THE DESIGN AND CONSTRUCTION OF A SMALL INTERMITTENT SUPERSONIC WIND TUNNEL

by

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INTRODUCTION

It is evident that the general trend in the field of aeronautical engineering is to higher and higher speeds. Aircraft speeds have increased threefold in less than two decades. Velocities of unmanned missiles have far exceeded this. To sustain these rapid technical advances and to ensure their continuance, the field of aeronautical engineering must continue to expand, and there must be a large number of technically qualified people entering this area.

In order to be suitably qualified to step into a technical position in aeronautics, a person must have knowledge of both theoretical and experimental methods that are likely to be employed. The single experimental tool finding the widest use in aeronautical engineering is the wind tunnel. Thus it is desirable to have a wind tunnel available at a university for use as an instructional aid and as a basic research tool.

Therefore it is the purpose of this thesis to present a design and to describe details for the construction of a supersonic wind tunnel suitable for use as an instructional aid and as a basic research tool.

The major limitation placed on this project is that imposed by the requirement of small total cost.

SYSTEM SELECTION

The Wind Tunnel System

A wind tunnel has the widest range of applicability of any tool available to the aeronautical researcher. As a research tool, the function of a wind tunnel is to produce data by the simulation in the laboratory of real conditions encountered in flight. An aerodynamic shape encounters varied conditions as it progresses through the atmosphere. It is impossible to satisfactorily simulate all conditions in one wind tunnel system. Therefore, to design a wind tunnel system it is necessary to decide which particular set of conditions are to be simulated.

Many specialized wind tunnels are in existence, and they attempt to simulate a particular set of flight conditions. For instance, spin tunnels, ice tunnels, and stability tunnels are in existence, and they attempt to explore these particular conditions. The particular set of flight conditions having the widest range of applicability is that of level unaccelerated flight. For this reason, the majority of wind tunnels in existence today attempt to simulate this set of conditions. This paper will be concerned only with the simulation of this condition.

All wind tunnels are made up of a great many components. Each component of the wind tunnel system must aid in the simulation of the chosen set of conditions or in obtaining data therefrom. All components must be designed with this in mind. The selection of the number and type of components will be governed by this consideration.

All wind tunnel systems must include the following things:

1. A means of creating flow
2. A means of directing the flow
3. A means of controlling the flow parameters
4. A means of obtaining data

The only practical means of causing a gas such as air to move is by creating a pressure differential in the gas in the desired direction of flow. A gas will move from a region of high stagnation pressure to a region of lower stagnation pressure. Thus if either high pressure or low pressure regions can be created in a gas, it is possible to cause motion of the gas. Regions of high stagnation pressure can be created by the use of a compressor. Regions of low pressure can be obtained by the use of a vacuum pump. Either method may be used to cause flow in a wind tunnel.

The direction of flow of a gas can be controlled by means of shaped channels enclosing the moving fluid. A shaped channel working in conjunction with a compressor or vacuum pump offers a means of controlling the direction of flow and of controlling flow parameters. Any such channel must be designed to withstand the pressures that will be encountered. It must be designed to present smooth surfaces to the moving fluid to avoid large pressure losses. The channel must be properly contoured to obtain the desired flow in the area where data will be taken.

The last necessity is a means of obtaining data from a wind tunnel. All data will be taken from a particular region in the wind tunnel system known as the test section. The type of instrumentation will depend entirely on the type of wind tunnel. For instance, ordinary force measuring instruments would be useless in a shock tube because of their slow response and low sensitivity. Generally it is advantageous to take four types of data; force data, pressure data, temperature data, and optical data. Even though it is possible to get by with only one or two types of data, a well equipped wind tunnel system will have means to take all four types of data.

Types of Wind Tunnels

Before it is possible to select the proper wind tunnel for any given situation, it is necessary to become familiar with the types and the characteristics of wind tunnels in use today. It is possible to classify wind tunnels in many different ways. They may be classified according to their being open or closed jet, according to their velocity range, or according to their use. For the purposes of this paper, it is advantageous to classify wind tunnels according to the time duration of the individual runs.

If wind tunnels are classified according to run duration, they naturally fall into three groups: continuous, quasi-steady, and transient. Each type is characterized by the duration of the individual run.

In the continuous type of wind tunnel equilibrium conditions prevail. That is, the aerodynamic parameters are time independent. This equilibrium condition can be maintained for a time duration of arbitrary length.

In the quasi-steady type of wind tunnel equilibrium conditions prevail, but for only a comparatively short time. Data is taken only during the steady flow portion of the run time. Run times ordinarily last thirty seconds to two minutes. Maximum run times are not usually longer than five minutes, but this is determined by the relative sizes of components in a particular wind tunnel. The minimum run time is fixed by the instrumentation of the particular wind tunnel. Blow-down wind tunnels and vacuum storage wind tunnels are examples of quasi-steady wind tunnels.

The transient type of wind tunnel is characterized by the fact that steady flow exists for extremely short periods only. The duration of steady flow is from several micro-seconds to several milli-seconds. Instrumentation is particularly critical for this type of wind tunnel. Shock tubes and ballistic tunnels are examples of wind tunnels that may be grouped in this category.

Comparison of Types

Wind tunnels have a great many significant differences. Careful comparison of the differences in various types of wind tunnels will enable one to select the best system for a given situation. These three general types will be compared on the following basis:

1. Cost
2. Utilization
3. Performance
4. Instrumentation

These factors as listed are interrelated to such an extent that each one cannot be isolated and optimized. Therefore, the final choice will be a compromise between various factors.

Continuous Type. Since cost is of paramount importance, it will be considered first. It is easy to see that continuous wind tunnels are by far the most expensive. This is due to several factors. Generally continuous wind tunnels are of the closed circuit type. This means that the surface area will be at least twice as large as that for an open circuit tunnel. This fact results in a twofold increase in the material cost and construction cost over the open circuit type. Initial investment and running costs will be large because of the large volume flow. Energy is expended continually, thus energy storage is not used. Due to large volume flows, axial flow compressors are usually required. They are inherently complicated and expensive. Since axial flow compressors can be matched to flow requirements for only a small range of Mach numbers, the Mach number range of a particular installation is limited.

The continuous wind tunnel has the widest utilization of the three types. It can be used for basic research, applied research and development, and as an instructional aid. Performance obtainable in continuous wind tunnels covers a great range; however a particular wind tunnel is limited in Mach number range and Reynolds number range by compressor matching and available power.

Instrumentation is the easiest of all three types. Pressure data, force data, temperature data, and optical data are easily obtainable by conventional methods.

Quasi-Steady Types. For a given test section size, the quasi-steady type of wind tunnel ranks between continuous and transient types on a cost basis. Costs may range from less than five thousand dollars to over one million dollars, dependent mainly on the size of the particular installation. Cost of a small quasi-steady wind tunnel is within reach of most universities. For this reason it is the most practical. Low cost can be attributed to several factors including the following: no-return feature, use of energy storage, feasibility of small size tunnels, and ordinary instrumentation. The major portion of the cost of a small quasi-steady wind tunnel is tied up in the air supply system. In many instances the design can be tied in with components already on hand. Such things as compressors and air storage tanks are usually available at most universities.

On the basis of cost and performance it appears that a blow-down wind tunnel offers important advantages over the vacuum storage type. A blow-down wind tunnel requires a compressor rather than a vacuum pump, an item that is generally more readily available and more likely to be on hand. A blow-down wind tunnel requires smaller storage volume for the same run time than a vacuum system. This storage volume can be smaller by a factor as much as thirty, depending mainly on the storage pressure. Drying of the air can be accomplished while the storage tank is being filled for a blow-down tunnel rather than as it is used, which is the case for the vacuum storage tunnel. Therefore, a smaller dryer can be used. Smaller pipes and valves may be used between the storage tank and the test section in a blow-down wind tunnel. The presence of a high efficiency diffuser is not necessary in the blow-down wind tunnel. Finally, the blow-down wind tunnel has an easily controllable stagnation pressure, whereas the vacuum storage wind tunnel is limited to a stagnation pressure equal to the ambient atmospheric pressure. For these reasons, a blow-down wind tunnel system is less expensive and more flexible in its application than a vacuum storage wind tunnel.

Quasi-steady wind tunnels are utilized widely, both in industry and at various universities. Due to its low cost and simplicity, it is very useful at universities for laboratory experiments and for basic research projects.

Blow-down wind tunnels offer performance in a high Reynolds number region, a region not covered by most other types of wind tunnels. They also afford a wide range of Mach numbers in one wind tunnel. Blow-down types offer an additional advantage in that the stagnation pressure, and thus the Reynolds number, can be easily varied.

Instrumentation problems are only slightly more difficult than those for the continuous type. Run times last approximately thirty seconds. This will require recording devices to take data. Pressure, force, temperature, and optical data are easily obtainable by conventional methods.

Transient Types. For actual tunnel costs, transient wind tunnels rank lowest of the three types. Long cylindrical pressure vessels of relatively small diameter are used. Standard commercial pipe is often used.

Utilization of shock tubes and gun tunnels is quite limited. They are used mainly for basic research problems. They find special application in non-steady aerodynamics, combustion processes, and compressible boundary layer problems.

Performance of transient tunnels enables study of the extremely high Mach number ranges. Steady state flow exists for periods measured in micro-seconds or milliseconds.

Instrumentation problems are the limiting factor in the usefulness of transient wind tunnels. Short run times require special instrumentation techniques. Optical data is obtainable by using high speed cameras. Pressure data of a crude nature can be taken. Force data cannot be taken. Synchronization and timing problems are not easily solved.

Conclusions

1. Continuous wind tunnels enjoy the widest utilization of the three types. All types of data are readily obtainable. Prohibitive initial cost excludes this type

from consideration.

2. Quasi-steady wind tunnels are widely used. The cost of small tunnels of this type is within reach of most universities. Instrumentation is conventional and all types of data can be taken. Blow-down types, as opposed to vacuum storage vacuum systems, appear to be the most satisfactory from all points of view.

3. Transient wind tunnels are quite limited in their range of application. Instrumentation problems are great, and definitely restrict their use.

4. Thus from the foregoing evidence it is concluded that the most feasible system for installation at Oregon State University is a small intermittent wind tunnel of the blow-down type.

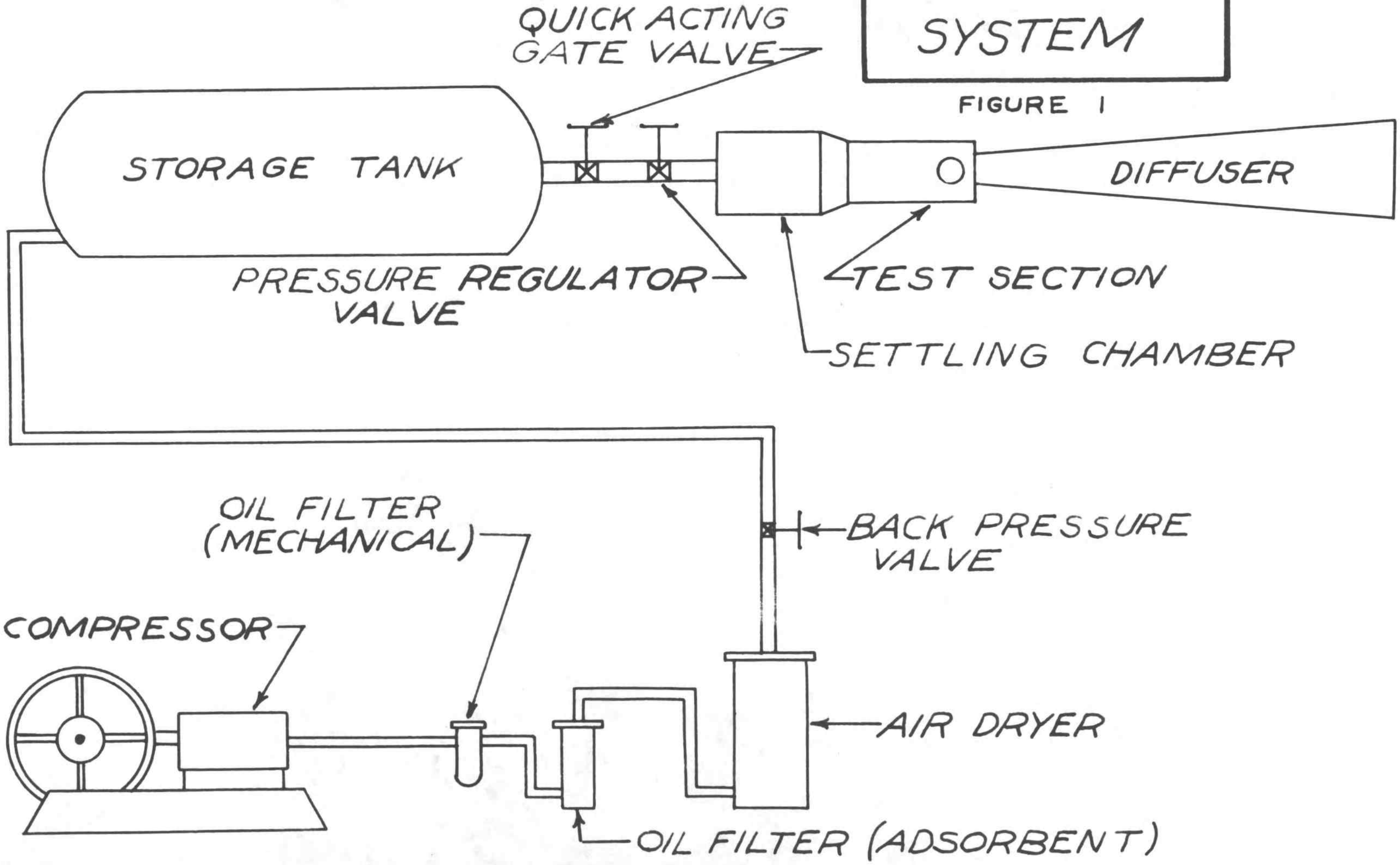
SYSTEM CONCEPT

The wind tunnel system is composed of several subsystems, each in turn having several major components. Figure 1 shows a schematic diagram of the wind tunnel system, showing the location of all components. The major components are grouped accordingly:

Major Components

A. Air Supply
   1. Compressor
   2. Oil Filter
   3. Air Dryer
   4. Storage Tank

B. Wind Tunnel
   1. Valves
   2. Settling Chamber
   3. Nozzle
   4. Test Section
   5. Diffuser



WIND TUNNEL SYSTEM

FIGURE 1

C. Instrumentation

    1. Optical System
    2. Force System
    3. Pressure System
    4. Temperature Measurement

Component Description and Purpose

Air Compressor. The purpose of the air compressor is to provide high pressure air. A compressor must be chosen to give required maximum output pressure and required volume flow. The maximum pressure needed is determined by required performance and economic considerations. The capacity necessary is fixed by determining the maximum allowable recharge time. In the case at hand, a compressor of given performance is available. The system is designed around its performance.

Oil Filter. Unless a compressor is equipped with special carbon piston rings it will contaminate the air with oil. Desiccants that are used in the air dryer have a great affinity for oil, in preference to water. Contamination by oil destroys its drying ability. Therefore it is necessary to install an oil filter between the compressor and the air dryer. Removal of oil by a filter also prevents contamination of the storage tank, the test section, and models that are being tested. Since the oil filter is in the high pressure line it must be designed to withstand the maximum output pressure of the compressor. However, since the pressure is high, the physical size may be small because of the small volume flow. Such a filter utilizes standard desiccants such as silica gel or activated alumina. It is envisioned that it can be constructed out of standard pipe fittings.

Air Dryer. Essentially the wind tunnel employs an expansion process where high pressure is sacrificed for velocity. With this process there is necessarily a large drop in the static temperature. In fact the temperature will fall far below the dew point of atmospheric air. Thus to prevent condensation of the water vapor a large portion of it must be removed. This is the function of the air dryer. It will make use of standard desiccant materials. Usually a dew point of -40°F is specified as sufficient to prevent condensation. Due to short dwell time in the test section of any given packet of air, it is possible to have a great deal more water vapor present than that of dew point. It is possible to operate up to a Mach number of about 1.6 without any drying. (17, p. 473)

Storage Tank. The function of the storage tank is to act as an "energy reservoir" by storing high pressure air. The storage tank must meet two specifications. That is, it must be rated for the desired maximum pressure, and it must be of sufficient volume to give the desired run time. For safety reasons it should meet the ASME Code for Unfired Pressure Vessels. Costs and space available will determine the maximum practical size.

Valves. It is necessary to incorporate one or two valves in the system between the storage tank and the settling chamber. Ideally, one valve would be a quick-acting gate valve for rapidly initiating the flow, and the second valve would be a pressure regulator valve. The functions of the pressure regulator are to reduce the storage tank pressure to the pressure necessary for a given Mach number, and to maintain it constantly at this value in the settling chamber. To adequately perform this task the valve must quickly stabilize from zero flow to full flow conditions. It is entirely possible to replace this automatic pressure regulator with a manually operated valve. By working in conjunction with a large pressure indicator from the settling chamber, an operator can successfully maintain the required pressure in the settling chamber after a little practice.

Settling Chamber. The function of the settling chamber is to act as constant pressure source of low turbulence air for the wind tunnel. The air is reduced in pressure by a pressure regulator. Air out of the regulator valve is turbulent. It is necessary to suppress this turbulence. This can be accomplished by providing a large area such that the flow slows down, and by incorporating damping screens in the settling chamber design.

Nozzle. The function of the nozzle is to efficiently expand the air from the settling chamber to the desired Mach number in the test section. It must produce uniform, parallel, shock-free flow in the test section. The nozzle must be of converging-diverging configuration. Variation of Mach number can be accomplished by any one of three methods: a flexible wall nozzle, a sliding block nozzle, and a nozzle employing replaceable nozzle blocks. Replaceable nozzle blocks are the most feasible for small intermittent wind tunnels.

Test Section. The test section is the region of the wind tunnel from which data are obtained. A square cross section is the most practical configuration for a small supersonic wind tunnel. Since a small wind tunnel is being contemplated, the test section and the nozzle must be designed as one unit. Provisions for windows in the test section must be made such that optical viewing is possible.

Diffuser. The function of the diffuser is to deccelerate the flow from the test section Mach number down to a low subsonic Mach number that can be exhausted to the atmosphere. Furthermore, it must do this efficiently. The diffuser must necessarily consist of a supersonic portion and a subsonic portion. The supersonic portion must be a decrease in area following the test section. The subsonic portion must consist of a gradually increasing area. Between the supersonic and the subsonic portions, the flow will pass through a shock wave or a series of shock waves. These will be either one normal shock wave or one or more oblique shock waves. The latter would be preferable from an efficiency standpoint. An increase in diffuser efficiency will be realized as an increase in run duration and a decrease in the noise level.

Instrumentation. Any wind tunnel is only as good as its instrumentation. This is the limiting factor. Provisions should be made to take force, pressure, temperature, and optical data. Ordinary sensing devices may be used, however automatic recorders will be necessary due to short run times. Force data may be obtained by incorporating a strain gage balance in the model support. Pressures may be obtained by use of a conventional manometer board. Temperatures may be taken by using rapid responding thermocouples. Shadowgraph and schlieren systems are practical means of obtaining optical data.

BASIC DESIGN CONSIDERATIONS

Proposed Uses

In order to successfully design any system, the proposed use of the system must be carefully studied. Wind tunnels may be designed with three different uses in mind. They are used for basic research, for design and development, and for instructional purposes. These three possible uses impose different requirements on the design of the system. For instance a wind tunnel to be used in design and development work needs to be quite elaborate. The wind tunnel should be as large as economically feasible to eliminate doubt in scaling factors. It should be automated as much as possible to enable the securing of data to be tied directly to a production schedule. These characteristics would be desirable to have in any type, however they are not required for satisfactory operation in all types. Particularly in the case of use for instructional purposes, where simplicity is a prime requisite, much of the equipment would prove to be costly luxuries.

Any wind tunnel built at a university such as Oregon State would be used primarily as an instructional aid and for basic research work. Both of these purposes can be served in one installation. The installation would necessarily be small and simple. It would be suitable for conducting basic research on small aerodynamic shapes. It would also be suitable for use by students in the conduction of simple experiments connected with the study of supersonic aerodynamics.

Required Performance

In order to decide what acceptable performance is to be, it must be decided how the performance of a wind tunnel is to be measured. A wind tunnel attempts to simulate true flight conditions in the laboratory where they can be studied. In order to have similitude, certain similarity parameters must be duplicated. The two most important similarity parameters are the Mach number and the Reynolds number. Thus the range of Mach numbers and Reynolds numbers that a wind tunnel can duplicate is a very good measure of the performance of that wind tunnel.

