry air each. This system provides 100,000 cu. ft. of free air to supply the tunnel (of 35,000 cu. ft. capacity) so that the tunnel may be purged three times with the available storage supply. The tunnel air drying procedure is to pump the tunnel down, bleed in dry air, and repeat this process two or three times. The dew point of the tunnel air when operating is usually about -70°F.

The cooler for this tunnel is located in the third corner where the duct has changed from a circular to a square section. The cooler is mounted in such a way that each element may be removed and replaced very easily. A large access door to the cooler is provided at the corner (see Figure 14). Another feature of interest in this section of the tunnel was the extremely high density of box stiffeners required to stabilize the tunnel walls in the square duct. Many of these stiffeners were added after completion of the tunnel.

The flexible wall for this tunnel is operated on a different principle from that at Cleveland. In this case the jacks are not run automatically by a remote control system. A view of one wall is given in Figure 15. Here the rolled corrugated sheet is fastened to the wall by nuts on studs welded to the wall surface. These studs are about 3/8-inch in diameter and placed on 3-inch centres.

There are two jacks for each pair of rollers in the corrugated strip which tie in to the rollers at each end by a cross-tree pin-jointed linkage. The jacks are mounted on axes fixed to the tunnel structure so that they are restrained to rotate about an horizontal axis perpendicular to the tunnel axis. To obtain the desired nozzle profile, templates are fixed against the vertical tunnel walls and the nozzle plates are drawn up against these templated. The jacks are operated by air motors with a torque overriding drive so that once the jacks reach a predetermined tension, the jack drive stops. The jack drive motors are mounted on a carriage and moved from one set of jacks to another as the jacks are drawn up. Although this method of wall control produces an acceptable profile accuracy, it takes about a day to change from one nozzle profile to another which adds to the test time required to obtain a complete set of data for one model.

The tunnel compressor is aerodynamically similar to the unit in the 8 ft. by 6 ft. tunnel at Cleveland. It has seven stages, a total of 1100 blades, and was designed for maximum pressure ratio of 2.0. To date the maximum pressure ratio used has been 1.8. One operating point obtained was a working section Mach No. of 2 for a compressor pressure ratio of 1.7 to 1.75. The compressor was built by Allis-Chalmeers and the design people at Langley felt that this company would accept further work in this line. An interesting point on the compressor was that although the casing as machined had a thickness of 4 inches, it has been pulled out of round when bolted down.

The control room for this tunnel is positioned so that the working section is visible through a large plate glass window. The panels in the control room have been very carefully laid out for ease of analysis and observation (see Figure 16). The tunnel speed controls are very simple at this station since the majority of the electric controls are handled by an operator in the central supply building. Provision has been made for the installation of strain-gauge balance dial indicators but these are not in use at present. Model sting traverse controls are designed to provide horizontal traversing of the model parallel to the tunnel axis as well as to move it in pitch (model span vertical in working section). This was done by driving the model sting on an aerofoil support (spanning the tunnel) by two lead screws interconnected through an epicyclic gear box. The model position is recorded by counters on the two drive shafts.

A large panel on the rear wall of the control room contained a plan view of the tunnel with a block diagram of the accessories interconnected by the basic electric circuits in which all warning and control lights were placed. This arrangement permitted the operator to tell at a glance what any warning signal meant and to assess the situation quickly to decide whether or not it was necessary to shut down the tunnel.

A cam-operated controller was built in to one of the panels to regulate the rate of increase of current drawn from the electrical distribution system when starting the tunnel drive. With this device in use, it was not possible to throw a sudden overload on the electric lines during starting. A maximum magnetizing current rate of 5,000 amperes/hour is used in this area.

A General Electric electronic dew-point recorder was installed on one panel but the operators said that this device did not provide very satisfactory data and was continually requiring maintenance.

5.5 2-Foot Blowdown Tunnel

There is, at Langley Field, a blowdown tunnel with a working section 2 feet square. It was not visited, but a certain amount of information was gathered concerning it. There was also some discussion of the usefulness of blowdown tunnels in general which is worth recording.

In a discussion with Mr. Stack at Langley Field the question of blowdown versus suction versus continuous operation was brought up. In his opinion the N.A.C.A.'s experience with blowdown tunnels is such that they will probably never build another suction tunnel unless some special requirement warrants it. The advantage of the blowdown scheme is, of course, its high Reynolds Number as well as the fact that with a downstream throttle valve, the Reynolds Number can be varied at constant Mach Number. In comparison with the large continuous tunnels, however, Stack considers the blowdown type to be a "physicists' tunnel", that is, it is not particularly suited to many kinds of measurement now being carried out in the continuous transonic and supersonic tunnels in the U.S. The running time is too short even at several minutes. When the authors mentioned that a proposal had been made at the N.A.E. for a blowdown tunnel having a running time of less than 10 seconds, Stack pointed out that pressure plotting or model skin temperature measurements were out of the question in such a scheme. That pressure plotting forms an important part of engineering tests at transonic and supersonic speeds is evidenced by the complexity of the apparatus which has been developed, for example, in the 16 foot tunnel (see paragraph 5.3). Furthermore, it has been found necessary in the continuous tunnels, even when pressures or temperatures are not being measured, to let the tunnel run for a few minutes before taking any kind of measurement in order to let the model temperature stabilize, since it can sometimes have a large effect on the boundary layer.

Other troubles with blowdown tunnels have been noise and the design of suitable heat exchangers and thus the stagnation temperature varies during a run.

The stagnation pressure is kept constant by a plug-type valve (built by S. Morgan Smith), which is controlled by a servomechanism from a pressure pick-up. The servomechanism was developed for the purpose by Brown of M.I.T. Servomechanisms Lab., who adapted an anti-aircraft gun aiming servo.

The tunnel settling chamber is 5 feet in diameter and is stressed to 150 lb./sq. in. Downstream of the working section there is a second valve which acts as a throttle in the system. This enables the stagnation pressure, and hence the tunnel Reynolds Number to be varied at a given Mach Number.

This tunnel was used to investigate the use of transonic slots on the roof and floor of a square working section. The N.A.C.A. feel confident that this is enough to get rid of most of the interference even for three-dimensional models, and the new 8 ft x 8 ft. transonic tunnel (para. 5.2) is being built to make use of this fact. The obvious advantage is that the side walls can still be used for unobstructed schlieren observations.

One of the problems with the 2 foot tunnel was its noise. The tunnel now discharge into the base of a steel tower about 10 to 12 feet in diameter and 40 ft. high inside of which are hung fibreglass baffles about 8 inches apart. These must be strongly supported because of vibration. The cost of this tower was about $15,000.

6.0 MISCELLANEOUS DISCUSSIONS

During the course of the tours through the various tunnels and discussions with the operating and design personnel of the three centres visited, an assortment of design details were collected which have not been discussed under the headings of particular tunnels. These data are collected and presented in this section for future reference.

6.1 Tunnel Shell Design

The procedure used at the N.A.C.A. for specifying the shell thickness is to design around a minimum plate thickness of one inch in all cases where this thickness is greater than that required for pressurization or evacuation stability. This reasoning was developed after a lot of experience with shells of lower thickness where noise, vibration, and over-stressing of the plate resulted. In some cases, such as the 16 ft. tunnel at Langley Field, the whole shell structure had to be braced due to plate vibration. The designers consider any plates less than ½-inch thick to be "sheet metal". Basically it was considered better to design for a thick wall with a small number of stiffeners since this configuration may be stiffened further by the addition of extra rings if necessary.

6.2 Tunnel Shell Inspection and Test

It was recommended that any specification for tunnel shell construction contracts should include a clause which permits the purchaser to make random radiographic inspection of welds. This clause results in more careful welding by the contractor. This clause would not be necessary if the specification called for complete radiographic weld inspection as part of the construction job. At Cornell, the welding on the initial structure was so faulty that almost all welds had to be cut out and redone with a resulting loss of about one year in construction time.

The method of final proof testing of the shell depends upon the design pressurization limits. Under the A.S.M.E. or A.S.A. codes, vessels designed for pressures up to 37 p.s.i.a. may be pneumatically tested but those for higher design pressures must be proven hydraulically. At Cornell, the tunnel could not be tested hydraulically although designed for a pressure of 4 atmospheres so it was necessary to test the tunnel pneumatically with the entire tunnel shell strain-gauged. In this case, the strain indications at one point restricted the tunnel to a maximum pressure of 2 atmospheres.

While not actually relevant under this section, a point of caution should be made here on the shop design of the tunnel shell details. The Co-op tunnel in California can be operated at 4 atmospheres while the tunnel at Cornell, which is basically identical, is restricted to 2 atmospheres due to critical stresses in the neck of the working section sphere. The difference between the two tunnels in this componet is the difference in detailed reinforcing resulting from the different shop practice of the two contractors.

6.3 Tunnel Shell Costs

For the basic tunnel shell, the estimated cost for steel was 50¢/lb. The pressure chamber around the working section should cost about the same as the shell.

The contraction section steel cost was estimated to be about 75¢/lb. due to the extra rolling and handling costs.

A complete slotted-wall working section for a tunnel of our specifications should cost roughly $300,000. when completed. For a breakdown of this total, it was estimated that the steel would cost $1.00 plus/lb. due to the machining required and the built-in flexibility requiring extra care in detail design and construction.

6.4 Guide Vanes at Corners

Except for cases as mentioned in the new 8 ft. by 8 ft. tunnel, the N.A.C.A. are using solid rolled plate turning vanes. It was considered that ½-inch plate was sufficiently strong to span a duct diameter of 24 feet without overdeflection or vibration under load. On larger diameters, horizontal bracing plates are used to stiffen the vanes. Vane spacings are usually about ½ the vane chord and no arithmetic or geometric progression of gap/chord ratio are being used. The vanes are rolled for a 90 degree deflection with small upstream and downstream tangential flat surfaces rounded at the leading edge (radius equal to ½ thickness) and tapered at the trailing edge with zero incidence to the flow. The lower ends of the vanes are fixed to the duct and the upper ends are permitted freedom to move vertically by using some form of tab and slot mounting. If screens are to be mounted in the corners they should be fixed clear of the vanes since the vibration of the screen will result in the wire cutting into the vanes if they are in contact.

6.5 Coolers

The fin-and-tube type of cooler segment is in standard use in the N.A.C.A. tunnels. However, there are considerable differences of opinion on the mounting arrangements for the coolers in the duct. At Cleveland, coolers were put in onions and the installation of coolers against turning vanes was not considered to be acceptable due to vibration resulting in leakage and the additional complexity in vane design. At the Cornell Laboratories, the coolers are mounted against the turning vanes (see Figure 18) and have presented no problem during the operating time of this tunnel. When questioned on this point at Cornell we were told that while their system had given no trouble, the Co-op tunnel in California, which is identical to theirs, has produced a lot of trouble through cooler leakage.

At Langley Field the designers had no objections to corner cooler mounting systems and have such units in some of their existing tunnels. The fact that they have experienced no trouble with this arrangement probably follows from their design philosophy of making all possible trouble spots very heavy and rigid. On future designs where large powers must be absorbed in cooling, they are going to onion coolers or are considering a conical cooler mounting system as shown in Figure 17. This latter system provides a large cooler surface area inside a small tunnel diameter. Where necessary this configuration could be incorporated in an onion if still larger areas were required.

Maximum coil approach velocities are of the order of 2000 ft./min. for commercial cooler elements of the fin and tube type. This value alone sometimes determines the tunnel contraction ratio or the required onion diameter.

The cooler elements should be easily accessible and easily removable for replacement or repair.

Coolers should be designed to maintain a tunnel stagnation temperature of 125°F.

One problem tied up with that of the coolers is that of oil seals in the tunnel circuit since any oil vapour which leaks into the tunnel air is deposited on the cooler surfaces and has a serious effect on the cooler efficiency. This possibility of oil deposition on the cooler tubes is one reason why cooler elements should be readily removable for inspection and cleaning. Current internal-bearing lubrication systems are all of the vacuum type to prevent oil leakage,

6.6 Cooling Towers

The chief point emphasized on the selection of cooling towers was that the tower should not be designed for too close an approach to wet bulk conditions. An approach temperature of 15°F from the wet-bulb temperature is considered to be a reasonable minimum design value.

At Cleveland some mention was made of a new cooling water system being developed in the southern U.S.A. where cooling water is passed through spiral-finned tubes while outside water is sprayed over the tube fins. This system promised to provide excellent evaporative cooling with a make-up water requirement of less than 1 percent.

6.7 Cooler Cost

A rough non-installed cost for a cooler bank was quoted as $15/sq. ft. of cooler area.

At Cornell, the replacement cost for their 3-bank coolers (about 80 units 2½ ft. by 5 ft.) was estimated to be $75,000 installed with an additional $12,000 required for the addition of the small vane deflectors.

One supplier noted at Langley Field was Griscom Russell.

6.8 Tunnel Air Temperature Control

While visiting the 4 ft. by 4 ft. supersonic tunnel at Langley Field, a problem on tunnel temperature control was discussed by one of the operators. In their original system, a tunnel air temperature pickup downstream of the cooler in the third corner operated a cooling water mixing valve through a Minneapolis-Honeywell controller. This mixing valve was used to bypass warm water from the cooling coils into the stream of cold water from the cooling tower to regulate the water temperature entering the cooling coils. This system of control resulted in an oscillating tunnel temperature of about ±10°F. The reason for this hunting was the delay time between the signal fixing the position of the mixing-valve and the arrival of the water at the cooler coils whose temperature was determined by the signal. In the next cycle, the water mixture would be overcompensated in the other direction.

The cure for this trouble was to install a water temperature pickup in the cooling water line upstream of the coils to operate the mixing valve. This modification cut down the tunnel air temperature variation to ±1°F which value is considered acceptable for their operations. The present control system is for the original tunnel air temperature pickup to operate the cooling water temperature pickup which then controls the mixing valve.

