Performance study of the MSU Mach 3 wind tunnel
by Bradley Barney Rogers

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Mechanical Engineering
Montana State University

Abstract:
The aerodynamic parameters governing the operation of a supersonic wind tunnel are considered. These parameters are determined from measurements of the supersonic flow stream. The Mach Number is found to be near 3 while the Reynolds Number can be varied between 30,000 and 60,000 per centimeter. The capabilities of the facility as a research tool are presented in a form that will be useful to future users of the facility.

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PERFORMANCE STUDY OF THE MSU

MACH 3 WIND TUNNEL

by

BRADLEY BARNEY ROGERS

A thesis submitted in partial fulfillment
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of

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in

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Approved:

Chairperson, Graduate Committee

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure	Page

NOMENCLATURE

Symbol	Description
A	Area
A^*	Area of nozzle throat
a	Speed of sound
a^*	Speed of sound at nozzle throat
a_o	Speed of sound at stagnation conditions
M	Mach Number
M_1	Mach Number ahead of shock
$\mathring{m}$	Mass flow rate
P	Pressure
P_i	Pump inlet pressure
P_o	Stagnation pressure
P_{o1}	Stagnation pressure ahead of shock
P_{o2}	Stagnation pressure behind shock
R	Universal gas constant
Re	Reynolds Number
T	Temperature
T_i	Pump inlet temperature
T_o	Stagnation temperature
V_i	Volume flow rate
γ	Ratio of specific heats (1.4 for air)
δ	Boundary layer thickness

Symbol	Description
δ^*	Displacement thickness
ρ	Density
ρ^*	Density at the nozzle throat
ρ_o	Stagnation density
ρ_i	Pump inlet density

ABSTRACT

The aerodynamic parameters governing the operation of a supersonic wind tunnel are considered. These parameters are determined from measurements of the supersonic flow stream. The Mach Number is found to be near 3 while the Reynolds Number can be varied between 30,000 and 60,000 per centimeter. The capabilities of the facility as a research tool are presented in a form that will be useful to future users of the facility.

CHAPTER 1

INTRODUCTION

In the summer of 1979, the Ford Aerospace and Communications Corporation, located in Newport Beach, California, donated the supersonic wind tunnel facility that was located on company grounds to the Mechanical Engineering Department of Montana State University. The facility was dismantled in California and moved to Bozeman, Montana in June of 1979. The wind tunnel was reassembled, with extensive modification, in Room 5-D of the Ryon Laboratory building on the campus of MSU. The facility was successfully operated in its new location in June of 1980.

When the tunnel was first operated in California, in 1965, a brief report concerning its operation was published.[2] This report had not been based on measurements extensive and accurate enough to provide a good understanding of the capabilities of the wind tunnel. Also, since the facility underwent extensive modification when it was reassembled in Montana, the applicability of the original report was questionable.

The purpose of this thesis is to provide, by measurement, the aerodynamic characteristics of the Supersonic Wind Tunnel (SWT), and to detail its capabilities as a research tool. Questions to be answered include the following:

1) What modifications have the components of the SWT undergone since being moved to MSU? How have these changes affected the performance of the tunnel?

2) Have the pump characteristics changed because of fatigue or other mechanical deterioration? If so, what is the characteristic now? At what stagnation pressure can flow breakdown ("choking") be expected?

3) What is the Mach Number along the nozzle? How does it differ from theory? How is it affected by stagnation pressure changes?

4) Are there any waves present in the test section? Is the flow in the test section uniform?

5) How thick are the boundary layers in the test section? Are they laminar or turbulent?

6) What range of stagnation temperatures are attainable in the tunnel?

These and other questions are addressed in this document.

The second chapter of this thesis deals with the components of the SWT. A description of each component and major accessory is provided. A brief discussion of the history and original purpose of the SWT is also provided.

The third chapter deals with the aerodynamic parameters governing the operation of the wind tunnel. Questions 2 - 6 above are, for the most part, answered by the results and discussions which are presented in this chapter.

The fourth chapter is a short section outlining the conclusions drawn from the results of Chapter 3.

A short appendix giving a condensed set of operating instructions for the SWT is also included.

CHAPTER 2

DESCRIPTION OF COMPONENTS

2.1 HISTORY

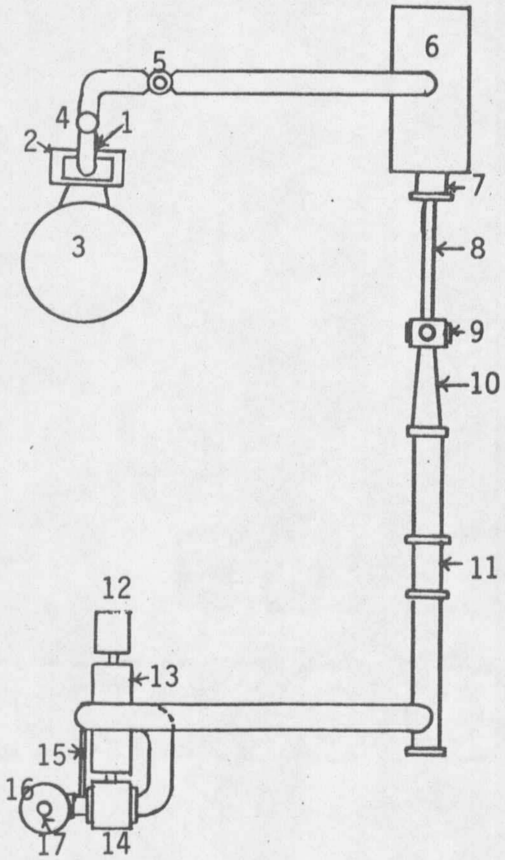
The supersonic wind tunnel at MSU is an open circuit, continuous wind tunnel.[4] The tunnel was first operated in Newport Beach, California in February of 1965. It was originally designed to study supersonic wakes; specifically, to generate information leading to an adequate description of the flow field behind re-entry vehicles. The original design parameters of the SWT are contained in reference 2.

When the tunnel was reassembled at MSU some repairs and routine maintenance were done on several of the major components. Some of the work that was done is listed below:

1) The dryer was taken apart and cleaned, and then refilled with desiccant.
2) Several components of the air drying mechanism were repaired.
3) The throttling valve was cleaned and repaired.
4) The piping was cleaned of rust and scale.
5) The interiors of the pumps were cleaned.
6) The controls and control console were modified.

Other repairs were also done on any part that was not obviously in good condition.