Since a special type of wind tunnel is being considered, at least two additional parameters must be considered. These parameters are the run duration and the recharge time. The run time is a measure of the length of time that steady state conditions exist in the test section. It is a function of many factors, including storage tank volume, stagnation pressure, stagnation temperature, and test section size. The recharge time is mainly a function of the compressor capacity and the storage tank volume. Each of the above listed parameters must be discussed in detail to determine acceptable values.

Mach Number. To make the proposed wind tunnel a useful tool it should be designed to cover a Mach number range that may reasonably be expected in flight. Presently airplanes that remain within the atmosphere are performing at Mach numbers up to 3.0. In the near future, Mach numbers approaching 4.0 can be expected. Missiles greatly exceed these Mach numbers already. Practical limitations on the Mach number of a simple installation occur at about Mach 4.5. At higher Mach numbers it is necessary to heat the air to prevent it from condensing. Mach numbers near 1.0 are hard to obtain without special test sections designed to overcome stability problems. Therefore, a Mach number range of 1.5 to 4.0 seems to be desirable and practical.

Reynolds Number. Reynolds numbers presently encountered in real flight are of the order of 10^8 based on the chord. Higher Reynolds numbers may be expected in the future. Reynolds numbers this high can be obtained only in very large systems or in systems using very high stagnation pressures. Neither of these methods is feasible for this design. A minimum Reynolds number of 1×10^6 is fixed as being the acceptable lower limit, if attainable at all Mach numbers.

Run Duration. The minimum useable run duration is a function of the instrumentation only. Data may be taken without automatic recorders in times of approximately ten seconds. Ordinary pressure reading manometers can be read in seven to ten seconds. (17, p. 475) Force data from strain gage balances can be obtained in ten seconds. Obviously automatic recording equipment reduces the necessary minimum run duration. A minimum acceptable run duration of ten seconds, at all Mach numbers, is deemed satisfactory.

Recharge Time. The recharge time is determined by the capacity of the compressor and the storage volume. Maximum acceptable recharge time is fixed by a utilization factor of the wind tunnel. If data must be produced on a rigid schedule, a small recharge time is required. Basic research and instructional applications can get by with longer recharge times. In the case at hand, the recharge time is fixed by the chosen storage volume and the capacity of the available compressor. A recharge time of the order of one-half hour is desirable and recharge times of the order of one hour are acceptable.

Performance Analysis

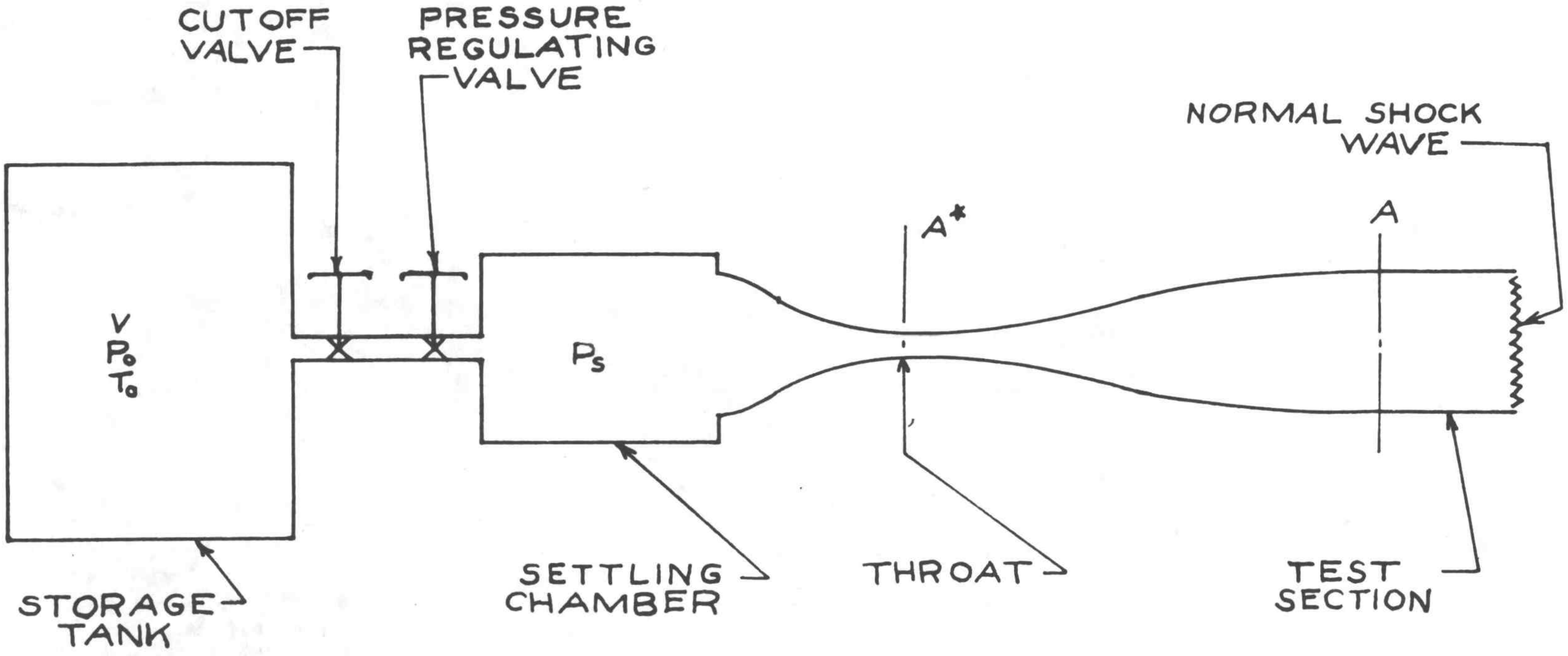
A quantitative description of the effects of various parameters on the performance of the wind tunnel must be presented. Parameters to be discussed include the Mach number, the Reynolds number, the run duration, and the recharge time. Certain characteristics of the air supply also enter into the problem. These include the stagnation temperature and the stagnation pressure.

In order to arrive at useable results, a model must be postulated as follows. Consider a large tank of volume V, initial pressure P_o, and initial temperature T_o that discharges into a settling chamber and then into a properly designed nozzle. A test section is located at the end of the nozzle. Following the test section, the air experiences a normal shock wave and is then discharged into the atmosphere. It should be noted that better performance can be realized by using a properly designed diffuser. However, assuming a model as shown in Figure 2, one will arrive at a conservative design.

At this point the choice of operating controls affects the analysis of the performance. The flow is controlled by valves installed between the storage tank and the settling chamber. One or two valves may be used. The first valve must be a cut-off valve. The second valve, if used, is a pressure-regulating valve. Its function is to reduce the high pressure air in the storage tank to a lower, constant pressure in the settling chamber. This has the effect of increasing the run duration as will be shown. Satisfactory systems can be designed with or without this pressure regulating valve.

PERFORMANCE ANALYSIS MODEL

FIGURE 2



Using the model in the figure, it is possible to derive the following equations.

Case I Without Throttling

For a polytropic process, in an isentropic perfect gas, in differential form.

$$\frac{dp}{dt} = n\frac{P}{\rho}\frac{d\rho}{dt} .$$

The time rate of change of density can be related to the mass flow out of the storage tank.

$$\rho = \frac{1}{V} M.$$

$$\frac{d\rho}{dt} = \frac{1}{V}\frac{dM}{dt} = \frac{-1}{V} w.$$

The mass flow at sonic velocity at the minimum area is given by the equation

$$w = \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}\ \frac{A*P}{\sqrt{T}} .$$

where P and T are the instantaneous values in the settling chamber. For the case with no throttling, these values are the same as the instantaneous values in the storage tank, assuming no losses inbetween. Therefore

$$\frac{dp}{dt} = \frac{-n}{v}\sqrt{kRT\quad\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}\ A*P.$$

But for a polytropic process the temperature and pressure are related by the equation

$$T = To\left(\frac{P}{Po}\right)^{\frac{n-1}{n}} ,$$

so that

$$\frac{dp}{dt} = -\frac{n}{v}\sqrt{kRTo(\frac{2}{k+1})^{\frac{k+1}{k-1}}}\quad P(\frac{P}{Po})^{\frac{n-1}{2n}}.$$

This equation may be integrated over the range P equals P_o to P equals P_s, and over the range t equals 0 to t equals t. This results in the following equation:

$$t = \frac{2}{n-1}\,\frac{V}{A^*}\,\frac{1}{\sqrt{kRTo}}\quad(\frac{2}{k+1})^{\frac{k+1}{2(1-k)}}\quad\left[(\frac{Po}{Ps})^{\frac{n-1}{2n}} - 1\right].$$

Assuming n equals k equals 1.4, it is possible to plot this equation in the following form:

$$t_c = \frac{tA^*\sqrt{To}}{V} = \frac{2}{(k-1)}\,\frac{1}{\sqrt{kR}}\,(\frac{2}{k+1})^{\frac{k+1}{2(1-K)}}\quad\left[(\frac{Po}{Ps})^{\frac{k-1}{2k}} - 1\right].$$

The results of this are shown in Figure 3.

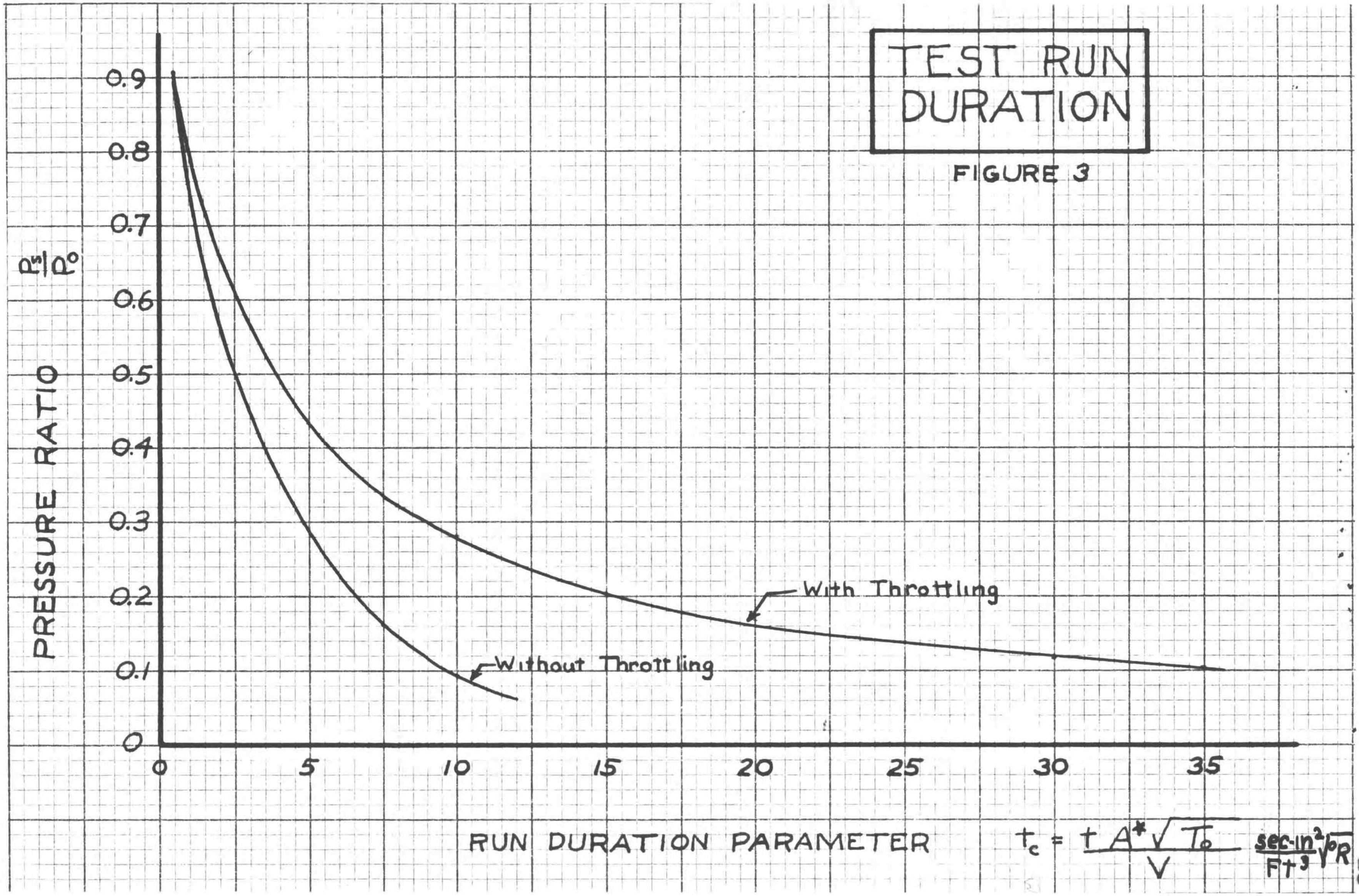
Case II With Throttling.

The derivation for the run duration with throttling proceeds in a similar manner up to the following equation:

$$\frac{dp}{dt} = \frac{n}{v}\,RT\,\frac{dM}{dt}\,x\ ,$$

$$\frac{dM}{dt} = -w = \sqrt{\frac{k}{R}\,(\frac{2}{k+1})^{\frac{k+1}{k-1}}}\quad\frac{A^*P}{\sqrt{T}}.$$

At this point the first difference appears. The pressure in the equation immediately above is now fixed as the minimum value acceptable to maintain supersonic flow at the desired Mach number. This results in



TEST RUN DURATION

FIGURE 3

$$\frac{dp}{dt} = -\frac{n}{v}\sqrt{kRTo\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}\quad A^{*}Ps\ \left(\frac{P}{Po}\right)^{\frac{n-1}{2n}}.$$

This can be integrated over the same range as the previous case to obtain

$$t = \frac{2}{n+1}\ \frac{V}{A^{*}}\ \frac{1}{\sqrt{kRTo}}\left(\frac{k}{k+1}\right)^{\frac{k+1}{2(1-k)}}\left[1 - \left(\frac{Ps}{Po}\right)^{\frac{n+1}{2n}}\right]\frac{Po}{Ps}.$$

Again this equation is plotted in the form

$$t_c = \frac{tA^{*}\ \sqrt{To}}{V} = \frac{2}{k+1}\ \frac{1}{\sqrt{kR}}\left(\frac{2}{k+1}\right)^{\frac{k+1}{2(1-k)}}\left[1 - \left(\frac{Ps}{Po}\right)^{\frac{k+1}{2k}}\right]\frac{Po}{Ps}.$$

The value of n is assumed to be the same. The plot is on the same coordinates as the case without throttling for easy comparison. (See Figure 3.)

Using the graphs in Figure 3 it is very easy to compute the run time for any given combination of test section size, tank volume, initial temperature, and fixed pressure ratio. It is interesting to compare run duration with throttling to run duration without throttling for the same conditions. Simple computations show that the ratio of throttled run time to unthrottled run time varies from 1.5 at low pressure ratios up to values approaching 4.0 for high pressure ratios. From this it is evident that a throttling valve is desirable, particularly in the case where tank volume is limited.

As can be seen from the equations, the run duration is dependent on the pressure ratio. The run duration increases as the pressure ratio increases. This pressure ratio is determined by the maximum initial pressure in the storage tank and the minimum pressure in the settling chamber that will maintain supersonic flow at a given Mach number. Since the wind tunnel exhausts to the atmosphere, the minimum pressure needed to maintain supersonic flow will be equal to the atmospheric pressure plus the pressure losses encountered between the settling chamber and the end of the diffuser. The largest single pressure loss in this portion of the wind tunnel will be the loss in total pressure as the supersonic flow passes through a shock wave, or through a series of shock waves. The worst loss that can be encountered is if the flow passes through a normal shock at the test section Mach number. By use of a second minimum area and a well designed diffuser, this loss can be minimized. A second method to reduce this loss is to cause the flow to pass through a series of oblique shocks instead of through one normal shock. To obtain conservative estimates of the performance and to circumvent difficulties in calculating exact frictional losses, it will be assumed that the flow passes through a normal shock. The minimum allowable pressure for each Mach number can be computed using shock relationships.

To start and maintain supersonic flow it is necessary to provide a pressure ratio high enough to overcome the decrease in stagnation pressure caused primarily by two different effects: friction and compression shock waves. Attempts to predict a necessary starting pressure ratio must consist of first estimating losses due to friction and then estimating losses due to compression shock waves. These losses will be expressed as pressure ratios. Their product is the pressure ratio needed to initiate supersonic flow.

The loss in stagnation pressure due to friction is intimately connected with the boundary layer. To further complicate things, the fluid is traversing a passage of changing area; thus a pressure gradient exists in the streamwise direction. Strictly theoretical solutions are impossible, or impractical due to the mathematical complexity of the problem. Available experimental evidence indicates that stagnation pressure losses, expressed as a ratio, will be in the range of 1.15 to 1.25. (12, p. 34) The fact that frictional losses are nearly constant as the velocity increases past Mach 1.0 is used to simplify the problem. The frictional loss at Mach 1.0 is used as the frictional loss, regardless of the Mach number. This pressure ratio would be the pressure ratio required to obtain sonic velocity in the throat of a converging-diverging nozzle. At Mach 1.0 no compression shocks exist, and therefore all losses are due to friction.

Losses due to compression shock waves are quite amenable to a theoretical treatment. The predictions will be arrived at by postulating the problem such that the worst possible set conditions will exist. This will result in a conservative estimate. The largest losses would be encountered if the flow experienced a normal shock wave at the test section Mach number. In practice, two methods will be used to reduce this loss. The first method is by reducing the flow area after the test section, and thereby reduce the Mach number and the associated loss. The second method is to induce the flow to pass through a series of oblique shock waves instead of one normal shock wave. This will also reduce the total loss in stagnation pressure.

Most texts concerned with compressible fluid flow derive the equation for the stagnation pressure ratio across a normal shock wave. (21) Within the assumption of a perfect gas, the following equation, in terms of Mach number before the shock wave, states a quantitative relationship between the stagnation pressure before and after a normal shock wave.

$$\frac{Po_2}{Po_1} = \left[\frac{\frac{k+1}{2} M_1^{\,2}}{1+\frac{k-1}{2} M_1^{\,2}}\right]^{\frac{k}{k-1}} \Bigg/ \left[\frac{2k}{k+1} M_1^{\,2} - \frac{k-1}{k+1}\right]^{\frac{1}{k-1}} .$$

where k is the ratio of specific heats at constant pressure and constant volume. For a perfect gas at normal temperature and pressure its value is 1.4 and the equation reduces to:

$$\frac{Po_2}{Po_1} = \left[\frac{1.2M_1^{\,2}}{1+0.2M_1^{\,2}}\right]^{7/2} \Bigg/ \left[\frac{2.8}{2.4} M_1^{\,2} - 0.167\right]^{5/2} .$$

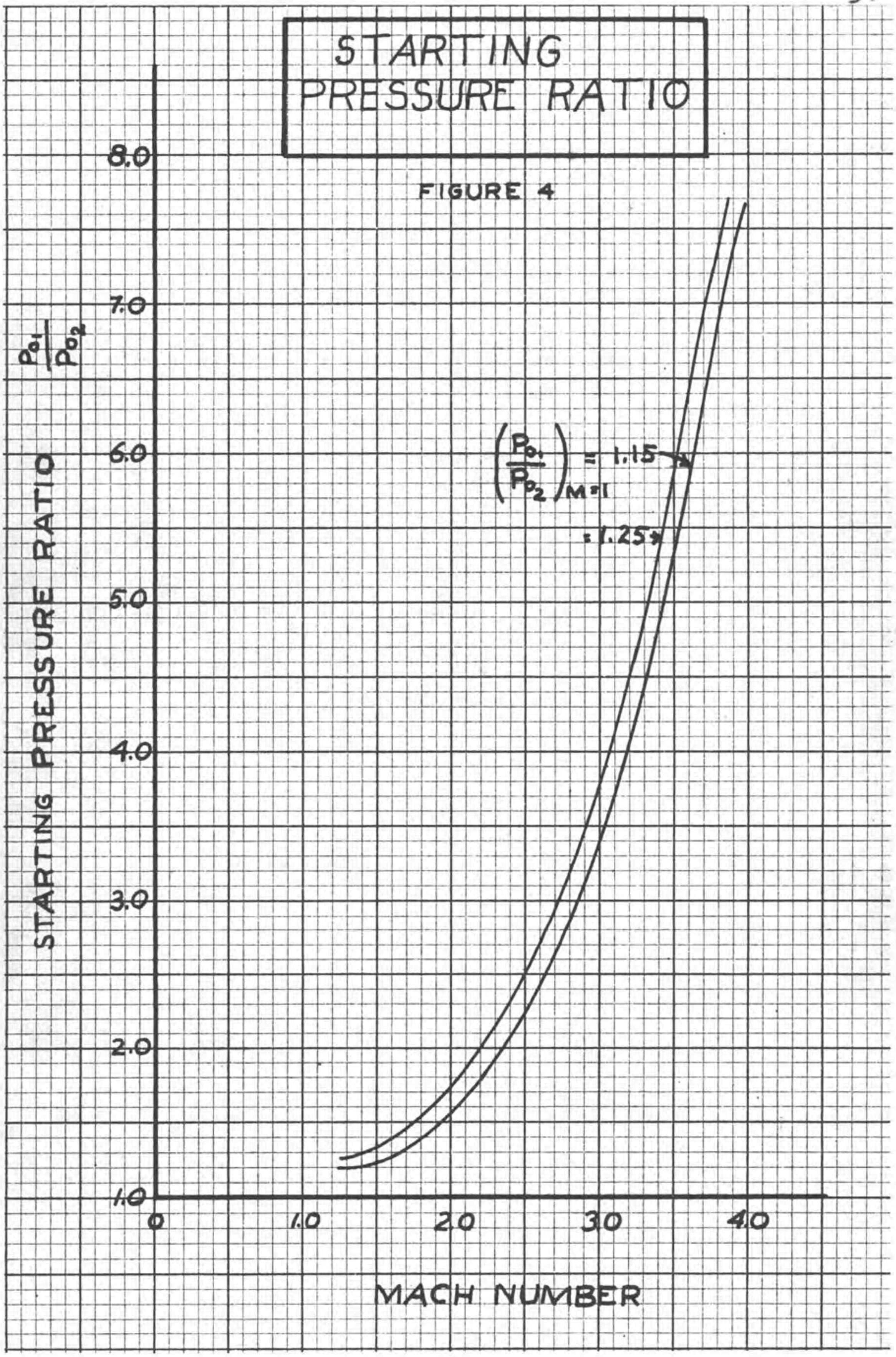
Thus the product of this ratio and the ratio of the pressures required to create Mach 1 flow at the minimum area will constitute the pressure ratio required to initiate and maintain the flow at the desired Mach number.

