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Development of an automated throw room and HVAC component acoustic test systems

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DEVELOPMENT OF AN AUTOMATED THROW ROOM AND HVAC COMPONENT ACOUSTIC TEST SYSTEM

by

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ABSTRACT

Two facilities for the testing of commercial and residential HVAC air delivery components were developed for the UNLV Ventilation and Acoustic Systems Technology (VAST) Lab. One facility, referred to as the HVAC Acoustic Test Facility (HCATS), will be used to measure the acoustic characteristics of in-duct and duct terminating components. This system will augment the test facility currently used for in-duct passive silencer testing. The other new facility will be used to rate the air performance of HVAC interior inlets and outlets. This system is commonly referred to as a throw room.

HCATS includes a supply air fan and closed circuit duct work to carry air to and from a reverberation room. Acoustic measurements are be made in the reverberation room, which has been qualified to ASTM standards. The duct components to be tested are be placed in the ductwork just as they would in normal use. The amount of air delivered to the component is measured using a bank of nozzles which are designed into the air delivery duct path.

The throw room is supplied air from an air circulation system designed specifically for the task. This system includes a temperature control system and a bank of nozzles similar to those for the HCATS system. Measurements of the air velocities and temperature in the throw room are made using thermal anemometers and thermocouples carried by a robotic mechanism. A PC computer is used to control the robotic mechanism and record data from the instruments.

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ACKNOWLEDGMENTS

A project of this size requires the work and resources of many people. Mark Jones, Eric Lyon and Al Sampson did a great deal of work in the shop and on the throw room. Rajkumar Rajgopalan analyzed the steel structure built in the throw room to support the variable height ceiling system. Dr. Culbreth provided guidance in selecting and using the instrumentation and stepper motors used in the throw room. Dr. Reynolds provided the guidance, vision and management that such a large project requires. I would like to thank all of these people for their involvement in this project and especially Dr. Reynolds for giving me the opportunity to work on this project. I would also like to thank Hart & Cooley and the many other companies that made this project possible through their donations. Finally, I would like to thank my wife, Tracy, for her patience and support during this project.

CHAPTER 1

INTRODUCTION

Two test systems were developed at the UNLV Ventilation and Acoustic Systems Technology (VAST) Laboratory. One test system will be used to measure the acoustic performance of HVAC in-duct and duct terminating components. This system will augment the test facility currently used for in-duct passive silencer testing. The other new test system will be used to rate the air discharge performance of duct terminating components. This system is commonly referred to as a throw room.

The results of tests conducted using both new test systems will be utilized by the university and industry in an effort to improve the performance of HVAC systems. This will be achieved by using the data generated by tests to verify theoretical models and develop empirical models of HVAC components and sub-systems. These improved models will then be used to develop better products.

The primary function of the HVAC component acoustic test system is to measure the acoustic characteristics of HVAC air distribution and terminating devices. Tests conducted using the HVAC component acoustic test system will characterize the amount of noise generated or attenuated by a device. The device will be placed in the system's air flow path as in normal use. Air will flow through the device over a range of normal operating rates. If the device is designed to attenuate sound, then pink noise will be introduced into the air flow path upstream of the device. Sound pressure measurements will be made in the reverberation room. A real time analyzer will be used to acquire the acoustic data. A computer will be used to record and analyze all acoustic and air flow rate data.

The throw room will be used to rate the performance of HVAC air outlets and inlets (hereafter referred to as air terminating devices or ATD's). The performance of ATD's are indicated by the results of certain tests. These tests determine the pressure loss across the ATD for a given set of air flow rates, the area factor of the ATD, and the isovelocity envelope of the ATD. The results of these tests are used to determine the effectiveness and ideal operating conditions for ATD's.

Performance rating tests of ATD's require measurements of the volumetric air flow rate supplied to the device and its discharge air velocity and temperature at a number of locations in the air discharge space. Further, these tests require that the test environment is physically similar to that for which the ATD was designed. The throw room will provide an environment with the space, flexibility, and instrumentation needed to make these measurements.

Rating the air diffusion performance of ATD's is standardized by ASHRAE standard 70[1]. As such the development of the throw room was guided by this document. The VAST lab throw room conforms to all applicable ASHRAE standards as dictated by ASHRAE standard 70.

A secondary objective in the development of the throw room was to automate the test procedures. The rating of ATD's is a very tedious process requiring a large number of carefully made measurements. Over 32 anemometer readings, each at a different location in the throw room, are required to determine the throw, spread, and drop of a single ATD at 4 different volumetric flow rates. To my knowledge, all of the throw rooms currently used in the United States are operated manually. All temperature and air velocity measuring instrumentation is positioned by a human lab operator. The VAST lab facility features an automated data acquisition and control system, that is the first of its kind in a facility such as this.

These additions to VAST lab where funded by the Hart & Cooley Corporation. They will enhance the vital link between private industry and the UNLV Mechanical Engineering Department currently realized through VAST lab.

1.1 Review of Literature

Very little literature is available on the primary topics discussed in this report. This is due to industry interest in these topics, which tends to make any useful information proprietary. A book by R. G. Nevins[2] entitled <u>Air Diffusion Dynamics</u> was useful as a general overview of the use and testing of HVAC air terminal devices, but provided very little detailed information. The book refers to standards by the now defunct Air Diffusion Council[3] (ADC) for the testing of ATD's. These standards were the prototype of the current ASHRAE standards. The ADC standards provide no more information than the current ASHRAE standards.

The primary sources of information used in the development of the throw room were the ASHRAE standards. ASHRAE standard 70[1], entitled "Method of Testing for Rating the Performance of Air Outlets and Inlets", is the benchmark by which the throw room was designed. It was referred to extensively during the development of the throw room. This standard also refers to several other ASHRAE[4,5,6] and ISO[7,8] standards, which were used in the development and selection of the instrumentation and measurement systems for the HVAC component acoustic test system and the throw room.

Other information sources used in the development of these projects concerned the design and use of nozzle chambers in the measurement of volumetric air flow rate. The work of Wile[9] done in the 1940's on the measurements of air flow was published in 1947. This paper was very useful in the design of the nozzle chambers. Wile discusses many issues that have a practical effect on air flow measurement, but gives no analytical treatment of the subject. A paper by Bohanon[10] was useful in developing the calculations for determining the volumetric flow rate of air as a function of the nozzle chamber measurements. The ASHRAE Fundamentals Handbook[11] and ASHRAE Brochure on Psychrometry[12] were also referred to in the formulation of these calculations.

The ASHRAE Handbooks[13] were of great use in the design of the ducting. Various other texts and handbooks were also used in these projects. They will be referenced in the following text. A complete list of the material referred to in this is project is in the References.

1.2 Report Organization

The development of the HVAC component acoustic test system's air flow path and air flow rate measurement station will be discussed in chapter two of this report. The reverberation room and the associated acoustic instrumentation required by this system already exist in the VAST lab. As such they will not be discussed. Appendix 2 will be devoted to the details of the HVAC component acoustic test system.

The complete development of the throw room will be discussed in this report. The throw room is a large and multifaceted system. Each of chapters three through six will discuss a major sub-system of the throw room. These chapters also have correspondingly numbered appendices that detail the information discussed.

CHAPTER 2

HVAC COMPONENT ACOUSTIC TEST SYSTEM

The HVAC Component Acoustic Test System (HCATS) is a ducted, closed circuit, air delivery system. Within this circuit are a fan to supply the air flow, an air flow measurement system, a test duct section and a reverberation room. The closed nature of the design acoustically isolates it from noise in the Multifunction Laboratory. Further, this design eliminates any safety problems caused by air jets or low pressure areas in the Multifunction Laboratory and prevents any pressure buildup within the reverberation room. The system was designed so that it can easily be modified for a variety of testing configurations. A drawing of the final system layout is shown in Figure 2.1.

The system, as shown in Figure 2.1, has a ducted air path that is about 215 ft long and requires about 148 ft^2 of multifunction lab floor space. This was accomplished by hanging most of the ducting, including the nozzle

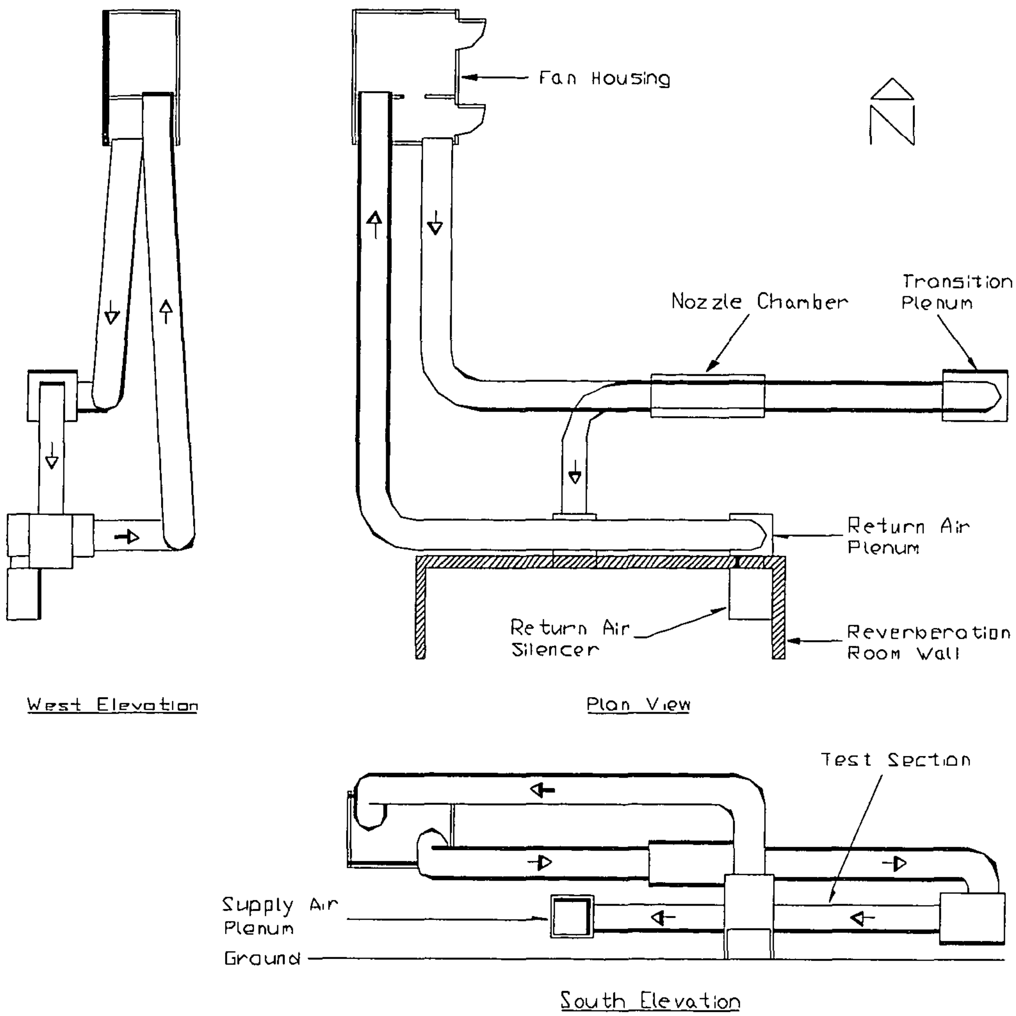


Figure 2.1: HVAC Component Acoustic Test System

housing, from the ceiling of the lab. Additionally, the fan housing was placed on an existing platform above the multifunction lab floor. The section of the system that is on the floor is the test section. This section must be at ground level so that the variety of tests, which the system is required to make, can be easily set up.

Every effort was made in the design of this facility to minimize the amount of background noise generated by system components and activities in the Multifunction Laboratory. Background noise, if excessive, can interfere with the measurement of insertion loss and regenerated sound power. The air delivery components in this system were constructed using sound insulating panels with perforated interior walls that will prevent sound break-in and reduce the transmission of sound in the system. The test section was constructed of sound insulating panels without interior perforation to reduce the amount of sound break-in and break-out. Plenums were used, where necessary, to reduce sound-generating air turbulence and minimize the amount of noise transmitted through the air stream path. Vibration isolation was also incorporated into the design to eliminate sound caused by structure-born vibration.

2.1 System Fan

The two basic criterion used to select the fan for this system are the volumetric flow rate required for testing and the total pressure drop due to system components. The maximum volumetric flow rate that will be required for any test should be no greater than 10,000 CFM. This value was a conservative estimation which should provide the flexibility to test almost any residential or industrial grill, register, diffuser or terminal unit. The total pressure drop was estimated as the sum of the maximum pressure drop across the flow nozzles, an estimated 0.5 in. w.g. for the duct work, and that required by the test unit. The flow nozzles used to measure the air flow rate require up to 3 in. w.g. The test unit may require up to 1.5 in. w.g. This resulted in an estimated total pressure requirement of about 5 in. w.g.

The Greenheck Fan Corporation was consulted in selecting the proper fan for this system. They suggested the use of a 33 inch diameter, air foil, single-width, centrifugal fan with inlet vane control. This fan will provide a near constant 5.3 in. w.g. static pressure at flow rates up to 10,000 CFM. All fan data is shown in Appendix 2.

The fan receives its power from a Graham 1576 motor transformer and speed controller. This unit is used as the primary control for volumetric flow rate. The variable inlet vanes on the fan inlet could also be used to control air volumetric flow rate.

In mounting the fan, measures were taken to prevent the propagation of vibration from the fan to the fan housing. The fan was mounted on open spring vibration isolators. Also, the ducted connection to the fan output plenum was made of loaded rubber sheet.

2.2 Fan Housing

The fan housing is required in the test system to make a closed air flow circuit. It is a container for the fan and provides a ducted air inlet and outlet to the system. Additionally, the fan housing was designed to maximize the efficiency of the fan, reduce the transmission of fan generated noise into the air distribution system, and minimize the amount of noise entering the system through the housing walls. The housing was also designed with doors for maintenance access. The final fan housing design is shown in Appendix 3.

Fans generate noise from their drive mechanisms and by creating turbulent flow conditions. To reduce the amount of turbulent flow noise, the fan housing was designed with input and output plenum chambers. Flow induced noise is reduced in the plenum chambers by "smoothing out" the turbulent air flow. Fan machinery and flow induced noise levels are further reduced by the acoustically absorbent material in the walls of the housing.

Fan performance can be compromised by the air intake conditions caused by an enclosure or ducting. To allow the fan to function at peak levels, the fan manufacturer recommended a minimum of one fan diameter of free space between the fan inlet vanes and any barrier. This constraint was considered in the design shown.

The housing was constructed using fiberglass filled panels that are 4 inches thick with a perforated steel sheet on the interior of the fan housing and a solid steel sheet on the exterior. Two 6 inch by 1 inch sheetmetal channel sections provide a mounting surface for the fan open spring vibration isolators.

2.3 Delivery Duct

The function of the delivery duct in HCATS is to route air to and from the test section and other system components. The type and size of duct was chosen based on its ability to limit the amount of noise transmitted through the system and to prevent the generation of noise caused by turbulent air flow. The duct was laid out so that other system components could be placed at unused or non-critical locations in the lab. The duct layout can be seen in Figure 2.1.

A circular cross-section, dual-walled, lined duct was selected for this system. The duct has 2 inches of fiberglass insulation between a perforated

22 gauge inner sleeve and a solid 18 gauge outer shell. The duct inner diameter is 30 inches. All elbows in the delivery duct were radiused to decrease the amount of turbulent flow.

A circular duct cross section was chosen to prevent rumble. Rumble is a sympathetic vibration induced into a duct wall by sound in the air carried by the duct. Rumble can be reduced and sometimes eliminated by using a more rigid duct. The circular cross section geometry is, in general, the most rigid for ducts.

The duct diameter was chosen to prevent noise generated by turbulent air flow. Noise generated by air turbulence is proportional to the fifth to sixth power of velocity. A maximum air flow velocity of 2,000 fpm is generally accepted in HVAC duct design to limit flow-generated noise. Given the maximum volumetric flow rate of 10,000 CFM supplied by the fan, a 30 inch diameter was calculated for the duct.

2.4 Reverberation Room Return Air Silencer

The reverberation room return air silencer is part of the return air circuit for the fan. The return air silencer, which is located in the reverberation room, allows air to flow back into the test system duct, while impeding the re-entrance of sound.

The silencer is a dissipative type silencer. Dissipative silencers are ducts with one or more passages that are lined with acoustically absorbent material. Fiberglass and mineral wool are commonly used for this purpose. Sound energy is attenuated when it is converted to heat by the acoustically absorbent material. The change in area in the air flow path also attenuates sound by creating an impedance discontinuity.

The silencer dimensions were chosen to be as large as possible while not interfering with other activities in the reverberation room. The size of the silencer has two effects on the return air circuit. The cross sectional area should be large enough to not cause a flow restriction. Also, the internal surface area of the silencer should be maximized so that the amount of acoustically absorbent material can be maximized.

The return air silencer has two air flow passages lined with fiberglass insulation. It is constructed of 18 gauge sheetmetal. It was designed so that it could be closed off from the reverberation room when the room is used for another purpose. The reverberation room return air silencer design is shown in Appendix 3.

2.5 Return Air Plenum

The return air plenum smooths the air flow turbulence caused by area discontinuities and a change in flow direction. Area discontinuities are present in the path from the return air silencer through the wall of the reverberation room. The flow direction makes a 90 degree turn to a vertical direction. This turn is required to conserve floor space in the multifunction lab. A radius elbow is not used for the same reason. Further, an elbow would not attenuate sound as well.

Sound attenuation is provided by fiberglass, which lines the whole interior surface area of the plenum. The plenum dimensions where chosen to

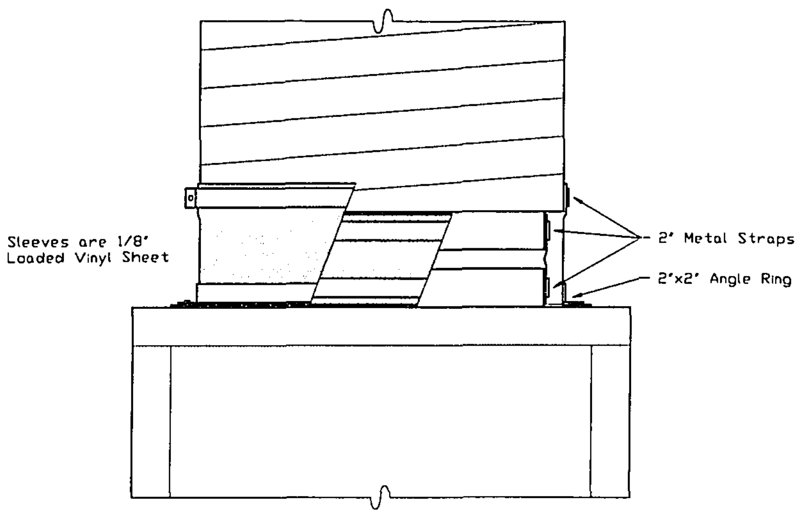


Figure 2.2: Flexible Duct Connection

be as large as possible and were constrained only by the practical use of space. The larger the plenum dimensions, the greater the amount of fiberglass lining and air flow volume. The return air plenum design is shown in Appendix 3.

The return air plenum is constructed of 2 inch thick fiberglass filled panels. The panels are made of 18 gauge sheetmetal with the interior side of the panel perforated. It is connected to the return air duct using a flexible connector made of loaded vinyl sheet to prevent the transmission of vibration induced noise into the reverberation room. The design of the flexible connector is shown in Figure 2.2.

2.6 Transition Plenum

The transition plenum makes a 360 degree turn in the flow direction (as can be seen in Figure 2.1). This change in direction is required to minimize the use of multifunction lab floor space. A plenum was chosen for this purpose for two reasons. It minimizes the amount of turbulence generated by such a turn and provides a means of changing the duct cross section in the system.

The transition plenum was designed to be large enough to allow flow settling, but not so large as to cause a significant obstruction in the multifunction lab. It was constructed of acoustically insulating panels. The panels are dual walled with a 4 inch cavity filled with fiberglass and an inner wall of perforated 18 gauge sheetmetal. The transition plenum design is shown in Appendix 3.

The plenum was designed so that speakers can be mounted to it. These will be used when sound insertion loss measurements are to be made. Passive duct silencers are tested in this way.

2.7 Reverberation Room Supply Air Plenum

The reverberation room supply air plenum terminates the test section into the reverberation room. This plenum provides a platform that could accommodate a variety of terminal unit test configurations. Many terminal units will be mounted directly to the open face of the plenum. The plenum can also be modified for tests that require a straight duct input to the terminal unit.

The plenum passes through a 4 ft square door in the reverberation room wall. It was designed so that the door could be closed if any tests not related to the HCATS facility need to be conducted. The plenum cross-sectional dimensions where constrained by the use of this door into the reverberation room.

The plenum is constructed of 18 gauge dual wall panels with 2 inches of fiberglass insulation. The interior side of the panels are perforated. The plenum interior could be covered with solid sheetmetal if any tests require an acoustically non-dissipative plenum. The plenum design is shown in Appendix 3.

The plenum is connected to the test section with a flexible connector. The connector prevents vibration in the test section from being transmitted to the plenum where it would be radiated as sound due to the rigid connection with the reverberation room wall. The connector is made of loaded vinyl. A similar connector is shown in Figure 2.2.

2.8 Test Section Duct

The test section is a length of duct used to test in-duct HVAC devices. It is composed of 5 duct sections, including a radiused elbow, that are bolted together. These duct sections could be removed from the system and replaced by devices to be tested. Devices which are likely to be tested in this fashion are straight and elbow silencers and elbows designed to reduce the turbulence caused by a change in airflow direction.

The test duct was designed to provide the most common platform for HVAC devices to be tested and to prevent sound break-in and break-out. The duct sections selected have a 2 ft square interior cross section and are manufactured from fiberglass insulated 2 inch thick panels with solid 18 gauge sheet metal skin on the interior and exterior. They are separately supported on wheeled carts so that they could be easily moved.

2.9 Air Flow Measurement System

The air-flow measurement system for this facility was designed in accordance with ASHRAE Standard 41.2[5] "Standard Methods for Air-Flow Measurement". This standard suggests the use of either flow nozzles or a Pitot traverse for the measurement of air flow rates. Flow nozzles were chosen because of their simple design and implementation requirements and because they could be used without calibration if they are constructed and used according to the standard.

The air flow measurement system is composed of a bank of flow nozzles and a chamber to house them as well as the appropriate required measurement instrumentation. The nozzle bank is a set of flow nozzles mounted on a common partition in the nozzle housing. Nozzles in the bank are used individually and simultaneously to measure flow rates in different ranges. The system can measure flow rates of up to 10,000 CFM with a measurable pressure differential across the nozzle bank up to 3 in. w.g.. This system satisfies requirements set forth by ASHRAE Standard 41.2[5] for the laboratory measurement of air flow rate in ducted systems.

2.9.1 Nozzle Bank

Two constraints were considered in the design of the nozzle bank. These were the size and measurement range of the nozzle bank. The nozzle bank for the HCATS system was required to measure flow rates up to about 10,000 CFM. The minimum size was limited by the number and size of the nozzles used to achieve the measurement range. These constraints were satisfied by the design shown in Appendix 4.

The type of nozzles used were explicitly defined in ASHRAE Standard 41.2[5]. An iterative process was used to select a set of nozzles that minimized the size of the nozzle bank and measured flow rates up to 9,774 CFM. ASHRAE Standard 41.2[5] states that the maximum throat velocity for the nozzle type specified shall not exceed 7,000 fpm and shall not go below 3,000 fpm. Given the throat diameter of a nozzle and the specified velocity range, the corresponding flow rate range for each nozzle was calculated. The selected nozzles were mounted to a nozzle housing partition in the arrangement shown in Appendix 4.

The nozzle bank is used by plugging and unplugging nozzles according to the range of the flow rate to be measured. Rubber plugs are used for this purpose. Multiple nozzles may be used to determine flow rates at rates between single nozzle measurement ranges. Table 2.1 shows the nozzles that should be used for flow rate ranges up to 9,774 CFM. Appendix 5 describes the equations and data required to calculate the air flow rate based on the measurements.

2.9.2 Nozzle Housing

The nozzle housing was designed around the nozzle bank and in accordance with ASHRAE Standard 41.2[5]. The housing cross section dimensions were constrained by the dimensions of the nozzle bank which requires a partition wall that is 57 inches square. The remaining dimensions are constrained by the ASHRAE standard. The nozzle housing was designed with two doors that allow access for maintenance and measurement adjustments

Nozzles by Throat Diameter						Flow Rates (CFM)	
1.6 in.	2.0 in.	3.0 in.	4.0 in.	6.0 in.	8.0 in.	min	max
1	0	0	0	0	0	41.9	97.7
0	1	0	0	0	0	65.5	152.7
0	0	1	0	0	0	147.3	343.6
0	0	0	1	0	0	261.8	610.9
0	0	0	0	1	0	589.1	1,374.5
0	0	0	0	0	1	1,047.2	2,443.5
0	0	0	0	0	2	2,094.4	4,886.9
0	0	0	0	0	3	3,141.6	7,330.5
0	0	0	0	0	4	4,188.8	9,774.0

Table 2.1: Nozzles Used For Flow Rates From 42 CFM to 9,774 CFM

inside the two nozzle housing chambers. The resulting design is shown in Appendix 4.

The nozzle housing consists of a receiving chamber and a discharge chamber, which are upstream and downstream of the nozzle bank partition respectively. Both chambers contain screens, as required by the standard, to provide flow settling. The receiving chamber contains two screens in tandem, which produce a more uniform velocity profile to exist upstream of the nozzles. The screen in the discharge chamber absorbs the kinetic energy of the nozzle jets and permit normal flow expansion as in an unconfined space[9]. All three screens were constructed of perforated 20 gauge sheet steel with a 58% open area, as suggested by ASHRAE Standard 41.2[5].

The nozzle housing was constructed of 2 inch thick fiberglass filled panels. The panel face on the interior of the housing is made of 22 gauge perforated sheet steel and the exterior face is made of solid 18 gauge sheet steel. Insulated panels were used to reduce the amount of noise transmitted through the nozzle housing and into the discharge duct and to prevent noise from entering the test system through the nozzle housing walls.

The pressure differential across the nozzle bank partition is measured using a differential pressure transmitter, which is connected to two piezometer rings. One piezometer ring is connected to four static pressure taps upstream of the nozzle bank partition and the other is connected to four static pressure taps downstream of the partition. The static pressure taps are mounted on each of the four nozzle housing walls 1.5 inches (according to ASHRAE standard) upstream and downstream of the nozzle bank partition. The piezometer rings are constructed of 1/2 inch diameter copper tubing and are connected to the static pressure taps with brass compression tube fittings. The static pressure taps were constructed as per standard.

CHAPTER 3

THROW ROOM HOUSING AND AIR SUPPLY SYSTEM

The throw room housing encloses all apparatus and instrumentation for the performance rating of HVAC grills, registers, and diffusers. It contains two rooms; a throw room and a control room. The throw room provides a controlled environment for all air flow measurements and house the instrumentation and traversing mechanism. The control room houses a data acquisition and control system and support equipment for the facility. The rooms are connected via a common wall as shown in Figure 3.1.

The housing dimensions were designed around the needs of the throw room and constrained by the area available. The throw room was designed to be large enough to conduct a variety of ATD performance tests. Thus, its size is dictated by the treated air space required for a test and the apparatus needed to conduct the test. This apparatus includes a variable height ceiling system and air handling ducts. The primary throw room dimension, affected

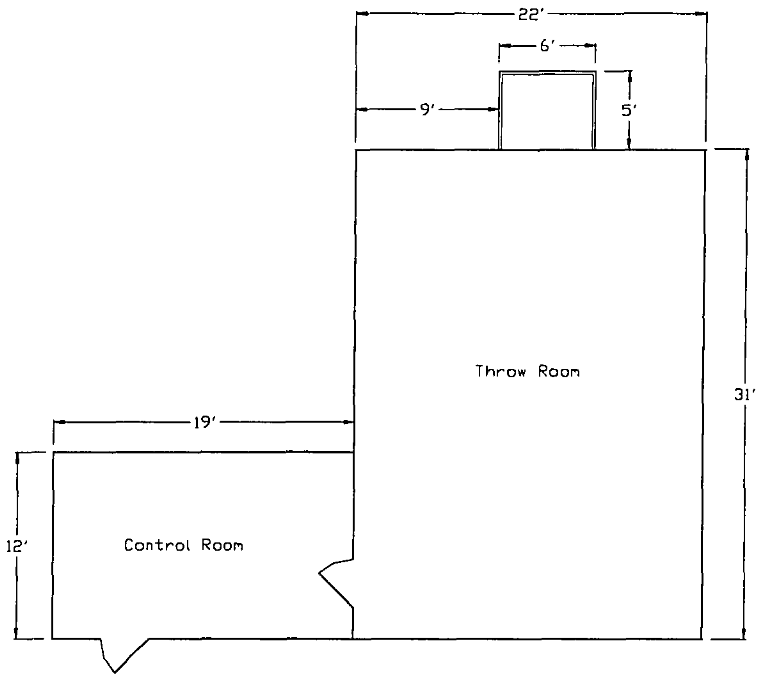


Figure 3.1: Throw Room & Control Room Plan View

by the space needs of the apparatus, is its height. The height was selected to accommodate the space needed for ducts beneath the throw room floor and above the throw room ceiling and for the variable height ceiling system. The length and width of the throw room and the dimensions of the control room were constrained by the space available to the facility. The housing dimensions are shown in Appendix 6.

The throw room housing was designed with a plenum built into its north wall. This will provide a great flexibility in the mounting of ATD's for tests. The plenum is the full height of the throw room (239.4 inches), 58 inches deep, and 68.4 inches wide. It is lined internally with 2 inches of fiberglass for thermal and acoustic insulation. The plenum is supplied air by a duct above the ceiling of the throw room.

The throw room housing is a prefabricated structure. It is constructed of 2 inch, mineral wool filled, galvanized, sheet steel, panels. The panels are framed together with extruded aluminum mullions and cast aluminum joints supplied by the vendor. It was assembled with tech screws and sealed using Dap Butyl-Flex Caulk.

The throw housing is built on a concrete pad designed and built for this project. The pad is made of fiber-reinforced concrete. The pad dimensions are shown in Appendix 6.

The throw room has a raised floor that is 3 ft above the concrete pad that the throw room housing is built on. The raised floor covers the entire length and width of the throw room. This facilitates the testing of floor mounted ATD's. It is built of wood and has removable panels for maintenance access. It is supported by the steel structure inside the throw room housing as shown in Figure 3.2.

3.1 Throw Room Interior Surfaces

The testing of ATD's will require measurement of airflow near the internal surfaces of the throw room. The variable height ceiling support structure (see Section 3.2) is an obstruction in the air flow path near the walls. In order to solve this problem and to further insulate the facility thermally and acoustically, interior panels were installed in the throw room. The panels cover the entire surface of the North, West and East walls except at the throw room door.

The panels are 18 gauge steel sheets that are fastened to the support structure columns and intermediate metal studs. All open space between the

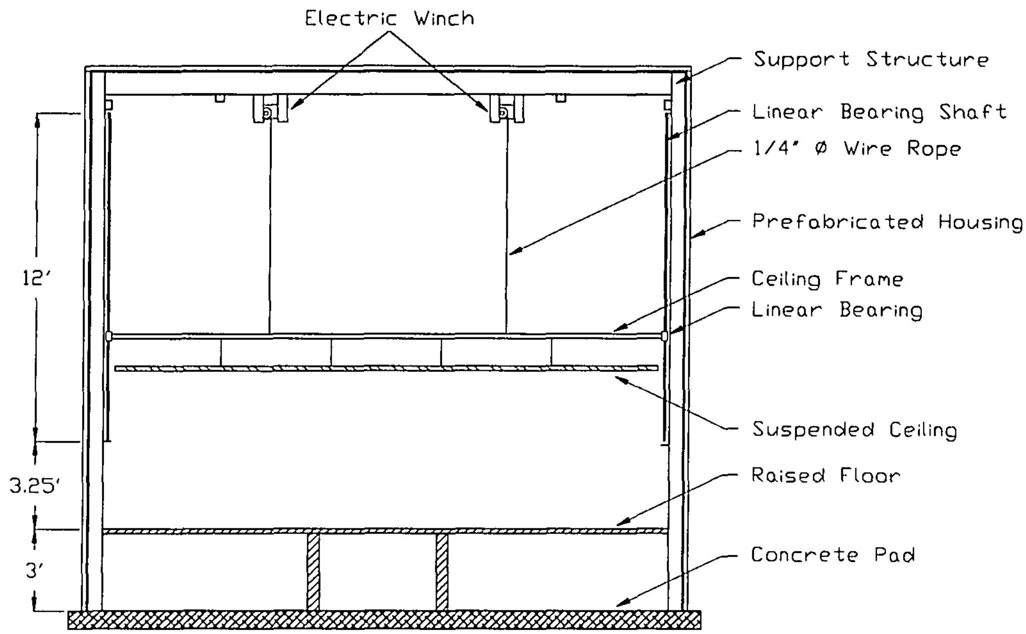


Figure 3.2: Cross Section of Throw Room

original interior walls and the panels is filled with fiberglass. Sheet metal screws were used to fasten the panels.

A set of perforated steel sheet panels were also made. These panels will be used to change the acoustic properties of the room when needed. Any number of the perforated panels can be installed to reduce the reverberation rate in the room.

3.2 Variable Height Ceiling System

Useful measurements of the performance characteristics of an ATD require that the treated space is geometrically similar to that of the ATD when in use. Many tests, such as those for ceiling diffusers, will require a specific ceiling height and type. For this reason the throw room was designed with a variable height ceiling.

The variable height ceiling system is essentially a steel frame that is hung from a winching mechanism. The winching mechanism is used to raise, lower and hold in place the steel frame. The steel frame can be set at any height from 3.5 ft to 12.5 ft This range should accommodate the needs of any test.

The frame was designed to provide mounting points for a standard 4 ft by 4 ft suspended ceiling anchoring scheme. Also, the frame was designed so that four linear bearings could be used for motion guidance. The linear bearings are mounted to the frame and the linear bearing shafts are mounted to the steal structure inside the throw room at four locations. The frame design and linear bearing locations are shown in Appendix 8.

A number of solutions were considered for the design of the winching mechanism for the variable height ceiling. The designs were compared according to implementation effort and projected reliability. The design selected consisted of a set of four commercially available winches. The winch selection is discussed in Section 3.2.1.

The prefabricated building used to house the throw room does not have the strength to carry the load of the variable height ceiling system. As a result a steel structure was designed to fit within the throw room to carry the load. The steel structure is free standing and completely independent of the throw room housing. The winches are mounted directly to the structure as shown in Figure 3.2. The design of the steel structure is discussed in Section 3.2.2.

3.2.1 Winch Selection

The winches were selected to provide continuous vertical pulling of an estimated maximum 2,300 lb load and to hold that load. The winches were also selected to use 220 V single phase alternating current for ease of installation. Pulling speed was not an important factor.

The maximum required pulling load of the winches was calculated from the sum of the weights of a worst case scenario. The sum included the weight of the steel frame and the weight of a layer of 5/8 inch gypsum board. The total weight of the ceiling frame was estimated to be about 1000 lb by determining the total weight of the steel in the structure. The weight of the gypsum board was determined by multiplying the area of the floor of the throw room by the area density of the gypsum board supplied by a local manufacturer. The weight of the gypsum is about 1,300 lb The total weight of the load is 2,300 lb.

Thern Inc. was consulted in the selection of the winches. They suggested that four of their model #473A3/4BM winches would satisfy the design requirements. The winches have an individual load rating (when the drum has 2 layers of cable) of 1000 lb This gives a total load rating of 4000 lb, which results in a safety factor of 1.74. With one layer of cable spooled onto the drum, a second layer can spool over 15 ft of coil which exceeds the required 9 ft range. The winches are equipped with braking motors which hold the vertical load of the ceiling once the ceiling is at test height.

Each winch is equipped with a 0.25 inch galvanized steel wire rope (with 7 strands and 19 wires per strand) to suspend the ceiling frame. Each wire rope has a breaking strength of 7000 lb, which far exceeds the required total ceiling load. The wire rope is anchored to the ceiling frame at the four points as shown in Appendix 8.

The winches were wired so that they could be controlled from the control room. The switching was setup so that each winch could be individually controlled if required. The circuit also includes limit switches that will cut power to the winches at a maximum height of 12.5 ft and a minimum height of 3.5 ft. A schematic of the circuit is shown in Appendix 9.

3.2.2 Support Structure

The primary function of the support structure is to carry the load of the variable height ceiling system. It is also used as a partial support for the raised floor and it carries the weight of the traversing mechanism. Negligible stress is induced in the structure by the weight of the raised floor and traversing mechanism as they are connected on the lower 3 ft of the structure.

The support structure consists of 6 pairs of columns evenly spaced along the length of the throw room. The columns are mounted at the ground to the concrete pad the throw room housing is built on. Each pair of columns supports a beam at the ceiling of the throw room housing, which spans the width of the room. The beams and columns fit closely to the interior surfaces of the throw room housing so that the structure is as non-intrusive into the throw room space as possible.

The columns of the structure are steel W6x20 columns and the beams are steal W10x22 beams. All joints in the structure are welded for maximum

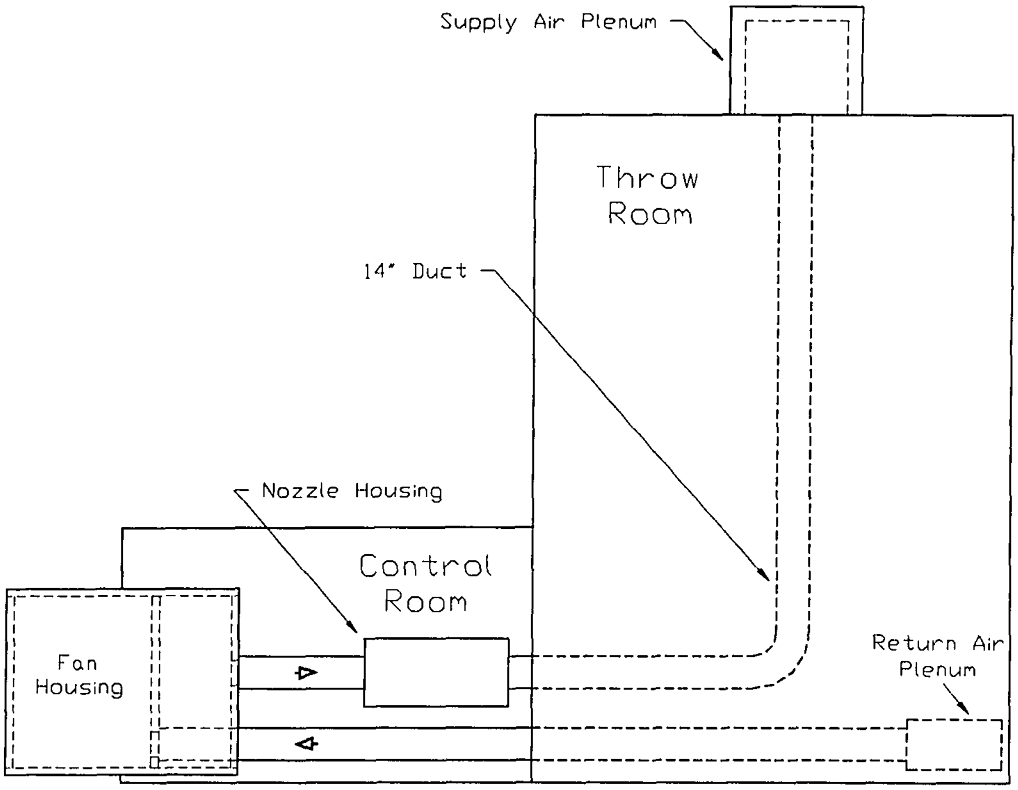


Figure 3.3: Throw Room Air Supply System

rigidity. The structure is mounted directly to the concrete pad of the throw room housing with 1 inch thick steel base plates. Analysis of the structure was performed by Rajkumar Rajagopalan. Detailed drawings are shown in Appendix 8.

3.3 Air Supply System

The ASHRAE 70[1] standard recommends that air velocity measurements to determine ATD air exit velocity and throw are made at steady state supply rates and temperatures. The air supply system for the throw room delivers air at a constant temperatures and flow rates to comply with the standard. Also, since the air supply system will be used for a variety of ATD performance rating tests, the system was designed to deliver air at flow rates up to 2000 CFM and temperatures common to HVAC systems.

The air supply system is composed of a fan, a heating element, a cooling element, a flow nozzle chamber and air handling duct components. The heating and cooling elements and the fan are enclosed in the fan housing, which is located outside the facility and above the control room as shown in Figure 3.3. The flow nozzles (see Chapter 4) are also enclosed in a housing located above the control room. The remainder of the components are located inside the throw room.

3.3.1 Air Supply System Fan

The two basic criterion used to select the fan for this system are the volumetric flow rate required for testing and the total pressure drop due to system components. The maximum volumetric flow rate that will be required for any test should be no greater than 2,000 CFM. The total pressure drop was estimated as the sum of the maximum pressure drop across the flow nozzles, an estimated 0.5 in. w.g. for the duct work, and that required by the test unit. The flow nozzles used to measure the air flow rate require up to 3 in. w.g. The test unit may require up to 1.5 in. w.g. This result in an estimated total pressure requirement of about 5 in. w.g.

The Greenheck Fan Corporation was consulted in selecting the proper fan for this system. They suggested the use of a 15 inch, backward inclined, single-width, centrifugal fan with inlet vane control. This fan provides a near constant 7 in. w.g. static pressure from 0 to 2,000 CFM. All fan data is shown in Appendix 10.

The fan receives its power from a Varispeed-616GII AC variable speed drive system and speed controller manufactured by Yaskawa Electric Manufacturing Co. This unit is used as the primary control for volumetric flow rate. The variable inlet vanes on the fan inlet may also be used to control air volumetric flow rate.

In mounting the fan, measures were taken to prevent the propagation of vibration from the fan to the fan housing. The fan was mounted on elastomer spring vibration isolators. Also, the ducted connection to the fan output plenum was made of loaded rubber sheet.

3.3.2 Temperature Control System

Heating and cooling load calculation were performed in order to properly select air supply system temperature control components. The heating and cooling loads of the throw room were assessed using methods suggested in the ASHRAE Fundamentals Handbook[11]. All calculations were performed by Daniel LaCour. A temperature control system was then selected based on the results of these calculations and the required volumetric flow rates for performance rating tests in the throw room.

The cooling load temperature difference (CLTD) method uses temperature differences as a basis for cooling load calculations as described in the ASHRAE Fundamentals Handbook[11] chapter 26. In this method, the building is characterized by the thermal resistivity of its walls, all heat sources in the building are identified, and the effect of solar radiation is assessed.

Since the facility housing has a different design than those used for standard CLTD calculations, a CLTD correction was made. These corrections were taken from the cooling load and weather data contained in the 1989 ASHRAE Fundamentals Handbook[11] chapter 26.34, table 29.

The effect of solar radiation on the cooling load of the throw room was assessed using data taken on June 21, 1992, which was the longest day of the year. The sun was tracked in relation to the building location and the amount of solar radiation impinging on each wall of the throw room was estimated. The roof was assumed to be a #1 roof with a suspended ceiling and the walls were assumed to be group G walls (from table 30 of the ASHRAE Fundamentals Handbook[11]). Further, heating loads due to occupants, lighting, and equipment in the throw room were considered. The heat transfer coefficient was found to be 0.048 Btu/[hr ft^2 °F]. The total cooling load peaks at 4:00 PM (on June 21) and was found to be 21,390 Btu/hr.

The heat load was also calculated for the coldest months of winter. The heat loss from the building at this time is at its maximum and is relatively constant during the day so the problem was considered to be steady state. The indoor design temperature was set at 80 °F. The outdoor design criterion was taken from the ASHRAE Fundamentals Handbook[11]. The outdoor temperature was found using table 1 of chapter 24.10 and the 99% dry-bulb temperature. It was determined that the building has a 2,620 W heating load.

To meet the needs of the building heating and cooling loads, a split system heat pump is used. In consultation with Seigler and Reese, a Carrier representative, the Carrier FB4A Direct Expansion Fan Coil with a 38YKB (60Hz) heat pump was selected. It was ordered with a Carrier

#KFAEH0101N03 3KW (240VAC) strip heater, which is used when the heating load exceeds the operating limits of the heat pump.

The expansion coil, fan, and strip heater in the Carrier FB4A system are packaged as a unit. For implementation in the air supply system for the throw room, the expansion coil and strip heater are mounted in the fan housing discussed in Section 3.3.3. The fan supplied with the Carrier system is not used.

3.3.3 Fan Housing

The fan housing is required in the throw room air supply system to make a closed air flow circuit and to protect system components from the environment. It is a container for the fan, evaporation coil, and heating strip, and provides a ducted air inlet and outlet to the system. In addition, the fan housing also maximizes the efficiency of the fan, reduces the transmission of fan generated noise into the air distribution system, and minimizes the amount of noise entering the system through the housing walls. The fan housing design is shown in Appendix 11.

Fans generate noise from their drive mechanisms and by creating turbulent flow conditions. To reduce the amount of turbulent flow noise, the fan housing was designed with input and output plenum chambers. Flow induced noise is reduced in the plenum chambers by "smoothing out" the turbulent air flow. Fan machinery and flow induced noise levels are further reduced by the acoustically absorbent material in the walls of the housing.

The fan housing was designed to allow the fan to function at peak levels and to allow room for fan maintenance. The fan manufacturer recommends, at least, one fan diameter of free space between the fan inlet vanes and any housing wall. This will provide good flow conditions for the fan air intake. Doors were designed into the input and output plenums for maintenance access to the fan housings input and output plenum chambers. All other dimensions were dictated by the fan size.

The housing was constructed using fiberglass filled panels that are 4 inches thick with a perforated steel sheet on the interior of the fan housing and a solid steel sheet on the exterior. Two 6 inch by 1 inch sheetmetal channel sections provide a mounting surface for the fan open spring vibration isolators.

3.3.4 Air Flow System Duct

The duct in the throw room routes air to and from the throw room and other system air handling components. The type and size of duct was chosen for its ability to limit the amount of noise transmitted through the system and to prevent the generation of noise caused by highly turbulent air flow. All elbows in the delivery duct are radiused to decrease the amount of turbulent flow.

A circular cross-section, dual-walled, lined duct was selected for this system. The duct has 2 inches standard fiberglass insulation between a perforated 22 gauge inner sleeve and a solid 18 gauge outer shell. The fiberglass insulates the duct both thermally and acoustically.

The duct inner diameter of 14 inches was chosen to prevent noise generated by turbulent air flow. Noise generated by air turbulence is proportional to the fifth to sixth power of velocity. The flow velocity of 2,000 fpm is a commonly accepted as an upper limit in order to minimize flow-generated noise. Given the maximum volumetric flow rate of 2,000 CFM supplied by the fan a 14 inch diameter was calculated for the duct.

CHAPTER 4

THROW ROOM INSTRUMENTATION

ASHRAE Standard 70[3] and ISO Standard 5219[7] standards define the types and characteristics of instruments that may be used in throw room facilities. Specifications were made for air velocity, temperature, pressure, and sound level measurements, as well as, the methodology of laboratory in-duct air flow measurements. This facility complies with all of the applicable standards.

Performance rating tests of HVAC air terminating devices (ATD's) requires the measurement of air velocity and temperature at a number of locations in the air discharge space as well as temperature, pressure, and volumetric flow rate measurements of the device supply air. Temperature and pressure measurements are made per ASHRAE Standards 41.1[4] and 41.3[6] respectively. Measurement of the in-duct volumetric air flow rate is made as per ASHRAE Standard 41.2[5].

4.1 Air Temperature Measurements

Temperature measurements are made in the duct upstream of the ATD being tested, in the nozzle housing and in the device discharge air. ASHRAE Standard 70[3], "Methods of Testing for Rating the Performance of Air Outlets and Inlets", requires that the accuracy of all temperature measurements is ±1.0 °F (0.5 °C) and that the resolution of any temperature scale is no greater than 1.0 °F (0.5 °C). This standard also states that all temperature measurements shall meet the requirements of ASHRAE Standard 41.1[4], "Standard Method for Temperature Measurement". This standard states that the maximum range required for the measurement of air temperature in association with HVAC tests is -40 °F to 100 °F (-29 °C to 60 °C).

Copper-Constantan, National Institute of Standards and Technology (NIST) Type-T, thermocouples are used to make all temperature measurements in the throw room facility. These thermocouples have a range of -328 °F to 662 °F (-200 °C to 350 °C), which is inclusive of the range defined above. They are also very rugged and provide exceptionally good measurement repeatability.

Thermocouple arrays are used for temperature measurements in the ducts and nozzle housing. Each array consists of four thermocouples with 18 inch steel sheaths. The thermocouple in each sheath is ungrounded and the sheaths are 1/8 inch in diameter. The thermocouples are arranged in the ducts as shown in Figure 4.1. The sheaths provide temperature averaging along their length. The thermocouples are wired in parallel to provide additional temperature averaging over the cross section of the duct. The sheaths are inserted in plastic tubing to prevent erroneous measurements due to forced convection cooling.

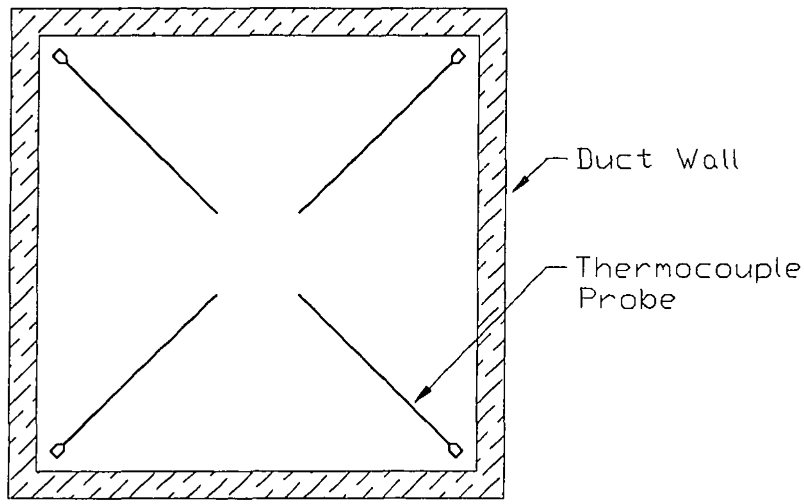


Figure 4.1: Duct Cross Section with Thermocouple Array

A single type-T thermocouple will be used for temperature measurements of the ATD discharge air. This thermocouple will be carried by the traversing mechanism along with the hot-film anemometer. The thermocouple is not in a metal sheath as the others but is in a plastic shield. The shield will prevent forced convection cooling of the thermocouple while allowing air to slowly circulate around the thermocouple for measurement. This measures the stagnation temperature of the air at one point in the flow.

An Omega OMNI-AMP IIB manufactured by Omega Engineering is used as a thermocouple amplifier and electronic ice-point reference junction for all thermocouples. It has a selectable output gain of up to 100. The output of the OMNI-AMP is wired directly to the data acquisition input terminal using shielded, 22 AWG, instrumentation wire. A voltage gain setting of 10 is used.

4.1.1 Thermocouple Calibration

The National Bureau of Standards (NBS) publishes tables of data relating the EMF (millivolts) to Temperature (°C) values for NIST type-T thermocouples. These tables can be found in the Temperature Handbook[13] published by Omega Engineering. Data for the range -30 °C to 60 °C was taken from these tables to generate a calibration curve. The data is in increments of 1 °C. A listing of the data is shown in Appendix 13.