There has been no change in the broad design goals of the SWT since it has been moved to MSU. Several changes have been made to the individual parts of the tunnel, however, mostly in the form of new safety



KEY

1 Air Inlet
2 Chiller
3 Dryer
4 Relief Valve
5 Throttling Valve
6 Stilling Tank
7 Upstream Transition
8 Nozzle and Test Section
9 Downstream Transition
10 Subsonic Diffuser
11 Bellows Expansion Joint
12 Pump Motor
13 Pump First Stage
14 Pump Second Stage
15 Bypass Valve
16 Silencer
17 Exhaust

Figure 2-1 Wind Tunnel Circuit

interlock systems. The rest of this chapter describes the components of the SWT as they exist today.

2.2 INLET SYSTEM

The MSU SWT draws its air supply from the atmosphere. Because of this, an air drying system is necessary to prevent condensation of moisture at the low static temperatures that occur in the test section. The system on the MSU tunnel is made by Desomatic Products of Alexandria, Virginia. The dryer is designed to provide a dewpoint of -30°F at dryer inlet flows ranging as large as 700 SCFM (Standard Cubic Feet per Minute).

The ambient air enters through a screen located on the side of the dryer. The air then passes through a chiller unit that lowers the air temperature to around 40°F. Some water is condensed off at this point. The air then passes through approximately 550 pounds of silica gel which dries the air further to a dewpoint of around -30°F.

Above the desiccant bed (silica gel bed) is a three-phase, 480 volt, 30 KW heater which is used to control the stagnation temperature of the air during an experiment. This heater is controlled from the main control panel.

Above the heater is a plenum filter section which removes any particles of silica gel which may be carried along with the stream.

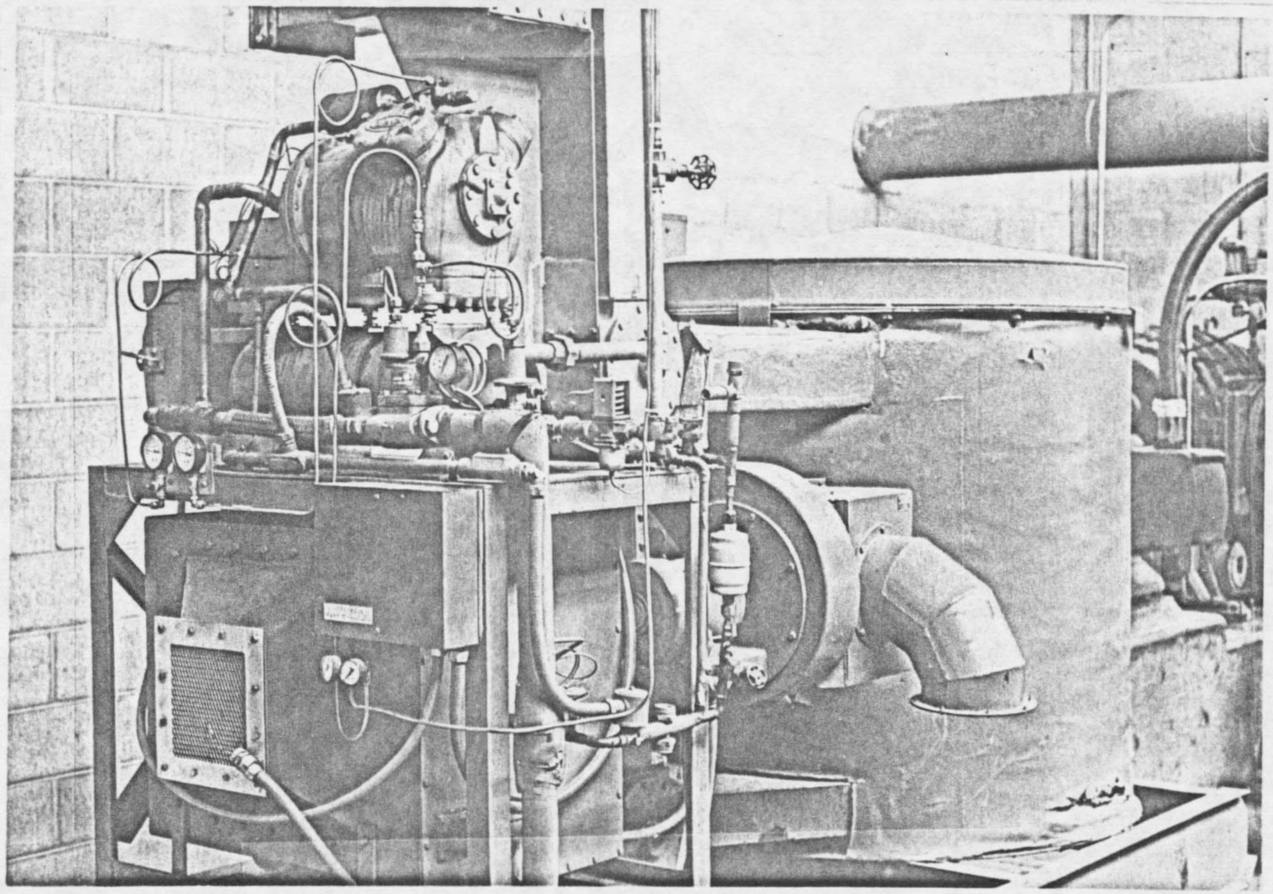


Figure 2-2   Inlet System

The dryer is designed to permit up to four hours of continuous operation at maximum flow. The dryer can operate longer at lower flow rates and, since the tunnel is not normally operated at maximum flow for such a long period of time, an experiment can be tailored to provide a full day's operation.

After the desiccant has become saturated it is necessary to regenerate the desiccant bed. This is accomplished by flowing air over the heater coils and down through the silica gel. Absorbed water is then carried out of the desiccant bed. The regeneration cycle lasts four hours and is normally done overnight. The desiccant bed can take as long as 72 hours to cool off after a regeneration cycle if it is left alone.[3] Once the tunnel is started, however, it cools off in less than 20 minutes.

The only major modifications on this section are that the on-off switch for the regeneration cycle has been removed and an on-off switch has been installed for the chiller. The reason for the removal of the on-off switch for the regeneration cycle is that when the desiccant tank was inspected its bottom was found rusted from insufficient regeneration of the silica gel. To make sure that the bed is always fully regenerated the on-off switch for the regeneration cycle was removed so that, once started, the cycle must run its full course.

The four-hour regeneration time was arrived at experimentally. It was found, by placing a temperature probe in the desiccant bed and starting the regeneration cycle, that the bed temperature stabilized after slightly less than four hours at a temperature of 350°F, indicating the bed was dry.*

In its previous installation, the chiller unit did not have an on-off switch. The only way it could be turned off after the main power was activated was by undergoing a safety shutdown, such as overheating. The chiller automatically "came on" when the main power was turned on. An on-off switch has been installed on the main control panel so the operator can shut the chiller off and continue operating the tunnel if the need should arise.