6.9 Supersonic Nozzle Design

Two types of variable supersonic nozzles have been discussed under the headings of the 8 ft. by 6 ft. tunnel at Cleveland and the 4 ft. by 4 ft. tunnel at Langley Field. It was felt by the design staff at Langley Field that nozzles of the cam-controlled multiple jack system or the jack and template system are the only acceptable symmetric nozzles in operation at present. They did not feel that nozzles of the single jack type with walls of varying stiffness to approximate a theoretical profile by a beam deflection curve gave sufficient profile accuracy and repeatability. Of the two forementioned types, the Cleveland system was more acceptable from the point of view of operational efficiency. A typical operating time schedule for the Langley 4 ft. tunnel is shown in Figure 20. Here it can be seen that any system which permits a change of speed during a run would increase the tunnel productivity to a large extent without an equal percentage increase in total tunnel operating time.

An alternate nozzle system has been used at Ames for high Mach No. tunnels combining the solid nozzle block and flexible wall methods. This alternative resulted from the requirement to reduce the high plate bending stresses which would occur in flexible plates at the throat of a high Mach nozzle where the profile curvature is high. A general view of this system is shown in Figure 19. Here the flexible wall would be controlled by jacks and templates since the nozzle could not be changed during a run.

On the subject of asymmetric nozzles, the design staff at Langley feel that they are a good solution for the variable nozzle problem when developed. In fact, they are designing a tunnel using this system at present. The disadvantages of the asymmetric nozzles are that there is at present a higher power loss resulting from diffuser difficulties through differences in boundary layer thicknesses on the walls and that it is difficult to maintain a uniform Mach Number over the whole Mach Number range. The advantages of the system are that, once the nozzle is working, it is possible to have quick changes of Mach Number during the run and good repeatability.

From the design point of view, the asymmetric nozzle is no easier to develop than the flexible wall due to the terrific axial loads to be overcome. The loads may be of the order of 500,000 pounds axially. There is no real cost difference between the two nozzle types - both cost roughly $1,000,000.

6.10 Tunnel Compressors

The general opinion was that there were several companies in the U.S. capable of building tunnel compressors to any specifications. The compressors for the 8 ft. by 6 ft. and the 4 ft. tunnels were fitted with adjustable stator blades but it had not been found necessary to modify the installed positions of these blades in either case. Both compressors were meeting their design pressure ratios and mass flows. The 4 ft. tunnel compressor at Langley Field delivered a mass flow 5 percent in excess of the design value.

The fan blades for the Cornell tunnel were of forged steel made by Hamilton Standard.

Aluminum blades should not be used in compressors of high pressure ratio since the temperatures of the blading in the final stages may be sufficiently high to promote blade creep. This same point applies for compressors operating in a tunnel with a high stagnation temperature.

As has been mentioned previously, the new 8 ft. tunnel at Langley Field has been designed using a one stage wooden-bladed fan of high pressure ratio. This type of unit necessitated a redesign of the blade mounting discs to prevent the highly-loaded blades from tilting on the mounts. A mounting disc assembly, as shown in Figure 21, was developed to prevent blade tilt under load.

6.11 Electric Drive Systems

The drive requirements for a transonic wind tunnel are more severe than those for sub or supersonic tunnels. For transonic operation the drive speed regulation should be ¼ of a percent to keep the drive control consistent with the possible uniformity of tunnel velocity distribution. At Langley Field, all transonic tunnels are being operated with a Kramer or a "modified" Kramer drive (this last developed by the N.A.C.A.).

The liquid rheostat control used on some of the tunnels visited is generally only good for a speed control over the top 10 percent of the speed range with a regulation of roughly ½ percent. This method alone is satisfactory for most supersonic operations. At Cornell, the liquid rheostat control used for the A.C. motor of their mixed drive has been shorted out to force the A.C.

motor to run at constant speed. This was done due to very poor speed regulation by this unit (of the order of 20 percent) when the electrode spacing was small, i.e. near the maximum speed position. Tunnel speed is now controlled in this tunnel by fan blade pitch changes.

The specifications to an electrical contractor for the tunnel drive system should include:

1. Power-speed spectrum
2. Speed regulation required
3. Allowable magnetizing inrush current
4. Acceptable power factor
5. Cooling water temperatures for forced cooling system
6. Complete push-button control
7. Shut-down requirements as specified by the Hydro-Electric Commission
8. Starting time
9. Miscellaneous detail specifications that will not be supplied unless requested such as:

    a. Stator-shift mounting for inspection and repair;

    b. Hand clearance holes in bearing pedestals for cleaning bearings;

    c. Electrical heaters to maintain constant temperatures in detached motor buildings during winter months;

    d. Pedestal and pipe insulation;

    e. Bored shafts to allow access for rotor copper thermocouples;

    f. Air gap sighting holes;

    g. Closed forced air cooling system for the motors;

10. Oil lift pumps to raise motor shaft off bearings for motor stator or fan blade inspection, power off.

11. Turning motors to rotate shaft during inspection.

12. Vacuum oil system with heaters in the sump and pumps immersed completely in the oil to prevent foaming.

Some of the points mentioned above may appear to be of minor importance but they all relate to the convenience of operation of the unit and are, in most cases, items which may be easily installed during construction but are difficult to incorporate as modifications.

The items on the electrical specifications which are of immediate concern to the Hydro-Electric Commission, other than the main problem of supplying the required electrical power, are the allowable magnetizing inrush current during starting, the operating power factor of the complete drive system, and the shut-down requirements. This last point is of interest to the power company since for part of the shutdown cycle, braking is supplied by regeneration which throws a large power pulse into the distribution system.

The polar moment of inertia of the complete fan system should be supplied to the electrical contractors since this item is of importance in conjunction with the specified starting time in determining the required motor characteristics. The capacity of braking devices other than regenerative also depends upon the system inertia.

The Kramer drive system is a fairly complicated and expensive unit for the initial installation but has the advantage of flexibility in adding future load sources off the same central station. Two-thirds of a Kramer drive may be installed in a central building with the final third in the tunnel drive housing. In this way, up to three tunnels may be run on the Kramer system on a planned operating schedule utilizing the common central component. Installing a drive system of this type would cost about $75./installed HP for the first unit but additional tunnel drives of the same power could be installed for only $20-$25/installed HP. This feature of such a unit may be important in the final choice of drives.

At Langley Field, the electrical engineering department have developed a modified Kramer system in which liquid rheostats are used to control speed variation of the set and the D.C. drive has only to regulate changes due to voltage fluctuations. Using this method a fairly large reduction in D.C. capacity can be effected over the original Kramer drive while retaining a ¼-percent speed regulation and increasing the speed of the set from 92 to 95 percent of synchronism. If this modification is made to an existing Kramer drive with its large D.C. capacity, the added available power from the D.C. set can increase the output of the drive by 10 to 20 percent. On a new set of the modified type a smaller D.C. set can be installed with a saving in installation costs.

The engineers felt that electrical drive equipment should be purchased, if possible, from American companies, in particular, from General Electric or Westinghouse. They have no preferences between these two companies and have units built by both in operation at present. The reasons for this statement on procurement were firstly that these companies now have a considerable amount of experience with large motors and secondly that it is possible to get major repairs completed very rapidly if the contractors are near at hand. In one case a 20,000 HP unit was completely rewound and operating in three weeks from time of failure. The point of experience is important because a large number of problems arose during the operation of the first large drive motors that were not foreseen from experience with smaller units. For example, the large masses of rotor copper and steel gave many overheating troubles and the opposing effects on the rotor windings of heat and centrifugal force caused the coils to work during starting and ratchet the slot liners out of place resulting in the liners fouling the stator coils.

Although several companies make units similar to the General Electric amplidynes for the control circuit, the G.E. units are by far the most accurate and reliable so the General Electric Company are the only accepted suppliers for such equipment.

6.12 <u>Drive Safety Devices</u>

At Langley Field, automatic shutdown equipment operated by thermal pick-ups is not used. Their system is to connect the temperature pick-ups (from bearings, stator coils, etc.) to an annunciator panel in the tunnel control room. If some component overheats, a warning light is lit and a number is tripped on the annunciation panel. At the same time a timing relay is started which will start the automatic tunnel drive shut-down sequence after five minutes from the time of warning. The operator has electric thermocouples available to check the danger point from the control room to determine the danger involved in completing the model tests. By checking various temperature circuits, the operator can assess the situation and decide his course of action. At any time the automatic shutdown timer may be nullified or recycled by the operator. The time delay is used to provide time for the operator to check the situation and to get the model in the tunnel into a safe configuration if a shutdown is required.

6.13 Design Personnel Requirements and Tunnel Construction Time

At the three research centres visited, the authors attempted to collect some information on the length of time required from the start of design to the completion of the tunnel construction and the number of men involved in the design and supervision program for the job. These estimates may be summarized as follows:

Project	Time to Completion	Man-Years	Cost
8 ft. x 6 ft. tunnel at Cleveland	3½ yrs.	158	$10,000,000.
Modifications to tunnel at Cornell	2 yrs.	12.2	$1,000,000.
Propulsion Laboratory at Cleveland (attempted minimum internal effort)	5 yrs.	114	$13,000,000.

At Langley Field the only estimate of value was the time of 3 years required to complete the new 8 ft. by 8 ft. tunnel.

An analysis of these figures shows that a working figure for the man time required for any tunnel job with a "minimum internal effort" would be about 8 man-years per million dollars of total tunnel cost. Of this figure, design time would account for 3 man-years per million dollars and supervision would account for the remainder.

6.14 Pressure Ratio Required

Three sets of data were obtained concerning the pressure ratio required to operate large tunnels at Langley Field. The eight-foot transonic tunnel has a maximum Mach Number of 1.10 with transonic slots and its fan pressure ratio at this speed is 1.09. Without slots and with a supersonic liner the same tunnel formerly operated at this Mach Number with a pressure ratio of 1.06. The new 8 ft. x 8 ft. transonic tunnel (still under construction) had a design pressure ratio of 1.19 and a design maximum Mach Number of 1.25. The 4 ft. supersonic tunnel achieves a Mach Number of 2.0 at a pressure ratio of 1.70 to 1.75. These data are summarized in graphical form in Fig. 22, where they are compared with estimates which had been made previously for a proposed 8 ft. x 8 ft. tunnel for the N.A.E. Qualitatively there is agreement between the N.A.C.A. data and the N.A.E. estimates, although in the low supersonic region it appears that the estimates are somewhat conservative. In fact the N.A.C.A. data for slotted walls is close to that estimated for solid walls in the transonic range.

7.0 DISCUSSIONS ON N.A.E. TUNNEL PROPOSAL

7.1 Size and Power

The N.A.E. proposal, as outlined in the Introduction to this note, was discussed with members of the staff of the N.A.C.A. at Cleveland and Langley Field. It will be noted that it corresponds closely to some of the large continuous tunnels which have been in operation for a number of years in the U.S., and in particular to the 8-ft. tunnel at Langley Field, which was the first large one to be fitted with slotted walls.

It seemed to be a unanimous opinion that the tentative choice of a 6 ft. x 6 ft. tunnel with about 20,000 horsepower in the drive was a good one and would lead to a most useful wind tunnel for general model work. The Reynolds Number is reasonably high and the tunnel dimensions are convenient from the point of view of model construction and the use of slotted walls. The slotted-wall technique permits the design of a tunnel which operates essentially like a subsonic tunnel (i.e. with no nozzle blocks or adjustable walls) up to a Mach Number of about 1.25 without blockage corrections.

That the slotted -wall technique is believed to have great future possibilities is further borne out by the decision to build, at Langley Field, the 8 ft. x 8 ft. tunnel specially for transonic operation.

No doubt the tendency of these members of the N.A.C.A. staff to favour continuous wind tunnels of this type is influenced to some extent by the fact that this is the field in which they have had most experience, as compared with other possible methods of high-speed model testing. It is suggested, however, that because this experience is by now very extensive, their opinions carry a great deal of weight.

7.2 Mach Number Range

A maximum Mach Number of 2.0 has been proposed as the upper limit for the speed range of the N.A.E. tunnel. The tunnel is to be capable, however, of operating at all speeds down to the incompressible range, which, for high lift coefficients, implies a Mach Number of 0.2 or less. Previous calculations had shown that such a requirement adds considerable difficulties to the fan design problem. Another complication is, of course, that a supersonic nozzle portion must be designed for the tunnel.

Discussions at Cleveland and Langley Field on this subject in every case drew the opinion that the specified Mach Number range was too much for a single wind tunnel unless a complicated layout were adopted. As far as the compressor problem is concerned, there are a few possible alternatives if it is definitely decided to design a tunnel for subsonic, transonic, and supersonic operation:

a) To forget the problem, and let the compressor operate at efficiencies that may be as low as 40 percent at subsonic speeds.

b) To provide adjustable compressor blading. Probably an adjustment of stator blades only would not give a great improvement in compressor flexibility over the entire speed range.

c) To provide a declutching arrangement which would allow some compressor stages to be free-wheeled or feathered for low Mach Number operation (Cornell tunnel).

d) To use two compressors in the circuit, one of which can be by-passed at low Mach Number operation (Cleveland 10 x 10 scheme).

e) To provide for removing some compressor stages from the tunnel circuit mechanically (Bedford scheme).

f) To provide two working section legs, each with a different area, one for supersonic operation and one for subsonic and transonic speeds (Ames proposal).

The above list may not be complete but it serves to show the character of the problem. In the discussions it was pointed out that only one wind tunnel in the U.S. (one at Ames) actually operates under alternative (a), but that it is essentially a supersonic tunnel. The low efficiency in the subsonic range, of course, results in a Reynolds Number which is also lower.

The authors were asked by Dr. Silverstein, the Director of Research at Cleveland, approximately how much it was hoped the N.A.E. tunnel would cost. When told that a very rough estimate had given a value of $2,000,000 plus, he said that in his opinion an adjustable nozzle section alone might cost that much. (A later and probably more reliable figure for adjustable nozzles was obtained from the tunnel design staff at Langley Field: approximately $1,000,000, regardless of type.