The pressure ratio that is required to start flow at a given Mach number is plotted in Figure 4 as a function of Mach number.

The effect of test section size on the allowable model size and the maximum Reynolds number must be investigated. By definition the Reynolds is

$$R_N = \frac{\rho VL}{\mu} .$$

The Reynolds number is determined by the test section stream parameters and by the size of the test model. The characteristic length of this equation is fixed by the size of the test section, the test Mach number, the angle of attack



STARTING PRESSURE RATIO

FIGURE 4

of the model, and the model configuration. This length is determined by the size of the test rhombus defined by the shock waves generated at the nose of the model and reflected from the walls of the wind tunnel as shown in Figure 5. The model must lie completely within this rhombus to avoid having the reflected shock wave impinging on it. It is easily seen that the model configuration, i.e., wing position, tail position, etc., will have a limiting effect on the allowable model size. For a simple flat plate, values of chord length divided by tunnel height versus Mach number are shown in Figure 6.

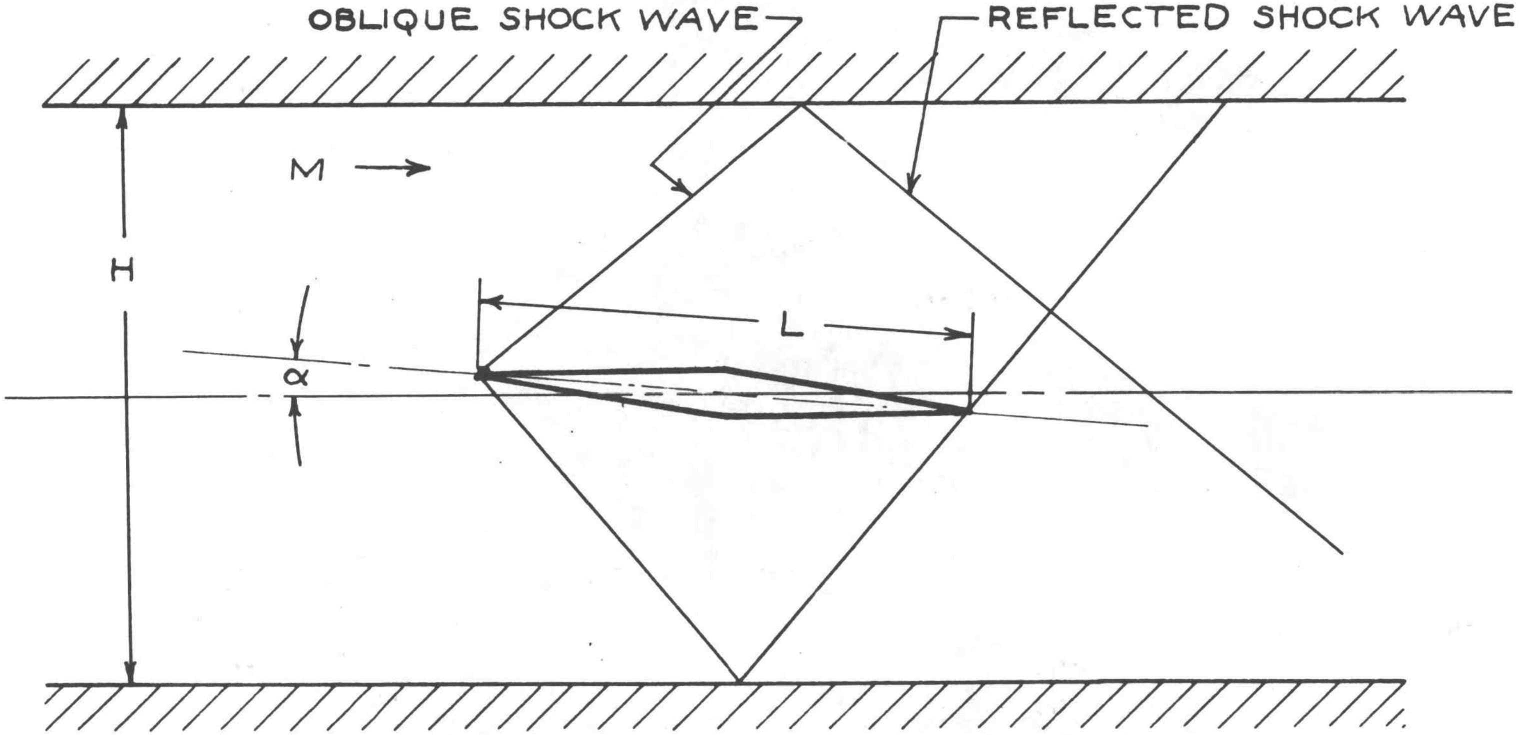
All properties of the air in the test section are uniquely determined by the conditions in the settling chamber and the geometry of the nozzle. The density and the velocity are directly related to the Mach number. The viscosity, according to the kinetic theory of gases, is dependent solely on the absolute temperature. Viscosity is related to the temperature by the Sutherland formula:

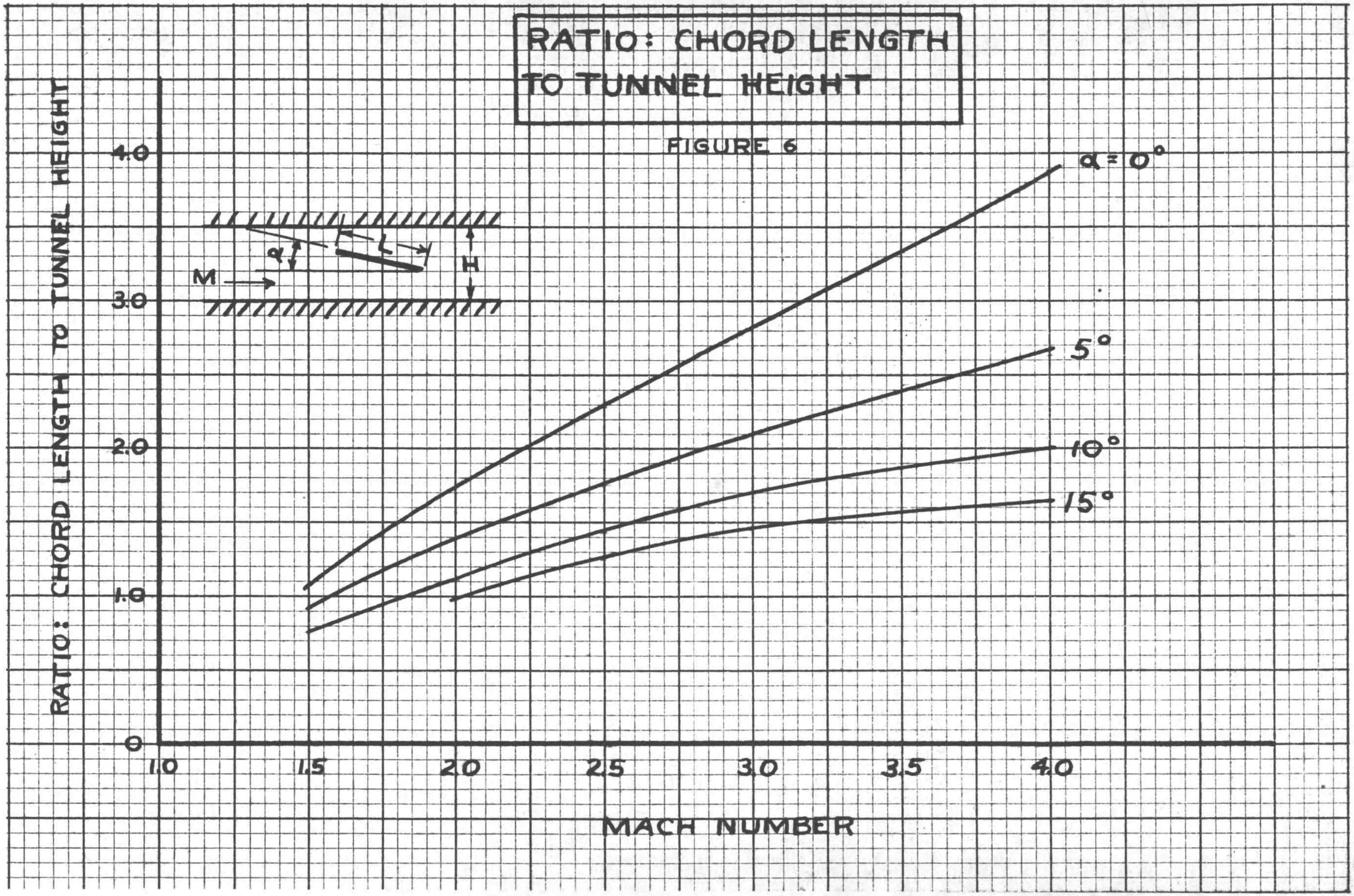
$$\mu = \frac{258.3}{T+216} \left(\frac{T}{500}\right)^{3/2} \times 10^{-6} \quad \frac{\text{lb sec}}{\text{ft}^2} \quad .$$

Using the above facts, it is possible to calculate the Reynolds number per inch versus Mach number for several values of settling chamber pressure. The results of these calculations are shown in Figure 7. These Reynolds numbers are based on a constant stagnation temperature of 520°R.

TEST RHOMBUS

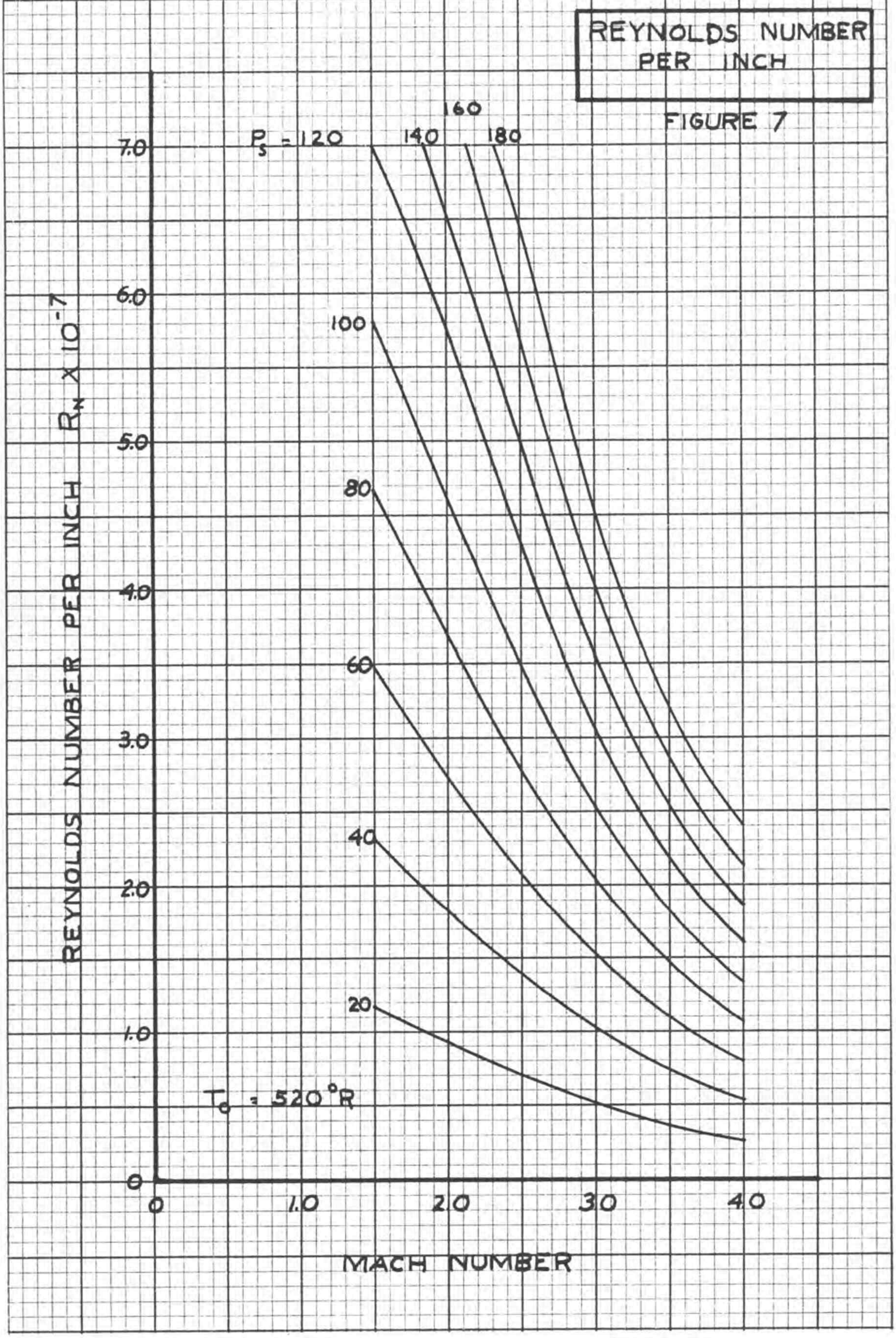
FIGURE 5





RATIO: CHORD LENGTH TO TUNNEL HEIGHT

FIGURE 6


REYNOLDS NUMBER PER INCH
FIGURE 7
REYNOLDS NUMBER PER INCH $R_N \times 10^{-7}$
MACH NUMBER
P_S = 120
140
160
180
100
80
60
40
20
T_O = 520°R
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
0
1.0
2.0
3.0
4.0

Size

The overall size and performance of an intermittent wind tunnel can be fixed by choosing values for the storage pressure, the storage volume, and the test section size. By using the contents of the previous section, it is possible to select values for these parameters.

The storage pressure is fixed at 200 psig by the capabilities of the available compressor. The maximum size of the storage tank is limited to a size that would pass through the existing crane-way; the weight was limited by the capacity of the crane. A tank volume of 300 cubic feet was chosen. It is satisfactory from the standpoint of run duration and cost.

As soon as the storage pressure and storage volume are fixed, it is possible to fix the size of the test section. The size should be as large as possible within the limitations of run duration and cost. At this point a size is selected and then checked against performance requirements. The test section was chosen to be four inches square. That is, the flow area is 16 square inches and the sides are four inches long.

By using data and equations of the previous section, it is possible to show that this size is satisfactory. A Reynolds number of 25×10^6 per inch is available at all Mach numbers, with a run duration of at least ten seconds.

It is also possible to show that the minimum run duration of ten seconds is obtainable over the Mach number range of 1.5 to 4.0.

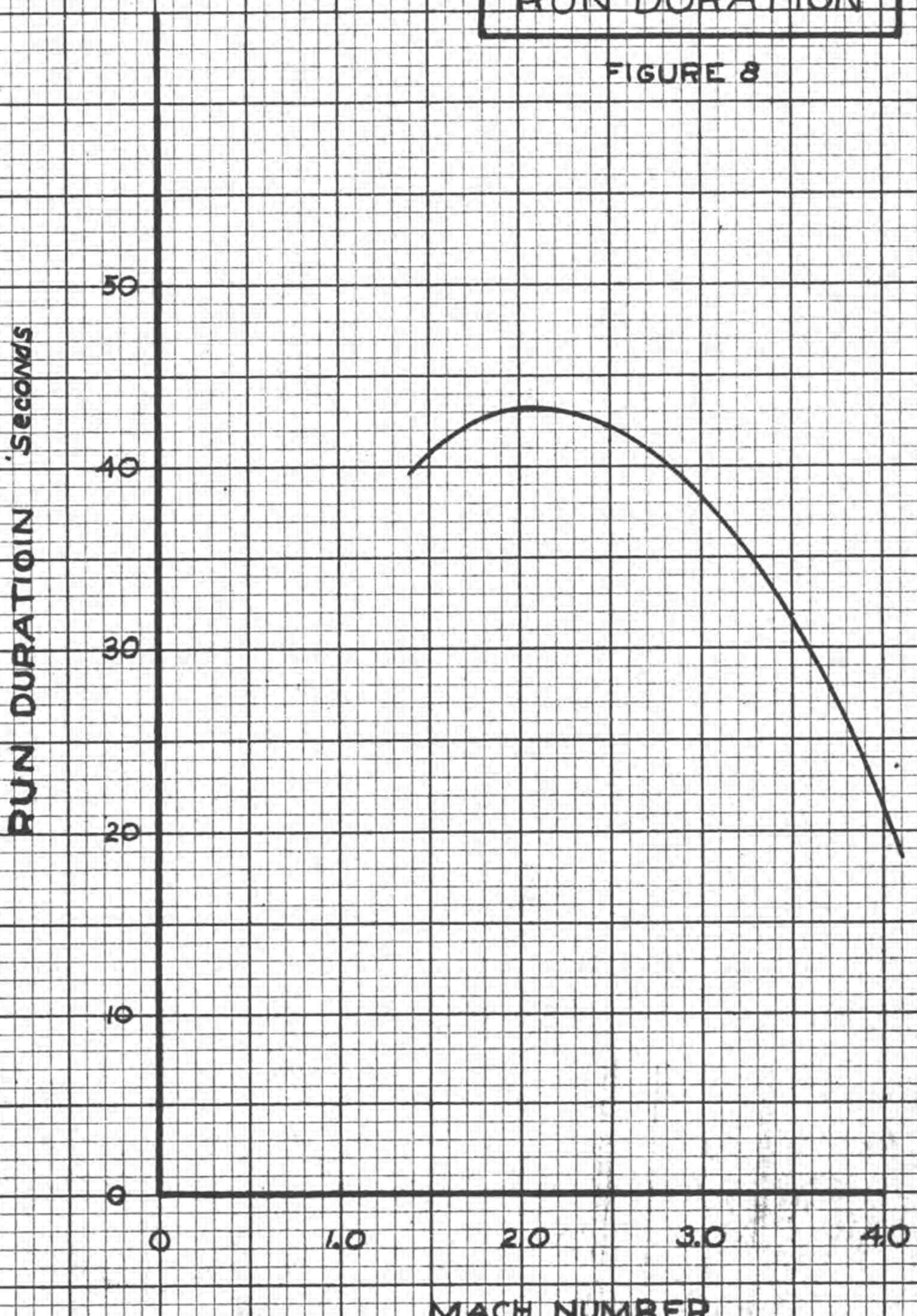
Performance

It is now possible to compute exact run duration, Reynolds number capabilities, and Mach number range for a wind tunnel of size just chosen.