2.3 THROTTLING VALVE

After passing through the plenum filter, the air moves on through four feet of 12-inch pipe. The flow channel then converges to a 6-inch flange, to which is connected a Mason-Neilan Model 37-3312 soft-seat butterfly valve. After passing through this valve, hereafter referred to as the throttling valve, the flow diverges back to a 12-inch diameter pipe and continues on to the stilling tank, which is described in the next section. (See Figure 2.3).

The throttling valve is used to regulate the air flow rate and, as a consequence, the stagnation pressure. This valve is pneumatically controlled by the operator from the main control panel. A Mason-Neilan

*This measurement was performed by Mr. D. H. Drummond.

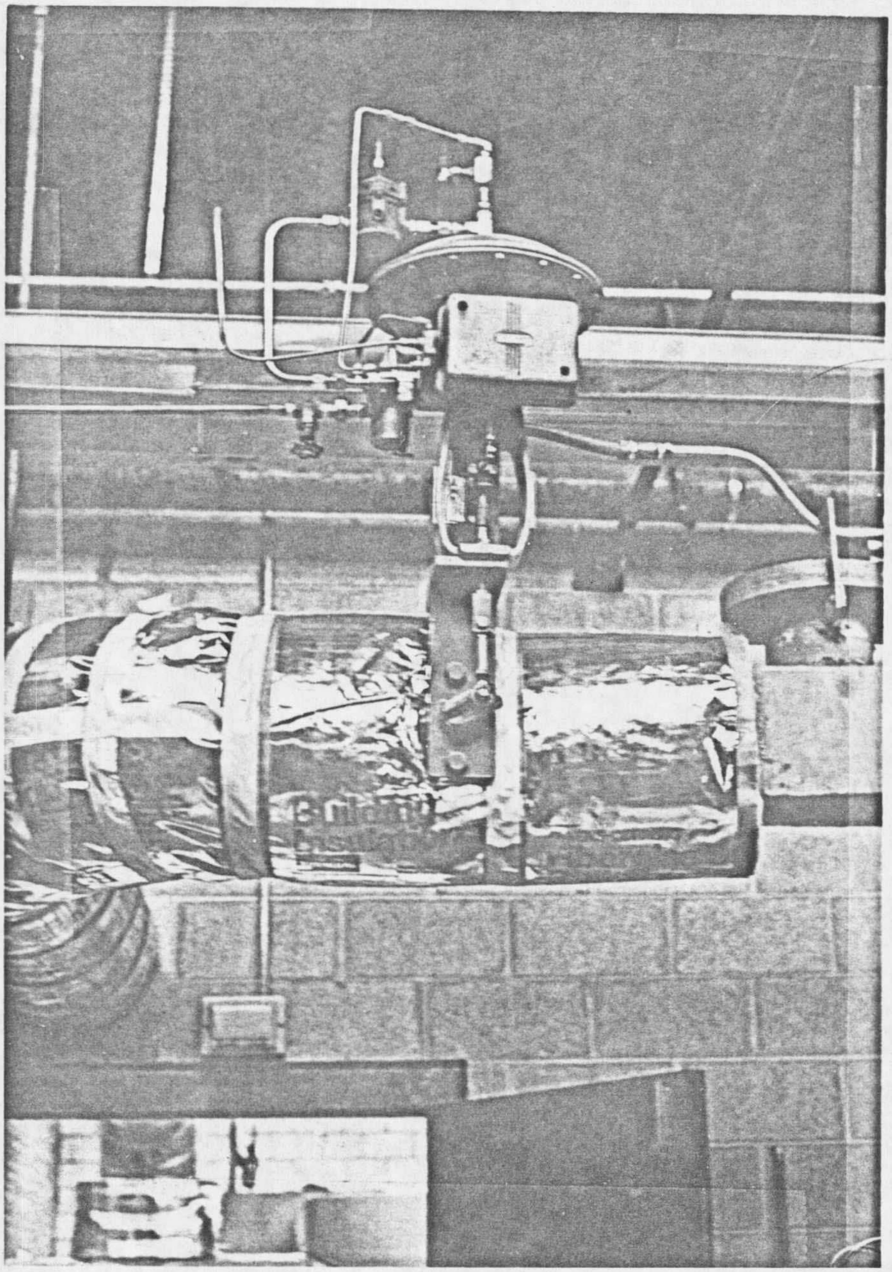


Figure 2-3 Throttling Valve

7000 series spring-diaphragm control valve positioner operates the valve and positions the butterfly for air flow control during operation.

A Mason-Neilan Model 141-2 Manual Loading Station is located on the main control panel so the operator can position the valve in order to obtain the desired stagnation pressure. There are two modes of operation for this system. These are a manual mode and an automatic mode. The manual mode is normally used when starting and stopping the tunnel, but will not provide stable operation during an experiment. In the manual mode, the position of the valve is fixed and, if left alone, no correction will be made for varying inlet or atmospheric conditions, thereby causing the stagnation pressure to fluctuate several millimeters of Mercury. For this reason, during a tunnel run, the automatic mode is normally used once the tunnel has been started and allowed to come into equilibrium. In this mode the desired stagnation pressure is set once by the operator and the system automatically maintains that condition by varying the position of the butterfly as inlet conditions change.

The throttling valve is opened by increasing the pneumatic pressure. If, for any reason, the control system loses its air pressure, the throttling valve will shut. When this happens the vacuum pump will pull a large vacuum throughout the system. This will cause the safety relief valve (check valve) that is located near the pumps to open, as is described later in this chapter. This valve does not open, however, until there is already a large vacuum throughout the wind tunnel circuit.

Because of this vacuum, the pumps will start freewheeling backwards after the motor shuts off, blowing whatever might be in the pumps, mostly rust and water, back through the test section. This can be very damaging to the test section and whatever might be in it at the time. For this reason, extreme care is always taken to never allow the throttling valve control pressure to get too low. As another safeguard against this possibility, a safety interlock system has been installed to prevent the vacuum pump motor from starting if the throttling valve is closed. A low-air-pressure shutdown sequence has also been installed to stop the motor if the building air supply pressure should fall too low to operate the pneumatic devices on the wind tunnel, such as the throttling valve. This sequence is set to start if the supply pressure falls below 70 psi.[3]

2.4 STILLING TANK

Directly downstream from the throttling valve is the stilling tank. The purpose of this tank is to allow chance disturbances, such as large scale turbulence, to damp out before the air enters the test section. It consists of a 7.5 feet long by 3 feet wide cylindrical vessel (see Figure 2.4). The humidity of the wind tunnel air is measured from an air sample taken from this tank during an experiment.