The calibration curve was generated using the curve fitting program TableCurve, which is a product of Jandel Scientific. The program finds a list of functions that best fit the data based on function categories selected by the user. The program then fits each equation and generates a list that is ordered from best fit to worst. The fit standard error for each function was used as the ranking criterion.

Rank	Polynomial Order	Fit Standard Error	Maximum Error	Floating Point Demand
1	8	0.0075285767	0.014883	17
2	9	0.0075649101	0.014834	19
3	10	0.0075862742	0.015360	21
4	7	0.0077973505	0.015875	15
5	5	0.0080255789	0.019910	11
6	6	0.0080392797	0.018991	13
7	4	0.0099330142	0.021796	8
8	3	0.0141539937	0.032410	10
9	2	0.0350034905	0.10740	5
10	1	0.6483194646	1.4264	2

Table 4.1: Results of Thermocouple Calibration Curve Fit

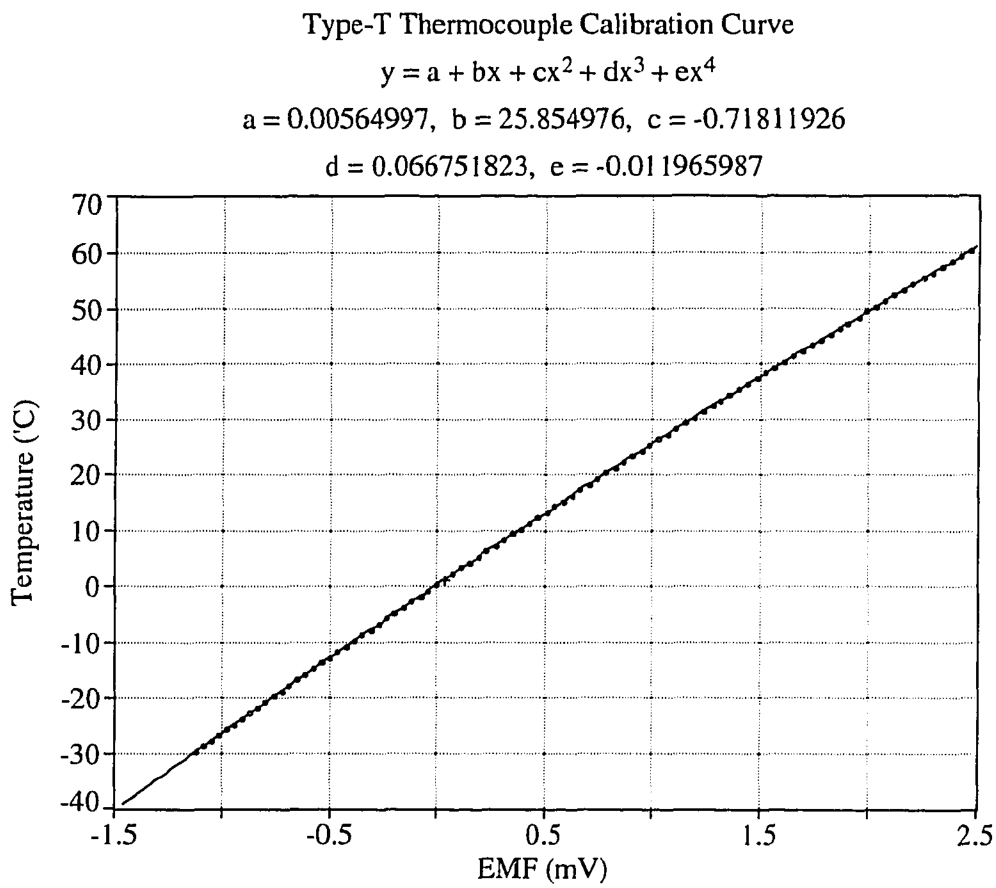


Figure 4.2: 4th Order Polynomial Calibration Curve

The set of standard polynomials up to the 10th order were used for this curve fit. Table 4.1 shows the results generated by TableCurve. The equations are in order of rank. The fit standard error, maximum error and floating point demand are shown. The floating point demand indicates the amount of computation required by an Intel 80386. It is a relative value and does not explicitly indicate computation time or number of compute cycles. For polynomials, the floating point demand is proportional to the order.

A review of Table 4.1 shows that only the 1st and 2nd order polynomials have maximum errors in excess of the requirement of ±0.5 °C. The 4th order polynomial was chosen for use. This equation shows a significant improvement over the 3rd order polynomial and has a low floating point demand. Figure 4.2 shows the 4th order polynomial plotted with the calibration data. The coefficients of the polynomial are shown above the graph.

4.1.2 Thermocouple Response Time

The response time of an instrument sets a practical limitation on how often a measurement can be read from the instrument. The response time indicates how long an instrument takes to respond to a change in the measured variable. Measurements made at shorter intervals than the response time will provide erroneous information about the value of the measured variable.

Approximate response times for thermocouples purchased from Omega Engineering can be found in The Temperature Hanbook[13]. The response time for an exposed thermocouple junction made by welding two 0.001 inch thermocouple wires is approximately 0.003 seconds in stagnant air. The response time of a ungrounded thermocouple junction in a 0.125 inch diameter steel sheath is approximately 22.5 seconds.

The maximum sample rate that the thermocouples should be read using the data acquisition system can be found by inverting the response time. The exposed thermocouple used on the traverse should be read at sample rates less than or equal to 333 Hz. The sheathed thermocouples used in the duct should be read at sample rates less than or equal to 0.04 Hz.

ATD tests will be done at steady state supply air temperatures so the low frequency response of the sheathed thermocouples should pose no problems. The possibility of an incorrect temperature reading from these thermocouples is reduced by the temperature averaging so a single measurement can be considered reliable. These thermocouples will be read at intervals during an ATD test to confirm a steady state condition.

The ATD discharge air temperature may fluctuate rapidly due to the turbulent mixing of discharge and room air. The quick response time of the exposed junction thermocouple is well suited to taking a large sample of data so that the average temperature can be calculated by the data acquisition program.

4.2 Air Velocity Measurements

Air velocity will be measured near the ATD to determine discharge air velocity and at a number of locations to determine the isovelocity envelope. ASHRAE Standard 70[1], "Methods of Testing for Rating the Performance of Air Outlets and Inlets", requires that the range of measurement for the determination of the isovelocity envelope is from 35 fpm to 600 fpm. The requirement for the range of measurement of discharge velocity is from 40 fpm to 2,400 fpm. If a single anemometer is used for both measurements then it must have a range of measurement of 35 fpm to 2,400 fpm.

Thermal anemometers were chosen for measurements of air velocity and air turbulence intensity in the throw room facility. Most air velocity measurements made in the facility are of transient velocities. No other method of anemometry is better suited for this type of measurement than thermal anemometry, with the possible exception of laser Doppler anemometry. Laser Doppler anemometry uses very expensive and complex instrumentation, which would provide no additional benefit in this application.

A single-element hot-film anemometer probe and a three-element hot-film anemometer probe were selected for this purpose. The single-element hot-film anemometer probe is commonly used by industry and has been accepted as standard instrumentation. This anemometer is used to measure the magnitude of the air velocity. The three-element hot-film anemometer probe is used to measure the magnitude and direction of the air velocity. This anemometer will be used in graduate study to further the understanding of HVAC air diffusion.

The probes are used with constant temperature anemometer circuits. These circuits are relatively inexpensive and readily available on the commercial market. They also provide a high frequency response for rapid measurements.

A three dimensional hot-film probe, TSI Inc. model number 1299-20-18, and a standard single element probe hot-film probe, TSI Inc. model number 1210-20, were selected for this facility. Four constant temperature anemometer circuits, TSI Inc. model number 1750, were selected for the probes. Hot-film probes were chosen instead of hot-wire probes because of their durability. According to TSI, these anemometers should have a maximum frequency response of 5k Hz to 10k Hz, which is more than adequate for low turbulence, low velocity, air velocity measurements.

4.2.1 Constant Temperature Thermal Anemometer Operation

The sensing part of the thermal anemometer, called the probe, is a very small solid conductor. It is commonly either a metal wire or film. The probe is kept at a temperature higher than ambient (about 300 °F) by a current flowing through it. When the probe is placed in a fluid with a mean velocity and lower temperature than its temperature, its electrical resistance will change with the velocity. This change in resistance is sensed using a Wheatstone bridge as shown in Figure 4.2.

The circuit shown in Figure 4.2 is a constant temperature thermal anemometry circuit. It operates by keeping the probe temperature at a constant level. Changes in the fluid velocity over the probe cause the probe temperature and thus the probe resistance to change. This results in a voltage unbalance in the Wheatstone bridge. The amplifier in the circuit senses this unbalance and increases or decreases its output voltage. The voltage change causes more or less current to flow through the probe which results in a

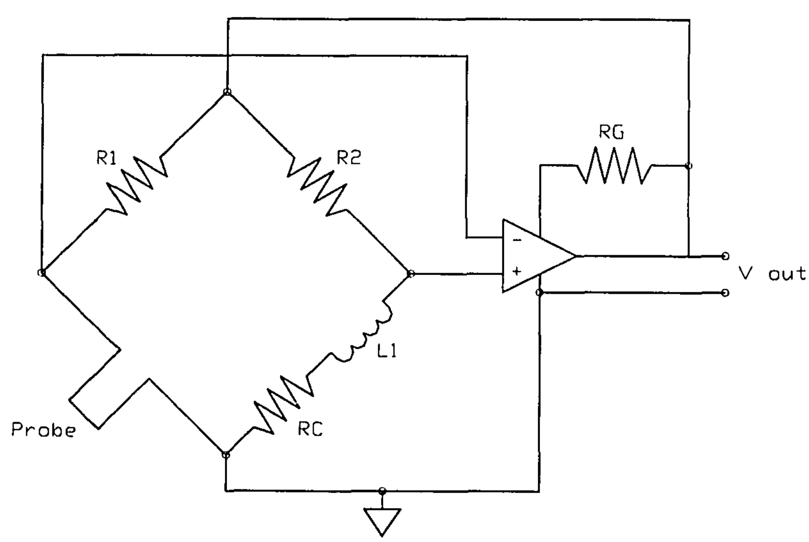


Figure 4.3: Constant Temperature Anemometer Circuit

temperature increase or decrease, thus restoring balance to the Wheatstone bridge. The voltage required to keep the probe at a temperature given some mean fluid velocity is the output. A calibration curve can be generated which relates this output voltage to the mean fluid velocity.

The inductor L1 in the Wheatstone bridge counteracts the dynamic effects of the probe cable. When a high frequency signal flows through a cable it will act as an inductor. This effect will cause an unbalance in the bridge, which is not due to the measured variable. L1 will react to the dynamic signal just as the probe cable and maintain bridge balance.

The resistor RG in the circuit sets the offset voltage for the amplifier. The Wheatstone bridge will be balanced when the probe is in a fluid with a zero mean velocity. In this case the amplifier will output the offset voltage to maintain the probe temperature.

4.2.2 Hot Film Anemometer Calibration

The hot-film anemometer can be calibrated just as any instrument. It is exposed to a range of known fluid velocities under conditions that are the same as those in which it will be used. These conditions are usually steady state and include all circuitry used with the anemometer. A large number of measurements (about 10^3) are recorded at discrete positions and averaged to reduce statistical uncertainty (which is proportional to the square root of the sample size). This data is used to generate a calibration curve that can be programmed into a computer. A second order curve should be accurate enough to produce acceptable results.

There are many methods that can be used to produce a known mean air velocity. These are usually categorized as either static, where the probe is held motionless and the air moves, or dynamic, where the probe is passed through still air. In the case of a dynamic calibration, the fluid velocity can be determined from the motion of the probe. In the case of a static calibration, the air velocity must be measured. A Pitot tube is usually used for dynamic calibration for velocity ranges that are not very low.

4.2.3 Turbulence Intensity Calculations

The turbulence intensity associated with a given measurement can be used to determine the validity of the measured value. When a discrete set of data is used the turbulence intensity indicates the range of the data set. If the turbulence intensity is large then the calculated mean value is weak.

The turbulence intensity can be calculated directly from the measured data set. The equation for turbulence intensity given a discrete data set of N values is:

$$I_T = \frac{\sqrt{\overline{u^2}}}{\overline{U}} \qquad \text{Equ. 4.1}$$

Where $\overline{U}$ is the mean velocity and $\overline{u^2}$ is the normal Reynolds stress and is calculated using:

$$\overline{u^2} = \frac{1}{N}\sum_{n=1}^{N}(\overline{U} - U_n)^2 \qquad \text{Equ. 4.2}$$

These calculations assume that the turbulence is isotropic and that the probe is oriented perpendicular to the air velocity[15].

4.3 Air Pressure Measurements

ASHRAE Standard 41.2[5], "Standard Methods for Laboratory Air Flow Measurement" defines the methods used for determination of air flow rate in a duct. This method requires the use of some type of differential pressure transducer (as discussed in Section 4.4). It requires that the accuracy of any pressure measurement is within 1% of the highest pressure reading during a test. This can be conservatively interpreted as 1% of full scale reading for the pressure transducer used. This requirement applies to the whole pressure measurement system.

Electronic pressure transmitters are used for all pressure measurements in this facility. This makes the data acquisition process simpler than if mechanical gauges are used. The output of the transmitters is connected to the data acquisition card. The data acquisition program reads, calibrates, and stores the data directly.

Two solid state, variable capacitance, differential pressure transmitters were purchased from Dwyer Instruments. They have measurement ranges of 0 to 5 in. w.g. and 0 in. w.g. to 10 in. w.g.. These transmitters are stable with time and temperature changes. They are also more sensitive than other electronic pressure transmitters. Both transmitters have a ±0.5% of full scale accuracy certified by the factory. This results in a ±0.025 in. w.g. accuracy for the 5 in. w.g. transmitter and a ±0.05 in. w.g. accuracy for the 10 in. w.g. transmitter.

The 5 in. w.g. pressure transmitter is used for differential pressure measurements in the nozzle chamber. The range of pressure drop across the nozzles is from 0 in. w.g. to approximately 3 in. w.g.. Refer to Section 4.4 for more information about the nozzle chamber.

The 10 in. w.g. pressure transmitter is used for differential pressure measurements across the ATD's to be tested. These devices may have any number of different pressure ranges. The value 10 in. w.g. was chosen as the foreseeable upper limit of these measurements. Pressure transmitters with smaller ranges may be used as needed to increase the accuracy of measurements.

The maximum response time of both pressure transmitters is rated by the factory as 250 msec. This is the greatest amount of time the transmitter requires to respond to a change in pressure. The corresponding response frequency is 4 Hz. This is the maximum rate that data should be read from the transmitter. The data acquisition system will be set up to read data from the pressure transmitters below this rate.

4.3.1 Pressure Transmitter Calibration and Use

The calibration curves of the transmitters are linear with an output of 4 mA to 20 mA. A 4 mA output corresponds to 0 in. w.g. and a 20 mA output corresponds to full scale. For the 5 in. w.g. transmitter this results in the calibration equation:

$$P = \frac{5}{16}(i - 4) \qquad \text{Equ 4.3}$$

where P is the pressure in in. w.g. and i is the current in mA. For the 10 in. w.g. transmitter the calibration equation is:

$$P = \frac{5}{8}(i - 4) \qquad \text{Equ 4.4}$$

where P is the pressure in in. w.g. and i is the current in mA.

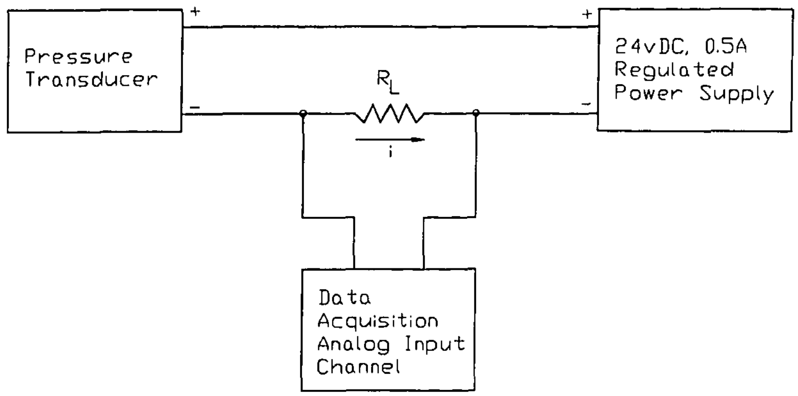


Figure 4.4: Pressure Transducer Circuit

The pressure transmitters are connected to the data acquisition system using the circuit shown in Figure 4.10. This circuit converts the mA output of the transmitters into a readable voltage. The data acquisition system reads the voltage dropped across the resistor, R_L. Since the input impedance of the data acquisition system is near infinite (greater than 10^{10} ohms), the combined parallel resistance of R_L and the data acquisition card input is approximately R_L.

Using Ohm's law, the calibration curve for the 5 in. w.g. transmitter becomes:

$$P = \frac{5}{16}\left(\frac{v}{R_L} - 4\right) \qquad \text{Equ 4.5}$$

Where v is the voltage reading and R_L is the value of the load resistance. The calibration equation for the 10 in. w.g. transmitter is:

$$P = \frac{5}{8}\left(\frac{v}{R_L} - 4\right) \qquad \text{Equ 4.6}$$

These equations (in their polynomial form) are used in the data acquisition program to calculate differential pressure from a voltage reading.

R_L was selected to meet the load requirements of the pressure transmitter and to provide a convenient voltage range. The maximum possible resistance (based on the manufacturers guidelines) for a supplied voltage of 24 V is 500 Ohms. A 220 ohm, 1/8 watt resistor is used for R_L. This results in a voltage drop of 0.88 V at 4 mA and 4.4 V at 20 mA. The data acquisition system is set to read voltages in the range of 0 V to 5 V.

4.3.1 Barometric Pressure

A National Weather Service type mercurial barometer is used to measure atmospheric pressure. Atmospheric pressure values are used in the calculations for in-duct air flow rate and air velocity (see Appendix 6). The barometer purchased is a Model Number 453 barometer manufactured by Princo Instruments, Inc. It is accurate to 0.01 inches of Hg after temperature and gravity corrections. It was calibrated at the factory to NIST standards.

4.4 In-Duct Volumetric Air Flow Measurements

The air-flow measurement system for this facility was designed in accordance with ASHRAE Standard 41.2[5] "Standard Methods for Air-Flow Measurement". This standard suggests the use of either flow nozzles or a Pitot tube traverse for the measurement of air-flow rates. The flow nozzle was chosen because of its simple design and implementation requirements and because they can be used without calibration.

The air flow measurement system is composed of a bank of flow nozzles and a chamber to house them, as well as the appropriate required measurement instrumentation. The nozzle bank is a set of flow nozzles mounted on a common partition in the nozzle housing. Nozzles in the bank are used individually and simultaneously to measure flow rates in different ranges. The system can measure flow rates of up to 2,443 CFM with a measurable pressure differential across the nozzle bank up to 3 in. w.g.. This system satisfies requirements set forth by ASHRAE Standard 41.2[5] for the laboratory measurement of air flow rate in ducted systems.

4.4.1 Nozzle Bank

Two constraints were considered in the design of the nozzle bank. These were the size and measurement range of the nozzle bank. The nozzle bank for the throw room was required to measure flow rates up to about 2,000 CFM. The minimum size was limited by the number and size of the nozzles used to achieve the measurement range. These constraints where satisfied by the design shown in Appendix 14.

The type of nozzles uses were explicitly defined in ASHRAE Standard 41.2[5]. An iterative process was used to select a set of nozzles that minimized the size of the nozzle bank and measured flow rates up to 2,443 CFM. ASHRAE Standard 41.2[5] states that the maximum throat velocity for the nozzle type specified shall not exceed 7,000 fpm and shall not go below 3,000 fpm. Given the throat diameter of a nozzle and the specified velocity range, the corresponding flow rate range for each nozzle was calculated. The

Nozzles by Throat Diameter				Flow Rates (CFM)	
1.6 in.	2.0 in.	3.0 in.	4.0 in.	min	max
1	0	0	0	41.9	97.7
0	1	0	0	65.5	152.7
0	0	1	0	147.3	343.6
0	0	0	1	261.8	610.9
0	0	0	2	523.6	1,221.7
0	0	0	3	785.4	1,832.6
0	0	0	4	1,047.2	2,443.5

Table 4.2: Nozzles Used For Flow Rates From 42 to 2,443 CFM

selected nozzles were mounted to a nozzle housing partition in the arrangement shown in Appendix 14.

The nozzle bank is used by plugging and unplugging nozzles according to the range of the flow rate to be measured. Rubber plugs are used for this purpose. Multiple nozzles may be used to determine flow rates at rates between individual nozzle measurement ranges. Table 2.1 shows the nozzles that should be used for flow rate ranges up to 2,443 CFM. Appendix 5 describes the equations and data required to calculate the air flow rate based on the measurements.

4.4.2 Nozzle Housing

The nozzle housing was designed around the nozzle bank and in accordance with ASHRAE Standard 41.2[5]. The housing cross section was constrained by the dimensions of the nozzle bank which requires a partition wall that is 34 inches square. The remaining dimensions are constrained by the ASHRAE standard. The nozzle housing was designed with two doors that allow access for maintenance and measurement adjustments inside the two nozzle housing chambers. The resulting design is shown in Appendix 14.

The nozzle housing consists of a receiving chamber and a discharge chamber, which are upstream and downstream of the nozzle bank partition respectively. Both chambers contain screens, as required by the standard, to provide flow settling. The receiving chamber contains two screens in tandem which produce a more uniform velocity profile to exist upstream of the nozzles. The screen in the discharge chamber absorbs the kinetic energy of the nozzle jets and permit normal flow expansion as in an unconfined space[9]. All three screens are constructed of perforated 20 gauge sheet steel with a 58% open area, as suggested by ASHRAE Standard 41.2[5].

The nozzle housing was constructed of 2 inch thick fiberglass filled panels. The panel face on the interior of the housing is made of 22 gauge perforated sheet steel and the exterior face is made of solid 18 gauge sheet steel. Insulated panels were used to reduce the amount of noise transmitted through the nozzle housing and into the discharge duct and to prevent noise from entering the test system through the nozzle housing walls.

The pressure differential across the nozzle bank partition is measured using a differential pressure transmitter which is connected to two piezometer rings. One piezometer ring is connected to four static pressure taps upstream of the nozzle bank partition and the other is connected to four static pressure taps downstream of the partition. The static pressure taps are mounted on each of the four nozzle housing walls 1.5 inches (according to ASHRAE standard) upstream and downstream of the nozzle bank partition. The piezometer rings are constructed of 0.5 inch diameter copper tubing and are connected to the static pressure taps with brass compression tube fittings. The static pressure taps were constructed as per standard.

4.5 Data Acquisition Hardware

A PC based data acquisition system will be used to collect data from instrumentation in the throw room. This decision was influenced by a number of factors. PC based data acquisition hardware is inexpensive and versatile. Measurements made in the throw room do not require incredibly high sample rates or special signal conditioning which would call for more specialized hardware. PC based systems can be controlled by programs written in DOS or Windows using a number popular of computer languages.

The PC used in this system is an IBM clone based on the Intel 486 microprocessor with math coprocessor running at 33 MHz. It has both 3.5 inch and 5.25 inch floppy drives, as well as a 250 MB tape-drive backup and 337 MB hard-drive. It also has 4 MB of internal RAM and a VGA video system. The cabinet is a full size unit with 7 open slots as shipped from the factory.

The data acquisition hardware used in this system is the WorkMate manufactured by STI. It comes in the form of a full size IBM AT card with an 8 bit bus interface and plugs directly into the computer motherboard. The WorkMate card has 8 differential (16 single-ended) analog-to-digital channels, 8 digital input/output channels, and 2 analog output channels. The analog input channels have a single channel sample rate of 200k Hz with a 12-bit resolution and software selectable gain and input ranges. Two WorkMate cards will be used to make all of the measurements in the throw room.

4.5.1 Measurement Uncertainty Due to Digital Sampling

There will be an uncertainty in measurements made using the WorkMate card due to the analog to digital conversion. This uncertainty will be present in any modern digital data acquisition system. The uncertainty can be determined from the sample resolution and voltage range used.

The WorkMate samples data with a 12 bit resolution. This means that the WorkMate card recognizes only 2^{12} or 4096 contiguous voltage levels. The uncertainty can be determined by dividing the voltage or measured variable range by 4096. For example, pressure readings from the 0 in. w.g. to 10 in. w.g. differential pressure transmitter will have an uncertainty of

$$\frac{10 \text{ in. w.g.}}{4096} = \pm 0.00244 \text{ in. w.g.}$$

CHAPTER 5

THROW ROOM TRAVERSING MECHANISM

The traversing mechanism is an automated mechanism capable of carrying instrumentation to any location in the throw room. It will carry thermal anemometers and thermocouples so that air flow measurements can be made. A PC based data acquisition and control system will direct traverse motion and take data from the instrumentation.

The primary consideration in the design of the traversing mechanism geometry was the definition of the workspace. The workspace is the set of all points that the traversing mechanism can reach. Since the traversing mechanism is three dimensional, the workspace is a volume.

The air discharge space of an HVAC air terminating device (ATD) defines the traverse workspace. This is the volume that the traverse must be able to position a measurement probe within, during an ATD test. The maximum discharge air space for any given test in the throw room is the interior volume of the throw room.

Since the throw room is rectangular, a Cartesian type mechanism was the most logical choice for the traversing geometry. The Cartesian traverse also lends itself well to simple drive mechanisms, as all motion is linear and orthogonal. This traverse geometry was chosen for the throw room traversing mechanism. Figure 5.1 shows a Cartesian traversing mechanism with four degrees of freedom.

The interior space of the throw room is not constant due to the variable height ceiling. The largest possible workspace for any given ATD test is governed by the height of the ceiling. The ceiling will be at a constant height for the duration of any given ATD test, but may change from test to test. Thus, the traverse workspace can be considered constant only during a single ATD test.

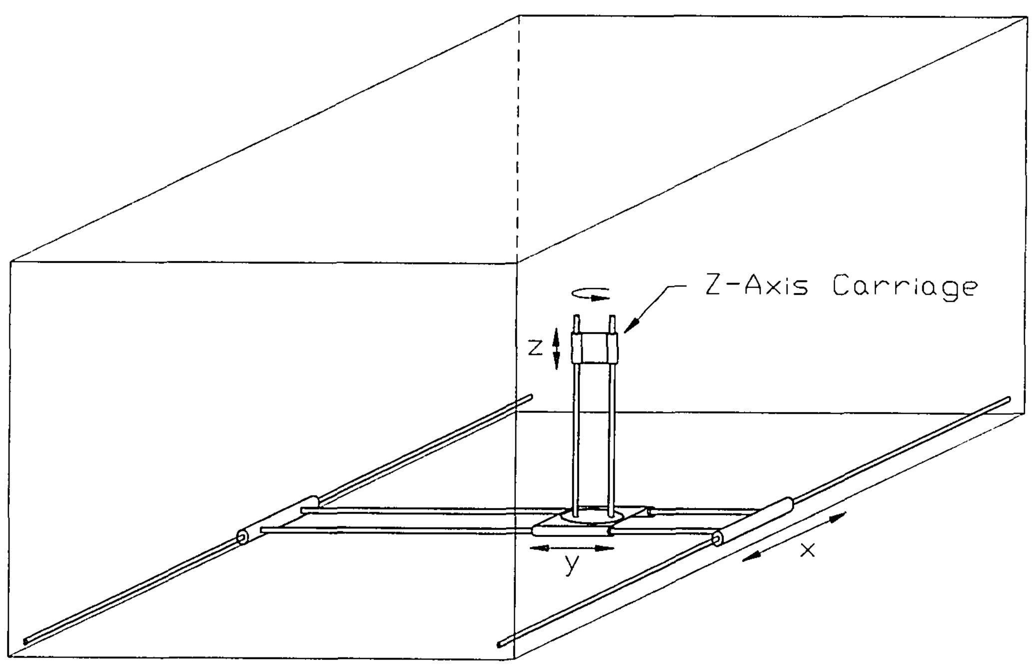


Figure 5.1: Cartesian-type Traversing Mechanism

If the vertical range of motion of the Cartesian traverse is to be an automated variable, as well as the vertical position, then a much more sophisticated drive mechanism would be required. Since the ceiling height does not change during tests, the vertical range of motion does not have to be an automated variable.

Other traverse designs were considered for this project. The two primary alternatives to the one chosen are a different geometry mechanism and a free running robot. An alternate geometry, such as a cylindrical traverse would require more complex drive mechanisms and would not provide access to the entire throw room geometry without causing great design dilemmas. A free running robot, which would move along the floor instead of anchor to it, is a much more complex system than the Cartesian traverse and the number of difficulties involved in this design far outweigh those for the Cartesian traverse.

The traversing mechanism was designed to be as simple and robust as possible. The goal of this project was to produce a usable automated throw room. A simple traversing mechanism design increases the chances that the mechanism could be properly constructed, used, and repaired.

5.1 Traversing Mechanism Design

The traversing mechanism has four degrees of freedom. Three degrees of freedom are linear (or prismatic) and the forth is rotational (or revolute). Each of the three linear degrees of freedom are orthogonal and aligned with the throw room. Along the 30 foot length of throw room is the x-axis. Along the 20 foot width of the throw room is the y-axis. The z-axis runs vertically from the floor to the ceiling. The rotational degree of freedom allows the z-axis to rotate normal to the x-y plane (the throw room floor). Figures 5.2 and 5.3 show the spans of the y and z axes with the x-axis along the throw room wall.

Each axis has a carriage. The carriage is the part of each axis mechanism that moves along the axis length. The x-axis carriage supports the y-axis and the y-axis carriage supports the z-axis. The z-axis carriage carries the instrumentation. All of the carriages in the traversing mechanism ride on linear bearings that constrain their motion to one degree of freedom.

The travel length of the linear bearings required for this project were the primary constraint in their selection. Many linear bearings are available. They are usually sold as a unit with a fixed length and are very expensive. The linear bearing assemblies chosen for this project consist of an open style

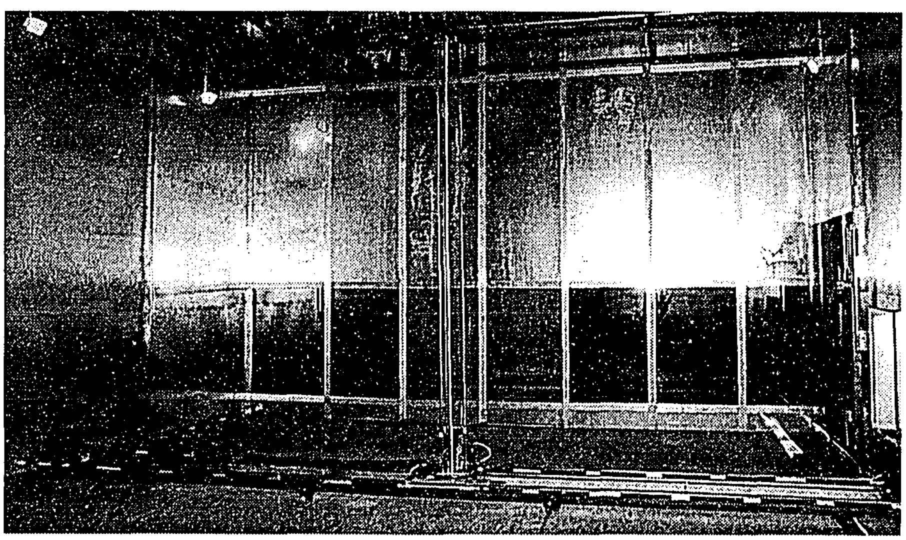


Figure 5.2: Traversing Mechanism

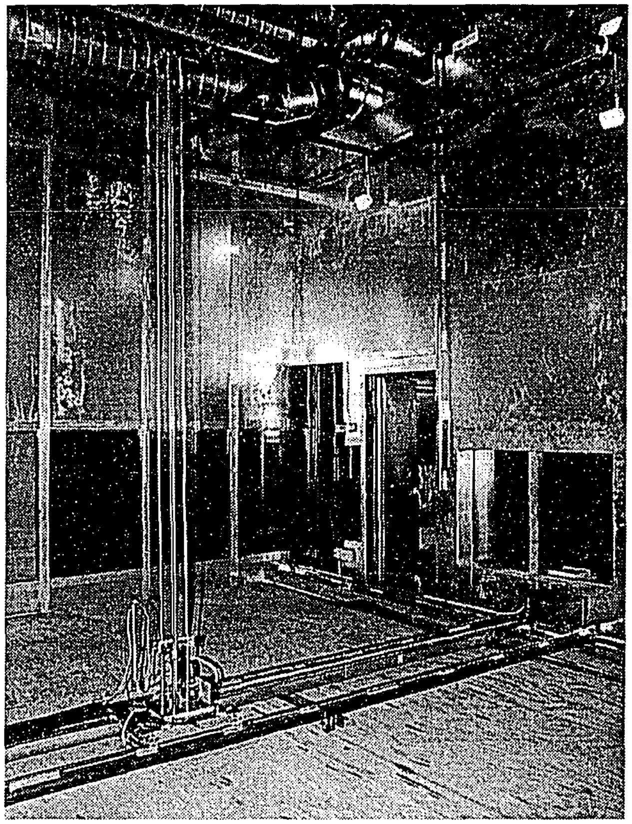


Figure 5.3: Traversing Mechanism

linear rotary ball bearing and a round steel shaft (see Appendix 16). The shaft is fixed to a surface and the bearing rides its length. The open style bearing does not completely encircle the shaft so that support brackets can be mounted to it. This type of bearing assembly is relatively inexpensive and can be used for any travel length by mounting bearing shafts end to end.

Four 1 inch diameter linear bearings are used to guide the x-axis carriage shown in Figure 5.4. Two are mounted at each end of the carriage. Each pair of linear bearings rides on one 1 inch diameter linear bearing shaft. Each linear bearing shaft is mounted to a 30 foot long, 4 inch by 4 inch angle,

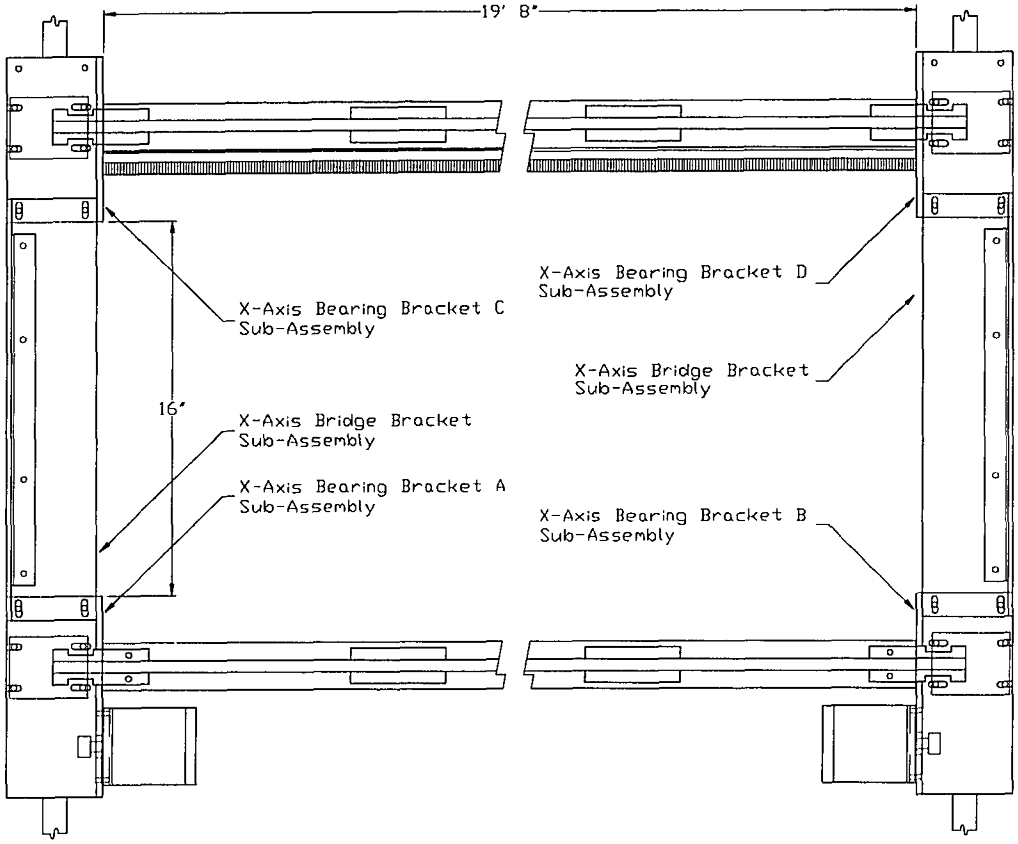


Figure 5.4: X-Axis Carriage

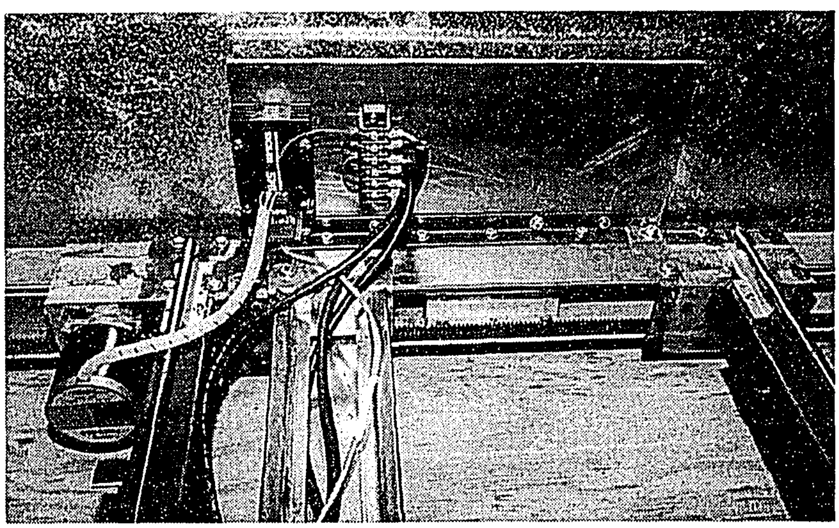


Figure 5.5: West End of the X-Axis Carriage

which is referred to hereafter as a rail. The x-axis rails are mounted directly to the steel structure constructed inside the throw room. One rail is on the West wall the other on the East wall. Figure 5.5 shows the West end of the x-axis carriage.

The x-axis carriage spans 20 feet from one linear bearing to the other. Since all of the other axes are supported by the x-axis carriage, deflection was a special consideration. Two 2 inch square structural tubes are used to span this length and support the other mechanisms as shown in Figure 5.6. This proved to be somewhat adequate with a measured maximum deflection of about 1/4 of an inch. This deflection was further reduced by mounting four

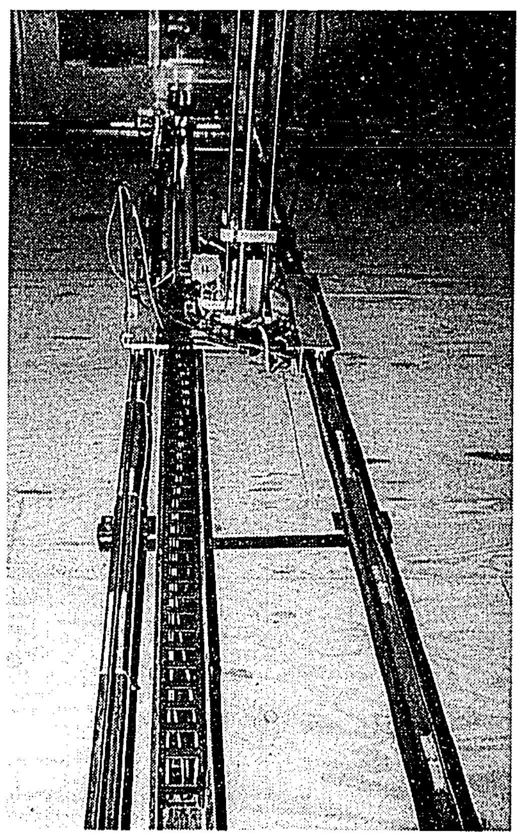


Figure 5.6: X-Axis Carriage with Cable Carrier

casters to the x-axis carriage which ride on the throw room floor and support the weight of the traverse.

Four 1/2 inch diameter linear bearings are used to guide the y-axis carriage. Two are mounted on each side of the carriage. Each pair of linear bearings rides on one 1/2 inch diameter linear bearing shaft. The linear bearing shafts are mounted to the x-axis carriage 23 inches apart. The y-axis carriage design is shown in Figure 5.7.

Three 1/2 inch diameter linear bearings are used to guide the z-axis carriage. Each linear bearing rides on a separate 1/2 inch diameter shaft. The shafts run vertically and are arranged in a right triangle. They are held in position by top and base plates (see Figures 5.8 and 5.9). At the centroid of the right triangle is a shaft that is slightly longer than the linear bearing shafts.

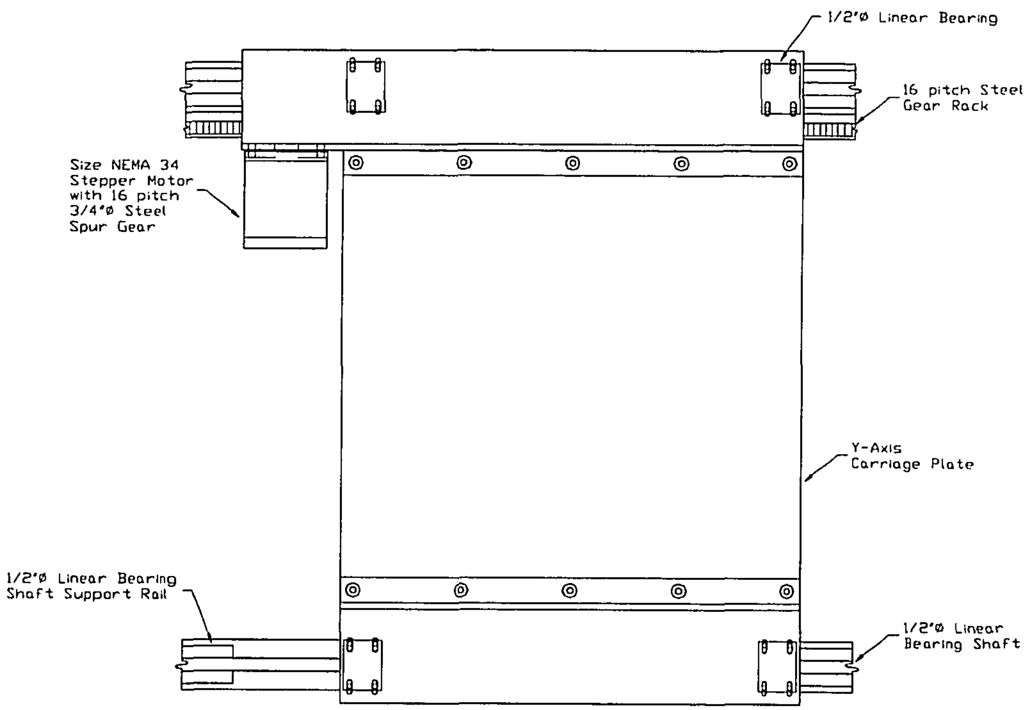


Figure 5.7: Y-Axis Carriage

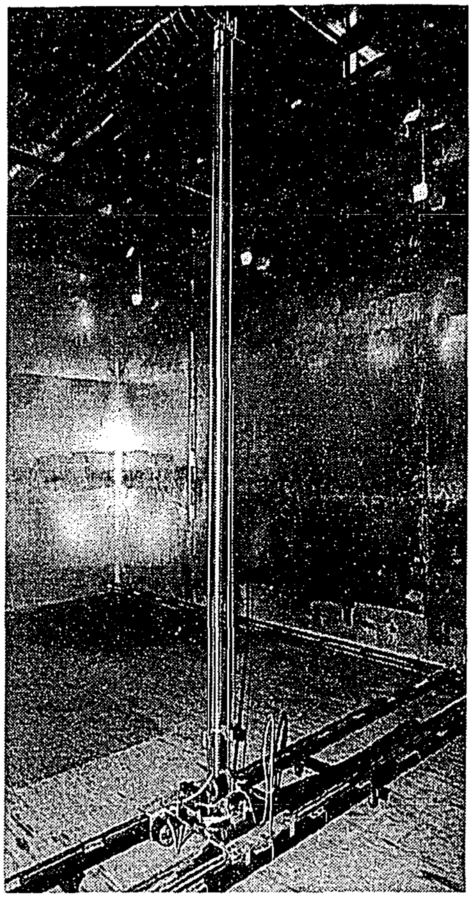


Figure 5.8: Z-Axis

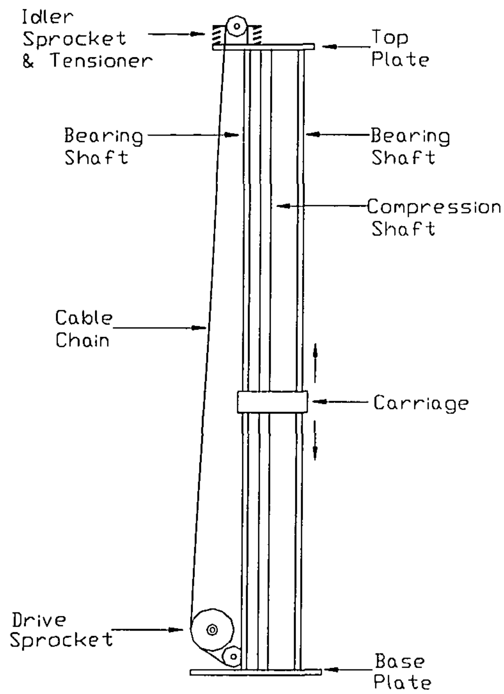


Figure 5.9: Z-Axis

When the z-axis is assembled the linear bearing shafts are put in tension. This was done to keep them straight and parallel.

A 12 inch diameter thrust bearing and a pillow block radial bearing are used in the y-axis carriage to allow z-axis rotation. The thrust bearing carries the vertical weight of the z-axis on the y-axis carriage. An axle passes from the z-axis to below the y-axis carriage where it is driven by a motor. The axle is centered by the flange mounted pillow block radial bearing. This assembly is shown in Figure 5.10 and in Figure 5.11 from above.

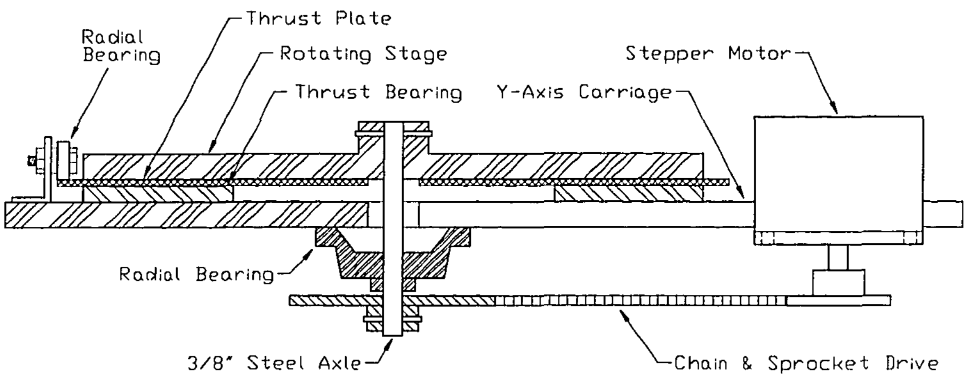


Figure 5.10: Z-Axis Rotating Stage

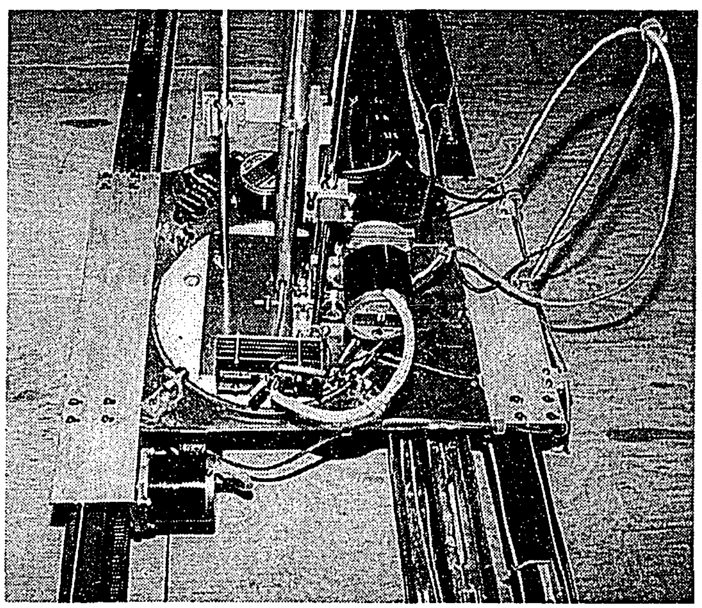


Figure 5.11: Y-Axis Carriage with Z-Axis Rotating Stage

Four radial bearings mounted to the y-axis carriage plate hold down the thrust bearing as shown in Figure 5.11. These allow the z-axis to rotate, but prevent it from swaying due to its own inertial load when the traverse accelerates. The thrust bearing is not designed to hold a load in tension.

Many of the components of the traversing mechanism were built in the engineering shop. As a result, practical constraints dominated the design of the traversing mechanism. Parts were designed to be built from readily available stock and manufactured using available methods. Lighter materials were used to reduce the weight of the mechanism where possible. Appendix 16 shows the design details.

5.2 Traversing Mechanism Motivation

The traversing mechanism is driven by five NEMA size 34 stepper motors. Stepper motors were favored in the selection of motor types because of the ease with which they can be controlled. They can be used in an open control loop where positional accuracy is a priority if used within their torque capacity. Stepper motors can also hold their position when at rest which is especially important for the z-axis.

The primary drawbacks in the use of stepper motors is that they have lower torque and move slower than most other motor types. Motor speed is not an issue in this project. The torque required to move the traverse should not be very great. The linear bearings reduce friction substantially and inertial loads are a function of the acceleration, which is not high. So the negative characteristics of stepper motors were not a problem for this project.

The stepper motors used in this project were chosen because of their high torque ratings. Four of the stepper motors have a holding torque of 306 oz·in. This is very large for a stepper motor. The fifth stepper motor, used to rotate the z-axis, is smaller but still powerful for its size. It has a holding torque of 174 oz·in.

All of the stepper motors have a 1.8 degree step size which can be cut in half if the motor drivers are set to half-step mode. This is a common step size for stepper motors. It provides a resolution of 200 steps/rotation in full-step mode and 400 steps/rotation in half step mode. This resolution is more than accurate for the positioning requirements of the traversing mechanism.

5.2.1 Drive Mechanisms

Two stepper motors are used to motivate the x-axis because of the great load. The entire moving mass of the traversing mechanism is carried by the x-axis carriage. The motors drive each end of the x-axis carriage. The x-axis carriage is 20 feet wide and is mounted to a linear bearing at each end. If the carriage was driven at one end only, the linear bearings would experience a twisting moment. The open type linear bearings should not be exposed to this type of load. They will deflect and cause binding.

Both the x-axis and y-axis carriages are driven with a 16 pitch rack and pinion mechanism. The x-axis has two 30 foot racks mounted to each linear bearing shaft rail. The y-axis has one 20 foot rack mounted to the inside of the x-axis carriage. Pinions, with a 3/4 inch pitch diameter, are mounted to the stepper motor output shafts with set screws to prevent slipping. The set screws thread through the pinions and into the shaft. The shafts were drilled and tapped to half the shaft diameter. This will prevent the set screws from vibrating loose.

