EPA-650/2-74-103

OCTOBER 1974

Environmental Protection Technology Series

DESIGN, FABRICATION, AND INSTALLATION OF A PARTICULATE AERODYNAMIC TEST FACILITY

Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

EPA-650/2-74-103

DESIGN, FABRICATION, AND INSTALLATION OF A PARTICULATE AERODYNAMIC TEST FACILITY

by

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Contract No. 68-02-0625
ROAP No. 21ADJ-080
Program Element No. 1AB012

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Prepared for

OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

October 1974

This report has been reviewed by the Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The program described in this report was carried out for the U.S. Environmental Protection Agency, Control Systems Laboratory, Research Triangle Park, North Carolina, under Contract No. 68-02-0625. The contract began September 1972 and was concluded March 1973. Technical management at EPA was provided by Jim Dorsey and Bruce Harris. The assistance of these individuals in carrying out this project is gratefully acknowledged.

Dr. Larry Anderson was the Aerotherm program manager for the work reported here. Project engineers were Dale Blann and Ken Green.

ABSTRACT

The trade-offs and design considerations, component selection criteria, and final design details for a particulate aerodynamic test facility are presented. The design meets a range of performance specifications for the test gas which include test section gas velocities to 90 ft/sec, temperatures to 450°F, variable humidity and gas composition, including particulates.

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SECTION 1

INTRODUCTION

Aerosols emitted from stationary sources constitute one of the most common and readily observable air pollutants currently being subjected to control measures. These aerosols, which are composed of solid and/or liquid* particles, originate in the fuel used in a typical combustion process, or in the pre- or post-combustion process itself. Noncombustible components of coal and oil fuels (the ash content) pass directly through the combustion zone of a burner and are emitted to the atmosphere generally in solid form, with characteristic dimensions of one-tenth to one hundred microns and larger. Sulfur and metallic trace species in the fuel oxidize during combustion to form other aerosol components. Fuel-rich combustion results in many types of condensible organics, whose state is dependent on local temperature. Dust from material handling operations can be a problem exclusive of any combustion. Many of these particulates are noxious, corrosive, or even toxic in large concentrations. Thus, the control of aerosols is seen to be desirable not only from an aesthetic point of view, but also from a property damage and health point of view.

Measures currently in use for the control of particulates concentrate both on the allowable pollutant content of the fuel (i.e., the sulfur content) and on the allowable particulate emissions at a given installation. Particulate emissions for a given process are often controlled by mechanical means, such as inertial separators, scrubbers, baghouses, and electrical precipitators. Further advancement in the "particulate control" state of the art will require basic information on the general behavior of particulates in flue gases. In addition, more sophisticated and automated instrumentation to test the performance of control equipment or compliance with air pollution regulations is needed. Such basic information and instrumentation will play key roles in the specification of particulate control legislation.

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*With the exception of water, which is not considered a pollutant.

In 1971, the U.S. Environmental Protection Agency commissioned Aerotherm Division of Acurex Corporation to perform a design study of a particulate aerodynamic test facility. The results of that study are contained in Reference 1. The study describes a laboratory facility which creates a steady state test stream whose velocity, temperature, dust concentration, and other properties are representative of conditions in the exhaust stack of a typical "stationary source" of air pollution, such as a utility powerplant. This laboratory facility could then be used to conduct research and development programs in the following areas:

- Basic particulate flows
- Instrumentation for stationary sources
- Control device development and testing

All these R&D programs could be performed in a laboratory situation, with control over the important variables of the process.

In 1972, the Control Systems Laboratory of the Particulate and Chemical Process Branch of the EPA commissioned Aerotherm to build this laboratory facility. At the same time, the Chemistry and Physics Laboratory of the Source Emissions Branch of the EPA contracted for construction of a similiar facility. Development of the two facilities proceeded in parallel and design decisions of each were impacted to varying degrees by both configurations. A simplified model of the final facility configuration is shown in Figure 1 and the actual installation, prior to installation of insulation, is shown in Figure 2.

Basically, the facility is a low speed, closed loop wind tunnel. Dust is injected just upstream of the test section and is collected in a large, cylindrical-bag filter dust collector located downstream of the diffuser. The test section is a modular, 24-inch diameter duct, 40-feet in length. The entire system is insulated for high temperature operation. Table I summarizes some of the facility capabilities.

This final report on the particulate aerodynamic test facility is intended to supplement the Reference 1 study, providing information on the final as-built configuration and some of the reasons for design decisions. Section 2 presents the design requirements, Section 3 is a review of the conclusions of the Reference 1 study, and Section 4 discusses some of the considerations for each of the major components. Appendix A describes step-by-step facility operation. Complete facility operation instructions are contained in the Operations and Safety Manual, Reference 2.