Air enters the stilling tank from the 12-inch line through a pipe flange that is welded to the top of the vessel. The air exits the tank

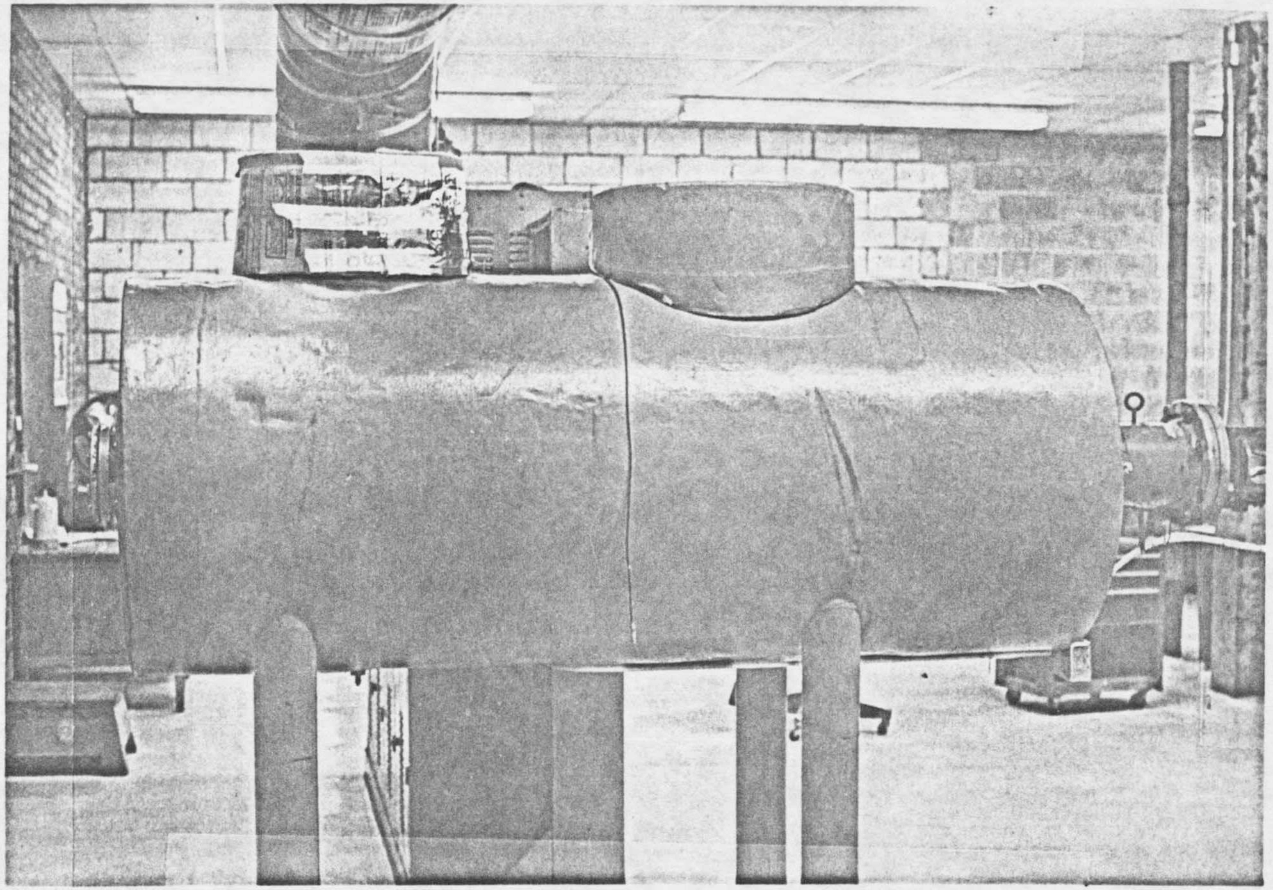


Figure 2-4 Stilling Tank

through the end as is shown in Figure 2.4. At the downstream end of the stilling tank, directly before the air enters the test section, is a honeycomb flow straightener. Each passage in this flow straightener measured one-half inch square in cross-section and is three inches long. The puspose of the flow straightener is to break up large eddies that may be coming from the stilling tank. It does little to damp out small scale turbulence. These small scale fluctuations are damped out to some degree by turbulence filter screens that are located at each end of the flow straightener. The upstream screen is 32 mesh, .006 inch diameter wires while the downstream screen is 40 mesh, .006 inch diameter wires (see Figure 2.5)

Hot wire measurements of the turbulence content of the free stream were made when the facility was at its previous location. The turbulence level was measured at both low (420 mm Hg) and high (735 mm Hg) stagnation pressures. The energy spectrum of the turbulence level was taken at these pressures primarily to ensure that the frequency level of the electronics was adequate and infer the scale of the disturbances. The mass flow fluctuations were 1.47 percent for the low pressure and .82 percent for the high pressure. The absolute temperature fluctuations were .42 percent for the low pressure and .23 percent for the high pressure. The correlation coefficient between these two fluctuations was found to be +.87 for the low pressure and +.50 for the high pressure.[2] These figures are a factor of two or three higher than was originally

