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SUPERSONIC COMBUSTION RESEARCH LABORATORY;

VOLUME 1 - DESIGN AND FABRICATION

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JAN 1993

INTERIM REPORT

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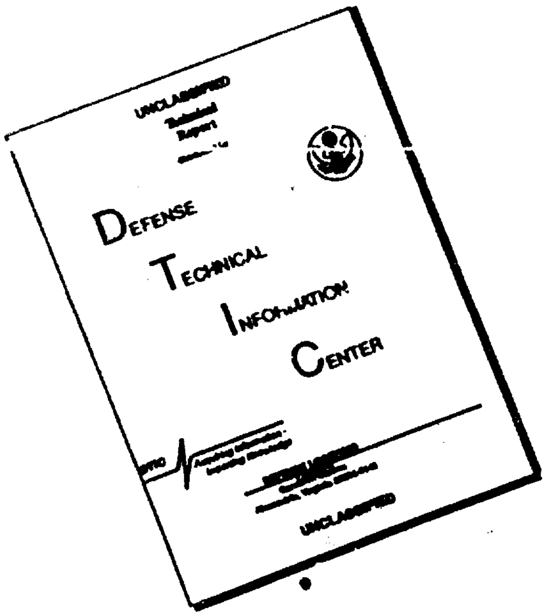

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The Experimental Research Branch of the Advanced Propulsion Division at Wright-Patterson Air Force Base began taking steps toward the development and installation of a supersonic combustion research facility during FY90. A large-scale in-house research facility devoted to the study of supersonic fuel air mixing and combustion has been designed, fabricated, and installed. The purpose of the report that follows is to present documentation of the features of the air supply system, the design details and the characteristics of the actual supersonic combustion tunnel, and a description of the control system and instrumentation.

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NOMENCLATURE

a	speed of sound (ft/sec)
A	area (in^2)
C_f	critical flow factor (valve specific)
C_v	flow coefficient
δ_x^*	local turbulent boundary layer thickness
γ	ratio of specific heats
g_c	gravitational constant (= 32.2 ft/sec^2)
G	gas specific gravity (= 1 for air)
G_f	specific gravity at flowing temperature (= G(520 °R)/$T_{operation}$)
$\dot{m}$	mass flow rate (lb_m/sec)
M	Mach number
M_x	Mach number at nozzle exit
M^*	nondimensionalized velocity
P	static pressure (psia)
P_0	total pressure (psia)
P_{01}	mixed air total pressure (psia)
P_{02}	settling chamber total pressure (psia)
P_C	cold line supply pressure (psia)
P_H	hot line supply pressure (psia)
P_1	upstream pressure (psia)
P_2	downstream pressure (psia)
ΔP	differential pressure (= P_1-P_2) (psi)
R	gas constant (= 53.35 (lb_f ft)/(lb_m °R))
Re_x	Reynolds Number based on streamwise distance
ρ	density (lb_m/ft^3)
T	static temperature (°R)

$T_{operation}$	valve operation temperature (°R)
T_0	total temperature (°R)
T_{01}	mixed air temperature (°R)
T_{02}	settling chamber total temperature (°R)
U	velocity (ft/sec)
W	mass flow rate (lb_m/hr)
x	streamwise location (in)
y	transverse location (in)
Z	compressibility factor (=1 for air)

1. INTRODUCTION

The Experimental Research Branch of the Advanced Propulsion Division at Wright-Patterson Air Force Base began taking steps toward the development and installation of a supersonic combustion research facility during FY 1990. With the push toward hypersonic flight regimes, a large-scale in-house research facility devoted to the study of supersonic fuel-air mixing and combustion provides a clear forum for enhancing the basic knowledge and data bases through the use of conventional and state-of-the-art, nonintrusive diagnostic techniques. These diagnostic techniques are employed to gain a better understanding of the behavior of turbulent flows within realistic combustor geometries with and without heat release.

To prepare the existing test cell in Building 18C, Room 19 for a supersonic test apparatus, extensive modification including the addition of a clean explosion-proof enclosure, an office space, utility fluids (including water, nitrogen, and shop air), and electricity was required. These modifications were completed during FY 1991. Also required for operation of a large-scale supersonic test facility was an air supply system that utilized the air handling capabilities of the Tech Air Facility within the Building 18 complex. The final components required were the actual test rig hardware and computer control system used to monitor the supply system valves and flow parameters. An in-house effort to design, fabricate, and install the test hardware began in January 1992 and finished in December 1992. Also during this time, the air supply system installation was completed and the control system logic was developed and installed. Check-out tests of the supply system were accomplished in early December 1992 and proved successful from the standpoints of system compatibility with the Tech Air Facility capabilities and control system functionality.

The purpose of the report that follows is to present documentation of the features of the air supply system, the design details and characteristics of the actual supersonic combustion tunnel, and a description of the control system and instrumentation. Each of these topics is covered in detail, and the basic control logic development is included in the appendix. Schematic illustrations and photographs of the facility are included as well to clarify some of the descriptions.

The contributions of the following personnel are very noteworthy and appreciated:

Design and Computer Drafting--Mr. Gary Haines

Control System Implementation--Mr. Dave Schommer

Facility Installation--Mr. Charles Smith.

2. COMBUSTION FACILITY DESIGN

Specific operational goals were set down at the initiation of this design effort. These goals dealt not only with the air flow characteristics of the facility, but the system maintenance features as well. The underlying objective of the effort was to develop an in-house supersonic research facility capable of allowing studies of the enhancement and control of fuel-air mixing in supersonic combustors with conventional and state-of-the-art, nonintrusive diagnostic techniques such as schlieren photography, LDV (Laser Doppler Velocimetry), PLIF (Planar Laser-Induced Fluorescence), PIV (Particle Image Velocimetry), Mie scattering, and CARS (Coherent Anti-Stokes Raman Scattering). Other design objectives are listed below:

- Variable Mach number capability (1.5 to 3.0)
- Continuous flow operation
- Maximum stagnation conditions of 400 psig and 1660 °R at a peak flow rate of 34 lb_m/sec
- Nominal 5-inch by 6-inch test section with allowances for nozzle boundary layer growth
- Nominal test section conditions of 7.35 psia and 525 °R
- Optical access to the test section on three sides and from the end
- Spray cooled diffuser to allow exhausting into the air facility coolers
- Modularity for ease of maintenance and future facility enhancement
- Thermal expansion compensation to minimize test section movement

The result of the design effort is shown via schematic in Figure 1 and photograph in Figure 2, and nominal operating conditions are given in Table 1.

It is informative to identify the components of the combustion facility prior to addressing the details of their design. Air is transported into Room 19 via two supply lines, each of which has its own remotely activated isolation valve. The first line is

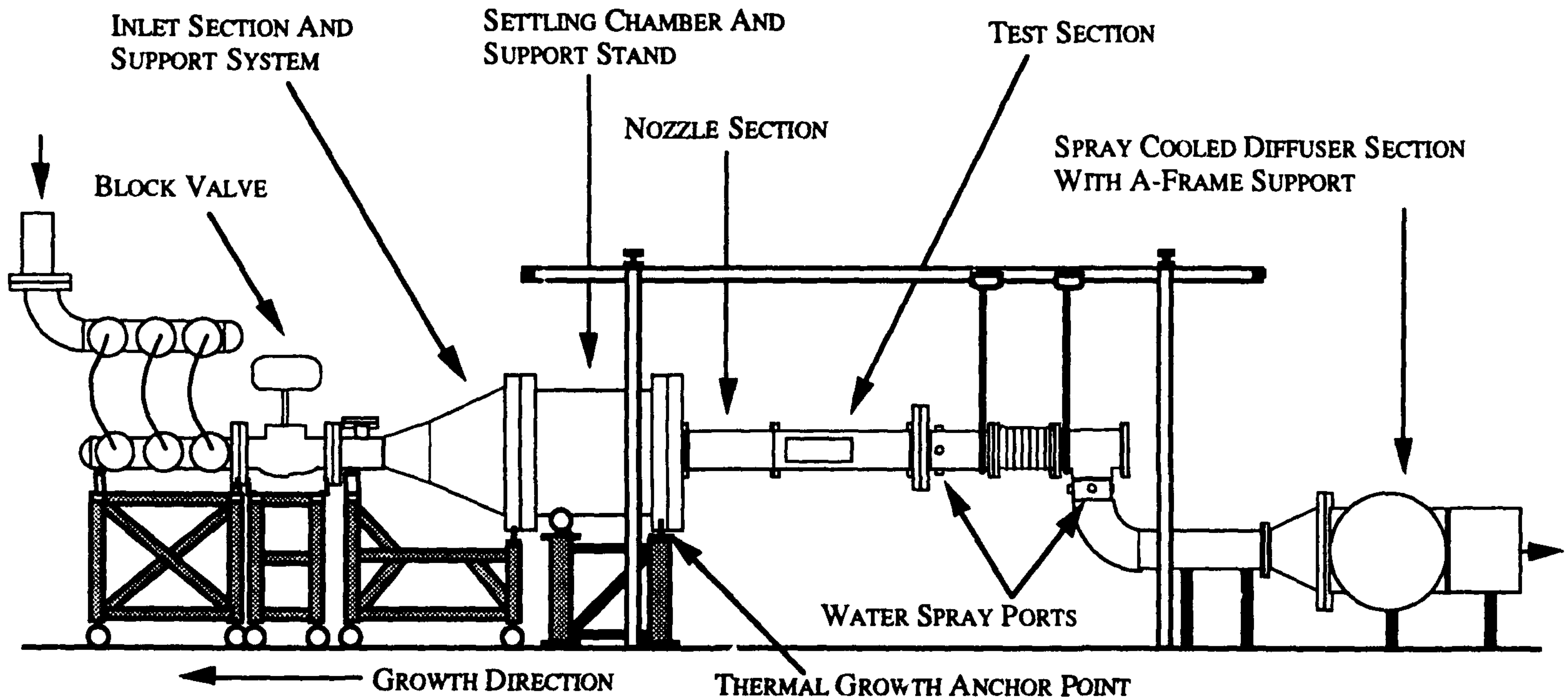

Figure 1 Schematic of Supersonic Combustion Tunnel

Figure 2 Photograph of Supersonic Combustion Tunnel

Table 1 Nominal Operating Conditions

Mach No.	P, psia	T, °R	P_0, psia	T_0, °R	$\dot{m}$, lb_m/sec
1.5	7.35	525	26.98	761.2	13.69
2.0	7.35	525	57.51	945.0	18.26
2.5	7.35	525	125.6	1181	22.82
3.0	7.35	525	270.0	1470	27.39

supplied with high pressure, high temperature air and is referred to as the hot air line. The second line is supplied with high pressure air at ambient temperatures and is referred to as the cold air line. The hot and cold lines are regulated independently with control valves, both of which are pneumatically actuated and are wired into the computer control system for position feedback and control. The cold air is fed through a check valve and into an air mixing station while hot air is supplied to the other entrance of the mixing station directly. The resulting mixed air is transported via a thermal expansion loop to a manifold section above the test cell that houses a vent line and a rupture disc line. From this location, the air is brought into the test cell through a pair of manifold sections connected with stainless steel flexible hose. Once in the test cell, another control valve is used as an open/close valve to allow air to flow into the settling chamber. After passing through the valve, the air flows through an expansion section and into the settling chamber where a conditioning section is housed. This conditioning section consists of screens and honeycomb designed to reduce the scale of the turbulence and straighten the flow prior to acceleration through the converging-diverging nozzle. After acceleration to the desired Mach number, air then enters the test section where numerous injection schemes may be examined using the various diagnostic techniques mentioned previously. A diffuser section then decelerates and cools the flow using water sprayers before the air is transported to the exhausters and coolers of the air facility. Further details of each component of the combustion tunnel are discussed in the sections which follow.

2.1 AIR SUPPLY SYSTEM

Various compressors and a gas fired heat exchanger are available to produce high pressure and high temperature air for use in the new supersonic research laboratory. However, this air is distributed to the various test cells in the Building 18C complex via a separate system of air lines, and in order to route that air into the test cell in Room 19, the design and installation of an air supply system which taps into the existing distribution piping was required. The effort to design, procure, and install this system was awarded to Calspan Advanced Technology Center under the Scholarly Research Program in Airbreathing Propulsion, Contract F33615-88-C-2832. What follows is a description of that system and its various components.