Mr. Stack at Langley field, and Mr. Gregory, the chief of their tunnel design staff, advised strongly against designing the tunnel for supersonic operation, if it were also to be used in the subsonic and transonic range. They pointed out that the fan configuration for a subsonic-plus-transonic tunnel is much simpler (e.g. in the new 8 ft. x 8 ft. tunnel) and that in any case if a flexible type of drive system, such as the Kramer, is used, it is comparatively inexpensive to buy a second drive motor for a second tunnel at a later date. Two-thirds of the cost of a Kramer system is in the variable-frequency supply system, which can be used to supply more than one installation. An excellent example of this type of design is the 4 ft. supersonic tunnel and the 16 ft. transonic tunnel at Langley, both of which have a 60,000 HP Kramer drive, using the same supply. There is said to be no difficulty about scheduling running times so as to avoid time wastes; in fact, a vacant lot near these tunnels is being kept open in case there should be a need for still another tunnel with a 60,000 horsepower requirement.

On the matter of supersonic nozzles, which will be necessary if the tunnel is to operate above a Mach Number of, say, 1.25, it is the opinion of the design staff at Langley that adjustable nozzles are practically a necessity because of the large size of solid nozzle blocks which would be very awkward to move about. Therefore there seems to be little hope of obtaining a nozzle section at a cost of less than $1,000,000. They had run out a design and cost estimate for an Ames'type of asymmetric, solid, sliding nozzle block but had found, surprisingly, that it would still cost as much because of the rigidity that would have to be built into it to withstand the tremendous pressure loads. There seems to be, therefore, an extra item of $1,000,000. to add into the cost estimate for supersonic operation, neglecting entirely the extra cost of the compressor, supersonic working section and so on.

The authors wish to make it clear that they are in almost complete agreement with the views given above. It is felt that stiff resistance should be put up against the suggestion that the proposed tunnel be designed for a continuous Mach Number range from zero to 2.0. This opinion is enlarged upon in the concluding paragraphs.

7.3 <u>Type of Drive</u>

For the N.A.E. tunnel it has been proposed that the drive be a mixed electric-gas turbine type in which a synchronous motor drives a compressor with an atmospheric air intake; the compressed air is then passed through combustion chambers to a turbine which drives the fan or compressor shaft. The turbine output power would be of the order of 1.5 times the synchronous motor power and thus the advantages from the electrical point of view are obvious. Speed regulation is obtained by throttling, blow-off, and fuel input.

This proposal was discussed with Dr. Silverstein at Cleveland and with Messrs. Stack and Gregory at Langley. Dr. Silverstein thought that the method had merits but objected to it on the grounds that from our point of view the tunnel itself will be an experiment in some respects, and that the addition of any extra equipment which will require some development should be avoided. Mr. Stack's opinion was essentially the same, although more violently expressed; it can be summed up in his own words: "Don't buy it!" He pointed out that no 20,000 horsepower gas turbine suited to the job is in existence. There may be large constant speed industrial gas turbines but there is more to the problem than simply bolting one to a tunnel drive shaft. He said that it was surprising how many small difficulties kept cropping up in electric drives in this power range, in spite of the fact that by now the electrical companies consider their construction straightforward. No large wind tunnel should be designed unless it is to run continually for at least twenty years with only minor maintenance troubles, and he doubted that any gas turbine could meet these requirements. The speed regulation required for a continuous tunnel is about one-quarter of one percent on r.p.m., (this seems to be made necessary partly by the fine control of velocity distributions which it has been found possible to achieve in the transonic tunnels), and this kind of accuracy would present still another development problem in the gas turbine throttling system.

Again, the authors find themselves in agreement with these opinions. It may be argued that the N.A.C.A. is accustomed to spending money, and can afford to buy expensive electric drives to avoid development problems. It is felt that in the first place this argument is probably fallacious, and in the second place it would be difficult to think of a better reason for going to some extra expense. Furthermore it is considered to be far from obvious that the cost of the proposed gas turbine system would in fact be much less than an all-electric drive, although this is the only valid advantage that might be claimed for it.

8.0 CONCLUSIONS

It is not the purpose of this note to discuss the merits of the tentative specifications for the proposed N.A.E. high speed tunnel, but some conclusions have been reached as a result of the visit described here which have a direct bearing on the N.A.E. proposal.

These conclusions may be summarized as follows:

1. The development of the slotted-wall technique for transonic wind tunnel testing has reached a stage in the U.S. such that there is no doubt that the design of an extremely useful tunnel of this type can be proceeded with in Canada. The fact that such wind tunnels are basically similar to subsonic types makes them attractive from the design point of view: no nozzle blocks are required, speed variation is by control of fan r.p.m., the pressure ratio required is such that multistage compressors are not needed, and in most cases fans with wooden blades can be used. Indeed it appears that the N.A.C.A. transonic technique is the most significant discovery in the field of wind tunnel testing since the development of the supersonic tunnel.

2. Discussions with N.A.C.A. personnel confirmed suspicions that there is no easy way out of the difficulty of designing a compressor which will drive a wind tunnel with reasonable efficiency over a speed range including the subsonic, transonic and supersonic regions. This problem is so troublesome, in fact, that it is strongly recommended that the requirement for a maximum Mach Number of 2.0 be dropped from the specification. The alternative is either an expensive design which would require longer to put into operation, or a compressor efficiency of probably less than 50 percent at subsonic and transonic speeds and consequently a model Reynolds Number about half of that available in an efficient design.

3. It is further recommended that the proposal to use a mixed gas turbine drive should be abondoned unless further investigations can prove beyond any reasonable doubt that such a system is cheaper to install and operate and that development and maintenance problems will be of a minor nature. It is felt that such proof is lacking and is probably not possible to demonstrate. The main reason for recommending such caution is simply that there exist types of electric drives which certainly can meet all the requirements

and the proposal to use an untried system therefore violates the principle that in an engineering undertaking which will in any case tax the resources of an organization there should be as few experimental components as possible.

4. In view of the above conclusions and recommendations it is suggested that the proposed tunnel should take the form of a subsonic and transonic tunnel only, with an electric drive, probably of the Kramer type, since this would allow a second drive of the same power to be installed relatively cheaply for a second later tunnel. It is further suggested that for the proposed tunnel no consideration should be given to its design and construction in two separate stages. It should be built with no provision for extension into the supersonic range. If a stage II development is desired later, it is suggested that it should be a separate tunnel.

5. The length of time which will elapse between the serious beginning of the design and the first run is likely to be about three to four years. This figure is based on N.A.C.A. experience with large continuous wind tunnels.

6. It appears that cost estimates already made for the N.A.E. proposal may be somewhat low, particularly the steel shell cost, and certain other items where a large amount of machining is required, such as the working section. If the requirement for supersonic operation (up to M = 2.0) is retained, the cost will increase still further by possibly $2,000,000.

7. An estimate of the amount of design effort which will be required for the N.A.E. tunnel can be made from data gathered during the visit. Even if as much as possible of the detail design is to be carried out by contracting firms, the number of design man-hours which will be required by N.A.E. personnel is likely to be large; in fact, it is more conveniently expressed as man-years. From the American data, it appears that a useful rule-of-thumb figure is 3 man-years of design time per million dollars of total cost and 5 man-years of construction supervision per million dollars, both figures applying to the type of "minimum-effort" scheme we are considering. Thus for a $3,000,000 wind tunnel, about 9 man-years of design time and about 15 man-years of supervision of construction will be required. This implies a design staff of between 4 and 9 personnel if

the design is to be completed in from one to two years.

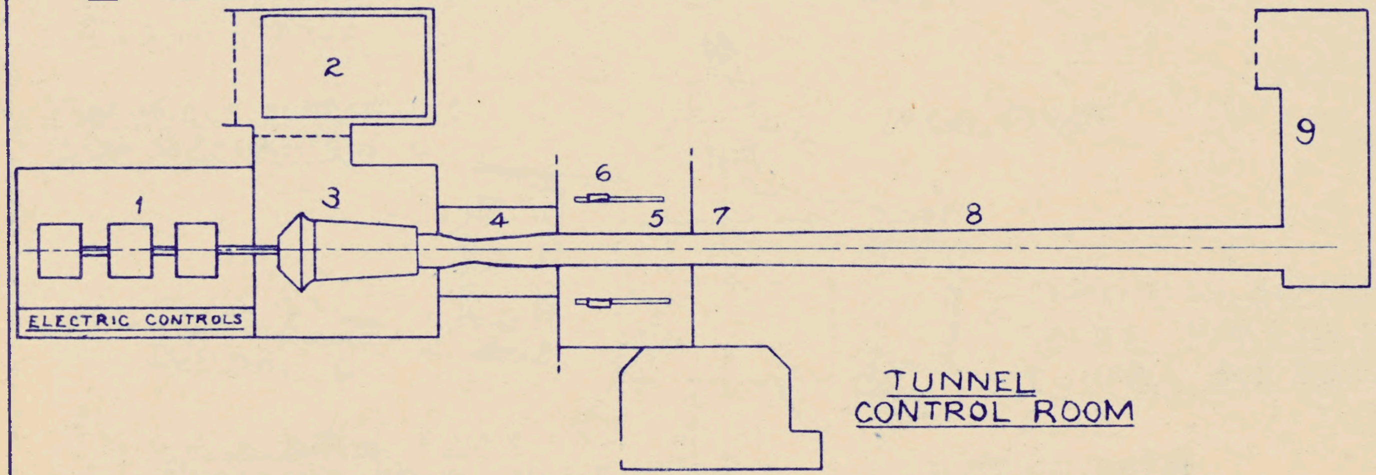
Admittedly these estimates are based on American figures, and it is well-known that in the U.S. the size of staffs assigned to various duties in research establishments often appears to be lavish. However, the above figures are actually the lower limit of the data obtained. Furthermore it should be remembered that in every case the design staffs who volunteered the data had several wind tunnel design and modification jobs behind them. It seems hardly likely that a staff starting out on their first large design task can better these figures.

/cc

FIG. 1

LEGEND

1. DRIVE UNIT - 3 27,000 HP WOUND-ROTOR MOTORS WITH LIQUID RHEOSTAT CONTROL - SPEED RANGE 700-880 RPM NO GEAR BOX
2. DRIER - POWDERED ALUMINA BEDS, PARALLEL AIR FLOW PAPER FILTERS AT INLET AND OUTLET
3. BELL-MOUTH 7 STAGE AXIAL COMPRESSOR IN PLENUM CHAMBER.
4. NOZZLE SECTION SEE FIGURE 2
5. WORKING SECTION
6. SCHLIEREN MIRROR - 42 IN. DIA.
7. TRANSITION SECTION
8. 5 DEGREE DIFFUSER
9. ACOUSTIC DAMPER (RECENT ADDITION)