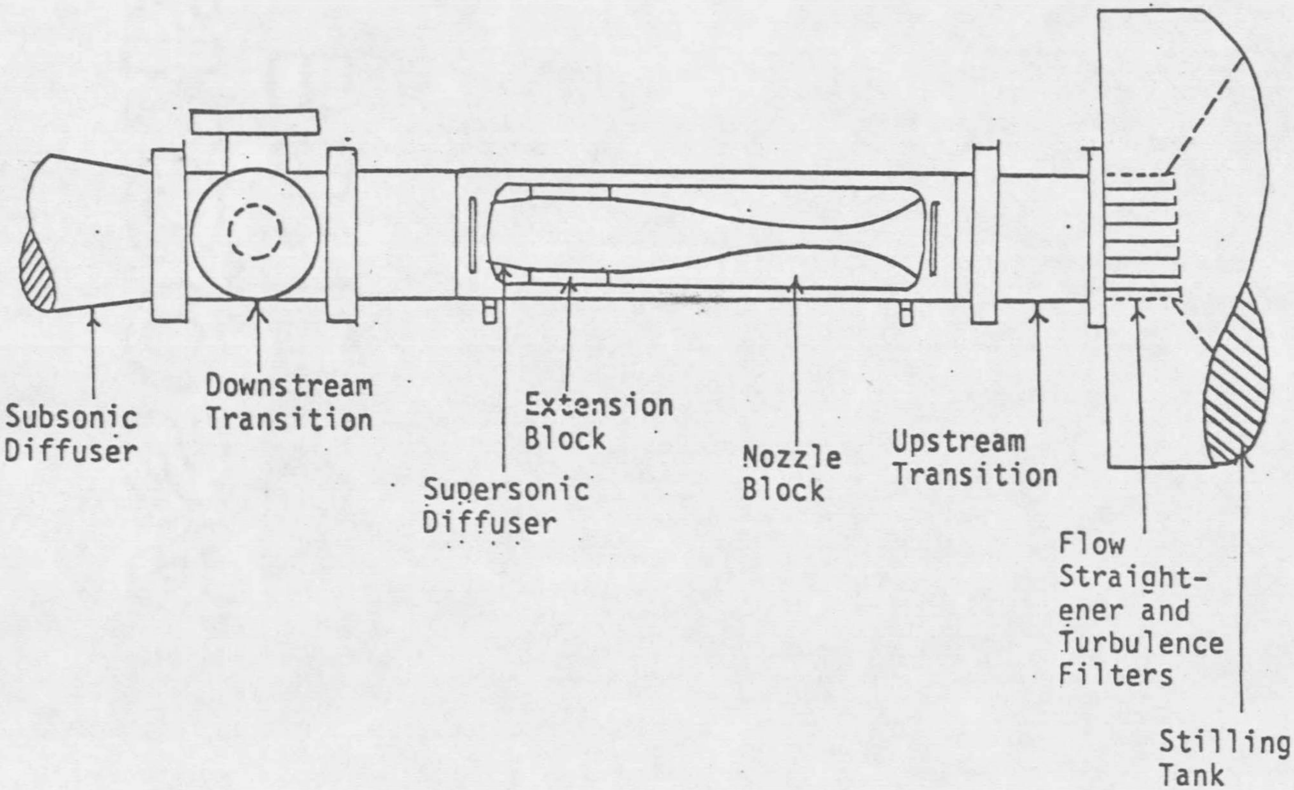


Figure 2-5 Supersonic Sections

desired, but they still represent an acceptable stream turbulence level. That is, they represent a level considerably lower than that which is found in a turbulent wake, which is what this tunnel was designed to study. The level has also been found to be uniform throughout the test section. Hot wire tests have suggested that these measurements have not changed to any great degree.

2.5 UPSTREAM TRANSITION SECTION

The geometrical transition between the 6-inch circular cross-section at the exit of the stilling tank and the 3.1 x 6 inch rectangular section that forms the test section inlet channel is handled by the upstream transition section. A 3 x 6 inch channel was first milled along the axis of this section, followed by a 6-inch base diameter right angle cone being milled along the same axis. The fluid enters through the plane of the cone, converges gently toward its apex, then gradually transits into the rectangular channel.

The intersection of the cone and the triangle forms a sharp edge and it was originally feared that this would generate vortices. Fortunately, the edge is nearly parallel to the flow and the flow component normal to it is practically nonexistent.

Total temperature and total pressure measurements of the tunnel air flow are performed by pressure and temperature probe connections in this section. Also, the support strut for axisymmetric test models is located in this section.

2.6 NOZZLE

The wind tunnel test section consists of a rectangular parallel piped made of brass and contains a two-dimensional DeLaval nozzle, a short straight section, and a supersonic diffuser, all made of aluminum.

The nozzle coordinates were computed by appropriate scaling from a Mach 3 nozzle calculation supplied by the Jet Propulsion Laboratory (JPL). The JPL design was for a 20 x 20 inch square nozzle exit with a turbulent boundary layer growing along the nozzle wall. For reasons of expediency, the JPL coordinates were reduced by a factor of 3:20 to obtain a 3 x 3 inch uniform or inviscid flow core. The turbulent boundary layer thickness was reduced by a factor of $(3:20)^{4/5}$ to account for the usual scaling of the turbulent boundary layer with linear distance. No account of the Reynolds Number was taken in this simple transformation of coordinates. In this manner, the actual distance from the floor to the ceiling in the test section was found to be 3.2 inches for a uniform flow core measuring 3 inches high. The nozzle coordinates are given in Table 2.1.

The distance between sidewalls could be calculated precisely only by accounting for the boundary layer growth along these walls which remained plane and parallel, a very difficult calculation. Instead, a sidewall-to-sidewall distance of 3.1 inches was chosen as an empirical

Table 2-1

Nozzle Coordinates (X is 0 at the throat, Y is 0 at the plane of symmetry)

x (inches)	y (inches)	x (inches)	y (inches)
0.0	.3541	5.7223	1.1043
0.1500	.3551	5.8951	1.1296
0.2999	.3581	6.0735	1.1551
0.4499	.3629	6.2577	1.1807
0.5999	.3696	6.4479	1.2064
0.7499	.3779	6.6440	1.2320
0.8999	.3879	6.8464	1.2575
1.0499	.3995	7.0551	1.2827
1.1998	.4124	7.1618	1.2952
1.3498	.4268	7.2703	1.3077
1.4998	.4426	7.4920	1.3322
1.6498	.4595	7.7204	1.3563
1.7998	.4776	7.9559	1.3799
1.9498	.4969	8.1987	1.4030
2.0997	.5170	8.4488	1.4254
2.2497	.5382	8.7066	1.4472
2.3997	.5600	8.9724	1.4682
2.5497	.5820	9.2434	1.4882
2.6996	.6060	9.5167	1.5071
2.8497	.6296	9.7922	1.5247
2.9996	.6545	10.0692	1.5402
3.1496	.6793	10.3475	1.5564
3.2996	.7046	10.6277	1.5706
3.4496	.7301	10.9074	1.5836
3.5996	.7558	11.1883	1.5956
3.7185	.7762	11.4693	1.6066
3.8224	.7942	11.7501	1.6167
3.9300	.8127	12.0304	1.6258
4.0414	.8318	12.3100	1.6341
4.1567	.8515	12.5888	1.6415
4.2761	.8720	12.8661	1.6483
4.3997	.8930	13.1419	1.6543
4.5277	.9144	13.4157	1.6598
4.6600	.9366	13.6882	1.6647
4.7970	.9592	13.9577	1.6691
4.9386	.9824	14.2257	1.6730
5.0851	1.0061	14.4906	1.6766
5.2364	1.0300	14.7605	1.6798
5.3932	1.0544	15.0125	1.6829
5.5551	1.0792	15.1411	1.6844

compromise. Equally empirical was the design of the section between the test section entrance and the nozzle throat. The contour chosen allows the flow to converge smoothly toward the throat and is tangent to the nozzle contour at the nozzle throat.

Sixteen .024 inch static pressure ports are drilled on the lower nozzle block extending along its centerline beginning at the exact location of the throat. The first port is 1.14 inches downstream of the throat. The ports are spaced one inch apart thereafter. The degree of choking can be easily determined by glancing at a Mercury manometer bank that is located next to the stilling tank and connected to these pressure ports.