Two air lines are required to supply the new facility with the necessary flow rates of air at the desired pressures and temperatures. Each line is separated from the distribution piping system by a remotely operated isolation valve. These valves are operated from the panel in the foyer of Room 19, and approval is required from the Tech Air Facility to open or close either valve. The hot line is a 6-inch pipe supplied with high pressure (up to 750 psig), high temperature (up to 1660 °R) air at a maximum flow rate of 17 lb_m/sec. A 4-inch Masoneilan Model 4530 (C_v = 130) pneumatically actuated globe valve is used as the control valve for the hot line, and is referred to as the hot valve (TVC-1902). This valve is configured to fail closed. The isolation valve for the hot line is referred to as RV-1900. After passing through the valve, hot air enters the 6-inch end of a mixing station directly. The cold line is also a 6-inch pipe supplied with high pressure (up to 750 psig), ambient temperature air at a maximum flow rate of 17 lb_m/sec. It enters Room 19 directly above the hot line and is isolated by valve RV-1901. Once in the room, the line turns 90° and is reduced to enter the second control valve. The cold line control valve (PVC-1903) is a 3-inch Masoneilan Model 88-41421 (C_v = 140) pneumatically actuated globe valve, referred to as the cold valve, which, like the hot valve, fails closed. After passing through the valve, the line is looped and lowered in order to be directed toward the mixing station. Before the cold line enters the 4-inch end of the mixer, a flexible section is mounted in line to allow for growth of the hot piping. Also, a check valve is positioned before the cold air enters the mixer to prevent any hot air from flowing back through the cold line.

The outlet of the mixing station is a 6-inch flanged port that now contains "mixed" air. This mixing station is of critical importance to the operation of the facility since it allows independent control of the supply air temperature. Fluctuations in the temperature of the hot supply air may be compensated for by adjusting the amount of cold air which is mixed with it so that a relatively constant mixed air temperature is achieved. The 6-inch mixed air line is now allowed to experience thermal growth in an expansion loop before being lowered into a 6-inch manifold positioned directly above the roof of the test cell. This expansion loop is anchored at the elevation change allowing the thermal growth of the manifold to be minimized and directed parallel to the flow direction.

The manifold itself has five branches. Three of these branches are directed into the clean room through penetrations in the roof. These three are the actual supply lines for the test hardware to be used during experimentation. The other two branches off of the manifold are vent and rupture disc lines. The vent line is a 6-inch line directed upwards through the roof of Room 19. A control valve is positioned in this line allowing it to be used to idle the system during warm up. The vent valve (VV-1905) is a 6-inch Masoneilan Model 88-41911 ($C_V = 400$) pneumatically actuated globe valve which is configured to fail open. The 4-inch rupture disc line is also directed upwards through the roof of Room 19. Currently, the rupture disc is a BS&B Safety Systems Model S-90 disc that fails at 382 psia at 532 °R and 302 psia at 1360 °R. For a schematic view of the supply system, see Figure 3.

The entire supply system is supported from the concrete roofing foundation of Room 19. All of the piping that will experience the effects of thermal growth has been supported using spring hangers and travelling hardware. Also, all of the piping that will

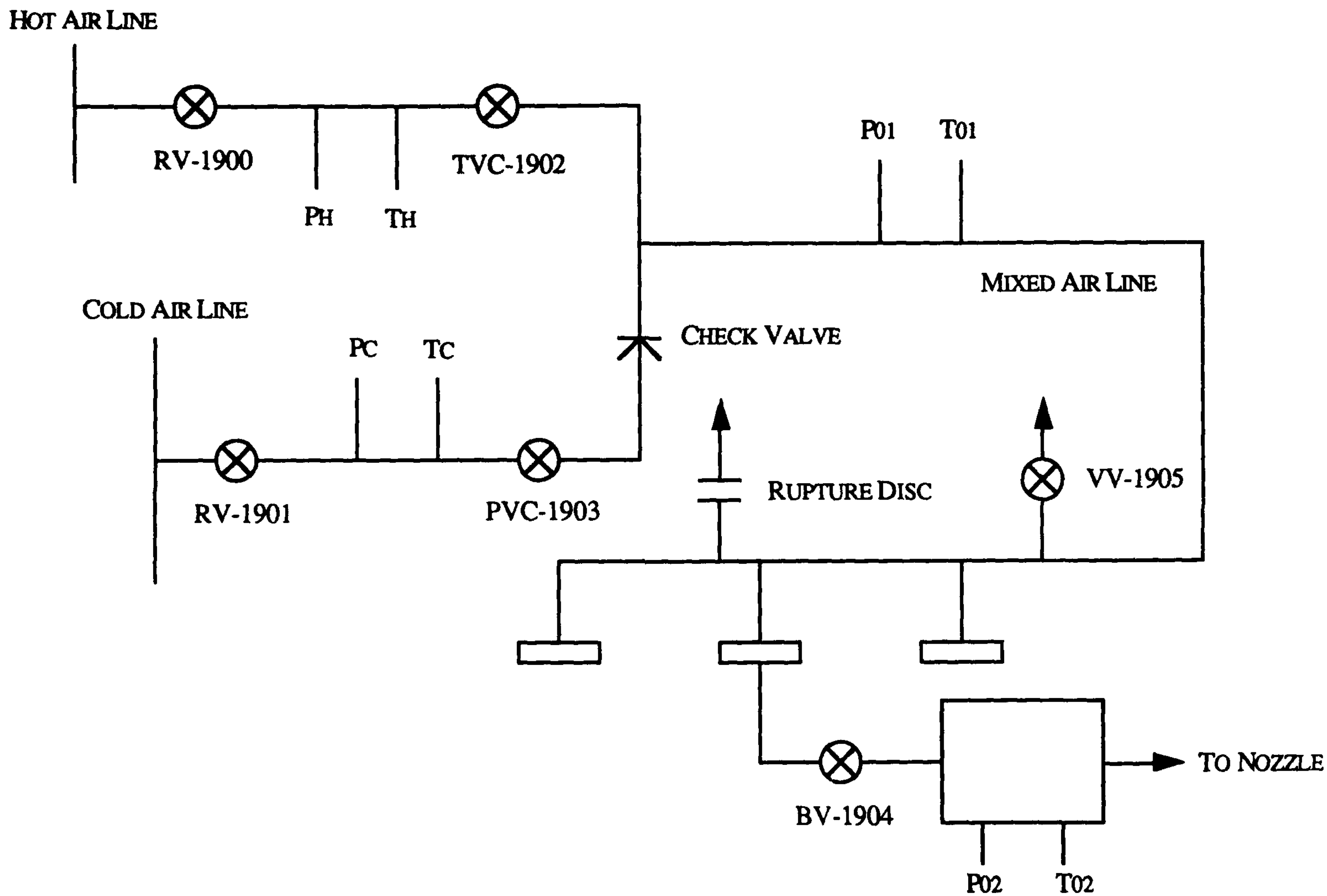

Figure 3 Air Supply System Schematic

experience high temperature air is insulated with 5 inches of calcium silicate insulation. The cold air line is not insulated inside Room 19.

Each valve requires two air lines for operation. The first line requiied is a 100 psig shop air line that is used to supply air to the valve actuator. A factory mounted regulator steps the shop air supply pressure down to an appropriate level that may not exceed 60 psig. The second air line required is a clean, dry 20 psig signal line. This line supplies the electropneumatic transducer which in turn sends a 3-15 psig pressure signal to the pneumatic positioner instructing it how far to open the valve. Further details of the valve control process and instrumentation are addressed in Chapter 3.

2.2 COMBUSTION TUNNEL PROPER

The combustion tunnel is comprised of five major components which include 1) the inlet section, 2) the settling chamber, 3) the nozzle section, 4) test section, and 5) the diffuser. Each of these will be described in further detail below. Discussion will be limited to the major features and functions of each component as well as an overview of the design criteria.

2.2.1 INLET SECTION

The entire inlet section is designed in accordance with the ASME piping code[1], where the design pressure and temperature are 400 psig and 1660 °R, respectively. This section is responsible for transporting the air from the supply manifold described above to the settling chamber. Four separate pieces are required to accomplish this task, the first of which is the upper manifold. This 6-inch section attaches directly to the flanged center leg of the supply manifold that penetrates through the ceiling of the clean room, and is supported using the structural supports of the supply piping and a structural member in the test cell ceiling. Outlet ports in this section are sized to provide roughly twice the flow area of the manifold itself. Accordingly, a total of six outlet ports at a nominal pipe diameter of 3 inches are used. These ports are flanged to allow connection to flexible stainless steel hoses which carry the air from the upper manifold to the lower manifold, and serve as a flexible joint during system warm up. The hoses are of a corrugated design reinforced by double braided stainless steel wire.

The final three pieces making up the inlet section are the lower manifold, block valve, and expansion section. All three pieces are mounted on support carts that roll on a pair of rails which are firmly anchored to the bed plate of the test facility. These carts allow for each of the three pieces to be disconnected and rolled away for maintenance purposes. The carts also allow for movement during system warm up when the piping expands and grows. The lower manifold is a 6-inch section that connects to the flexible hose and the block valve. This piece is nearly identical to the upper manifold and is anchored to its support cart on the downstream side while the upstream side is allowed to move on a rolling support.

The block valve (BV-1904) is a 6-inch Masoneilan Model 88-41911 ($C_V = 400$) pneumatically actuated globe valve configured to fail closed . The valve is used as a ball valve (i.e., either open or closed). Both flanges of the valve are anchored to its support cart so that the valve itself may be separated from the inlet section and rolled away. As with the previously mentioned valves, two air lines are required for block valve operation.

Finally, the expansion section is the transition piece between the 6-inch supply piping and the settling chamber diameter. A 3-inch port is included in this piece for use as a seed injection area or for future facility expansion. The expansion section is mounted in a similar manner as the lower manifold in that the downstream flange is anchored to its support cart while the upstream end is allowed to move on a rolling support. All of the thermal growth of the inlet section is then accounted for and the growth occurs in the upstream direction. Figure 4 is a photograph of the inlet section of the tunnel looking in the upstream direction.