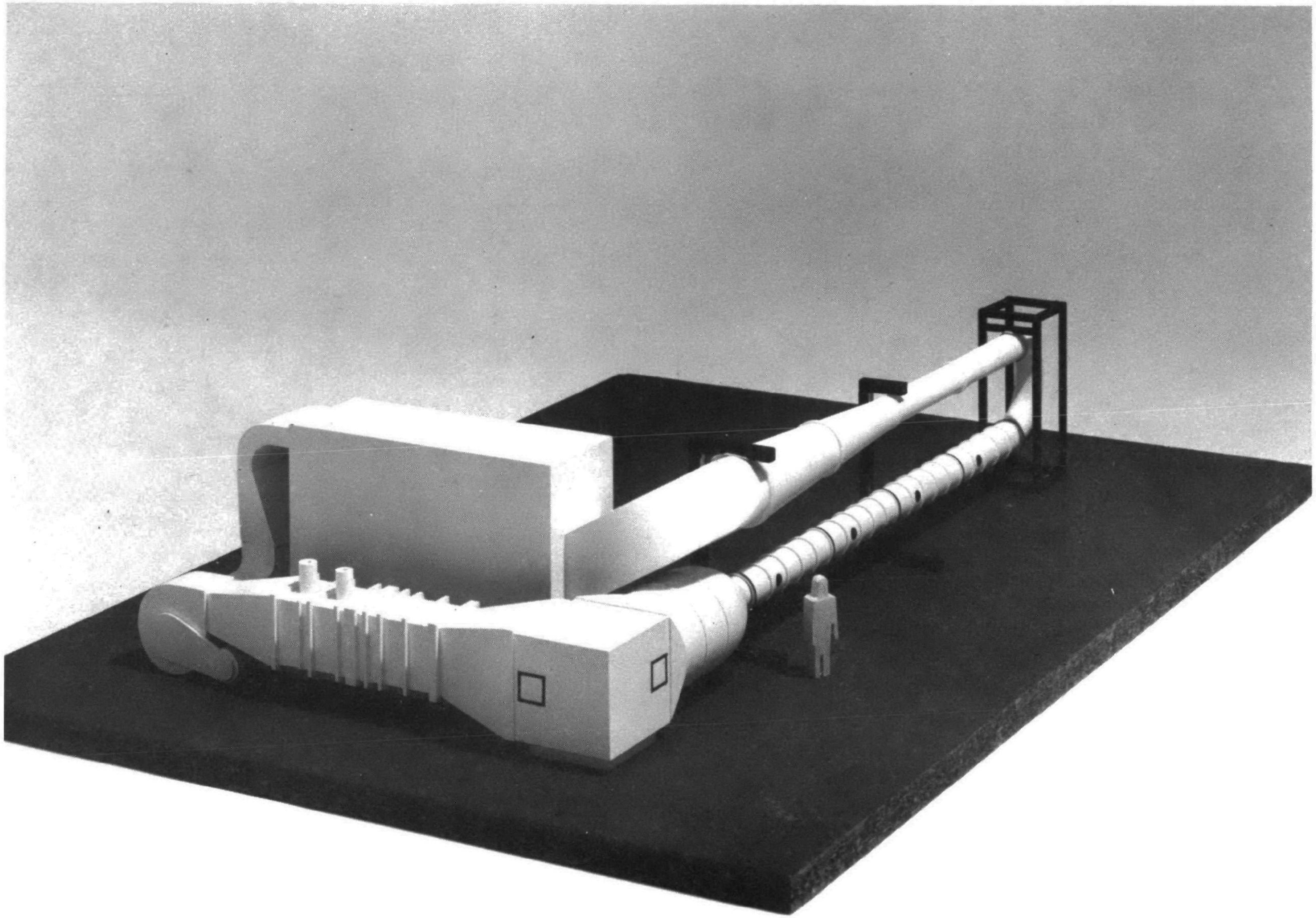

Figure 1. Model of Particulate Aerodynamic Test Facility

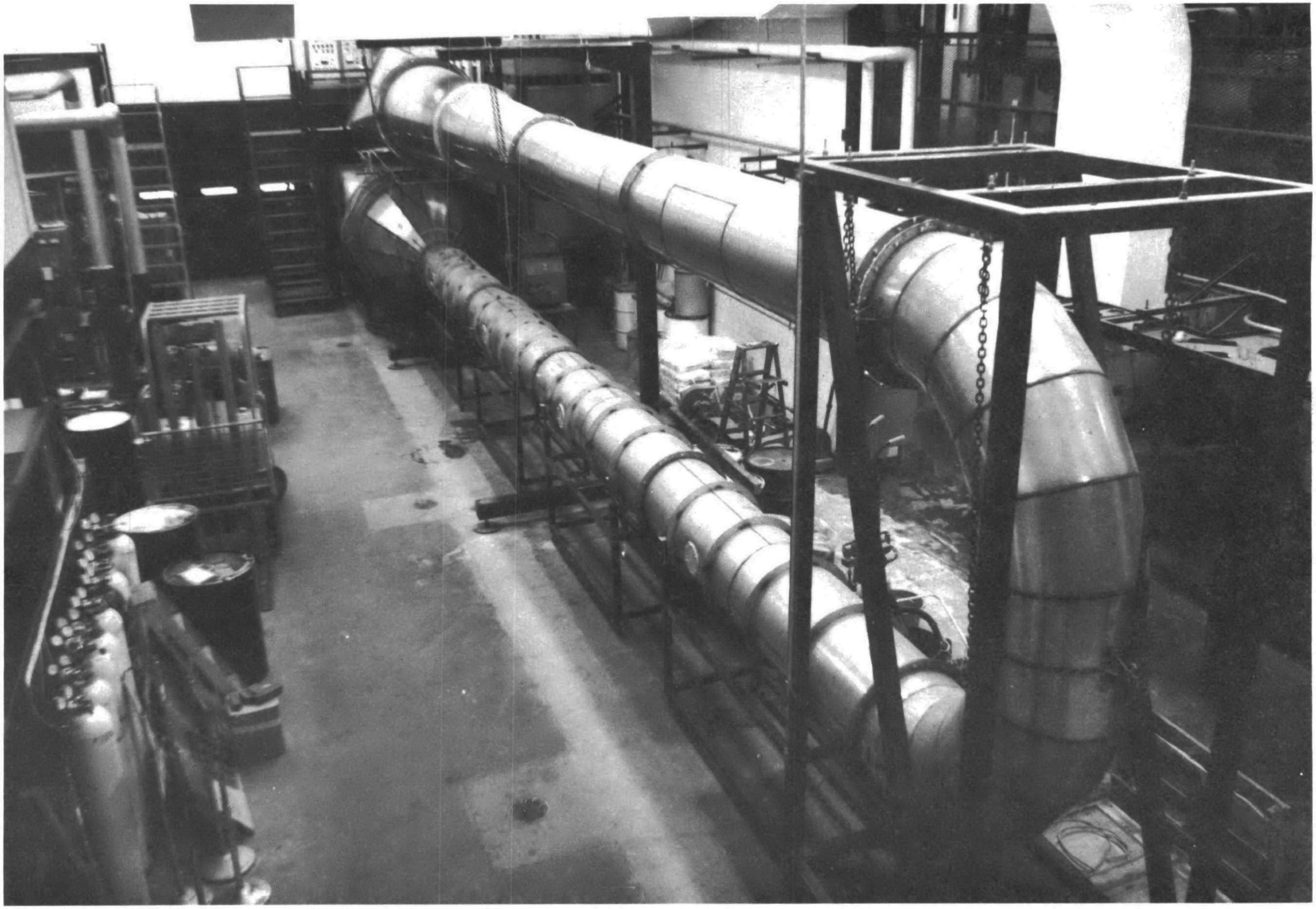

Figure 2. Particulate Aerodynamic Test Facility for Control Systems Laboratory, Environmental Protection Agency

TABLE I

SUMMARY OF MAJOR PERFORMANCE SPECIFICATIONS OF PARTICULATE AERODYNAMIC TEST FACILITY

Test Section	
Dimensions	24" Diameter 40' Long (four 10-foot test section modules)
Velocity	0-90 fps
Gas Conditioning Capability	
Temperature	Ambient to 450°F
Moisture Content	Humidifier capable of supplying 50 lb/hr dry steam
Composition	0 to 100 percent combustion products from gas fired boiler; other constituents by separate injection
Particulates	0-10 gr/ft^3 fly ash, depending on test section velocity

SECTION 2

FACILITY REQUIREMENTS

The basic design requirements for the particulate aerodynamic text facility were established in the design study conducted for the EPA by the Aerotherm Division of Acurex Corporation (Reference 1). Following is a summary of the requirements defined by the study including those areas where the design study-generated requirements were modified in the actual design.

Conditioned Air Test Stream

The facility will operate with air as a test gas. The original requirement stated that the air temperature in the test section would be 70°F - 100°F with a 10-80 percent relative humidity level. Precision control of the temperature and humidity level at any intermediate setting will be provided. These test conditions will be attainable on a 24-hours-per-day, 365-days-per-year basis using the ASHRAE 99 percent climate criteria for Durham, North Carolina.

As designed, the test facility will operate with air at any temperature setting in the range 70°F - 450°F in the test section.

A consideration was given in the design study to the achievement of 10 percent R.H. at room temperature. Cost consideration strongly favored a chilled water cooling coil, which relies on the central chilled water supply available in the EPA research facility Wing G. Since the chilled water supply temperature may be as high as 45°F, the lowest dew point achievable in the test stream is approximately 50°F, which corresponds to R.H. values ranging from 18 percent at 100°F to 50 percent at 70°F air temperature. These values must be considered the low humidity design points.

The requirement for operation at elevated humidity in the range 70°F - 100°F was relaxed during the design and development effort and emphasis was placed by the EPA technical monitor on achievement of typical combustion products humidity levels with or without exhaust gases. The primary design goal that evolved for the upper limit humidity requirement is a dew point temperature of 125°F - 130°F, achievable at typical exhaust gas dry bulb temperatures (in excess of 200°F).