A schematic of a rack and pinion drive is shown in Figure 5.12. It is kinematically identical to a wheel on a surface with no slipping. The

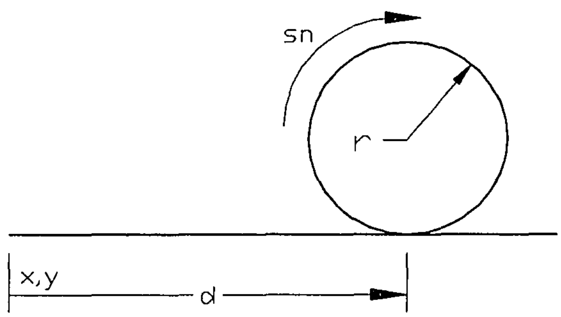


Figure 5.12: Rack and Pinion Schematic

kinematic equation in terms of steps is:

$$d = \frac{\pi}{180} r \cdot s \cdot n \qquad \text{Equ 5.1}$$

where d is the distance traveled in inches, r is the pinion pitch radius in inches, s is the step size in degrees/step, and n is the number of steps taken.

Substituting the values for r (0.375 inches) and s (1.8 degrees/step) into Equation 5.1 we can get a conversion factor for the distance traveled in inches per step. The factor is 0.01178 inches/step. This factor is also the smallest linear displacement that the x and y axes can achieve in full step mode. This factor will be used in the traverse control program to calculate the unit conversions for the x and y axes.

The z-axis carriage is driven with a cable chain and sprockets. Cable chain is composed of two steel cables with a polyurethane coating. The polyurethane coating forms links between the cables making a chain. Cable chain is noted for its light weight and silent, zero backlash operation. Further, it does not require lubrication. The cable chain selected for this project has a tensile strength of 100 lb.

The cable chain is driven at the bottom of the z-axis by a sprocket on a stepper motor. An idler sprocket is at the top of the z-axis. This sprocket

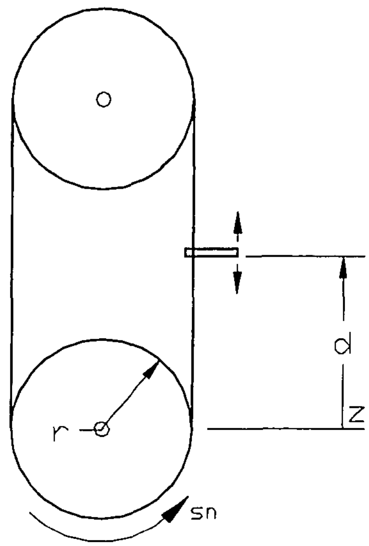


Figure 5.13: Chain and Sprocket Schematic 1

is mounted to the top plate with springs to put the cable chain in constant tension. The cable chain is looped around the two sprockets. The loose ends of the cable chain are fixed to the z-axis carriage.

The sprocket diameters were chosen based on a kinetic analysis of the z-axis carriage load. This load was assumed to be about 40 oz. Given the 306 oz·in rating of the motor a 3.82 inch pitch diameter sprocket could be used (with a safety factor of two). A 4 inch pitch diameter sprocket was chosen for the drive sprocket. Two 2 inch pitch diameter sprockets are used for idlers.

A schematic of the chain and sprocket drive applied to the z-axis is shown in Figure 5.13. The kinematic equation in terms of steps is:

$$d = \frac{\pi}{180} r \cdot s \cdot n \qquad \text{Equ 5.2}$$

where d is the distance traveled in inches, r is the sprocket radius, s is the step size in degrees/step, and n is the number of steps taken.

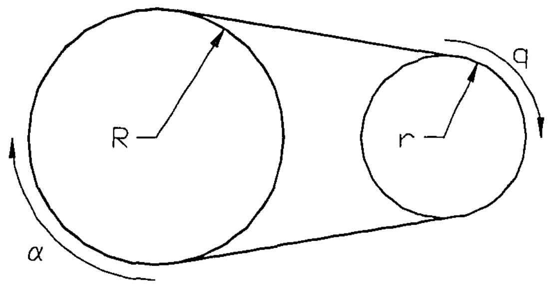


Figure 5.14: Chain and Sprocket Schematic 2

Substituting the values for r (2 inches) and s (1.8 degrees/step) into Equation 5.2 we can get a conversion factor for the distance traveled in inches per step. The factor is 0.06283 inches/step. This factor is also the smallest linear displacement that the z-axis can achieve in full step mode. This factor will be used in the traverse control program to calculate the unit conversion for the z-axis.

The z-axis rotates using cable chain and two sprockets. A schematic of the chain and sprocket drive is shown in Figure 5.14. The kinematic equation in terms of steps is:

$$\alpha = \frac{r}{R} s \cdot n \qquad \text{Equ 5.3}$$

where α is the angle of the z-axis rotation in degrees, R is the driven sprocket radius, r is the drive sprocket radius in inches, s is the step size in degrees/step, and n is the number of steps taken.

Substituting the values for R (2 inches), r (1 inch) and s (1.8 degrees/ step) into Equation 5.3 we can get a conversion factor for the angle traveled in degrees per step. The factor is 0.9 degrees/step. This factor is also the smallest linear displacement that the z-axis can rotate in full step mode. This factor will be used in the traverse control program to calculate the unit conversion for the z-axis rotation.

A cable and pulley drive and a power screw drive were both considered for the x and y axes. The cable-pulley drive is prone to slipping which would not be acceptable for positional accuracy. Cable chain could solve this problem, but would be impractical to use given the extreme horizontal lengths of the axes. The power screw would provide the positional accuracy, but is simply more difficult to use than a rack and pinion. The rack and pinion drive is inexpensive and easy to use.

The power screw drive was also considered for the z-axis. It was not used because of the modular design chosen for the z-axis linear bearing shafts. This would require the power screw to also be modular. It would be difficult to make the power screw axially modular. This would most likely result in thread discontinuities which would be unacceptable. A rack drive was not used for the z-axis because the cable chain drive was just a simpler implementation.

5.3 Traversing Mechanism Construction

The construction of the traversing mechanism was critical, in that each axis has to be carefully adjusted during construction. The x, y and z axes all use multiple linear bearing shafts which must be parallel. If the linear bearing shafts are not parallel then the axes will bind. Also, the x and y axes use a rack in their drive mechanisms which must also be parallel to the linear bearing shafts. These concerns were especially important due to the size of the traverse.

A transit was used in the mounting of the x-axis rails to insure that the linear bearing shafts were level and at the same height. A jig was built and mounted at each end to two linear bearings. Each linear bearing pair rides on a linear bearing shaft. The joint on one end was slotted to allow the jig to slide perpendicular to the shafts. A dial indicator was used to measure variations in the distance between the two linear bearing shafts. The rails were then shimmed out from the columns of the structure until the linear bearings were parallel along their entire length. Since the linear bearing shafts and the racks were mounted on the same surface, the racks were parallel to the shafts.

The x-axis carriage, which supports the y-axis linear bearing shafts, was designed so that it could be adjusted similar to the x-axis rails. All components mounted to the carriage were designed with slotted joints so that they could be adjusted. The rack for the y-axis was bolted to a length of angle welded directly to the x-axis carriage.

The y-axis linear bearing shafts and rack were made parallel by shimming their mounting to the x-axis carriage. This was tested by running the y-axis carriage along the length of the shafts. This was done repeatedly until the carriage moved freely along the shafts.

The z-axis did not pose the same alignment problems as the x and y axes. This is due to the design (discussed in last Section) which forces the linear bearings to be parallel. The only adjustments made to the z-axis were at the joints from one linear bearing shaft to another. This adjustment will become unnecessary when solid continuous shafts are used for each length required.

5.4 Traversing Mechanism Control Circuitry

Stepper motor control for the traversing mechanism is handled by a 4-axis stepper motor controller card manufactured by Oregon Micro Systems (OMS) (model PC34). It has an on-board Motorola 68000 microprocessor that handles all motor control functions. The card can control four axes and two simultaneously. It is completely programmable and has built in velocity and acceleration curves. It also has one auxiliary output line, two limit switch inputs and one home switch input per axis.

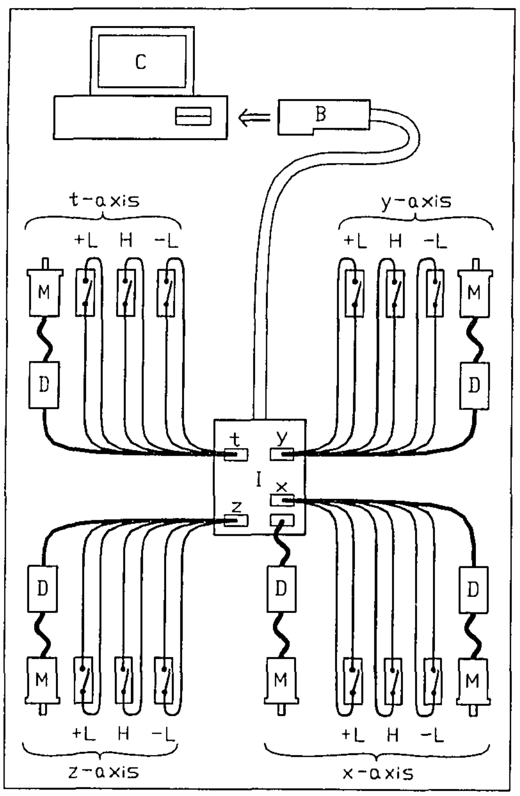
The OMS card was part of a package purchased for this project from Cyber Research Inc. The package also included four stepper motors, four stepper motor drivers, and a 28 v, 15 A power supply. Another stepper motor and driver were also purchased for z-axis rotation.

Each of the four axes of the OMS card is used to control a different traversing mechanism axis. The axes of the OMS card are labeled x, y, z, and t. The x, y, and z axes correspond directly to those of the traverse. The t axis is used to control the z-axis rotation.

The two stepper motors used to motivate the x-axis carriage are both controlled by the same OMS card axis. To move the x-axis carriage forward, the motor on the East side has to turn clock-wise while the motor on the West side must turn counter clock-wise. They have to turn in opposite directions due to their relative orientation. The motors are mounted axially aligned but facing opposite directions. This is accomplished by wiring the phase coils of the West side motor opposite the other. This arrangement also insures that the motors will always be synchronized.

Each motor used in the traversing mechanism has a driver. The driver interprets the logic signal from the OMS card and charges the coils of the stepper motor in response. The drivers have the capability of running full-step or half-step modes. The auxiliary output from each of the OMS card axes are used to control this.

The OMS card output and input signals are TTL standard. The stepper motor drivers are not. A circuit was designed to interface the two. The circuit schematics are shown in Appendix 17. This circuit replaces the terminal block originally supplied with the OMS card. Five 25-pin sub-D connectors connect the circuit to each stepper motor driver. The limit and home switches



Legend:

B = Stepper Motor Controller Card

C = 486-33 PC Computer

D = Stepper Motor Driver

H = Axis Home Switch

I = Interface Circuit

+L = Positive Axis Limit Switch

-L = Negative Axis Limit Switch

M = Stepper Motor

Figure 5.15: Traverse Control Circuit

are also wired to these connectors. The full circuit layout is shown in Figure 5.15 and all parts are listed in Appendix 15.

The limit and home switches used in the traverse are low power micro-switches with roller end levers. The limit switches are monitored by the OMS card to detect traverse position near each axes limit of travel. The home switches are used to position the traverse at a known location in the room. The switches are mounted to the traversing mechanism.

5.4.1 Cable Carriers

The stepper motors, stepper motor drivers and limit switches are carried on the traversing mechanism. This minimizes the amount of cable running to the traverse. The cable that must connect moving and stationary components of the traverse circuitry are housed in cable carriers.

Two cable carriers are used in the traverse. One cable carrier runs along the x-axis. It is mounted at one end to the throw room floor and at the other to the traverse x-axis carriage. This cable carrier can be seen in the background of Figure 5.3. The other cable carrier is mounted at one end to the x-axis carriage and at the other to the y-axis carriage. This cable carrier can be seen in Figure 5.6.

CHAPTER 6

THROW ROOM CONTROL PROGRAM OVERVIEW

The throw room data acquisition and control (DAC) program automates air diffusion tests in the throw room. It directs the traversing mechanism to locations in the throw room where measurements are to be done. Then, it collects sets of air velocity and temperature data and calculates their statistics. This is done repeatedly for each test. The program archives all data collected and the position of the traverse at each measurement. It performs these tasks interactively with the throw room operator. This program was design and implemented for the VAST Lab automated throw room.

The functional requirements of the DAC program are shown in Table 6.1. These requirements outline all the program is required to do to automate the throw room facility. The functional requirements are addressed in Section 6.2 in the discussion about program architecture. In addition to the functional requirements, the DAC program was designed with the practical requirements

DAC Program Functional Requirements	
1	It must control the traversing mechanism using the OMS stepper motor controler card and TSR driver.
1a	It must be able to instantly stop the motion of the traversing mechanism to prevent damage.
1b	It must be able to calculate the traverse position in user specified units.
1c	It must display the status of the traversing mechanism home and limit switches.
1d	It must display the position of the traversing mechanism.
2	It must read and calibrate data from the throw room instrumentation using the STI data acquisition card.
2a	It must read and calibrate the data according to user specified parameters.
2b	It must display the calibrated data with units and standard deviation.
2c	It must record calibrated data and standard deviation for latter analysis.
3	It must perform and synchronize functions (1) and (2) at the command of the user.
3a	It must be able to receive operator commands directly from the computer console.
3b	It must be able to read commands from a file.

Table 6.1: DAC Program Functional Requirements

DAC Program Practical Requirements	
4	It must be relatively easy to maintain and modify.
4a	It must be well documented.
5	It must be relatively easy to use.

Table 6.2: DAC Program Practical Requirements

shown in Table 6.2. These requirements outline the characteristics required of the program to continue its role in the throw room.

Practical requirement four is included in any program project requirement list, but in this case it is particularly important. The DAC program is a prototype in a prototype facility. The extent of change this program will go through is unknown at this time. There is no doubt that it will meet changing needs in the future. Whomever modifies the program will probably be most concerned about effecting a quick change in the program. This need can only be fulfilled if the program architecture is clear and the code is well commented.

The ease with which any software package can be used is a complex and relative issue. The extent to which a software package is easy to use corresponds directly to the effort applied in user interface development by the software designer. This project is a prototype development which will be used by a few "computer literate" engineers. Given the nature of the users and the limited resources of the project, the target level of ease with which the DAC program could be used was set to that which could be easily achieved.

In order to satisfy requirements four and five, Microsoft Visual Basic was chosen as the program development package for this project. Visual Basic (VB) is a program development package that can be used to create programs for the Microsoft Windows environment. It allows the programmer to make executable programs using a language similar to BASIC in a seamless environment with tools that can be used to create a Windows graphical user interface. Because most engineers have used BASIC and Windows, Visual Basic was a natural choice for program development in this project.

6.1 DAC Program Architecture

The DAC program has three primary tasks outlined in the functional requirements above. It controls the traversing mechanism. It reads and calibrates data acquired from instrumentation. It coordinates these two tasks according to commands issued by a user. The procedures required to accomplish these tasks have very little in common. For example, the code required to receive user commands has little in common with the code required to collect data from a data acquisition card. Further, the three tasks are individually complex. As a result, the program naturally decomposes into three functional modules. The modularity inherent in these three tasks is the basis of the DAC program architecture.

The three functional modules each contain the procedures required to accomplish one of the three primary functions of the DAC program. The modules also contain the procedures to perform the other tasks shown in Table 6.1. Table 6.1 is organized to show the partitioning of the tasks among the three functional modules. The tasks are divided based on their dependence upon the three primary functions of the DAC program.

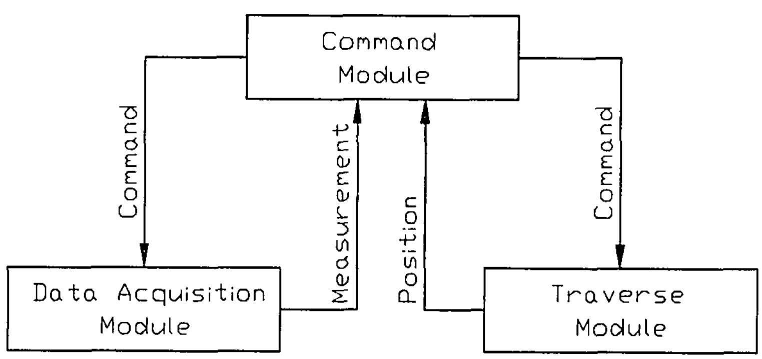


Figure 6.1: Functional Modules of The DAC Architecture

The interfaces between the modules which are required for the program to function as a whole are very well defined. The Command Module sends commands to the Traverse and Data Acquisition Modules. Those modules then execute the commands and send a response to the Command Module. The coordination of these tasks is accomplished by forcing the Command Module to wait, after each command is sent, for a response. Figure 6.1 shows the functional modules and their corresponding interfaces.

6.2 DAC Program Implementation

The DAC program was implemented in a way that takes advantage of the Windows environment and the program architecture discussed above. In Windows, more than one program can run at a time. Further, each program can communicate with the others. This allows separate programs to exchange data and operate as a unit. This powerful feature of Windows was utilized in the implementation of the DAC program. The DAC program was implemented as a set of three programs corresponding to each of the three modules.

Programs created to run in a multitasking environment, such as Windows, must be designed differently than those created for a non-multitasking environment, such as DOS. In a multitasking environment, programs interface with the system and the programmer takes an active role in deciding how this interface is used. This interface is often referred to as the Application Program Interface (API). The API provides standard functions to perform routine system tasks, inquire about system variables and communicate with other programs.

The Windows API takes the form of a number of libraries of functions and data that can be accessed by programs at run time. Because the libraries can be accessed at run time, they are said to have a dynamic link with the program and are called Dynamic Link Libraries (DLL's). Windows itself is a collection of these DLL's. By using DLL's, the programmer has access to the core of Windows. DLL's can be created for any purpose and can contain any number of functions and data.

VB has full access to the Windows API. This makes it completely extensible, as any capability that VB does not offer can be added to it by accessing a DLL. Many of the functions in the API are implemented in VB for ready use by programmers. One example that is used in the DAC program is a set of functions that allow separate programs to communicate. This communication is referred to as Dynamic Data Exchange.

Dynamic Data Exchange (DDE) allows programs running simultaneously in Windows to communicate. Using DDE, programs can act as a source and/or client. Data can be transferred as ASCII text or bitmap graphics. DDE also allows client programs to trigger events in source programs by sending a command string to a specific DDE event handling routine in the source program. DDE is built into all VB applications and can be utilized with very little code.

Using VB in conjunction with DDE and a few DLL's, the DAC program was implemented as a set of three executable VB programs running simultaneously in the Windows environment. Each functional module is a self contained program with a uniformity of purpose that makes for more efficient construction and maintenance in the VB environment. This

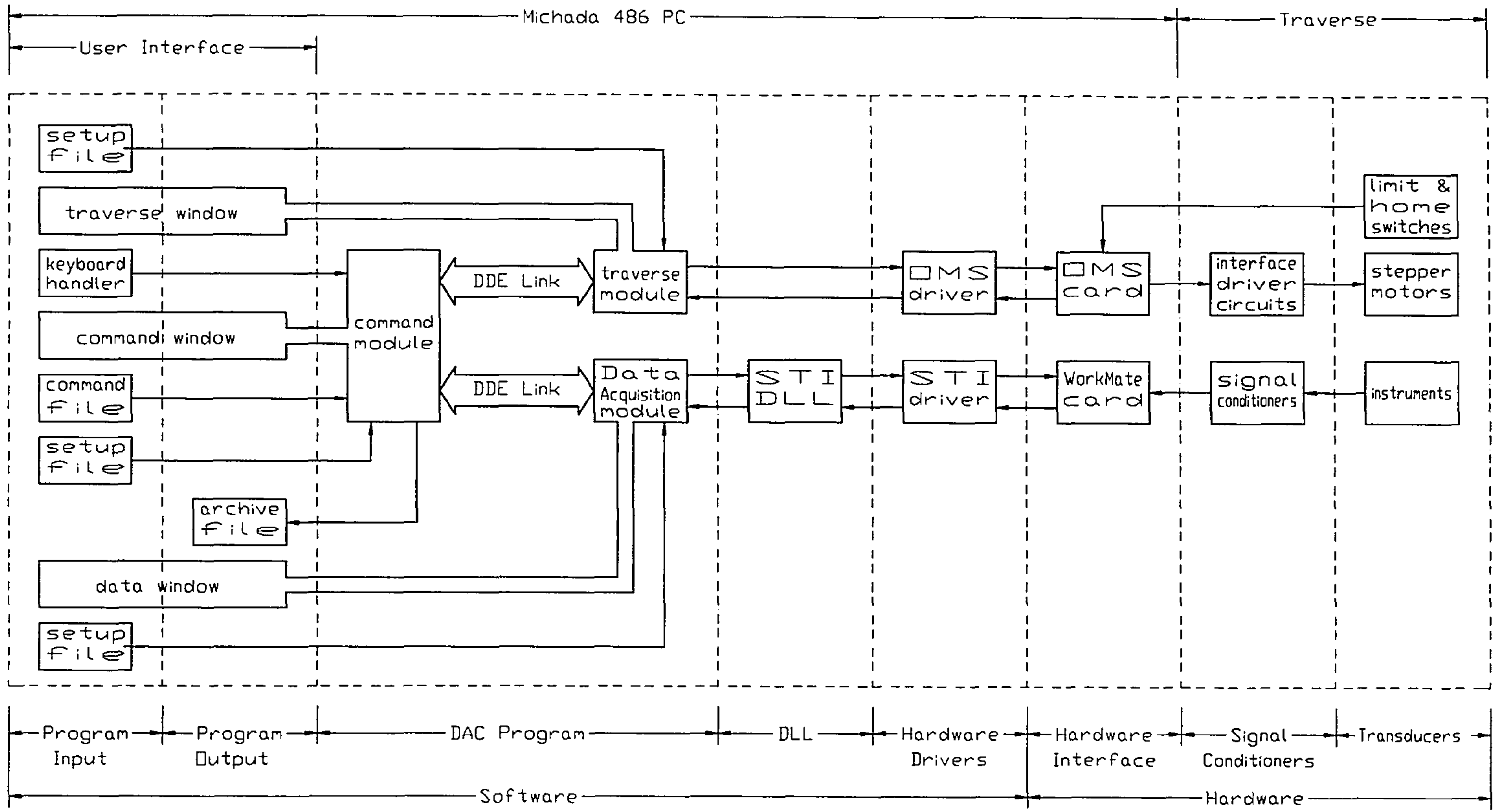


Figure 6.2: DAC Program and System Architecture

implementation takes advantage of what Windows and Visual Basic provide.

The final DAC program architecture implementation is shown in Figure 6.2. This figure shows all hardware and software components in the throw room automated system except a few native Windows DLL's used to perform system inquiries. The figure is stratified along a continuum from the user interface to the hardware in the throw room. Each component is defined as it exists in the software or hardware environment. Arrows indicate an exchange of data.

6.3 The Command Module Program

The Command module acts as the primary input for the user and coordinates the operations of the Traverse and Data Acquisition modules. This module has a Windows interface (shown in Figure 6.3) that allows the user to enter commands with the keyboard or a menu. The commands are interpreted and the appropriate action is taken. It also reads commands from a text file.

All commands issued to the DAC program group go through the command module. The other modules can receive commands directly (see manual mode in sections 6.3 and 6.4), but this is not encouraged during a test. The command window is visually and functionally similar to a UNIX X-Window shell. Commands are entered as text strings into a scrolling text box. The end of a command is signaled by pressing the ENTER key. The commands are interpreted, executed, and a response string is displayed on the line below. Following the response string is a prompt for the next command.

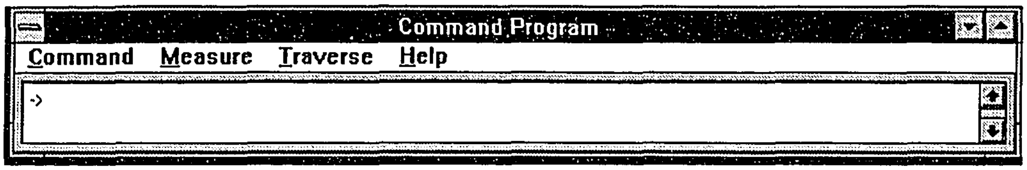


Figure 6.3: Command Module Window

Commands can also be entered using a text file. This is very similar to a batch file in DOS. A command file can be nested in another command file. In other words, a command file can command the program to open and execute another command file. As the command file is being executed, the commands and responses are displayed in the command window. A special prompt, #>, is used to remind the user that a command file is being read. It shows the nested level of the command file currently being read (#) and a greater than sign. Command files can be used to perform complex or repetitive tasks with the DAC program group.

The menu allows the user to issue commands by simply choosing the command from the menu. The code to implement the menu simply piggy-backs the code for the command window. Some of the commands used in the program require data. For example, to command the traverse to move the x axis, the command is "traverse x #", where # is the target position of the x axis. To implement these commands, dialog boxes are used to request data from the user.

6.3.1 Command Structure

The command structure of the Command module is really very simple. Table 6.3 is a list of the commands, their syntax, and actions. The commands are divided into module specific commands and global commands. Global commands effect all modules. Module specific commands are interpreted by the Command module then passed on to the addressed module. Commands that are addressed to the Traverse or Data Acquisition modules are interpreted by the Command module so that it can coordinate the actions of the entire DAC program group.

The address column of Table 6.3 shows which modules each command applies to. The address for the Data Acquisition module is the word "measure". This was done to simplify the command interpretation procedure. The address must proceed the commands in the case of the Data Acquisition and Traverse modules. The address for global and command addresses are understood.

The global commands "manual" and "quit" can be addressed specifically to the Data Acquisition and Traverse modules. If they are addressed to the Command module or not addressed at all, they will act as global commands.

All commands are delimited by space characters and end with the carriage return character. This is just like the DOS or UNIX shell. Commas or other commonly used delimiter characters cannot be used and will result in a syntax error. Also, multiple commands cannot be entered on a single line. If the user wishes to reduce typing commonly used commands they should use command files.

Address	Syntax	Action
Command	help	Displays a list of the commands.
Command	clear	Clears the command window display.
Command	execute[filename]	Opens and executes a command file.
Command	archive open|close	Open or close an archive file.
Measure	ao n #	Sends the value # to analog output channel n.
Measure	ai n [tag]	Reads analog input channel n.
Measure	do n 1|0	Sends binary value to digital output channel n.
Measure	di n [tag]	Reads binary value from digital input n.
Traverse	x #|home	Moves x-axis to # (user units) or home.
Traverse	y #|home	Moves y-axis to # (user units) or home.
Traverse	z #|home	Moves z-axis to # (user units) or home.
Traverse	t #|home	Rotates z-axis to # (user units) or home.
Traverse	a # # # #|home	Moves traverse to #,#,#,# (user units) or home.
Global	manual on|off	Turns manual mode on or off.
Global	quit	Terminates DAC program group.

Table 6.3: DAC Program Commands

6.3.2 Dynamic Data Exchange

When the Command module is run, it executes the other modules in the DAC program group if they are not already running. If the other modules are running, then it will not attempt to start them again. The Command Module then initiates a DDE link with the other modules. This link remains intact until the program group is terminated when the "quit" command is issued as a global command.

The Command module acts as a DDE client to the Traverse and Data Acquisition modules. In DDE, client modules are responsible for initiating links. As the client module, it can send commands to the other modules and receive data. Data is passed between objects in the module windows. The objects used for DDE exchange in the DAC program group are called labels. Labels are used in VB to display text strings.

Commands are sent as text strings in a Link Execute command. This is a DDE event that causes Windows to call a subroutine in the source module. The subroutine is supplied with the command string as an argument. When this occurs, the client module immediately becomes active. The source module interprets the command string and executes the command. When it is done, it updates its window and becomes inactive, returning focus to the client module.

The subroutine that receives the command string in the Data Acquisition and Traverse modules is called LinkExecute. It is a subroutine that is built into every form in VB. The code in the subroutine is supplied by the programmer. These two modules each use the LinkExecute subroutine as a command interpreter procedure. It interprets the command string and directs execution of the command.

The type of DDE link established by the Command module is called an automatic link. This means that when the data in the source module's label objects is updated, the data in the client labels of the client module is automatically updated by Windows. To insure that the source module is finished executing a command and that the updated data is valid, a VB label object named DDEFlag is used. When the source module is finished executing a command, it sets the value of the DDEFlag text to "1", otherwise it is set to "0". When the Command module DDEFlag label object reads "1", it records the data and waits for the next command.

6.3.3 Data Archival

The Command module archives all of the data collected by the Data Acquisition Module. This is initiated by the user with the "archive open" command. When the Command module receives this command, it asks the user for a file name using a standard Windows dialog box ,then opens the file. The file is closed when the "archive close" command is received.

The Command module archives data when a measure command is received. It passes the command to the Data Acquisition module and waits. When the Data Acquisition module is finished and becomes inactive, the Command module then archives the measurement data including the standard deviation, the traverse position, and a user specified tag. The tag is an optional part of the measure command. It can be used to identify measurements when the data is analyzed. The data is stored in a comma delimited format so that any spreadsheet program can be used in the analysis.

6.3.4 Program Variables and The Setup File

The Command Module reads the setup file, command.set, every time it is run. This file is a text file that contains user defined variables for the program to use. The format of the file is in Appendix 18. The variables stored in the command.set file are the location of the Command module window on the screen and the paths of the Traverse and Data Acquisition modules. This file will rarely be modified, but it is formatted and commented for human eyes.

6.4 The Traverse Control Module Program

The Traverse Control module program directs the traversing mechanism to move according to the commands it receives. It receives all command data in user specified units. These commands are interpreted and translated to commands that can be understood by the OMS stepper motor controller card. The translation process takes into account the user defined units and the traversing mechanism geometry, as well as other user specified variables. This module also displays the current location of the traverse axes and the home and limit switch states. The window of the traverse module is shown in Figure 6.4.

The Traverse module can receive commands through its window or from a DDE client. The mode of input is specified at the program command line or through DDE. If manual mode is specified, the program will receive commands from its window interface and a DDE client. If manual mode is not specified, the program will receive commands through a DDE link only. This capability was provided so that user input could be strictly controlled during a test in the throw room. Manual mode is the default.

Commands are input directly to the Traverse module window by pressing virtual buttons just as in any Windows program. These buttons cause the traverse to move a specified increment. Two increments values can be set in the program setup file for each axis. There are four move buttons for each axis, two in the forward direction and two in the reverse direction. A fifth button, on each axis, allows the user to send the axis home. This causes the traversing mechanism axis selected to roam until it hits the home switch. If no home switch is found, the program will indicate an error has occurred.

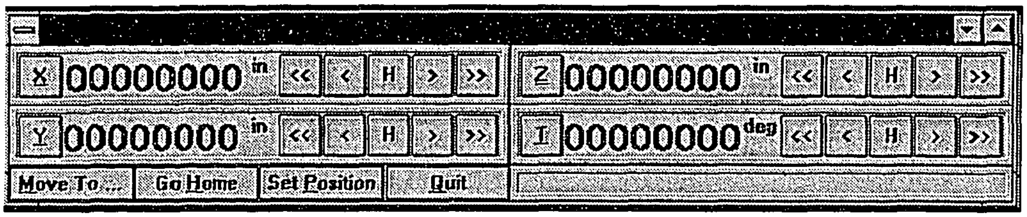


Figure 6.4: Traverse Module Window

The status of the home and limit switches are indicated by the color of the characters on the buttons. If the ">" or "<" characters on the move buttons are red then the limit switch has been triggered in that direction. If the "H" on the home button is red then the home switch has been triggered. If the H on the home button is blue then the home switch is suspected of malfunctioning. Black characters indicate that no switches have been triggered.

The traverse module also has a status panel. This is the panel on the bottom of the window. This panel indicates the present state of the traverse module. For example, if the traverse x-axis is moving then this panel will read "Moving x-axis to ###.". Any error that occurs will also be displayed in the status panel.

User defined run-time variables can be set using the setup file traverse.set. The units used, conversion factors, and many other variables can be specified. It is read by the module every time the module is run. This file is a text file formatted with comments for user interaction. It can be seen in Appendix 19.

6.4.1 Communicating with The Stepper Motor Controller Card

The Traverse module program communicates with the OMS stepper motor controller card through a device driver supplied by OMS. A device driver is a program that is used by other programs to interface with peripheral devices. It loads itself into the memory of the computer and waits to be used. The OMS device driver is loaded into memory when the computer initializes itself with the config.sys file.

Communicating with the OMS device driver is similar to reading and writing to a text file. The driver is opened using the BASIC open statement. The name of the driver used by the OPEN statement is "board1", but can be set to any character string at the device driver command line. Communication is terminated using the BASIC CLOSE statement.

Data read from the OMS driver may be a response to a query or an external physical event. If a limit or home switch changes state or if a motor ceases to move, the OMS card will attempt to notify the user through the driver program. The driver acts as a buffer. The data is not automatically sent to the user program, it must be read. The user program cannot assume it knows what the data will be when it reads data from the driver program. The data may be a response to an external event or a query. If a query is initiated by the user program, the driver program may have already serviced the OMS card in response to an external event.

Data is read from the driver using a complex procedure that reads one character at a time. It is set up to receive and interpret any character read from the driver. Data is read from the driver only after a command is sent. The procedure reads data from the card until it receives data that is an appropriate response. The data it reads up to that point is acted upon.

Commands are sent to the OMS card through a driver using the BASIC PRINT # statement. The commands are text strings that are constructed by the Traverse module. They are based on the command received from the user, the current state of the traverse, and the units specified by the user. The OMS card command structure is complex and terse. It will not be discussed in this report.

6.4.2 User Defined Unit Conversion and Step Units

The units used by the OMS stepper motor controller card are steps. The card only understands the rotation of the stepper motors. The gearing of the motors, the geometry of the traversing mechanism, and the units used by the user are all interpreted by the Traverse module program. While the geometry of the traversing mechanism is programmed into the Traverse module, the units and gearing are specified by the throw room operator. The geometry is discussed in Chapter 7.

The setup file used by this module contains conversion factors specified by the user for conversion of units. These conversion factors are based on the gearing of the stepping motors and the units used in the throw room. The conversion factors are in units of steps/d, where d can be inches or any distance measure. The distance measure currently used is inches. The conversion factors are based on the drive kinematics discussed in Chapter 5.

6.5 The Data Acquisition Module Program

The Data Acquisition module reads and calibrates data from the instruments in the throw room. Data is collected by two STI Workmate data acquisition cards. The program is capable of utilizing any number of Workmate cards simultaneously and without modification. Each Workmate card has eight differential analog input channels, eight digital input/output channels, and two analog outputs channels.

The setup of each analog input channel is programmable on the Workmate card. The setup variables are made fully accessible by the Data Acquisition module using the text file measure.set. The program reads the file every time it is used and sets the Workmate card accordingly. The format of this file can be seen in Appendix 20.

The data sample size used for each analog input channel is also specified in the module setup file. The maximum sample size depends on the amount of memory available to the STI DLL. It is displayed in the module introduction window.

The setup data for any analog input channel can be viewed in the analog input channel statistics window. This window is viewed by clicking the analog input data display. It also shows the current mean and standard deviation values, as well as a histogram of the current calibrated data set. This window can be used to identify a bad data set or verify the channel setup.

The Data Acquisition module window is currently composed of a set of sixteen cells. Each cell represents an analog input channel (see Figure 6.5). The cell contains a channel label/virtual button, a mean value display, a unit display, and a standard deviation display. The channel label/virtual button

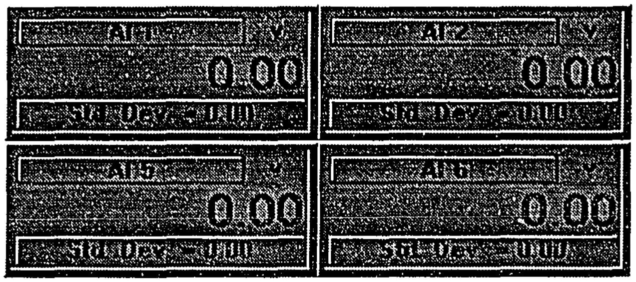


Figure 6.5: Four Analog Input Cells of Data Acquisition Window

can be used to direct that channel to measure by clicking on the button when the program is in manual mode. The format of the mean value display and the text in the unit display are specified by the user in the program setup file.

The source code for the Data Acquisition module has all the procedures required to utilize the digital input/output and analog output channels. Since these channels are not used in this project, they are not included in the module window. The module setup file is formatted so that the user can setup these channels as desired. This code will be retained for possible future use.

The Data Acquisition module can receive commands through its window or using DDE, just as the Traverse module. From the window, the user can direct any channel to make a measurement by clicking the label for that channel. This capability is only allowed in manual mode.

In manual mode the Data Acquisition module receives measure commands from its window and from DDE. When manual mode is off commands can only be received through DDE. Manual mode can be turned on and off, at the program command line, when it is executed or through DDE. This facility was provided so that the throw room operator can examine the automated system and still restrict input during testing. Manual mode is on by default.

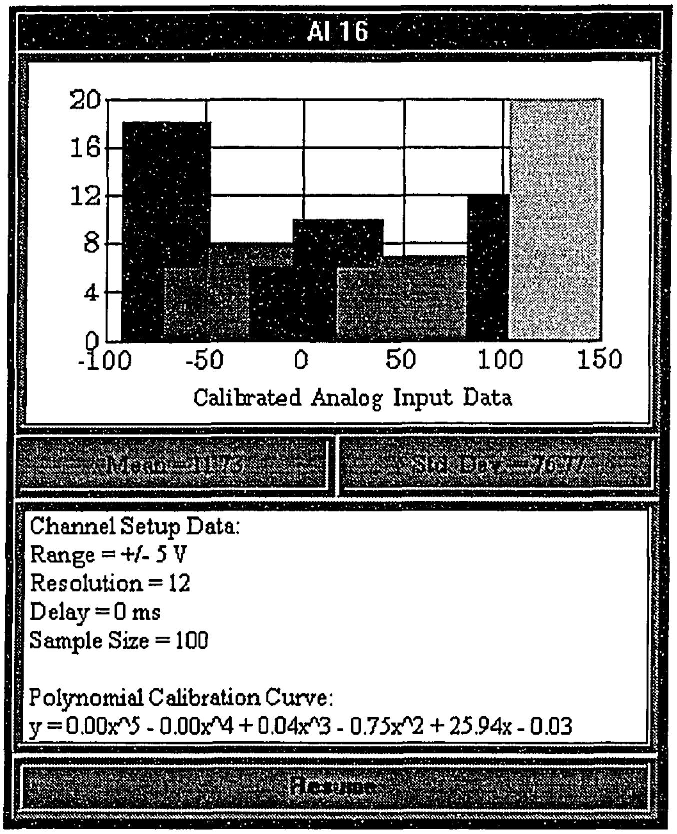


Figure 6.6: Analog Input Channel Statistics Window

6.5.1 Communicating with The Data Acquisition Card

The Data Acquisition module communicates with the Workmate card using the STI DLL and the Workmate driver programs (see Figure 6.2) which were provided by the vendor. The driver is actually two programs. Aside from the loading procedure, these driver programs act as a unit. They were not designed to be used like the driver for the OMS stepper motor controller card. The STI DLL is used by the Data Acquisition module to communicate with the driver program.

The STI DLL is a library of functions used to communicate with the driver program. It contains two functions for initializing and de-initializing the DLL. Another function is used to send commands to the Workmate card and the other functions are used to transfer data. These functions are accessed by VB just as any other functions. The only difference in their usage is in the declaration statement which declares them as external.

6.5.2 Analog Input Data Calibration and Statistics

The user can specify any polynomial calibration curve using the setup and calibration files. The calibration file contains the order and coefficients of the polynomial. The name of the calibration file to use for each analog input channel is specified in the setup file.

A polynomial calibration curve was chosen because of its widespread use and simplicity. The procedure required to implement a polynomial calibration is a simple FOR loop. The mean and standard deviation calculations are also embedded in the same FOR loop. Since the calculations are performed simultaneously and only require multiplication and addition, they are very quick.

CHAPTER 7

THROW ROOM CONTROL PROGRAM IMPLEMENTATION

Visual Basic (VB) uses a simple file structure to assist the programmer in organizing source code. The programmer can create two types of source code files in VB, form files and basic module files. Form files contain all of the data required by VB to create a form (or window). This includes information about the objects on the form and the code created by the user to make the form work. Basic module files contain code only, which can generally be accessed by code in other form and basic module files.

A single VB program can have any number of form and basic module files. These files are organized by VB using make-files. The make-file is generated by VB. Every VB program has a make-file. The programmer usually does not edit the make-file, but the file is in ASCII format and can be read by NotePad.

All of the program modules in the DAC program group have multiple source code files. One file, Error.Bas, is shared by all three program modules. This file contains code used in the programs to inform the user of an error or ask the user a yes\no question.

Use is made in these programs of the constant definitions provided by Microsoft for VB programming. These constants are contained in the file constants.txt. They provide a easy and efficient way of interfacing with many of the functions built into VB. These constants will not be discussed as they are an accessible and uniform component of the VB programming package.

The following section will describe the implementation of each program module. One section is used to describe the math used in the traverse program for coordinate transformations. These sections will discuss only the major points of each program implementation. For more information the reader should refer to Appendices 21 to 23 which contain the source code for the DAC program group.

7.1 Command Module Program Implementation

The Command module program code was implemented as a set of three files other than the Error.Bas file. These files include two forms and one basic module. One form, Command.Frm, is the main form which is used to receive user input and display commands. The other form, Commlist.Frm, is a simple help window that displays a list of commands available to the user. The basic module, Command.Bas, contains a type definition, VB standard global constants used with the SetWindowPos() subroutine and an external declaration. The make-file is called Command.Mak.

The external declaration is for the subroutine SetWindowPos() located in the User.Dll which is a part of the Windows API. This subroutine is used to make the windows used in this and the other modules float. A floating window cannot be covered by another window unless that window also calls the SetWindowPos() subroutine. Most programs use this effect only for error dialog boxes. This was done so other windows programs could not interfere with the DAC program modules.

The Command.Frm file contains the core routines for the Command module program. The routines that set up and maintain DDE links with the other modules are located here, as well as the routines used to archive data. The routines that are used to interpret and execute user commands from the command line, the menu and command files are also located here. Lastly, the routines used to make the Windows interface work are located in this file.

7.1.1 Command Interpretation Procedure

Commands received from the menu, command line and command files are all processed the same way. The commands are received as strings. These command strings are sent to the InterpretCommand() subroutine. This subroutine calls the TranslateCommand() subroutine to convert the string to a set of meaningful sub-strings. These are then used by the interpreter to determine which course of action to take.

The TranslateCommand() subroutine uses the GetTokens() subroutine to break up the command string. This subroutine will return a set of sub-strings contained in any string, where the sub-strings are separated by space characters.

7.2 Traverse Module Program Implementation

The Traverse module program code was implemented as a set of three files other than the Error.Bas file. These files include two forms and one basic module. One form, Traverse.Frm, is the main form which is used to receive user input and display the traverse position and limit switch states. The other form, Travstat.Frm, is used to display the setup of an axis. The basic module, Traverse.Bas, contains a type definition, global constants and variables and two external declarations. The make-file is called Traverse.Mak.

One of the external declarations is for the subroutine SetWindowPos() discussed in Section 7.1. The other is for the function GetAsyncKeyState() with is used to detect if the user has pressed the escape key. It is also located in the User.Dll.

The Traverse.Frm file contains most of the core routines of the program. The routines used to communicate with the OMS controller card are located in this file. It also contains the routines used to interface with the user, communicate via DDE, and perform coordinate calculations. For a discussion of the user interface and DDE see Chapter 6. The equations used for coordinate calculations are discussed in Section 7.3.

7.2.1 Traversing Mechanism Emergency Halt

The escape key is used to signal an emergency halt to the program when the traversing mechanism is moving. The GetAsyncKeyState() function is used to pole the keyboard directly through Windows while the traverse module is waiting for the OMS controller card to signal that the traverse is done moving. If this technique were not used then the program would receive user input only after the traversing mechanism is done moving.

7.2.2 The Axis Data Type

The axis data type is a user defined data type defined in the Traverse.Bas file. It is used to hold all information regarding each axis of the traversing mechanism. The data type is used as an array of four elements. The index of the array is ranges from 0 to 3. Four constants are defined in the same file which are used to make access to the array easier. These are XAXIS, YAXIS, ZAXIS and TAXIS which have integer values of 0, 1, 2 and 3 respectively. The data type is defined:

```
Type AxisType
    Name As String * 1          'name of axis
    HomePosition As Single      'home location in real space units
    PositiveLimit As Single     'positive limit location in real space units
    NegativeLimit As Single     'negative limit location in real space units
    Position As Long            'position in step space units
    Velocity As Integer         'velocity in steps/s
    Acceleration As Integer     'acceleration in steps/s/s
    StepMode As Single          'step mode as 1.0 (FULL) or 0.5 (HALF)
    Conversion As Double        'conversion factor real/step units
    Direction As Integer        'travel direction flag
    LimitFlag As Integer        'limit switch flag
    HomeFlag As Integer         'home switch flag
    DoneFlag As Integer         'done moving flag
    UnitStr As String * 3       'units string
    BigJump As Single           'big jump value in real space units
    SmallJump As Single         'small jump value in real space units
End Type
```

The comments indicate the use of the data type members.

7.3 Traverse Coordinate Calculations

The coordinate system used in the throw room is of vital importance to the proper testing of ATD's. Definitions of the ATD's diffusion performance are based on this coordinate system. In the VAST Lab throw room, the traversing mechanism adds complexity to the coordinate system.

The throw room operator will give coordinate values to the Traverse module program in terms of points of actual measurement. He will also want those locations recorded. Since the traversing mechanism will have a probe and four degrees of freedom, the control program will have to calculate the actual traverse location coordinates based on the requested measurement coordinates.

7.3.1 The Room Coordinate System

The Room Coordinate System (RCS) is a constant coordinate system, which serves as the reference for all coordinates in the throw room. It is oriented in the throw room as shown in Figure 7.1. The x axis is normal to the South wall. The y axis is normal to the West wall. The z axis is normal to the throw room floor. The origin is located at the home position of the traversing mechanism.

The home position of the traversing mechanism is that point in the throw room where the traverse goes when given the "traverse home" command. It is defined by the position of the home switches in the room. The limit switches were positioned so that the traversing mechanism will find the home position in the Northwest corner of the throw room.

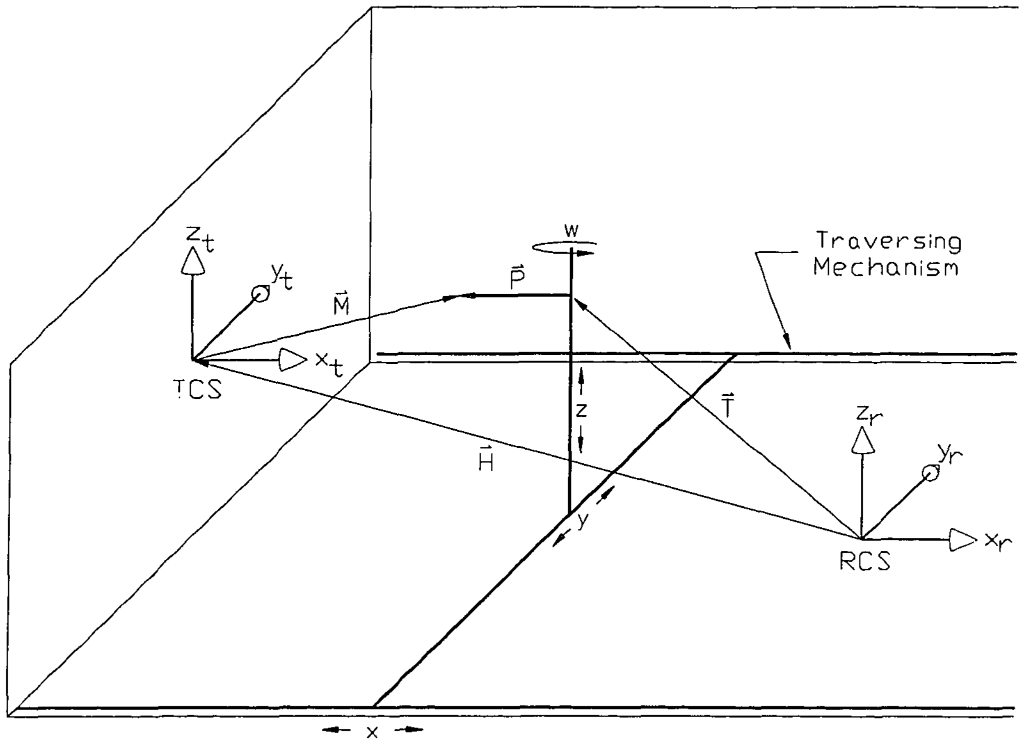


Figure 7.1: Throw Room Coordinate Systems

7.3.2 The Test Coordinate System and The Home Vector

The Test Coordinate System (TCS) serves as the reference for all measurements made in the throw room. Its origin is at the center of the face of the ATD to be measured. It is oriented in space the same as the RCS. This orientation was selected to conform with that used in ASHRAE Standard 70[1] and ISO Standard 5219[7].

The testing methodology of ATD's as specified by ASHRAE Standard 70[1] and ISO Standard 5219[7] includes implied coordinate related definitions. The terms throw, spread, rise and drop have specific implied coordinate directions which are +X, +/-Y, +Z, and -Z respectively. These coordinate definitions will be used in the VAST Lab throw room.

The TCS is located in the throw room by the home vector, H, referenced from the RCS. The home vector must be measured before each test and supplied to the Traverse module program via the Traverse.Set file (see Appendix 18). It is defined by measurements made from the traverse home position (the RCS origin) and the center of the ATD. The home vector will be measured in either inches or meters.

7.3.3 The Measurement Vector

The measurement vector, M, specifies the location of the measurement probe with reference to the TCS. This vector will be specified and recorded for each measurement to be made in the throw room during an ATD test. All commands to move the traverse given to the Traverse module program by the operator will be in terms of the measurement vector. The measurement vector will be measured in either inches or meters.

7.3.4 The Traverse and Probe Vectors

The traverse is located in the throw room by the traverse vector, T, referenced from the RCS. The traverse vector defines the location of the z-axis carriage of the traversing mechanism with reference to the throw room coordinate system. The z axis carriage is shown in Figure 7.1 as the base of the probe vector.