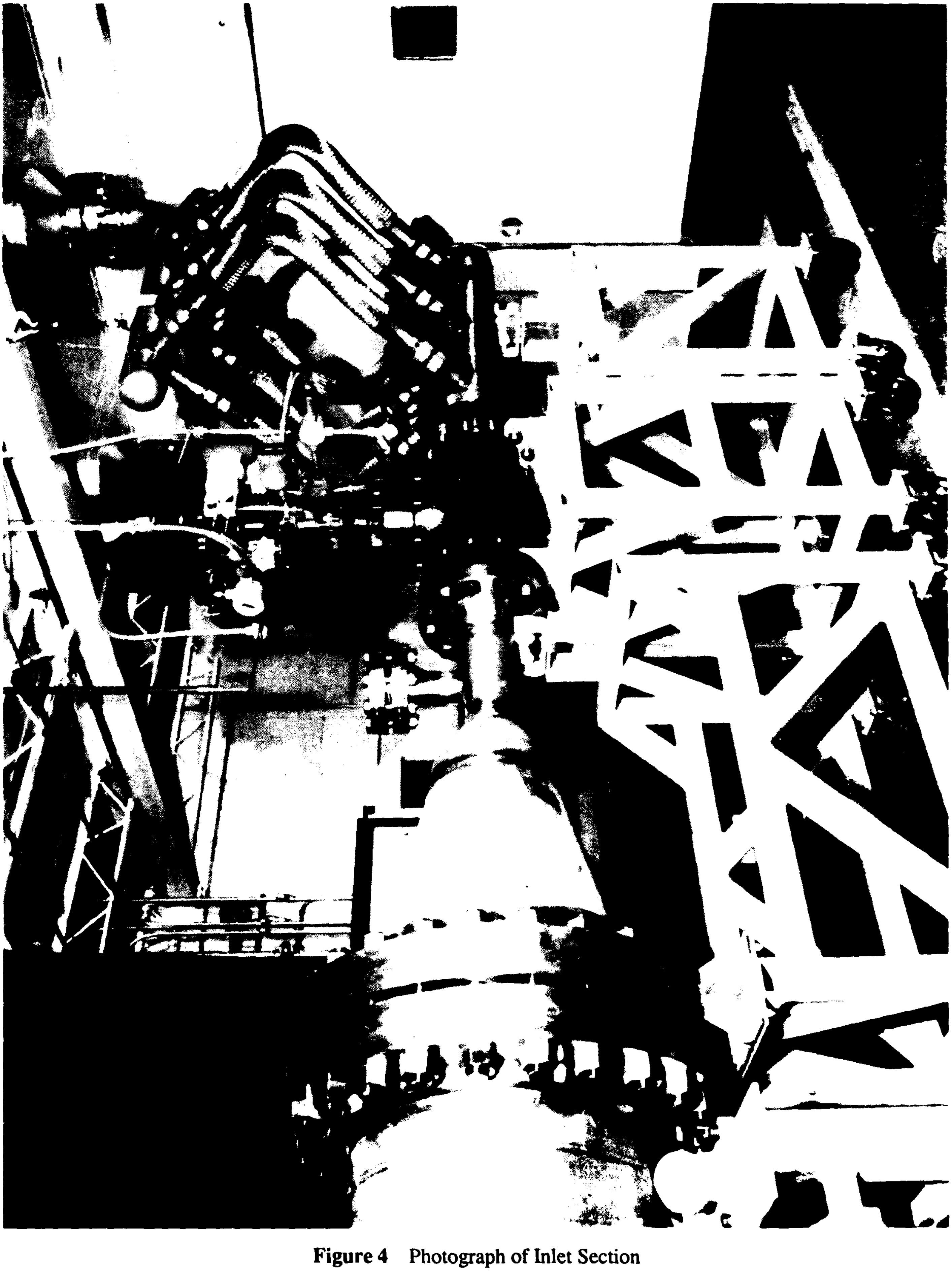

Figure 4 Photograph of Inlet Section

2.2.2 SETTLING CHAMBER

The settling chamber conditions the air using devices which promote a more uniform flow at the entrance to the nozzle with small scale turbulence before it is accelerated by the supersonic nozzle. This chamber is again designed in accordance with the ASME piping code[1]. Design pressure and temperature are 400 psig and 1660 °R, respectively.

The diameter of the settling chamber is sized to produce air velocities of approximately M = 0.04 over the range of desired operating conditions for the combustion tunnel. Calculations resulted in a 24-inch Schedule 60 stainless steel pipe. Both ends of the chamber are flanged with stainless steel slip-on flanges that meet the ANSI specification for the design pressure and temperature conditions[2]. The entire chamber is mounted to a support stand designed to carry the weight of the chamber and the lateral force experienced due to the subatmospheric pressure of the exhauster. This support stand is firmly anchored to the bed plate of the test cell. As with the inlet section components, the settling chamber is anchored to its stand at the downstream end while the upstream end is allowed to move on a roller during system warm up.

Flow conditioning is accomplished through the use of screens and honeycomb placed within the settling chamber. These devices act to break up large scale turbulence within the flow and to produce a more uniform velocity profile at the entrance to the nozzle. Three screens are used with two being of a finer mesh than the third; the facility uses one screen having a mesh size of 12 x 12 x 0.018 inch and two screens having a mesh size of 20 x 20 x 0.013 inch. The screens are manufactured using stainless steel wire cloth brazed to stainless steel mounting rings at a sustained temperature of 1900 °F with a Nicrobraz filler material. The stainless steel honeycomb section is 3 inches thick and 22 inches in diameter with a foil thickness of 0.005 inch and a cell size of 0.25 inch. Inside the settling chamber the coarse mesh screen is placed farthest upstream followed by a fine mesh screen, the honeycomb section, and finally the second fine mesh screen. A photograph of the settling chamber shell is presented in Figure 5. Once the flow is properly conditioned,

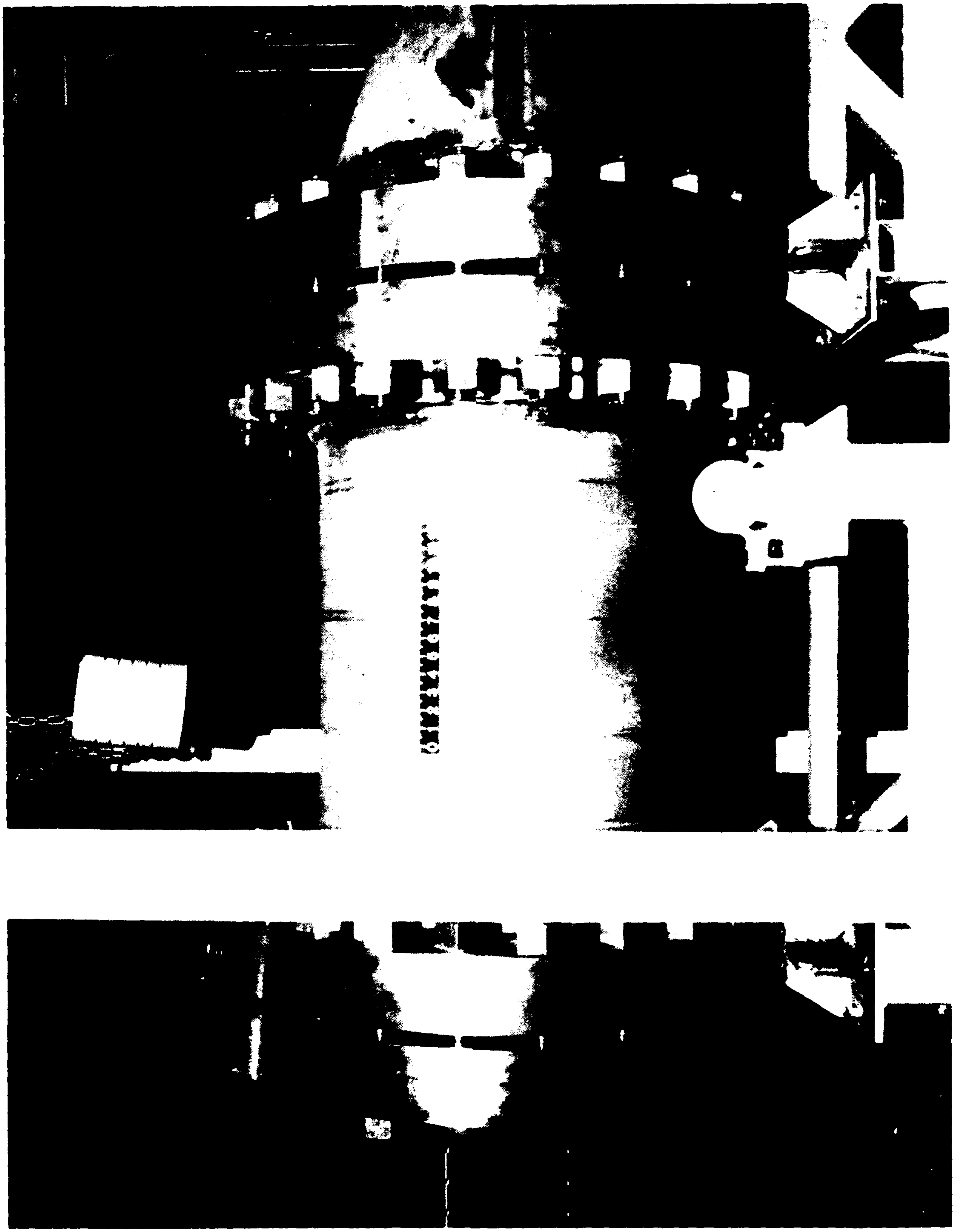

Figure 5 Photograph of Settling Chamber

it is brought into the planar two-dimensional nozzle section where acceleration to the desired nominal Mach number occurs.

2.2.3 NOZZLE SECTION

The nozzle section is an extremely important feature of the facility. As mentioned earlier, one of the gaols was to design a nozzle section capable of operating at different Mach numbers. For the initial configuration, a nominal Mach number of 2.0 has been selected; however, other Mach numbers are easily achievable by simply designing and fabricating new nozzle blocks. The following discussion is devoted to the design of the three major components of this section: the nozzle flange, nozzle block, and nozzle walls.

The stainless steel nozzle flange is responsible for connecting the nozzle section to the settling chamber, but performs other functions as well. First, this flange houses a contoured section that makes the transition from the circular cross-section of the settling chamber to the rectangular cross-section of the nozzle section. This is accomplished through the use of four precision machined pieces that round off the sharp corners that would normally exist without such a transition. Each piece is made from one-quarter of a 6-inch-diameter piece of stainless steel with its ends are mitered to 45° angles. When assembled, the four pieces form a rectangular section 3 inches deep with outer edge dimensions of 12.00 inches x 12.16 inches and inner edge dimensions of 6.00 inches x 6.16 inches. In order to hold these pieces, the nozzle flange has a 6.00 inches x 6.16 inches rectangular hole cut through the center and a 3-inch deep recess which is 12.00 inches x 12.16 inches outlining that hole. The transition pieces are anchored into this "frame" from the downstream side of the flange and are sealed using a pair of graphite packing rings placed in grooves at the bottom of the recess. For further clarification on this part of the design, Figures 6 and 7 are included. Figure 6 is a photograph of the flange with only one of the four pieces installed. This photo shows the recessed area, anchor bolt holes, and the sealing grooves. Figure 7 displays the flange with all four pieces installed.