G. A. OF N.A.C.A. 8 FT. x 6 FT. SUPERSONIC TUNNEL
CLEVELAND, OHIO

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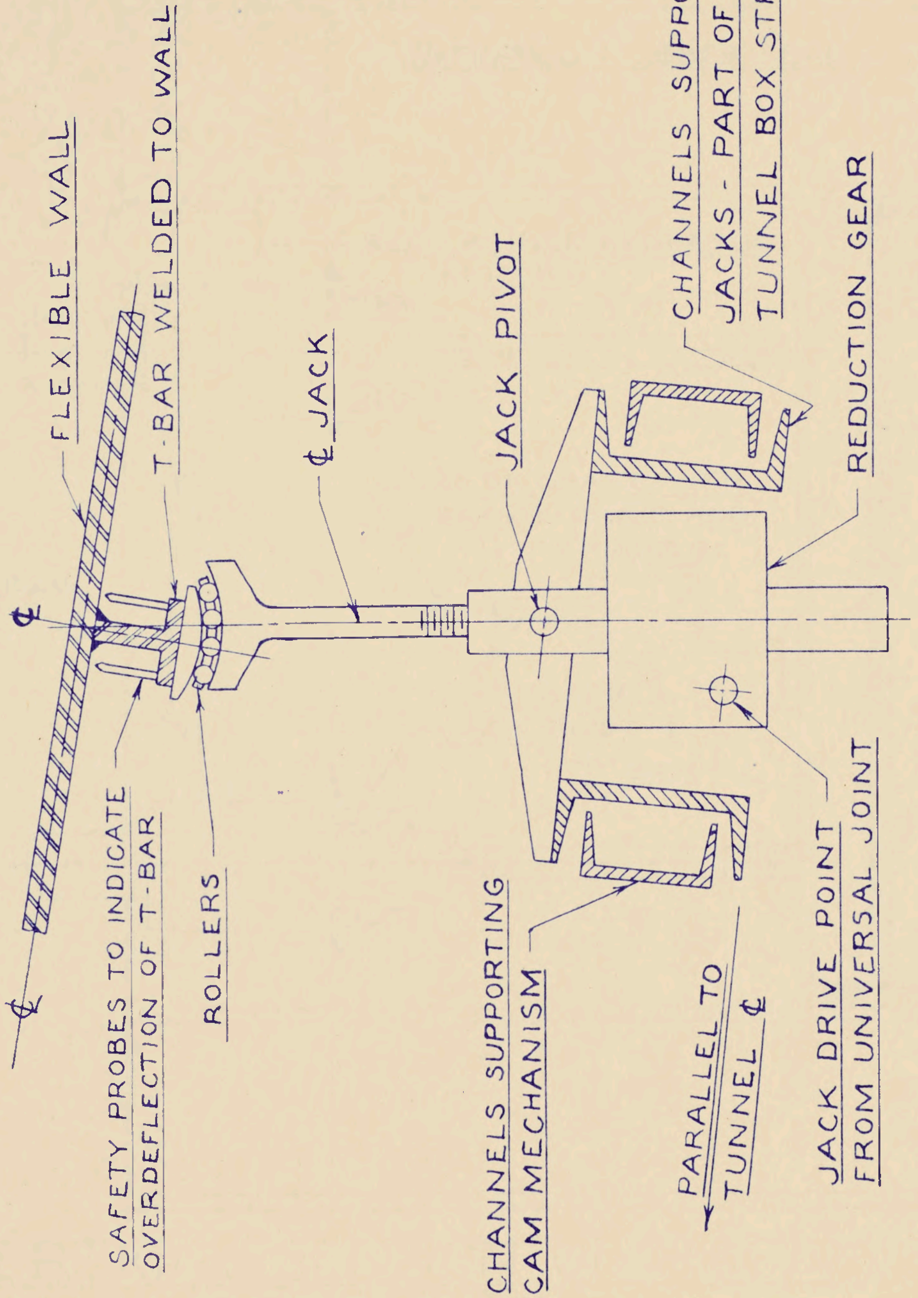
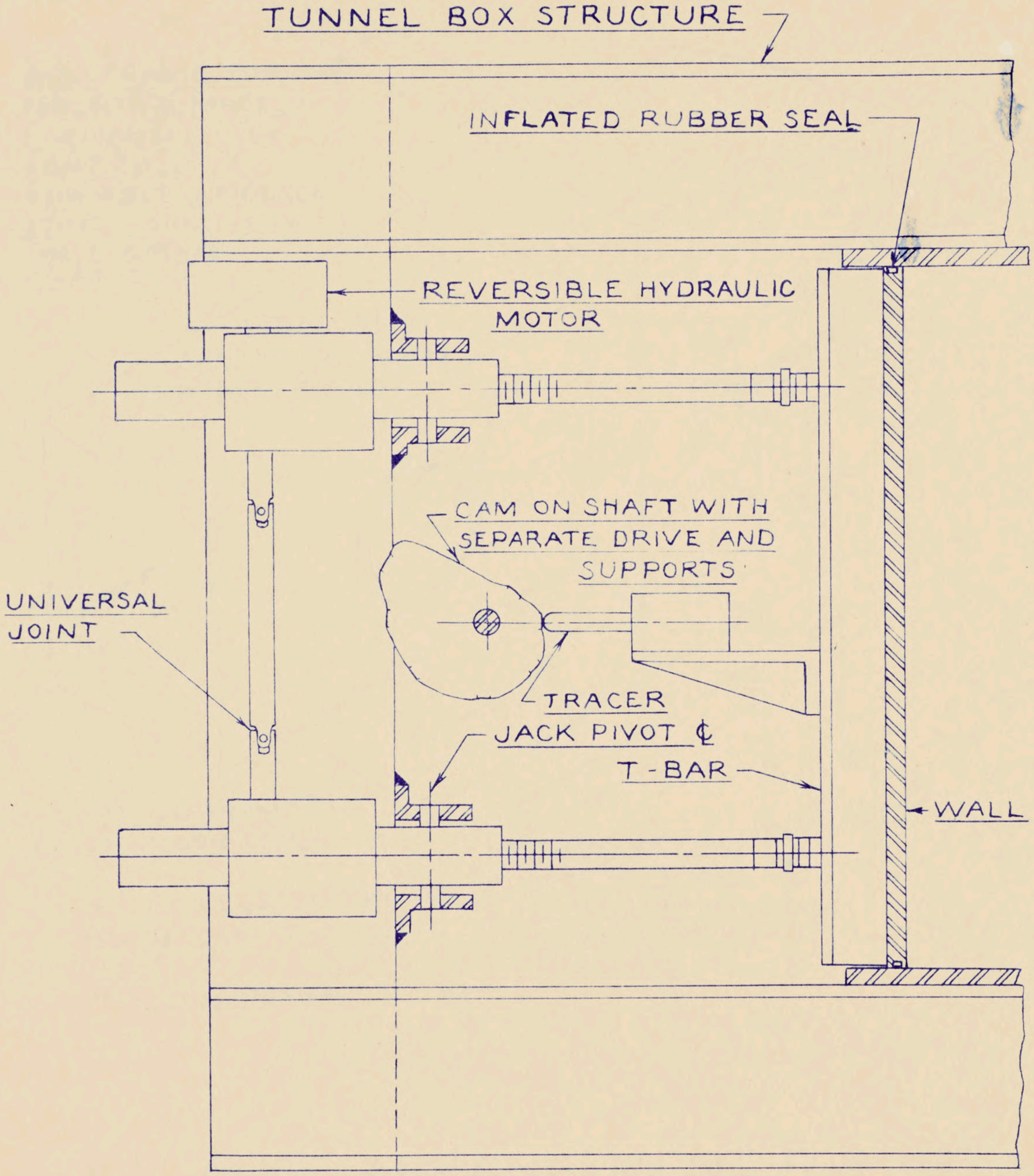
FIG. 2



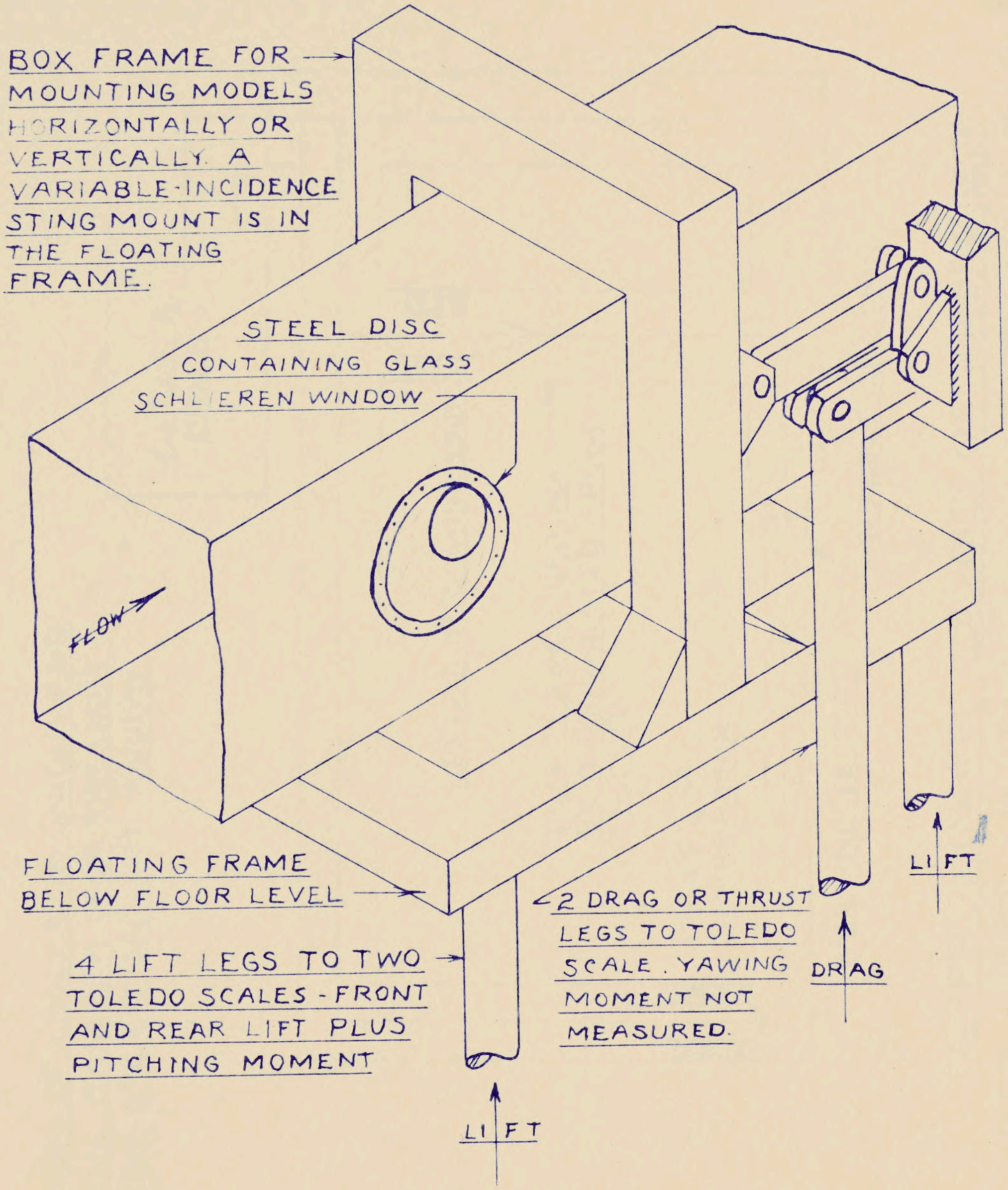
DETAILS OF ONE FLEXIBLE WALL JACKING STATION