The probe vector, P, locates the measurement probe in the throw room. It is referenced from the z axis carriage (the head of the traverse vector). The probe vector is defined by the length, L, and orientation, w, of the probe carried by the z axis carriage. Since the z axis of the traversing mechanism can rotate (w in Figure 7.1), the probe vector may not be constant during a test. The angle w is in the x-y plane. It is zero when the probe vector is parallel to the x-axis. It is positive clockwise and negative counterclockwise when view from above. The probe vector is defined:

$$P = [\ L\cos(w) \quad L\sin(w) \quad 0\ ]^T \qquad \text{Equ. 7.1}$$

The traverse vector will ultimately be used in the control program to locate the three axes of the traverse in the throw room. The probe carried by the traverse on the z axis carriage can also be rotated to achieve better test conditions. The control program will take both of these vectors into account when moving the traverse to the requested location specified by the measurement vector. The traverse vector will be determined by the traverse control program using the equation:

$$T = M + H - P \qquad \text{Equ. 7.2}$$

Expanding equation 7.2 and including the unit conversion factors from real units to steps the following equations are generated.

$$x_T = C_x(\ x_m + x_h - L\cos(w)\ ) \qquad \text{Equ. 7.3}$$
$$y_T = C_y(\ y_m + y_h - L\sin(w)\ ) \qquad \text{Equ. 7.4}$$
$$z_T = C_z(\ z_m + z_h\ ) \qquad \text{Equ. 7.5}$$

where the subscript T indicates a component of the traverse vector, the subscript m indicates a component of the measurement vector and the subscript h indicates a component of the home vector. Cx, Cy and C_z are the conversion factors calculated in Chapter 5. These equations are used to calculate the step coordinates given to the OMS controller card to move the traversing mechanism given the desired measurement vector M.

7.4 Measure Module Program Implementation

The Measure module program code was implemented as a set of three files other than the Error.Bas file. These files include two forms and one basic module. One form, Measure.Frm, is the main form which is used to receive user input and display the traverse position and limit switch states. The other form, Aichstat.Frm, is used to display the setup of any analog input channel. The basic module, Measure.Bas, contains a type definitions, global constants and variables and an external declaration to the SetWindowPos() subroutine. The make-file is called Measure.Mak.

The Measure.Frm file contains most of the core routines of the program. The routines used to communicate with the Workmate card are located in this file. It also contains the routines used to interface with the user, communicate via DDE, and perform data reduction. For a discussion of the user interface and DDE see Chapter 6. The data reduction procedure is discussed in Section 8.4.2.

Routines and data types have been defined for all of the Workmate channels. This was done for future use. The routines for interfacing with the digital and analog output channels are not actually used in the programs present state.

8.4.1 User Defined Data Types

The Measure.Bas file contains definitions of user defined data types which store information regarding the Workmate analog input channels, analog output channels and digital input\output channels. These data types are declared as global array variables in the same file. The arrays are declared so that their length can be dynamically changed during program execution. This was done so that the program can work with any number of Workmate cards. The program is set up to detect the number of each type of channel available to it.

The data types are defined:

```
'Analog Input Channel Setup Data Type
Type AnalogInputChannel
    name As String * 15            'user specified description
    unit As String * 4             'unit string to be displayed
    format As String * 10          'format string for displaying values
    range As Integer               'input voltage range code
    resolution As Integer          'input sample resolution code
    delay As Integer               'delay between readings
    samplesize As Integer          'number of samples / measurement
    order As Integer               'order of calibration polynomial
    coefficient(0 To 10) As Single 'coefficients of calibration poly
End Type

'Analog Output Channel Setup Data Type
Type AnalogOutputChannel
    name As String * 15            'user specified description
End Type

'Digital Channel Setup Data Type
Type DigitalChannel
    name As String * 15            'user specified description
    iostate As Integer             'input = 0, output = 1
End Type
```

The analog input voltage range and sample resolution codes are defined in the Workmate user manual. The analog input sample size is defined by the user, but may be modified by the program if it detects a memory limitation. The definition of the AnalogOutputChannel data type may seem useless but is used for code clarity.

8.4.2 Data Reduction Algorithm

The analog input data reduction algorithm takes advantage of the characteristics of the polynomial calibration curve. The code used in the program is:

```
'initialize sum and sum of squares
Sum1 = 0
Sum2 = 0

'for each sample point
For j = 0 To AIChannel(Chan).samplesize - 1

    'calibrate measured sample and record in array
    Values(Chan, j) =
AIChannel(Chan).coefficient(AIChannel(Chan).order)
    For i = AIChannel(Chan).order To 1, Step -1
        Values(Chan, j) = Values(Chan, j) * Sample(j) +
AIChannel(Chan).coefficient(i-1)
    Next i

    'sum calibrated data and square of calibrated data
    Sum1 = Sum1 + Values(Chan, j)
    Sum2 = Sum2 + Values(Chan, j) * Values(Chan, j)

Next j

'calculate mean
mean = Sum1 / AIChannel(Chan).samplesize

'calculate standard deviation
sdev = Sqr((Sum2 - (Sum1 ^ 2) / AIChannel(Chan).samplesize) /
(AIChannel(Chan).samplesize - 1))
```

where mean is the mean value and sdev is the standard deviation. The array Values() is global and stores the calibrated data during each measurement so that a histogram of the data can be generated. This procedure uses the nested form of the polynomial to improve calculation speed. Note the use of the data type AnalogInputChannel as the variable array AIChannel() where the index is the analog input channel number Chan..

CHAPTER 8

CONCLUSION

The HCATS facility is complete. The ducts and fan have been installed. The nozzle bank and instrumentation were installed by Ian Aguirre and he reported that the nozzle bank measures air flow rates accurately. All of the system components fit together well and do not interfere with previously installed facilities.

The HCATS facility was used successfully by Alex Jackovich to perform zero flow acoustic insertion loss measurements. In these tests, the amount of acoustic attenuation caused by a duct element was measured. The components tested were fiberglass lined, round ducts with diameters from 2 ft. to 5 ft. and lengths up to 10 ft..

This installation has fulfilled its primary design objectives. It provides an air flow path which can accommodate the installation of a variety of HVAC components. It provides a variable air flow rate up to 10,000 CFM that can be controlled by the motor speed controller in the multifunction lab and measured by the nozzle bank. It also uses a minimum of floor space in the multifunction lab.

The throw room housing, air supply system and variable height ceiling system have been constructed and perform their functions as intended. The throw room interior will be completed within a week. The air supply system has been running for about a month without any problems. The variable height ceiling works without any problems.

The instrumentation and nozzle bank for the throw room are near completion. The instrumentation has been ordered and Jim Ventresca has calibrated the hot-film anemometers. Four of them will be mounted to the traverse z-axis carriage. The nozzle housing is complete and the pressure transmitters and thermocouples are currently being installed.

The traversing mechanism was recently completed and it works. From initial tests it has been determined that the y and z axes can run at velocities up to about 500 steps/s. The x-axis can move at velocities up to about 300 steps/s. The OMS stepper motor controller card has functions for linear, cosine and parabolic velocity curves. Of these the parabolic velocity curve seems to work the best. An acceleration rate of about 1000 steps/s/s to 2000 steps/s/s seems to work well. The DAC program group is working well.

APPENDIX 1

REFERENCES

1. American Society of Heating, Refrigeration, and Air Conditioning Engineers, *Method of Testing for Rating the Performance of Air Outlets and Inlets*, ASHRAE Standard 70-1991

2. Nevins, R. G., *Air Diffusion Dynamics Theory, Design and Application*, Business News Publishing Company, 1976

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4. American Society of Heating, Refrigeration, and Air Conditioning Engineers, *Standard Method for Temperature Measurement*, ASHRAE Standard 41.1-1986

5. American Society of Heating, Refrigeration, and Air Conditioning Engineers, *Standard Methods for Laboratory Air-Flow Measurement*, ASHRAE Standard 41.2-1987

6. American Society of Heating, Refrigeration, and Air Conditioning Engineers, *Standard Method for Pressure Measurement*, ASHRAE Standard 41.3-1989

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8. International Standards Organization, *Air Distribution and Air Diffusion -Rules to Methods of Measuring Air Flow Rate in an Air Handling Duct*, ISO Standard 5221-1984

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10. Bohanon, H. R., "Fan Test Chamber-Nozzle Coefficients", *ASHRAE Transactions* 81, 1975

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12. American Society of Heating, Refrigeration, and Air Conditioning Engineers and Air-Conditioning Engineers Inc., *ASHRAE Brochure on Psychrometry*, 1977

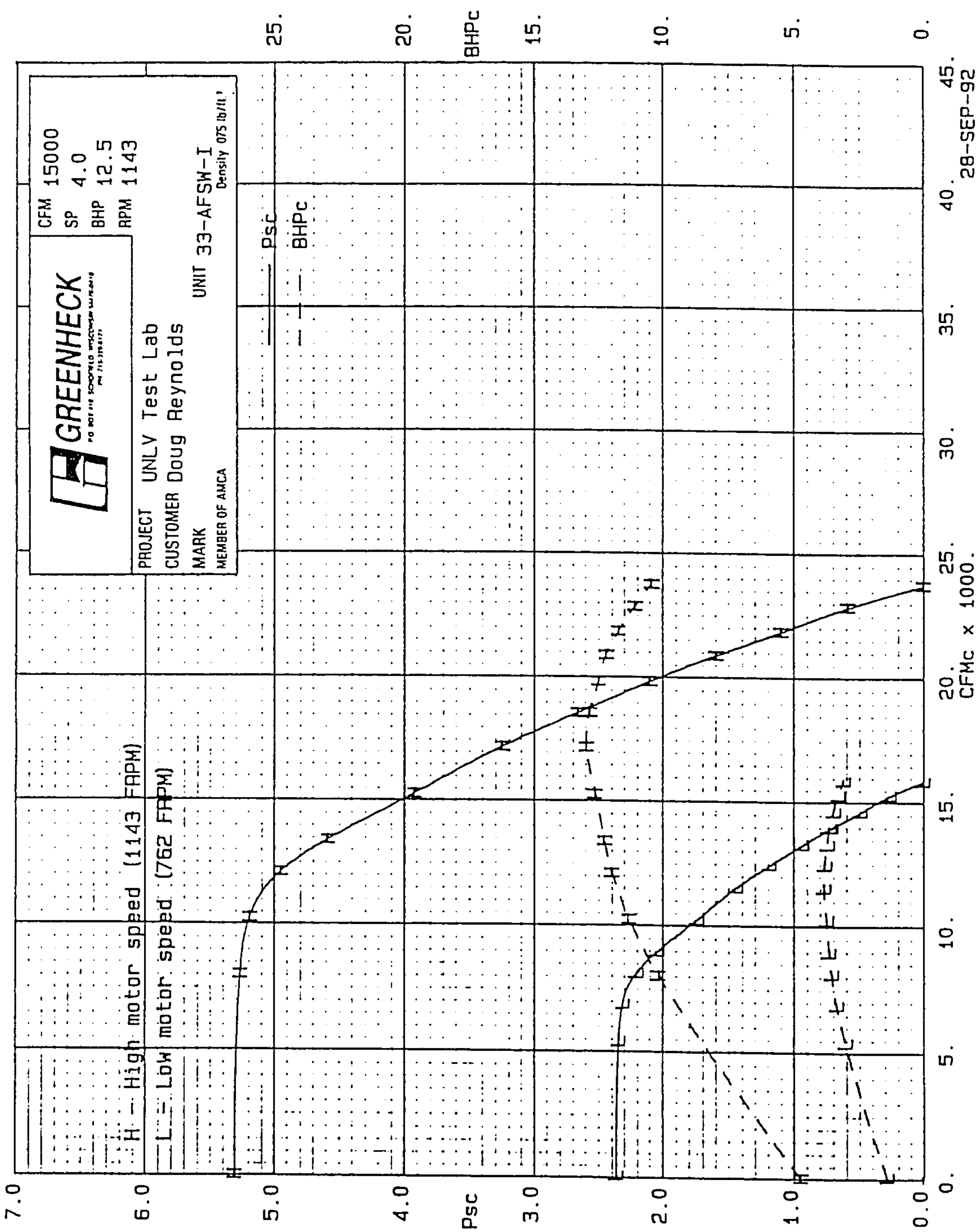
13. Omega Engineering Inc., *The Temperature Handbook* vol 28, 1992

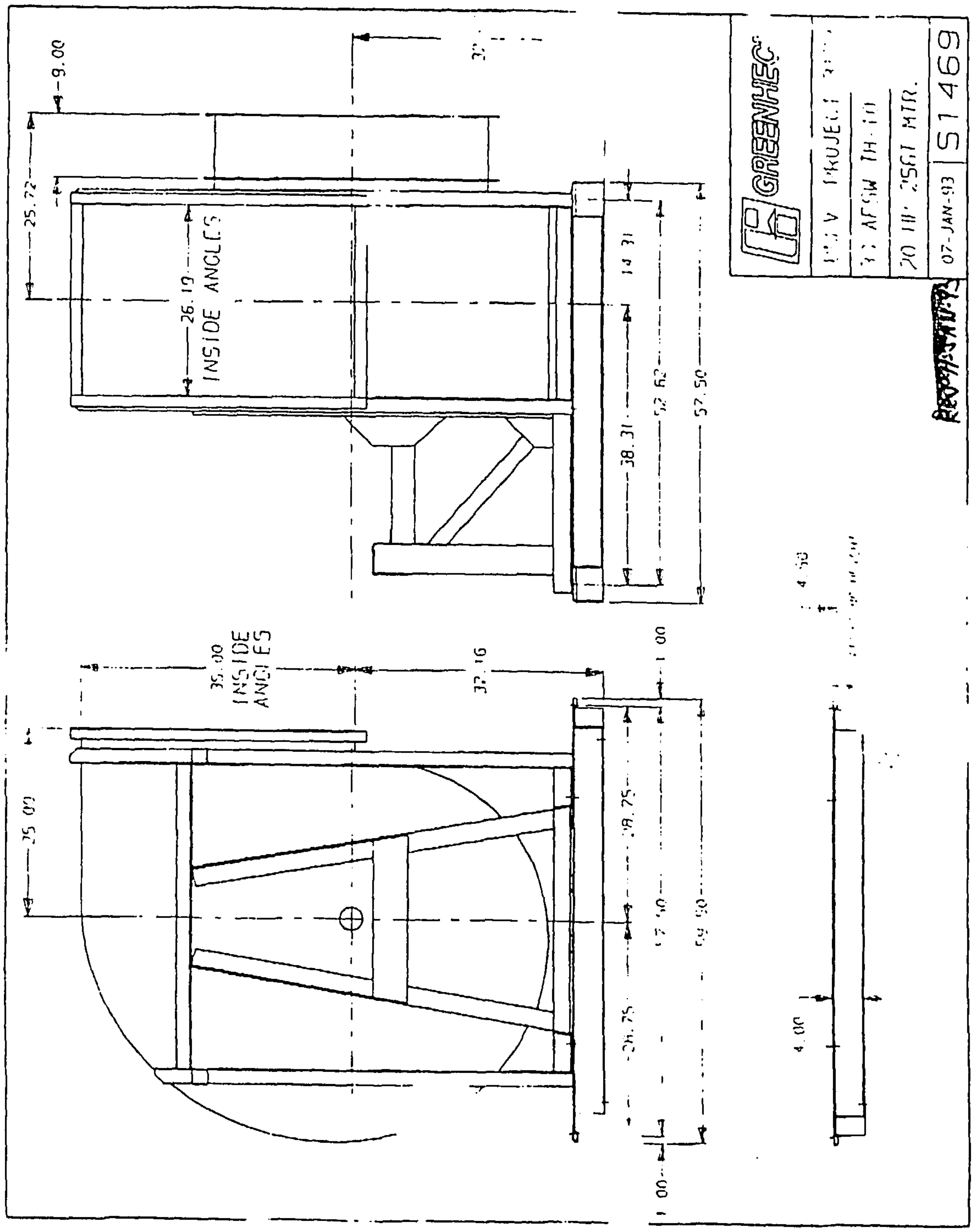
14. Princo Inc., *Instruction Booklet for use with Fortin Type Mercurial Barometers*, 1983

15. B. Lakshminarayana, "Three Sensor Hot Wire/Film Technique for Three Dimensional Mean and Turbulence Flow Field Measurement", *TSI Quarterly,* Volume 8, Issue 1

APPENDIX 2

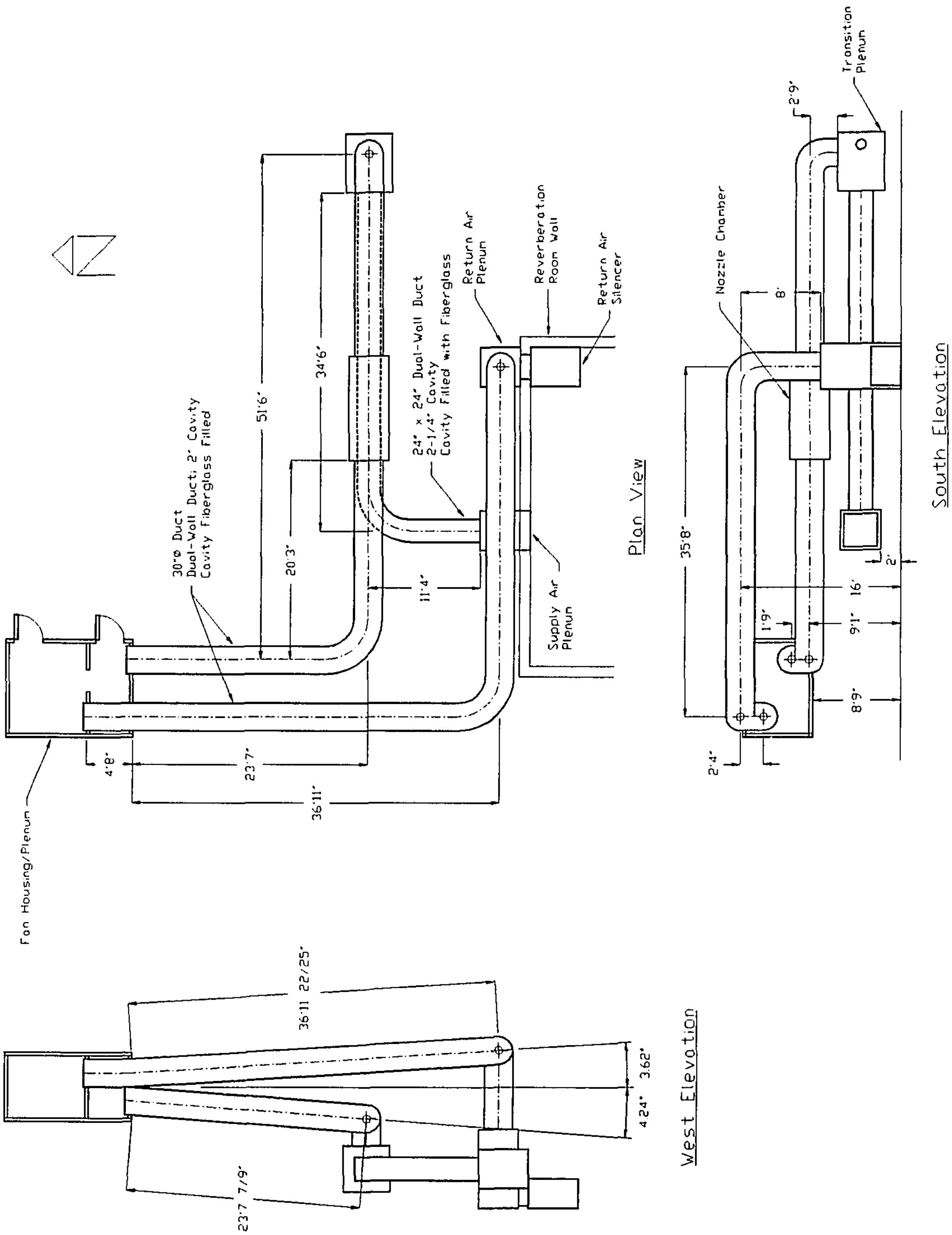
HCATS FAN DATA

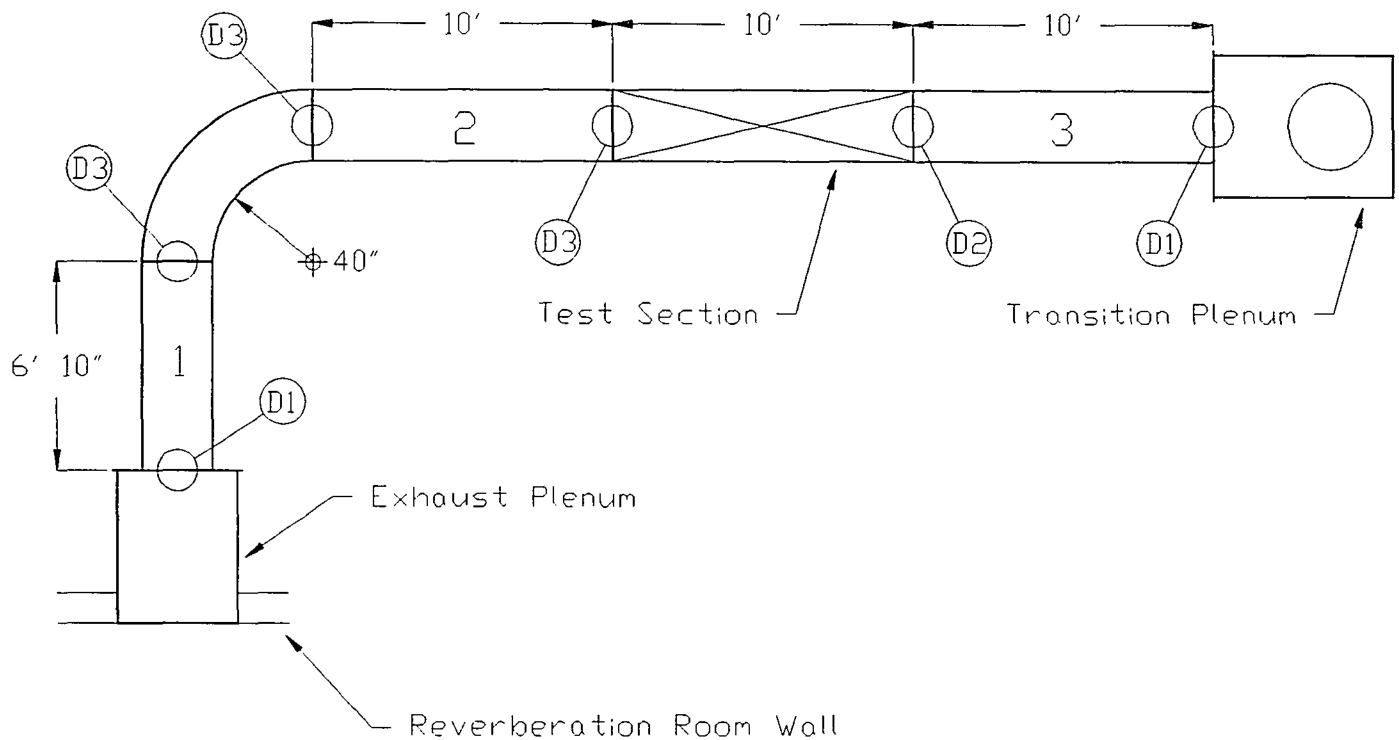

GREENHECK
PROJECT UNLV Test Lab
CUSTOMER Doug Reynolds
MARK
MEMBER OF AMCA
UNIT 33-AFSW-I
CFM 15000
SP 4.0
BHP 12.5
RPM 1143
Psc
BHPc
H -- High motor speed (1143 FRPM)
L -- Low motor speed (762 FRPM)
Psc
BHPc
CFMc x 1000.
28-SEP-92


GREENHECK
07-JAN-93
51469
20 HP 256T MTR.
INSIDE ANGLES
26.19
25.72
9.00
38.31
57.50
35.00
INSIDE ANGLES
37.16
25.00
1.00
4.00

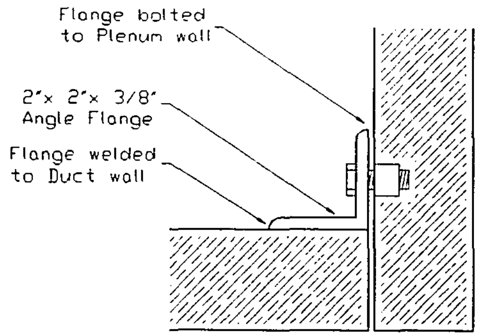
APPENDIX 3

HCATS DETAILED DRAWINGS

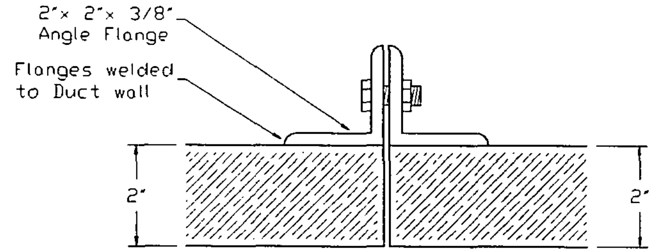

N
30"Ø Duct
Dual-Wall Duct; 2" Cavity
Cavity Fiberglass Filled
24" x 24" Dual-Wall Duct
2-1/4" Cavity
Cavity Filled with Fiberglass
Return Air
Plenum
Reverberation
Room Wall
Return Air
Silencer
Supply Air
Plenum
Fan Housing/Plenum
51'6"
34'6"
20'3"
11'4"
4'8"
23'7"
36'11"
Plan View
Transition
Plenum
Nozzle Chamber
2'9"
8'
35'8"
1'9"
16'
9'1"
2'
8'9"
2'4"
South Elevation
36'11 22/25"
3.62"
4.24"
23'7 7/9"
West Elevation



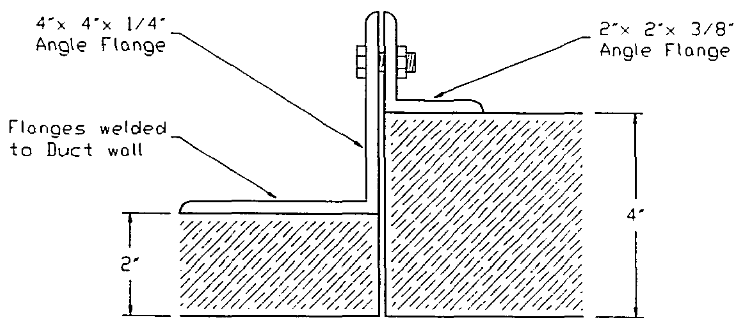
Detail of Test Setup



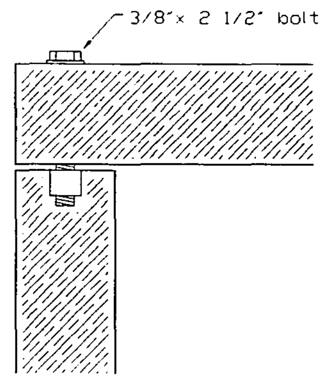
D1 Duct/Plenum Connection



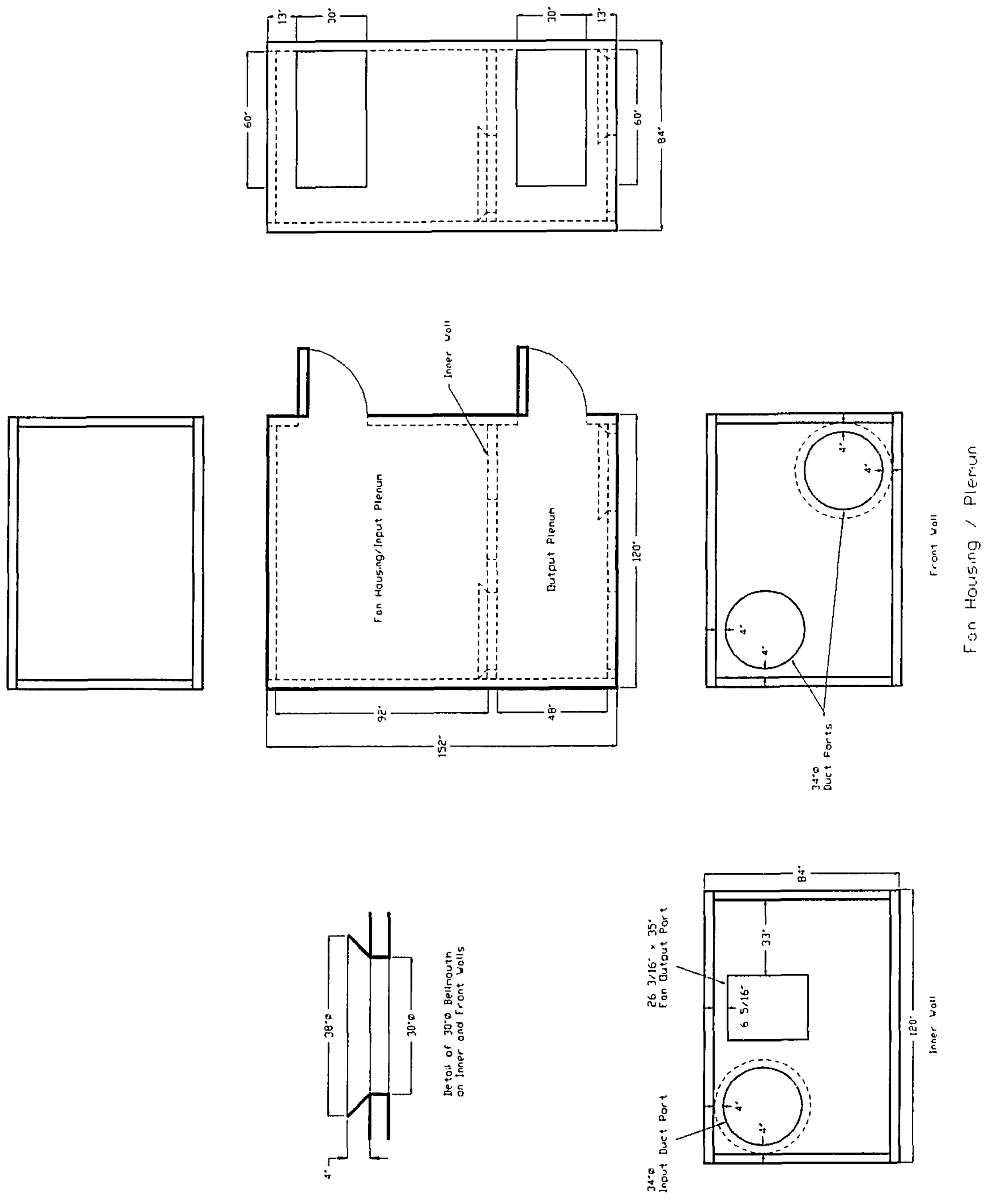
D3 Duct/Duct Connection



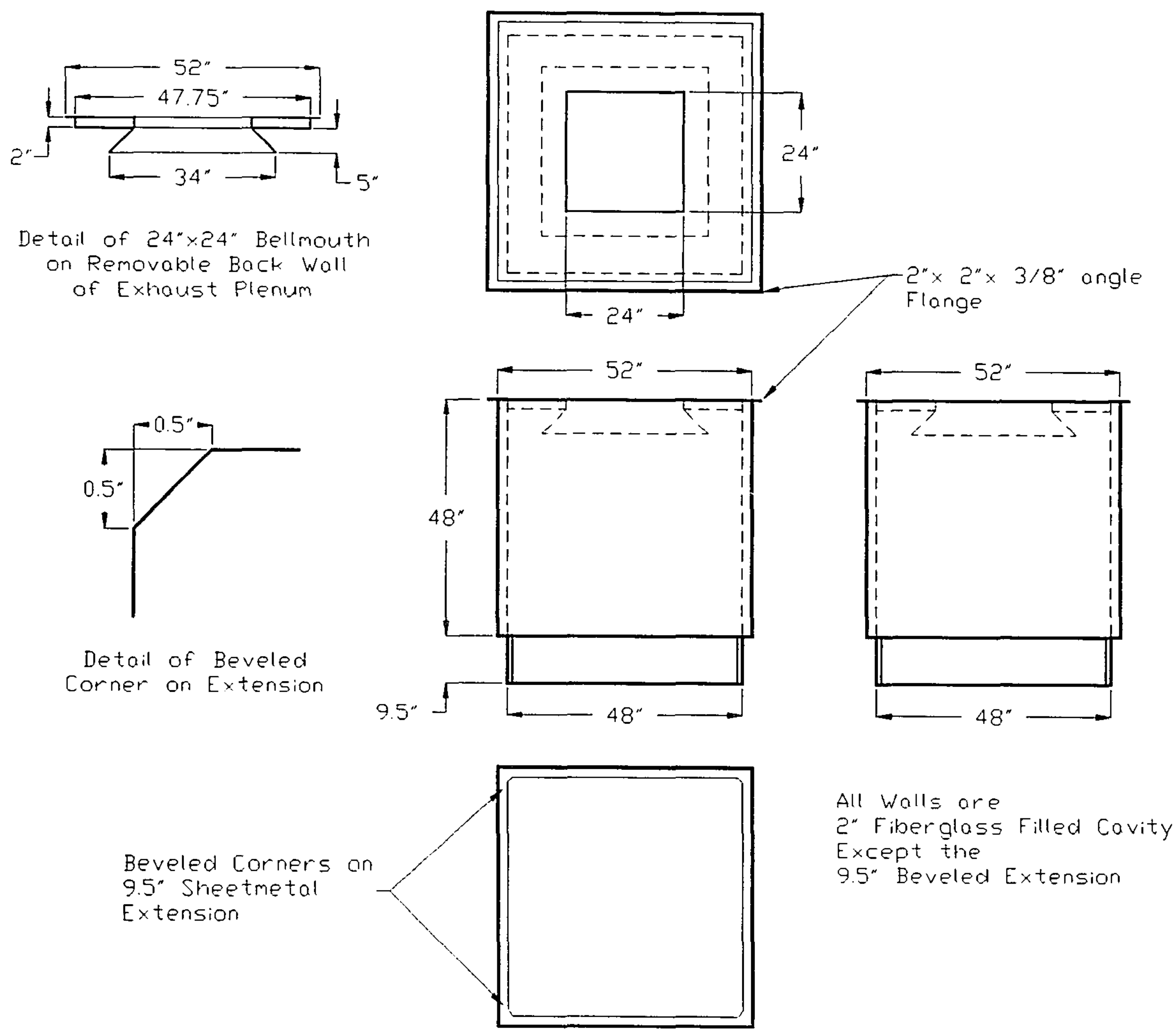
D2 Duct/Duct Connection



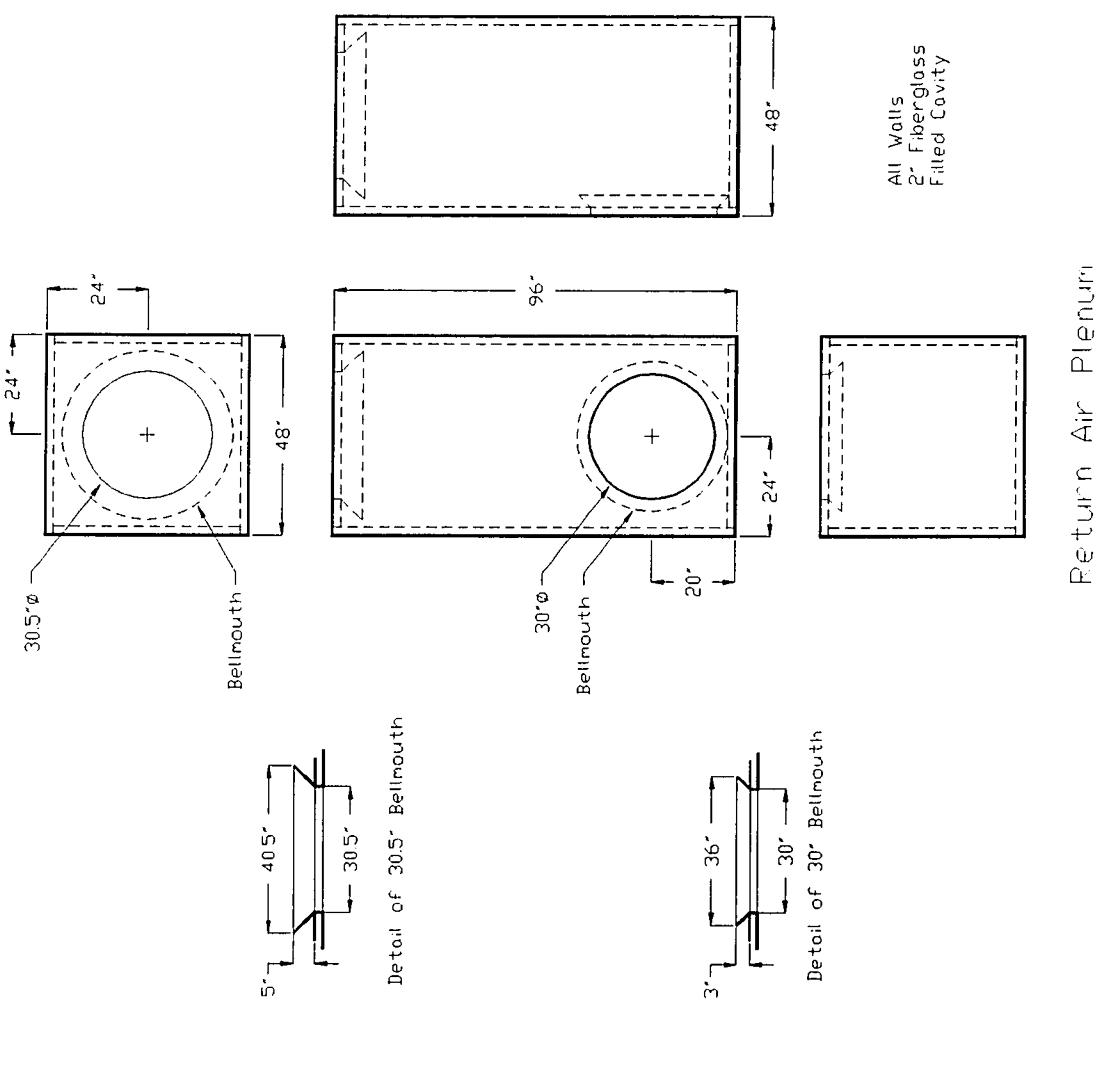
D4 Test Section Wall/Roof Connection



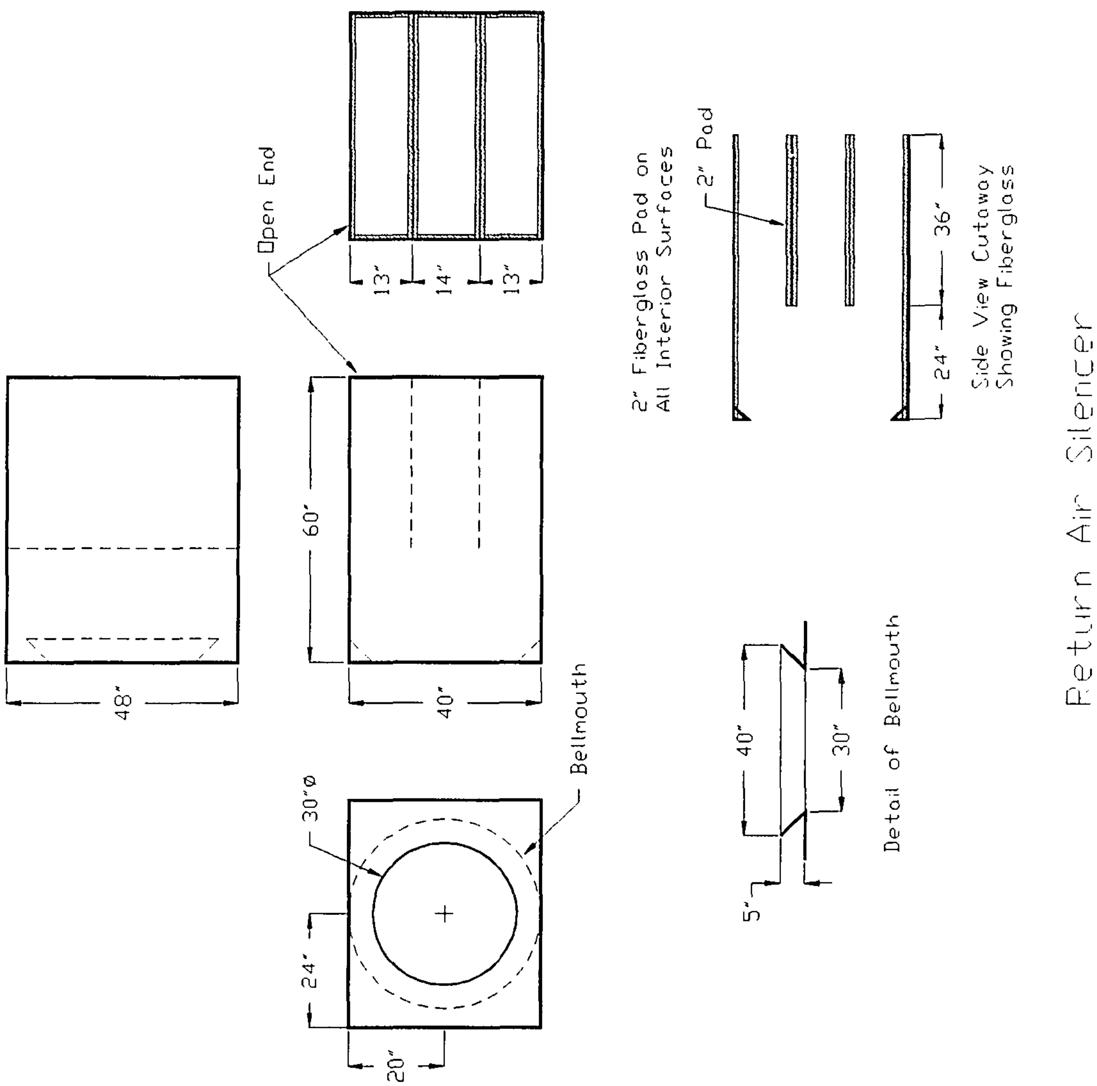
Fan Housing / Plenum
Fan Housing/Input Plenum
Output Plenum
Inner Wall
Front Wall
34"ø Duct Ports
Detail of 30"ø Bellmouth on Inner and Front Walls
26 3/16" x 35" Fan Output Port
34"ø Input Duct Port
6 5/16"
13"
30"
60"
84"
120"
92"
48"
152"
33"
38"ø
30"ø
4"

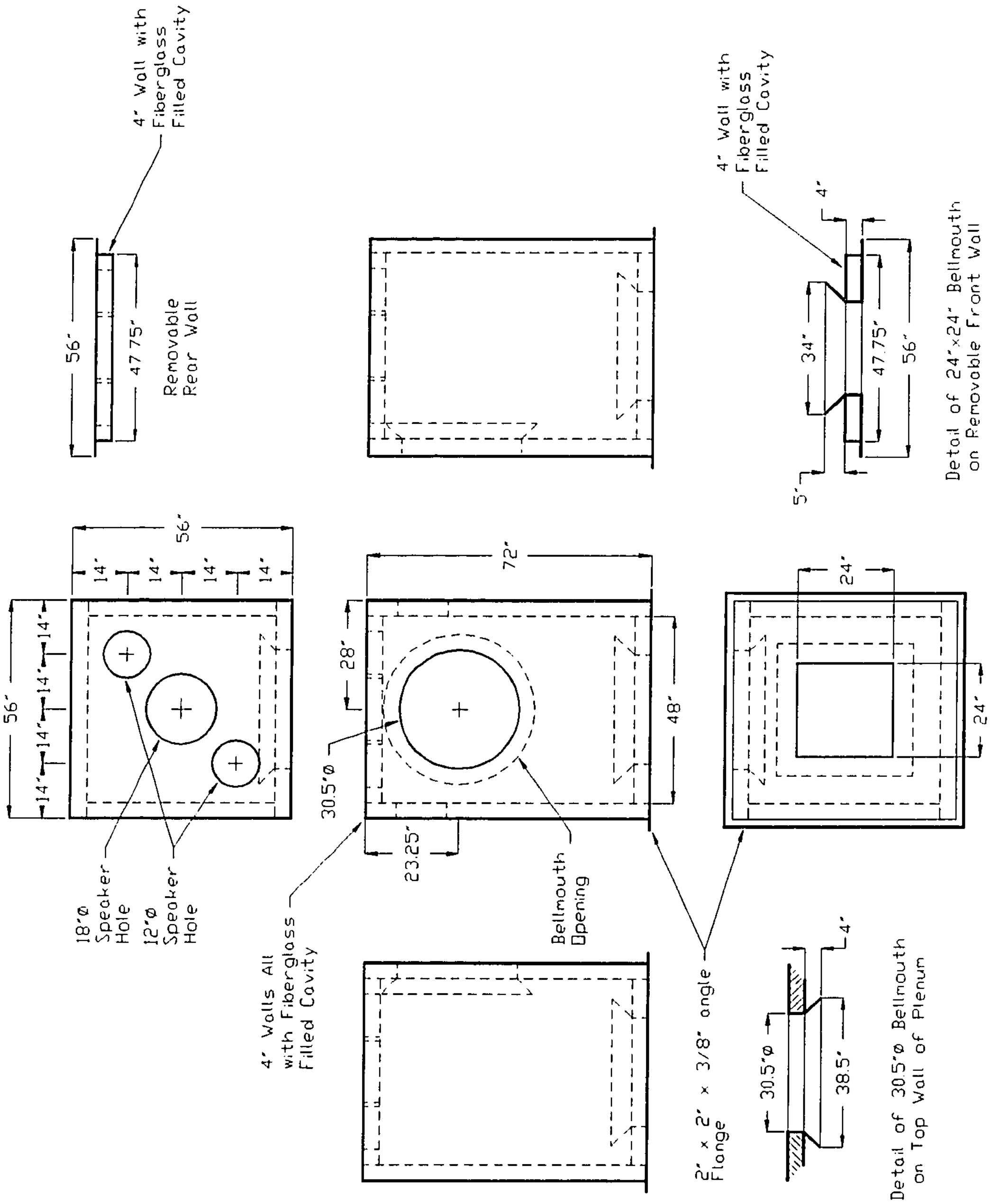


Supply Air Plenum



24"
24"
48"
30.5"ø
Bellmouth
96"
30"ø
Bellmouth
24"
20"
48"
All Walls
2" Fiberglass
Filled Cavity
Return Air Plenum
40.5"
30.5"
5"
Detail of 30.5" Bellmouth
36"
30"
3"
Detail of 30" Bellmouth

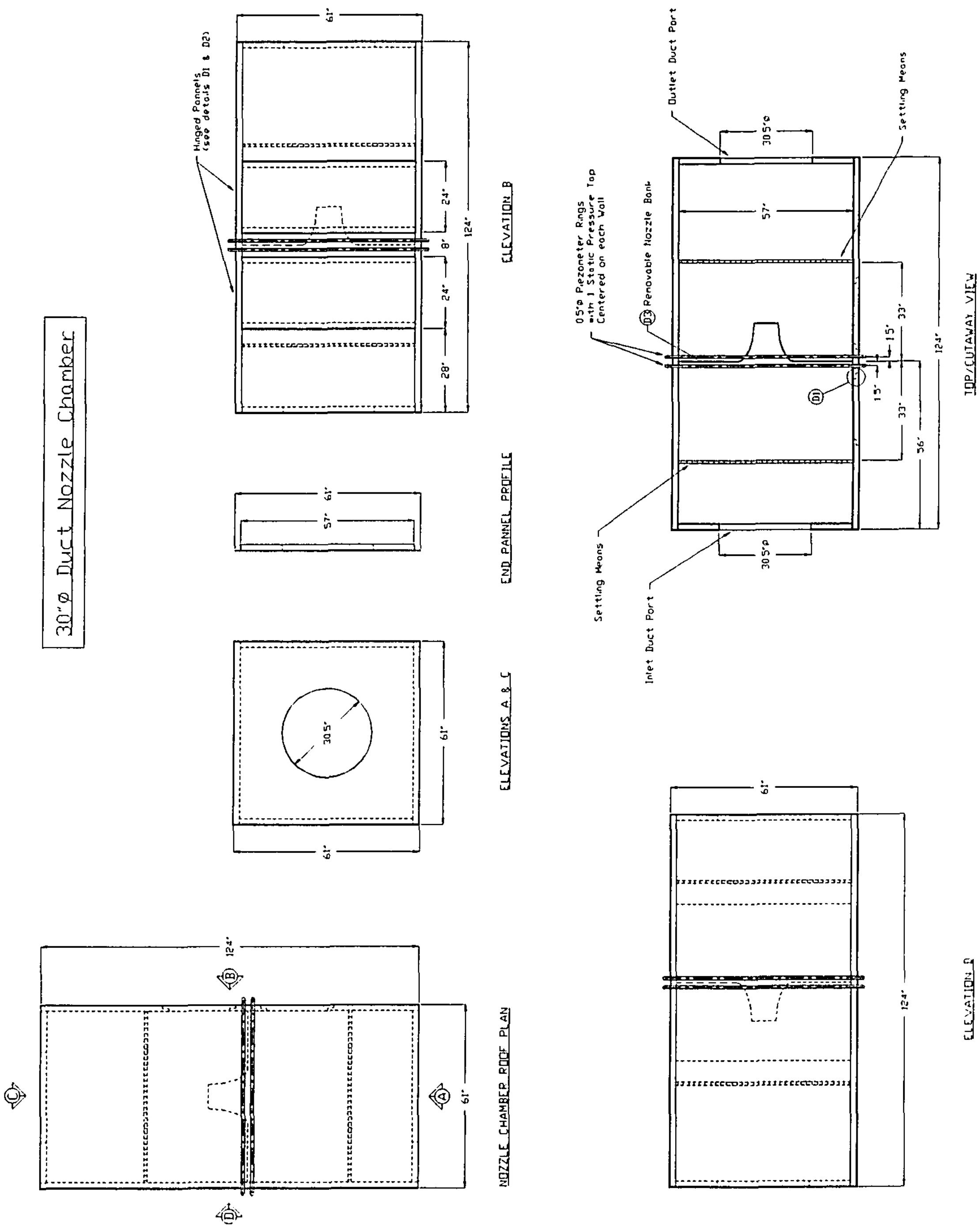

Open End
13"
14"
13"
48"
60"
40"
30"ø
Bellmouth
24"
20"
2" Fiberglass Pad on
All Interior Surfaces
2" Pad
36"
24"
Side View Cutaway
Showing Fiberglass
40"
30"
5"
Detail of Bellmouth
Return Air Silencer

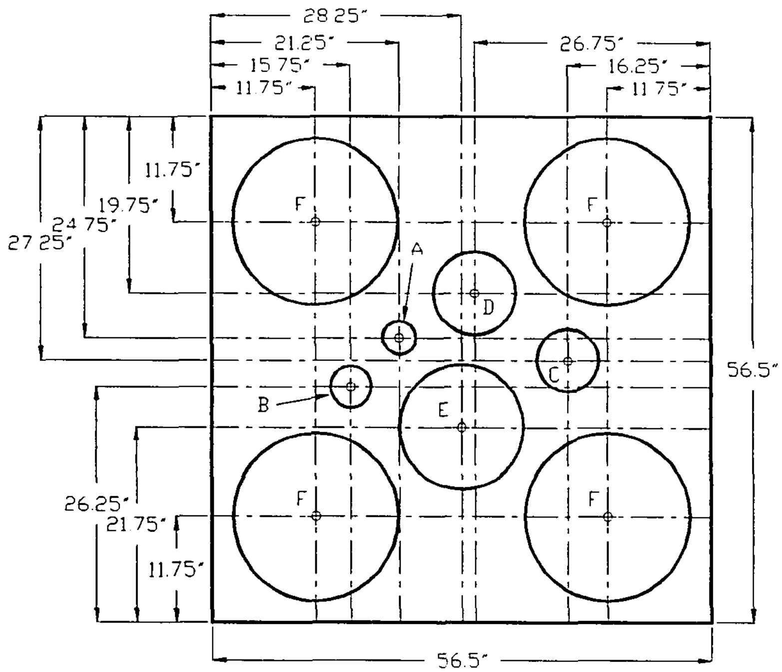


Transition Plenum

APPENDIX 4

HCATS NOZZLE ASSEMBLY DRAWINGS


30"ø Duct Nozzle Chamber
NOZZLE CHAMBER ROOF PLAN
ELEVATIONS A & C
END PANNEL PROFILE
ELEVATION B
TOP/CUTAWAY VIEW
ELEVATION D
Hinged Pannels (see details D1 & D2)
0.5"ø Piezometer Rings with 1 Static Pressure Tap Centered on each Wall
D3 Removable Nozzle Bank
Outlet Duct Port
Inlet Duct Port
Settling Means
Settling Means
30.5"ø
30.5"
57"
61"
124"
24"
8"
28"
33"
15"
56"



Ref. Letter	Nozzle Size	Hole Size
A	1.6 in Ø	3.75 in Ø
B	2.0 in Ø	4.67 in Ø
C	3.0 in Ø	7.00 in Ø
D	4.0 in Ø	9.34 in Ø
E	6.0 in Ø	14.00 in Ø
F	8.0 in Ø	18.67 in Ø

A	B	C	D	E	F	Flow Rate Range
1	0	0	0	0	0	41.9 to 97.7 CFM
0	1	0	0	0	0	65.5 to 152.7 CFM
0	0	1	0	0	0	147.3 to 343.6 CFM
0	0	0	1	0	0	261.8 to 610.9 CFM
0	0	0	0	1	0	589.1 to 1374.5 CFM
0	0	0	0	0	1	1047.2 to 2443.5 CFM
0	0	0	0	0	2	2094.4 to 4886.9 CFM
0	0	0	0	0	3	3141.6 to 7330.5 CFM
0	0	0	0	0	4	4188.8 to 9774.0 CFM

D3 Nozzle Bank Plate for 30" Ø Duct

APPENDIX 5

NOZZLE AIR FLOW RATE CALCULATIONS

This appendix documents the equations and data required to calculate the flow rate of air in a ducted system measured using a standard nozzle bank. All equations and data used in this appendix are based on information in ASHRAE Standard 41.2[5] "Standard Methods for Laboratory Air-Flow Measurement" and the book ASHRAE Fundamentals Handbook[11].