A 5-inch long aluminum extension in the form of separate upper and lower blocks, is located immediately downstream of the nozzle. These blocks form a straight section and extend the useful test area.

2.7 SUPERSONIC DIFFUSER

The fixed supersonic diffuser was designed by simply contracting the flow channel to the minimum diffuser throat area allowing a normal shock to be swallowed during the starting operation. The pressure ratio required to run the tunnel with this diffuser was deduced from data accumulated from other wind tunnels and found to be about 5.2.[4]

The pertinent area ratio, without boundary layer corrections, is found to be:

$$\frac{\text{Nozzle Throat Area}}{\text{Diffuser Throat Area}} = \frac{0.708}{1.350} = 0.524$$

Diffuser boundary layer corrections were not made. Instead the diffuser throat was enlarged by milling the apex of its triangular profile so that the profile became trapezoidal. Rough computations showed that by this means the displacement thickness of the boundary layer, as well as the model support struts passing through the nozzle throat, could be accounted for.

2.8 DOWNSTREAM TRANSITION

The transition from the downstream test section end back to a 6-inch diameter pipe is accomplished with the same configuration as is described in Section 2.5 (Upstream Transition). The section is simply turned around to allow transition back to the round piping configuration.

Three four-inch pipe studs are arranged in a "T" around the centerline of the tunnel through this transition. These studs are equipped with four-inch pipe flanges and allow access to the flow channel for instrumentation. The X-actuator mechanism is located on the top flange of this section.

2.9 SUBSONIC DIFFUSER

This section of the tunnel is located directly downstream of the downstream transition section. It is a conically-shaped tube, 36 inches long, diverging from a 6-inch diameter at the downstream transition connection to a 12-inch diameter at the diffuser exit for connection to the standard 12-inch wind tunnel plumbing.

A 12-inch diameter bellows expansion joint downstream of this section allows enough in-line movement to remove and replace any wind tunnel component from this point to the stilling tank exit.

2.10 VACUUM SYSTEM

A Roots-Connersville No. 36-RGVS-2 vacuum pump generates the flow in the wind tunnel. The pump consists of two Roots blowers connected on the same shaft with a 200 Horsepower Westinghouse 480 Volt, three-phase induction motor, turning at 890 revolutions per minute (see Figure 2.6).

Near the first stage inlet, a check valve is located to protect against pump overloading should an excessive vacuum occur. If the pump inlet pressure goes below 48 mm Hg this valve will open and allow air into the inlet of the blower, since dangerous overheating will occur if the pump operates below this pressure for any other than a very short period of time. The opening of the check valve should not be confused with the low air pressure safety shutdown sequence. (The low air pressure shutdown occurs when the building supply pressure is too low to operate the pneumatically controlled devices on the wind tunnel.) The check valve does not shut the system off when it opens. Its only function is to prevent overheating of the pumps due to excessively low inlet

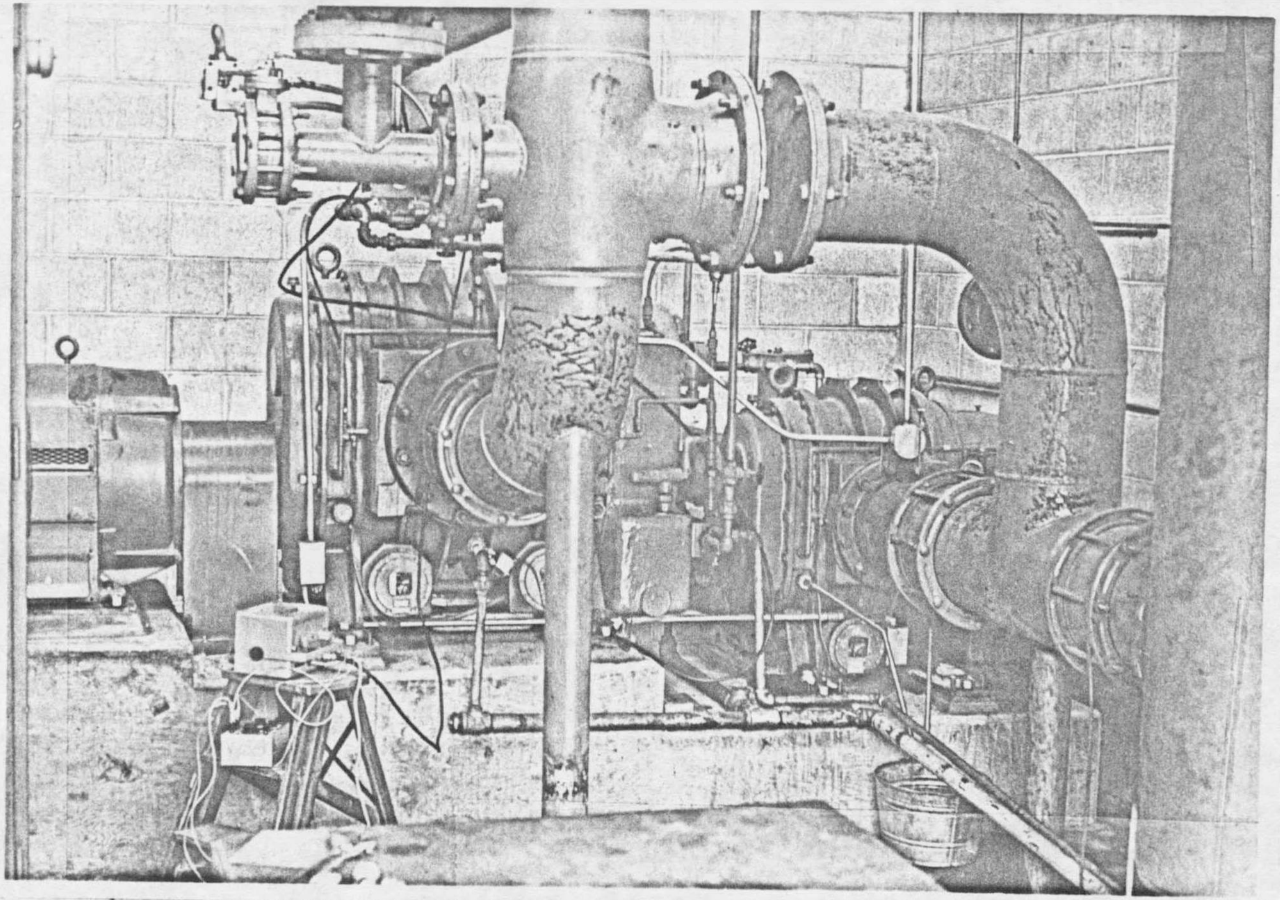


Figure 2-6 SWT Pump

pressure.