FIG. 3



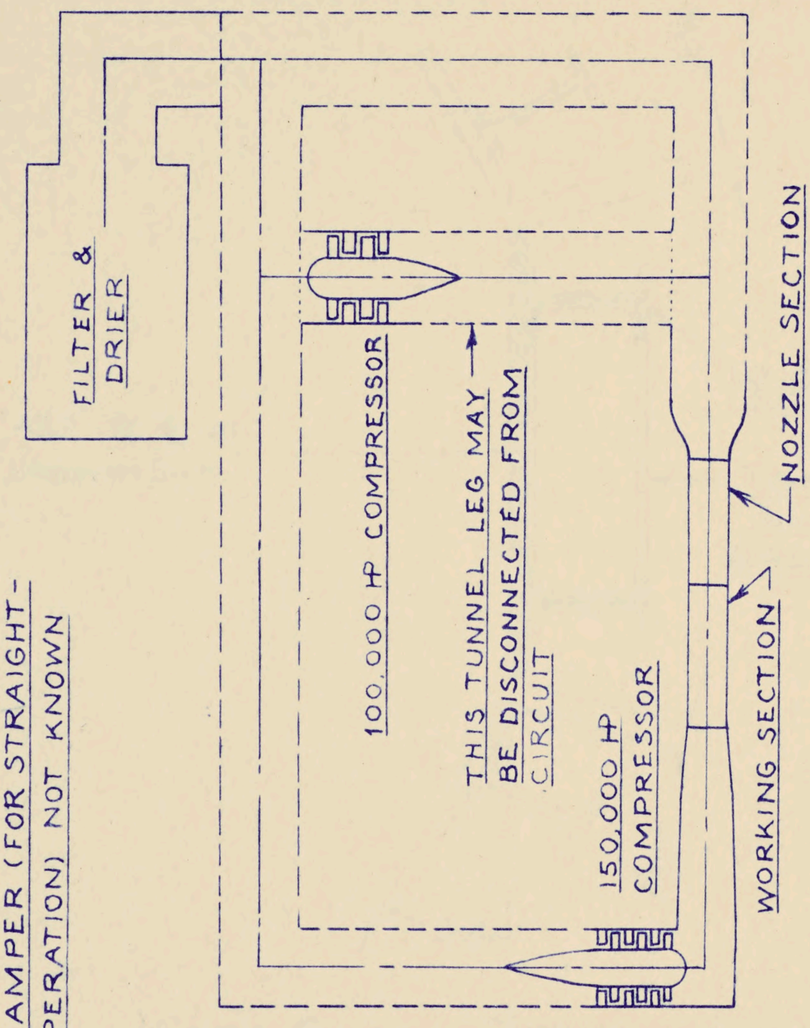
VERTICAL SECTION OF JACKING STATION

FIG. 4



BALANCE ARRANGEMENT FOR 8 FT. x 6 FT. SUPERSONIC TUNNEL

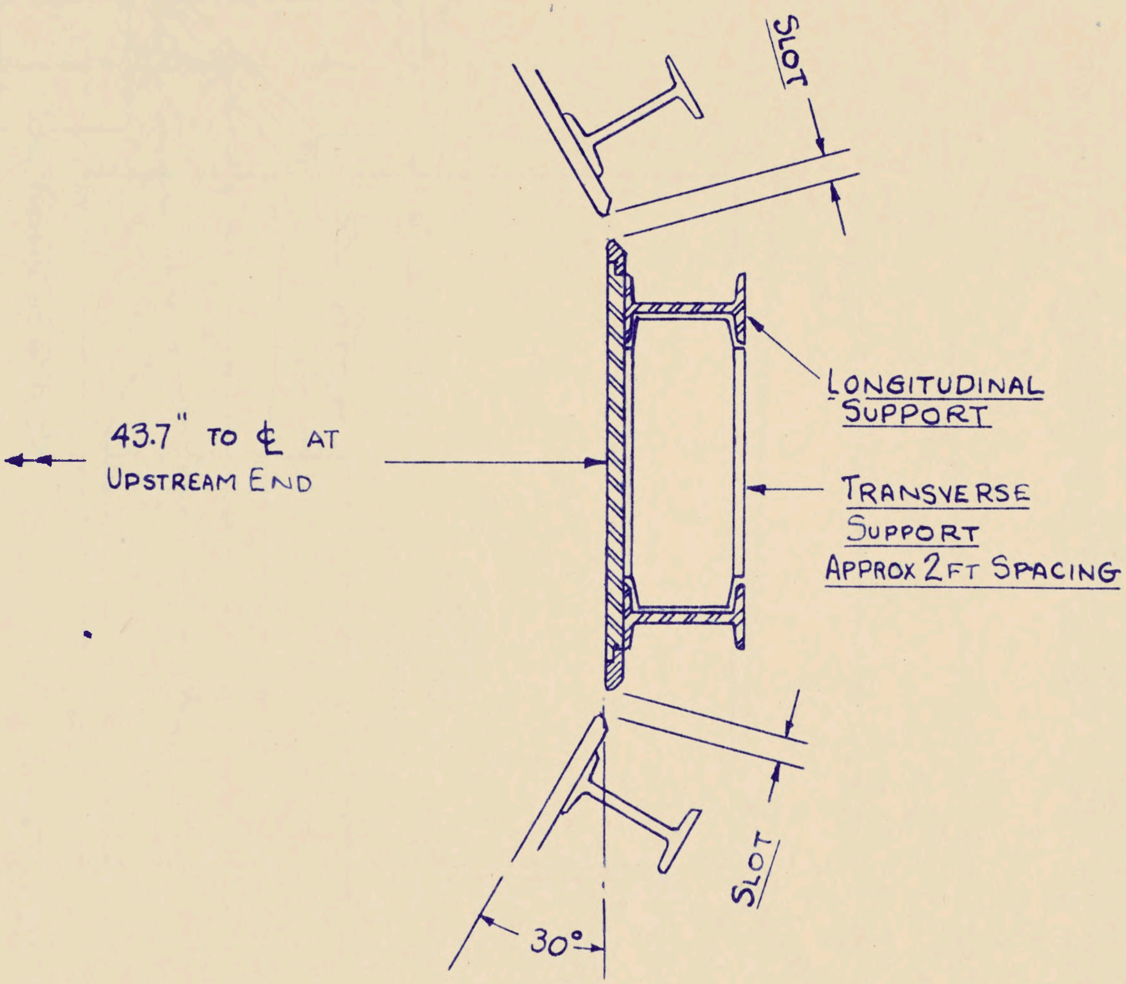
FIG. 5



LOCATION OF COOLER (IN ONION) AND ACOUSTIC DAMPER (FOR STRAIGHT-THROUGH OPERATION) NOT KNOWN

APPROXIMATE LAYOUT OF PROPOSED 10 FT. x 10 FT. UNITARY PLAN SUPERSONIC TUNNEL

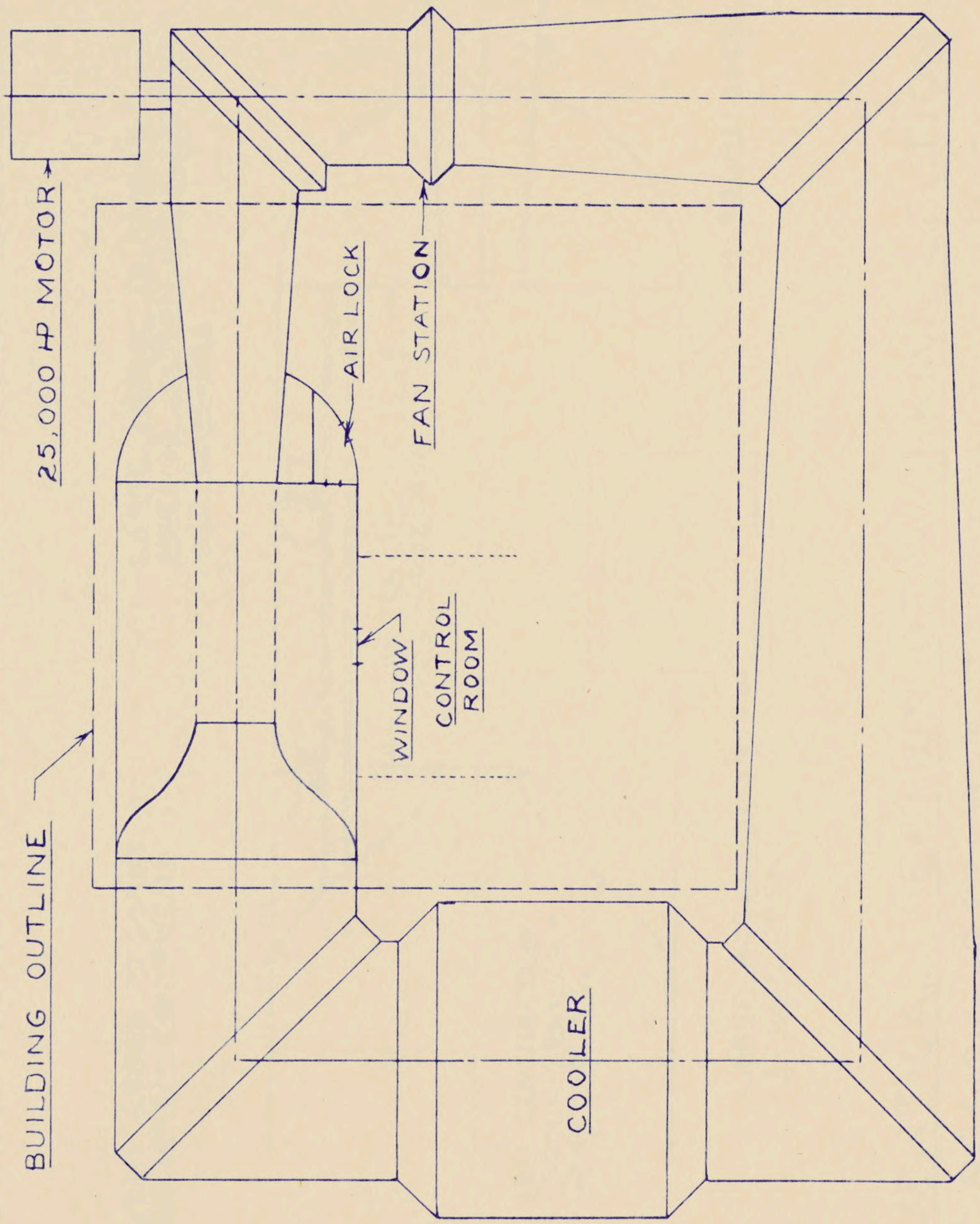
FIG. 6



CROSS SECTION THROUGH WALL PANEL
8-FOOT TRANSONIC TUNNEL
LANGLEY FIELD

SCALE: APPROX. $1\frac{1}{2}$" = 1'-0"

FIG. 7



SKETCH OF 8 FT. x 8 FT. TRANSONIC TUNNEL UNDER CONSTRUCTION AT LANGLEY FIELD

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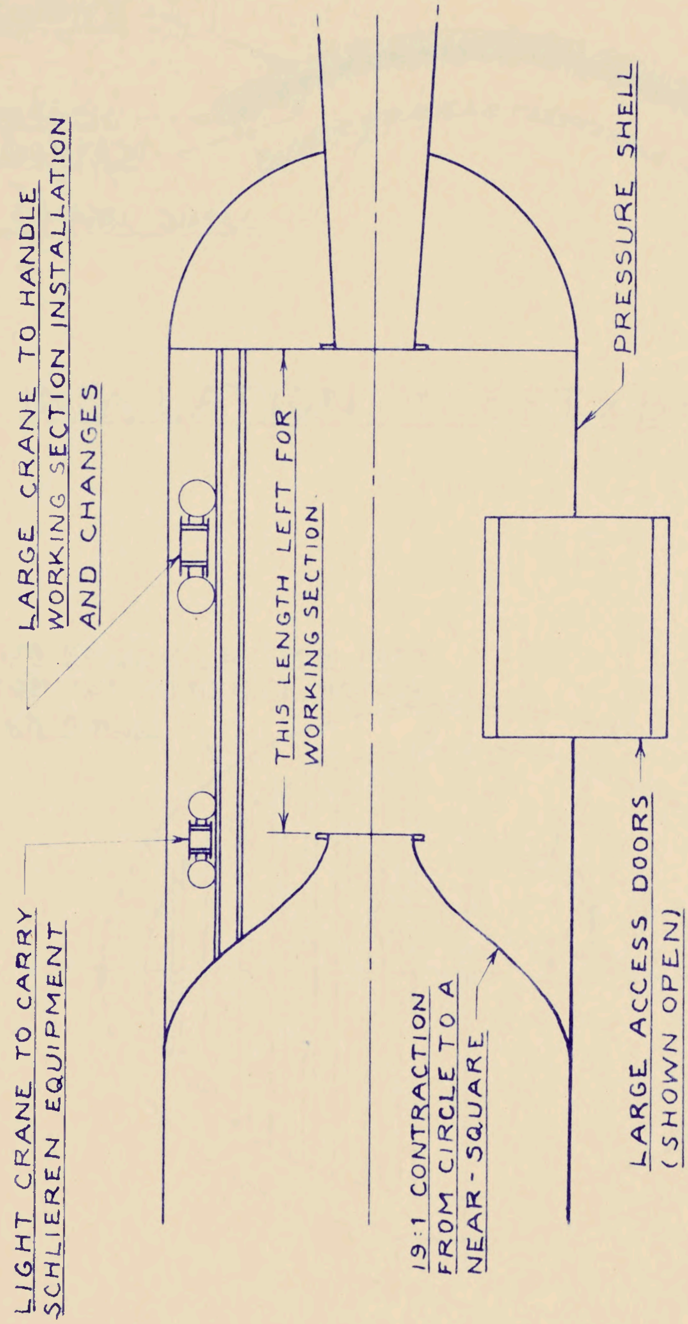
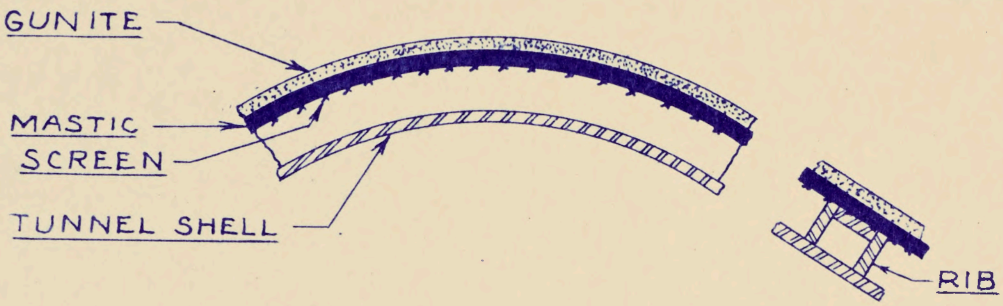
FIG. 8