Operation at high humidity at 70°F - 100°F, a situation in which the baghouse may be at dew point or below with resultant condensation on the filters, is an undesirable condition because of possible "blinding" of the filter bags. Therefore such operation, although attainable, requires extreme caution.

Exhaust Gas Test Stream

The facility will also generate and operate with typical power plant combustion products as a test stream. The exhaust products temperature in the test section will be 170°F to 450°F, with precision control of the gas temperature and composition provided. Exhaust products will be generated with natural gas fuel.

Particulate Loading

The conditioned air or exhaust products test stream will be loaded with 0.1-5.0 grains/ft^3 of solid particulate material. The particulate material will range from 0.2-20 microns mean diameter, and will be uniformly mixed in the test gas at a known axial station in the test section.

Test Section

The test stream will flow through an enclosed test section of round cross-section, with a two-foot maximum internal diameter. The test section construction will allow interchangeable duct sections typical of fossil fuel combustion system breechings to be installed at several locations as an integral part of the test section. Test section length and minimum diameter will be determined as part of the design effort. The facility design should be such that a "low" free stream turbulence level will be encountered in the test section. Observation and lighting windows will be an integral part of the test section construction, with window material of suitable quality for transmissometer or photographic data-taking. The flow velocity in the test section will be 5-90 ft/sec with precision control to any intermediate velocity setting.

Hot and Cold Operation

The facility will be capable of running in either the hot flow or cold flow mode, with a reasonably convenient method of changing from one mode to the other. The changeover need not be performed while the facility is in operation.

Exhaust Streams

Any gaseous exhaust streams from this test facility must meet local, state, federal, and EPA air pollution and safety regulations.

Controls

A single control station will be provided for the operation of this facility. Instrumentation will include all diagnostic and safety equipment typical of a combustion facility of this size.

Facility Cleanout

Means for accomplishing a rapid cleanout betwen tests of all flow surfaces exposed to the particulate material will be provided.

Miscellaneous Requirements

In addition to the operational specifications listed above, a few other requirements less obvious do have to be considered. The most important of these is the space allotment for facility installation in Wing G of the EPA research center. Figure 3 shows the floor space available for this facility. Ceiling height is nominally 20 feet, with numerous air conditioning and utility ducts hanging from the ceiling.

Another requirement is the insulation of nearly all tunnel components for safety reasons. With a test stream temperature of 450°, the possibility of burns and high heat load to the laboratory requires that insulation be installed.

Noise and vibration from the fan must be considered. The large capacity fan required to move greater than 17,000 scfm of air or test gas may result in very high noise levels in the vicinity of the fan, and is a potential source of vibration for the supporting structure if adequate measures are not taken to eliminate them.

Finally, ready and reasonably convenient access should be provided to the test section for rapid modification of probe or model set-ups.