A graph of maximum run duration versus Mach number is presented in Figure 8. This graph shows that a maximum run duration exists at a Mach number of 2.0. This can be explained as follows. At low Mach numbers the throat area is large, and therefore the mass flow is large. Consequently the run durations at low Mach numbers will be low. As the Mach number increases, the throat area decreases. Thus the run duration increases. Another effect is occurring concurrently however. As the Mach number increases, the required settling chamber pressure also increases. This increase is necessary to overcome the higher losses associated with a normal shock wave at the higher Mach number. This effect increases rapidly with Mach number, and becomes the dominant factor for Mach numbers above 2.0. Thus the run duration will fall off above Mach 2.0 as is shown. Essentially the run duration is limited at low Mach

RUN DURATION

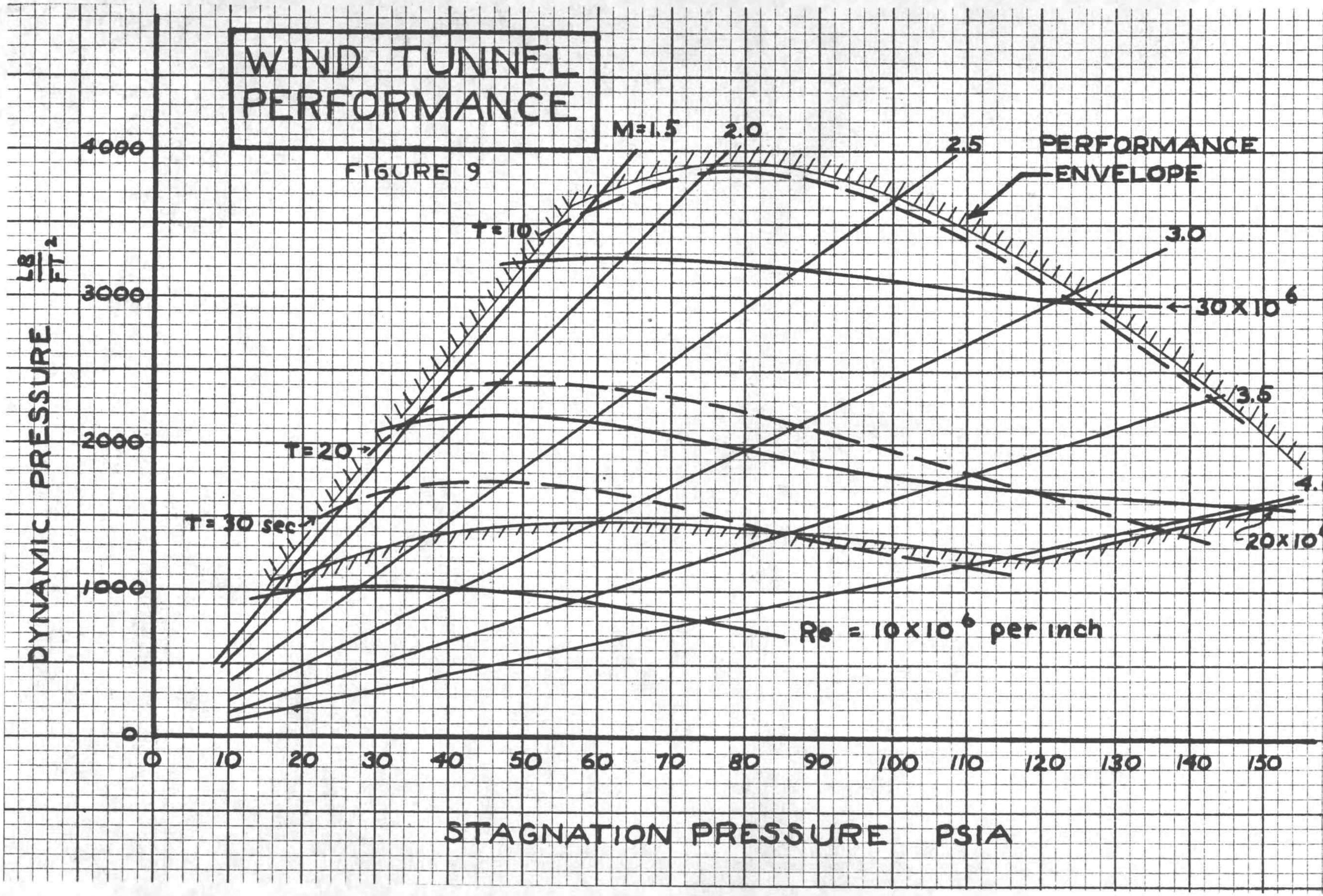
FIGURE 8



numbers due to excessive mass flow, and at high Mach numbers due to large pressure losses associated with normal shock waves at high Mach numbers. The first set of nozzle blocks was designed for a Mach number of 2.0 to take advantage of this maximum.

The performance of this wind tunnel can be summarized on one graph. The ordinate of the graph is the dynamic pressure, and the abscissa is the pressure in the settling chamber. Lines of constant Mach number appear as straight lines passing through the origin. Lines of constant Reynolds number per inch appear as solid lines. Lines of constant run duration are shown as dashed lines. Capabilities of this particular wind tunnel fall within the envelope defined by minimum settling chamber pressure, maximum allowable test section pressure, minimum acceptable run duration, and maximum Mach number. This graph is shown in Figure 9.

The capacity of the compressor and the storage volume determine the length of time that is required to recharge after each run. The compressor that is being used in this system has a capacity of 200 cfm at all output pressures up to 200 psig. A simple calculation fixes the recharge at about 15 minutes. This is true with the compressor working against a constant output pressure. This is ensured by the back pressure valve in the system between the



WIND TUNNEL PERFORMANCE

FIGURE 9

drier and the storage tank.

Safety Considerations

High pressure air is very dangerous if not handled with the respect that it deserves. Safety is the first design consideration in all components of the system. Neglect of safety considerations will endanger personnel and equipment. This section enumerates specific safety problems.

All pressure vessels in the system must be designed to comply with the safety standards listed in the *ASME Code for Un-Fired Pressure Vessels*. There are four pressure vessels in the system that must meet these standards. They are the oil filter, the air dryer, the storage tank, and the settling chamber. The actual design of the storage tank and the settling chamber was not attempted. Specifications were submitted to various fabricators for final design and bid. Safety was assured by requiring that these vessels be registered ASME Code vessels. The design of the oil filter and air dryer makes use of standard pipe and pipe fittings. These vessels must be hydrostatically tested to one and one-half times their rated working pressure before they can be registered. No difficulties are envisioned in obtaining certification for these vessels.

Safety in operation as well as safety in design must be carefully considered. Initial trials must be at low settling chamber pressures and subsonic velocities. The full capabilities of the system should be reached gradually.

Intermittent wind tunnels impose large loads on test models. This necessitates a careful and complete stress analysis of the test models. Loads are highest during starting and stopping operations. These starting loads may be partially alleviated by avoiding abrupt starts or stops. The starting or stopping operations should last for at least one second. (27, p. 51) The loads may also be reduced by having the test model initially at zero degrees angle of attack and by reducing the stagnation pressure to the minimum value required for starting. The model and sting can also be braced during starting and stopping.

Future Expansion

The wind tunnel must be designed with possibilities of future expansion in mind. This is particularly true due to the manner in which funds become available. Several profitable additions will be described.

The first desirable addition would be a means of varying the Mach number continuously over the entire Mach number range of the system. This would require a complete re-design of the test section. Procedures for designing variable Mach number sliding-block nozzles have been developed. (1) (24)

Three things can be done to the air supply to improve either performance or operating procedure. The first one is to install an automatic pressure regulating device in the system in place of the manually operated valve. This would simplify operation and reduce the number of personnel needed to run the system. The second improvement would be an attempt to stabilize the stagnation temperature. This can be done by adding a heat sink, in the form of a metallic matrix, in the storage tank. This matrix must have a large surface area and a small volume. Larger installations have successfully used ordinary tin cans with the ends removed. (6, p. 5) A constant stagnation temperature would result in a constant Reynolds number for an entire run. The third improvement would be the addition of storage volume. This would increase the run duration available at all Mach numbers.

After the initial installation is completed, the most profitable additions to the system would be to the instrumentation. The eventual goal should be to have automatic recording of all force and temperature data. A multi-channel recording oscillograph would be the ideal instrument to accomplish this. An eight channel recorder would be sufficient.

The Mach number range of the system can be extended to the transonic and subsonic regions by re-design of the test section. A ventilated test section is required for operation in the transonic range. A two-dimensional test section would be the most useful for subsonic testing in a tunnel of this sort.

DETAILED DESIGN CONSIDERATIONS

Air Supply

At the heart of any wind tunnel system is the air supply. The performance of the wind tunnel is intimately connected with the air supply. The air supply is composed of four major components: The compressor, the oil filter, the air dryer, and the storage tank. Each will be considered in detail.

Compressor. In order to economize, a compressor already owned by the Mechanical Engineering Department was chosen for the air supply. Its characteristics and capabilities will influence the choice of other components. The important performance characteristics of this compressor will now be listed.

The compressor is a two stage Chicago Pneumatic compressor with an intercooler. It is powered by a 60 horsepower electric motor that drives it at +200 rpm. At this rate, the capacity of the compressor is 200 cfm at all discharge pressures up to 200 pounds per square inch. The discharge temperature is approximately $200^{\circ}F$ at this pressure. The working pressure and temperature specifications for the storage tank were based on these values.

The fact that the compressor is equipped with an intercooler is an additional benefit. The intercooler helps to condense out a good deal of the humidity taken in in the inlet air. Based on tests, it was determined that, due to compression and intercooling processes, the dew point of the exit air was about 45°F at standard temperature and pressure. It is felt that this will enable running at Mach numbers of up to 2.0 without further drying the air. According to Pope (17, p. 273) it is possible to run at Mach numbers up to 1.6 without drying at all. Therefore the initial installation will not include an air dryer. The dryer may be added later when it is needed.

A detrimental characteristic of this compressor, and most others, is that it contaminates the air with a good deal of oil. To protect the desiccant in a dryer, and to prevent contamination of the test section and test models, it is necessary to install an oil filter in the system between the compressor and the air dryer.

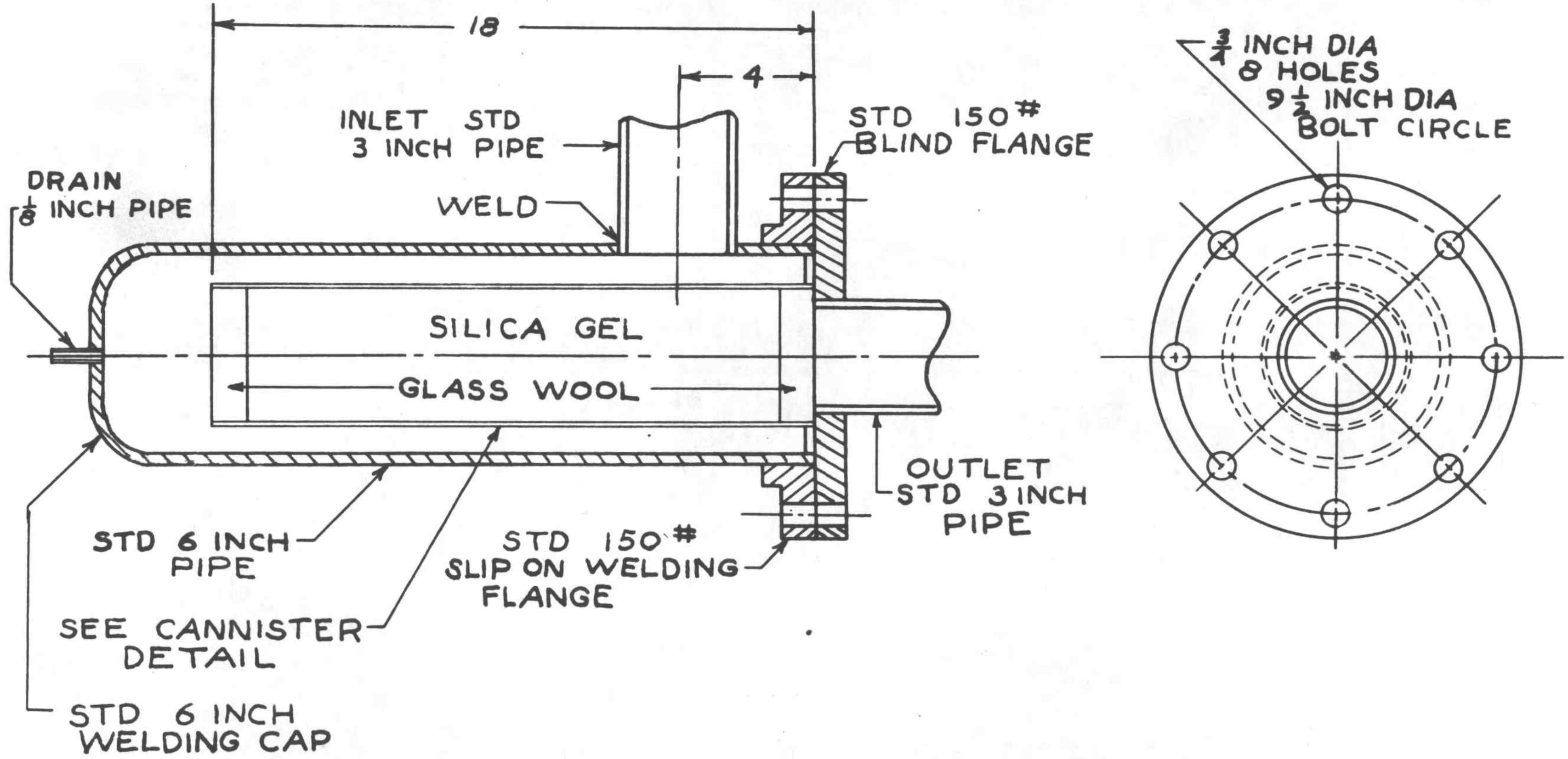
<u>Oil Filter</u>. A simple oil filter making use of both mechanical action and chemical action is proposed. It is

constructed out of a piece of standard six-inch pipe 18 inches long. A seamless welding cap is used to close one end. The other end is blocked with a standard slip-on welding flange and a blind flange. The blind flange is drilled in the center to receive a standard three-inch pipe that acts as the outlet. The inlet to the oil filter is through a three-inch pipe welded to the side-wall of the six-inch pipe. A tube, four inches in diameter, extends down the center of the six-inch pipe, and acts as a holder for the desiccant. The inlet air is forced to make a right angle turn upon entering. It is then forced to travel down along the outside of the four-inch tube. When it reaches the end of this tube it must turn through an angle of 180° so that it can continue up through the desiccant to the exit. The sharp turns will cause a certain amount of oil and water to be separated from the air. This condensate will collect at the bottom of the filter and must be drained off occasionally through the drain provided. The filter is shown in Figure 10. The filter should be installed in the vertical position.

Because of low volume flow at high pressure, the flow velocities are sufficiently low to preclude large pressure losses in the filter. Calculations show that

OIL FILTER

FIGURE 10



the velocity through the silica gel will be about 30 feet per second. At this velocity the pressure loss through the desiccant will be about one inch of water.

For best operation of the desiccant oil filter, a simple mechanical filter should be installed between the compressor and the desiccant filter. Mechanical air line filters are commercially available. This will increase the useful life of the desiccant in the oil filter. (12, p. 11, 12)

Air Dryer. Temperatures near or below the liquification point of the constituents of air are encountered at high Mach numbers. To prevent condensation it is necessary to remove an appreciable amount of the water vapor in the air. Actually condensation does not occur when the dew point of the air is reached, but super-cooling occurs. The degree of super-saturation is determined mainly by the rate of growth, size, and number of condensation nuclei, the velocity of the air, and the time that is required for condensation to occur. A theoretical treatment of this subject, backed by some experimental evidence, is given by Burgess and Seashore (3). From their results it is possible to predict an inlet dew point necessary to prevent condensation from occurring for a given inlet temperature and Mach number. Examples of values predicted by this theory are as follows: for an inlet temperature of 200°F and a Mach number of 2.0, a dew point of -20°F is required. An even more extreme case is that a dew point of less than -70°F is required for operation at Mach 4.0 with a stagnation temperature of 650°F.

As the above figures indicate, complete prevention of condensation requires extensive drying. Experience has shown that condensation shocks occurring in air with a dew point of -40°F are very weak and difficult to detect. Therefore, for all except the most exacting experiments, an inlet dew point of -40°F is considered sufficiently low. Several authors concur in this opinion. (7, p. 268; 12, p. 11; 17, p. 470; 23, p. 2) Therefore the dryer employed in this system will be designed to give a dew point of -40°F. Estimations of the error caused by weak condensation shock waves can be obtained by methods outlined in the work of Smolderen. (22, p. 4, 5)

Methods of drying air must now be considered. They generally fall into two categories, defined by the method in which they remove the water from the air. One group relies on the thermodynamic properties of the air-water mixture. Compression or cooling of the mixture can cause saturation to occur, resulting in the water's being condensed. A second general method makes use of the physical properties of some materials that enable them to selectively adsorb certain molecules. These materials are characterized by extremely large surface areas for a given volume. This property enables them to trap molecules of water on their surface and retain them there. This process is known as adsorption. Silica gel, activated alumina, and activated charcoal are typical examples of good adsorbents.

A combination of the two methods of drying illustrated will be employed. A certain amount of water is removed by the compression process in the compressor. A further amount is separated out by the cooling effect of the intercooler of the compressor. Aftercooling of the effluent air would condense even more of it. An aftercooler is not presently available, but it would be beneficial for two reasons. It would condense water out of the air, and it would lower the temperature of the outgoing air, thereby increasing the efficiency of the adsorptive dryer following the aftercooler. This final dryer would employ a desiccant in sufficient volume to complete the drying process down to the desired dew point. Tests on the compressor indicate that the compression and intercooling processes depress the dew point by about 15°F at best. The desiccant dryer will be designed to give an outlet dew point of -40°F with inlet air taken directly from average atmospheric conditions.

Since the dryer is to follow the compressor, it must be designed to withstand the maximum output pressure of the compressor. The effect of increasing pressure on the performance of a desiccant is not well known. It is known however that the effects are beneficial. Experimental evidence indicates that equilibrium moisture content of a desiccant increases with pressure and decreases with temperature. (14, p. 267) Therefore the dryer should be on the high pressure side of the compressor, and it should be preceded by an aftercooler if possible. An additional benefit of high pressure is the small volume flow and low air velocities. This permits the use of small components.

The mechanical arrangement of the dryer must be such that the air is forced to pass through a bed or series of beds of the desiccant. A means of regeneration of the desiccant must be provided. This regeneration can be accomplished by circulating hot air through the desiccant in a direction opposite to the normal air flow direction or by removing the desiccant and heating it in an oven. The latter method will be used in this system because of its simplicity and low cost. By using this method, several fittings and a heater are eliminated. Two charges of the desiccant should be available so that operation will not be interrupted for long periods of time.

Factors governing the actual design of the desiccant dryer include the required dew point, the average inlet humidity and temperature, the type of desiccant, pressure in the dryer, volume flow of air, and length of time between regenerations. The dew point requirement, as stated previously, is -40°F. The average inlet humidity will be taken as 60 per cent. The inlet temperature to the dryer will be dictated by the temperature of the outlet air from the compressor. It is about 200°F. Silica gel is selected to be used as the desiccant because it is the most efficient of the common adsorbents. The volume flow is fixed by the capacity of the compressor as 200 cubic feet per minute at standard conditions.

A closer look must be given to the length of time between regenerations. This parameter, more than any other, determines the overall size of the dryer. Long periods of time between regenerations require large amounts of desiccant, and thus large dryers. A compromise between size and regeneration frequency must be reached. Since this wind tunnel is to be used for research and instructional purposes, it is likely to be utilized periodically rather than continuously. The capacity of the compressor will enable a maximum of three runs per hour. This is more than really necessary. Probably three runs in a three-hour laboratory period is a more realistic estimate of the utilization. If the tunnel was used continuously for an eight hour day, the number of runs would probably not exceed ten. However, this requires a dryer that is not economically feasible. Five runs between each regeneration is selected as an acceptable compromise. This will not be a serious limitation if a second charge of desiccant is available. The only lost time would be that necessary to change the desiccant.

By assuming a useful concentration of five per cent, 245 pounds of silica gel are required to remove the necessary amount of water. This silica gel is arranged in a bed 36 inches deep with a flow area of two square feet. This results in a face velocity of approximately nine feet per minute at 200 pounds per square inch. This is a low value compared to standard practice but is beneficial in at least two respects. It gives a contact time of about one-half minute. It also gives a very low pressure drop. The silica gel is contained in a removable cannister for ease of replacement. Glass wool is packed on the top and bottom of the silica gel to prevent dust from being carried to other parts of the system. Regeneration of the silica gel is to be accomplished by heating in an oven at a temperature of at least 350°F.