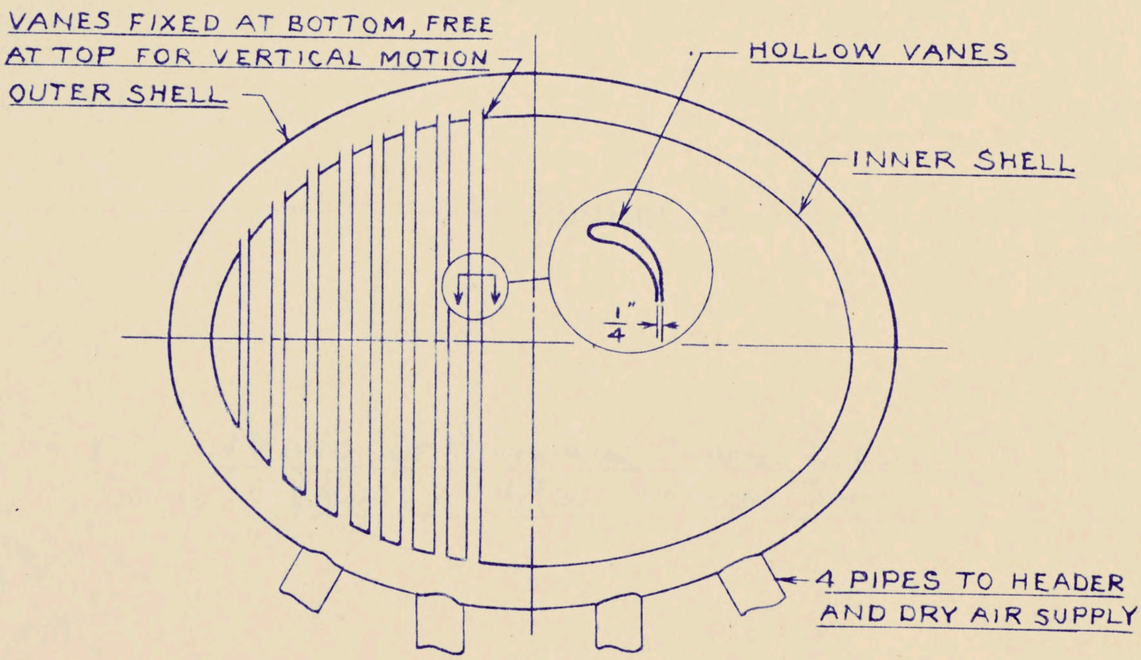


VERTICAL SECTION OF WORKING-SECTION REGION 8FT. x 8FT. TRANSONIC TUNNEL

FIG. 9

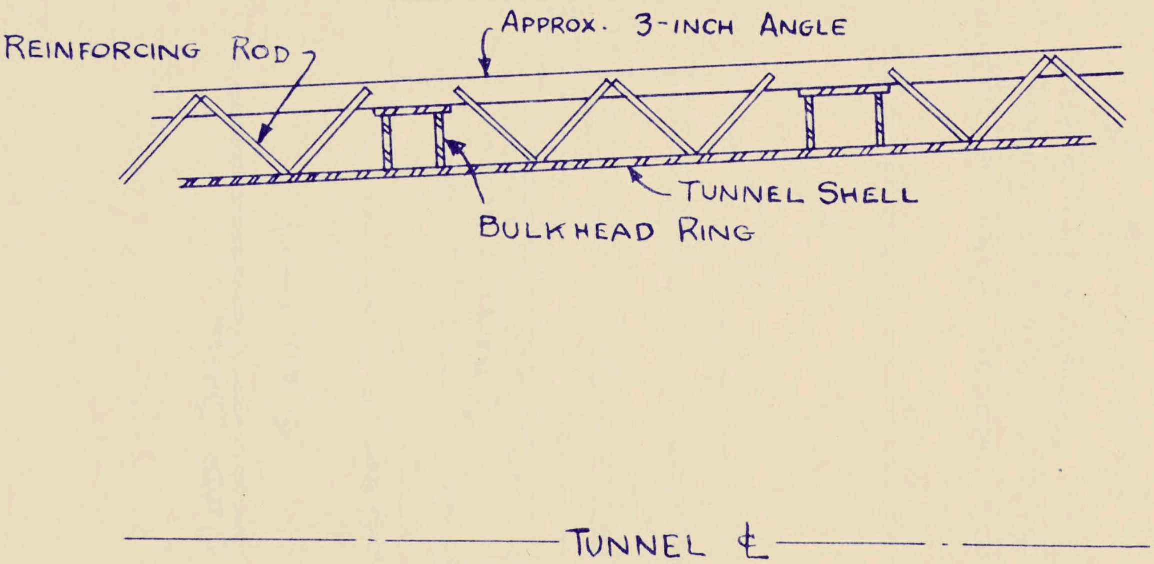


INSULATION ON 8 FT. x 8 FT. TUNNEL



SKETCH OF FIRST CORNER & VANES

FIG. 10



METHOD OF STIFFENING TUNNEL SHELL
LANGLEY 16-FOOT TRANSONIC TUNNEL

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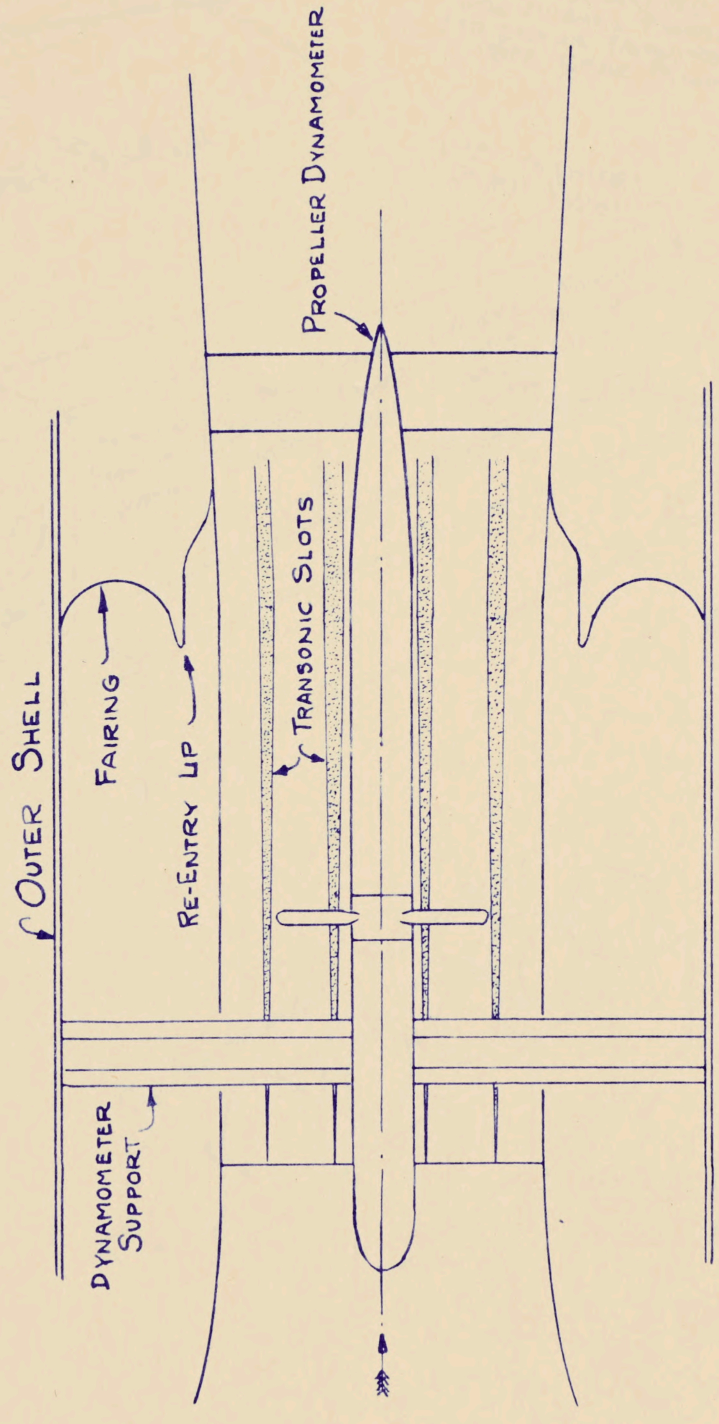
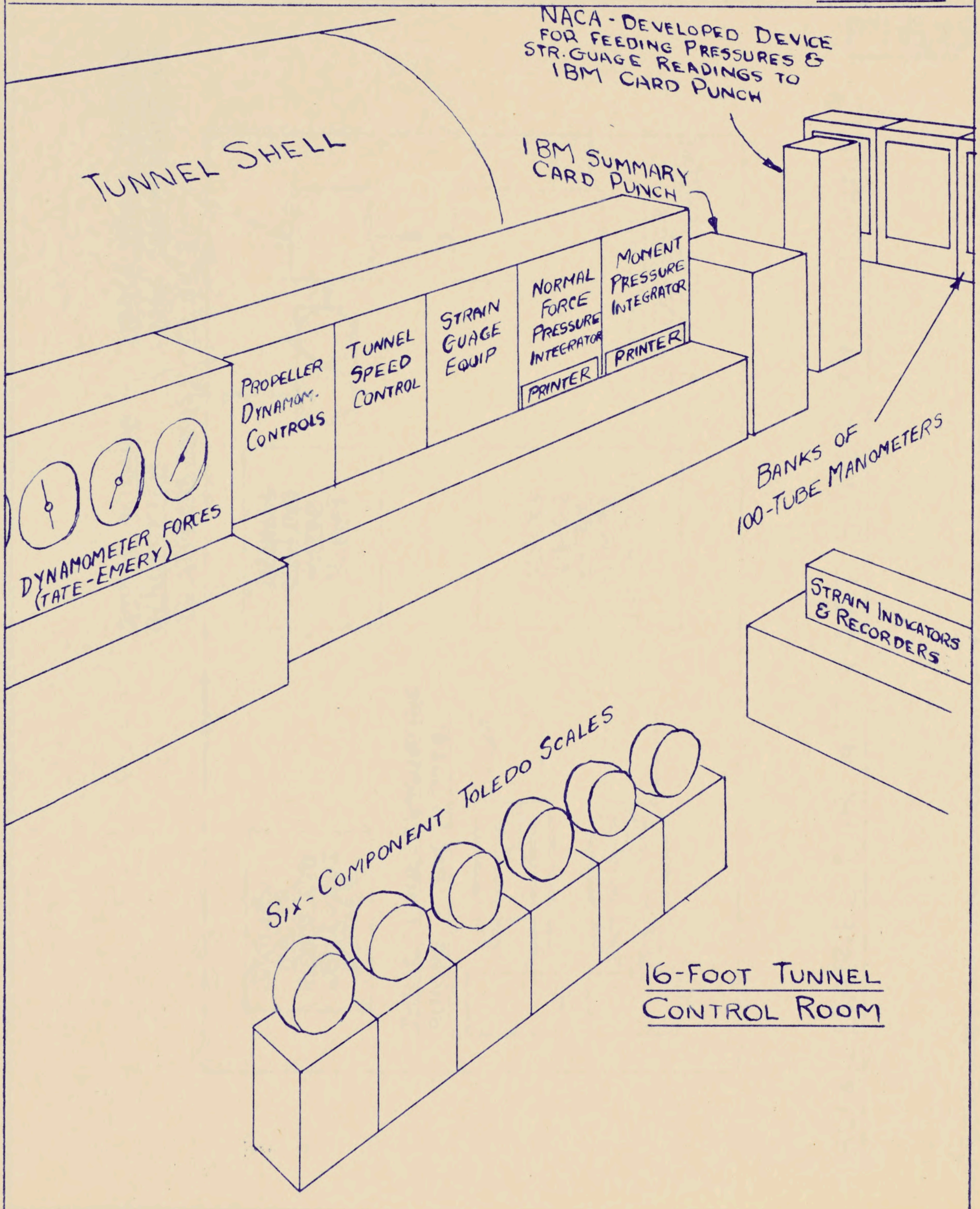
FIG. 11



SECTION THROUGH WORKING SECTION
16-FOOT TRANSONIC TUNNEL
WITH PROPELLER DYNAMOMETER

SCALE : APPROX. $\frac{1''}{8} = 1'$-0"

FIG. 12



16-FOOT TUNNEL CONTROL ROOM

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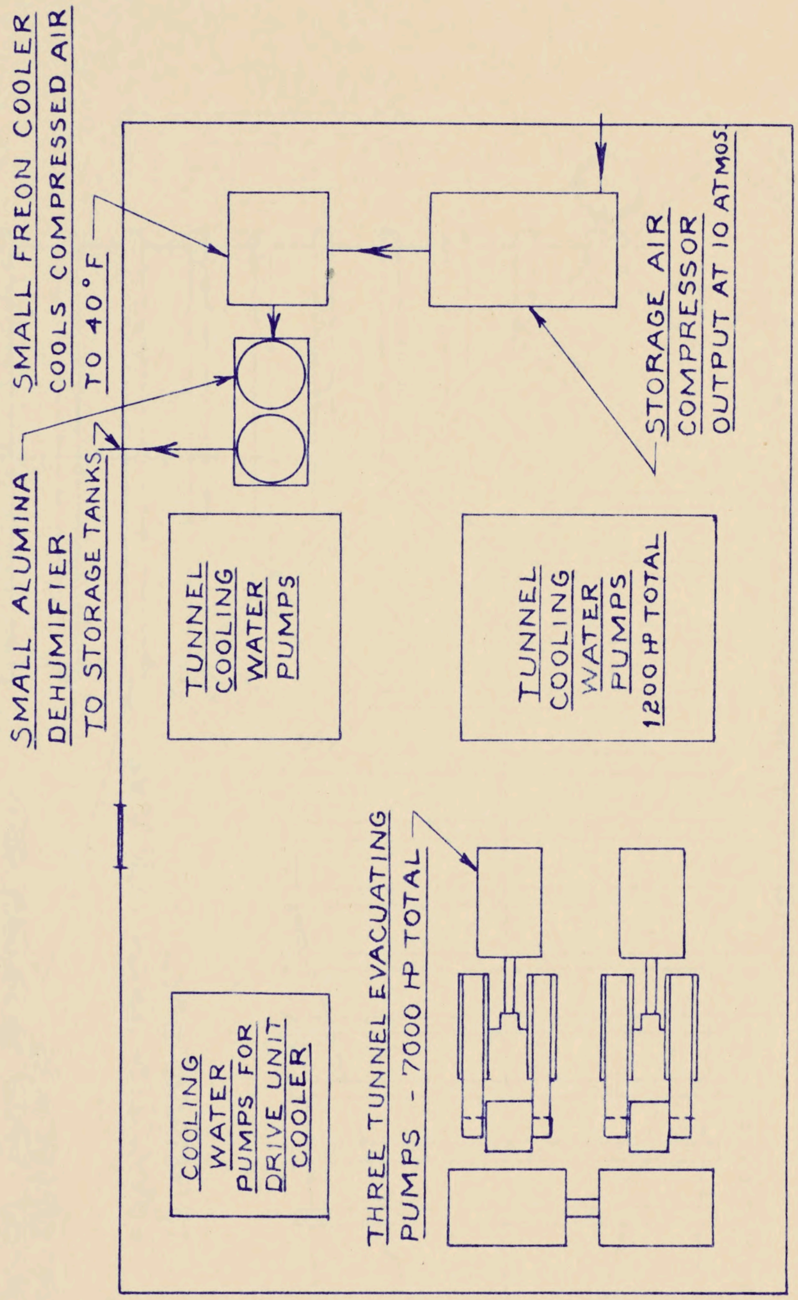
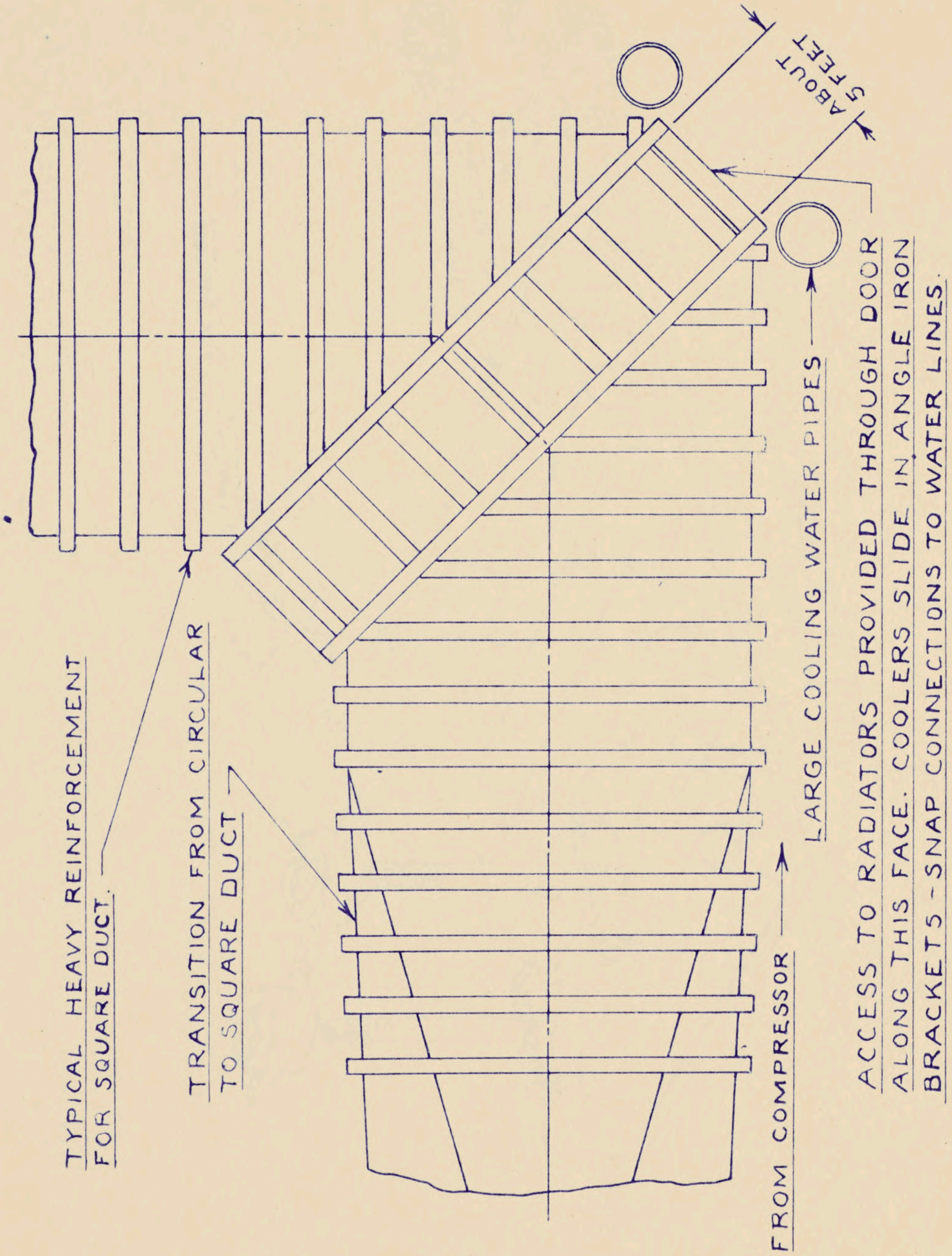
FIG. 13