Just upstream from the inlet to the first stage of the vacuum pumps is the tunnel bypass valve. This is a pneumatically operated valve that allows atmospheric air into the first stage of the vacuum pumps. This valve is closed except during the startup of the tunnel. It opens as the motor is started to allow the blowers to get up to speed without having to "pull" a vacuum throughout the entire wind tunnel circuit. Once the blowers have reached operating speed, the bypass valve is shut and the tunnel is in operation.

The blowers are water sealed. Each blower has a pipe running into the air duct on the inlet side. Water is directed, in the form of a fan-shaped spray, over the surface of the rotor to provide sealing.

A low water pressure safety shutdown sequence has been installed and is activated should the water pressure in the lines feeding the blowers fall below 25 psi. At times, this shutdown has been activated by sudden momentary drops in the water pressure. To prevent this, it has become necessary to install a surge tank to maintain the pressure in the water lines during these momentary pressure drops. Thus, the water pressure must fall below 25 psi and stay there for a finite period of time (a few seconds) before the low water pressure shutdown is activated.

The oil system on the blowers also has two safety interlocks installed in it, one for low oil pressure and another for high oil temperature. The motor will automatically shut off if either one of these sequences is activated. A warning light will also be displayed on the main control panel should either one of these problems arise.

When the blowers arrived here at MSU they were very rusted. This had occurred because in the past they had been allowed to remain inactive for long periods of time with water in them. To prevent this from occurring again, a dry shutdown sequence has been installed. When the dry shutdown is activated the sealing water flow to the blowers is shut off and air is blown through the water system around the blowers and through the spray nozzles themselves. This is done to protect the blowers from the corrosion problems that arise when stagnant water is left in them. After three minutes of operation in the dry shutdown mode the motor automatically shuts off. The dry shutdown is normally used only when the tunnel is not going to be restarted again for the rest of the day.

Inside the motor is a thermistor imbedded in the armature windings that will shut the motor off if it gets too hot. If this should occur, there will be no indication of the cause of the shutdown.

It has been observed that the nozzles directing the fan-shaped spray over the lobes of the blowers often get plugged due to particles that have been carried along through the water system. When this occurs the nozzles must be taken out and cleaned.

The first indication of loss of water is a temperature rise at the blower outlets. Because of the damage that could result to the blowers if this went unnoticed, these temperatures must be watched continuously while the tunnel is in operation.

After the air has passed through the blowers, the wet exhaust is directed into a large discharge line silencer which removes some collected water to a drain and reduces the pump discharge noise. After leaving the silencer, the air is directed up through the ceiling and is discharged outside into the atmosphere.

2.11 WIND TUNNEL X-Y-Z PROBE ACTUATORS

A probe actuator system capable of moving a probe in three directions at variable speeds and at closely calibrated distances is installed in the wind tunnel test section. Positioning to 0.001 inch is accomplished with direct geared mechanical output while an electric position output is provided by a 10-turn helipot on each axis. The actuator drives the electric motors with associated reversible variable speed control. The vertical actuator is equipped with an adjustable limit system. Actuator speeds and limits of travel are given in Table 2.2.

2.12 SCHLIEREN SYSTEM

An 8-inch portable Schlieren system has been fabricated for observing the wind tunnel test section flow. The system consists of two wheeled tables supporting all optics and electronics in a pre-aligned position. Two light sources are used with associated condensers and plane mirrors providing either continuous illumination for optical

TABLE 2.2

Actuator Speeds and Limits of Travel

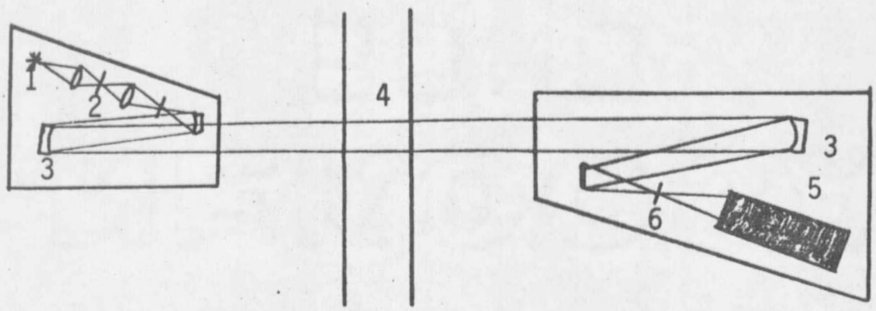
Axis	Linear Speed min	Linear Speed max	Limits of Travel
X	.003 in/sec	.070 in/sec	8 in
Y	.002 in/sec	.066 in/sec	3 in
Z	0.0 in/sec	.016 in/sec	0.40 in

alignment and timed photography, or a spark source for use in high speed photography at exposure times of 0.5 microseconds. The 8-inch parabolic mirrors cover the working section adequately while their 64-inch focal length allows a compact design. The camera is of fixed focal length design equipped with a shutter-diaphragm and polaroid back pack. Image magnification at the camera is 0.73, reducing the entire Schlieren field to a 4 x 5 inch polaroid pack film size. Optical components employed in the system are ground to within one-fourth wavelength of Mercury light per inch while the tunnel test section windows are of selected striation-free plate glass providing high system sensitivity and minimum distortion (see Figure 2.7).

2.13 WIND TUNNEL PRESSURE STATION

The SWT is equipped with a pressure measuring system capable of monitoring 12 separate input pressures. The system is equipped with three Wallace and Tiernan absolute pressure gages and three impedence type pressure transducers.

Pressure gage A reads from 0 to 20 mm Hg, gage B reads from 0 to 100 mm Hg, and gage C reads from 0 to 400 mm Hg. Pressure transducer B reads from 0 to 50 mm Hg, transducer c reads from 0 to 250 mm Hg, and transducer D reads from 0 to 750 mm Hg. The electrical output from these transducers can be fed into various other pressure-monitoring electronic components. A photograph of the system is shown in