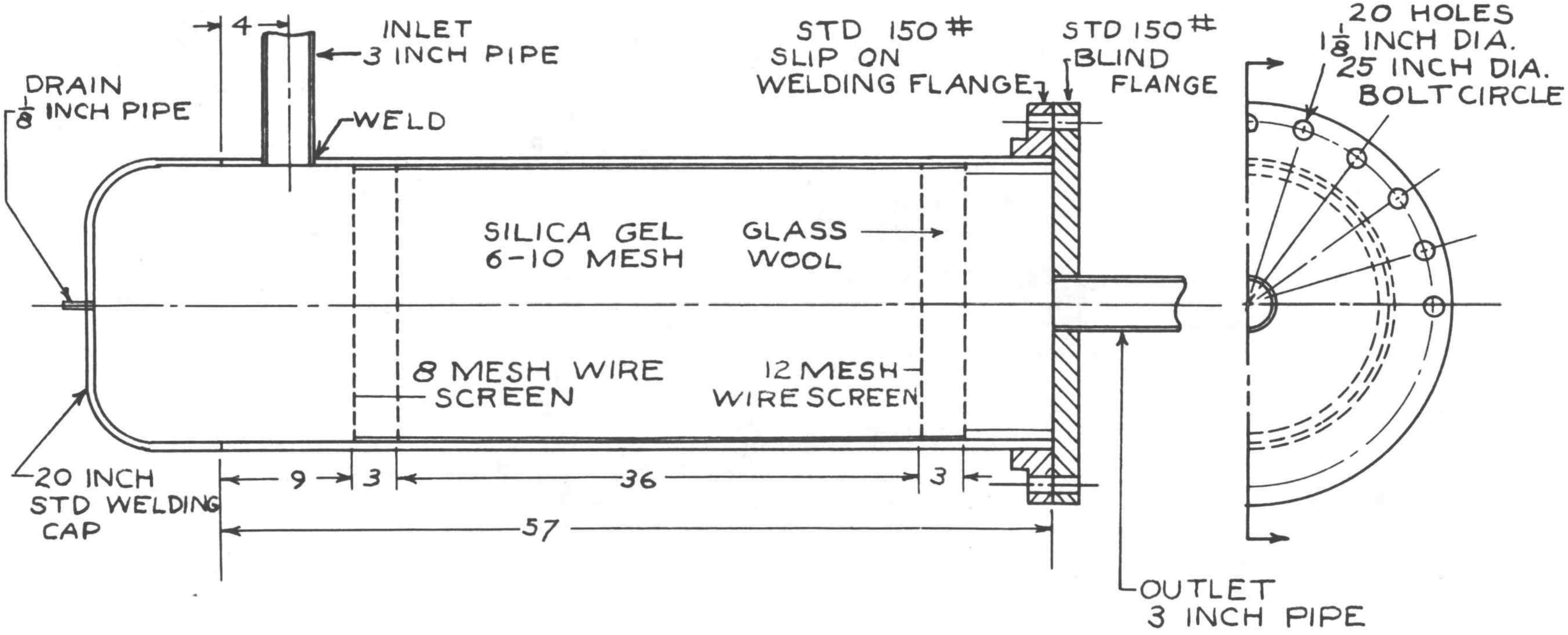
One last consideration is the pressure drop across the dryer. It can be readily estimated by a simple calculation as given by Smolderen (22, p. 33). This method results in a pressure drop of less than one inch of water. A graph of pressure drop versus face velocity given by Emley (7, p. 270) concurs in this estimate. This is very satisfactory.

The dryer is constructed out of standard 20 inch steel pipe. One end is closed by means of a welding cap. The other end has a slip-on welding flange and a blind flange. The dryer is to be installed in the vertical position with the welding cap at the bottom. The inlet is three-inch pipe welded on the side of the large pipe near the bottom. The exit is also a three-inch pipe. It is threaded into the center of the blind flange. The cannister is made out of sheet metal. The silica gel is supported on small mesh screen supported by larger mesh screen. Details of the dryer are shown in Figure 11.

Storage Tank. No attempt was made to actually design the storage tank. Specifications were written and submitted to interested manufacturers for final design and bidding. Working pressure and temperature of the tank were

AIR DRYER

FIGURE 11



fixed by characteristics of the compressor. Maximum volume of the tank was fixed by the requirement that the tank be able to pass through existing doors and crane-wells in the Engineering Laboratory.

The tank specifications were:

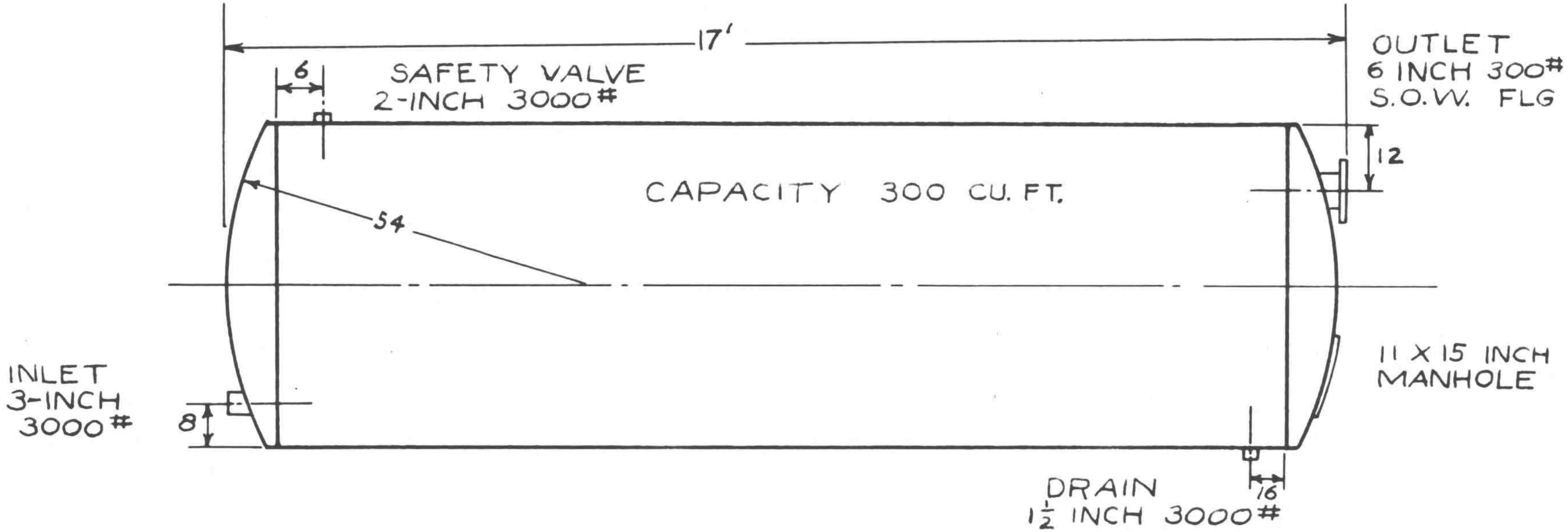
1. The tank shall meet all requirements of the ASME Code for Un-fired Pressure Vessels.
2. Working pressure -- 200 psig.
3. Working temperature -- 200°F.
4. Volume -- 300 cubic feet.
5. Overall dimensions not to exceed:
    a. Length 17' 0"
    b. Diameter 5' 6"
6. Maximum weight not to exceed 5 tons.
7. Fittings:
    a. Inlet -- Standard 3" pipe, threaded
    b. Outlet -- Standard 6" pipe, flanged

A detailed sketch of the tank is shown in Figure 12.

Control Valves. At least two valves are required for satisfactory operation of a wind tunnel of the type under consideration here. A quick-acting cutoff valve is needed to efficiently initiate flow. Any wasted time in this operation subtracts just that much time from the useable run durations of the system. The second valve required is a pressure regulator to reduce the pressure from the storage

STORAGE TANK

FIGURE 12



60" O.D. x 17'0" OVERALL
½ INCH SHELL ⅝ INCH HEADS
ASTM GR B STEEL

tank to some lower desired pressure in the settling chamber. A further job of this valve is to maintain the desired pressure in the settling chamber. The reason for the use of a pressure regulator valve is to increase the run time for given storage volume and pressure.

The size of these valves is of course chosen to fit the pipe from the storage tank. This pipe size was chosen to be standard six-inch flanged pipe. This size is larger than needed immediately. It does allow for later expansion when a larger test section might be employed with the addition of more storage volume.

The cutoff valve was chosen to be quick-acting gate valve because of the characteristic of gate valves that they offer little obstruction to flow when in the full open position. The pressure regulating valve was chosen to be a gate valve because they are relatively cheap and are readily available. It is intended to make use of a manually operated pressure regulating system. Such a system is adequate, especially for small installations. (22, p. 2) An operator will control the position of the valve to give the desired pressure, in the settling chamber. He will make the necessary corrections in the valve setting by watching a large, accurate pressure gage attached to the settling chamber.

Starting procedure has a material effect on the starting loads experienced by a test model. It has been found that very fast or very slow starting procedures will impose large loads on a test model. Starting procedures wherein the flow is initiated in a few seconds imposes the smallest starting loads on the model. Either an increase or a decrease in this starting time causes increased loads. (27)

Wind Tunnel

The several components of the wind tunnel include the settling chamber, the transition section, the test section and nozzle blocks, and the diffuser. The detailed design of each of these components will be discussed in this section.

Settling Chamber. The detailed design of the settling chamber must take into account several factors. These are cost, working pressure, working temperature, size, instrumentation, safety considerations, and prevention of turbulence.

The settling chamber is a pressure vessel with a working pressure of 200 psig and a working temperature of 200°F. To ensure safety, this vessel must comply with the safety standards of the *ASME Code for Un-Fired Pressure Vessels*.

The size of the settling chamber is patterned after the size of the settling chamber described by Lindsay and Chew. (12, p. 15) This results in a settling chamber 20 inches in outside diameter and 36 inches in length. This will give a contraction ratio of 22.5:1 at Mach 1.5. This ratio will be higher for all higher Mach numbers. It is sufficient to provide flow of low turbulence. (6, p. 7) Damping screens are also included to help suppress turbulence.

One end of the settling chamber must be designed to mate with a standard six-inch pipe flange that comes from the storage tank. The other end of the settling chamber must provide a transition from the circular area of the settling chamber to the rectangular area at the entrance to the nozzle. This is accomplished in two steps. Within the settling chamber itself, a cylindrical transition contracts the flow area from a circular shape to a rectangular shape 4.0 by 18.85 inches. Beginning at the end of the settling chamber a transition section further contracts the flow area into a rectangular area of 4.0 by 10.27 inches. The slope of the walls of this transition section is 15^o to match the slope of the nozzle blocks at the entrance.

Design details for the settling chamber are given in Figure 13. Details of the transition section are given in Figure 14.

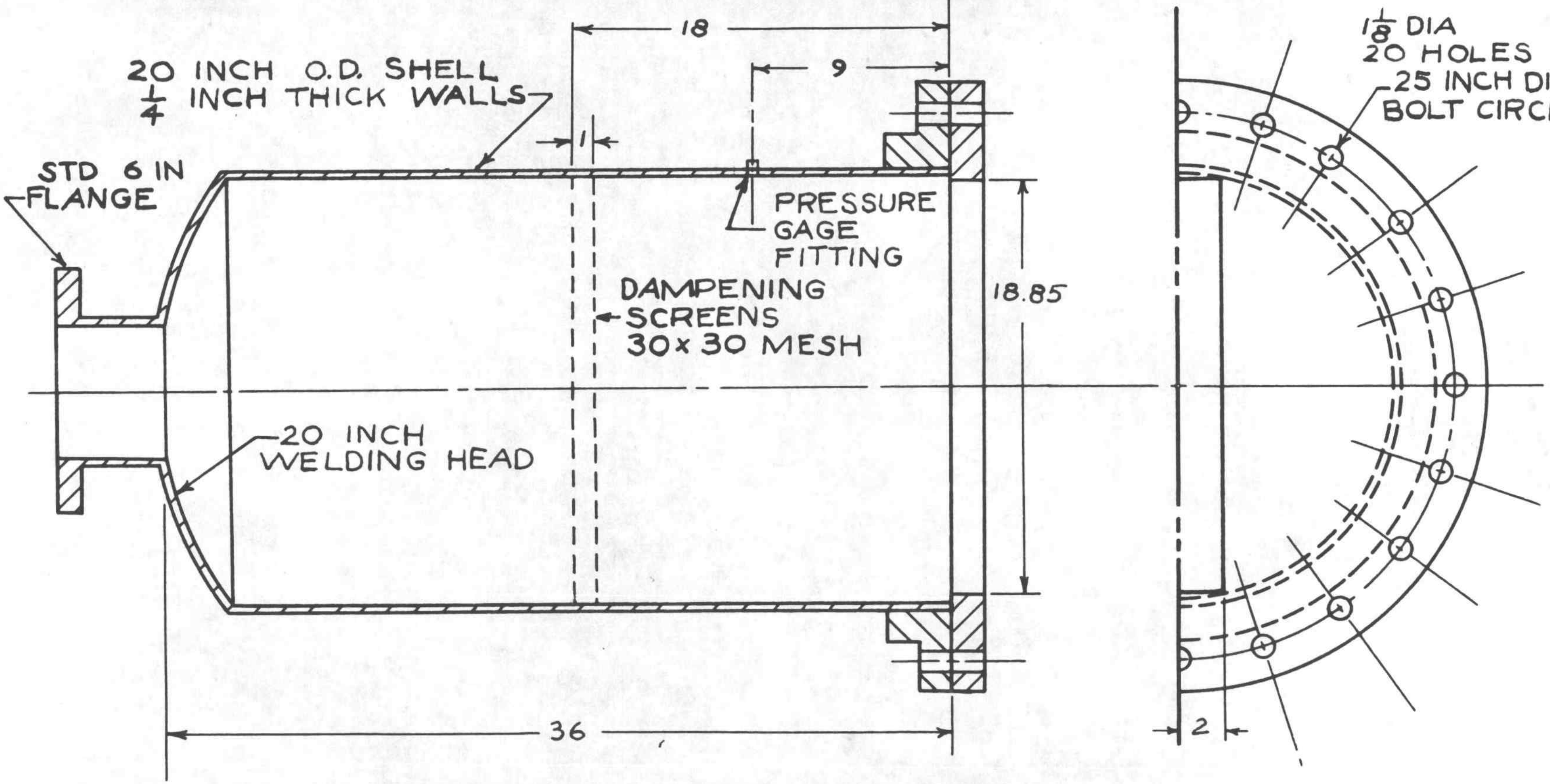
Test Section. The test section must be designed in conjunction with the nozzle blocks because of the small size of the test section. An additional requirement is that the nozzle blocks be removable. The test section acts as a positioning jig for the nozzle blocks, and as side walls for the tunnel. These side walls must be provided with windows to allow optical viewing of the test models. The test section must mate with the transition section on the upstream end and the diffuser on the downstream end.

The test section was designed to withstand a pressure of 200 psig. In normal operation this pressure will never be realized. However the deflection of the side walls will be small during operation for a test section designed for this pressure. This is very desirable in order to prevent distortions in the optical system due to the windows becoming non-parallel from wall deflections. Details of the test section design are shown in Figure 15.

The side walls of the test section are designed to be removable. The side walls also support the windows.

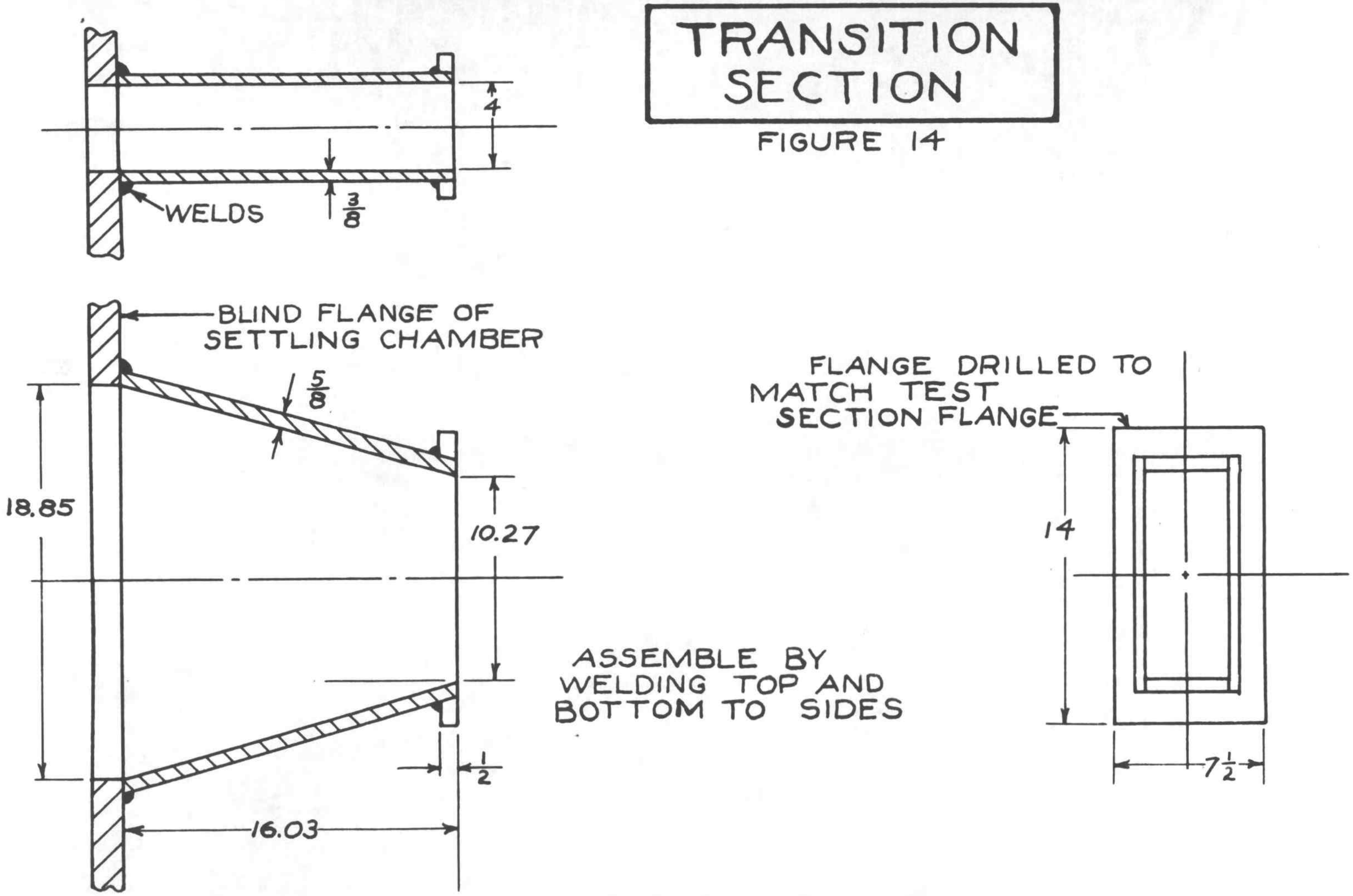
SETTLING CHAMBER

FIGURE 13



TRANSITION SECTION

FIGURE 14



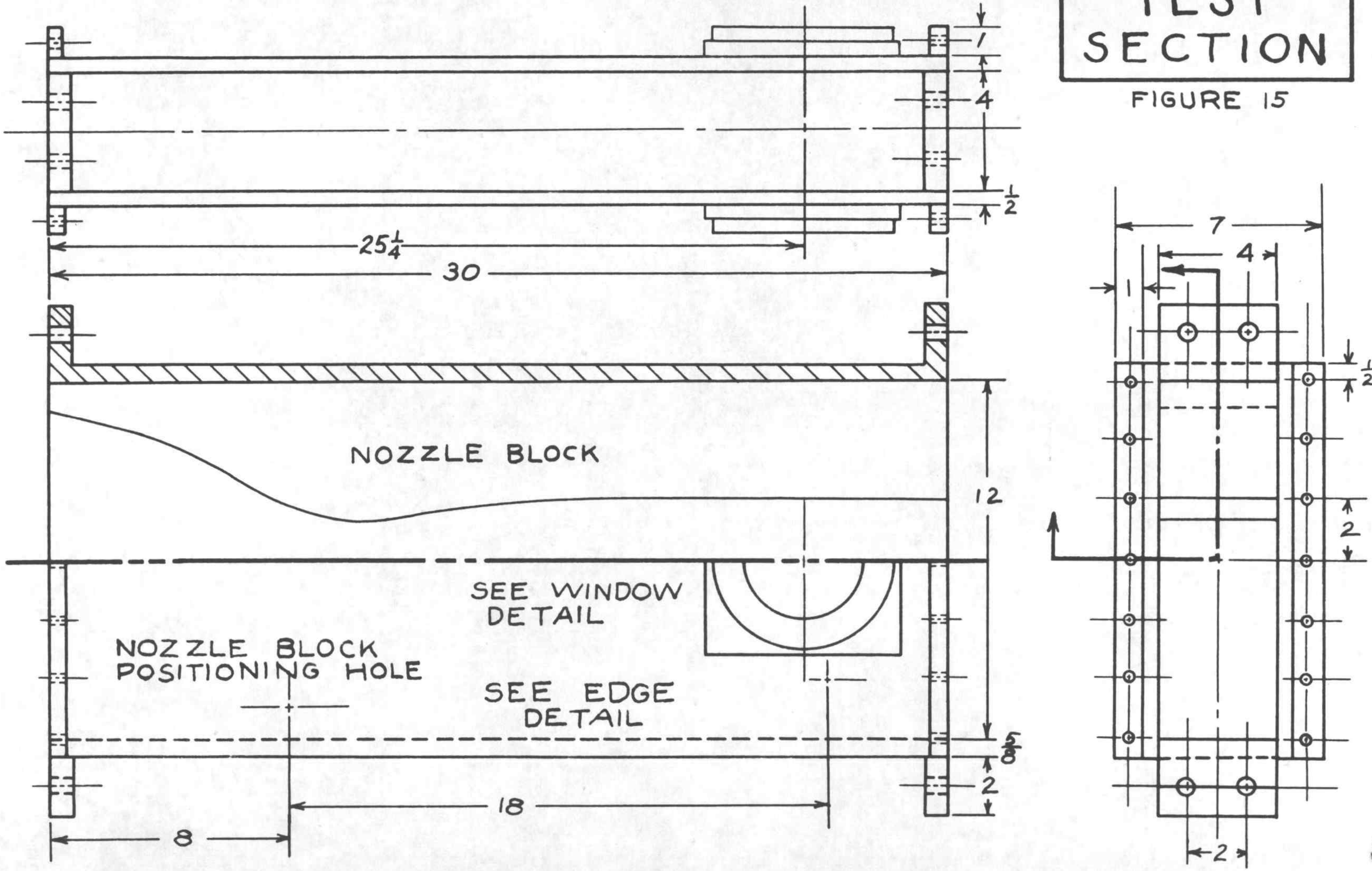
Details of mounting of the windows are shown in Figure 22 (Appendix). Seals must be provided on all mating surfaces. These seals take the form of neoprene strips supported in rectangular slots as shown in Figure 23 (Appendix).