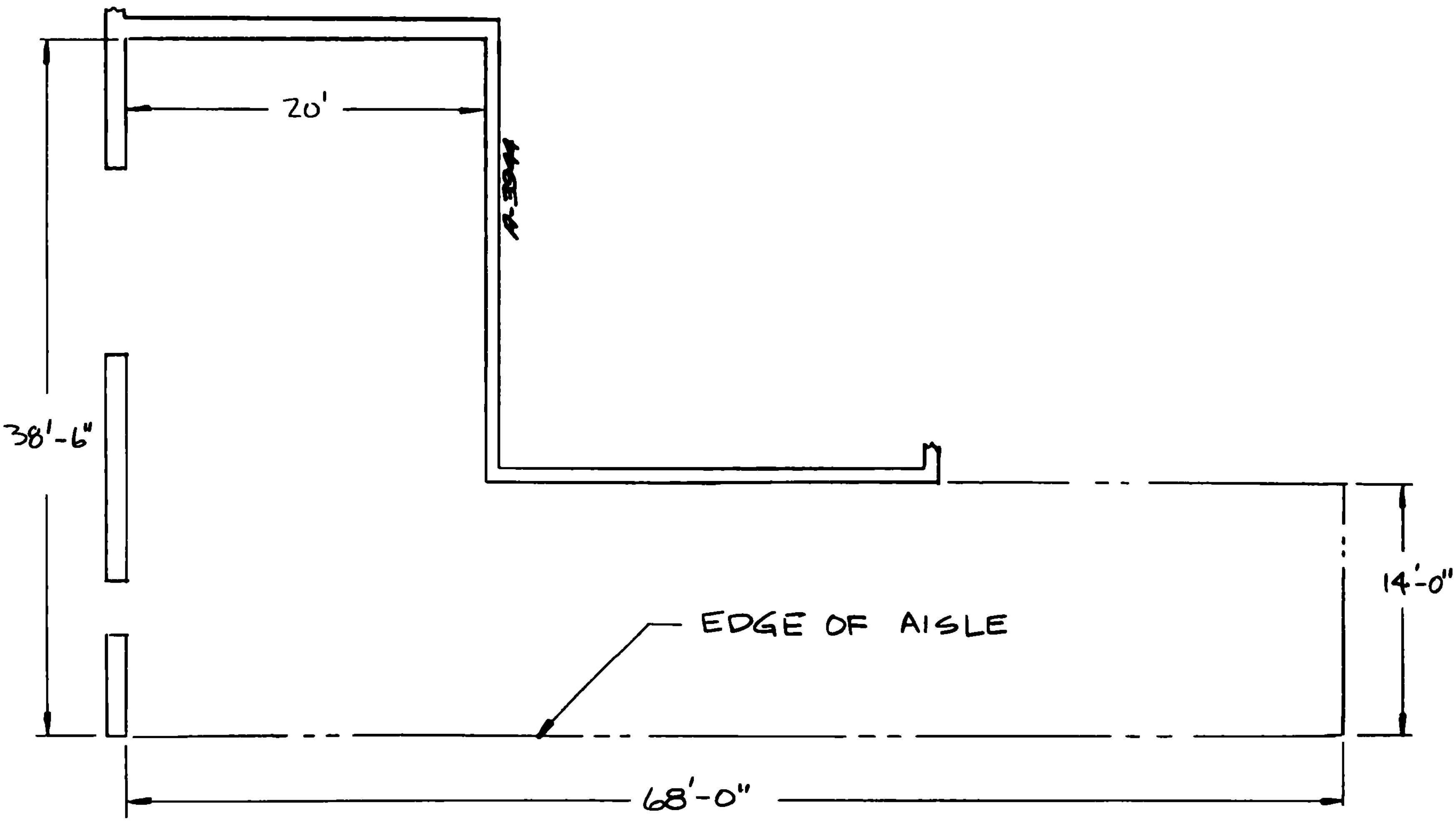

Figure 3. Floor Space Available at North Carolina Research Facility

SECTION 3

DESIGN STUDY SUMMARY

The design study (Reference 1) considered engineering trade-offs for the major components in the particulate aerodynamic test facility, thus laying the ground work for component selection in the development and fabrication effort. As background information for this final report, a brief summary follows of the design recommendations that were made in the design study.

3.1 OPEN CIRCUIT VERSUS CLOSED CIRCUIT TUNNEL

The design study concluded that the test gas circuit should be closed loop and the particulate circuit should be open loop. Open loop operation with exhaust gases would consume a large amount of fuel (300-400 gallons/hour of fuel oil at 90 ft/sec test section velocity) and require a large heat exchanger system to cool the exhaust gases to tunnel operating temperature. Similarly, open loop operation in cold flow would require a large air conditioning unit. In addition, experience in other facilities has shown that a closed circuit tunnel results in better control over the test stream and less noise.

The particulate circuit should be open loop because in the closed loop design the particle loading becomes degraded with time by agglomeration, wall deposition and particle fracture. In addition, fan blades may become coated and eroded, degrading performance.

Figure 4 is a schematic of the closed-loop particulate wind tunnel, showing the relative orientation of major components. Particles are injected ahead of the test section and collected downstream of the diffuser.

3.2 HORIZONTAL VERSUS VERTICAL TEST SECTION

The design study concluded that on the basis of cost, convenience, and flexibility a horizontal test section is the most practical. A brief technical analysis showed that technical objectives would not be seriously compromised for the particle size range of interests.