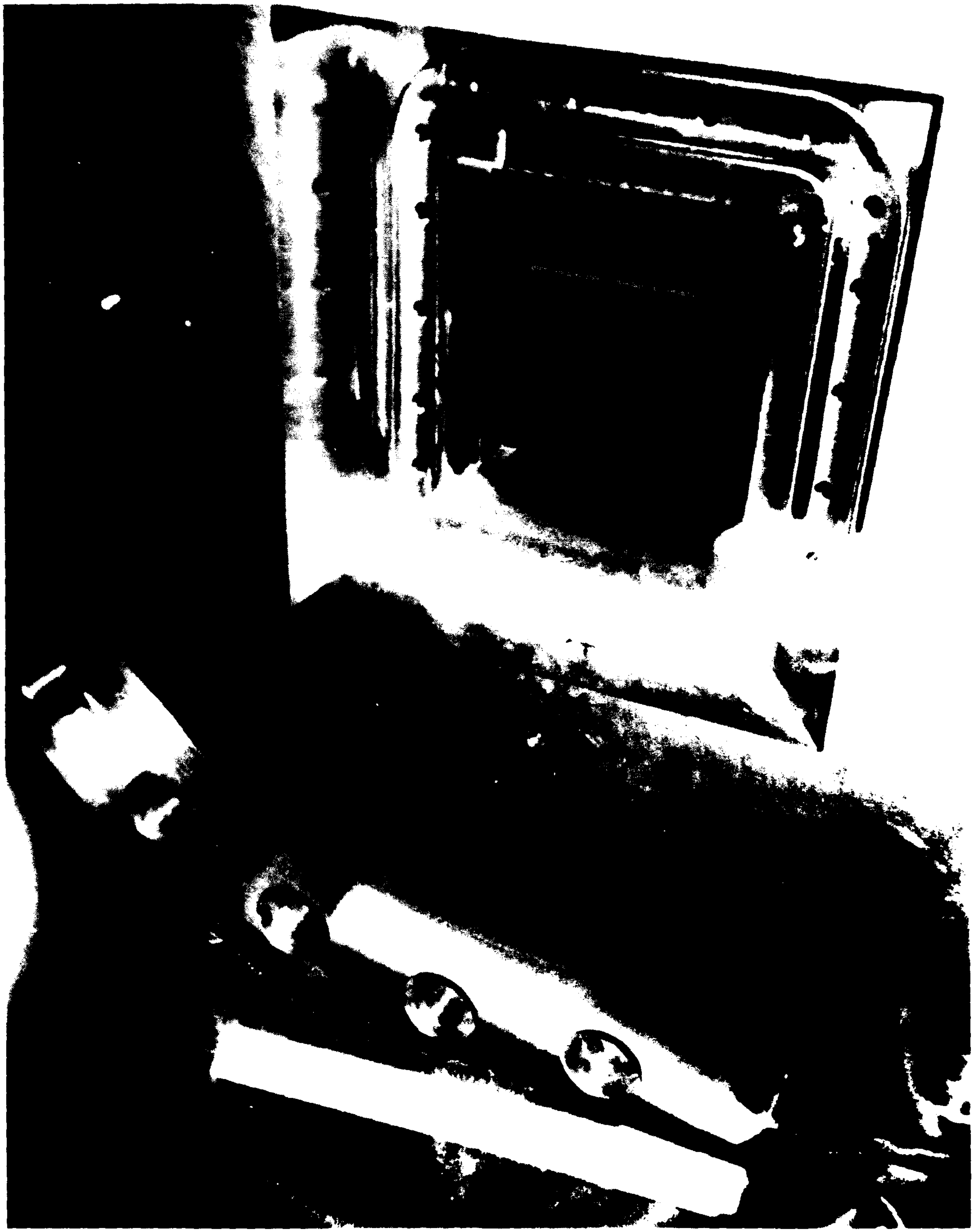

Figure 6 Photograph of Transition Section with One Piece Installed

Figure 7 Photograph of Transition Section with Four Pieces Installed

Another of the functions of the nozzle flange is anchoring the flow conditioning within the settling chamber. A pair of rods are threaded into the flange and through a retaining ring at the upstream end of the flow conditioning section keeping it in place. Finally, the nozzle flange is used to mount the stagnation pressure and temperature probes for instrumenting the settling chamber. Another feature that is available for future use is a pair of ports that may be used as seed injection for diagnostic techniques that require the flow to be seeded with a particulate matter such as LDV or PIV, for example

The supersonic portion of the nozzle block contour is designed using a method of characteristics code developed by Carroll et al.[3]. This code computes the contour of a continuous slope nozzle yielding a uniform exit flow aligned with the nozzle axis. Calculation begins with the assumption of constant $M^* = 1.01$ along a characteristic, where M^* is defined as the local velocity divided by the critical speed of sound. Boundary layer growth is not accounted for in the code; however, the boundary layer displacement thickness has been calculated using Burke's equation[4] which relates the local turbulent boundary layer displacement thickness to the local Mach and Reynolds numbers as follows:

$$\frac{\delta_x^*}{x} = 0.0463 \frac{M_x^{1.311}}{Re_x^{0.276}}$$

The displacement thickness on a 24-inch-long Mach 3.0 nozzle block at the exit plane was calculated to be 0.0279 inch and 0.0303 inch for test section static pressures and of 7.35 psia and 5.44 psia, respectively, and a static temperature of 524 °R. Using these conditions, along with the ideal gas equation and isentropic flow relations, the Reynolds numbers at the nozzle exit were calculated to be 1.10×10^7 and 8.12×10^6, respectively. In an effort to avoid recompression of the flow at lower Reynolds numbers, the larger displacement thickness value was chosen and rounded up to 0.040 inch. This correction procedure assumes that the displacement thickness starts at the nozzle throat and is a linear function of x. Such a procedure introduces negligible errors into the correction[5]. The entire viscous correction is applied to the contoured walls to preserve the parallel nature of the sidewalls making the final nozzle exit dimensions 5.16 inches high x 6.00 inches wide. In addition to the supersonic portion of the nozzle block, the specification of a compression region upstream of the throat is necessary. This region was designed using a transition code developed by Chen and Nejad that matches the zero slope and physical dimension at the entrance to the zero slope and physical dimension at the throat, which is 11.5 inches downstream of the entrance. The resulting coordinates for a Mach 2.0 nozzle are provided in Table 2; the geometry of a typical nozzle block is shown in Figure 8.

The chamber that holds the stainless steel nozzle blocks is composed of four stainless steel walls: two sidewalls and top and bottom walls. This enclosure was designed in accordance with Appendix 13 of the ASME piping code[1] which is concerned with the design of noncircular vessels. Both sidewalls are interchangeable and are flanged on the upstream side allowing for anchoring into the nozzle flange. Each sidewall is equipped with 17 pressure taps for examining the static pressure distribution along the centerline of the nozzle. Four of the taps are located upstream of the throat, one is at the throat, and twelve are placed in the expansion region with the final tap being located at the geometric exit of the nozzle. The downstream end of each sidewall is mitered at a 70° angle and grooved for the placement of packing material to seal the joint between the nozzle and test sections.

The top and bottom walls are bolted to the nozzle blocks and are flanged at both the upstream and downstream ends so that they may be connected to the nozzle flange and the test section. Locating pins are placed in the flanged ends of these walls and a pair of shoulder screws are used to locate the nozzle blocks on each wall. Once the nozzle blocks are secured to the top and bottom walls, the grooves on the blocks are filled with 0.1875-inch-square John Crane graphite packing material. The sidewalls are then bolted to the top and bottom walls. The entire assembly is now bolted to the nozzle flange where another graphite packing groove is located.

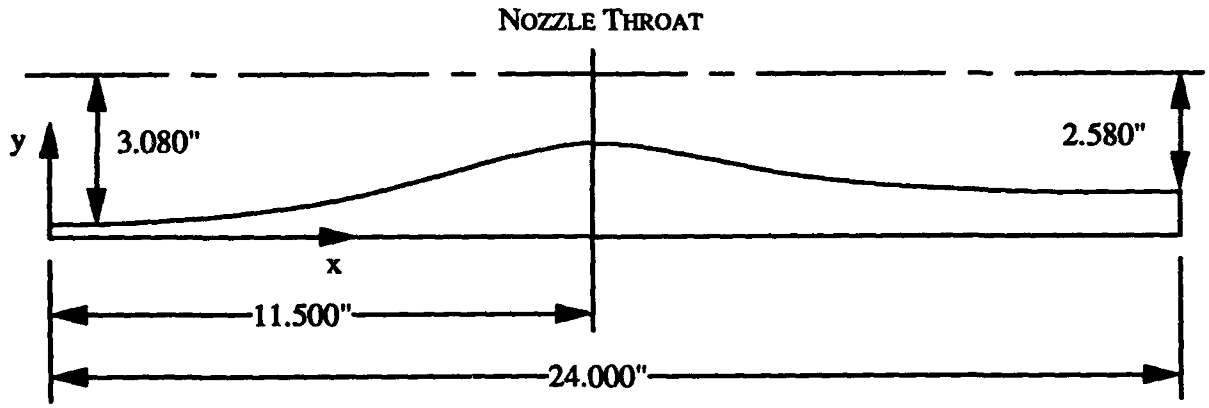

Figure 8 Nozzle Block Geometry

Table 2 Mach 2.0 Nozzle Coordinates

x (in)	y (in)	x (in)	y (in)	x (in)	y (in)	x (in)	y (in)
0.0000	0.3000	5.4596	0.6679	10.919	1.8463	13.600	1.5739
0.1162	0.3000	5.5758	0.6940	11.035	1.8485	13.650	1.5631
0.2323	0.3000	5.6919	0.7210	11.151	1.8499	13.700	1.5524
0.3485	0.3000	5.8081	0.7489	11.268	1.8507	13.750	1.5418
0.4646	0.3000	5.9242	0.7775	11.384	1.8510	13.800	1.5312
0.5808	0.3000	6.0404	0.8070	11.500	1.8510	13.850	1.5206
0.6970	0.3001	6.1566	0.8372	11.550	1.8508	13.900	1.5102
0.8131	0.3002	6.2727	0.8681	11.600	1.8503	13.950	1.4998
0.9293	0.3003	6.3889	0.8996	11.650	1.8495	14.000	1.4895
1.0455	0.3005	6.5051	0.9317	11.700	1.8484	14.050	1.4792
1.1616	0.3008	6.6212	0.9643	11.750	1.8469	14.100	1.4690
1.2778	0.3012	6.7374	0.9973	11.800	1.8451	14.150	1.4589
1.3939	0.3017	6.8535	1.0308	11.850	1.8430	14.200	1.4489
1.5101	0.3024	6.9697	1.0645	11.900	1.8405	14.250	1.4389
1.6263	0.3033	7.0859	1.0985	11.950	1.8378	14.300	1.4290
1.7424	0.3044	7.2020	1.1327	12.000	1.8346	14.350	1.4192
1.8586	0.3057	7.3182	1.1669	12.050	1.8312	14.400	1.4094
1.9747	0.3074	7.4343	1.2012	12.100	1.8275	14.450	1.3997
2.0909	0.3094	7.5505	1.2353	12.150	1.8234	14.500	1.3901
2.2071	0.3117	7.6667	1.2693	12.200	1.8190	14.550	1.3806
2.3232	0.3145	7.7828	1.3031	12.250	1.8142	14.600	1.3711
2.4394	0.3177	7.8990	1.3365	12.300	1.8091	14.650	1.3618
2.5556	0.3214	8.0152	1.3694	12.350	1.8037	14.700	1.3525
2.6717	0.3256	8.1313	1.4018	12.400	1.7980	14.750	1.3432
2.7879	0.3304	8.2475	1.4337	12.450	1.7920	14.800	1.3341
2.9040	0.3357	8.3636	1.4648	12.500	1.7856	14.850	1.3250
3.0202	0.3418	8.4798	1.4951	12.550	1.7789	14.900	1.3160
3.1364	0.3485	8.5960	1.5246	12.600	1.7719	14.950	1.3071
3.2525	0.3559	8.7121	1.5531	12.650	1.7645	15.000	1.2983
3.3687	0.3641	8.8283	1.5806	12.700	1.7568	15.050	1.2896
3.4848	0.3731	8.9444	1.6070	12.750	1.7488	15.100	1.2809
3.6010	0.3829	9.0606	1.6323	12.800	1.7405	15.150	1.2723
3.7172	0.3935	9.1768	1.6562	12.850	1.7318	15.200	1.2638
3.8333	0.4050	9.2929	1.6789	12.900	1.7228	15.250	1.2554
3.9495	0.4175	9.4091	1.7003	12.950	1.7135	15.300	1.2470
4.0657	0.4308	9.5253	1.7202	13.000	1.7038	15.350	1.2388
4.1818	0.4451	9.6414	1.7387	13.050	1.6939	15.400	1.2306
4.2980	0.4604	9.7576	1.7557	13.100	1.6836	15.450	1.2225
4.4141	0.4767	9.8737	1.7712	13.150	1.6729	15.500	1.2144
4.5303	0.4940	9.9899	1.7853	13.200	1.6620	15.550	1.2065
4.6465	0.5122	10.106	1.7978	13.250	1.6510	15.600	1.1986
4.7626	0.5315	10.222	1.8088	13.300	1.6398	15.650	1.1908
4.8788	0.5518	10.338	1.8184	13.350	1.6286	15.700	1.1831
4.9949	0.5730	10.455	1.8266	13.400	1.6175	15.750	1.1755
5.1111	0.5953	10.571	1.8333	13.450	1.6065	15.800	1.1680
5.2273	0.6186	10.687	1.8388	13.500	1.5956	15.850	1.1605
5.3434	0.6428	10.803	1.8431	13.550	1.5847	15.900	1.1531