Nozzle Blocks. It has been concluded elsewhere that the test section size will be 4 inches x 4 inches. The function of the nozzle and test section is to provide a jet of uniform parallel flow in which to test various models. In addition, this jet must be of the desired Mach number and it must be shock free. This requires careful design of the contours downstream of the throat.

A further requirement is that the Mach number be variable over a range from 1.25 to 4.0. This may be done by one of three methods:

1. Flexible nozzle
2. Sliding block nozzle
3. Replaceable nozzle blocks

The last method is chosen as being the most practical for the immediate needs. As a later extension of this system a sliding block arrangement could be incorporated. Extreme complexity of a flexible nozzle eliminates it from use for a small wind tunnel of this nature. The use of replaceable nozzle blocks requires that one set of nozzle blocks



TEST SECTION

FIGURE 15

be designed for each Mach number desired. Sets for Mach 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 would be desirable. As a start, nozzle blocks for a Mach number of 2.0 will be designed and fabricated. This Mach number is chosen because maximum run time is achieved at this point.

Two design problems must be faced in the design of a set of nozzle blocks for a particular Mach number. The first problem is to design the nozzle contours to produce the desired Mach number in the test section. These are designed on the assumption that the air is frictionless. These contours are then corrected for the growth of the boundary layer along the surfaces of the nozzle. Thus at each station the value of h/2 is increased by an amount equal to the boundary layer displacement thickness at that point.

First let us consider the problem of designing the initial nozzle contours. This proceeds by applying the method of characteristics. Generally, there are three schemes by which this is done:

1. Busemann's method
2. Puckett's method
3. Foelsch's method (5)

Busemann's method is a direct application of the

Method of Characteristics. It begins with the assumption of the shape and the position of the sonic line in or near the nozzle throat. From this starting point, the flow is expanded in a series of equi-angular corners out to the desired degree. The resulting Mach waves are cancelled out by then turning the flow inward as required. The result will be uniform, parallel, shock-free flow in the test section.

Puckett's method is similar to Busemann's except the one starts at the inflection point and works both ways. It must be realized, of course, that all converging-diverging nozzles except the sharp cornered nozzle will have an inflection point in the wall curve. Starting at this point, the following boundary conditions are assumed. The flow at this point is of uniform speed, and uniformly varying direction of flow. It is then possible to design the downstream portion of the nozzle to provide the required uniform, parallel flow at the exit. By working upstream from the inflection point it also is possible to design the initial curve. It can be shown that an infinite number of initial curves will be satisfactory. Thus, within reason, it is possible to use any curve, for this initial curve, that satisfies the following requirements:

1. The slope of the assumed curve must be that required for the given Mach number.

2. The curve must contain no discontinuities.
3. The curve must provide the required area ratio.

The advantages of this method over Busemann's method is that it cuts the work in half. An initial curve is assumed, and only the final curve is designed by the method of characteristics.

The Foelsch method takes advantage of the fact that there is a region in the downstream portion of a nozzle where the equations of flow can be solved in closed form. Starting at the inflection point, the following boundary conditions are chosen:

1. Along Mach lines emanating from the inflection point, the velocity vectors are co-original.
2. The Mach number is constant along the arc of the circle passing through the inflection point with its center located at the origin of the velocity vectors.
3. In the region between this arc and the Mach line from the inflection point, the Mach number is a function of the radius from the vector origin only.

As with Puckett's method, an initial curve is assumed. The obvious advantage of this method is that it is analytical. Coordinates of the terminal curve can be computed to any desired degree of accuracy from the following equations:

$$x - x_1 = x_2 - x_1 + l \cos (v_t - v + d)$$

$$y = y_2 + l \sin (v_t - v + d)$$

Terms are defined in Figure 16.

Experience shows that a good nozzle design should lie between the sharp cornered nozzle and the excessively long nozzle. The short nozzle is very sensitive to small errors in the region of the throat. These small errors result in large errors in the test section. Also some adverse boundary layer effects may be encountered at the sharp corner. The excessively long nozzle suffers from excessive boundary layer growth, and the fact that it requires more material to fabricate it.

A satisfactory initial curve is given by the following equation:

$$Y = Y_o + \left(\frac{\tan \theta_1}{X_1}\right) X^2 - \left(1 - \frac{X}{3X_1}\right)$$

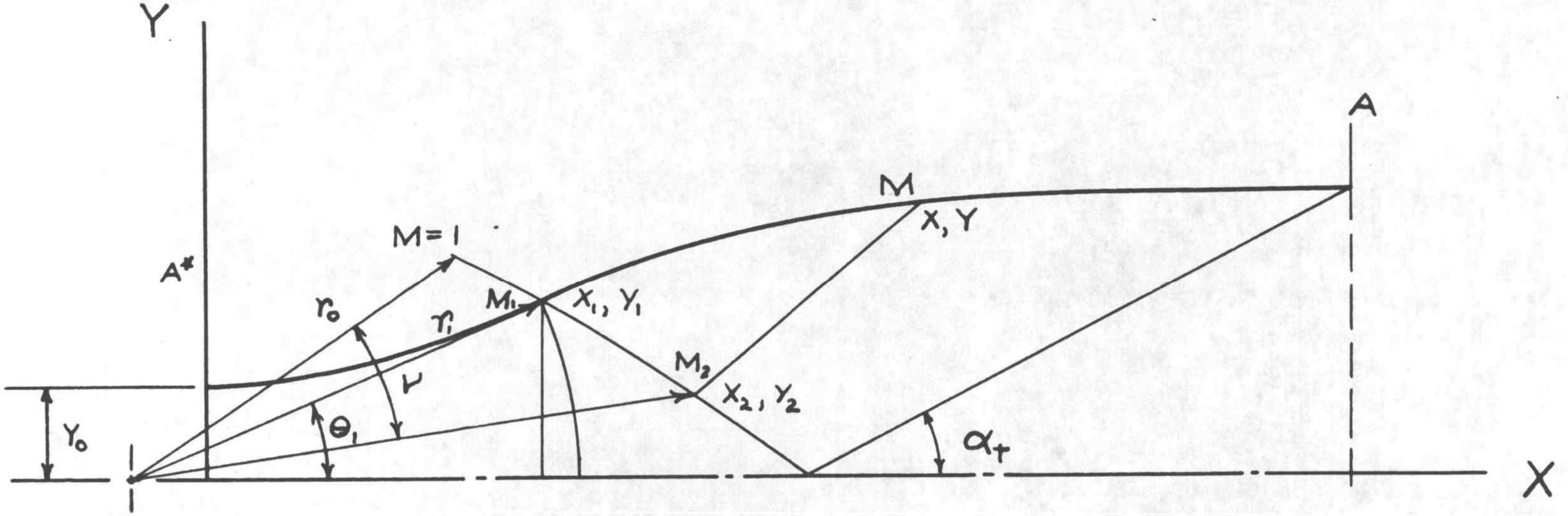
where

$$X_1 = \frac{3}{2} (Y_1 - Y_o) \cot \theta_1$$

The frictionless contours of the nozzle blocks used in this system were obtained as follows. The contours of the Mach 2.0 blocks were patterned after those given by Lindsay and Chew (12, p. 47). The subsonic portion of these blocks was changed to match the slope of the walls of the transition section. A second set of nozzle blocks

NOZZLE DESIGN PARAMETERS FOELSCH'S METHOD

FIGURE 16



was designed for a Mach number of 3.0 by the Foelsch method. These contours are included in the appendix.

To obtain shock-free flow at the desired Mach number in the test section, it is necessary to correct the nozzle contours for boundary layer growth. This is accomplished by computing the boundary layer displacement thickness at each station, and adding this to the value of h/2 at that point. Calculation of the boundary layer displacement thickness is a long involved process at best. It consists of a stepwise solution of the boundary layer equations for a compressible fluid under the influence of a favorable pressure gradient. To make any progress at all, simplifying assumptions must be made. The nozzle must be assumed to be insulated, that is, no heat transfer takes place through the walls. A second assumption concerns the shape of the boundary layer velocity profile. It is assumed to be of the form $\frac{u}{u_1} = (\frac{y}{\delta})^{\frac{1}{N}}$ where N is an integer ranging from 5 to 11. Values of skin friction coefficient must be known at each point along the wall. These are determined experimentally in the subsonic regime, and extrapolated. For ease of computation, the method outlined by Tucker was used. (26) Various parameters are machine computed for generalized cases, and tabulated for convenience. Results of these calculations are tabulated in the appendix with the nozzle contours.

Transferring the computed contours to the materials to be shaped presented quite a problem. The simplest and most accurate method for machining a contour such as this, would be to use a contour milling machine. Since none was available at Oregon State University, another method was used. The method used consisted of transforming h/2 values at each station into heights above a reference line. Two plates of aluminum alloy were bolted together and mounted on the table of a milling machine. Starting from a known point at one end of the plates, a series of steps were cut, approximating the desired profile. The horizontal position was determined by the horizontal feed indicator of the milling machine. Heights above the base of the plate were measured to the nearest thousandth of an inch with a micrometer. Thus, the coordinates of the inner corner of each step were known within 0.002 inches. Using these corners as check points, the final profile was obtained by hand filing of the plates until the corner lines just disappeared. Of course accuracy was lost in this operation. It is estimated that the finished contour is accurate within 0.02 inch.

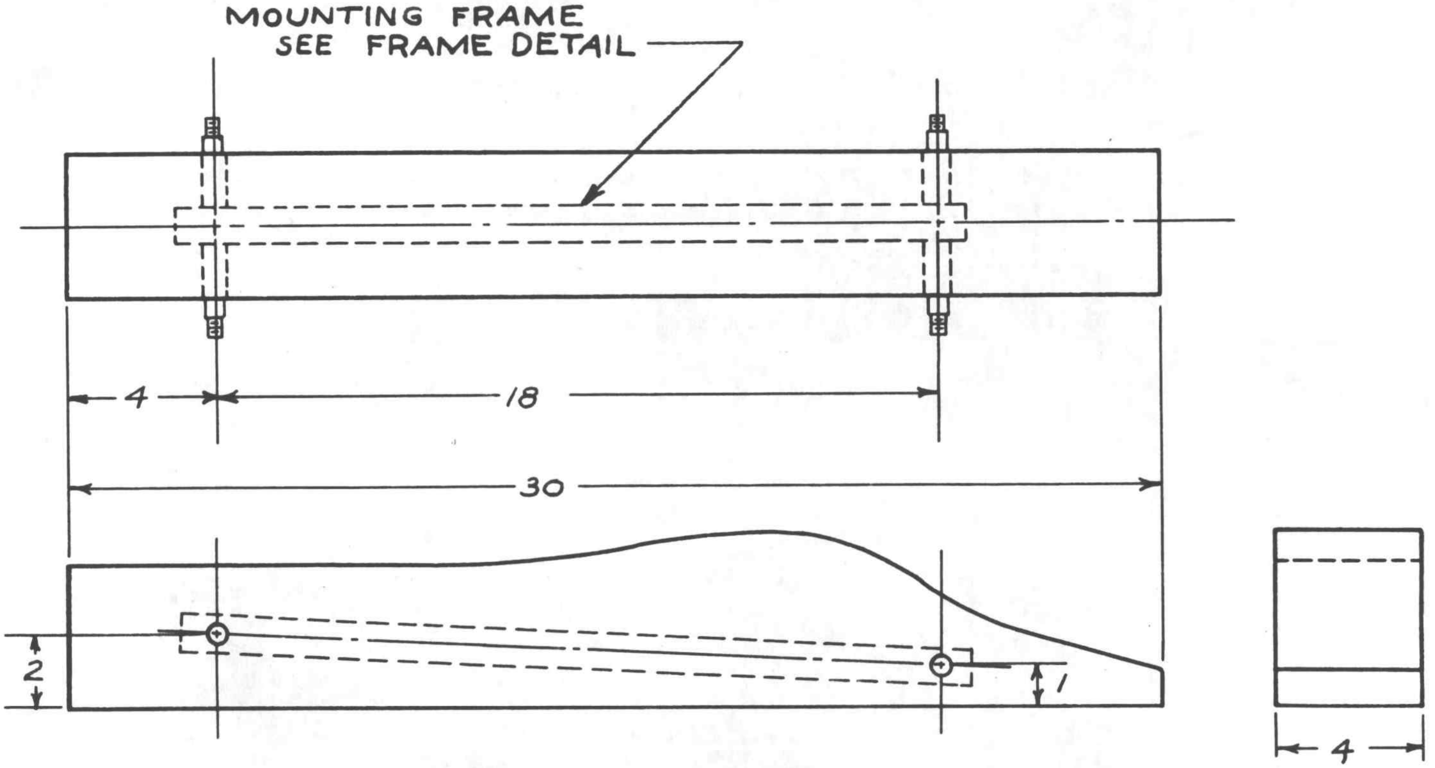
Using these plates as sides, a mold was made by bolting a flexible plate along the contour. The ends were blocked such that the mold could be poured full of Plaster of Paris. Plaster of Paris was chosen as the material for several reasons. First, upon setting it expands slightly. This ensures a sharp, true reproduction of the mold. Secondly, Plaster of Paris is relatively cheap when compared to aluminum, brass, or even fibre glass; particularly when the volume of each block is approximately 450 cubic inches. A very smooth surface was obtained. Some difficulty may be encountered due to erosion in the vicinity of the throat. If it occurs, it can be somewhat alleviated by coating the surface with a strong plastic such as fibre glass resin.

The nozzle blocks must be securely mounted in the test section and accurately positioned to ensure proper operation. The nozzle blocks were designed with this in mind. A mounting frame was integrally cast into the center of the nozzle blocks. Mounting bolts are attached to this frame, and protrude from the sides of the nozzle blocks. These bolts extend through the side-walls of the test section. In effect, bolts pass through the entire test section and secure the nozzle blocks in place. A typical nozzle block is shown in Figure 17. Details of the mounting frame are shown in Figure 24 (Appendix).

Supersonic Diffuser. Supersonic diffusers employ two processes to decelerate supersonic flow to a subsonic Mach number. These methods are the employment of a decrease in the flow area, and the employment of a shock wave or

TYPICAL NOZZLE BLOCK
AND MOUNTING DETAIL

FIGURE 17



series of shock waves. A supersonic airstream cannot be decelerated to a subsonic Mach number by a decrease in area only. Because of this the flow must experience a shock wave of some sort. Thus the first method cannot be independent of the second.

A decrease in the flow area after the test section implies a second minimum, or throat in the diffuser. The minimum size of this second throat is dictated by frictional effects and starting processes that go on in a wind tunnel. The second minimum must have a larger area than the first throat to allow for these effects. Frictional effects are realized as an increase in the boundary layer thickness between the two throats. The second throat must be large enough to account for this. A more serious increase in the area of the second throat over the first is a requirement of starting processes. The flow accelerates from zero velocity to the desired velocity of operation. During this process a normal shock wave traverses the wind tunnel. Supersonic flow will not be established in the tunnel unless this happens. It is known that the stagnation temperatures across a normal shock wave is constant. This combined with continuity requirements show that the second minimum area must be larger than the first by a factor equal to the ratio of the stagnation pressure ahead of the shock wave to that after it. That is

$$A^*_2 = A^*_1 \frac{Po_1}{Po_2}$$

This stagnation pressure ratio is a function of the Mach number in the test section. Therefore, the areas of the second throat must be either variable, or large enough to allow for the worst condition that will be encountered. This means that the diffuser will operate at less than optimum conditions at all except one Mach number. Thus the advantage of a variable diffuser is clear. As a future addition to this system, a variable diffuser could be designed and installed.

It has been shown that the area of the second minimum must be larger than the throat area. In the supersonic portion of a nozzle the Mach number at any point is fixed by the area ratio. Since the second throat is larger than the first, the Mach number at the second throat must be higher than at the first. Therefore the Mach number at the second minimum will never be sonic and the flow must undergo a shock wave to become subsonic. The losses associated with this shock wave will be less than the losses through a shock wave at the test section Mach number.

A second possible way to decelerate the flow is by using shock waves. One normal shock wave at the exit of the test section will decrease the Mach number to a subsonic one. However, the losses in such a process are large and should be avoided if possible. The flow can also be decelerated by causing it to undergo a series of weak oblique shock waves. This process can also end up at a subsonic Mach number. The total losses incurred in such a process are much less than the losses associated with a normal shock, starting from the same initial Mach number.

Due to the small size of the test section, it is not feasible to use an area contraction. Any such contraction will restrict the range of incidence angles. Thus the supersonic diffuser makes use of shock waves to decelerate the flow. These shock waves are induced into the flow by the test model, the sting, and the model support.

Subsonic Diffuser. The subsonic diffuser for this installation must accomplish two things. First, it must decelerate the air to a reasonably low velocity, approximately 100 to 150 feet per second, and second, it must turn the flow through a right angle so that it may be exhausted outside of the building. Any pressure recovery that is obtained at the same time is just that much to the good. Due to space limitations, a diffuser of relatively short length is desired. An absolute maximum length is 20 feet.

Experimental evidence indicates that there are two important design parameters when considering a two-dimensional subsonic diffuser. These are the total divergence angle 2θ, and the tunnel height to wall length ratio L/W_1. Optimum values for these parameters have been found to be 2θ = seven degrees, and L/W_1 equal to between 25 and 30. Consider for a moment the physical sizes that are required by these optimums. Assuming that the inlet velocity is about 1000 feet per second, the area ratio must be about 10:1 to give the desired outlet velocity. If one is limited to a two dimensional diffuser, the height of the diffuser at the outlet must be about 70 inches. If the optimum value of divergence angle is used, the length of the diffuser would be well in excess of 20 feet. Obtaining the necessary length would also require violating the requirement that L/W_1 be between 25 and 30. From these considerations, it is clear that this arrangement is not satisfactory.