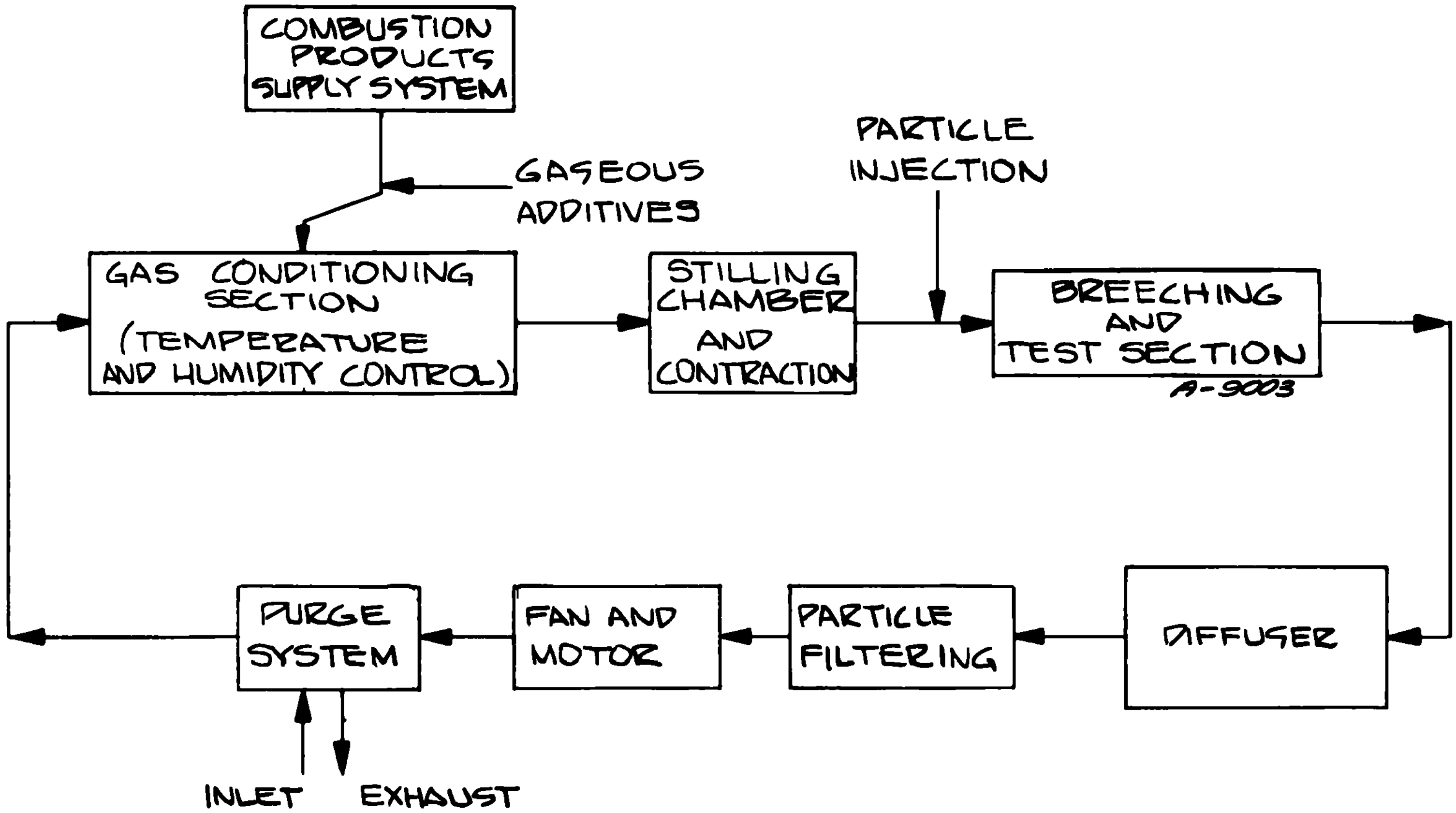

Figure 4. Schematic Diagram of Major Components of Test Facility

3.3 DUST INJECTION TECHNIQUE

The study recommended that the most cost effective dust feed system that would satisfy specifications is a vibrating hopper dust supply feeding dust to an air aspirator. Dust metering would be done with either variable orifice valve or a screw conveyor. The resulting aerosol would be injected isokinetically into the tunnel through multiple nozzles in the tunnel settling chamber.

3.4 TEST SECTION DIAMETER AND LENGTH

In determining the test section size, consideration was given to wall boundary layer thicknesses, test model sizes, probable dust mixing length, and flow entrance and exit transition lengths. A 2-foot diameter 40-foot long test section was determined optimum.

3.5 TEST GAS HEATING

An electric resistance duct heater was recommended on the basis of control accuracy, cost, and availability.

3.6 AIR CONDITIONING

As indicated in Section 2 on facility requirements, a chilled water coil was recommended in the design study to provide dehumidification capability. It was noted that the minimum humidity requirement as originally specified by EPA could not be achieved with this approach. However, the alternate design of a direct expansion refrigerator containing ammonia or freon would offer a small improvement in relative humidity limits and would be quite expensive.

3.7 CHARGING THE TUNNEL WITH COMBUSTION PRODUCTS

In a closed loop system, the enclosed volume may be precharged with a test gas consisting of combustion products (primarily N_2, CO_2, and H_2O) in the proper proportions. The precharged tunnel is then ready for testing. The design study concluded that a small burner should be used to supply the combustion products. Cooling the gases from combustion chamber temperature to wind tunnel operating temperature was considered a difficult problem and the tentative conclusion was to dilute with tunnel gas prior to injection into the tunnel.

3.8 FAN, MOTOR AND SPEED CONTROL

The presence of particulate matter downstream of the test section dictates that the fan should be upstream of the test section. The large flow resistance of the baghouse requires that the fan should be a centrifugal blower to overcome the pressure drop. An airfoil blade design minimizes the noise and pulsating flow characteristic of radial-blade centrifugal blowers.

The obvious choice for the drive was an electric motor. Speed control by means of an eddy current coupling to a constant speed AC motor was recommended from the various alternates on the basis of range, low cost, and simplicity.

3.9 MATERIALS OF CONSTRUCTION

Recommended tunnel material was steel, based primarily on the 450°F operating requirement. Depending on the criticality of the application, stainless steel, bare mild steel, and coated mild steel were recommended in the study in various sections of the tunnel.