Table 2 (continued)

x (in)	y (in)	x (in)	y (in)	x (in)	y (in)	x (in)	y (in)
15.950	1.1458	18.300	0.8920	20.650	0.8010	23.000	0.8000
16.000	1.1386	18.350	0.8885	20.700	0.8007	23.050	0.8000
16.050	1.1314	18.400	0.8850	20.750	0.8005	23.100	0.8000
16.100	1.1244	18.450	0.8816	20.800	0.8003	23.150	0.8000
16.150	1.1174	18.500	0.8783	20.850	0.8002	23.200	0.8000
16.200	1.1105	18.550	0.8750	20.900	0.8000	23.250	0.8000
16.250	1.1037	18.600	0.8719	20.950	0.8000	23.300	0.8000
16.300	1.0969	18.650	0.8688	21.000	0.8000	23.350	0.8000
16.350	1.0903	18.700	0.8657	21.050	0.8000	23.400	0.8000
16.400	1.0837	18.750	0.8627	21.100	0.8000	23.450	0.8000
16.450	1.0772	18.800	0.8598	21.150	0.8000	23.500	0.8000
16.500	1.0708	18.850	0.8570	21.200	0.8000	23.550	0.8000
16.550	1.0644	18.900	0.8543	21.250	0.8000	23.600	0.8000
16.600	1.0582	18.950	0.8516	21.300	0.8000	23.650	0.8000
16.650	1.0520	19.000	0.8489	21.350	0.8000	23.700	0.8000
16.700	1.0459	19.050	0.8464	21.400	0.8000	23.750	0.8000
16.750	1.0398	19.100	0.8439	21.450	0.8000	23.800	0.8000
16.800	1.0339	19.150	0.8416	21.500	0.8000	23.850	0.8000
16.850	1.0280	19.200	0.8392	21.550	0.8000	23.900	0.8000
16.900	1.0222	19.250	0.8370	21.600	0.8000	23.950	0.8000
16.950	1.0165	19.300	0.8348	21.650	0.8000	24.000	0.8000
17.000	1.0109	19.350	0.8327	21.700	0.8000		
17.050	1.0054	19.400	0.8306	21.750	0.8000		
17.100	0.9999	19.450	0.8286	21.800	0.8000		
17.150	0.9945	19.500	0.8267	21.850	0.8000		
17.200	0.9893	19.550	0.8248	21.900	0.8000		
17.250	0.9841	19.600	0.8230	21.950	0.8000		
17.300	0.9789	19.650	0.8213	22.000	0.8000		
17.350	0.9739	19.700	0.8196	22.050	0.8000		
17.400	0.9689	19.750	0.8180	22.100	0.8000		
17.450	0.9640	19.800	0.8165	22.150	0.8000		
17.500	0.9591	19.850	0.8150	22.200	0.8000		
17.550	0.9544	19.900	0.8135	22.250	0.8000		
17.600	0.9497	19.950	0.8122	22.300	0.8000		
17.650	0.9451	20.000	0.8109	22.350	0.8000		
17.700	0.9406	20.050	0.8098	22.400	0.8000		
17.750	0.9361	20.100	0.8087	22.450	0.8000		
17.800	0.9317	20.150	0.8076	22.500	0.8000		
17.850	0.9274	20.200	0.8067	22.550	0.8000		
17.900	0.9232	20.250	0.8058	22.600	0.8000		
17.950	0.9190	20.300	0.8050	22.650	0.8000		
18.000	0.9149	20.350	0.8042	22.700	0.8000		
18.050	0.9109	20.400	0.8035	22.750	0.8000		
18.100	0.9070	20.450	0.8029	22.800	0.8000		
18.150	0.9031	20.500	0.8023	22.850	0.8000		
18.200	0.8994	20.550	0.8018	22.900	0.8000		
18.250	0.8957	20.600	0.8014	22.950	0.8000		

2.2.4 TEST SECTION

The test section is the region of the combustion tunnel where the performance and basic characteristics of the various fuel injection schemes are investigated. This section is mounted directly to the downstream end of the nozzle section and to the upstream end of the diffuser. Due to the interrogative nature of the experiments conducted in this tunnel, the test section requires a large degree of optical access so that a wide variety of diagnostic techniques may be used to examine the flow. It is also desirable that the test section be easily modified to accept other injector configurations. The design of the components of the test section is discussed in detail in what follows.

As with the nozzle section, the test section is comprised of four walls including two sidewalls and a top and bottom wall. The entire enclosure is designed in accordance with Appendix 13 of the ASME piping code[1]. All of the walls are made of stainless steel in order to withstand heats of combustion and any corrosive injectant that may be used. Both sidewalls are interchangeable and are flanged on the downstream side allowing for anchoring into the diffuser flange. The upstream ends of the sidewalls are mitered to mate with the downstream gasketed ends of the nozzle sidewalls in order to seal the joint between the two sections. Each sidewall has an opening in it large enough to accept a sidewall window frame, which is sealed using an o-ring around its perimeter. These window frames, which are designed to have upstream and downstream positions, hold a window which allows access to the entire transverse dimension as well as 31 inches in the streamwise dimension of the test section. Utilizing two window positions prevents the need for one large, and prohibitively expensive, window which covers that entire viewing area. The two orientations overlap by 4 inches so that no region of the test section is left blind to investigation. Using this configuration, the nominal side window size is reduced to 6.0 inches x 17.5 inches. Figure 9 illustrates the nozzle and test sections with the openings in the test section sidewalls shown, while Figure 10 is a photograph of the nozzle and test sections with the respective sidewalls removed (flow is from right to left). A cross

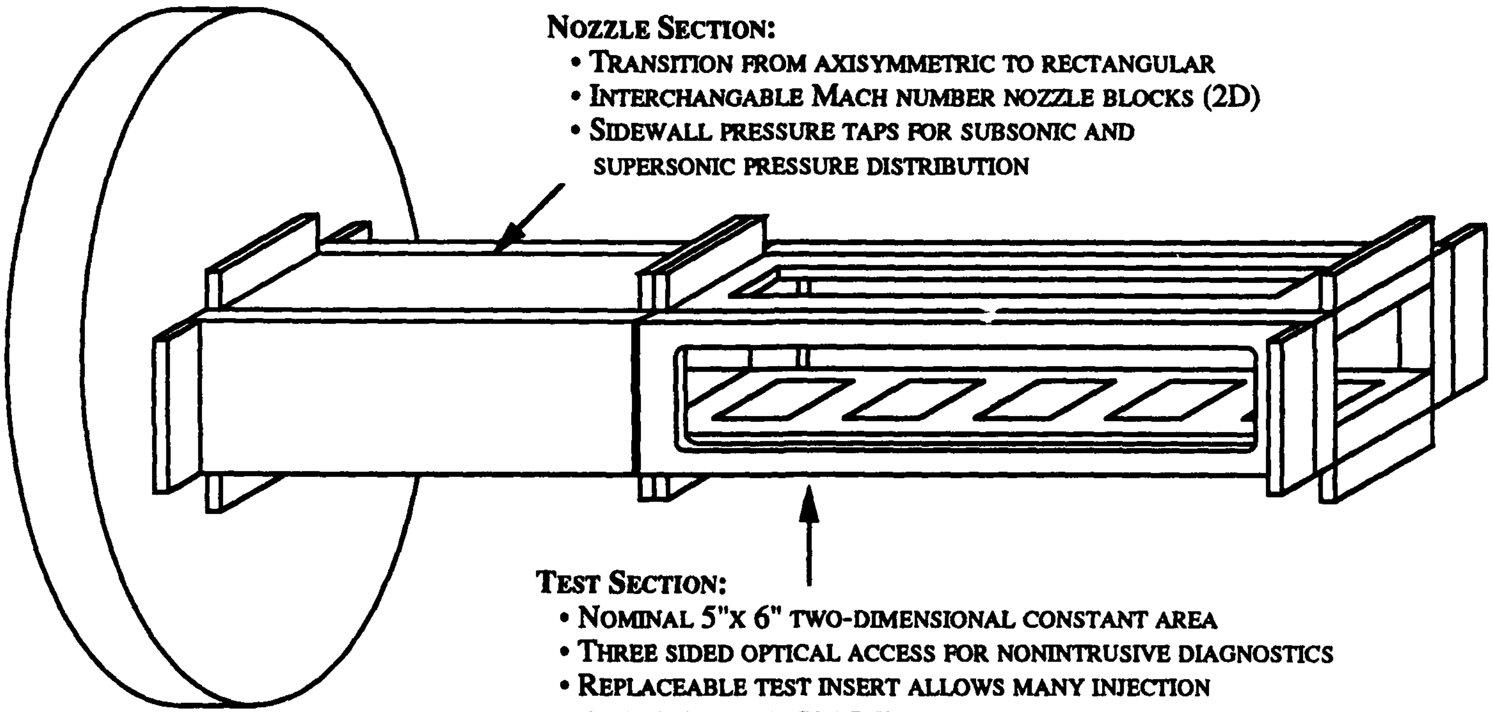

Figure 9 Nozzle Section/Test Section Schematic

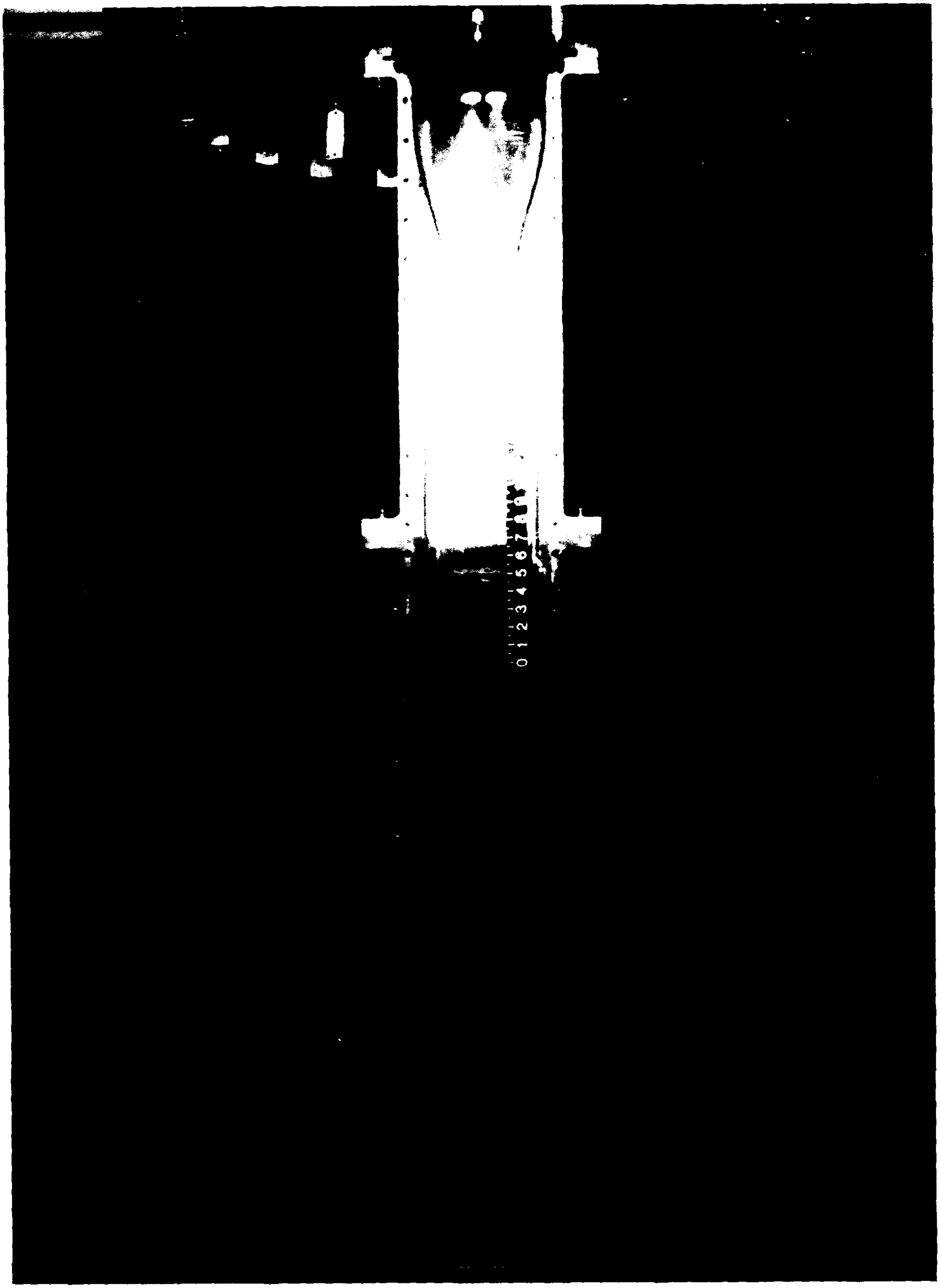

Figure 10 Photograph of Nozzle/Test Section

section view of the test section is shown in Figure 11, where the flow direction is out of the page. This view illustrates the placement of the side windows in relation to the other geometric features of the test section.