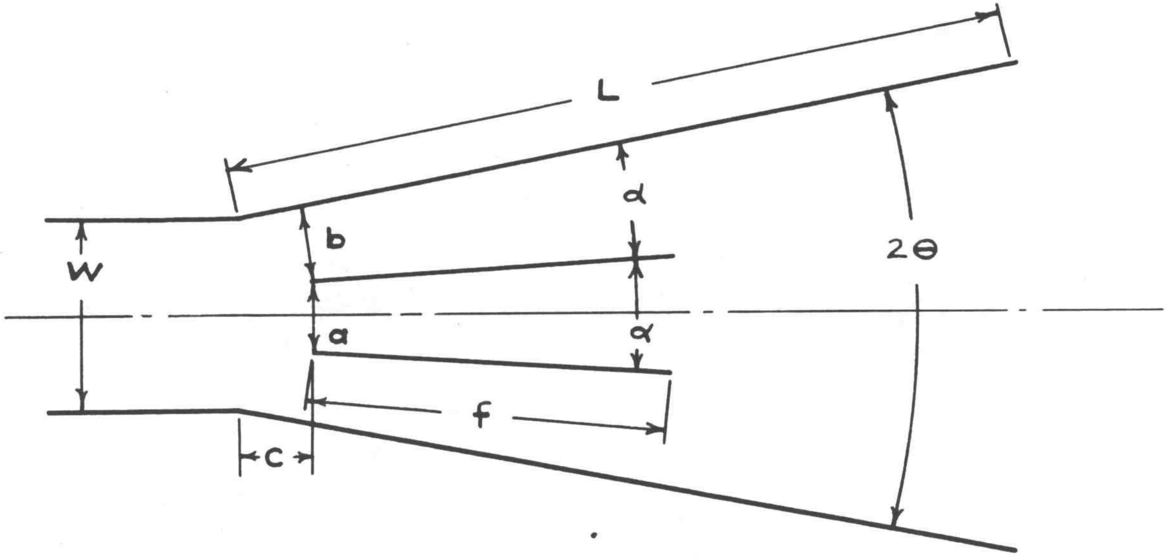
The work of Cochrane and Kline (4) suggests a way out of the foregoing dilemma. They found that it is possible to use large divergence angles and still maintain efficient operation by the use of short vanes placed in the diffuser near the throat. Experimentally they determined several design criteria for the optimization of the vane location and length. These are: (1) the vanes are relatively short and are located in the vicinity of the throat, (2) the vanes are symmetrically arranged, (3) the number of vanes is chosen so that the individual vane-passage divergence angles are approximately 7.0°, and (4) the length of the vanes is chosen so that each passage is at or near the line of appreciable stall obtained in high-turbulence water table experiments. Optimum values of various parameters, as shown on the defining sketch, Figure 18, were determined according to the author's method.

Before these parameters are quoted, another departure from the ordinary should be explained. To avoid such large diffuser heights at the outlet as required by the area ratio, increases in both height and width are employed. However this does not occur within the same length of diffuser. The top and bottom of the first section diverge at 21 degrees. In the throat of this section, two vanes are used. When the height has increased to 24 inches, the top and bottom become parallel. From this point on, the sides diverge at an angle of 14 degrees, until a width of 24 inches is reached. One vane is employed in the throat of this section. The outlet area is 288 square inches and thus the area ratio is approximately 10.

Optimum values for the location and size of the vanes located in the first throat are as follows. The value of a is 2.33 inches, b is 2.8 inches, c is 2.5 inches, and the optimum value for f is 46.6 inches. The length can

SUBSONIC DIFFUSER DESIGN PARAMETERS

FIGURE 18



be reduced appreciably from its optimum value with little adverse effect. Therefore a value of f is chosen to be 30 inches. One vane is used in the second portion of the diffuser. The values are as follows: a is 1.0 inches, b is 1.2 inches, c is 1.1, and f is 20 inches.

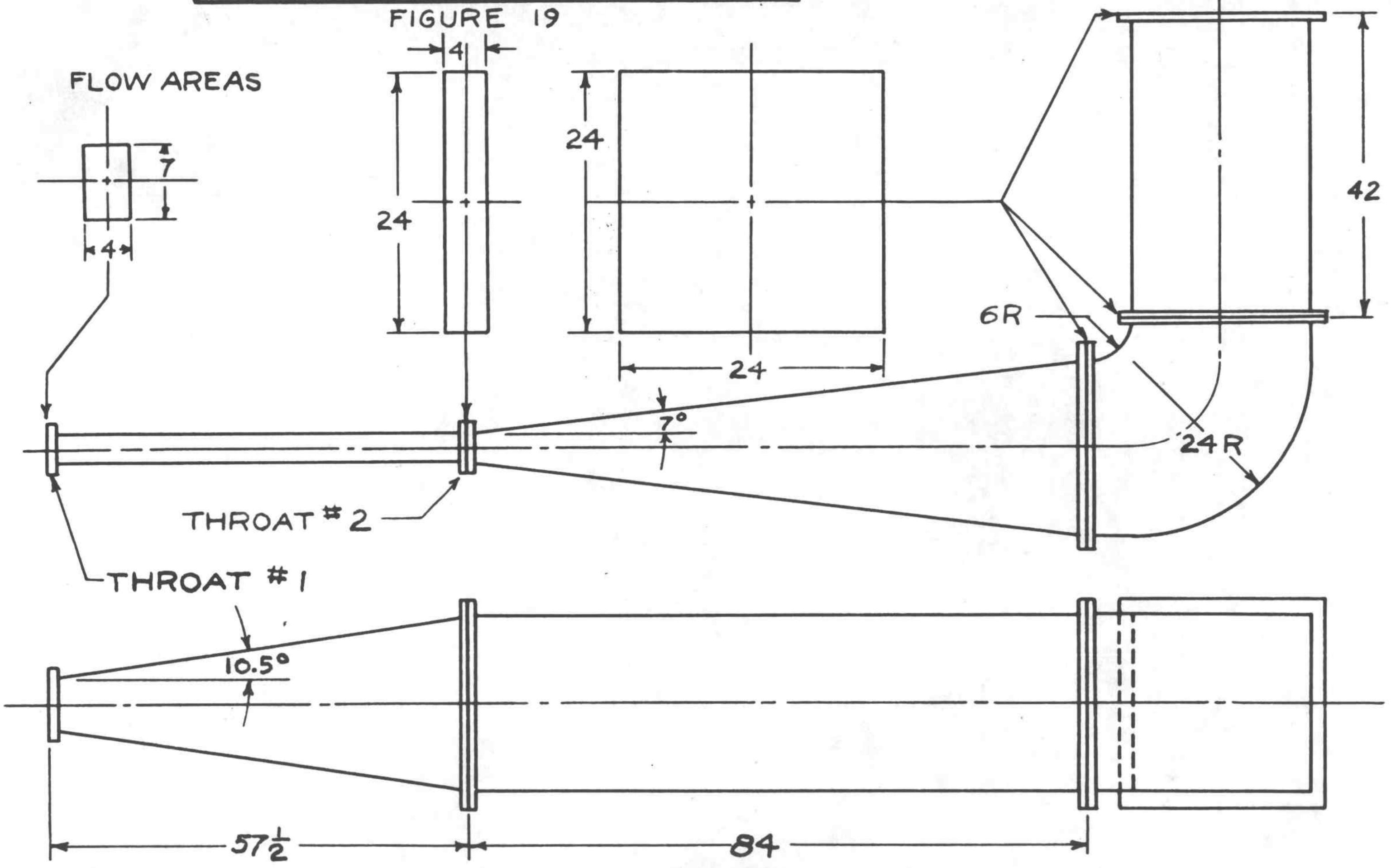
To the end of the diffuser, a right angle bend is added so that the flow can be directed outside. A schematic of the diffuser is shown in Figure 19.

Instrumentation

The operation of this wind tunnel is determined by the settling chamber pressure, the stagnation temperature, and the nozzle geometry. To properly control the operation, it is necessary to monitor the settling chamber pressure and the stagnation temperature. A large, accurate pressure gage must be attached to the settling chamber. The tunnel operator will make corrections to the settling chamber pressure by observing this gage and controlling the pressure regulating valve. The stagnation temperature will be steadily decreasing during any given run. It is necessary to record the time history of this parameter in order that the Reynolds number of the run can be computed. This task can be easily accomplished by

SUBSONIC DIFFUSER

FIGURE 19



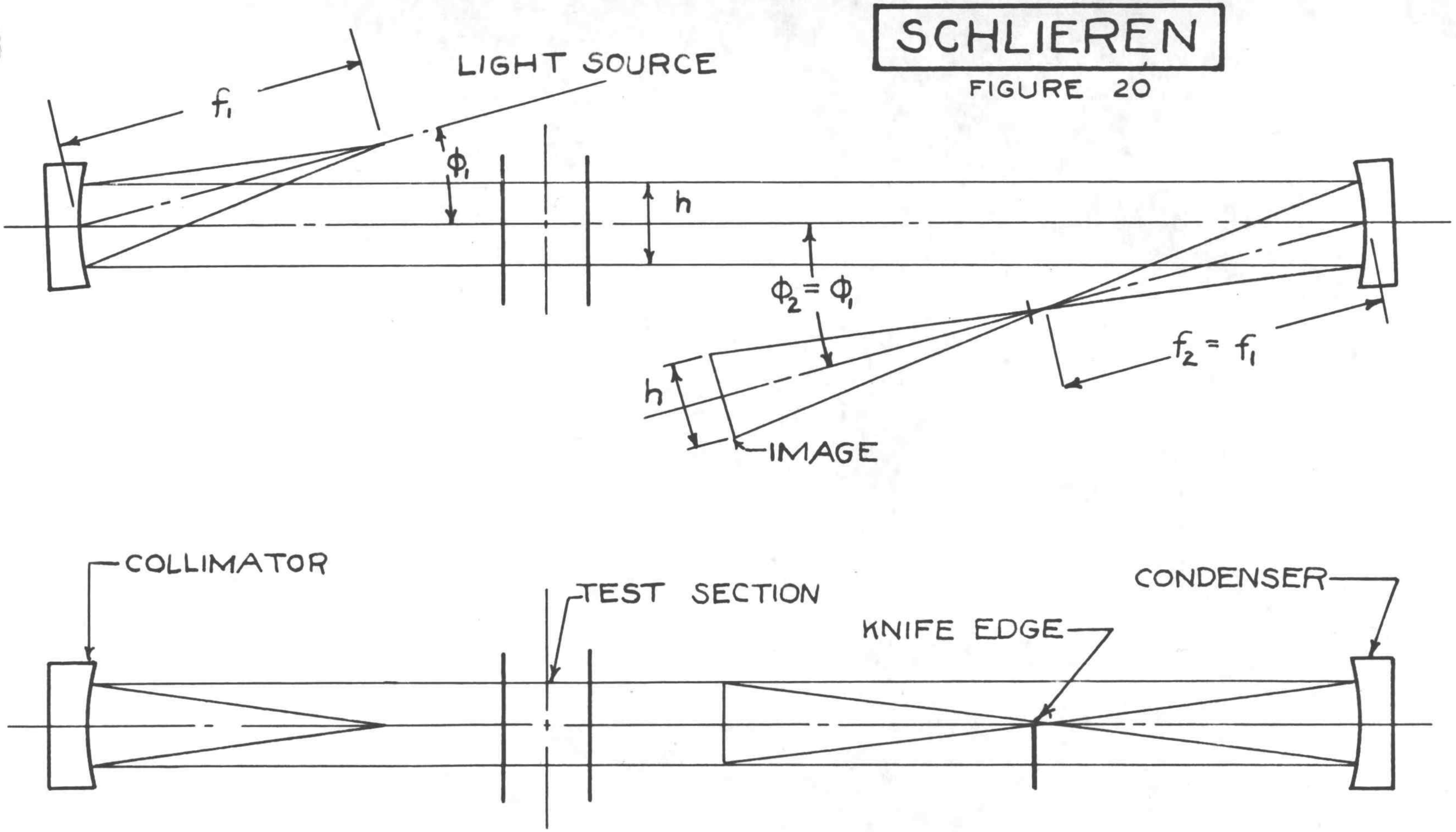
the use of a thermocouple and a recording oscillograph.

A schlieren system is the most suitable optical viewing system for this wind tunnel. A schlieren system consists of two lenses or concave mirrors, a light source, a knife edge, and a viewing screen. Photographs can be taken if a camera is added to the system. An additional requirement is that optical quality windows must be used in the test section. A satisfactory schlieren system would consist of mirros of 40 inch focal length and six inch diameter. The windows should be four inches in diameter and at least one inch thick. These components will permit viewing of the entire flow field. A schematic of the schlieren system is shown in Figure 20.

Force data can be obtained with the use of a strain gage balance. Essentially it consists of an instrumented cantilever beam. The model is attached to the free end of this beam, usually called a sting, and the fixed end is supported by the sting support. Air loads on the model are transferred to the sting and cause it to bend. Readings from the strain gages on the sting can be translated into forces and moments by proper calibration. The sting support is designed to hold the sting and to provide a means of varying the angle of attack of the model.

SCHLIEREN

FIGURE 20



The drag cannot be obtained directly from the bending of the sting. It is usually obtained from a drag link that is incorporated in the sting support. The drag link has flexures that bend when a drag load is applied to the model. These flexures are instrumented with strain gages. Force values can be obtained from the strain gage readings by proper calibration.

Pressure data may be obtained by using either ordinary manometers or pressure transducers. The latter method is preferable because it enables one to record pressure continuously. Manometers must either be visually or photographically recorded. Manometers remain the most practical for an installation such as this because of the high cost of transducers.

Temperature data can be obtained by the use of thermocouples. The output of a thermocouple is a voltage that can be easily recorded.

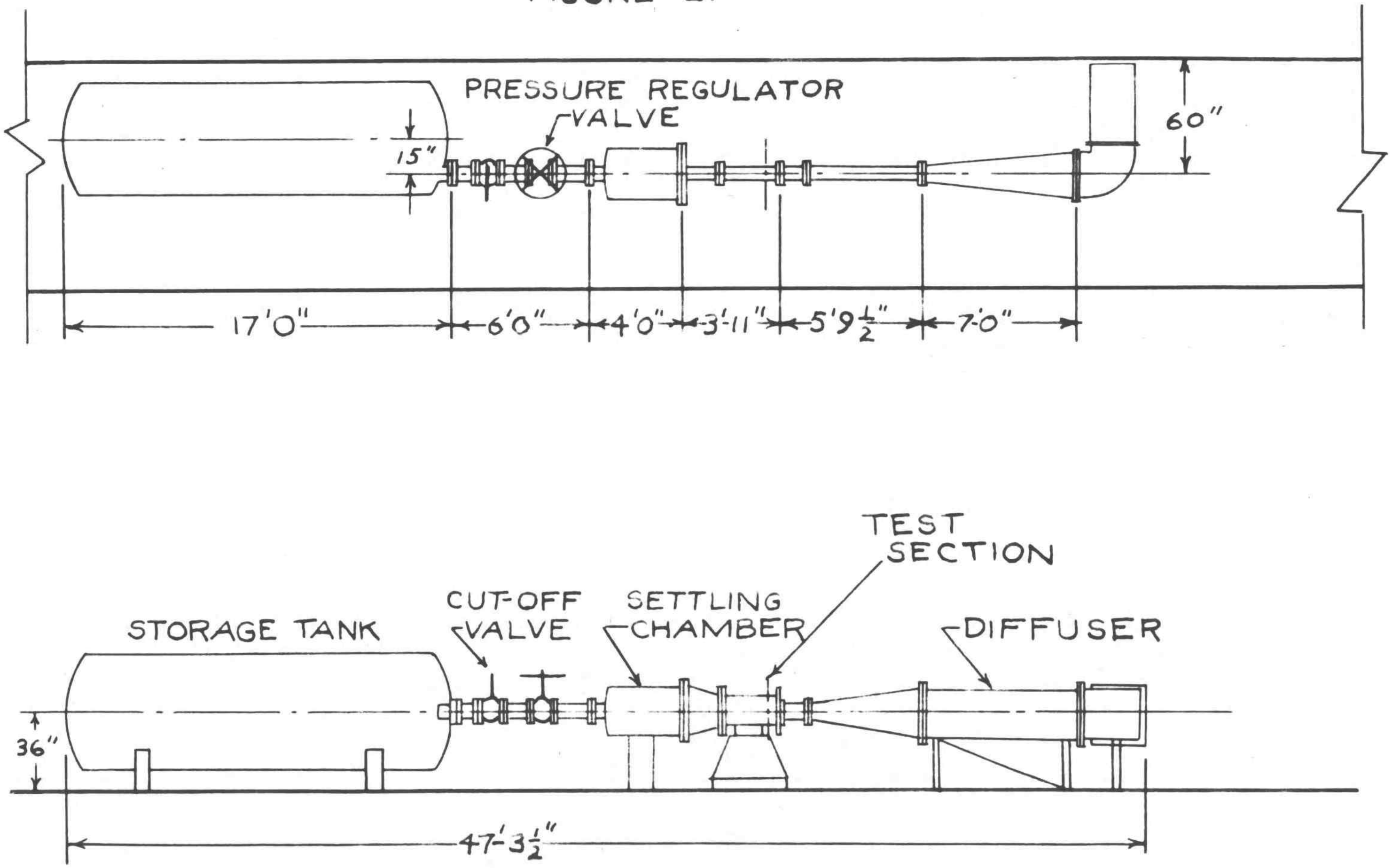
As an ultimate goal, completely automatic data recorders are desirable. If a six channel recording oscillograph was available, three channels would be used for force data, one channel for stagnation pressure, one channel for stagnation temperature, and the last channel for the angle of attack. This would make a compact useful instrument package. All data except for pressure distributions, would be contained on one record.

SYSTEM INSTALLATION

The entire wind tunnel system, except the compressor, is designed to be installed on the balcony of the engineering laboratory at Oregon State University. The compressor is located one floor below on the main floor of the laboratory. The layout of the equipment on the balcony is shown in Figure 21.

SYSTEM INSTALLATION

FIGURE 21



CONCLUSIONS

On the basis of this study the following conclusions can be made:

1. A supersonic wind tunnel is a desirable and useful addition to the laboratory equipment at any university.

2. A small intermittent supersonic wind tunnel of the blow-down type is the most feasible for such an application.

3. A satisfactory system must include a compressor, an oil filter, an air dryer, a storage tank, control valves, a settling chamber, a test section, and a diffuser.

4. The design presented herein offers a system capable of covering the Mach number range of 1.5 to 4.0. The maximum attainable Reynolds number is 30×10^6 per inch. The maximum run duration is 43 seconds at Mach 2.0. A minimum run duration of ten seconds is available at all Mach numbers from 1.5 to 4.0.

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APPENDIX

NOMENCLATURE

A.....Area, square inches

A^*....Throat area, square inches

a.....Throat parameter in subsonic diffuser, inches. (See figure 18)

b.....Throat parameter in subsonic diffuser, inches. (See figure 18)

c.....Vane placement parameter in subsonic diffuser, inches. (See figure 18)

f.....Vane length in subsonic diffuser, inches. (See figure 18)

f_1....Focal length, inches

H.....Test section height, inches.

k.....Ratio of specific heats, 1.40.

L.....Length, inches.

M.....Mach number, dimensionless.

M.....Mass, slugs.

N.....Velocity profile factor, 5 to 11.

n.....Polytropic process exponent, 1.0 to 1.4.

P_o....Pressure in storage tank, psia.

P_s....Pressure in settling chamber, psia.

P_{o1}...Stagnation pressure upstream of a normal shock wave, psia.

P_{o2}...Stagnation pressure downstream of a normal shock wave, psia.

R_n....Reynolds number, dimensionless.

R.....Gas constant, 53.34 ft-lbf/lbm R.

T.....Temperature, degrees Rankine.

T_0....Temperature in the storage tank, degrees Rankine.

t.....Time, seconds.

u.....Velocity in the X direction.

u_1....Freestream velocity in the X-direction.

V.....Storage tank volume, cubic feet.

w.....Mass flow, slugs per second.

W.....Throat height in subsonic diffuser, inches.

x.....Cartesian coordinate.

y.....Cartesian coordinate.

α.....Angle of attack, degrees.

δ.....Boundary layer thickness.

δ^*....Boundary layer displacement thickness, inches

ρ.....Density, slugs per cubic foot.

μ.....Viscosity, lb sec/ ft^2.

HISTORICAL DEVELOPMENT OF THE WIND TUNNEL

It has been stated that no scientific endeavor can progress very far or rapidly by hypothesis alone. A thorough, fundamental basis in experimental fact is necessary at every step along the way. Perhaps this is a basic reason for the relatively recent appearance of the airplane. Earliest man must have conceived of the idea of human flight after observing the flight of birds. Such ideas are part of Greek Mythology. It is recorded that scientists as early as Leonarda da Vinci (1452-1519) conceived of flying machines of various sorts. Yet, it was not until 1903 that the first successful airplane was built. The Wright brothers succeeded where others failed due, in large measure, to their skillful use of data obtained from wind tunnel experiments.

The wind tunnel is perhaps the most useful of all research tools available to the aeronautical scientist. From very simple beginnings it has developed and diversified greatly. Perhaps it would be well to digress a moment and trace the development of the wind tunnel.

The concept of the wind tunnel was first stated by John Smeaton in 1759, when he stated that there are two alternative methods available for aeronautical research. It is possible to move the model against the wind or move the wind against the model. The latter half of this statement is first statement of the concept of the wind tunnel.

Over a century elapsed before the concept was applied. Francis Herbert Wenham designed the first wind tunnel for the Aeronautical Society of Great Britain in 1871. This wind tunnel was built at the Messr's Penn Marine Engineering Works in Greenwich. The second wind tunnel was built by Horatio Philips in 1884. In an effort to overcome turbulence troubles caused by the fan in Wenham's tunnel, Philips used a steam induction system. He placed a steam ejector downstream of the test section and induced a flow through the test section by exhausting steam downstream. This can be considered to be the forerunner of the modern induction tunnels.