The calculations in this appendix deviate from those outlined in the ASHRAE standard. Changes that where made were deemed necessary to facilitate automation of the data acquisition and calculation process. The calculations that differ from those in the standard are for room air density and the nozzle discharge coefficient. For a detailed explanation of these changes the reader should refer to Sections 2 and 7 of this appendix.

In this appendix and else were in the report, the term air refers to moist air. Moist air is the binary mixture of water vapor and dry air. In all calculations, water vapor and dry air (and thus moist air) are assumed to be ideal gasses.

The following is a summary of the quantities that must be measured for calculations of air flow rate. Use of these measured values will be discussed in detail in the following sections.

1) p_{si} = static pressure at nozzle entrance [in. w.g.]

2) p_{dn} = differential pressure across nozzle bank [in. w.g.]

3) p_{st} = static pressure at test unit entrance [in. w.g.]

4) p_{ub} = uncorrected barometric pressure [in. Hg]

5) t_n = temperature at nozzle entrance [°F]

7) t_t = temperature at test unit entrance [°F]

8) t_R = temperature in room [°F]

9) ϕ = relative humidity [dimensionless]

The calculation process presented here can be used for any nozzle bank arrangement and for either of the two ISO standard nozzle designs. The nozzle banks used in this the VAST Lab are discussed in Chapters 2 and 4. The nozzle type used is referred to as a long radius, low ratio nozzle. Its design is illustrated in Figure A5.1. The data associated with this nozzle is shown in Table A5.1. The following sections describe the equations used to calculate the volumetric flow rate of air. The equations are presented in the order of calculation.

Nozzle Throat Diameter [in]	Nozzle Throat Area [in^2]	Volumetric Flow Rate Range [CFM]	
		minimum	maximum
1.6	2.01	42	98
2.0	3.14	65	153
3.0	7.07	147	344
4.0	12.57	262	611
6.0	28.27	589	1,374
8.0	50.27	1,047	2,443

Table A5.1: Flow Rate Ranges Coresponding to Nozzle Sizes

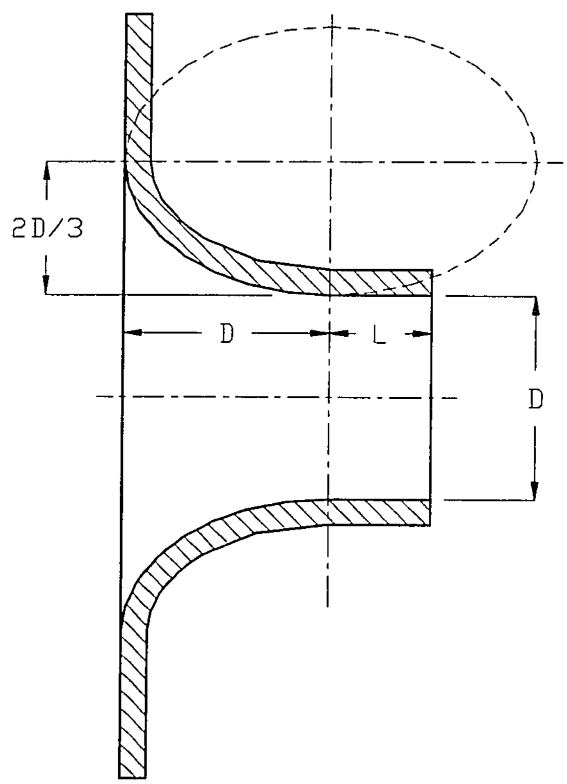


Figure A5.1: Long Radius, Low Ratio Nozzle

A5.1 Corrected Barometric Pressure

The corrected barometric pressure is the barometric pressure reading in in. Hg corrected for temperature, gravity, and altitude. The following correction equations are based on those found in the Instruction Booklet[14] for the Princo fortin type mercurial barometer used in the VAST Lab. Their forms have been changed to enhance clarity.

$$p_b = C_t \, C_g \, p_{ub} + \Delta p_s \qquad \text{Equ A5.1}$$

The temperature correction factor, C_t, is:

$$C_t = \frac{1 + 0.0000102\,(t_R - 62)}{1 + 0.0001010\,(t_R - 32)} \qquad \text{Equ A5.2}$$

The gravity correction factor, C_g, is:

$$C_g = \frac{980.616}{980.665}\,(1 - 0.0026373\cos(2\theta) + 0.0000059\cos^2(2\theta)) \qquad \text{Equ A5.3}$$

where θ is the latitude in degrees north or south of the equator. The latitude for Las Vegas, Nevada is approximately 36.2 °North.
The sea level differential pressure for standard conditions is:

$$\Delta p_s = p_o\,(1 - (1 - 0.3048\,h\frac{0.0065}{288.16})^{5.2561}) \qquad \text{Equ A5.4}$$

where h is the elevation above sea level in ft and p_o is the standard pressure at sea level (p_o = 29.921 in. Hg).

A5.2 Room Air Density

The density of the air in the ducted path is referenced to the density of the room air. Room air is the air in the facility that is at atmospheric pressure. This excludes air in any part of the ducted path, which will most likely be at positive gauge pressures.

The ASHRAE standard calls for the calculation of room air density based on dry and wet-bulb temperature measurements. Wet-bulb temperature measurements are not conducive to automated instrumentation. In order to automate the measurement process a dry-bulb (thermocouple) temperature measurement, t_R, and a relative humidity (hygrometer) measurement, ϕ, will be used in stead. The instruments used to make these measurements are discussed else were in this report. The following equations are used to calculate the density of the room air.

The saturated vapor pressure of air over liquid water, p_{ws}, for the temperature range of 32 °F to 392 °F is given by equation A5.5 in psia.

$$\ln(p_{ws}) = \frac{C_1}{t_A} + C_2 + C_3 t_A + C_4 t_A^{\,2} + C_5 t_A^{\,3} + C_6 \ln(t_A) \qquad \text{Equ A5.5}$$

where: $t_A = t_R + 459.67$ (room temperature °R)

$C_1 = -1.0440397E+04$

$C_2 = -1.1294650E+01$

$C_3 = -2.7022355E-02$

$C_4 = 1.2890360E-05$

$C_5 = -2.4780681E-09$

$C_6 = 6.5459673$

The partial vapor pressure, p_w , is calculated using the definition of relative humidity in terms of the partial pressures p_w and p_{ws}.

$$\phi = \left. \frac{p_w}{p_{ws}} \right|_{t,\,p} \qquad \text{Equ A5.6}$$

where p_w and p_{ws} correspond to their respective mole fractions saturated at the same temperature and pressure. Since ϕ is a dimensionless ratio p_w is in units of psia.

To use p_w in the equation for room air density it must be converted to units of in. Hg. The conversion of psi to in. Hg requires a conversion factor, C_f, that is referenced to a specific temperature and gravitational acceleration. The converted pressure must then be corrected for the temperature and gravity at the location of measurement. The conversion equation is:

$$[\text{in. Hg}] = C_f\, C_t\, C_g\, [\text{psia}] \qquad \text{Equ A5.7}$$

where $C_f = 2.036$ and C_t and C_g are from equations A5.2 and A5.3.

The room air density in lb_m / ft^3 is:

$$\rho_R = \frac{70.73\,(\,p_b - 0.378 p_w\,)}{R\,(\,t_R + 459.67\,)} \qquad \text{Equ A5.8}$$

Where R is the universal gas constant:

$$R = 53.35\, \frac{ft \cdot lb_f}{lb_m \cdot R}$$

A5.3 Air Density in the Ducted Path

The air density at locations inside the ducted air path will be different from the room air density. Variations in air density at these locations will effect the calculations of the air flow rate. The density of the air at the nozzle entrance and at the device being tested will need to be calculated.

The following equation will give the air density, ρ_x, at location x based on the room air density, ρ_R, and the pressure, p_x, and temperature, t_x, at location x. The equation assumes that the moisture content of the air in the air flow path is the same as that for the room air.

$$\rho_x = \rho_R \frac{(p_x + 13.63 p_b)(t_R + 459.67)}{13.63\, p_b\, (t_x + 459.67)} \qquad \text{Equ A5.9}$$

A5.4 Nozzle Pressure Ratio

The nozzle pressure ratio, α, is the ratio of nozzle exit pressure to nozzle entrance pressure.

$$\alpha = 1 - \frac{5.187\, p_d}{R\, \rho_n\, (t_n + 459.67)} \qquad \text{Equ A5.10}$$

Where R is the gas constant for air and ρ_n is the air density at the nozzle inlet based on equation A5.4.

A5.5 Expansion Factor

The flow rate equation is based on an incompressible fluid model. Since air is a compressible fluid, the flow rate equation must be corrected to give accurate flow rate values. The expansion factor, Y, is a dimensionless correction factor that is used for this purpose. Many empirical and analytical equations exist that attempt to predict the expansion factor. The equation suggested by the standard for a nozzle in a chamber is:

$$Y = 0.452 + 0.548\alpha \qquad \text{Equ A5.11}$$

A5.6 Reynolds Number

The following equation is for the Reynolds number, Re, of the air jet exiting the nozzle throat. In the case of a nozzle bank, were multiple nozzles may be used at one time, the Reynolds number must be calculated for each nozzle.

$$Re_i = 1.363\times10^6 \ d_i \sqrt{p_d \, \rho_n} \qquad \text{Equ A5.12}$$

Where the subscript i indicates the nozzle, ρ_n is air density at the nozzle inlet based on equation A5.4, and d_i is the nozzle throat diameter. This equation is an approximation suggested by the standard. It is valid for temperatures between 40 °F and 100 °F.

A5.7 Discharge Coefficient

The discharge coefficient, D, is the ratio of the actual and the ideal mass flow rates through a nozzle. It is used as a correction factor in the flow rate equation. The ideal mass flow rate through the nozzle is based on an effective flow area equal to the nozzle throat area. In application, the effective flow area is reduced by a boundary layer in the nozzle throat due to friction.

Many equations have been developed to predict the discharge coefficient. The ASHRAE standard supplies a table of discharge coefficients for given values of Re. That table is based on equations found in the paper "Fan Test Chamber-Nozzle Coefficients" by Bohanon[10]. Equations will be used in stead of the table so that the calculation process can be automated.

The discharge coefficient equations are empirical. They are valid for Reynolds numbers above 12,000 and are specific to the geometry of the nozzle used. Equation A5.13a should be used for long radius, low ratio nozzles where L = 0.5D and equation A5.13b should be used for long radius, low ratio nozzles where L = 0.6D (see Figure A5.1).

$$D_i = 0.99855 - \frac{6.688}{\sqrt{Re_i}} + \frac{131.5}{Re_i} \qquad \text{Equ A5.13a}$$

$$D_i = 0.99855 - \frac{7.006}{\sqrt{Re_i}} + \frac{134.6}{Re_i} \qquad \text{Equ A5.13b}$$

The nozzles used in HCATS and the Throw Room have an L = 0.6D.

A5.8 Flow Rate at the Nozzle Entrance

The equation for the flow rate at the nozzle entrance, Q_n, in CFM is:

$$Q_n = 1{,}096\ Y \sqrt{\frac{p_d}{\rho_n}} \sum_{i=1}^{m} D_i A_i \qquad \text{Equ A5.14}$$

This equation is explicitly for use with nozzles in a chamber and may be used for situations where more than one nozzle is employed for a single air flow measurement. The limit of summation, m, is equal to the number of nozzles used to make a single air flow measurement. The values D_i and A_i are the nozzle discharge coefficient and nozzle throat area and are specific to each nozzle used.

A5.9 Air Flow Rate at the Test Unit

The air flow rate at the test unit, Q_t, may be found using the equation of continuity. This equation is expressed here to affirm the fact that air is a compressible fluid. The air flow rate at the nozzle entrance may only be used as a reference to the air flow rate at the test unit. Equation A5.4 can be used to find the density of the air at the test unit.

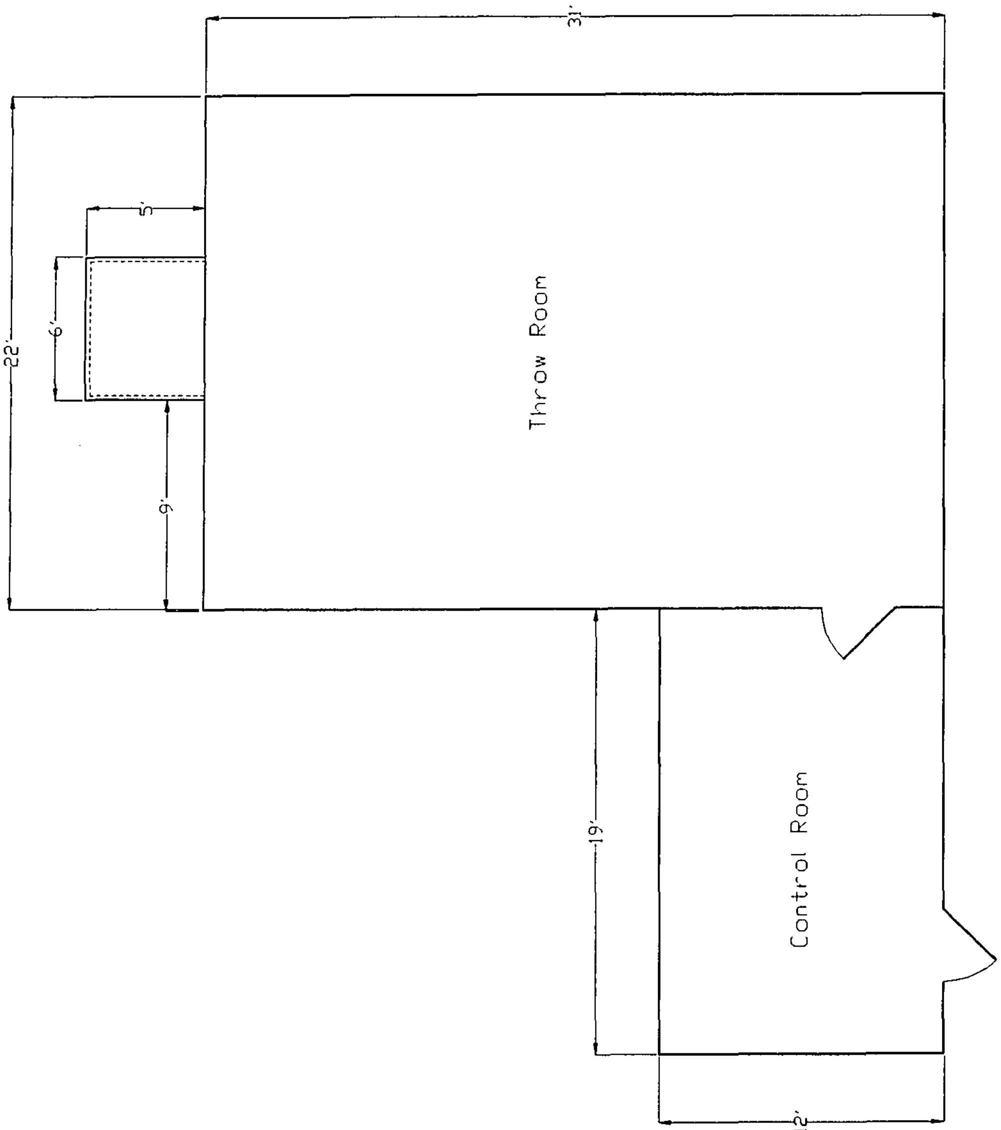
$$Q_t = Q_n \frac{\rho_n}{\rho_t} \qquad \text{Equ A5.15}$$

where

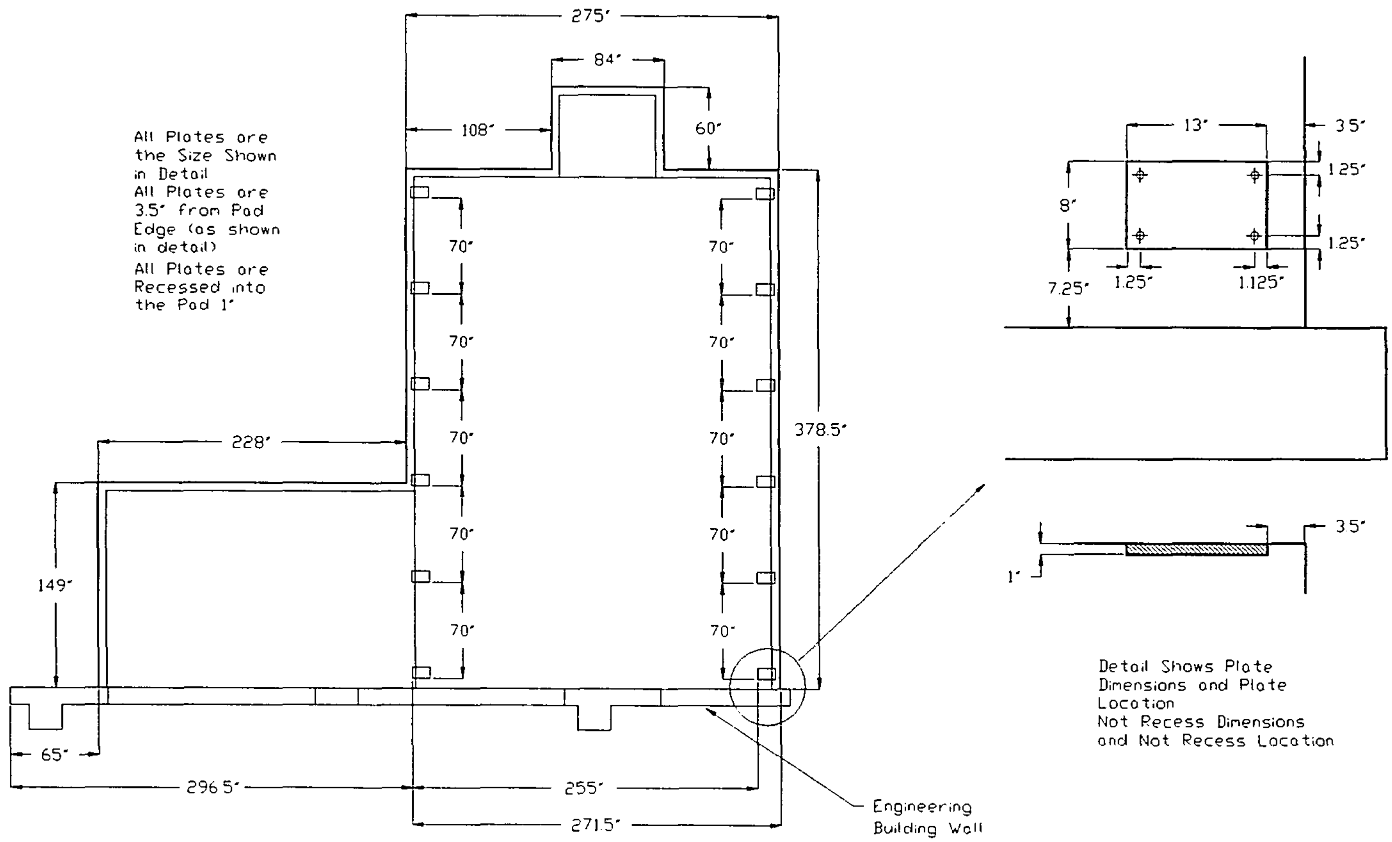
$$\rho_t = \rho_R \frac{(p_{st} + 13.63\,p_b)(t_R + 459.67)}{13.63\ p_b\,(t_t + 459.67)} \qquad \text{Equ A5.16}$$

APPENDIX 6

THROW ROOM HOUSING DRAWINGS



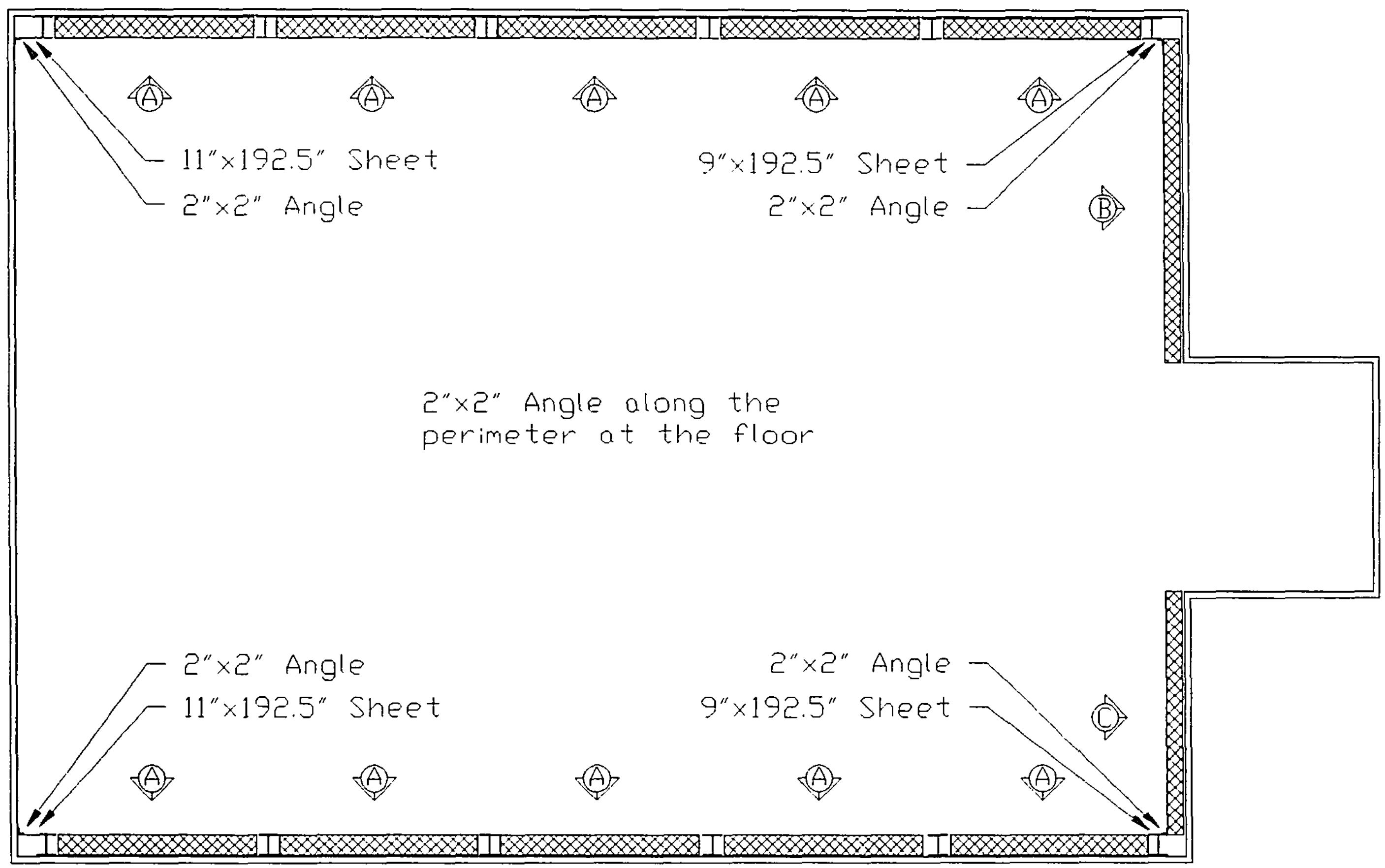
Throw Room & Control Room Plan View



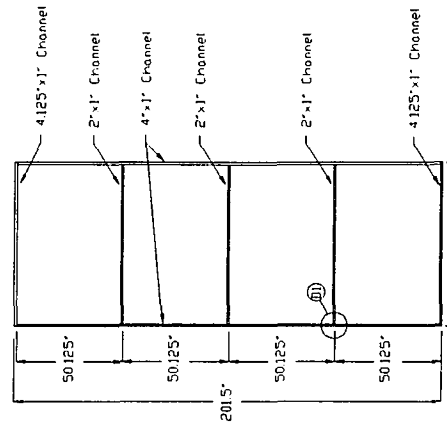
Plan View of Concrete Pad

APPENDIX 7

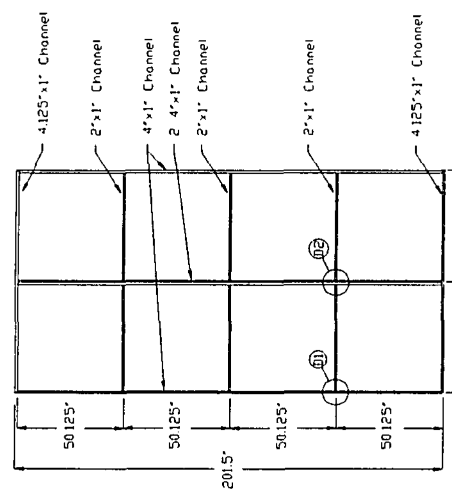
THROW ROOM INTERIOR WALL DRAWINGS



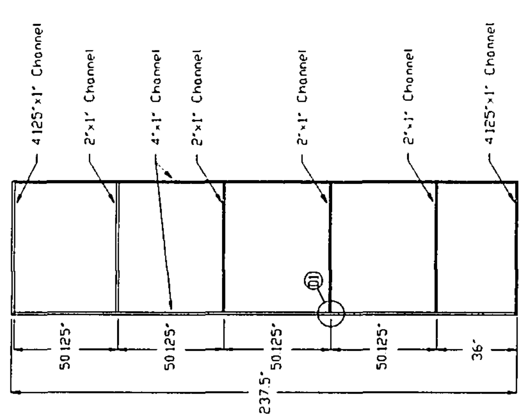
Top View of Throw Room
Showing the Locations of the Interior Panel Sub-Frames



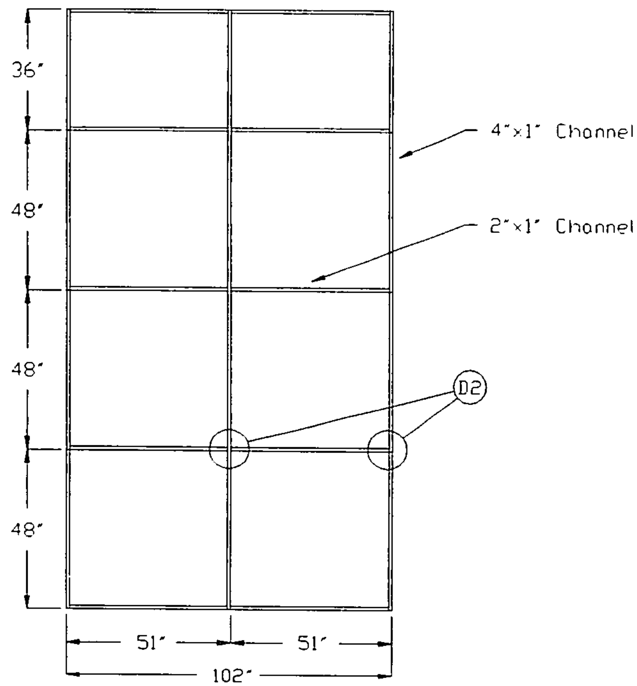
INTERIOR PANEL SUB-FRAME C



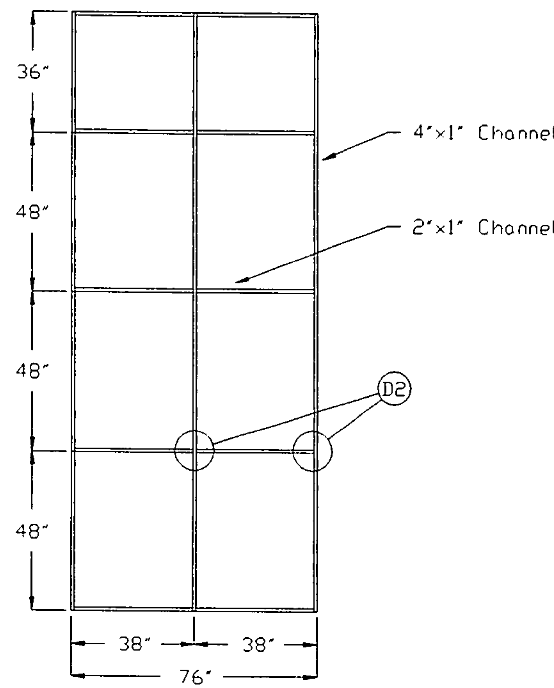
INTERIOR PANEL SUB-FRAME B



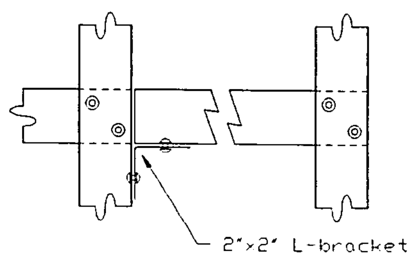
INTERIOR PANEL SUB-FRAME A



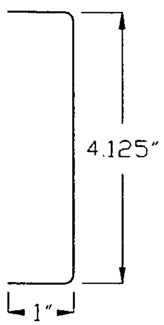
INTERIOR PANNEL SUB-FRAME B



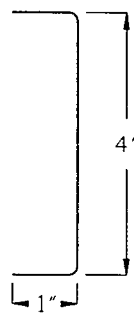
INTERIOR PANNEL SUB-FRAME C



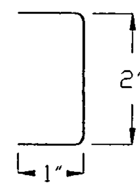
D2 CHANNEL JOINT DETAIL



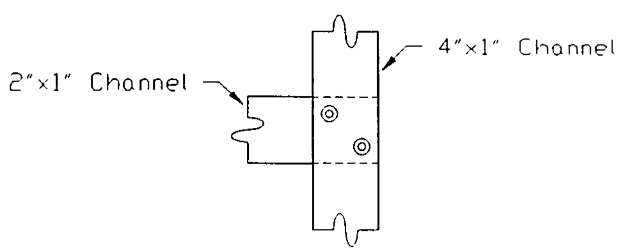
4.125"x1" CHANNEL DETAIL



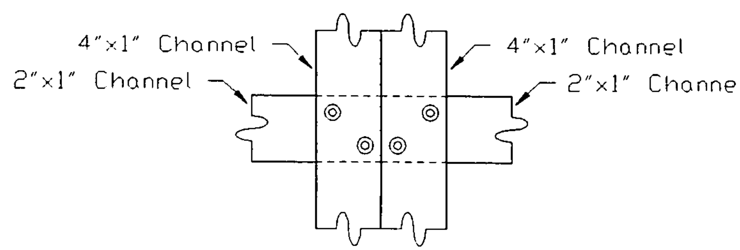
4"x1" CHANNEL DETAIL



2"x1" CHANNEL DETAIL



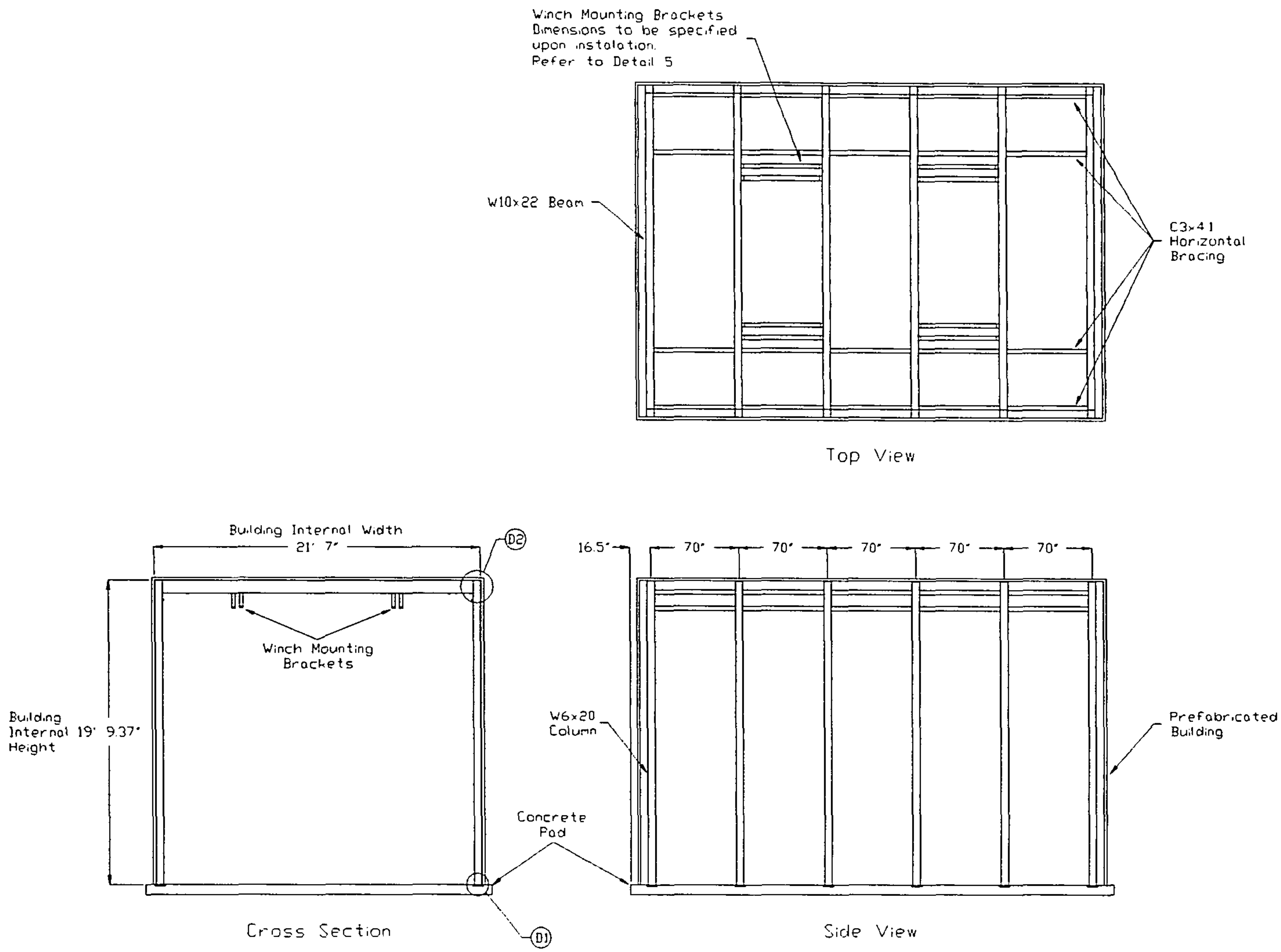
(D1) CHANNEL JOINT DETAIL



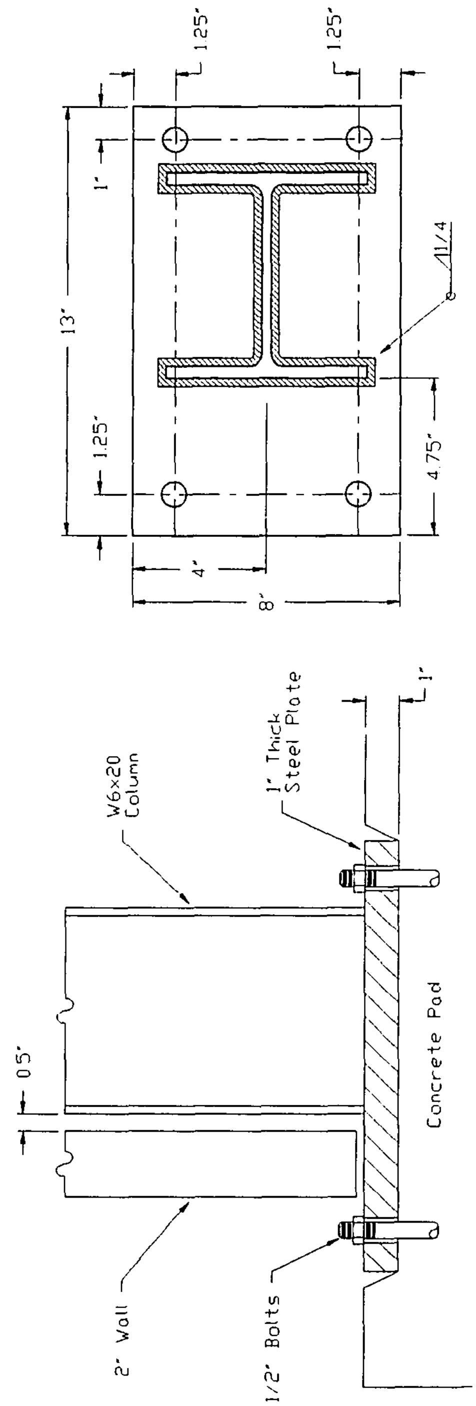
(D2) CHANNEL JOINT DETAIL

APPENDIX 8

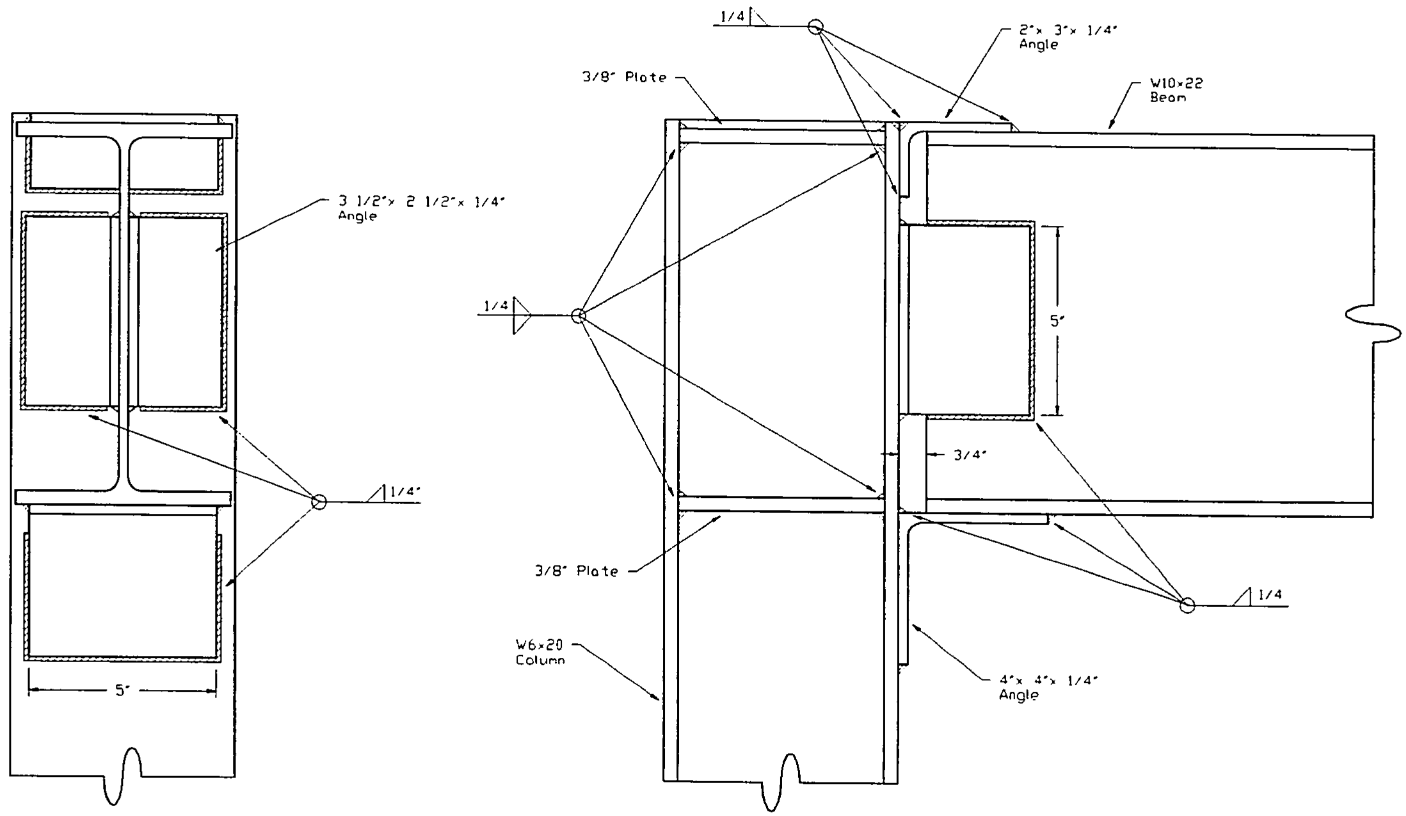
VARIABLE HEIGHT CEILING SYSTEM DRAWINGS



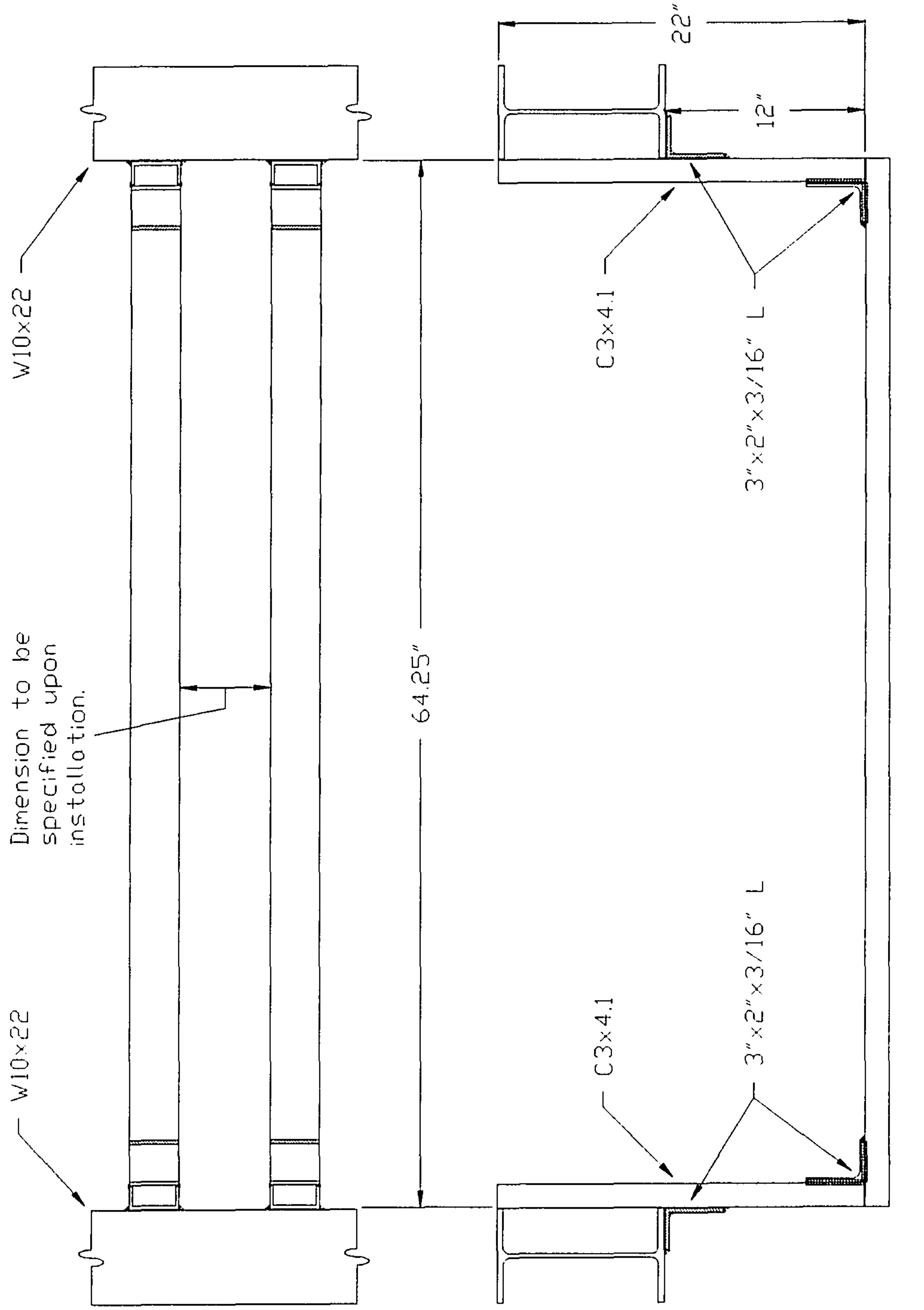
Variable Height Ceiling Support Structure



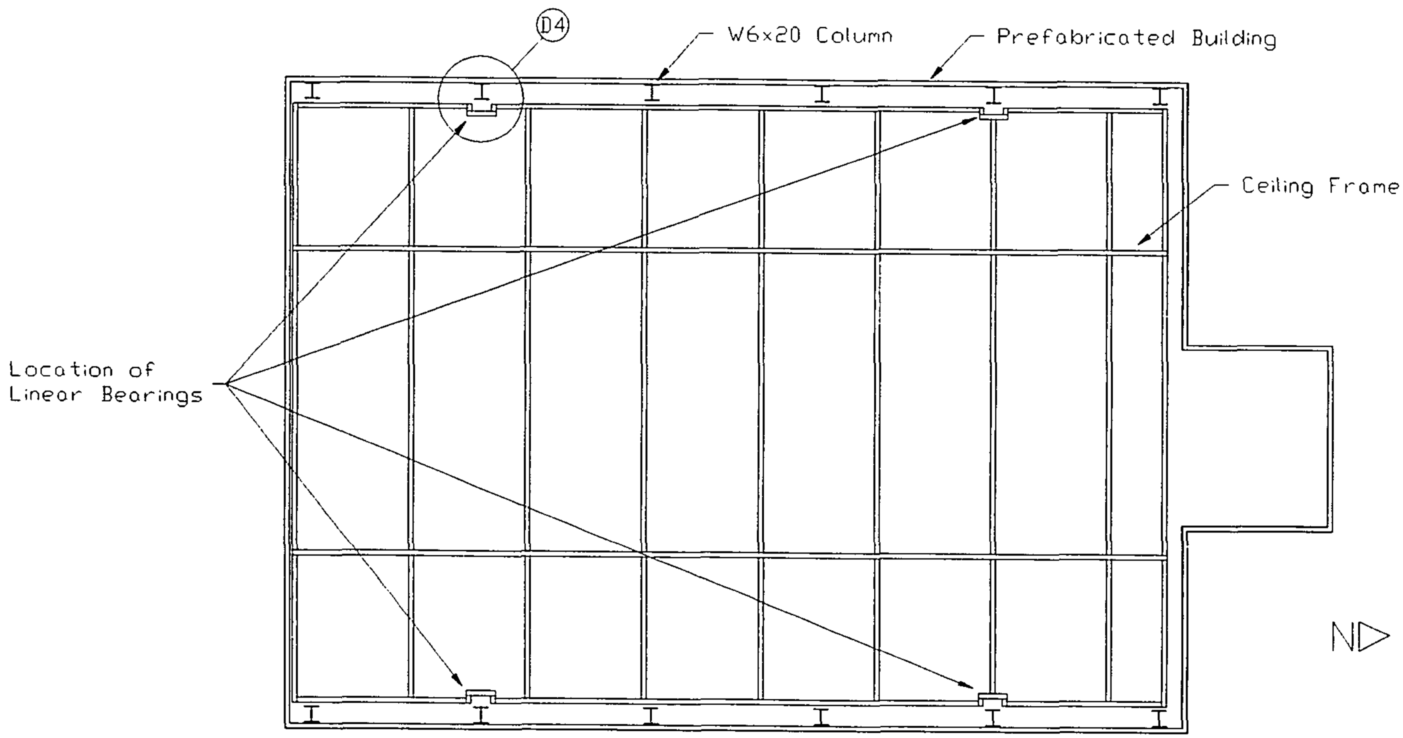
D1 Column Base Plate Assembly



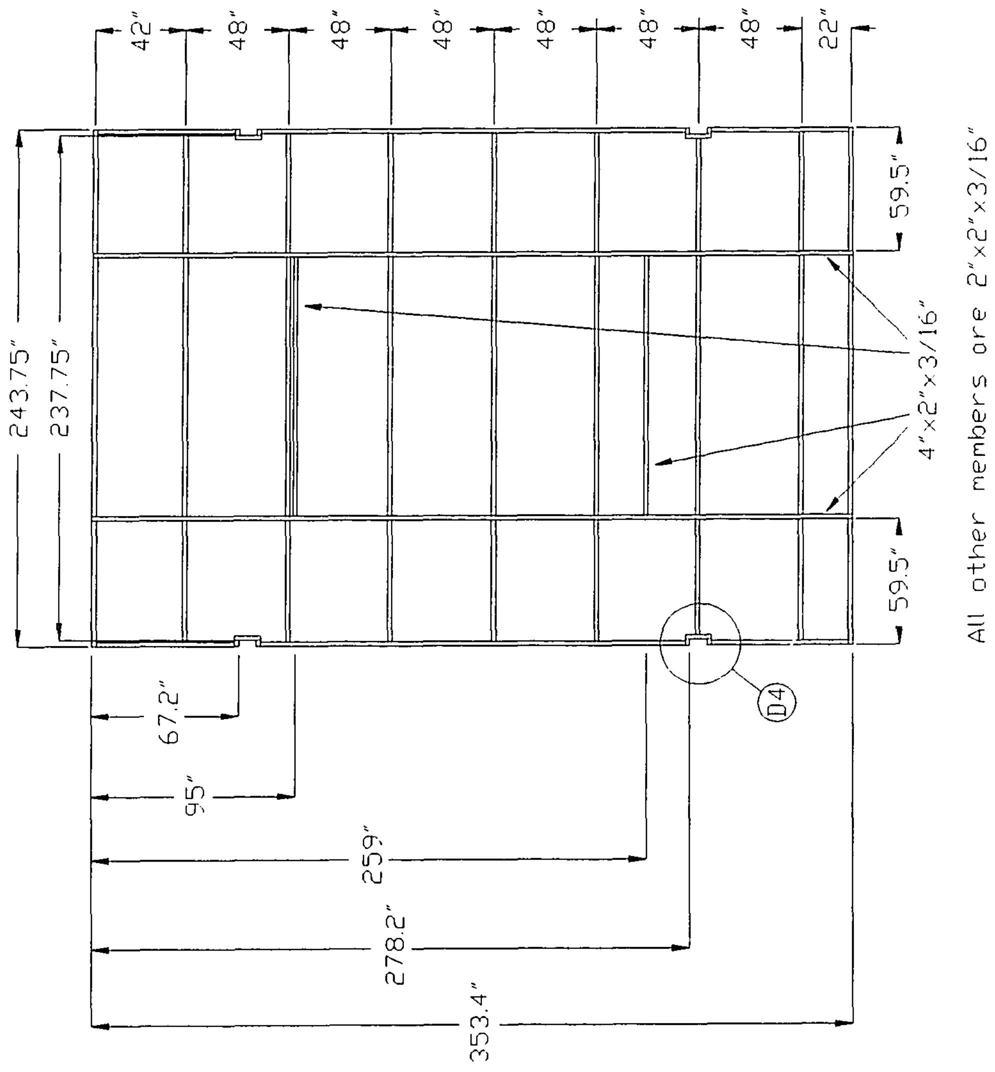
D2 Column/Beam Connection



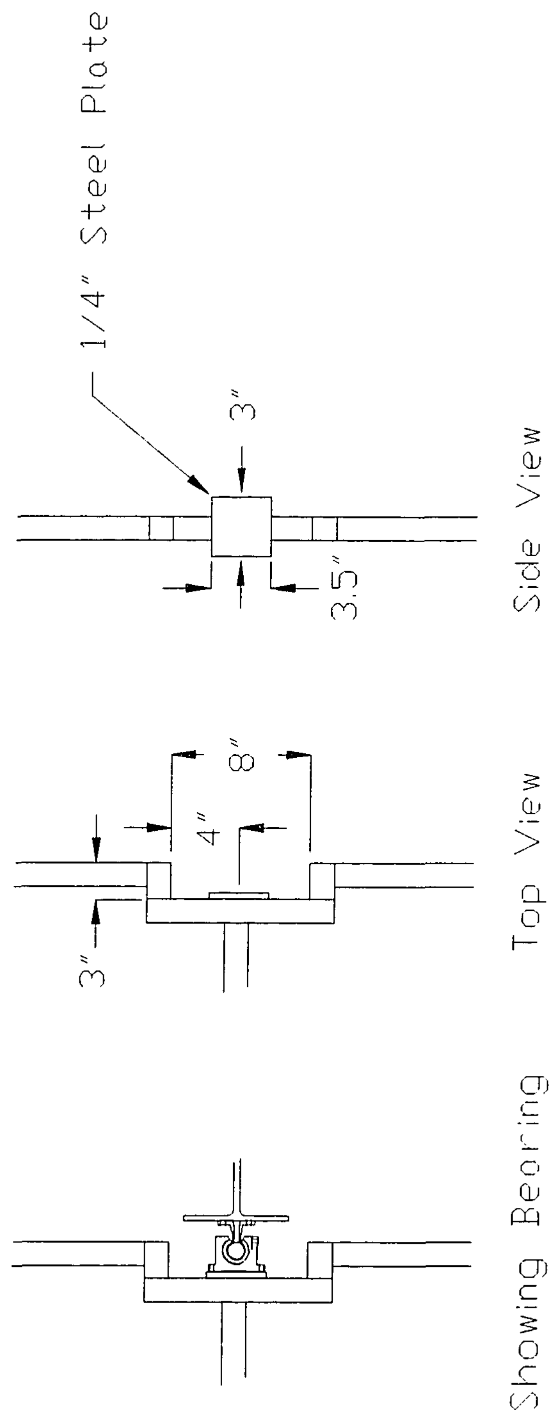
D5 Detail of Winch Mounting Bracket



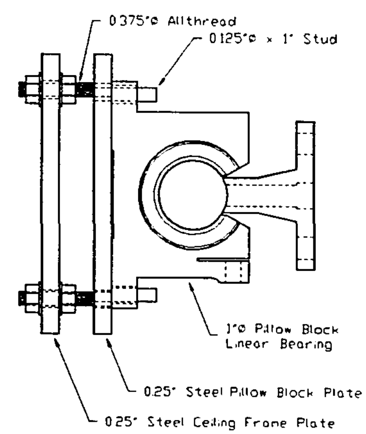
Top View of Throw Room
Showing Location of Linear Bearings