One of the initial design goals was a test section with three sides available for optical access. The sidewalls provide two of those sides; the third is accomplished using the top wall. This wall is similar in design to the nozzle top wall in that both ends are flanged in order to anchor into the adjacent sections. However, this wall also has an opening large enough for a third window frame, which is sealed using an o-ring around its perimeter. As with the test section sidewall window frames, this frame holds a window which allows access to 31 inches in the streamwise dimension. Due to spatial constraints, however, half of the spanwise dimension is accessible. Again, upstream and downstream window locations are available with the same 4 inch overlap region as afforded by the sidewall window frames. Using this configuration, the nominal window size for the top wall is 3.5 inches x 17.5 inches. See Figures 9 and 11 for illustrations of the top opening and window coverage. Two final features of the test section top wall are the sealing groove around three sides and the cushion grooves for the sidewall windows. The sealing groove is used to hold packing material similar to that used in the nozzle section. Both sides of the wall require this material along with the upstream end that mates to the nozzle section. The cushion grooves on either side of the top wall are used to hold an o-ring that prevents the side window from contacting the stainless steel surface of the top wall. These grooves are noted in the cross section view illustrated in Figure 11.

The bottom wall of the test section is similar in design to the top wall in that it is flanged on both ends allowing it to be anchored to the adjacent sections. Also, the same sealing and cushion groove arrangements used in the top wall design are used in this wall. Five removable test inserts are placed along the length of the bottom wall. These inserts may be used to test various transverse injection schemes such as simple hole injectors or more complex ramped injectors. Multiple inserts are used so that the effects of a growing

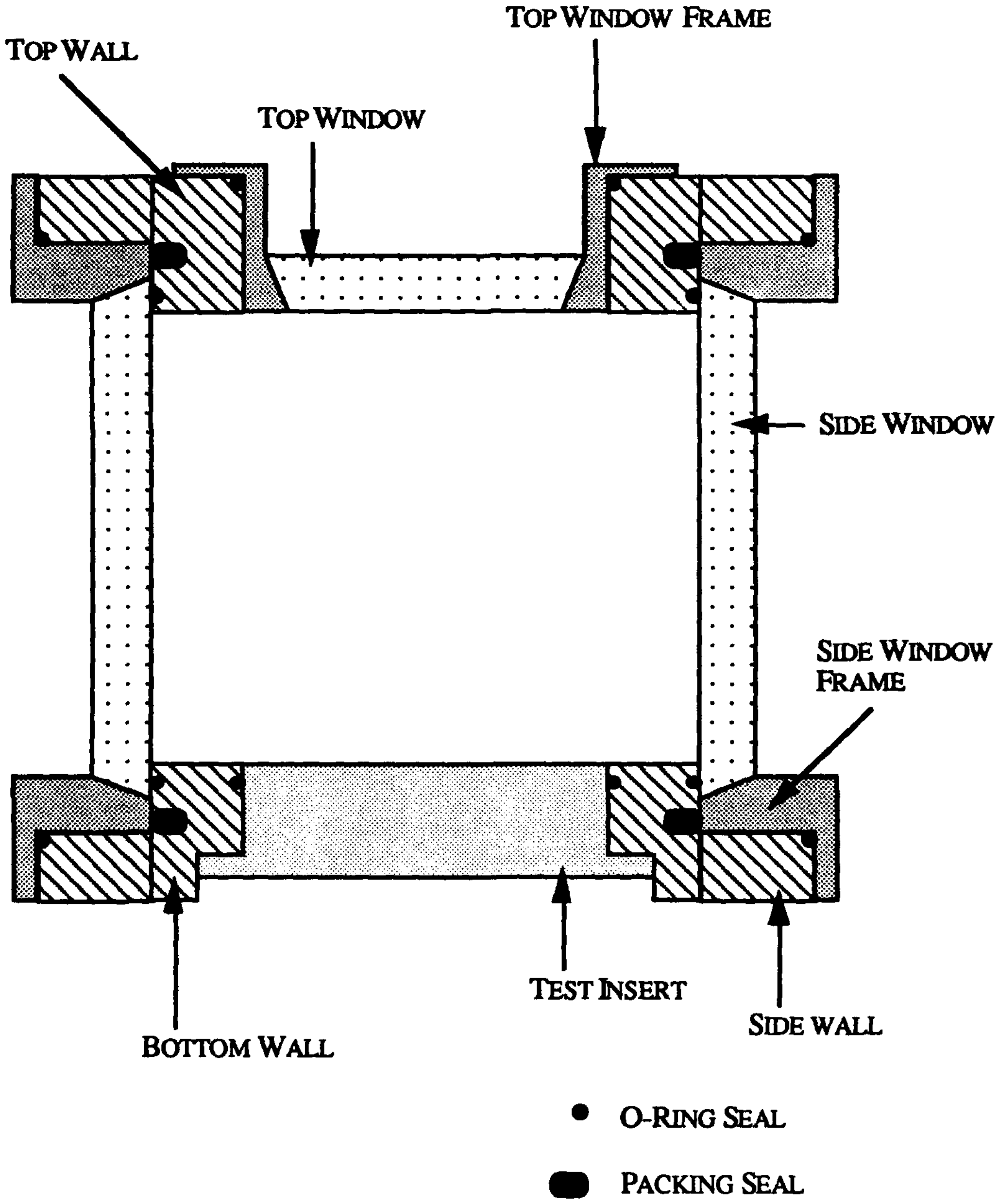

Figure 11 Test Section Cross-Section Schematic

boundary layer on the injection dynamics may be examined. These inserts are shown schematically in Figures 9 and 11.

The final components of the test section are the windows. For initial studies, acrylic windows are used. These windows are suitable for many reasons. Principally, the acrylic is a strong material with very good optical qualities. Also, transmission in the visible spectrum is excellent making conventional LDV feasible. Since static temperatures within the test section are nominally at the ambient level, no thermal degradation of the acrylic is expected. Finally, the minor expense of the material and machining make it perfect for initial runs and interrogation. The major disadvantage of the acrylic material is the poor transmission qualities in the ultraviolet spectrum. This spectrum is exclusively used in other diagnostic techniques that will be employed in this facility, such as PLIF or OH-Flow-Tagging velocimetry[6]. For this reason, windows will be required in the future which are made of a fused silica material so that a high degree of transmission in the ultraviolet range is achievable. The window frames have been designed to allow a window which is 0.625 inch thick to be installed. For the given size, a quartz window of this thickness will have a safety factor of 10 at a pressure differential across the window of 18.5 psig[7]. A safety factor of 1 is maintained at a pressure differential of 185 psig. This condition corresponds to the shock transient at a stagnation pressure of 200 psia.

2.2.5 DIFFUSER SECTION

The diffuser section is responsible for decelerating and cooling the flow before it is piped to the exhausters and coolers of the Tech Air Facility. In addition to these two basic jobs, the diffuser is required to house a window to allow optical access looking into the flow, an expansion joint to allow for thermal growth of the test section during combustion, and an exhaust manifold with three inlets and a single outlet connected to an exit port in the west end of the test cell. Design details of this final component are discussed below.

There are some distinct constraints that fix certain aspects of the diffuser design. Initially, the exit port leaving the test cell is a 14-inch Victaulic grooved pipe coupling.

This requires the downstream end of the diffuser to be 14-inch and grooved to match. Second, the elevation of the centerline of the tunnel is 54 inches above the floor while the centerline of the exit port is 29 inches above the floor. This obviously means that a drop section is required in the diffuser. Third, it is desirable to have enough floor space beneath the tunnel to place a large optical table used to support the diagnostic hardware employed during experiments. This constraint requires the upstream end of the diffuser be of as small a diameter as possible since it connects directly to test section. With these constraints in mind, the details of the diffuser section may be further examined.

In order to specify the diffuser material requirements from a strength standpoint, a design pressure and temperature within the section are required. Once established, these design parameters may be used in connection with the ASME piping code[1] and the ANSI flange specification[2] to determine the appropriate material and wall thickness. To define these conditions, a normal shock is assumed to exist at the entrance of the diffuser and the flow upstream of this shock is assumed to be Mach 3.0. At the nominal test section conditions described previously, the resulting ideal recovery would produce a diffuser pressure and temperature of approximately 76 psia and 1400 °R. Since the exit temperature of the diffuser must be a maximum 660 °R (as required by the Tech Air Facility), and water cooling is provided to produce this condition, 660 °R will be used as the design temperature for the diffuser. Using these conditions and the appropriate material design codes result in Schedule 40 carbon steel for the diffuser piping.

Once the pipe material specification is made, attention must be given to the size of the pipe. As mentioned previously, it is important to use the smallest diameter pipe as possible in order to maximize the space available beneath the test section. An 8-inch pipe is used in the initial region of the simple dump diffuser. This choice combines minimum expense with maximum space available in order to decelerate and cool the flow properly. Recall that the exit of the diffuser section is a 14-inch pipe. Another expansion is required which continues to decelerate the flow. With those details, it is possible to finally describe the entire diffuser section. Flow leaves the test section and enters the 8-inch initial diffuser section where the first array of water spray ports are placed. This pipe is immediately followed by an 8-inch expansion joint, and then by a tee section. One of the other two ends of the tee is used as a window port looking into the flow direction, while the final end of the tee is connected to a vertically oriented piece housing the second array of water spray ports. Following the elevation change, an expansion station is used to change the pipe diameter to the 14-inch exit size. Just downstream of the expansion, a manifold section, which has two other inlets, is mounted and fed into the Victaulic coupling at the west end of the test cell.

In addition to the piping system which makes up the diffuser, a cooling water system is employed to spray water into the exhaust in order to help decelerate and cool it. This water system taps into the 3-inch CPVC line in the test cell that carries city water. A 1-1/2-inch hand operated bronze globe valve is used to regulate the flow of water supplied to either of two manifold sections. These manifolds are isolated from the main line using a pair of hand operated ball valves. Each manifold has four hoses connected to it in order to supply the diffuser water in two locations. The first location is upstream of the aft viewing port and is used when the window is not in use. The second location is downstream of the port making unobstructed visualization of the flow possible. Eight atomizing nozzles (four at each location) are used to spray the water into the diffuser. The system is sized to allow water flow rates on the order of 50 gallons per minute into the diffuser section. A photograph showing the water cooling system is presented in Figure 12.

The aft viewing port is a 9-inch diameter quartz window, large enough to allow the entire cross section of the flow to be examined, and it is mounted on a flange at the open end of the pipe tee at the end of the diffuser. An aluminum retaining ring is used to holdthe window in place. The seals between the window and both the flange and the retainer are silicone o-rings.