KEY

1 Light Source
2 Slit
3 Mirrors
4 Field of View
5 Camera Box
6 Knife Edge

Figure 2-7 Schlieren System

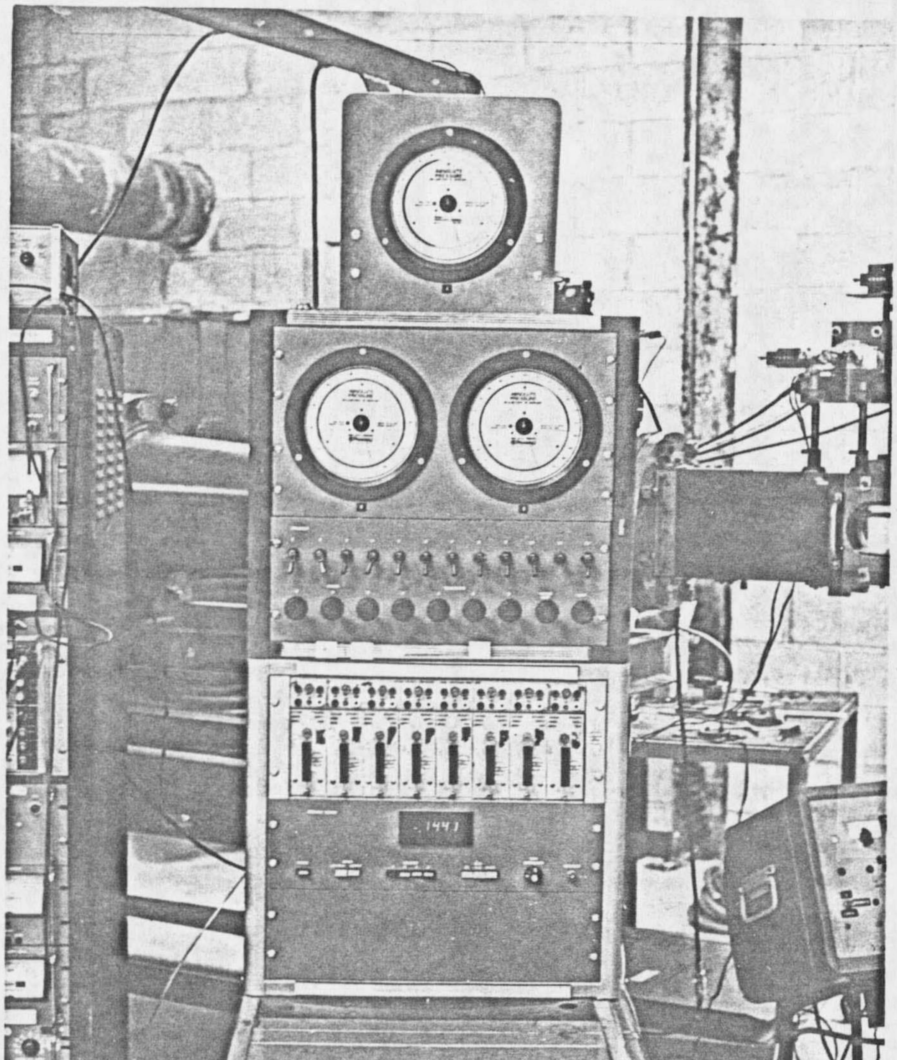


Figure 2-8 Wind Tunnel Pressure Station

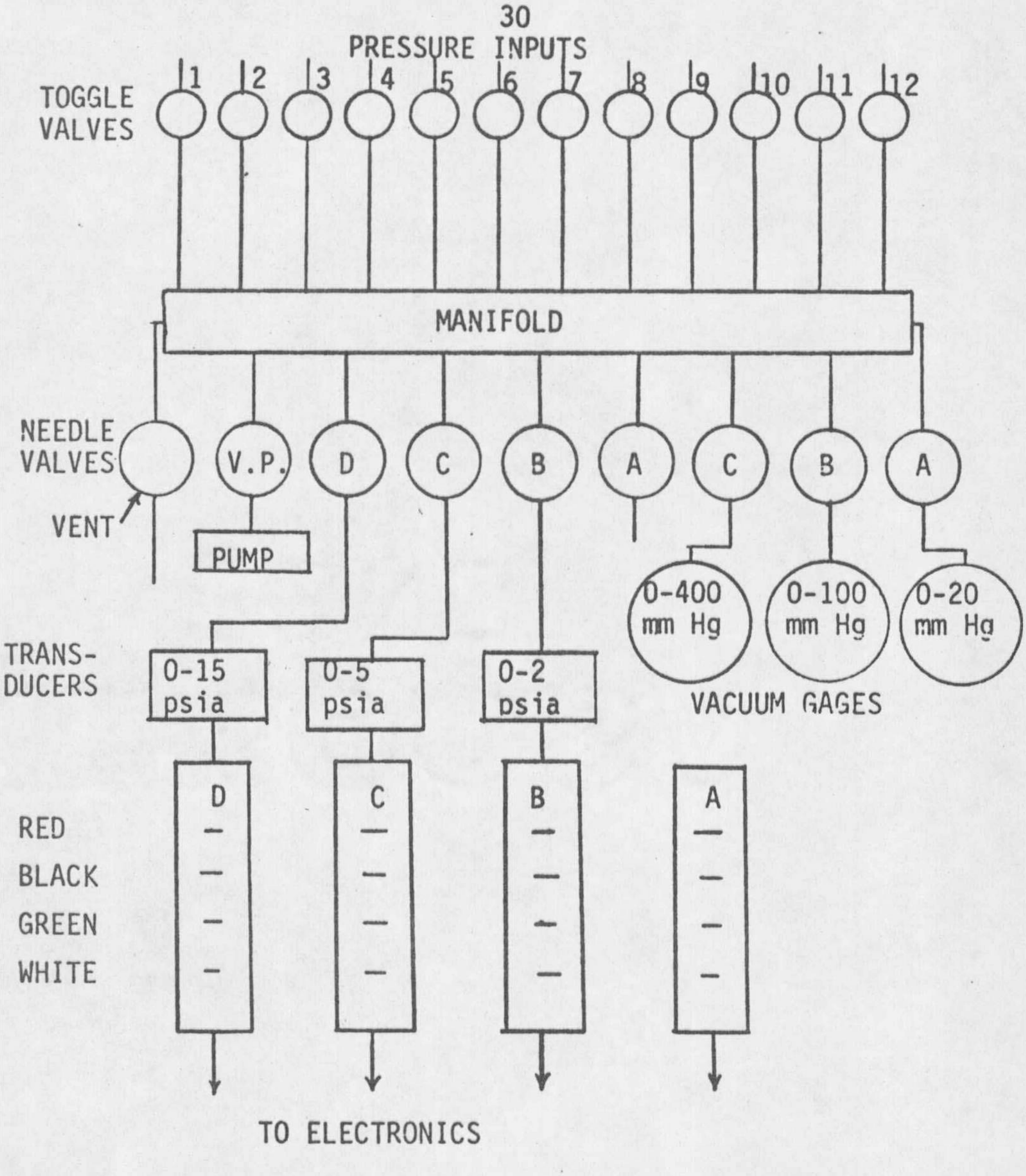


Figure 2-9 Schematic of Pressure Station