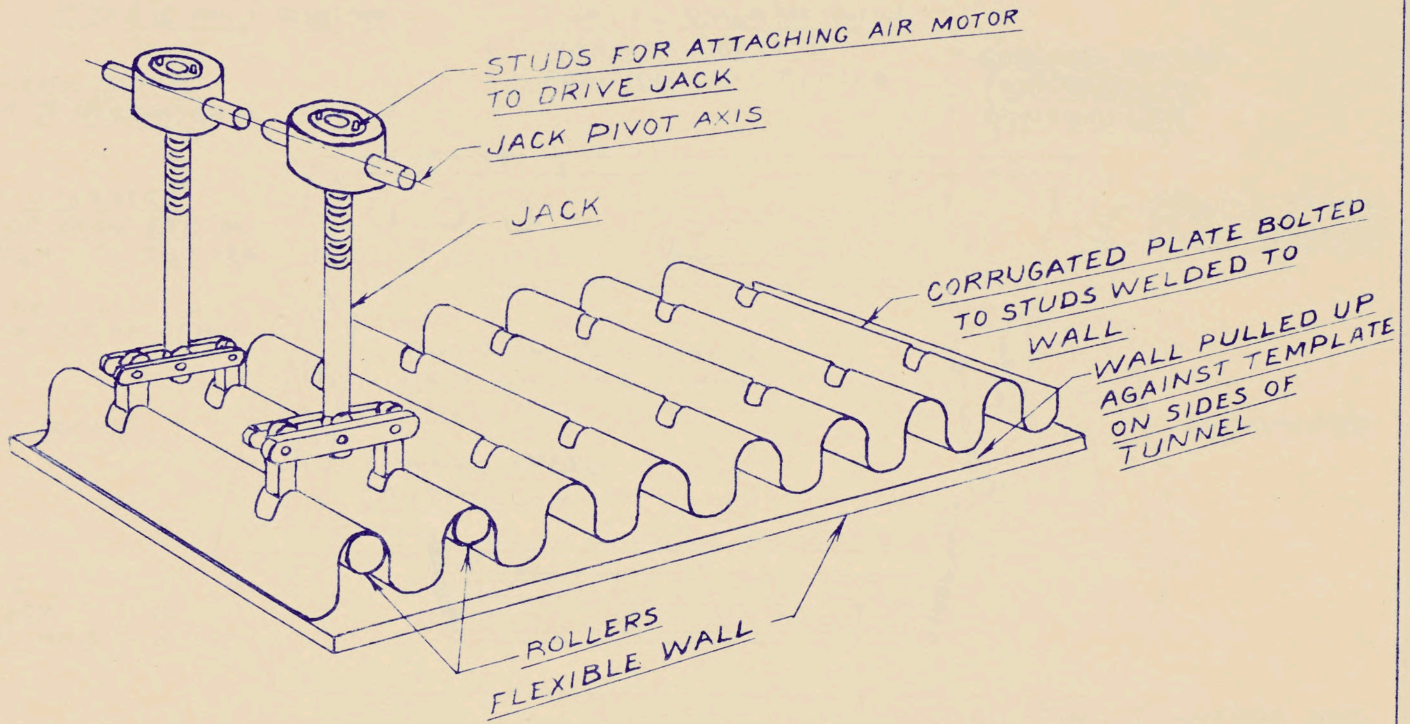
AUXILLIARIES FOR 4 FT. x 4 FT. SUPERSONIC TUNNEL

FIG. 14



PLAN OF THIRD CORNER - 4 FT. x 4 FT. TUNNEL

FIG. 15



FLEXIBLE WALL FOR 4 FT. x 4 FT.
SUPERSONIC TUNNEL

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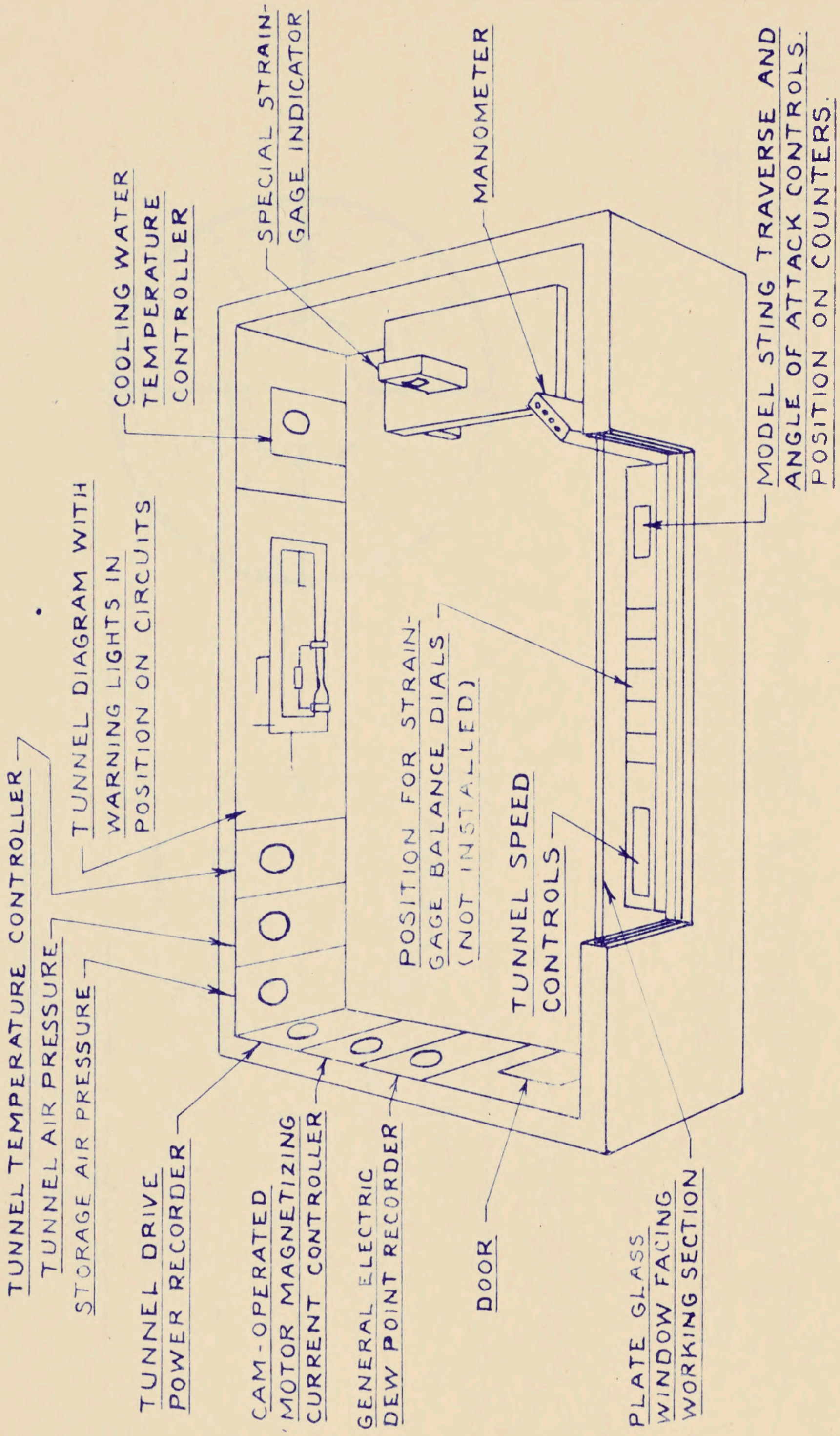
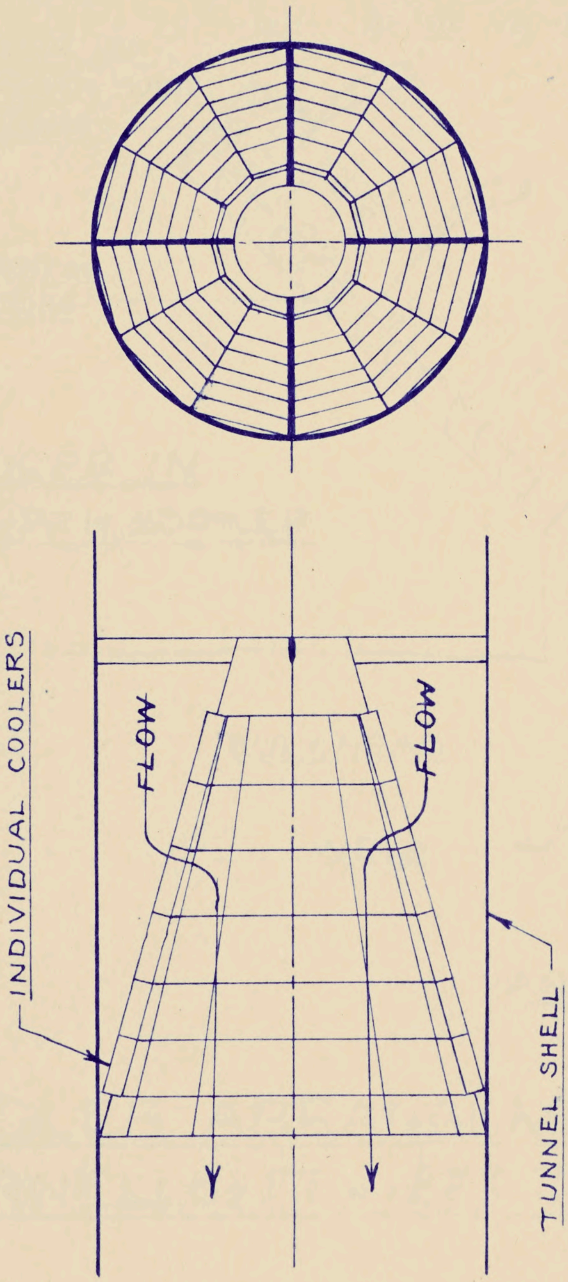


FIG. 16

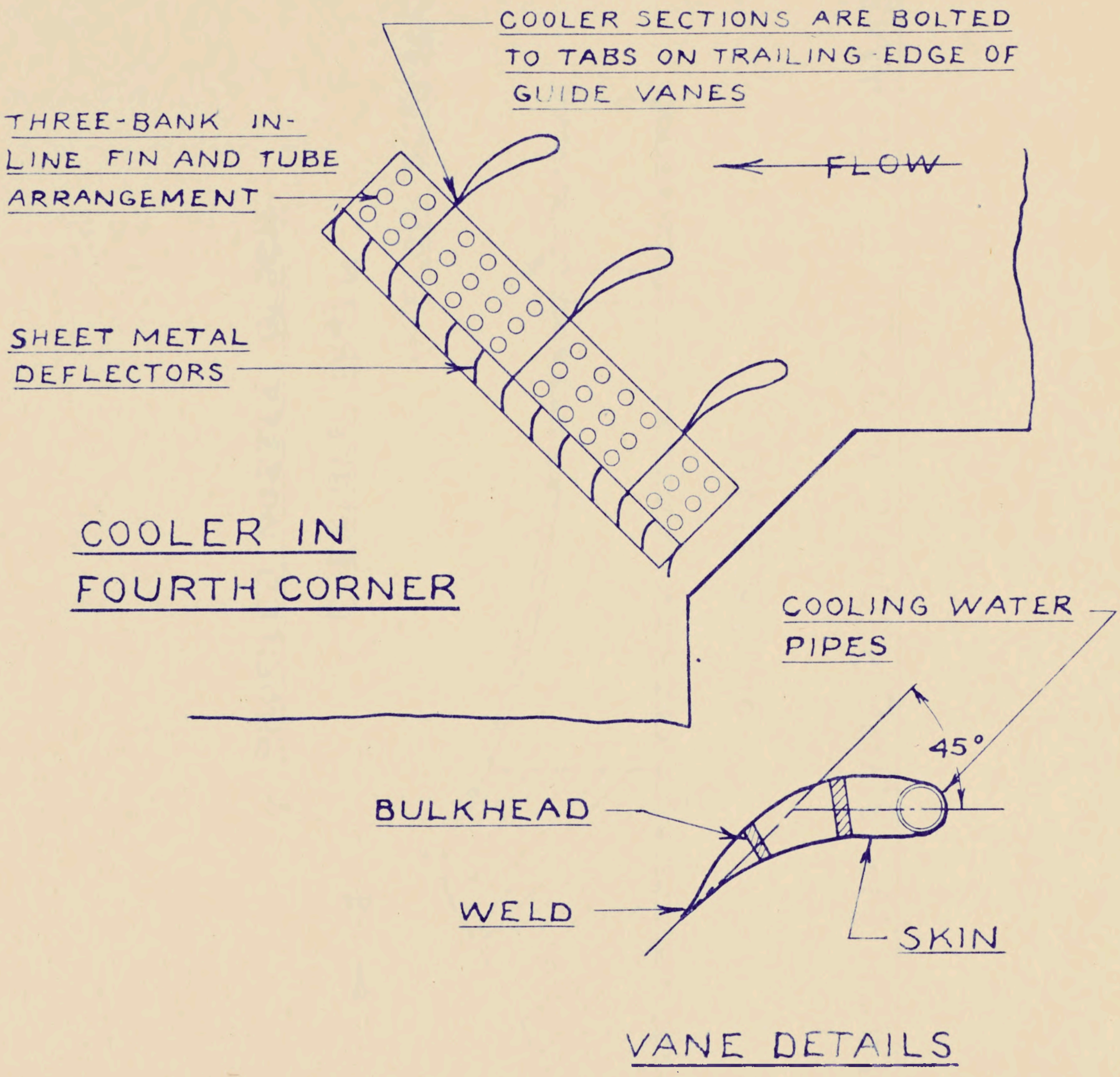
LAYOUT OF CONTROL ROOM FOR 4 FT. x 4 FT. SUPERSONIC TUNNEL