SECTION 4
MAJOR COMPONENT DESIGN CONSIDERATIONS

The particulate Aerodynamic Test Facility, as built, met or exceeded all the design requirements presented in Section 2. As would reasonablly be expected, however, in a project of this magnitude, the detailed design and fabrication phases did produce some variances between the actual facility as built and what was presented in the original design study. The differences were not so much in principle as in detail.

Most of these variances can be attributed to a closer evaluation of the economics of the situation, while others resulted simply from engineering considerations unforeseen or ignored for simplicity in the original design study. This section, which is the main body of this report, will deal with the specifics of these variances and discuss the considerations that entered into the design and/or specification of the wind tunnel components.

Figure 5 is a plan view of the Particulate Aerodynamic Test Facility with major components labeled. Table II summarizes the tunnel component selection including a brief description of each of the major components and the supplier.

4.1 FAN AND VARIABLE SPEED DRIVE

As noted in Section 3, the design study had concluded, after rather detailed engineering trade-off study, that a centrifugal type fan was an optimum choice over other types for the wind tunnel facility. Specifically, an airfoil blade centrifugal was recommended for its higher pressure rise, wider speed range with good flow quality, and low swirl component at the fan exit.

The fan and drive selection followed this procedure:

1. Fan static pressure requirements were determined using preliminary tunnel layouts and duct dimensions.
2. Fan characteristic curves were cross-plotted with tunnel characteristic curves for a number of fan sizes. Horsepower and efficiency were calculated.
3. Preliminary size selection was made and bids solicited from several manufacturers.