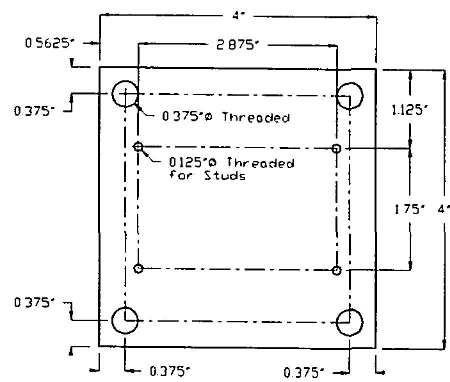
D3 Variable Height Ceiling Frame



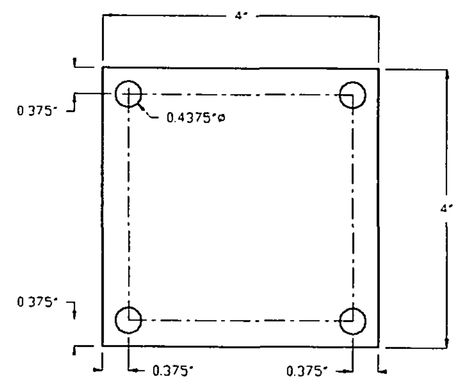
D4 Detail of Bearing Mount



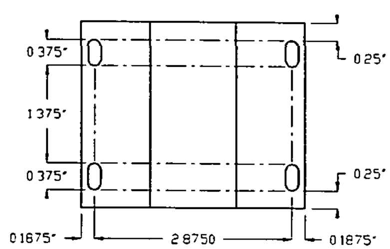
PILLOW BLOCK/CEILING FRAME
CONNECTION ASSEMBLY



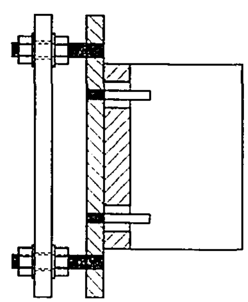
PILLOW BLOCK PLATE



CEILING FRAME PLATE



0.1875" SLOTS IN PILLOW BLOCK
FOR THE 0.125"ø STUDS

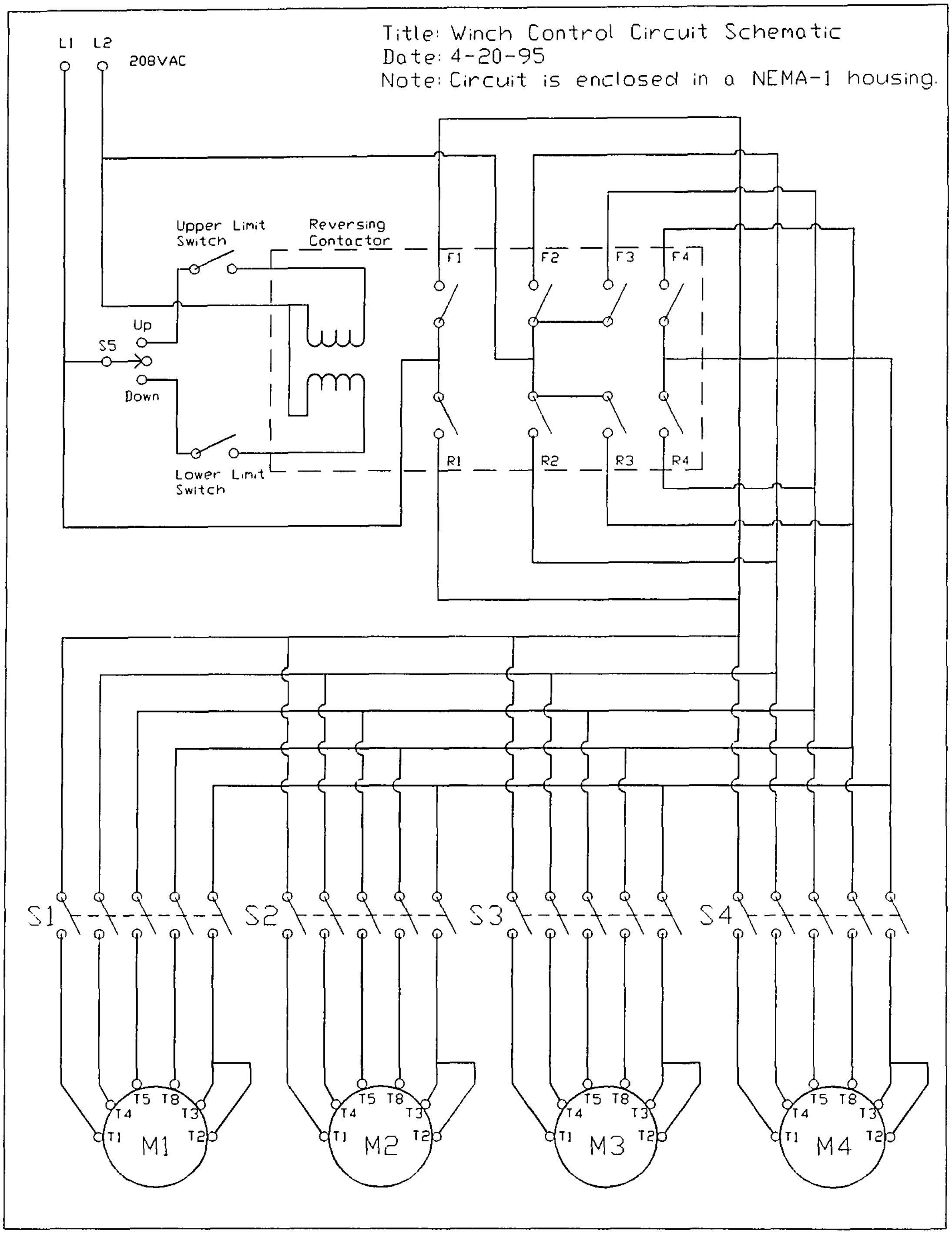


CUTAWAY SHOWING SLOT/STUD
AND THREADED CONNECTIONS

Ceiling Frame
Bearing Connection

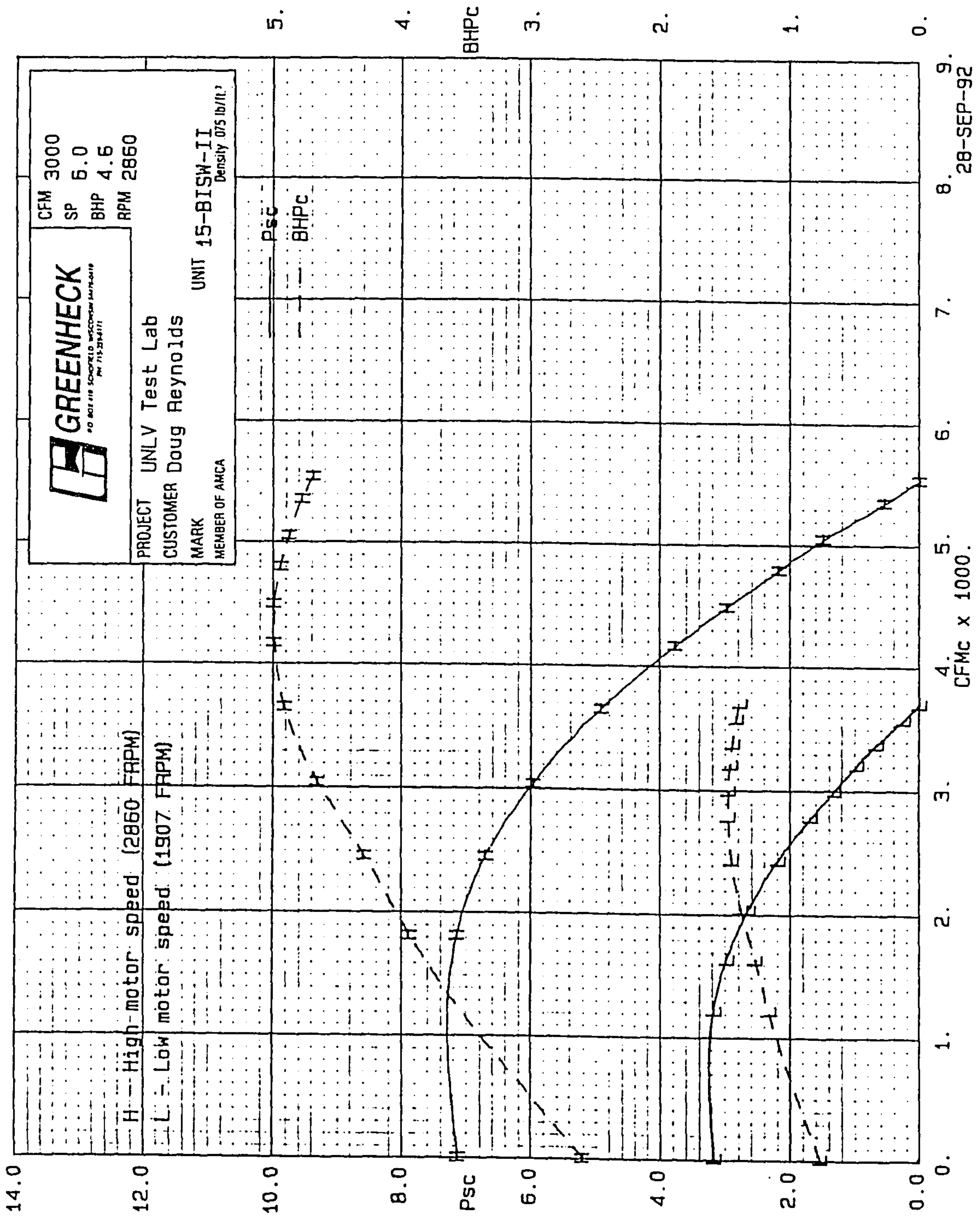
APPENDIX 9

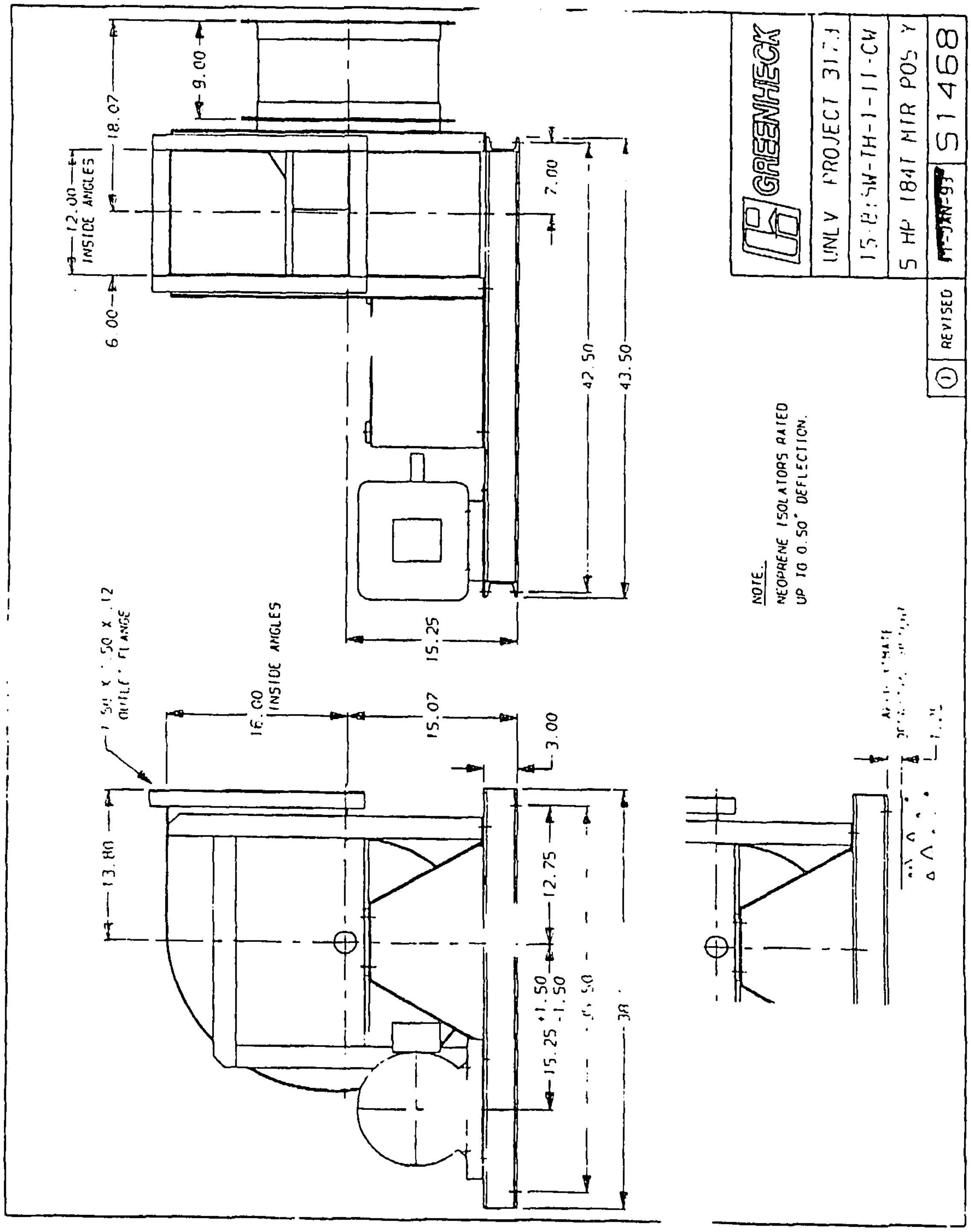
WINCH CONTROL CIRCUIT SCHEMATIC


Title: Winch Control Circuit Schematic
Date: 4-20-95
Note: Circuit is enclosed in a NEMA-1 housing.
L1 L2
208VAC
Upper Limit Switch
Reversing Contactor
F1 F2 F3 F4
Up
S5
Down
Lower Limit Switch
R1 R2 R3 R4
S1 S2 S3 S4
T5 T8
T4 T3
T1 T2
M1
M2
M3
M4

APPENDIX 10

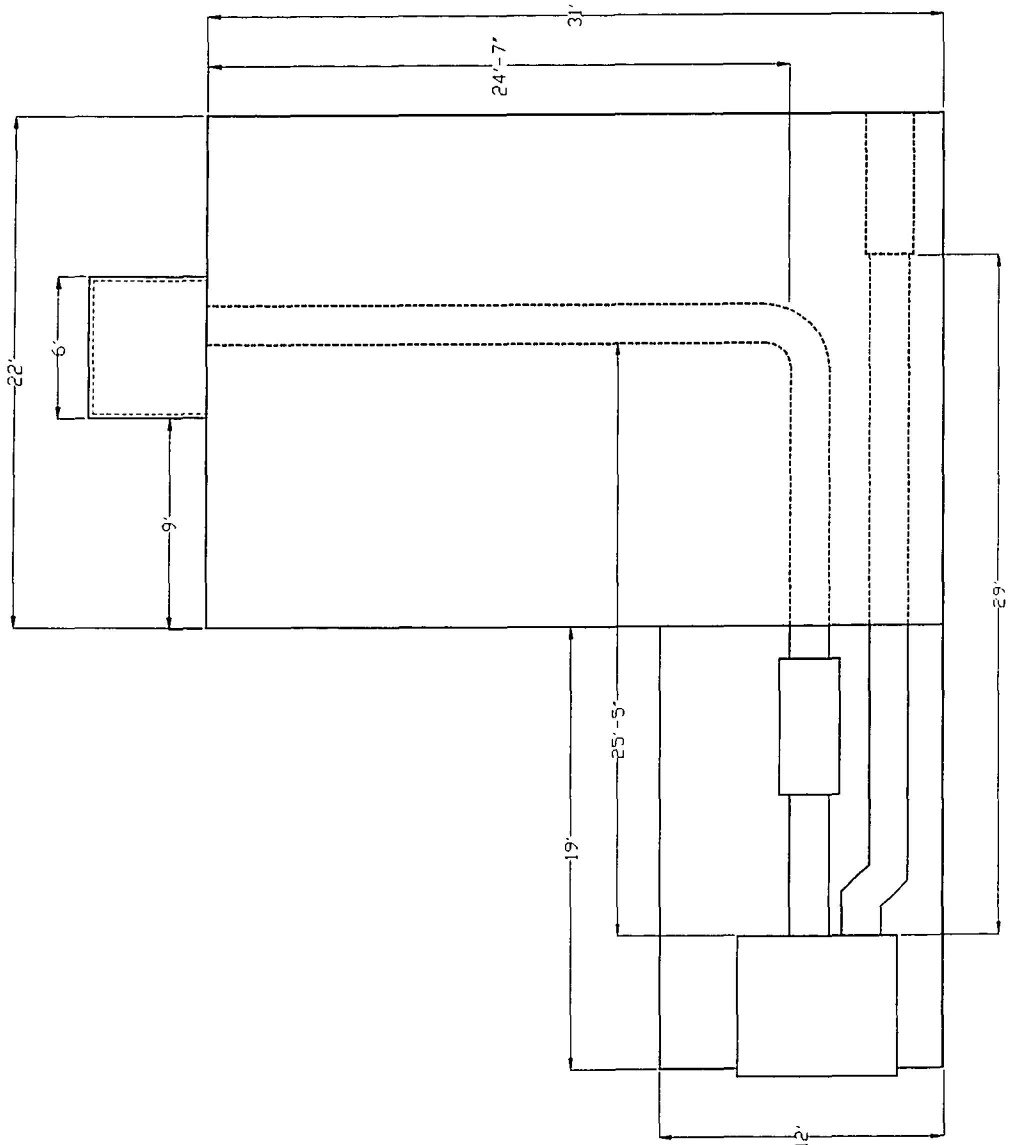
THROW ROOM FAN DATA


GREENHECK
PROJECT UNLV Test Lab
CUSTOMER Doug Reynolds
MARK
UNIT 15-BISW-II
Density .075 lb/ft.³
MEMBER OF AMCA
CFM 3000
SP 6.0
BHP 4.6
RPM 2860
Psc
BHPc
H — High motor speed (2860 RPM)
L - Low motor speed (1907 RPM)
Psc
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
BHPc
0.
1.
2.
3.
4.
5.
CFMc x 1000.
0.
1.
2.
3.
4.
5.
6.
7.
8.
9.
28-SEP-92

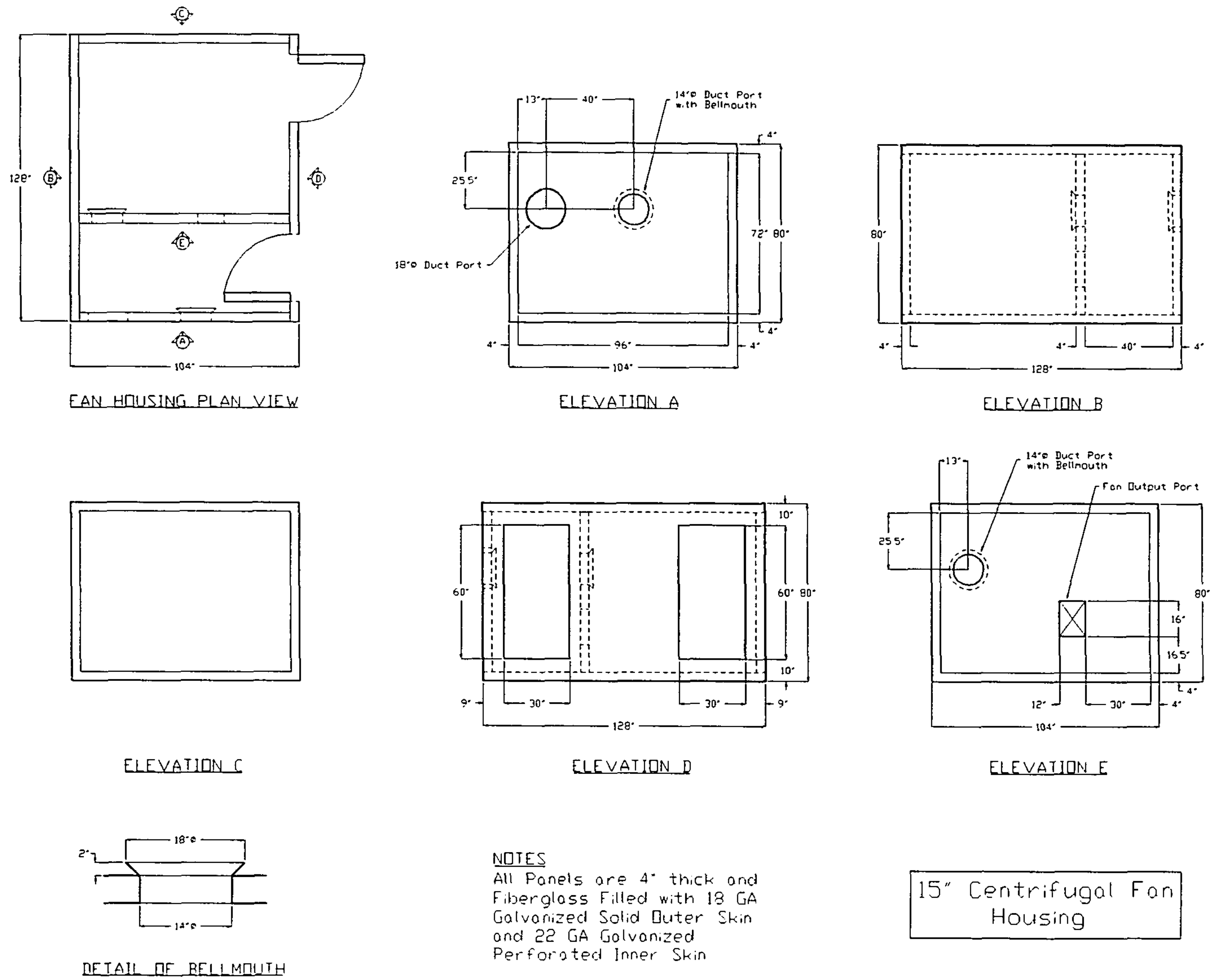

GREENHECK
S1468
REVISED
INSIDE ANGLES
NOTE:
NEOPRENE ISOLATORS RATED
UP TO 0.50" DEFLECTION.

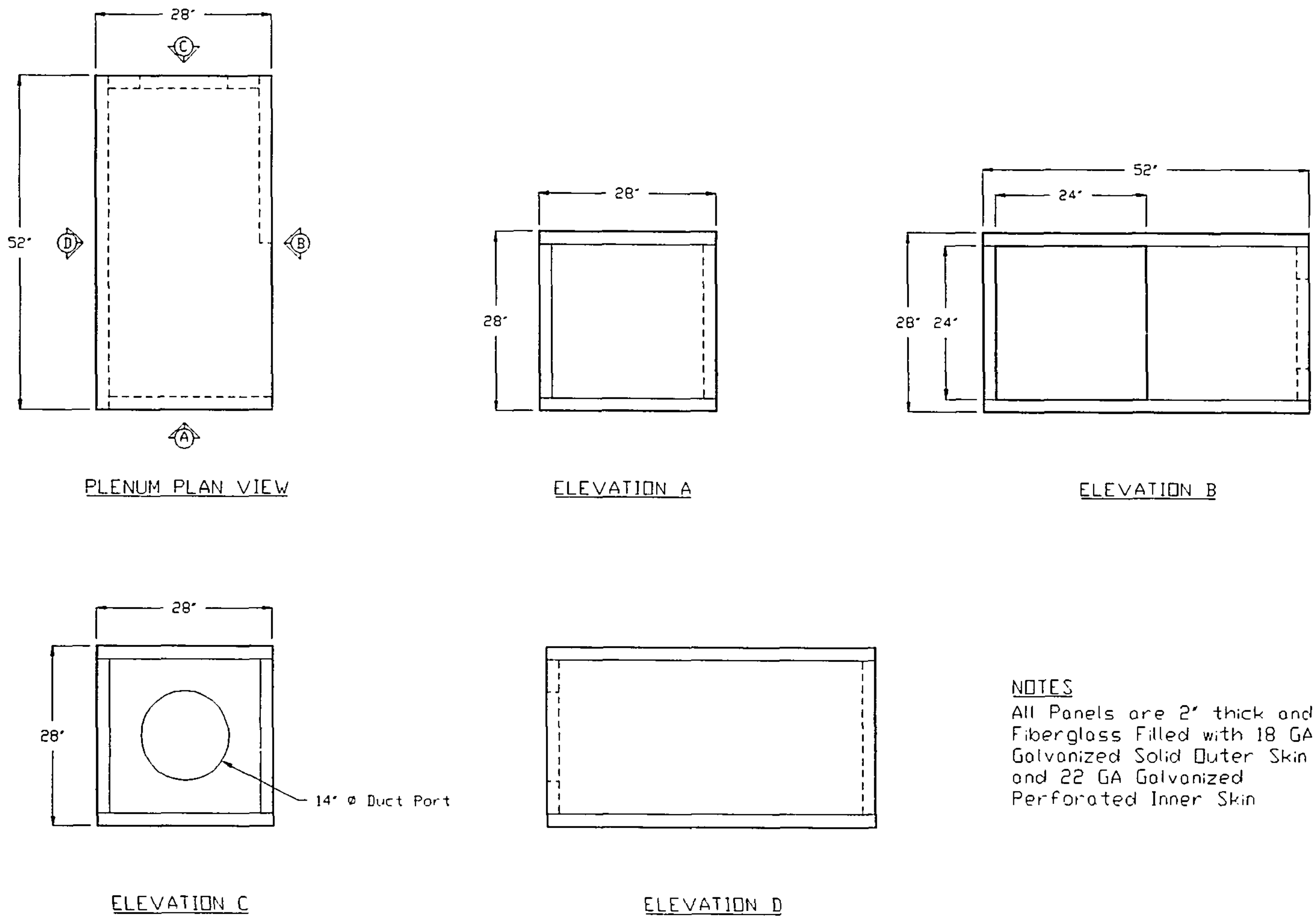
APPENDIX 11

THROW ROOM AIR DELIVERY SYSTEM DRAWINGS



Duct Path Plan View


FAN HOUSING PLAN VIEW
128"
104"
14"ø Duct Port with Bellmouth
18"ø Duct Port
13"
40"
25.5"
72" 80"
96"
104"
ELEVATION A
80"
40"
128"
ELEVATION B
ELEVATION C
10"
60" 80"
60"
30"
9"
128"
ELEVATION D
Fan Output Port
16"
16.5"
12"
30"
104"
ELEVATION E
18"ø
14"ø
2"
DETAIL OF BELLMOUTH
NOTES
All Panels are 4" thick and
Fiberglass Filled with 18 GA
Galvanized Solid Outer Skin
and 22 GA Galvanized
Perforated Inner Skin
15" Centrifugal Fan
Housing



Throw Room Return Air Plenum

APPENDIX 12

THROW ROOM INSTRUMENTATION PARTS LIST

Air Temperature Measurement

Part Description	Quantity
0.001"Ø wire Type-T thermocouple, pkg of 5	1
Type-T thermocouple with 18" long 1/8"Ø SS sheath	16
24 AWG, Type-T thermocouple wire with tinned overbraid	200 ft.
Type-T thermocouple connector pair	8
Omega Omni-Amp IIB, ice point reference junction	3

Air Velocity Measurement

Part Description	Quantity
TSI #1299-20-18, 3D hot-wire anemometer probe	1
TSI #1210-20, hot-film anemometer probe	4
TSI #1750, constant temperature anemometer	4
TSI #1150-18, anemometer probe support	4

Air Pressure Measurement

Part Description	Quantity
Dwyer #607-8, 0-10"WC differential pressure transmitter	1
Dwyer #607-7, 0-5"WC differential pressure transmitter	1
Dwyer #607-2, 0-1/2"WC differential pressure transmitter	1
national weather service type mercurial barometer	1

Air Humidity Measurement

Part Description	Quantity
Omega #HX92v, relative humidity transmitter	1
Omega #HV92-Cal, humidity transmitter calibration kit	1

Data Acquisition

Part Description	Quantity
Workmate data acquisition board for IBM-AT bus	3
general purpose screw terminal panel for Workmate	3

Miscilaneous

Part Description	Quantity
Panasonic #ETU-15k34, 50W 15vDC 3.4A power supply	1
Dwyer #A-701, 24-28vDC regulated power supply	2

APPENDIX 13

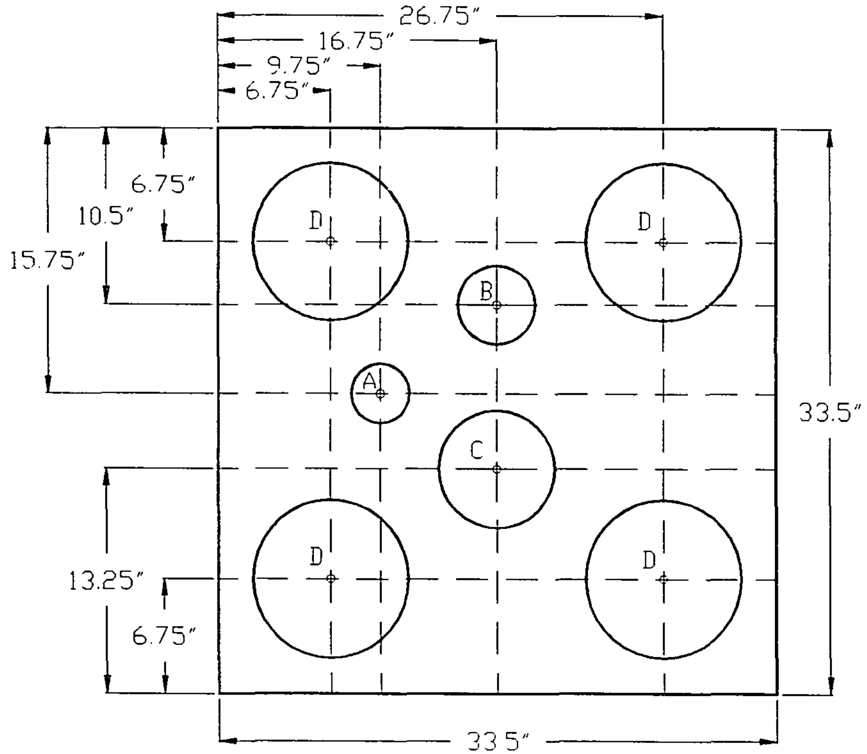
NIST TYPE-T THERMOCOUPLE CALIBRATION DATA

EMF (mV)	Temp. (°C)	EMF (mV)	Temp. (°C)	EMF (mV)	Temp. (°C)
-1.121	-30	-0.116	-3	0.951	24
-1.085	-29	-0.07	-2	0.992	25
-1.049	-28	-0.03	-1	1.032	26
-1.013	-27	0	0	1.073	27
-0.976	-26	0.039	1	1.114	28
-0.94	-25	0.078	2	1.155	29
-0.903	-24	0.117	3	1.196	30
-0.867	-23	0.156	4	1.237	31
-0.83	-22	0.195	5	1.279	32
-0.794	-21	0.234	6	1.32	33
-0.757	-20	0.273	7	1.361	34
-0.72	-19	0.312	8	1.403	35
-0.683	-18	0.351	9	1.444	36
-0.646	-17	0.391	10	1.486	37
-0.608	-16	0.43	11	1.528	38
-0.571	-15	0.47	12	1.569	39
-0.534	-14	0.51	13	1.611	40
-0.496	-13	0.549	14	1.653	41
-0.458	-12	0.589	15	1.695	42
-0.421	-11	0.629	16	1.738	43
-0.383	-10	0.669	17	1.78	44
-0.345	-9	0.709	18	1.822	45
-0.307	-8	0.749	19	1.865	46
-0.269	-7	0.789	20	1.907	47
-0.231	-6	0.83	21	1.95	48
-0.193	-5	0.87	22	1.992	49
-0.154	-4	0.911	23	2.035	50

EMF (mV)	Temp. (ºC)
2.078	51
2.121	52
2.164	53
2.207	54
2.25	55
2.294	56
2.337	57
2.38	58
2.424	59
2.467	60

APPENDIX 14

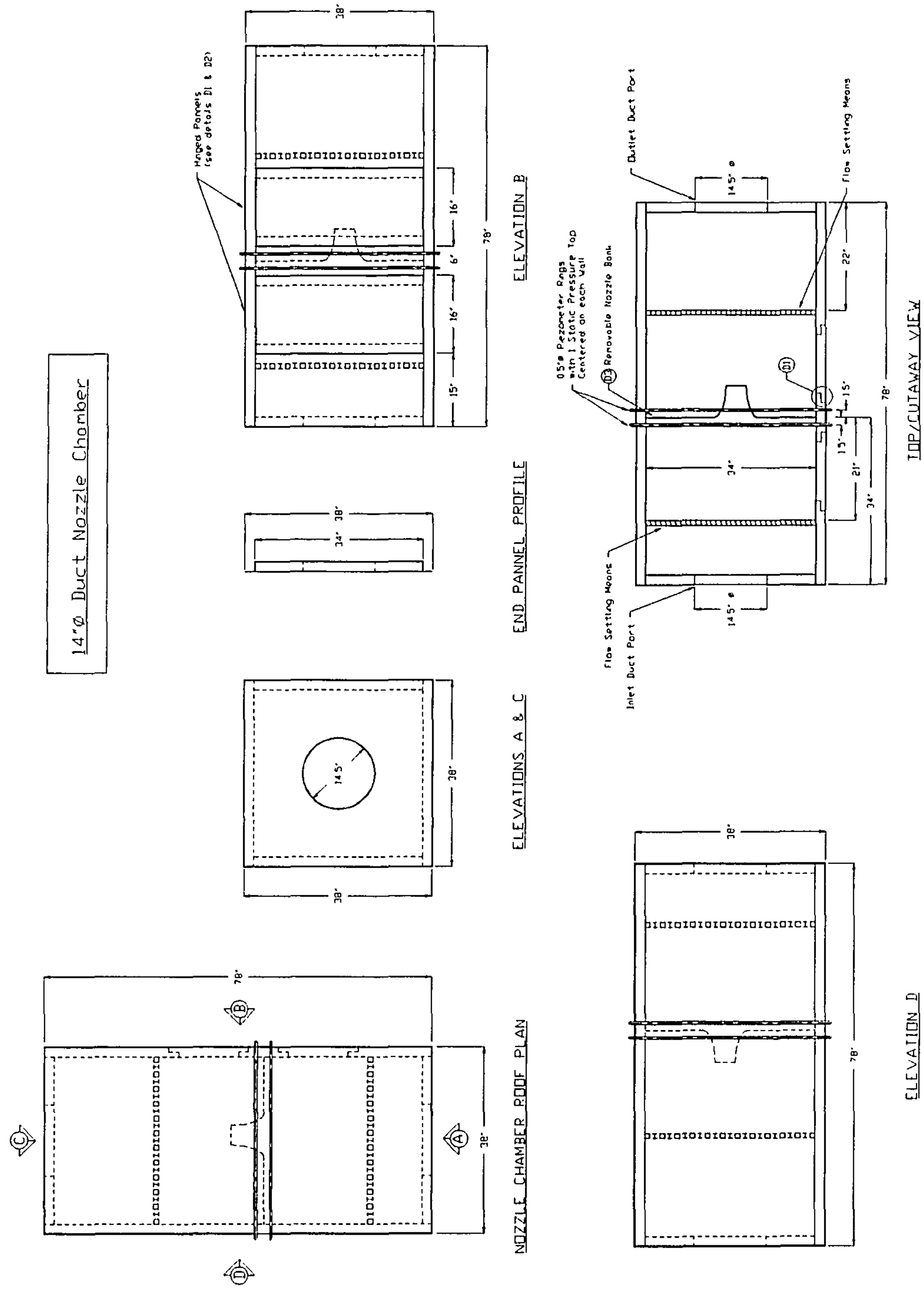
THROW ROOM NOZZLE ASSEMBLY



Ref. Letter	Nozzle Size	Hole Size
A	1.6 in Ø	3.75 in Ø
B	2.0 in Ø	4.67 in Ø
C	3.0 in Ø	7.00 in Ø
D	4.0 in Ø	9.34 in Ø

A	B	C	D	Flow Rate Range
1	0	0	0	41.9 to 97.7 CFM
0	1	0	0	65.5 to 152.7 CFM
0	0	1	0	147.3 to 343.6 CFM
0	0	0	1	261.8 to 610.9 CFM
0	0	0	2	523.6 to 1221.7 CFM
0	0	0	3	785.4 to 1832.6 CFM
0	0	0	4	1047.2 to 2443.5 CFM

D3 Nozzle Bank Plate for 14" Ø Duct


14"Ø Duct Nozzle Chamber
ELEVATION B
END PANNEL PROFILE
ELEVATIONS A & C
NOZZLE CHAMBER ROOF PLAN
TOP/CUTAWAY VIEW
ELEVATION D
Outlet Duct Port
Inlet Duct Port
Flow Settling Means
Removable Nozzle Bank

APPENDIX 15

TRAVERSING MECHANISM PARTS LIST

X-Axis Mechanical Components

Part Description	Quantity
1"Ø open type linear bearing with pillow block	4
1"Ø linear bearing shaft, 6 foot length	10
linear bearing shaft supports, 2 foot length	10
16 tpi 1/2"x1/2" steel gear rack, 6 foot length	10
16 tpi, 3/4" pitch diameter spur gear	2
NEMA 34 stepper motor, 306 oz-in holding torque	2
100V, 6A stepper motor chopper driver	2
4"x4"x1/4" steel angle, 20 foot length	3
2"x2"x1/8" square steel tubing, 20 foot length	2
1"x1"x1/8" steel angle, 20 foot length	2

Y-Axis Mechanical Components

Part Description	Quantity
1/2"Ø open type linear bearing with pillow block	4
1/2"Ø linear bearing shaft, 6 foot length	7
linear bearing shaft supports, 2 foot length	6
16 tpi 1/2"x1/2" steel gear rack, 6 foot length	10
16 tpi, 3/4" pitch diameter spur gear	1
NEMA 34 stepper motor, 306 oz-in holding torque	1
100V, 6A stepper motor chopper driver	1

Z-Axis Mechanical Components

Part Description	Quantity
1/2"Ø open type linear bearing with pillow block	3
1/2"Ø linear bearing shaft, 6 foot length	6
linear bearing shaft supports, 2 foot length	4
12"Ø, 5/16" thick, thrust bearing (100 lb. max)	1
1/2"Ø bore, flange mount pillow block radial bearing	1
1/2"Ø bore, base mount pillow block radial bearing	4
1/2"Ø to 3/8"Ø steel reducer bushing	1 pkg.
4mm pitch cable chain with 100 lb tensile strength	50 ft.
cable chain splice bushings	1 pkg.
4" pitch diameter aluminum sprocket (80 teeth)	3
2" pitch diameter aluminum sprocket (40 teeth)	3
3/8"Ø bore, steel sprocket hub	6
cable chain guide rails, 2 foot length	5

Z-Axis Mechanical Components Continued

NEMA 34 stepper motor, 306 oz-in holding torque	1
NEMA 34 stepper motor, 174 oz-in holding torque	1
100V, 6A stepper motor chopper driver	2

Miscellaneous Mechanical Components

4"x4"x1/4" and 1"x1"x1/8" steel angle

1/2"Ø steel round stock

1/8", 1/4" and 1/2" aluminum plate

4"x4"x1/4" and 3"x3"x1/8" aluminum angle

Stepper Motor Control Circuit Components

Part Description	Quantity
OMS PC34 4-axis stepper motor controller card	1
50 pin ribbon cable, 6 foot length	1
28V, 15A, regulated DC power supply	1
roller actuator, momentary, SPST micro switch	12
2 circuit, polarized, nylon connector pair	12
470 ohm, 1/8 watt resistor	5
1000 micro farad, 50v electrolytic capacitor	5
1/4" female tab connectors	1 pkg.
miscellaneous 20 AWG solid and multistrand wire	

Interface Circuit Components

Part Description	Quantity
50 pin male ribbon cable connector	1
25 pin male D connector	5
25 pin female D connector	5
shielded hood for 25 pin D connector	5
2.5"x5.5"x7" plastic project box	1
4"x6" generic circuit board	1
2"x6" generic circuit board	1
74LS04 hex inverter chip	2
14 pin chip socket	2
1k ohm, 1/8 watt resistor	12
510 ohm, 1/8 watt resistor	16

Power Carrying Cable

Part Description	Quantity
12 AWG, multistrand, 2 conductor cable	100 ft.
18 AWG multistrand wire	misc.

Motor Control Cable

Part Description	Quantity
22 AWG, multistrand, 9 conductor cable	300 ft.

Instrumentation Cable

Part Description	Quantity
RG11 A/U coaxial cable (22 gauge)	300 ft.
shielded, 22 AWG, multistrand, 2 conductor cable	300 ft.

X-Axis Cable Carrier

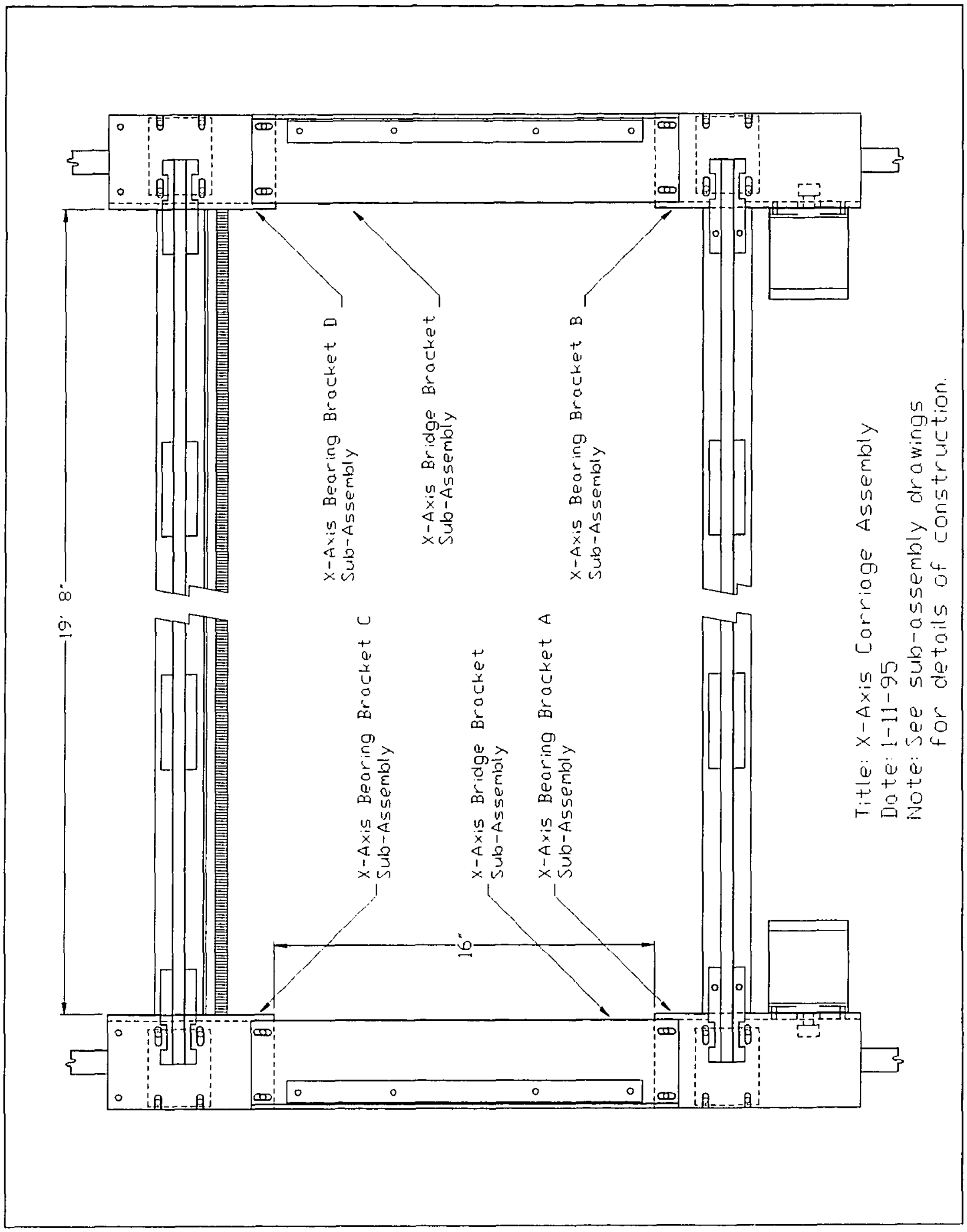
Part Description	Quantity
3.08"x1" window, flip-top, nylon cable tray	16 ft.
standard galvanized steel guide tray	31 ft.
standard bracket kit	1

Y-Axis Cable Carrier

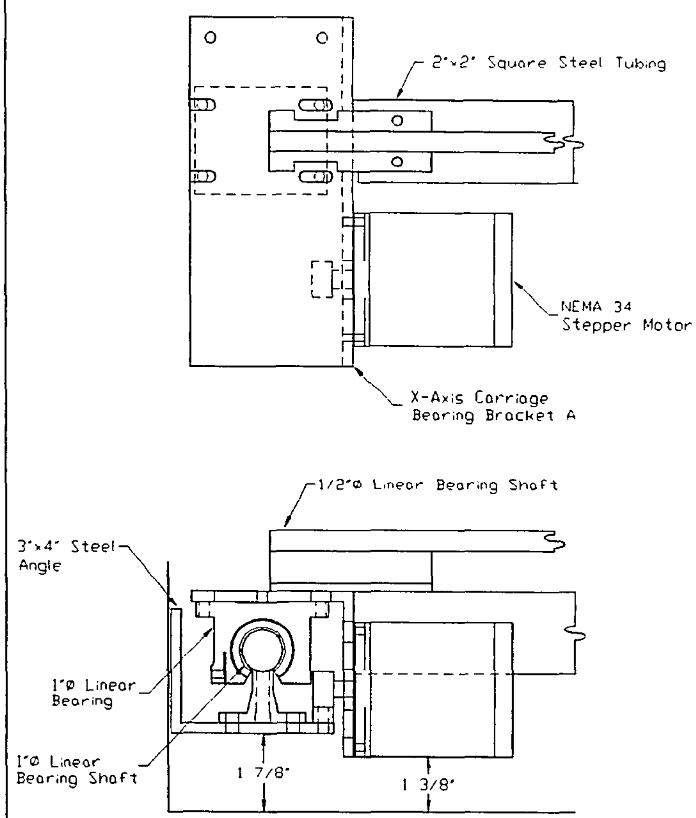
Part Description	Quantity
2.28"x1" window, flip-top, nylon cable tray	11.5 ft.
standard galvanized steel guide tray	21 ft.
standard bracket kit	1

APPENDIX 16

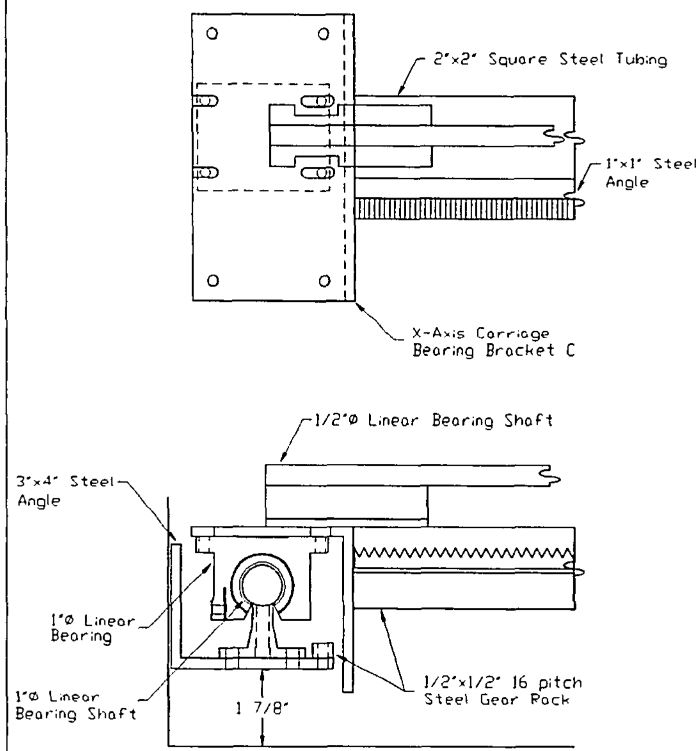
TRAVERSING MECHANISM DETAILED DRAWINGS



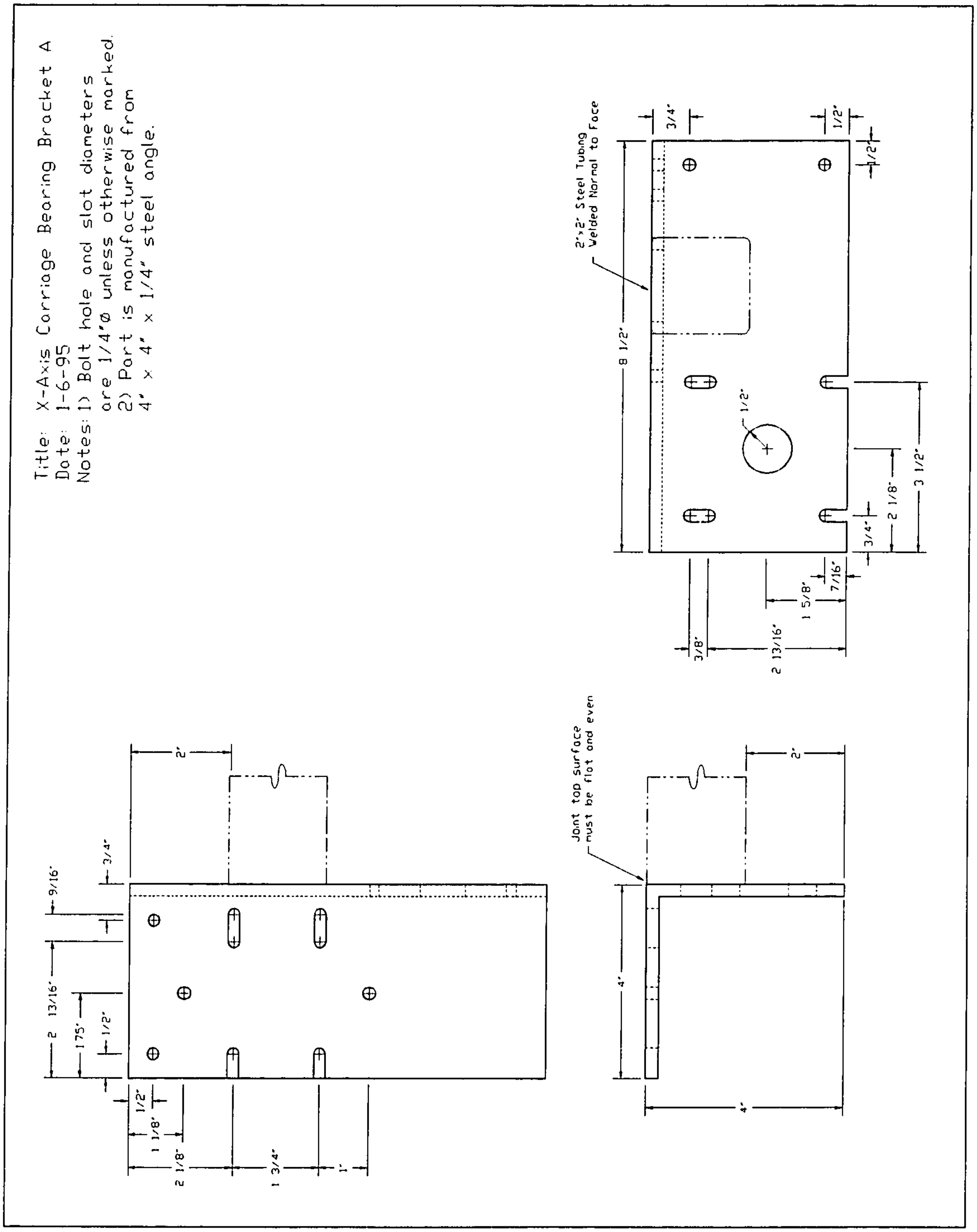
19' 8"
16"
X-Axis Bearing Bracket D
Sub-Assembly
X-Axis Bridge Bracket
Sub-Assembly
X-Axis Bearing Bracket B
Sub-Assembly
X-Axis Bearing Bracket C
Sub-Assembly
X-Axis Bridge Bracket
Sub-Assembly
X-Axis Bearing Bracket A
Sub-Assembly
Title: X-Axis Carriage Assembly
Date: 1-11-95
Note: See sub-assembly drawings
for details of construction.