Many others built small wind tunnels around 1900. John Irminger and H. C. Vogt built the first suction-type wind tunnel during this period, by making use of the draft of a large chimney. A. F. Zahm designed and built the first fully equipped aeronautical research laboratory in the United States during this period. The Wright brothers finished their small wind tunnel in October of 1901. They used the wind tunnel as an aid in designing their first airplane, the first successful powered airplane.

Although wind tunnels were being constantly enlarged and improved, no major steps forward were made until 1908 when Ludwig Prandtl designed and built the first closed circuit wind tunnel at Göettsingen. This improvement enabled a significant reduction in power required to operate at any given velocity. (19)

The next significant advancement was proposed in 1889 by Ernst Mach. He suggested that one could produce very high velocities by discharging air from a tank at high pressure. This idea was neglected until 1916 when Langevin built a crude tunnel of this type. E. Huguenard constructed an improved version in 1917. In October of that year he observed shock waves about certain projectile models. This wind tunnel is the first blowdown wind tunnel. (8)

It has been suggested that aeronautical supremacy is directly attributable to possession of superior aeronautical research equipment, i.e., wind tunnels. History bears this out. The Wright brothers were successful in large part due to their wind tunnel research. This U. S. Supremacy was short lived. France came to the fore with the cross-channel flights of the Bleriot. These successes can be traced to the Eiffel wind tunnel. This aeronautical lead passed to Great Britain around the close of the first decade of the Twentieth Century due to the research carried on at the National Physical Laboratory and in the NPL wind tunnel. Just before the start of World War I, Germany became the leader in the field of aeronautics. This was largely due to the installation at Göettsingen and the work of such famous researchers as Ludwig Prandtl. Germany retained this lead throughout the war as is evidenced by their air superiority. (18)

Between wars, the science of aeronautics progressed relentlessly toward higher and higher speeds. Tunnels of the type pioneered by Hugenuenard in 1917 afforded the only means of high speed research until the advent of continuous supersonic tunnels in the late 1930's. The first continuous supersonic wind tunnel was built in Zurich, Switzerland. The second one was built in Guidonia, Italy in 1939. (9)

Throughtout World War II, Germany relied on intermittent types for the bulk of their research. Perhaps their greatest successes were in the field of rockets. At Peenemunde on the Baltic Sea considerable research was carried out on guided missiles. This program relied entirely on data from intermittent wind tunnels.

During World War II and immediately thereafter, in the United States, great emphasis was placed on the development of continuous supersonic wind tunnels. The United States became the world leader in the field of aeronautics with completion of the extensive NACA research installations.

To the present day, continuous tunnels hold the upper hand. However due to the enormous initial cost, intermittent wind tunnels have been constructed by many of the smaller countries and by private companies. With recent improvement in instrumentation, data output from intermittent tunnels is on a par with that of the continuous wind tunnels.

NOZZLE BLOCK CONTOURS

M = 2.0

X	h/2	δ^*
0.000	5.000	0.000
0.500	4.866	0.002
1.000	4.732	0.003
2.000	4.464	0.007
3.000	4.196	0.010
4.000	3.928	0.013
5.000	3.460	0.017
6.000	2.830	0.020
7.000	2.290	0.024
8.000	1.625	0.027
9.000	1.284	0.030
9.500	1.232	0.032
9.900	1.215	0.033
10.210	1.210	0.035
10.370	1.209	0.035
11.000	1.208	0.037
11.500	1.208	0.039
11.920	1.213	0.043
12.341	1.227	0.046
12.761	1.251	0.050
13.181	1.280	0.053
13.602	1.339	0.057
14.022	1.396	0.060
14.443	1.454	0.064
14.863	1.513	0.067
15.704	1.631	0.074
16.544	1.739	0.081
17.805	1.783	0.092
18.646	1.853	0.099
19.487	1.906	0.106
20.327	1.948	0.113
21.115	1.978	0.120
21.500	1.996	0.123
27.500	2.000	0.174
28.250	2.000	0.181
30.000	2.000	0.195

M = 3.0

X	h/2	δ^*
0.000	5.000	0.000
0.500	4.866	0.003
1.000	4.732	0.003
2.000	4.464	0.006
3.000	4.196	0.009
4.000	3.988	0.012
5.000	3.660	0.015
6.000	3.330	0.018
7.000	2.771	0.021
8.000	2.040	0.024
9.000	1.289	0.027
9.500	1.060	0.029
+10.000	0.811	0.030
10.500	0.612	0.030
11.000	0.490	0.032
11.350	0.475	0.033
11.500	0.472	0.035
12.000	0.508	0.043
12.500	0.603	0.050
13.000	0.739	0.058
13.500	0.904	0.067
14.000	1.060	0.074
14.387	1.109	0.079
14.636	1.174	0.083
14.919	1.242	0.088
15.106	1.307	0.091
15.552	1.377	0.097
15.890	1.477	0.103
16.270	1.516	0.109
16.652	1.578	0.114
17.095	1.681	0.121
17.570	1.706	0.128
18.050	1.763	0.136
18.590	1.817	0.144
19.170	1.864	0.153
19.680	1.892	0.161
20.360	1.934	0.171
21.040	1.964	0.182
21.780	1.987	0.194
22.520	1.995	0.205
22.950	2.000	0.211
30.000	2.000	0.320

CANNISTER DETAIL

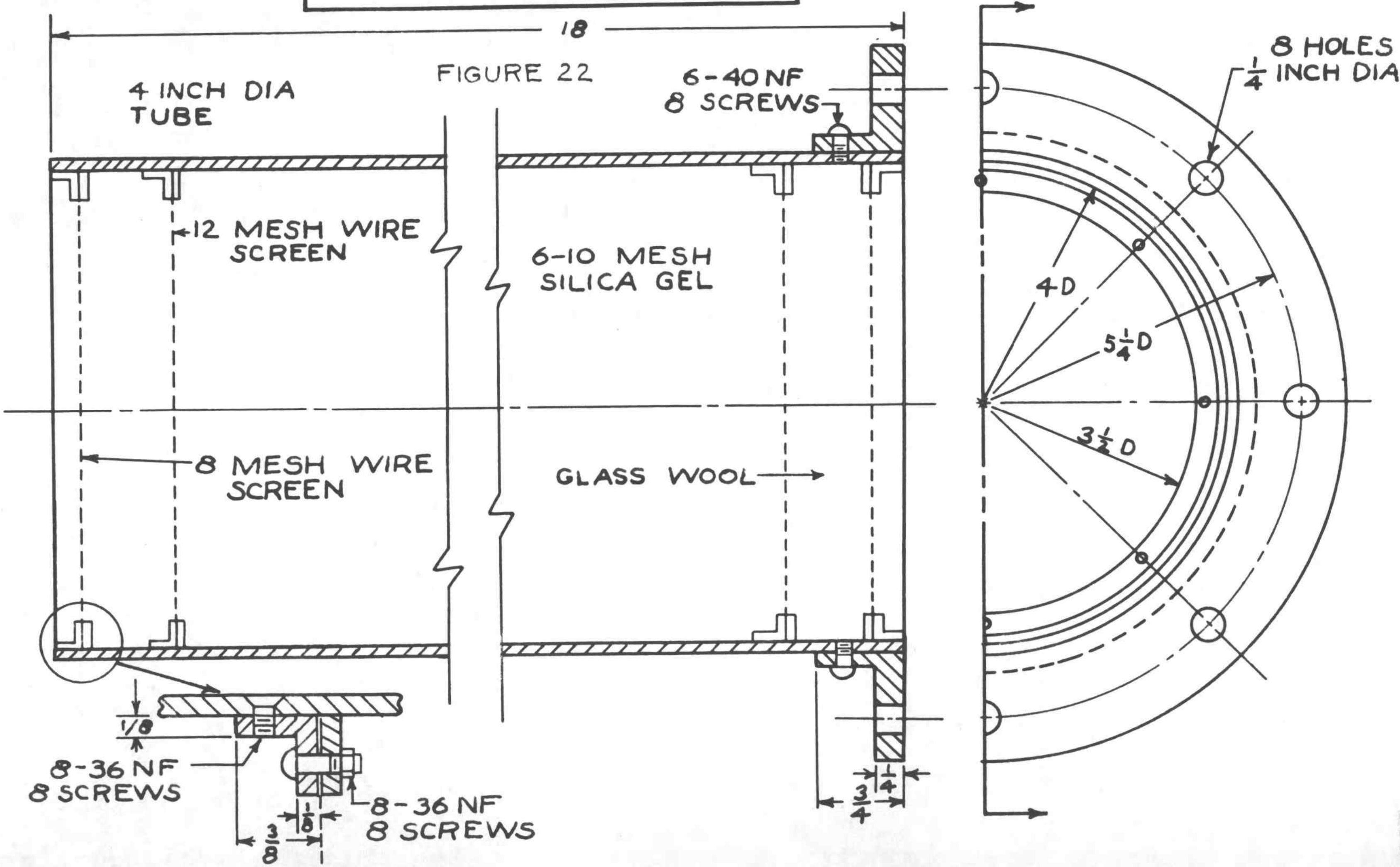
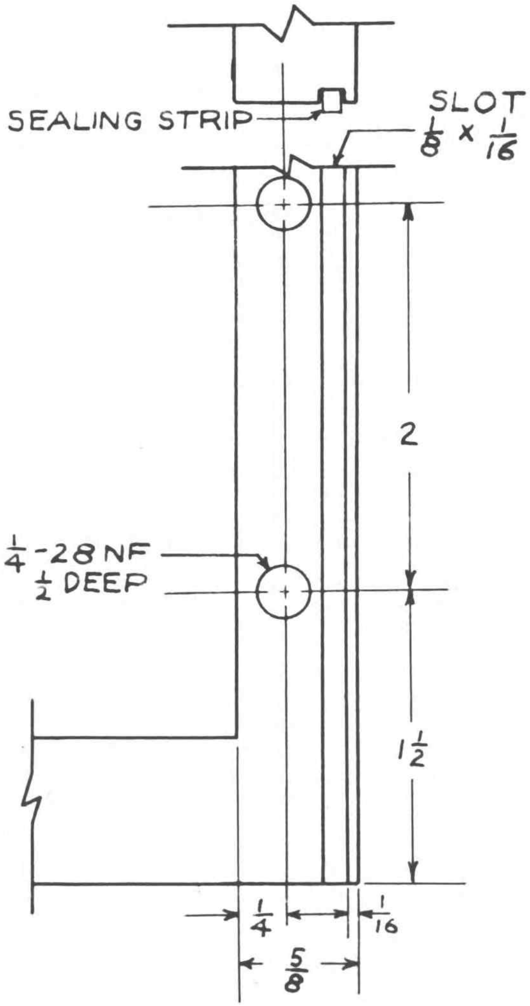


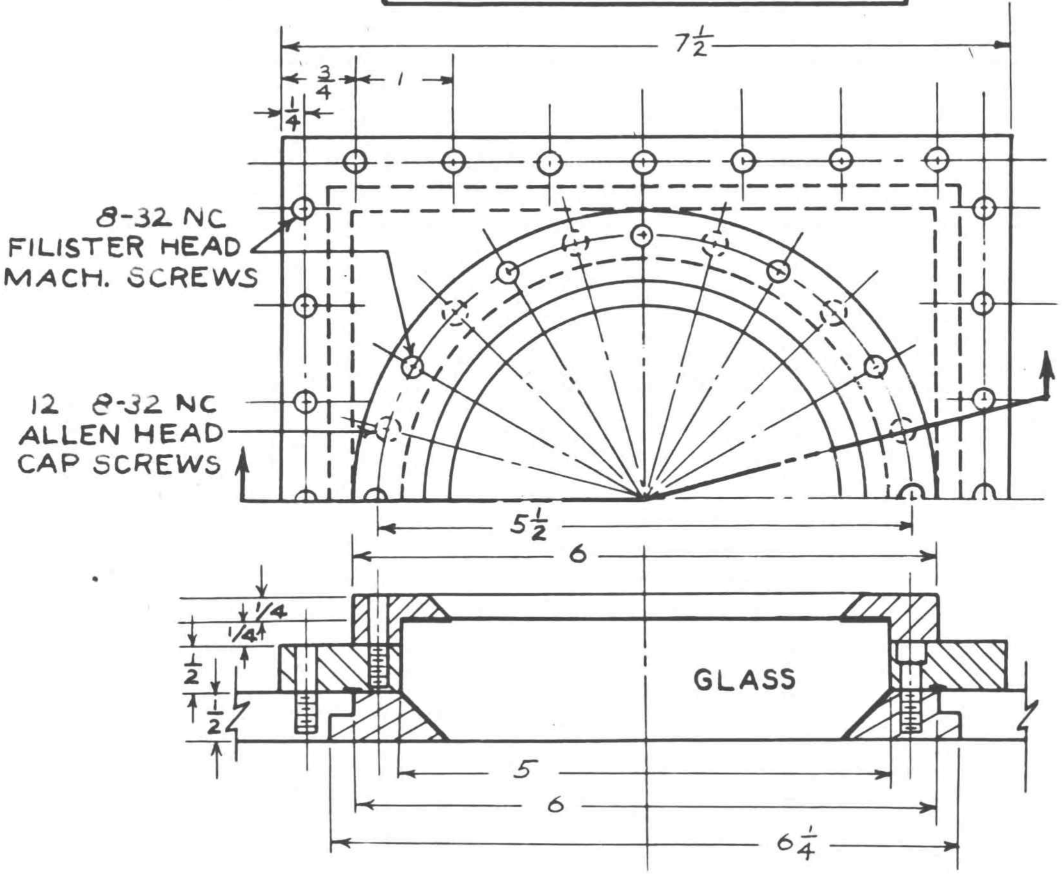
FIGURE 22

FIGURE 23

EDGE DETAIL

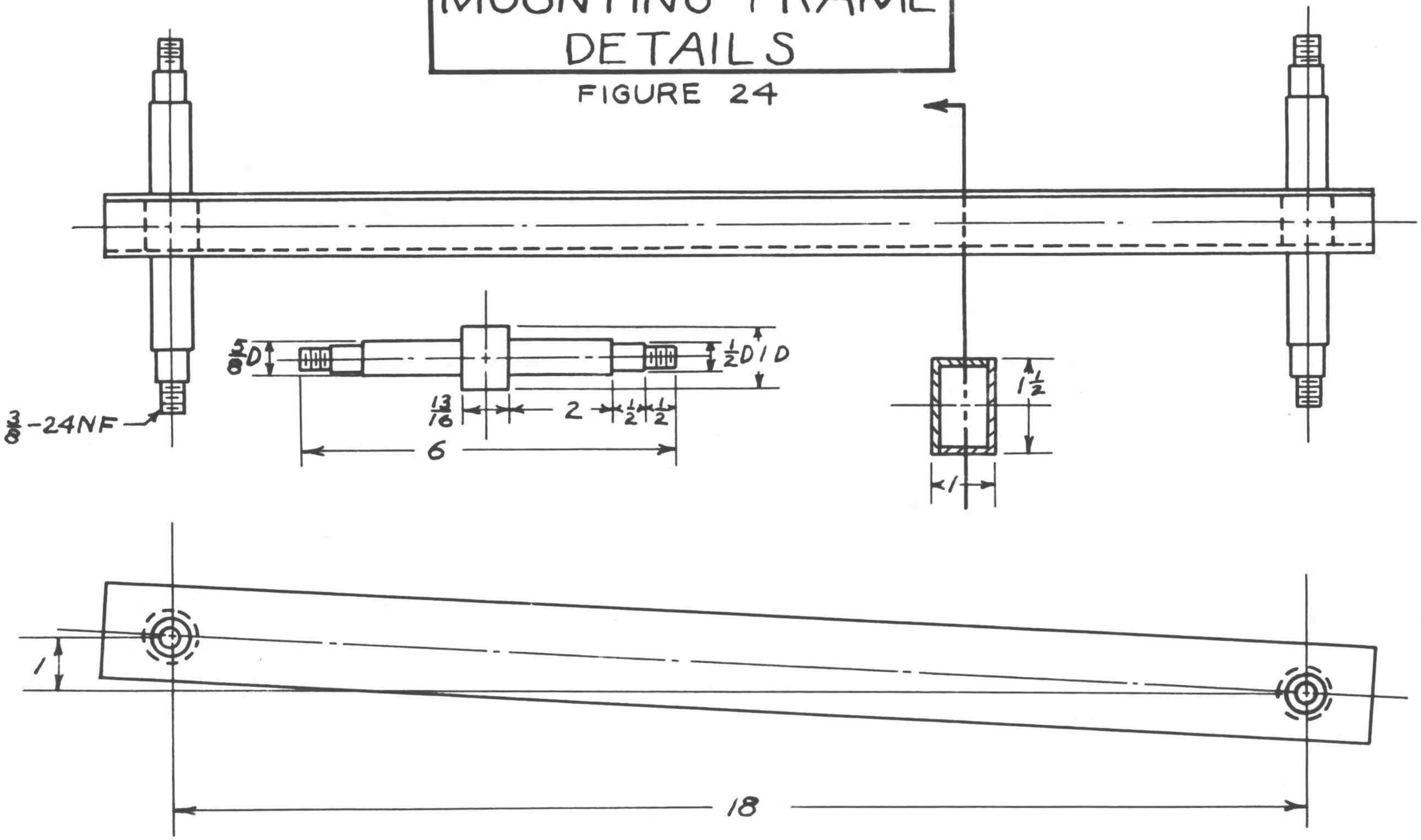


WINDOW DETAIL



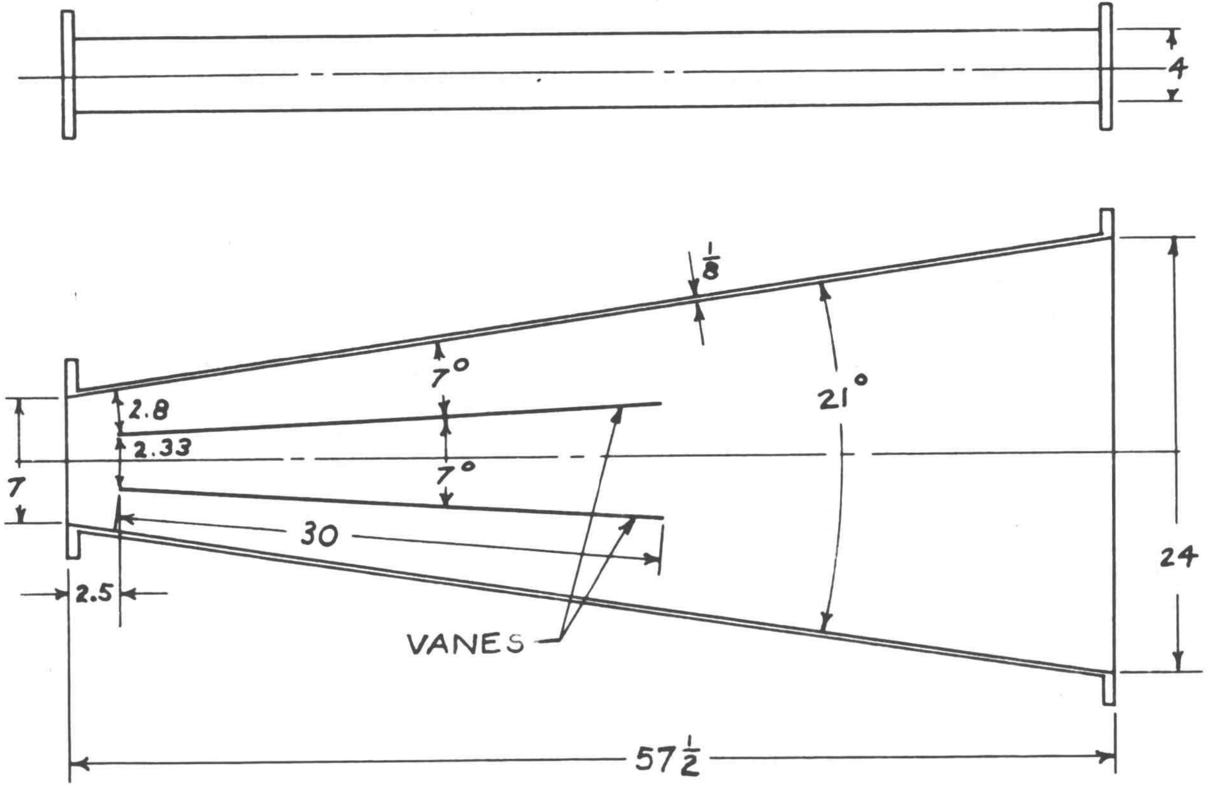
MOUNTING FRAME DETAILS

FIGURE 24



SUBSONIC DIFFUSER DETAILS
THROAT #1

FIGURE 25



SUBSONIC DIFFUSER DETAILS
THROAT #2

FIGURE 26