FIG. 17



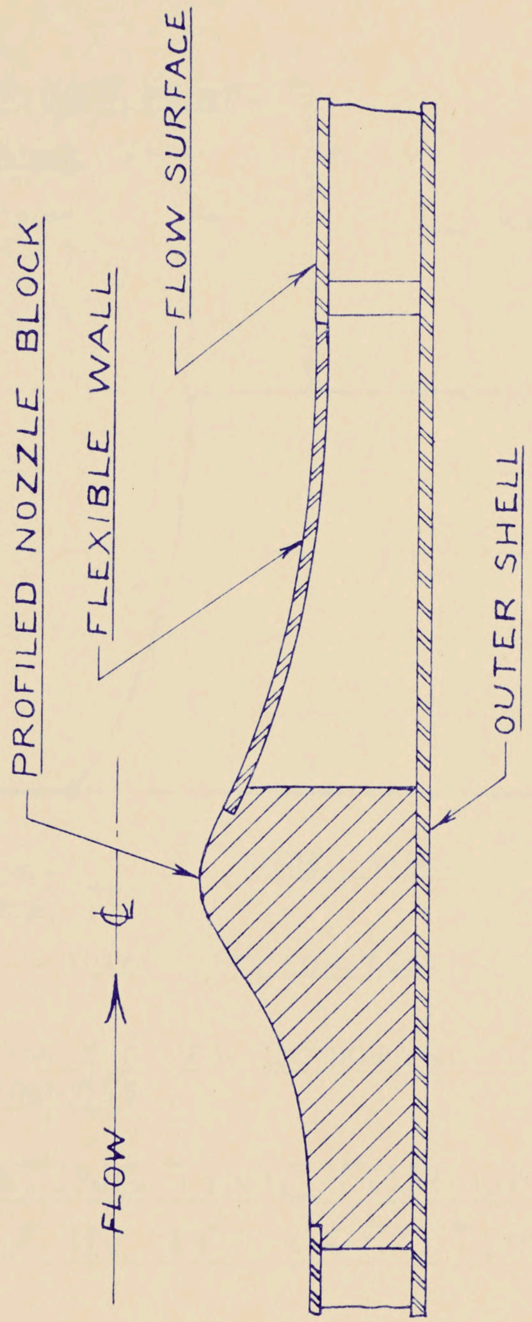
CONICAL COOLER ARRANGEMENT FOR LARGE SURFACE AREA IN SMALL DUCT DIAMETER

FIG. 18



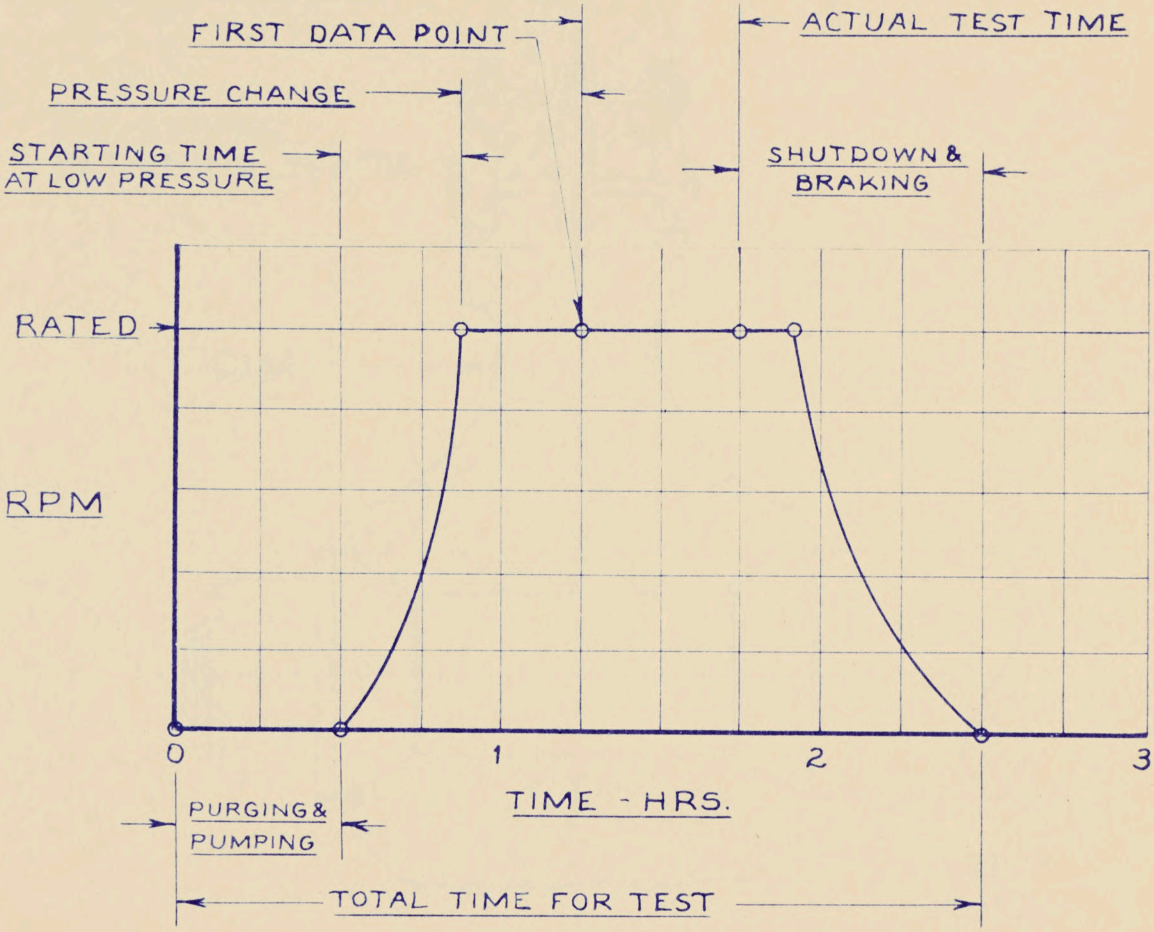
COOLER ARRANGEMENT IN CORNELL $8\frac{1}{2}$ FT. x 12 FT. TUNNEL

FIG. 19



HIGH MACH Nº SUPERSONIC NOZZLE AT AMES

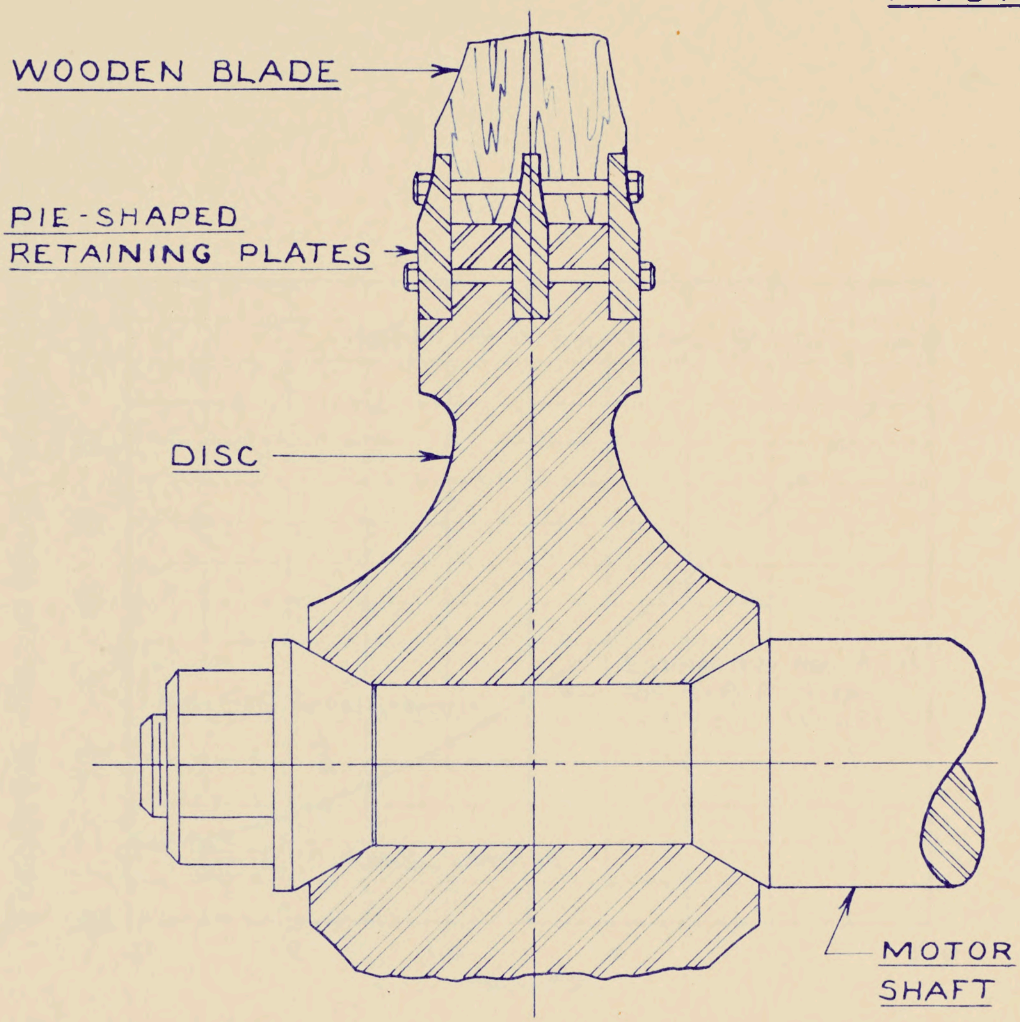
FIG. 20



NOTE: TIMES GIVEN DO NOT INCLUDE NOZZLE CHANGES.

OPERATING TIME FOR ONE MODEL TEST IN 4 FT. x 4 FT. TUNNEL

FIG. 21



WOODEN FAN BLADE MOUNTING ARRANGEMENT

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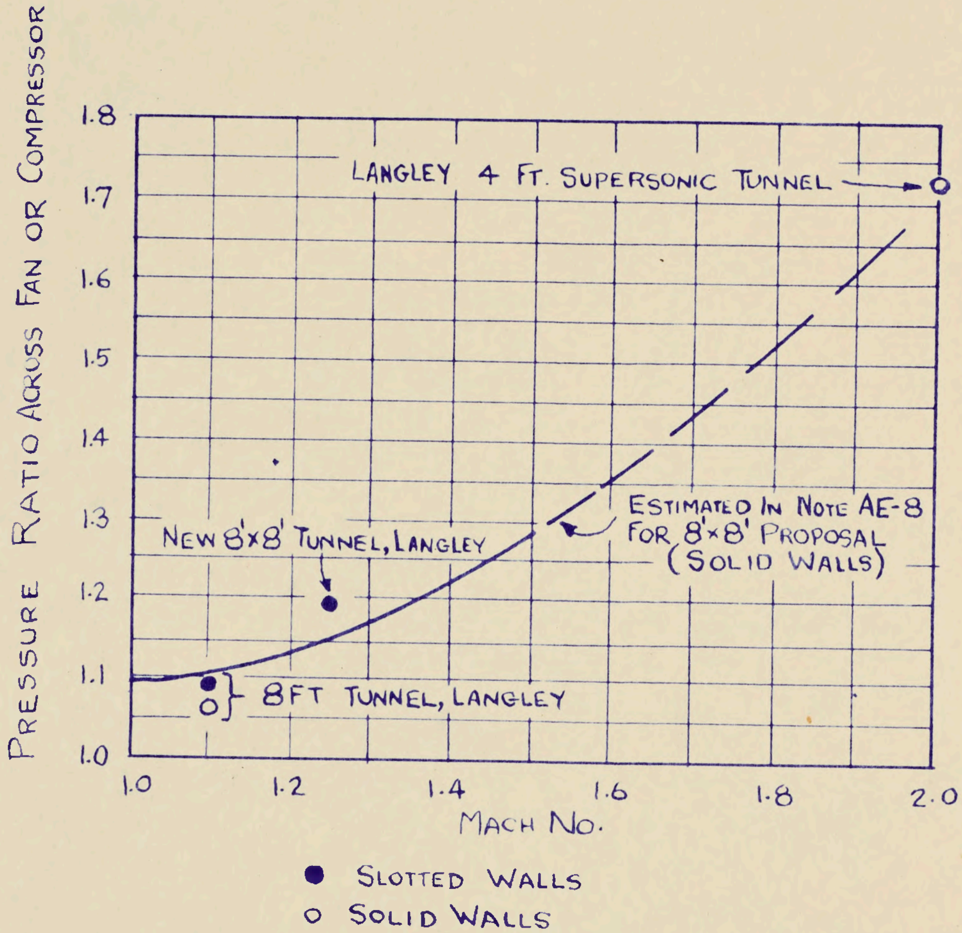
FIG. 22



SOME ISOLATED DATA ON PRESSURE RATIO FOR LARGE TUNNELS AT LANGLEY FIELD COMPARED WITH NAE ESTIMATES