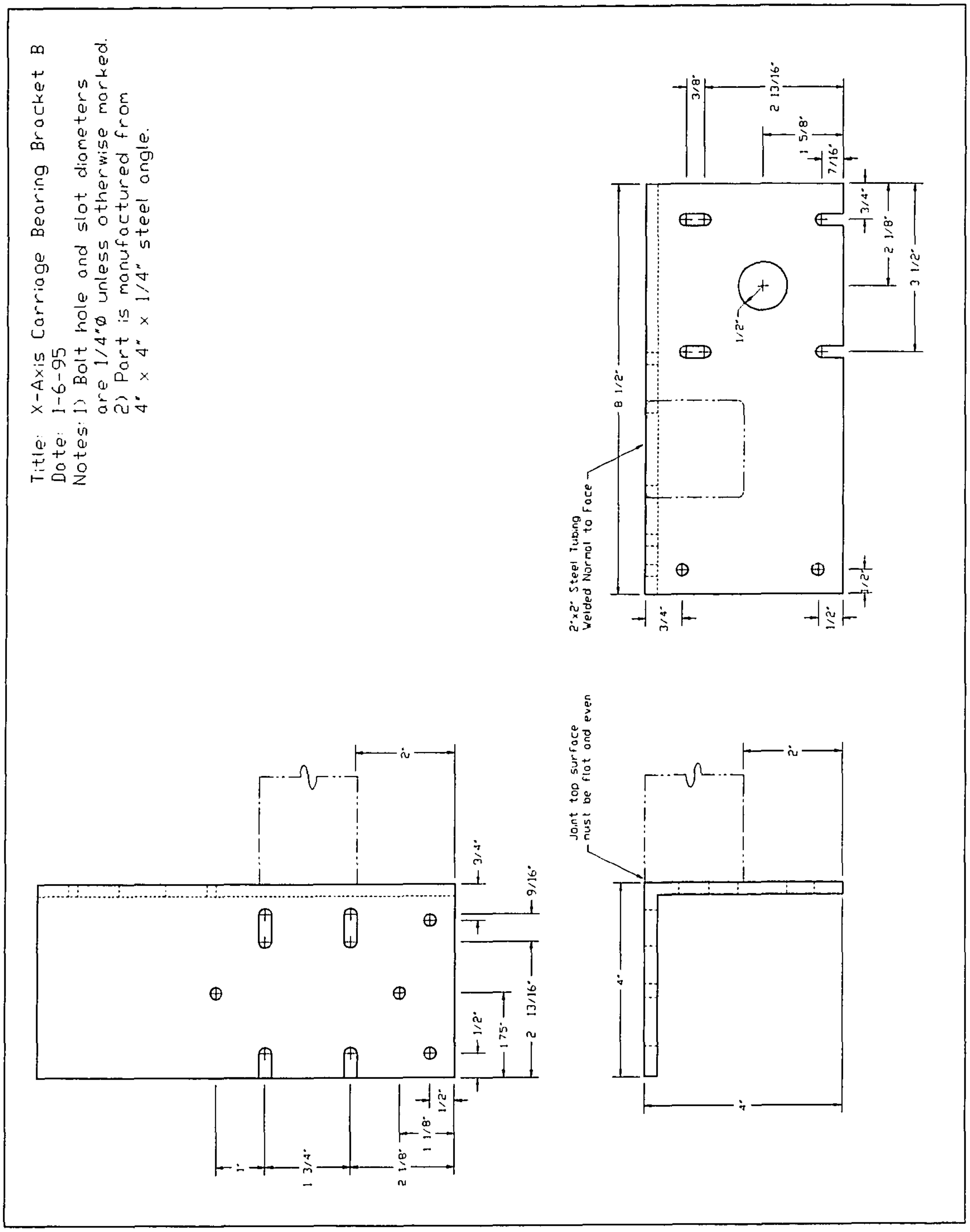
Title: X-Axis Bearing Bracket A Sub-Assembly
Date: 1-10-95
Notes: 1) Bearing bracket B sub-assembly is mirror of this.

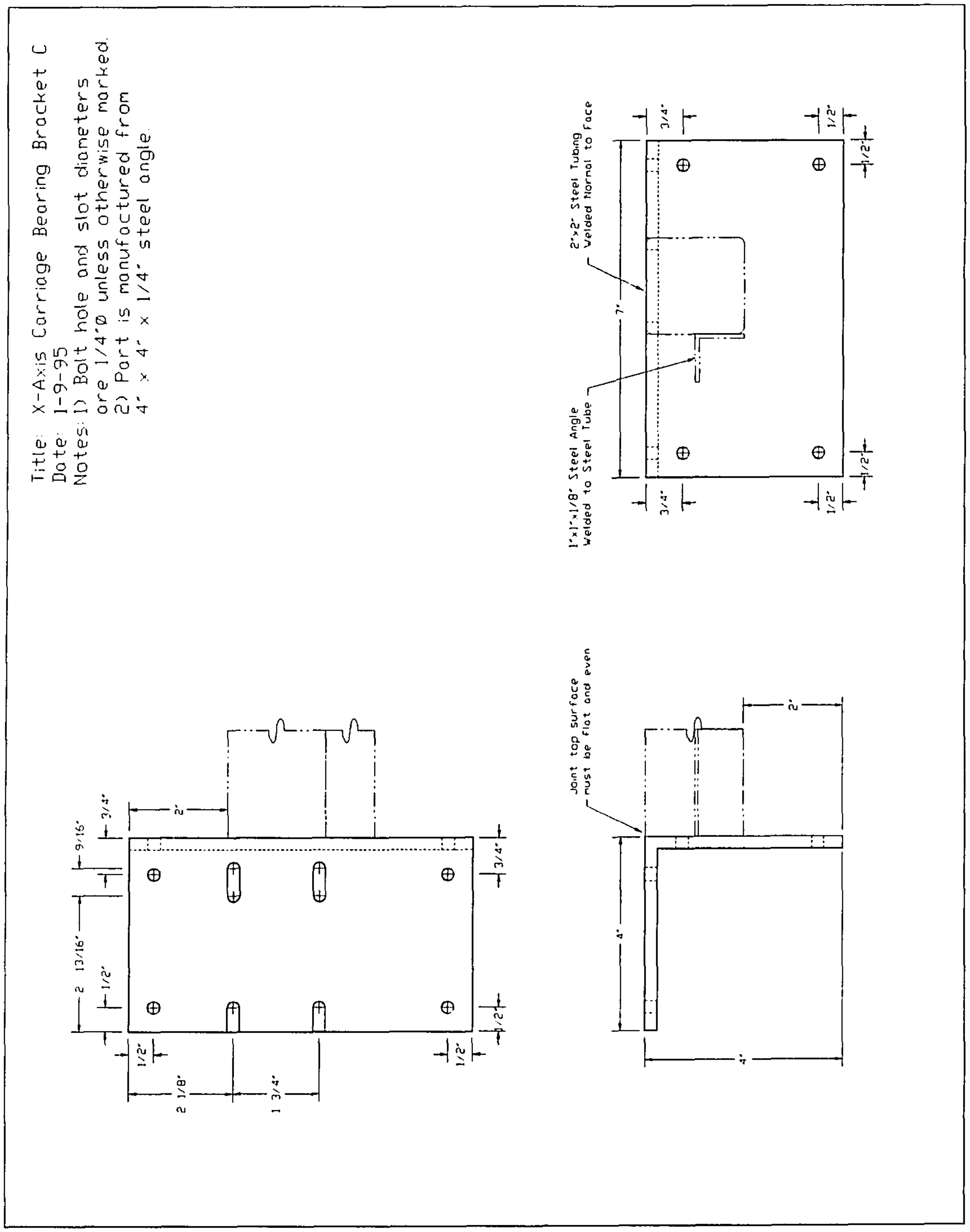


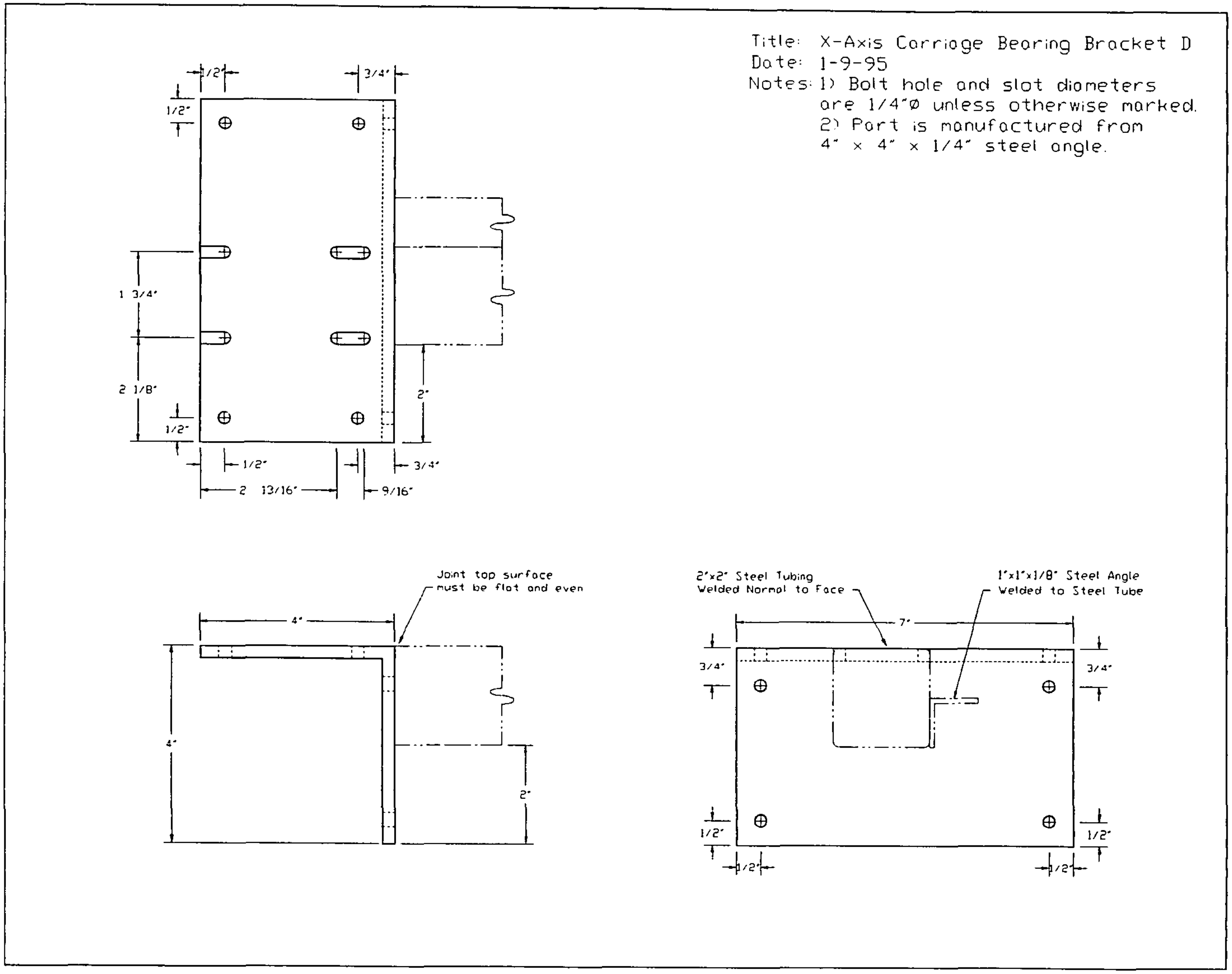
Title: X-Axis Bearing Bracket C Sub-Assembly
Date: 1-10-95
Notes: 1) Bearing bracket D sub-assembly is mirror of this.

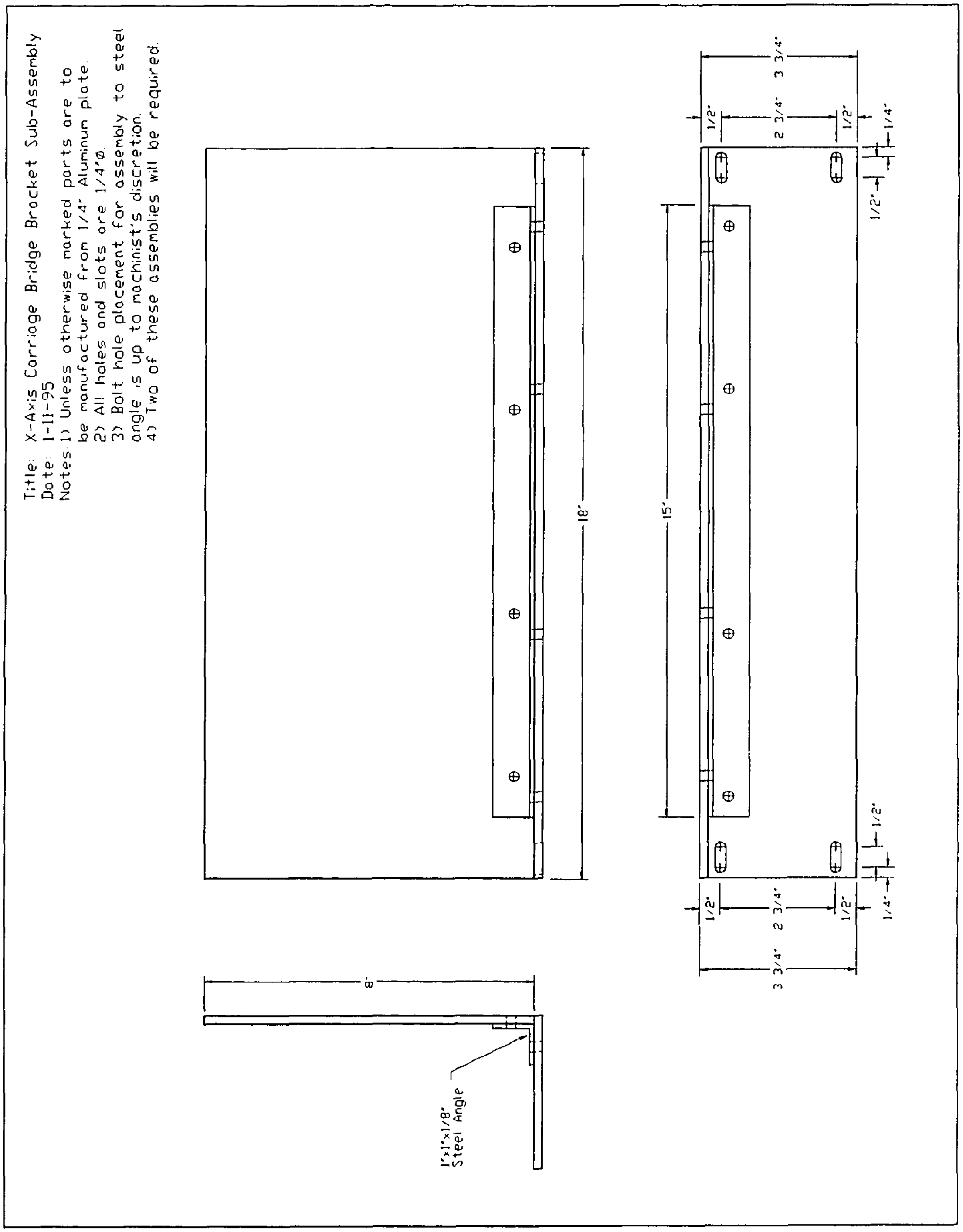


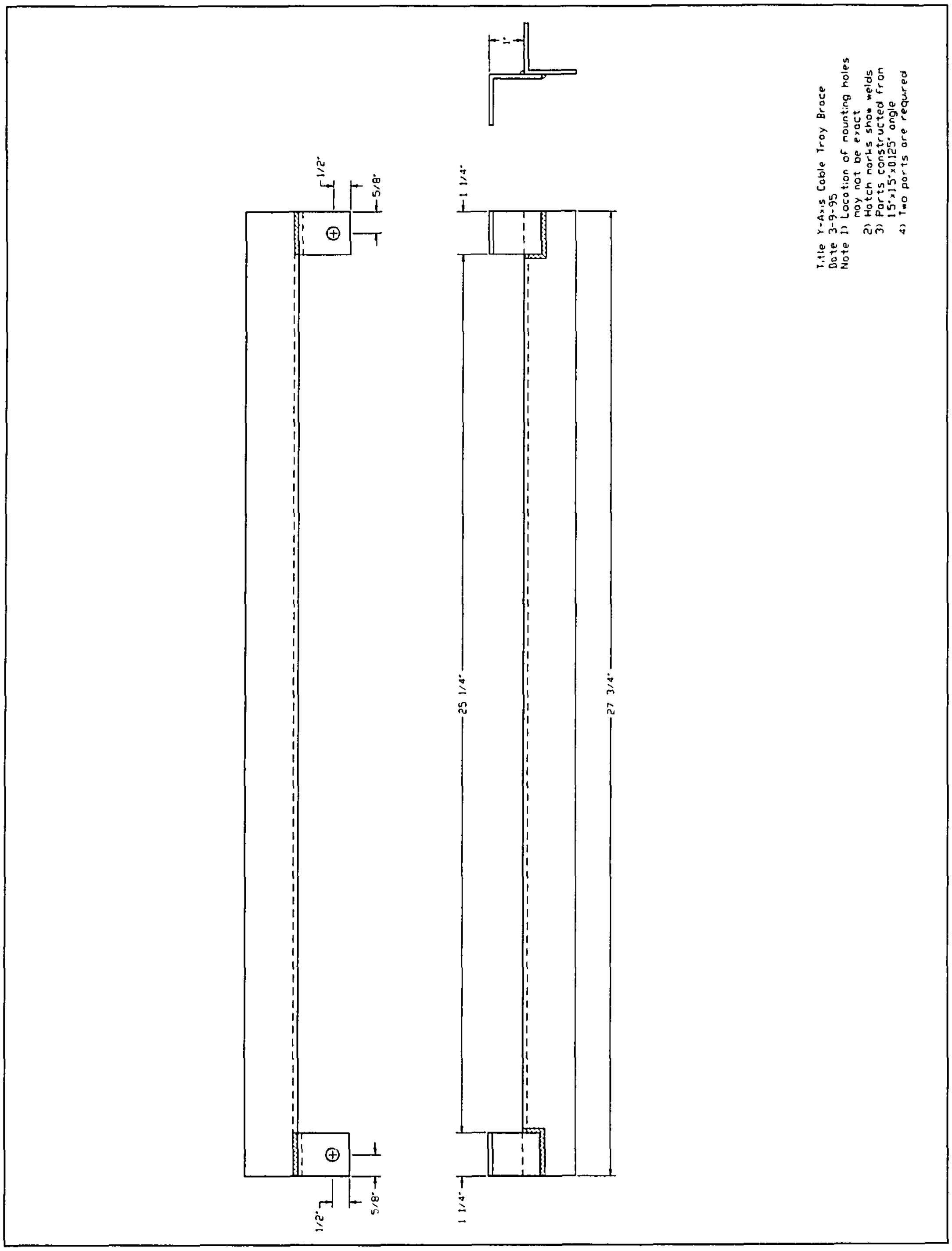
Title: X-Axis Carriage Bearing Bracket A
Date: 1-6-95
Notes: 1) Bolt hole and slot diameters are 1/4"ø unless otherwise marked.
2) Part is manufactured from 4" x 4" x 1/4" steel angle.
2"x2" Steel Tubing Welded Normal to Face
Joint top surface must be flat and even

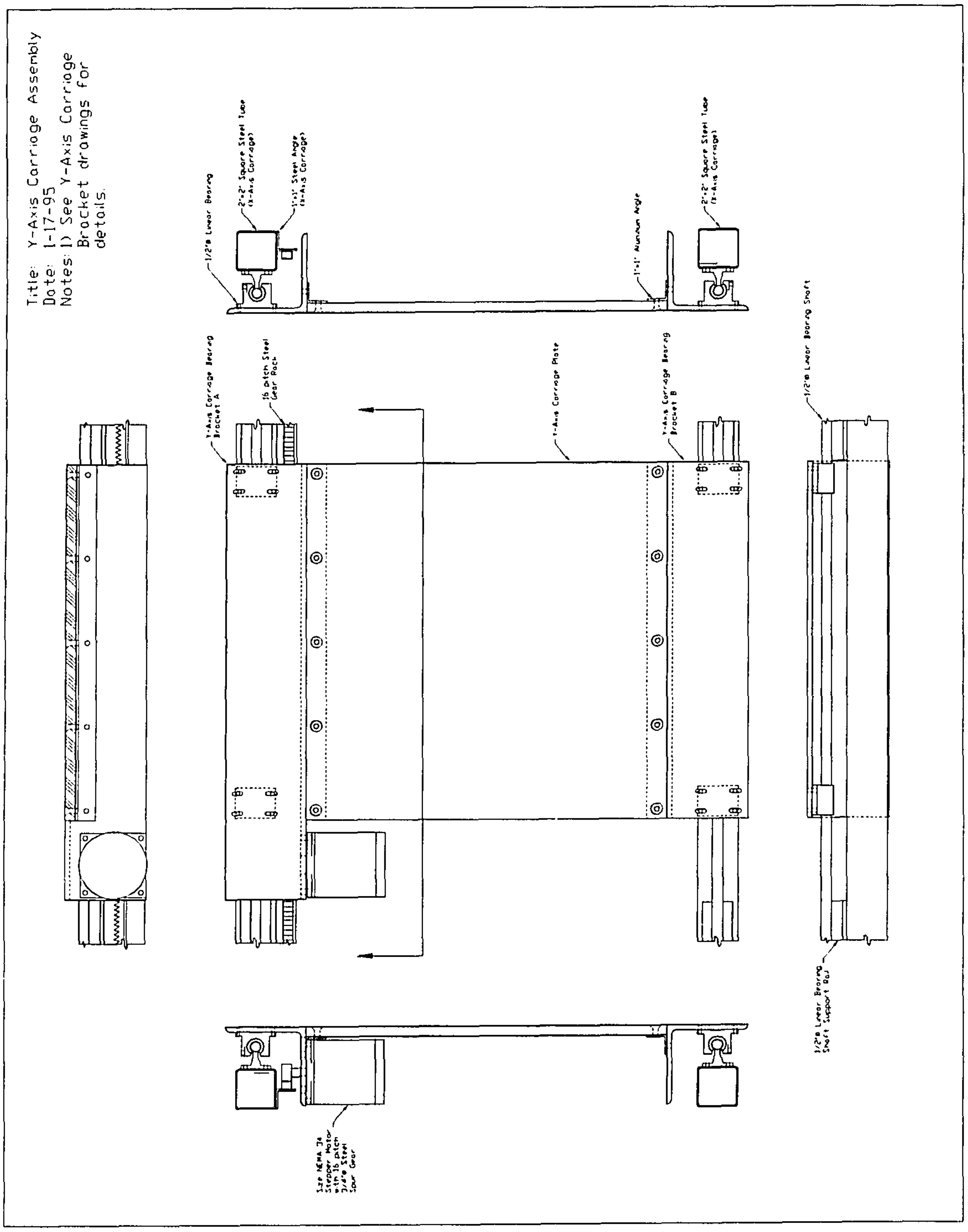

Title: X-Axis Carriage Bearing Bracket B
Date: 1-6-95
Notes: 1) Bolt hole and slot diameters are 1/4"Ø unless otherwise marked.
2) Part is manufactured from 4" x 4" x 1/4" steel angle.
2"x2" Steel Tubing Welded Normal to Face
Joint top surface must be flat and even

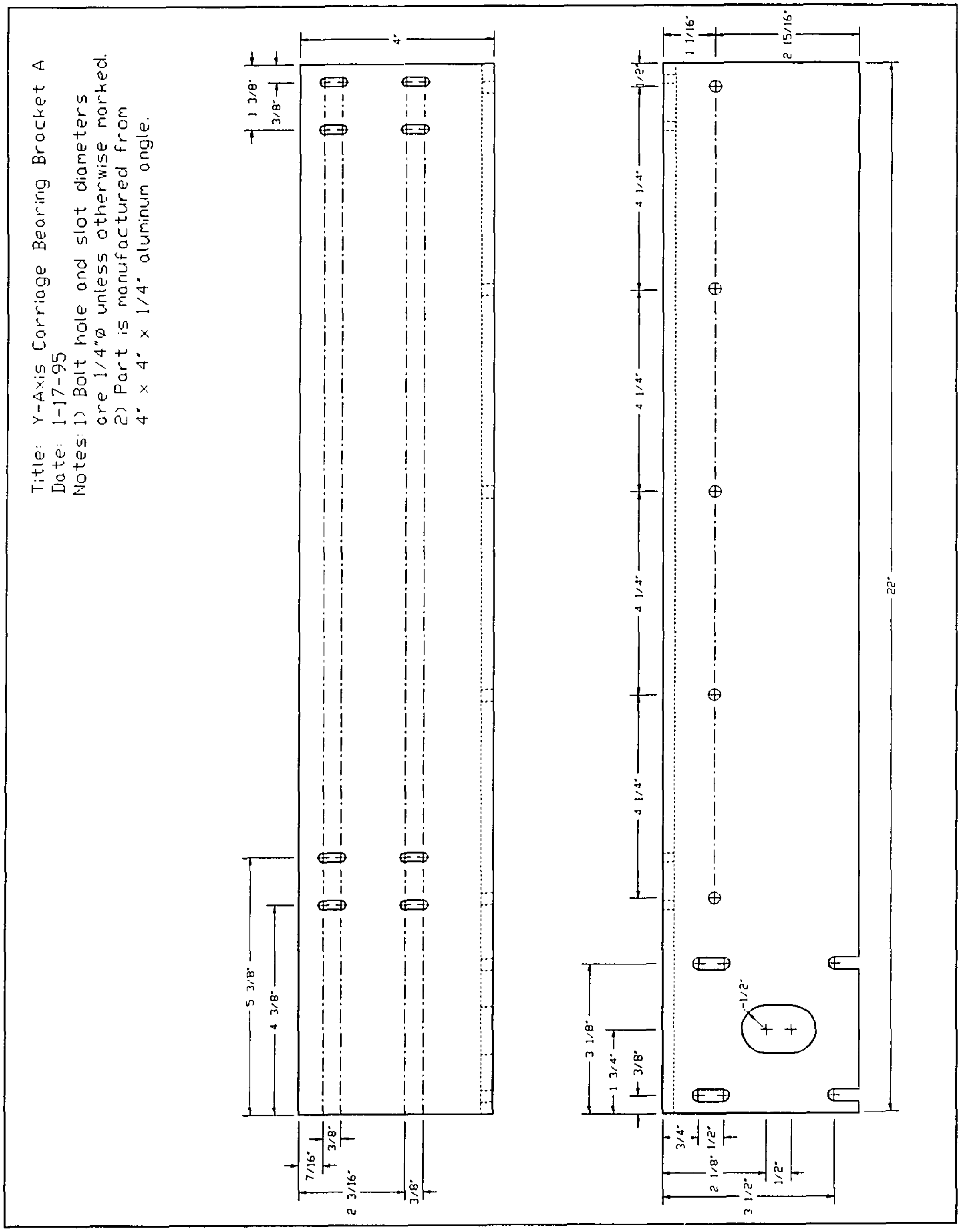

Title: X-Axis Carriage Bearing Bracket C
Date: 1-9-95
Notes: 1) Bolt hole and slot diameters are 1/4"Ø unless otherwise marked.
2) Part is manufactured from 4" x 4" x 1/4" steel angle.
2"x2" Steel Tubing Welded Normal to Face
1"x1"x1/8" Steel Angle Welded to Steel Tube
Joint top surface must be flat and even


Title: X-Axis Carriage Bearing Bracket D
Date: 1-9-95
Notes: 1) Bolt hole and slot diameters
are 1/4"Ø unless otherwise marked.
2) Part is manufactured from
4" x 4" x 1/4" steel angle.
1/2"
3/4"
1 3/4"
2 1/8"
2"
2 13/16"
9/16"
Joint top surface
must be flat and even
4"
2"
2"x2" Steel Tubing
Welded Normal to Face
1"x1"x1/8" Steel Angle
Welded to Steel Tube
7"

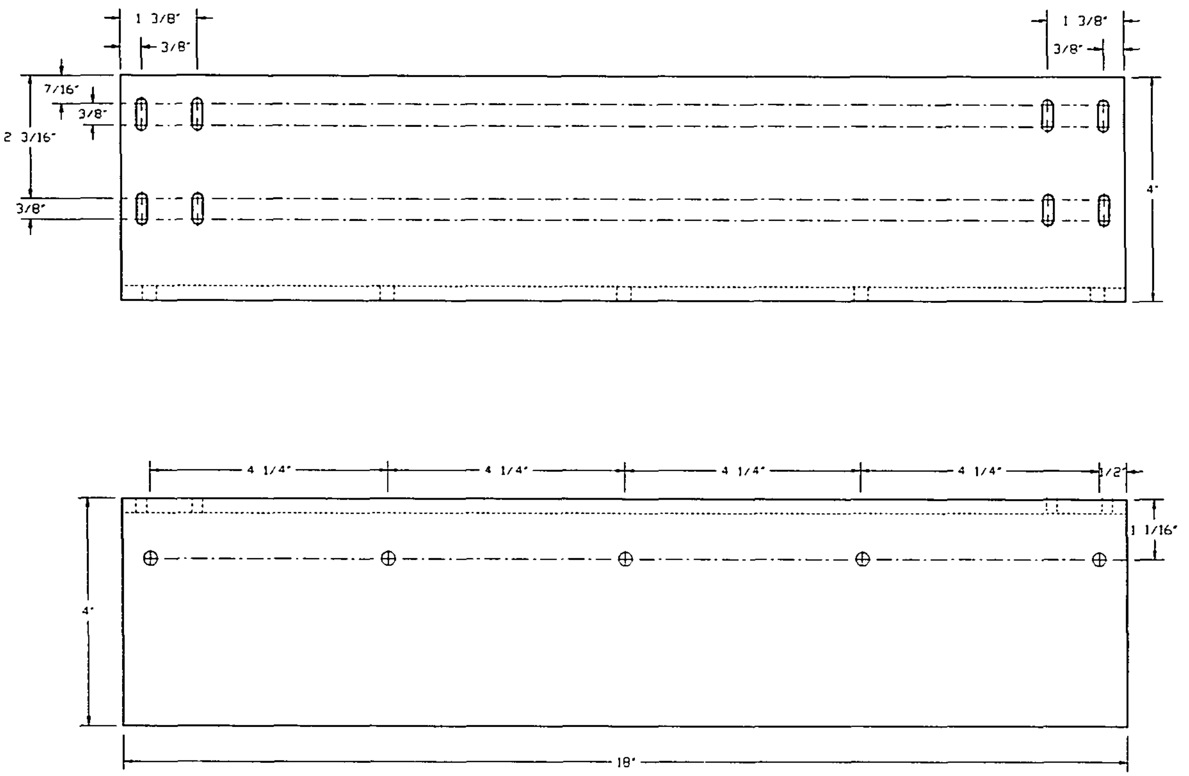

Title: X-Axis Carriage Bridge Bracket Sub-Assembly
Date: 1-11-95
Notes: 1) Unless otherwise marked parts are to be manufactured from 1/4" Aluminum plate.
2) All holes and slots are 1/4"ø.
3) Bolt hole placement for assembly to steel angle is up to machinist's discretion.
4) Two of these assemblies will be required.
18"
15"
8"
1/2"
2 3/4"
3 3/4"
1/4"
1"x1"x1/8" Steel Angle

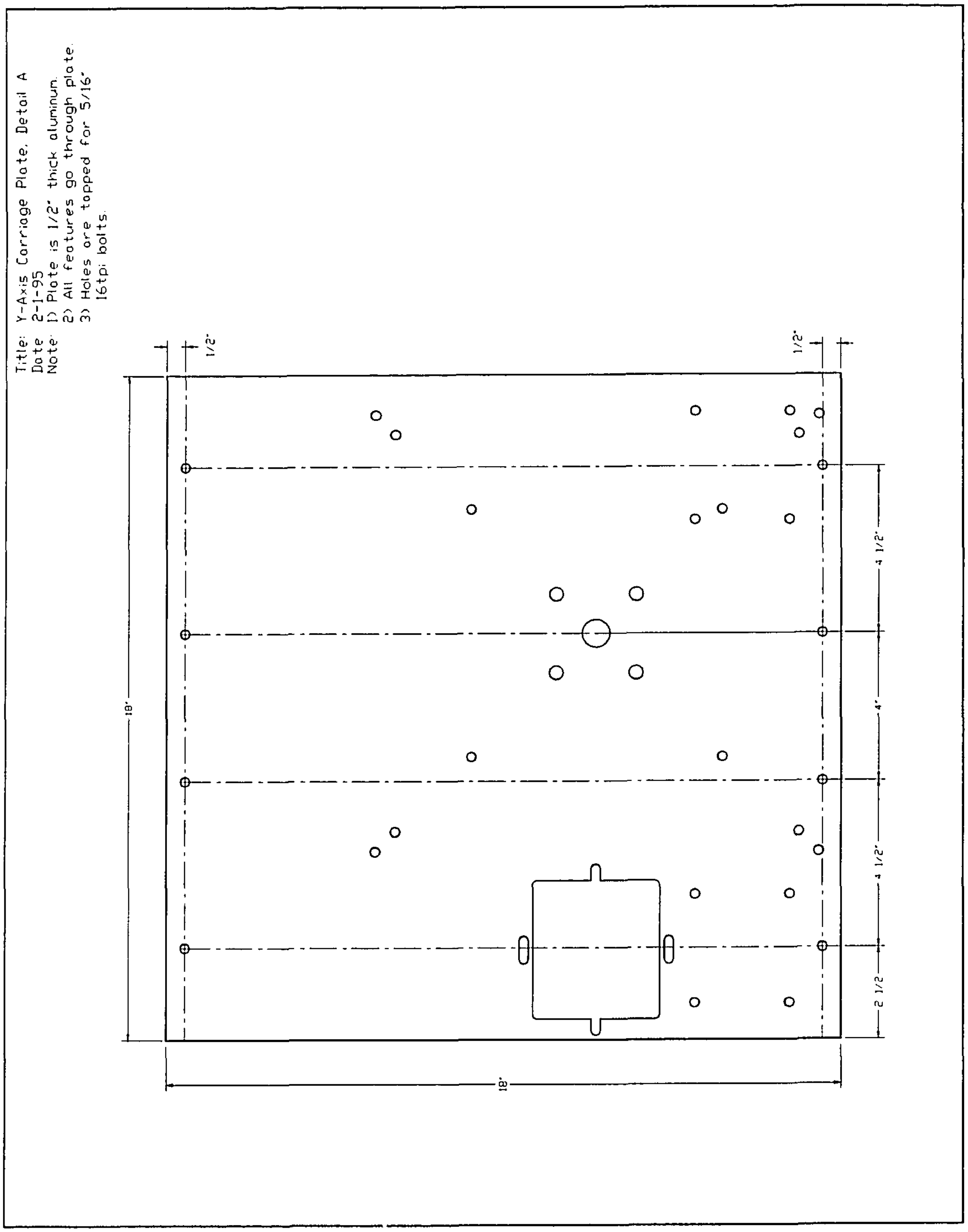

1/2"
5/8"
1 1/4"
1"
25 1/4"
27 3/4"
1/2"
5/8"
1 1/4"
Title Y-Axis Cable Tray Brace
Date 3-9-95
Note 1) Location of mounting holes
may not be exact
2) Hatch marks show welds
3) Parts constructed from
15"x15"x0.125" angle
4) Two parts are required


Title: Y-Axis Carriage Assembly
Date: 1-17-95
Notes: 1) See Y-Axis Carriage Bracket drawings for details.

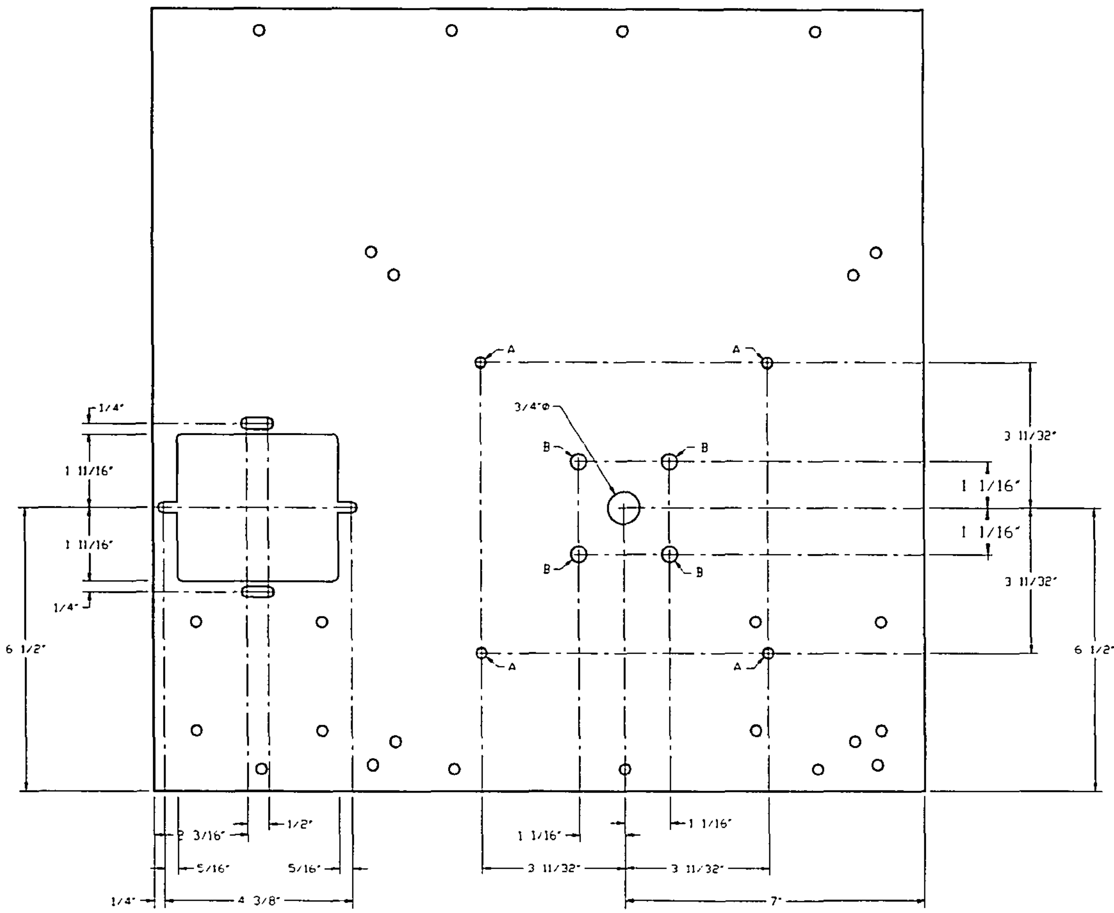

Title: Y-Axis Carriage Bearing Bracket A
Date: 1-17-95
Notes: 1) Bolt hole and slot diameters
are 1/4"ø unless otherwise marked.
2) Part is manufactured from
4" x 4" x 1/4" aluminum angle.
4"
1 3/8"
3/8"
5 3/8"
4 3/8"
7/16"
3/8"
2 3/16"
3/8"
1 1/16"
2 15/16"
1/2"
4 1/4"
4 1/4"
4 1/4"
4 1/4"
22"
1/2"
3 1/8"
1 3/4"
3/8"
3/4"
1/2"
2 1/8"
1/2"
3 1/2"

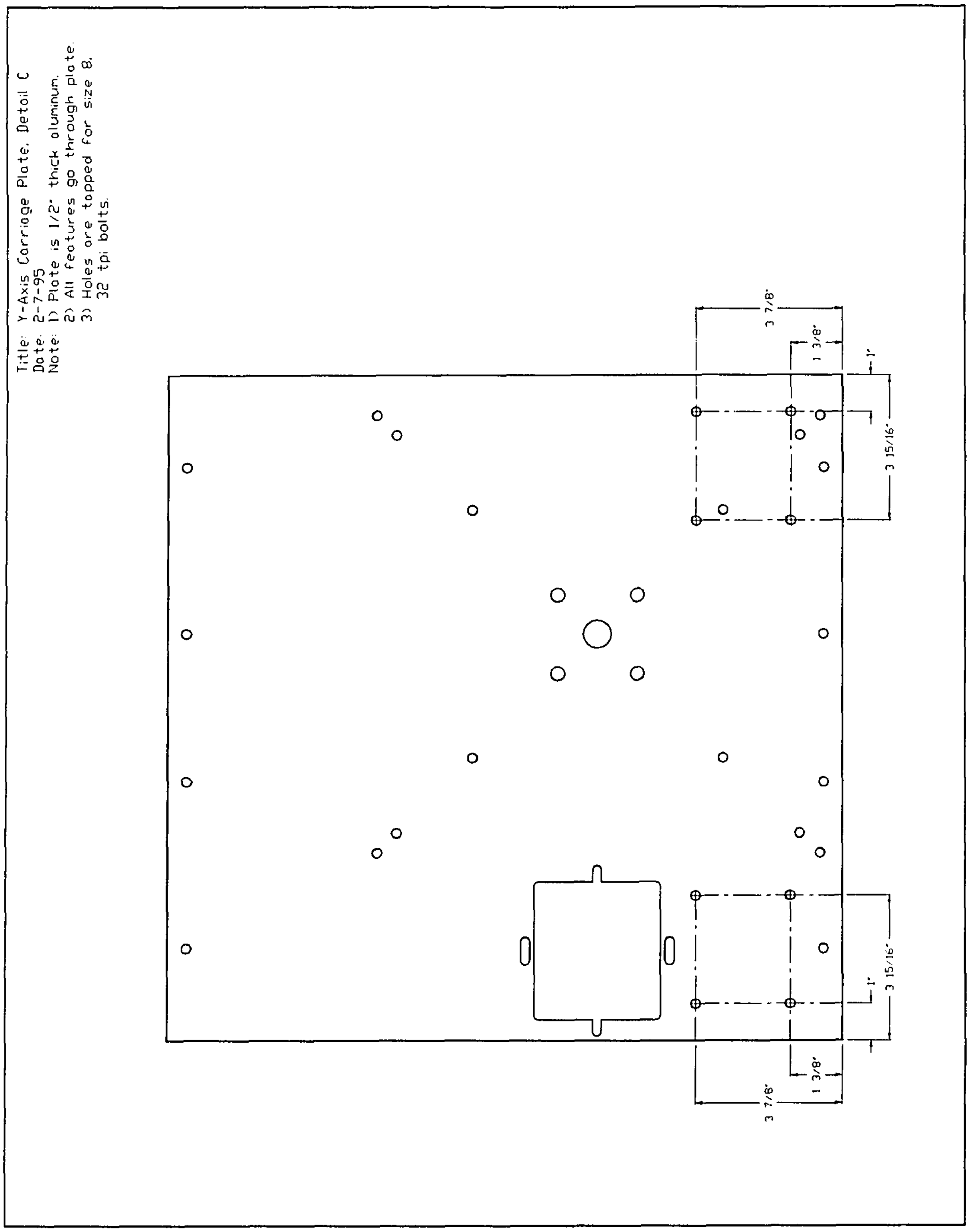
Title: Y-Axis Carriage Bearing Bracket B
Date: 1-17-95
Notes: 1) Bolt hole and slot diameters are 1/4"Ø unless otherwise marked.
2) Part is manufactured from 4" x 4" x 1/4" aluminum angle.