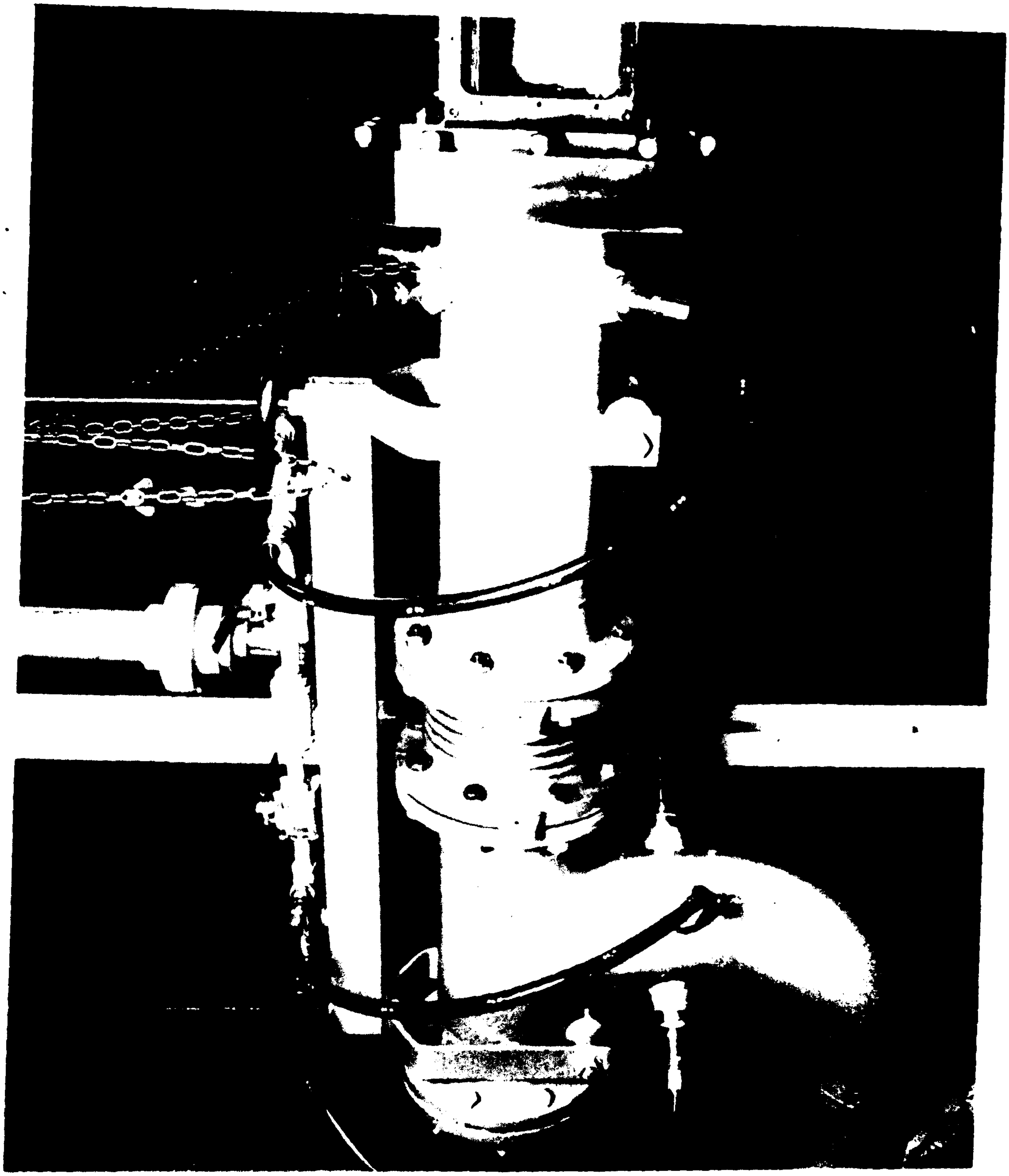

Figure 12 Photograph of Diffuser Section

Support of the diffuser section is accomplished two ways. First, the aft end of the section is supported using pipe stands anchored to the floor. This part of the assembly is essentially fixed and will not be moved. The upstream end of the diffuser is supported from above using pipe hangers and an overhead A-frame. This A-frame consists of four legs and a long main rail constructed of I-beam. The rail is fitted with hoisting equipment that is used during maintenance and assembly of the test section and nozzle section. It is also fitted with clamps that hang the diffuser below. The A-frame is tied directly to the bed plate of the test cell and to a structural support in the ceiling. It provides another means for keeping a large unobstructed area beneath the combustor for placement of large optical table and assorted hardware.

The description of the design of the actual flow facility is now complete. The following chapter presents a description of the control system and instrumentation employed in the facility, as well as a discussion of the control logic employed.

3. CONTROL SYSTEM AND INSTRUMENTATION

The supersonic facility incorporates numerous devices which require monitoring and control. For instance, each of the four control valves has a solenoid valve, a high and low limit switch, an electropneumatic transducer, and a position transmitter. Each of these instruments has a distinct job to perform and requires the operator to be in constant communication in order to accomplish its task to the operator's satisfaction. In addition to those hardware items on each valve, pressure and temperature sensors are located throughout the system which relay important information concerning the overall system status. These are the instruments whose signals are used by the operator to make decisions which affect the system conditions. For example, if the temperature of the mixed air is too high but the pressure is within a specified margin of error, the hot valve should be closed slightly and the cold valve should be opened slightly to balance the pressure and temperature requirements. The following sections are devoted to discussions of the control system and instrumentation hardware and the automatic control logic employed.

3.1 CONTROL SYSTEM AND INSTRUMENTATION OVERVIEW

The system chosen for control of the air supply to the supersonic combustion research laboratory is a Johnson-Yokogawa μXL distributed control system. This device allows the operator to have complete control of all the components used in the air supply system. Sequence logic is used to automate the control process based on feedback signals from the various instruments in the system. The information that follows describes the computer control system hardware as well as the various instruments used to control the air supply process.

The μXL is comprised of numerous components including the operator station and the field control unit. The operator station is made up of the color monitor, the operator and engineering keyboards, the printer, and the computer itself. The field control unit is housed in a cabinet and is connected to the operator station via a bus line. This component holds the various input/output (I/O) boards that send and receive signals to and from the instruments. Each of these components will be described in more detail below.

The present operator station is a standard type; it uses a 68020 CPU with 4 megabytes of RAM, a 20-megabyte hard drive, and a high density 3.5-inch floppy drive. The color monitor displays any of a variety of panels that contain important information concerning the process at hand. These panels may be anything from a main graphic panel, which displays an overview of the entire air supply system, to any of a number of control panels, which display graphical instruments indicating the status of the real instruments. Two keyboards are used during operation. The first, called the engineering keyboard, is used mainly during the configuration and programming phases of operation. The second, called the operator keyboard, is used mainly during actual process operation. The dot matrix printer (Model YPR104) is connected directly to the computer via the RS232C port. It serves to document the various process actions which take place during operation. It may also be used to document conditions and trends by simply printing any of the various display screens.

The field control unit (FCU) is connected to the operator station via an RL bus network. It is this device that is responsible for all of the instrument I/O interfaces and for handling all of the sequence control functions. A variety of I/O devices are housed in the FCU including both analog and digital. A total of 16 analog and 32 digital channels are presently available for use. Each field device that requires monitoring (i.e., pressure transmitters, limit switches, etc.) has a separate I/O location in the FCU. Each of the limit switches and solenoid valves incorporated on the air supply control valves use a separate digital location, while each of the pressure transmitters, thermocouples, position transmitters, and electropneumatic transducers use a separate analog location. These devices are described in the paragraphs to follow.

Each of the four air system control valves uses a solenoid valve and two limit switches during its operation. The solenoid valve is a digitally controlled on/off switch plumbed between the pneumatic positioner and the diaphragm of the valve. When closed, the solenoid valve will not allow air to flow into the dome of the valve thereby making it inoperable. Also, when closed the solenoid valve allows all of the air within the dome of the valve to escape, thereby closing the valve (or opening it, depending on its operating characteristics). The two limit switches are used to indicate either a full open or a full closed status. An intermediate position is indicated when the valve does not close either switch.

The other components used by each of the control valves are analog in nature. The electropneumatic transducer (Masoneilan I/PEX 9000 Model 590010-011-999) receives 4-20 mA signals from the operator station via an EC0 signal conditioner card. The rotary position transmitter (Thunderco Model PX-3.1) interprets the position of the valve and sends a 4-20 mA signal back to the operator station through an EA1 conditioning card in the FCU. Now that all of the electrical and pneumatic components of each valve have been described in some detail, it is useful to walk through the process whereby each valve carries out its designated action. Recall that two air lines supply both the actuator and the electropneumatic transducer. The first action required to manipulate any control valve is to open the solenoid valve. Once this is accomplished, a desired position may be entered. This position is translated into a 4-20 mA signal (i.e., 50% = 12 mA) and is sent to the electropneumatic transducer. The electrical signal is transformed to a pneumatic signal from 3-15 psig (i.e., 50% = 12 mA = 9 psig) and is sent to the pneumatic positioner. This device uses the pneumatic signal to actuate the valve with supply air from the actuator supply air line. As the valve stem moves, the rotary positioner senses the degree of motion and sends a proportional 4-20 mA signal back to the FCU. The FCU conditioning card receives the 4-20 mA signal and converts it to a 1-5 V signal which is then relayed to tne operator station and displayed on the corresponding graphical instrument.

The analog signals from the thermocouples used in the air supply system are sent directly to calibrated thermocouple input cards (ET5) housed in the FCU. These cards are calibrated for the specific type of thermocouple used in the system; all thermocouples used in this system are Type K. The 4-20 mA linear signals sent by the pressure transmitters are fed into special signal conditioning cards (EA1) within the FCU which transform the current signals to 1-5 V signals. The pressure transmitters used throughout the system are either Yokogawa Model YA-43 gage transmitters or Rosemount Model 1151 gauge transmitters. Each type requires a 24 V supply voltage.

This section has presented a brief discussion of the actual hardware involved in the air supply control process. A discussion of the logic behind the control procedure is presented in the following section, and a development of the control equations with an example calculation is given in the Appendix.

3.2 AUTOMATIC CONTROL LOGIC

The control logic used by the Johnson-Yokogawa computer system relies on feedback from the various valves in the system and constant monitoring of the pressure and temperature sensors placed at strategic locations throughout the air supply system. In the paragraphs to follow, a verbal description of the control logic is presented. The Appendix presents an itemized illustration of the process as well as a discussion of the calculation procedure used to determine and set various parameters for system operation.

There are two starting sequences that are used during operation of the facility. The first sequence is referred to as the "cold start" because it is used during the first operation of the day. The second sequence is called the "hot start" sequence since it commences in the middle of an experiment which required temporarily stopping.

Cold start begins by executing a status check of each of the four Masoneilan valves in the air supply system. The vent valve must be open fully while the block, cold, and hot valves must be closed fully. Once this status has been confirmed, appropriate values of the various flow parameters are input. Included in this list of parameters are the desired settling chamber stagnation pressure and temperature, the nozzle throat area, the test section Mach number, the cold and hot line supply pressures, and the ratio of specific heats (γ). After inputting the appropriate values for these, a calculation is done to determine the mass flow rate through the choked nozzle.

Now that all of the important flow parameters are available, the sequence moves on to set the valve positions. The air supply system requires a finite time to achieve the desired stagnation temperature due to the warm up time associated with the heat exchanger and the thermal mass of the pipe. During this warm up time, the air is vented to the atmosphere through the vent valve. In order to establish an appropriate pressure condition in the system, the vent valve is used to simulate the throat area of the nozzle. To accomplish this, the pressure drop through the block valve is computed based on its flow coefficient. Then, knowing the pressure upstream of the block valve, the flow coefficient of the vent valve is determined. This is then the appropriate opening for the vent valve that sets the desired pressure condition in the supply line.

With the vent valve set at its computed position, the pressures in the cold and hot supply lines are read and compared to the desired set values. Once these pressures are within a certain tolerance band, the hot valve is allowed to be opened. As with the vent valve, the position of the hot valve is computed based on the upstream supply pressure and the desired mass flow rate. Once this computation is done, the hot valve may be appropriately set for system warm up. Now that the vent and hot valves are both open to computed positions, the system is allowed to heat up. The mixed air pressure and temperature are constantly monitored during this time. Once the mixed temperature exceeds the desired value, the cold valve is slowly opened. The cold and hot valves are now modulated until the mixed temperature and pressure are within ±5% of the desired values. As soon as a steady state condition is established, flow through the test section is initiated by opening the block valve and closing the vent valve. The pressure and temperature measurement stations are switched from the mixed air line to the settling chamber. Another period of cold and hot valve modulation occurs until the desired stagnation conditions are met, after which testing may commence.

The hot start procedure picks up the previous procedure directly before opening the block valve and closing the vent valve. This procedure is the sequence that reinstates flow in the test section after a temporary shut down has been engaged. It allows for an indefinite idle time in order to avoid restarting the entire warm up procedure.

Three shut down procedures are available for use. The first is referred to as a temporary shut down. This operation merely opens the vent valve to its calculated position while closing the block valve. No other valves are closed during this procedure as it is designed to allow the system to remain in an idle mode while maintenance is done inside the test cell. Normal shut down is achieved by engaging the temporary shut down procedure followed by a manual closure of both the cold and hot control valves. The final shut down procedure is engaged in an emergency situation, and is a completely automatic process. The first action of an emergency shutdown is to close the cold and hot control valves. Following this, the vent valve is opened fully and the block valve is closed fully. Further depth concerning the control logic, including an itemized description of the control process, a list of the appropriate equations used to determine the various parameters, and an example of the calculations used to set the valves, is given in the Appendix.

This concludes the discussion of control system and instrumentation. Some conclusions and recommendations for future work are discussed in the chapter to follow.

4. CONCLUSIONS AND RECOMMENDATIONS

The Experimental Research Branch of the Advanced Propulsion Division at Wright-Patterson Air Force Base has developed a new and unique in-house research laboratory devoted to the study of the enhancement and control of fuel-air mixing in supersonic combustors with and without heat release. This large-scale facility may be operated continuously over a wide range of conditions using simple and complex combustor geometries. Emphasis has been placed on the ability to have a large degree of optical access to the flowfield for the application of conventional and state-of-the-art diagnostic techniques.

Much work remains for this facility before mixing experiments commence. First of all, continued checkout tests are required in order for all personnel associated with the system to become intimately familiar with its operation. The checkout tests also provide important information concerning every system in the facility including the behavior of the air supply system, the water cooling system, and the emergency system.

In addition to the checkout tests, a complete facility calibration is necessary to document the flow qualities of the new tunnel. Of specific interest are tunnel boundary layer surveys, test section Mach number distributions, nozzle pressure distributions, and flow visualizations within the test section all for a variety of design and off-design operating conditions. These tests will serve as baseline documentation for all future experiments which will be undertaken in the new facility.

In addition to checkout and calibration tests, additional instrumentation is required to document the pressure and temperature conditions within the diffuser manifold. Other instrumentation requirements include the automation of the water cooling system, and the incorporation of the emergency shutdown procedure with the facility emergency evacuation alarm system. Another safety feature that is important to consider is an interlock system that will not allow tunnel operation if the windows are not installed.

A final issue for the supersonic facility at this time is a method of introducing seed material into the freestream at sufficient levels for use in experiments. Due to the high flow capacity of the tunnel, a great deal of seed material may be required in order to sustain adequate signal levels for using LDV or other particle based measurement techniques. In addition to the high flow capacity, the high temperatures experienced in the settling chamber may have a serious impact on the seeding technique and material chosen.

5. REFERENCES

1. "ASME Boiler and Pressure Vessel Code B31.1, Section VIII, Unfired Pressure Vessels," The American Society of Mechanical Engineers, 1989.

2. "American National Standard Steel Pipe Flanges and and Flanged Fittings, ANSI B16.5 2," The American Society of Mechanical Engineers, 1977.

3. Carroll, B.F., J.C. Dutton, and A.L. Addy, "NOZCS2: A Computer Program for the Design of Continuous Slope Supersonic Nozzles," UILU ENG 86-4007, University of Illinois at Urbana-Champaign, 1986.

4. Burke, A.F., "Turbulent Boundary Layers on Highly Cooled Surfaces at High Mach Numbers," AFASD TR 61-645, ASD Symposium on Aerothermoelasticity, Dayton, Ohio, 1961.

5. Fiore, A.W., D.G. Moore, D.H. Murray, and J.E. West, Major, USAF, "Design and Calibration of the ARL Mach 3 High Reynolds Number Facility," ARL TR 75-0012, 1975.

6. Chen, T.H., L.P. Goss, D.D. Trump, B. Sarka, and A.S. Nejad, "The Effects of Nozzle Geometry upon Sonic Fuel Injection as Studied by OH-Flow-Tagging Velocimetry," AIAA Paper 91-0575, 1991.

7. Pope, A. and K.L. Goin, High-Speed Wind Tunnel Testing, John Wiley and Sons, Inc., 1965.

APPENDIX

CONTROL LOGIC EQUATIONS AND DEVELOPMENT

This section of the appendix documents the basic control outline including the start up and shut down procedures described in section 3.2. Also, the relations used in developing the control logic for the supply system in the supersonic facility, as well as an example of the calculation procedure, are outlined.

Start Up Procedures

1. Cold Start

   a. Open the vent valve fully.

      Close the block valve, cold valve, and hot valve fully.

      (Note: This is a status check since valves should be in these positions already)

   b. Input desired values for the following parameters:

P_{02} (psia)	Settling chamber total pressure
T_{02} (°R)	Settling chamber total temperature
A_{throat} (in^2)	Nozzle throat area
M	Mach number (user reference only)
P_C (psia)	Cold line supply pressure
P_H (psia)	Hot line supply pressure
γ	Ratio of specific heats

   c. Calculate mass flow rate using Equation 4 with Equations 1,2,3, and 5.

   d. Determine and set appropriate opening for the vent valve to simulate the choked nozzle using the calculated mass flow rate and Equations 6 and 7, where P_2 in Equation 6 is the required stagnation pressure, P_{02}.

   e. Read the cold and hot line supply pressures. Compare these to the input values of step (a). If the readings are within 20% of inputs, operator is allowed to open the hot valve. If the readings are not within the desired range, the operator must take appropriate action to correct problem.

f. Open the hot valve to a position determined using Equation 7 where P_1 in the equation is the hot line supply pressure, P_H. The mass flow rate used is the maximum value available (use the calculated value from step 1.c. or 15 lb_m/sec, whichever is less).

g. Holding the vent and hot valves at these positions, allow the system to heat up while constantly monitoring the mixed air temperature and pressure (T_{01} and P_{01}).

h. When the mixed temperature (T_{01}) exceeds the desired value of T_{02}, open the cold valve while monitoring mixed air temperature and pressure (T_{01} and P_{01}).

i. Modulate the hot and cold valves until the mixed temperature and pressure are within ±5% of desired values (i.e., T_{02} input in 1.b. and P_{01} calculated in 1.d.).

j. Upon achieving a steady state, a test may be initiated by opening the block valve and closing the vent valve. Also, the pressure and temperature monitoring station switches to the settling chamber. Modulate the hot and cold valves to maintain ±5% of the desired values (i.e., T_{02} and P_{02} input in 1.b.).

2. Hot Start--Used after a temporary shutdown--picks up the Cold Start sequence at step j.

Shut Down Procedures

1. Temporary Shut Down

   a. Open the vent valve to the preset position determined in step 1.d. of the cold start procedure.

   b. Close the block valve after a set delay with step 1.a. of the temporary shut down procedure.

2. Normal Shut Down

   a. Open the vent valve to the preset position determined in step 1.d. of the cold start procedure.

b. Close the block valve after a set delay with step 1.a. of the normal shut down procedure.

c. Close the hot and cold valves fully.

3. Emergency Shut Down

a. Close the hot and cold valves fully.

b. Open the vent valve fully.

c. Close the block valve after a set delay with step 1.b. of the emergency shut down procedure.

Equations

Isentropic Flow:

$$\frac{T_0}{T} = \left(1 + \frac{\gamma-1}{2}M^2\right) \tag{1}$$

$$\frac{P_0}{P} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{(\gamma-1)}} \tag{2}$$

Ideal Gas:

$$P=\rho RT \tag{3}$$

Mass Flow:

$$\dot{m}=\rho UA \tag{4}$$

Speed of Sound:

$$a=\sqrt{\gamma R g_c T}\ ,\ U=Ma \tag{5}$$

Valve Operation:

Subcritical Operation ($\Delta P < 0.5C_f^2P_1$)

$$C_v=\frac{W\sqrt{Z}}{3.22\sqrt{(P_1^2-P_2^2)G_f}} \tag{6}$$

Critical Operation ($\Delta P \geq 0.5C_f^2P_1$)

$$C_v=\frac{W\sqrt{Z}}{2.8C_fP_1\sqrt{G_f}} \tag{7}$$

Example Calculations

For Mach 2.0 operation with test section pressure and temperature conditions of 7.35 psia and 525 °R, calculate the required stagnation conditions using Equations 1 and 2 assuming $\gamma = 1.4$.

$$\frac{P_0}{7.35\ \text{psia}} = \left(1 + \frac{(1.4 - 1)}{2}(2.0)^2\right)^{\frac{1.4}{(1.4 - 1)}} \Rightarrow P_0 = 57.51\ \text{psia}$$

$$\frac{T_0}{525\ ^\circ\text{R}} = \left(1 + \frac{(1.4 - 1)}{2}(2.0)^2\right) \Rightarrow T_0 = 945.0\ ^\circ\text{R}$$

The operator now inputs the desired values for the parameters listed in step 1.b. of the cold start procedure.

P_{02} (psia) = 57.51	P_C (psia) = 300
T_{02} (°R) = 945.0	P_H (psia) = 400
A_{throat} (in^2) = 18.348	$\gamma = 1.4$
$M = 2.0$	

For these parameters, calculate the mass flow assuming a choked nozzle throat (i.e., M=1) in Equations 1,2,3,and 5:

Calculate throat temperature using Equation 1.

$$\frac{945^\circ\text{R}}{T} = \left(1 + \frac{(1.4 - 1)}{2}(1.0)^2\right) \Rightarrow T = 787.5\ ^\circ\text{R}$$

Calculate throat pressure using Equation 2.

$$\frac{57.51\ \text{psia}}{P} = \left(1 + \frac{(1.4 - 1)}{2}(1.0)^2\right)^{\frac{1.4}{(1.4 - 1)}} \Rightarrow P = 30.38\ \text{psia}$$

Calculate ρ using Equation 3.

$$(30.38\ \text{psia}) = \rho\left(53.35\frac{\text{lb}_f\ \text{ft}}{\text{lb}_m\ ^\circ\text{R}}\right)(787.5\ ^\circ\text{R}) \Rightarrow \rho = 0.1041\ \frac{\text{lb}_m}{\text{ft}^3}$$

Calculate U using Equation 5.

$$a = \sqrt{(1.4)(53.35\frac{lb_f\,ft}{lb_m\,°R})(32.2\frac{ft}{sec^2})(787.5\ °R)} \Rightarrow a = 1376.2\ \frac{ft}{sec}$$

$$U = (1.0)(1376.2) \Rightarrow U = 1376.2\ \frac{ft}{sec}$$

Calculate mass flow rate using Equation 4.

$$\dot{m} = (0.1041\ \frac{lb_m}{ft^3})(1376.2\ \frac{ft}{sec})(18.348\ in^2)(\frac{1\ ft}{12\ in})^2 \Rightarrow \dot{m} = 18.26\ \frac{lb_m}{sec}$$

Calculate P_{01} (upstream of block valve) knowing P_{02} and the calculated mass flow rate using Equation 6. Note that C_v for both block and vent valves is 400 and C_f for the vent valve is 0.90.

Solve Equation 6 for upstream pressure

$$P_1 = \sqrt{P_2^2 + [\frac{3.22 C_v \sqrt{G_f}}{3600 \dot{m} \sqrt{Z}}]^{-2}} = \sqrt{(57.51)^2 + [\frac{3.22(400)\sqrt{520/945}}{3600(18.52)\sqrt{1}}]^{-2}}$$

$P_{01} = P_1 = 90.43$ psia (mixed air pressure)

Calculate C_v required for vent valve using P_{01} as input to Equation 7.

$$C_v = \frac{(18.52)(1.0)(3600)}{2.8(0.90)(90.43)\sqrt{520/945}} \Rightarrow C_v = 394.4 = 98.6\%\ \text{open}$$

Calculate the appropriate opening for the hot valve using Equation 7 where P_1 in the equation is now the hot line supply pressure, P_H. The mass flow rate used is the maximum value available (use calculated value from above or 15 lb_m/sec, whichever is less). Note that the hot valve C_v is 130 and C_f is 0.76.

Solving for C_v:

$$C_v = \frac{(15)(1.0)(3600)}{(2.8)(0.76)(400)\sqrt{520/945}} \Rightarrow C_v = 85.52 = 65.8\%\ \text{open}$$

Now that the positions of the vent and hot valves have been determined, the cold start procedure has reached step 1.g. From this point on, no calculations are required to complete the operating procedure except for feedback comparisons monitoring temperatures and pressures.

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