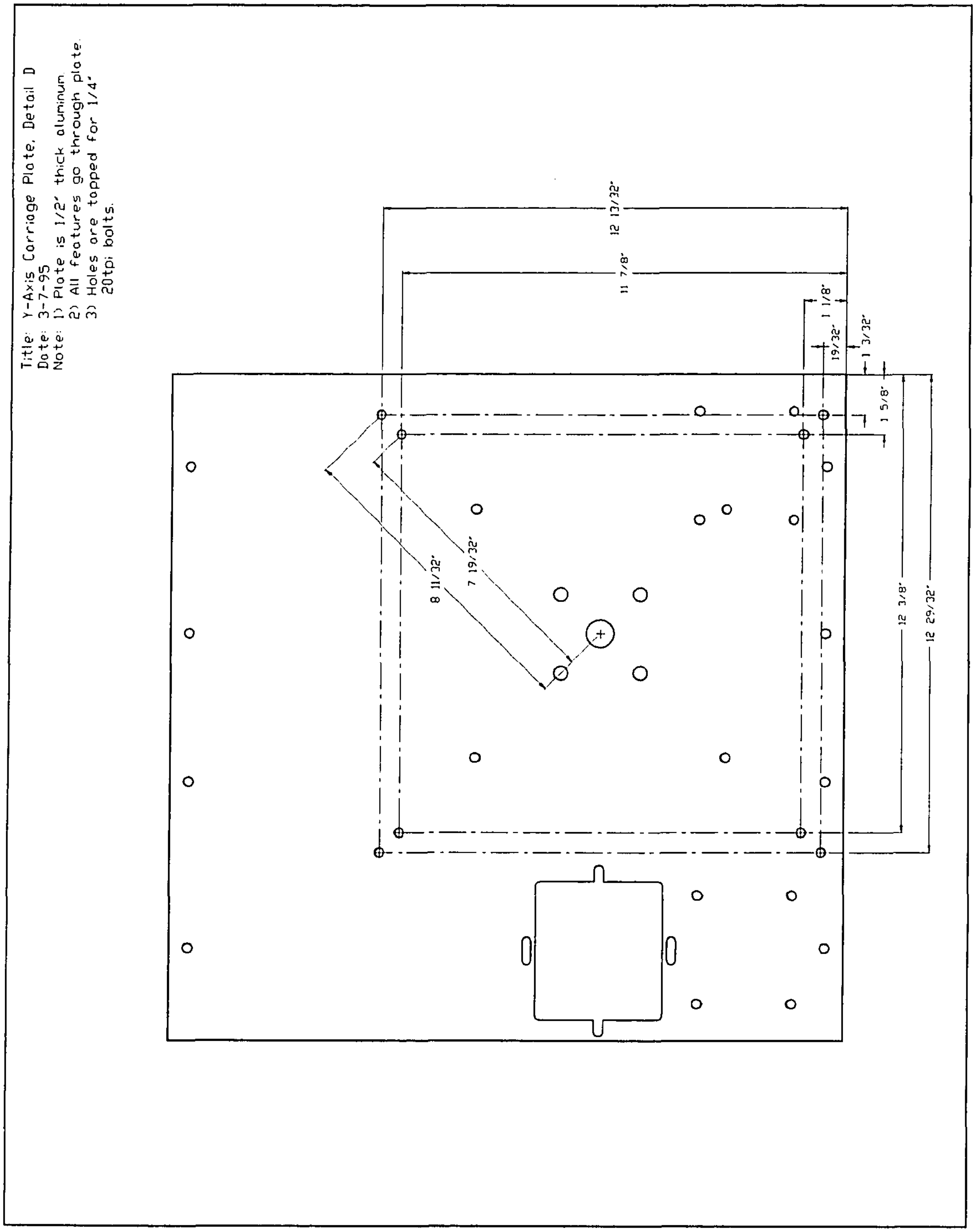


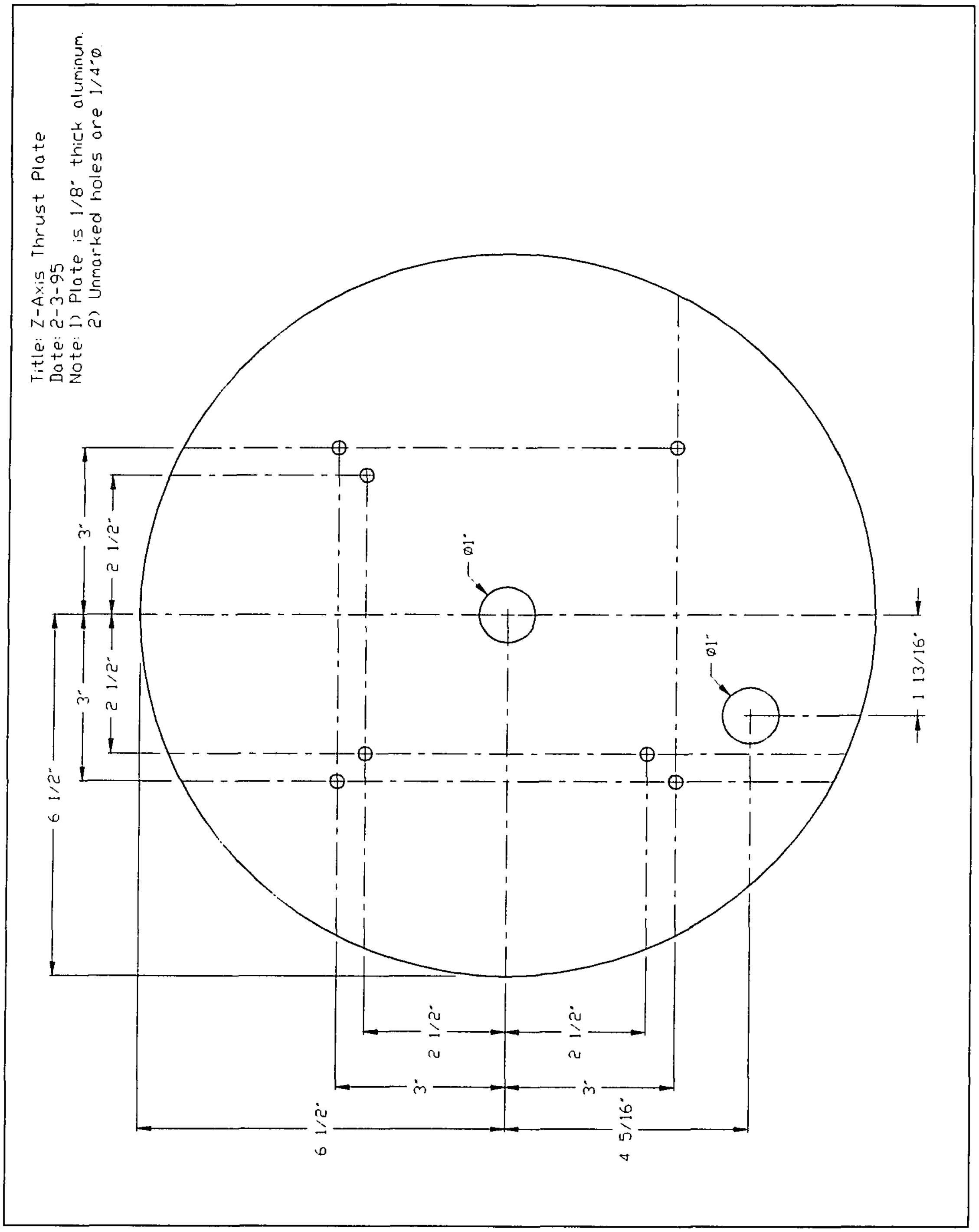

Title: Y-Axis Carriage Plate, Detail A
Date 2-1-95
Note: 1) Plate is 1/2" thick aluminum.
2) All features go through plate.
3) Holes are tapped for 5/16" 16tpi bolts.
1/2"
1/2"
18"
18"
4 1/2"
4"
4 1/2"
2 1/2

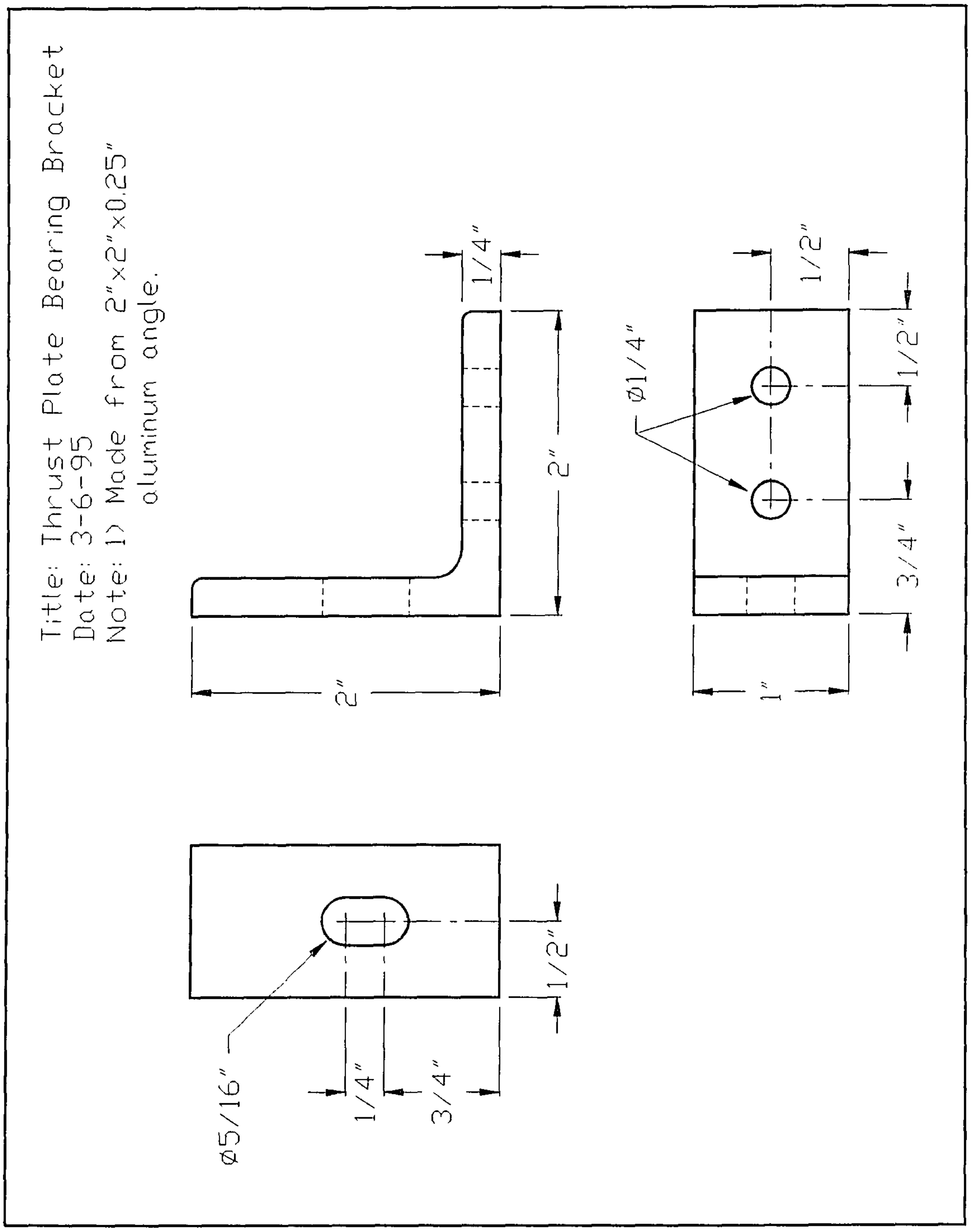
Title: Y-Axis Carriage Plate, Detail B
Date: 2-1-95
Note: 1) Plate is 1/2" thick aluminum.
2) All features go through plate.
3) A = tapped for 1/4" 20tpi bolts
4) b = tapped for 3/8" 16tpi bolts
5) Slots are 1/4"Ø

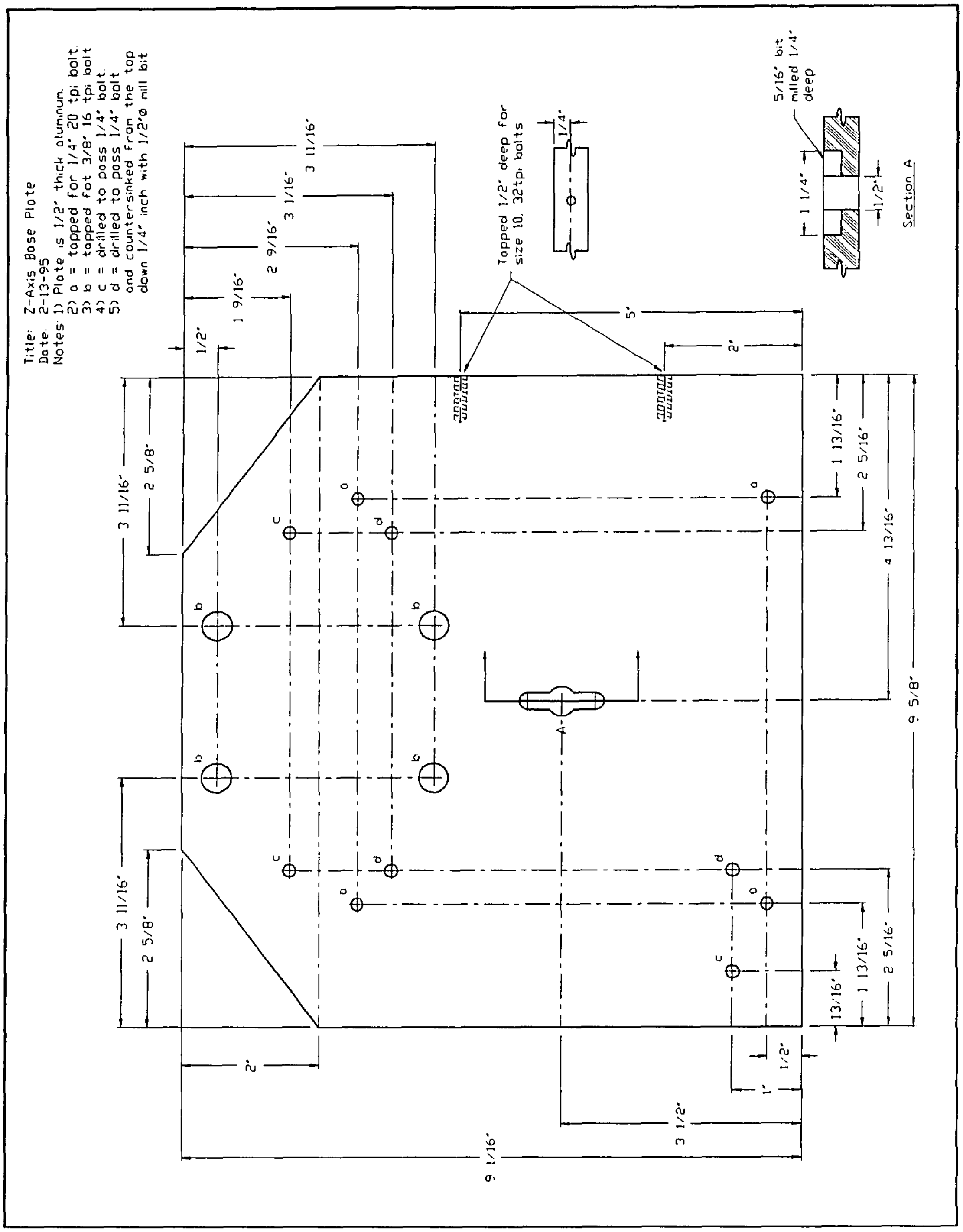


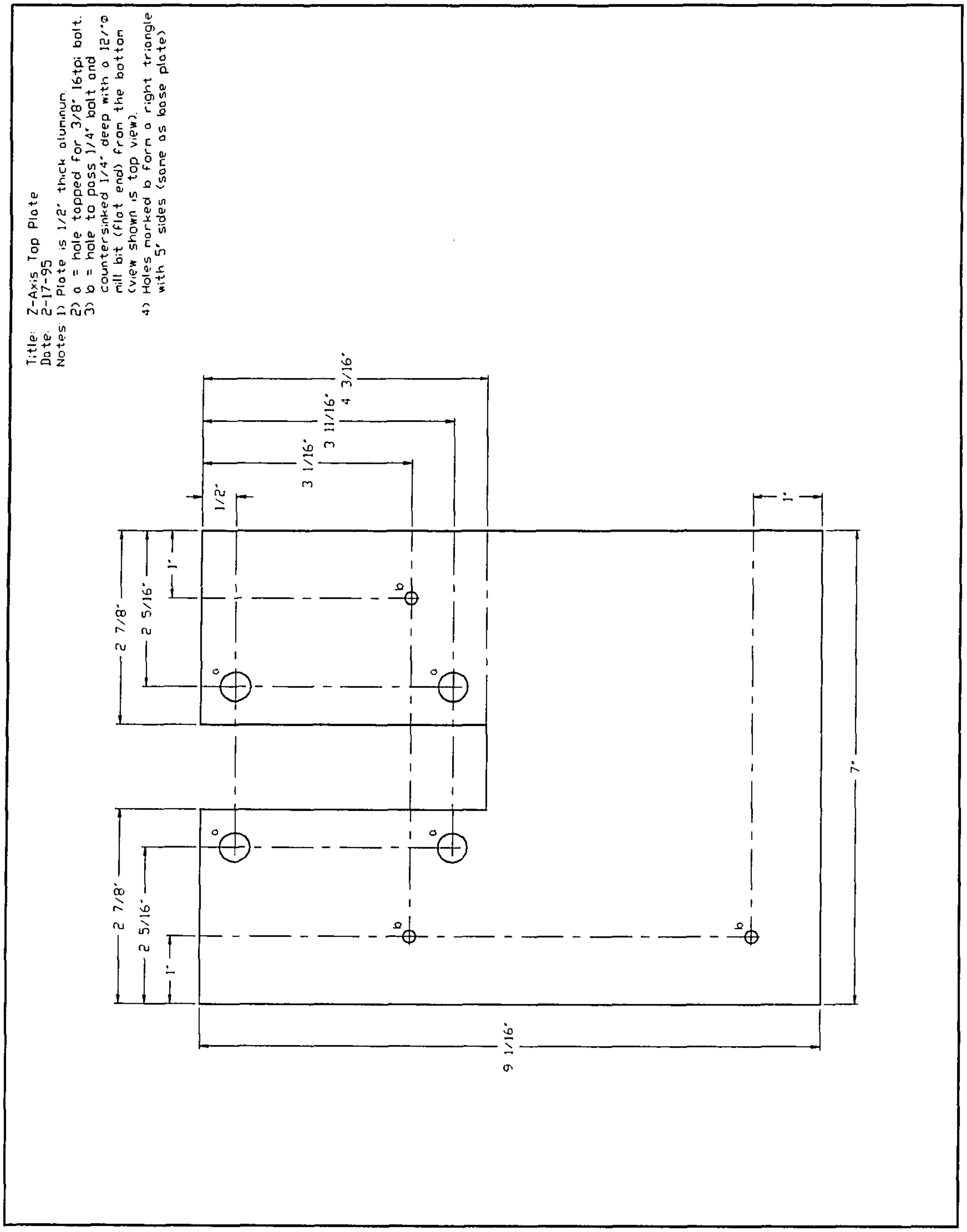

Title: Y-Axis Carriage Plate, Detail C
Date: 2-7-95
Note: 1) Plate is 1/2" thick aluminum.
2) All features go through plate.
3) Holes are tapped for size 8, 32 tpi bolts.
3 7/8"
1 3/8"
1"
3 15/16"
3 15/16"
1"
1 3/8"
3 7/8"

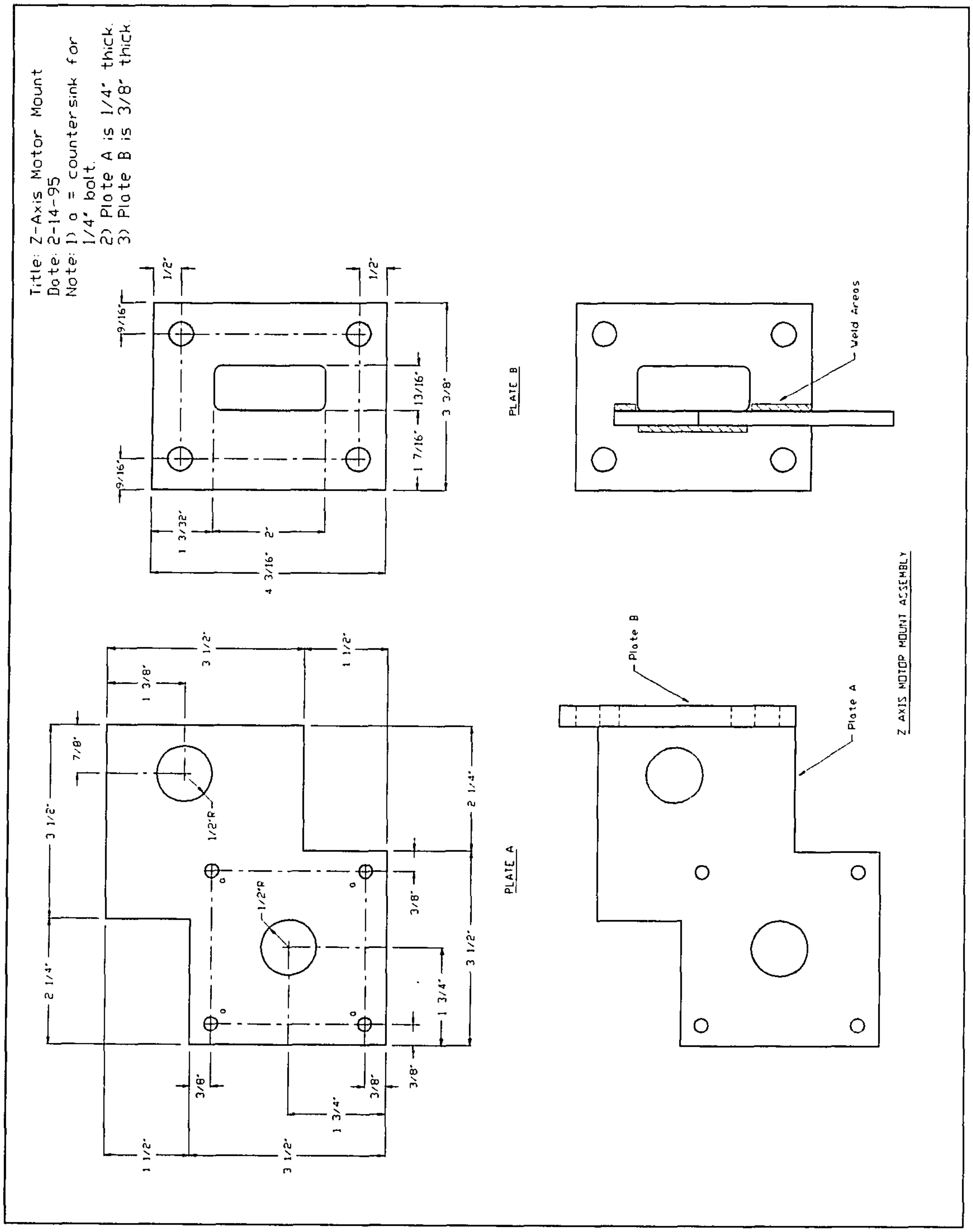

Title: Y-Axis Carriage Plate, Detail D
Date: 3-7-95
Note: 1) Plate is 1/2" thick aluminum.
2) All features go through plate.
3) Holes are tapped for 1/4" 20tpi bolts.
12 13/32"
11 7/8"
1 1/8"
19/32"
1 3/32"
1 5/8"
12 3/8"
12 29/32"
8 11/32"
7 19/32"

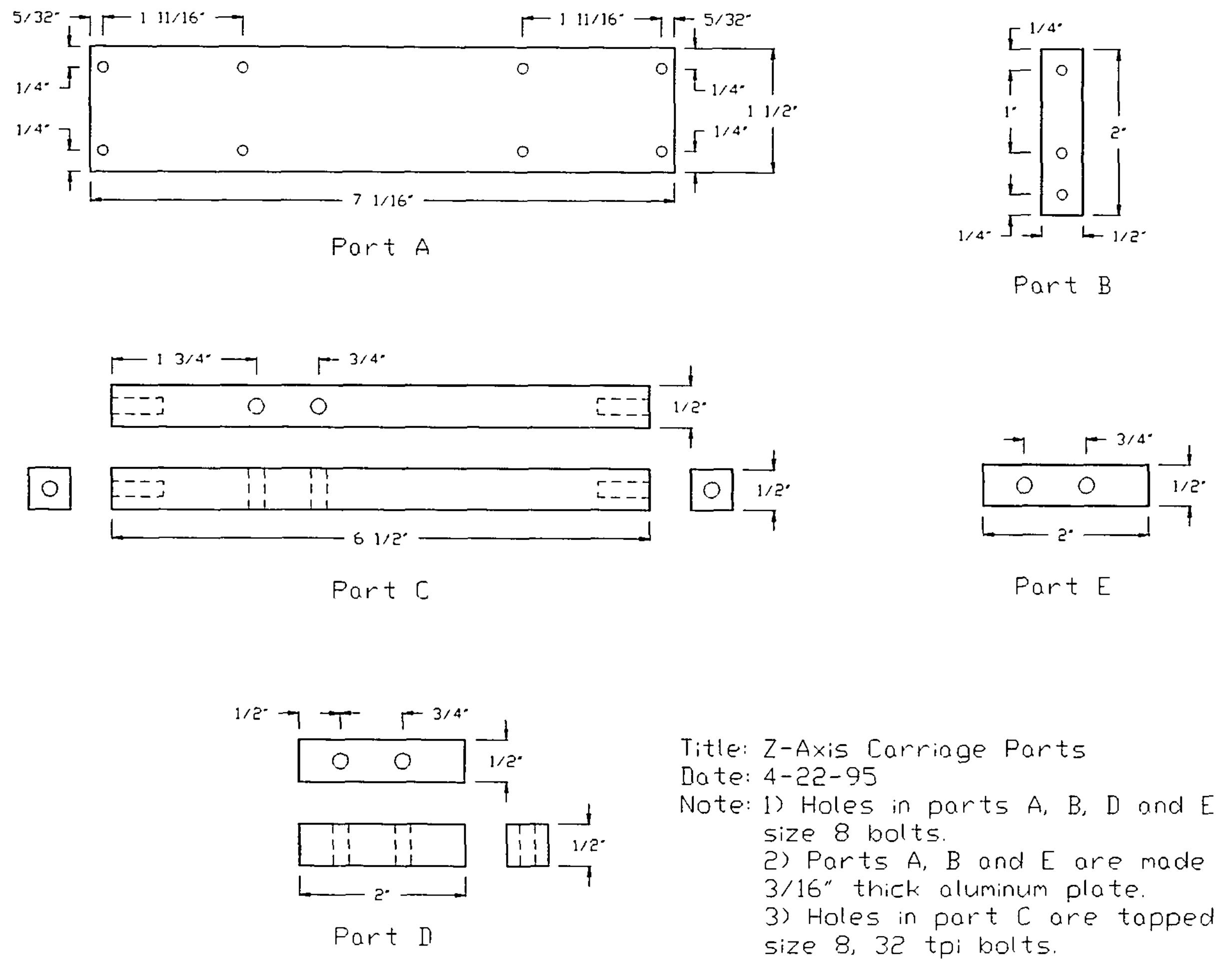

Title: Z-Axis Thrust Plate
Date: 2-3-95
Note: 1) Plate is 1/8" thick aluminum.
2) Unmarked holes are 1/4"Ø
Ø1"
Ø1"
3"
2 1/2"
3"
2 1/2"
6 1/2"
1 13/16"
2 1/2"
2 1/2"
3"
3"
6 1/2"
4 5/16"


Title: Thrust Plate Bearing Bracket
Date: 3-6-95
Note: 1) Made from 2"x2"x0.25"
aluminum angle.
1/4"
2"
2"
1/2"
1/2"
Ø1/4"
3/4"
1"
Ø5/16"
1/4"
3/4"
1/2"

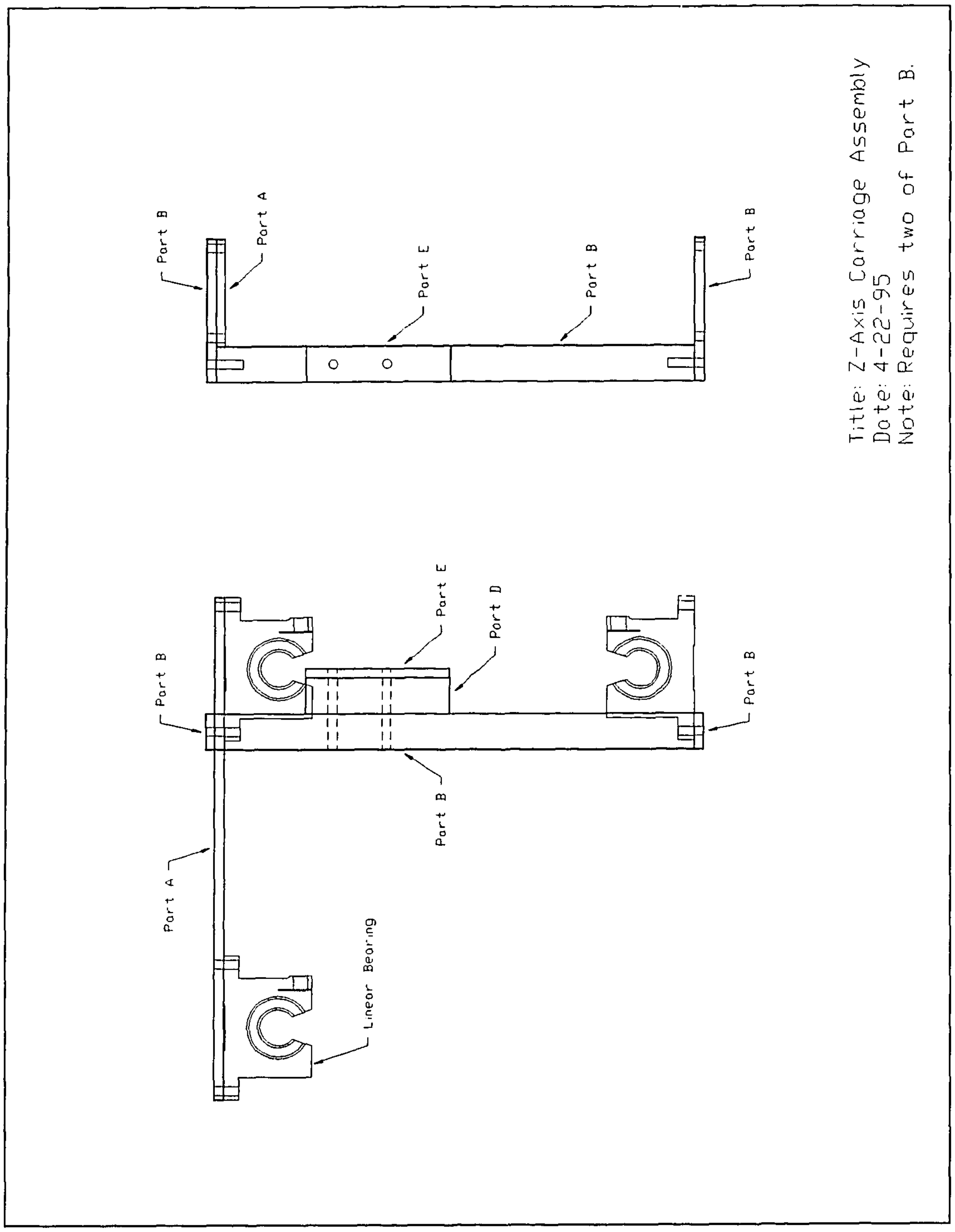

Title: Z-Axis Base Plate
Date: 2-13-95
Notes: 1) Plate is 1/2" thick aluminum.
2) a = tapped for 1/4" 20 tpi bolt
3) b = tapped fot 3/8" 16 tpi bolt
4) c = drilled to pass 1/4" bolt
5) d = drilled to pass 1/4" bolt and countersinked from the top down 1/4" inch with 1/2"ø mill bit
Tapped 1/2" deep for size 10, 32tpi bolts
5/16" bit milled 1/4" deep
Section A

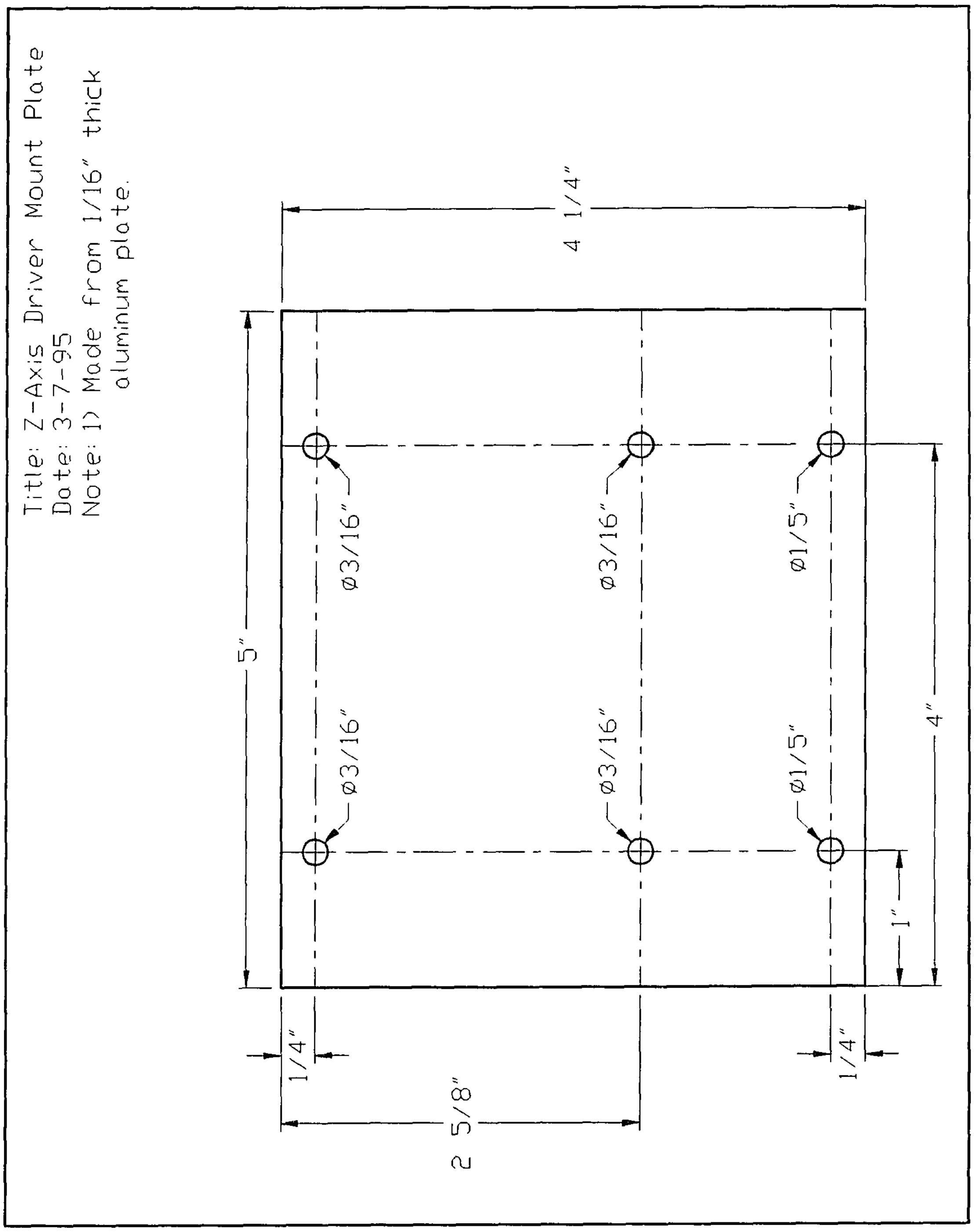

Title: Z-Axis Top Plate
Date: 2-17-95
Notes: 1) Plate is 1/2' thick aluminum.
2) a = hole tapped for 3/8' 16tpi bolt.
3) b = hole to pass 1/4' bolt and countersinked 1/4' deep with a 12/'ø mill bit (flat end) from the bottom (view shown is top view).
4) Holes marked b form a right triangle with 5' sides (same as base plate)
4 3/16'
3 11/16'
3 1/16'
1/2'
1'
2 7/8'
2 5/16'
1'
a
b
7'
9 1/16'


Title: Z-Axis Motor Mount
Date: 2-14-95
Note: 1) a = countersink for 1/4" bolt.
2) Plate A is 1/4" thick.
3) Plate B is 3/8" thick.
PLATE B
PLATE A
Weld Areas
Plate B
Plate A
Z AXIS MOTOP MOUNT ASSEMBLY
1/2"
9/16"
13/16"
1 7/16"
3 3/8"
1 3/32"
2"
4 3/16"
3 1/2"
1 1/2"
1 3/8"
7/8"
1/2"R
2 1/4"
3/8"
1 3/4"



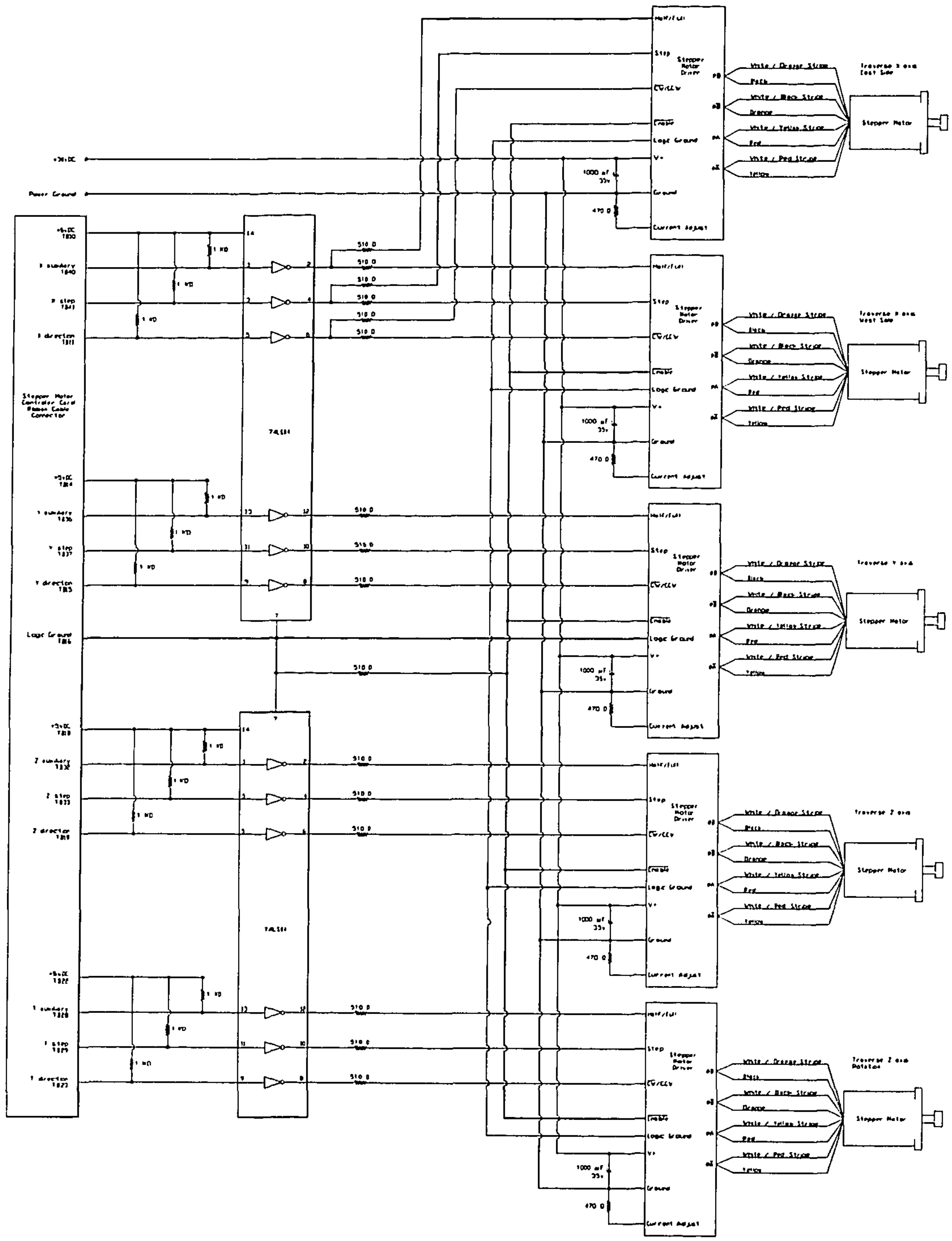
Title: Z-Axis Carriage Parts
Date: 4-22-95
Note: 1) Holes in parts A, B, D and E pass size 8 bolts.
2) Parts A, B and E are made from 3/16" thick aluminum plate.
3) Holes in part C are tapped for size 8, 32 tpi bolts.
4) Parts c and D are made from 1/2" square aluminum stock.


Part B
Part A
Part E
Part B
Part B
Part B
Part E
Part D
Part B
Part B
Part A
Linear Bearing
Title: Z-Axis Carriage Assembly
Date: 4-22-95
Note: Requires two of Part B.

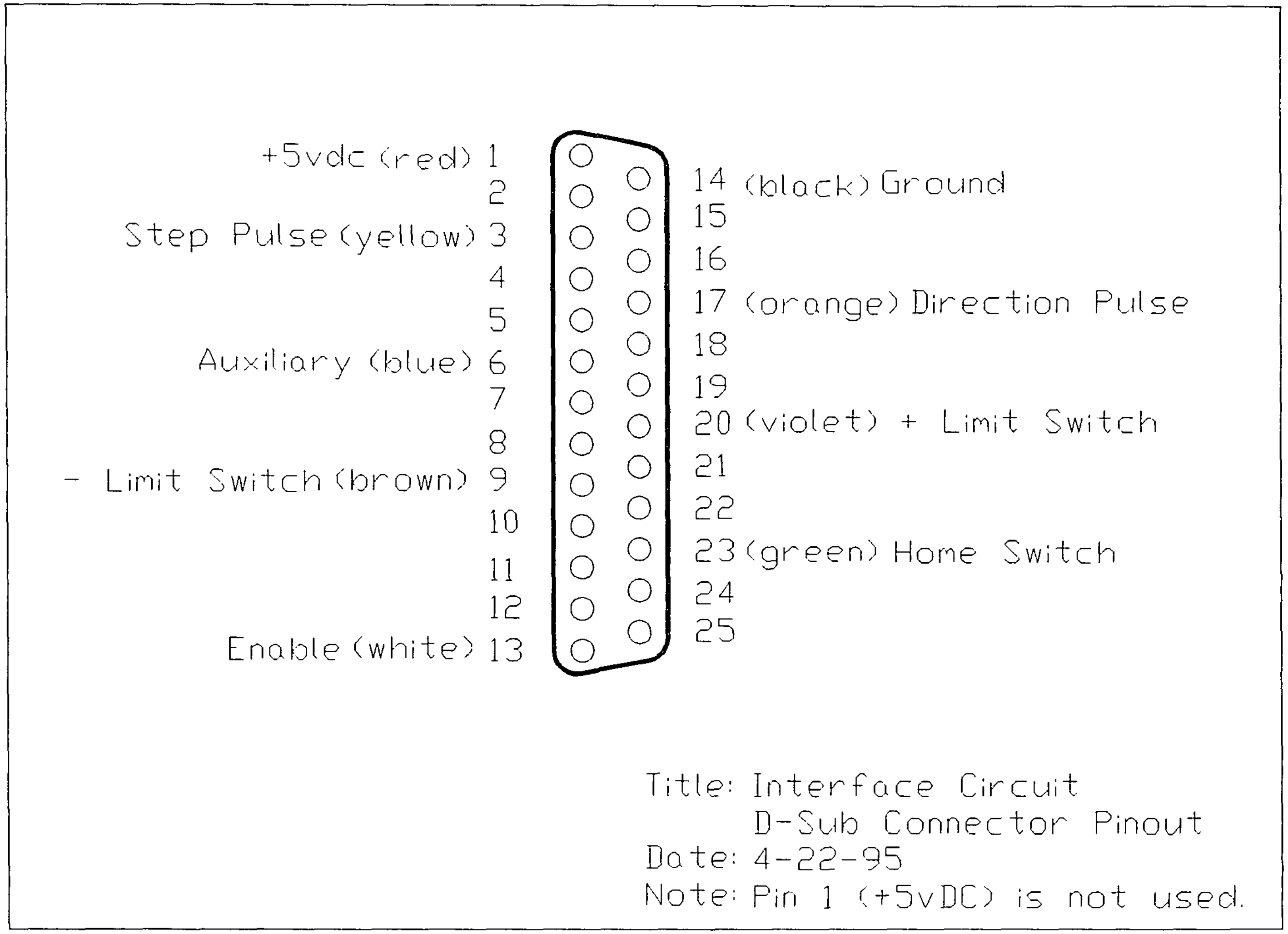

Title: Z-Axis Driver Mount Plate
Date: 3-7-95
Note: 1) Made from 1/16" thick aluminum plate.
4 1/4"
5"
ø3/16"
ø3/16"
ø3/16"
ø3/16"
ø1/5"
ø1/5"
4"
1"
1/4"
1/4"
2 5/8"

APPENDIX 17

TRAVERSING MECHANISM INTERFACE CIRCUIT



Power Ground
Stepper Motor Controller Card Ribbon Cable Connector
Half/Full
Step
Stepper Motor Driver
CW/CCW
Enable
Logic Ground
V+
Ground
Current Adjust
Stepper Motor


+5vdc (red) 1
2
Step Pulse (yellow) 3
4
5
Auxiliary (blue) 6
7
8
- Limit Switch (brown) 9
10
11
12
Enable (white) 13
14 (black) Ground
15
16
17 (orange) Direction Pulse
18
19
20 (violet) + Limit Switch
21
22
23 (green) Home Switch
24
25
Title: Interface Circuit
D-Sub Connector Pinout
Date: 4-22-95
Note: Pin 1 (+5vDC) is not used.

APPENDIX 18

COMMAND PROGRAM SETUP FILE FORMAT

4230,	window top edge location (twips)
4800,	window left edge location (twips)
c:\throw\program.vb3\traverse\,	Traverse module path
c:\throw\program.vb3\measure\,	Measure module path

APPENDIX 19

TRAVERSE PROGRAM SETUP FILE FORMAT

1430,	window top edge location (twips)
50,	window left edge location (twips)
0,	probe length (inches)
in,	x axis unit string
0.00589,	x axis conversion factor (inch/step)
0,	x axis home position (inches) (0.00589*53835)
10,	x axis big jump value (inches)
1,	x axis small jump value (inches)
53835,	x axis positive limit relative to home (steps)
0,	x axis negative limit relative to home (steps)
100,	x axis velocity (steps/s)
200,	x axis acceleration (step/s/s)
in,	y axis unit string
0.00589,	y axis conversion factor (inch/step)
0,	y axis home position (inches) (0.00589*35553)
10,	y axis big jump value (inches)
1,	y axis small jump value (inches)
35553,	y axis positive limit relative to home (steps)
0,	y axis negative limit relative to home (steps)
300,	y velocity (steps/s)
800,	y axis acceleration (step/s/s)
in,	z axis unit string
0.031415,	z axis conversion factor (inch/step)
0,	z axis home position (inches) (0.031415*3716)
10,	z axis big jump value (inches)
1,	z axis small jump value (inches)
3716,	z axis positive limit relative to home (steps)
0,	z axis negative limit relative to home (steps)
200,	z axis velocity (steps/s)
800,	z axis acceleration (step/s/s)
deg,	t axis unit string
0.45,	t axis conversion factor (degree/step)
0,	t axis home position (degrees)
5,	t axis big jump value (degrees)
1,	t axis small jump value (degrees)
200,	t axis positive limit relative to home (steps)
-200,	t axis negative limit relative to home (steps)
20,	t axis velocity (steps/s)
1000,	t axis acceleration (step/s/s)

APPENDIX 20

DATA ACQUISITION PROGRAM SETUP FILE FORMAT

30,	window top edge position (twips)
50,	window left edge position (twips)
16,	number of analog input channels
AI 1,	channel 1 name string
v,	channel 1 unit string
0.00,	channel 1 display format
8,	channel 1 range code
12,	channel 1 resolution (bits)
0,	channel 1 delay (milliseconds)
100,	channel 1 sample size
unity,	channel 1 calibration file
AI 2,	channel 2 name string
v,	channel 2 unit string
0.00,	channel 2 display format
8,	channel 2 range code
12,	channel 2 resolution (bits)
0,	channel 2 delay (milliseconds)
100,	channel 2 sample size
unity,	channel 2 calibration file
AI 3,	channel 3 name string
v,	channel 3 unit string
0.00,	channel 3 display format
8,	channel 3 range code
12,	channel 3 resolution (bits)
0,	channel 3 delay (milliseconds)
100,	channel 3 sample size
unity,	channel 3 calibration file
AI 4,	channel 4 name string
v,	channel 4 unit string
0.00,	channel 4 display format
8,	channel 4 range code
12,	channel 4 resolution (bits)
0,	channel 4 delay (milliseconds)
100,	channel 4 sample size
unity,	channel 4 calibration file
AI 5,	channel 5 name string
v,	channel 5 unit string
0.00,	channel 5 display format
8,	channel 5 range code
12,	channel 5 resolution (bits)
0,	channel 5 delay (milliseconds)
100,	channel 5 sample size
unity,	channel 5 calibration file

AI 6,	channel 6 name string
v,	channel 6 unit string
0.00,	channel 6 display format
8,	channel 6 range code
12,	channel 6 resolution (bits)
0,	channel 6 delay (milliseconds)
100,	channel 6 sample size
unity,	channel 6 calibration file
AI 7,	channel 7 name string
v,	channel 7 unit string
0.00,	channel 7 display format
8,	channel 7 range code
12,	channel 7 resolution (bits)
0,	channel 7 delay (milliseconds)
100,	channel 7 sample size
unity,	channel 7 calibration file
AI 8,	channel 8 name string
v,	channel 8 unit string
0.00,	channel 8 display format
8,	channel 8 range code
12,	channel 8 resolution (bits)
0,	channel 8 delay (milliseconds)
100,	channel 8 sample size
unity,	channel 8 calibration file
AI 9,	channel 9 name string
v,	channel 9 unit string
0.00,	channel 9 display format
8,	channel 9 range code
12,	channel 9 resolution (bits)
0,	channel 9 delay (milliseconds)
100,	channel 9 sample size
unity,	channel 9 calibration file
AI 10,	channel 10 name string
v,	channel 10 unit string
0.00,	channel 10 display format
8,	channel 10 range code
12,	channel 10 resolution (bits)
0,	channel 10 delay (milliseconds)
100,	channel 10 sample size
unity,	channel 10 calibration file
AI 11,	channel 11 name string
v,	channel 11 unit string
0.00,	channel 11 display format

8,	channel 11 range code
12,	channel 11 resolution (bits)
0,	channel 11 delay (milliseconds)
100,	channel 11 sample size
unity,	channel 11 calibration file
AI 12,	channel 12 name string
v,	channel 12 unit string
0.00,	channel 12 display format
8,	channel 12 range code
12,	channel 12 resolution (bits)
0,	channel 12 delay (milliseconds)
100,	channel 12 sample size
unity,	channel 12 calibration file
AI 13,	channel 13 name string
v,	channel 13 unit string
0.00,	channel 13 display format
8,	channel 13 range code
12,	channel 13 resolution (bits)
0,	channel 13 delay (milliseconds)
100,	channel 13 sample size
unity,	channel 13 calibration file
AI 14,	channel 14 name string
v,	channel 14 unit string
0.00,	channel 14 display format
8,	channel 14 range code
12,	channel 14 resolution (bits)
0,	channel 14 delay (milliseconds)
100,	channel 14 sample size
unity,	channel 14 calibration file
AI 15,	channel 15 name string
C,	channel 15 unit string
0.00,	channel 15 display format
8,	channel 15 range code
12,	channel 15 resolution (bits)
0,	channel 15 delay (milliseconds)
100,	channel 15 sample size
therm_p4,	channel 15 calibration file
AI 16,	channel 16 name string
C,	channel 16 unit string
0.00,	channel 16 display format
8,	channel 16 range code
12,	channel 16 resolution (bits)
0,	channel 16 delay (milliseconds)

100,	channel 16 sample size
therm_p5,	channel 16 calibration file
16,	number of digital channels
DIO 1,	digital channel 1 name string
1,	digital channel 1 input\output state (1 = output; 0 = input)
DIO 2,	digital channel 2 name string
1,	digital channel 2 input\output state (1 = output; 0 = input)
DIO 3,	digital channel 3 name string
1,	digital channel 3 input\output state (1 = output; 0 = input)
DIO 4,	digital channel 4 name string
1,	digital channel 4 input\output state (1 = output; 0 = input)
DIO 5,	digital channel 5 name string
1,	digital channel 5 input\output state (1 = output; 0 = input)
DIO 6,	digital channel 6 name string
1,	digital channel 6 input\output state (1 = output; 0 = input)
DIO 7,	digital channel 7 name string
1,	digital channel 7 input\output state (1 = output; 0 = input)
DIO 8,	digital channel 8 name string
1,	digital channel 8 input\output state (1 = output; 0 = input)
DIO 9,	digital channel 9 name string
1,	digital channel 9 input\output state (1 = output; 0 = input)
DIO 10,	digital channel 10 name string
1,	digital channel 10 input\output state (1 = output; 0 = input)
DIO 11,	digital channel 11 name string
1,	digital channel 11 input\output state (1 = output; 0 = input)
DIO 12,	digital channel 12 name string
1,	digital channel 12 input\output state (1 = output; 0 = input)
DIO 13,	digital channel 13 name string
1,	digital channel 13 input\output state (1 = output; 0 = input)
DIO 14,	digital channel 14 name string
1,	digital channel 14 input\output state (1 = output; 0 = input)
DIO 15,	digital channel 15 name string
1,	digital channel 15 input\output state (1 = output; 0 = input)
DIO 16,	digital channel 16 name string
1,	digital channel 16 input\output state (1 = output; 0 = input)
4,	number of analog outputs
AO 1,	analog output 1 name string
AO 2,	analog output 2 name string
AO 3,	analog output 3 name string
AO 4,	analog output 4 name string