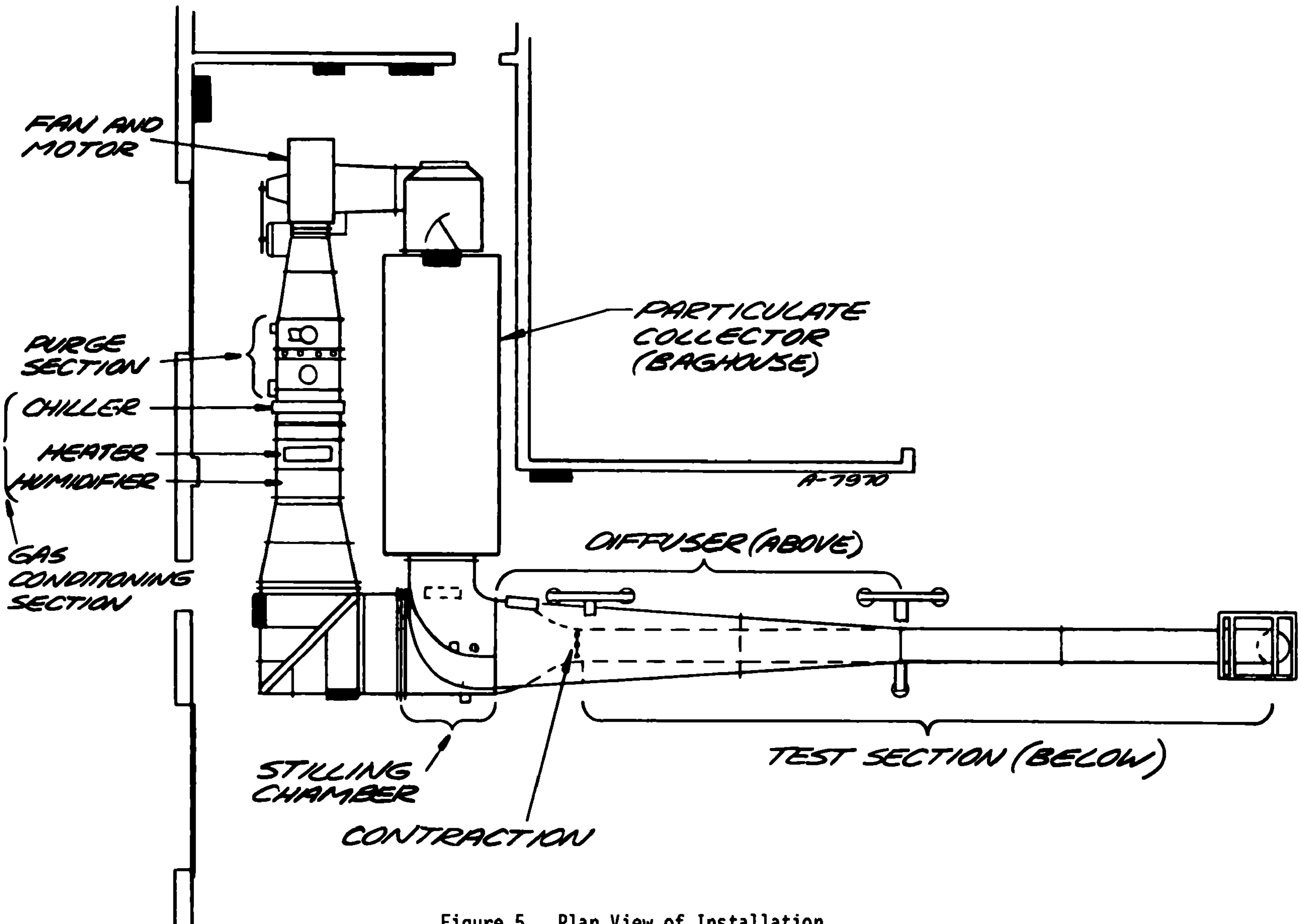

Figure 5. Plan View of Installation

TABLE II

MAJOR EQUIPMENT DESCRIPTION

Item	Qty.	Description	Supplier
1	1	Airfoil blade, centrifugal blower, 30-inch tip diameter, insulated housing, 304 stainless steel construction on all gas stream surfaces, flanged inlet and outlet, access door, V-belt drive, belt guard. Operating conditions: 22.200 cfm @ 10.6" W.G. ΔP 2100 rpm @ 70°F 22.200 cfm @ 6.2" W.G. ΔP 2100 rpm @ 450°F.	Garden City Fan and Blower Co. Niles, Michigan
2	1	Constant speed, squirrel cage motor, 480 vac 3ϕ, integral with eddy current clutch. Horizontal foot mountings, blower cooled, continuous duty. Solid state single channel speed controller with ac tachometer in separate wall-mounted enclosure (WER Industrial Corp.) Motor rating: 50 hp @ 1800 rpm	U.S. Electrical Motors Burlingame, California
3	1	48" x 48" opposed blade damper, vertically oriented, 304 stainless steel on all gas stream surfaces.	American Warming & Ventilating Inc., Toledo, Ohio
4	2	Butterfly valves, 12" inside diameter, 304 stainless steel, flanged.	Same as item 3
5	3	Electric actuators, Model 1026, for items 3 and 4	Leeds & Northrop Company North Wales, PA
6	1	Duct heater, 200 kw, 480 v 3ϕ in two 62.5 kw and one 75 kw circuit, 90 U-bent incoloy sheathed tubular elements, fits in 48" x 48" duct, rectangular terminal housing	Pacific Chromalox Division Emerson Electric Co. Colton, California
7	1	Heater control panel in wall-mounted enclosure, 300-amp main contactor; two 90-amp contactors, one 100 kw 3ϕ 480 v SCR power controller, one adjustable-band proportional controller driver unit with set point adjustment, one set point controller unit with manual reset, two heater overtemperature controllers.	Same as item 6
8	1	Chilled water cooling coil, 48" x 48" frontal area, finned tubes, drainable, flanged, condensate collection pan with loop seal drain, 304 stainless steel construction on all gas stream surfaces.	Rempe Company Chicago, Illinois
9	1	Steam humidifier, air operated, modulating with operator, steam jacketed manifold, steam trap, temperature switch, stainless steel construction on all gas stream surfaces.	Armstrong Machine Works Three Rivers, Michigan

TABLE II (Continued)

Item	Qty.	Description	Supplier
10	1	Dry Materials Volumetric Feeder, 2-1/2 ft^3 vibrating hopper, screw feeder, 10:1 variable speed transmission, 4 screw sizes (GFE systems, which will be superseded by 2nd generation aerosol generator, in development)	Acrison Inc. Carlstadt, N.J.
11	1	Bag filter system, 2088 ft^2 minimum filter area, enclosed insulated housing, screw conveyor and drive, compressed air manifold with valves and timer, venturi throats, Nomex filter bags, removable internal grating, hatch access to clean and dirty air plenums, 300 series stainless steel on all gas stream surfaces except in specified locations.	Miller Industrials Division Industrial Clean Air Berkeley, California
12	1	Hot water boiler, 30 lb, 20 hp, Progress model, four-pass horizontal five-tube, forced draft natural gas burner, FIA-approved burner controls.	Cleaver Brooks Company Milwaukee, Wisconsin
13	1	Heat exchanger, pump, and expansion tank for hot water system for item 12.	Bell and Gossett Fluid Handling Div. of ITT Morton Grove, Illinois
14	1	Combustion products diverter valve set (two 6-inch valves)	W. C. Morris Division Dover Corporation Tulsa, Okla.
15	1	Pneumatic actuator for item 14	Contromatics Corporation Division of Litton Ind. Rockville, Conn.
16	1	Boiler draft modulator valve (one 6-inch valve)	Same as item 14
17	1	Electric actuator for item 16	Ramcon Actuators and Controls Hills-McConna Carpentersville, Ill.
18	1	Wind tunnel ductwork, all sections, 304 stainless steel on all gas stream surfaces, flanged	A. R. Peterson and Sons Hayward, California
19	1	Ductwork support carriages and support towers, boxbeam construction, primed and painted.	Master Metals San Jose, California

TABLE II (Concluded)

Item	Qty.	Description	Supplier
20	1	Exhaust 12-inch diameter ducting and combustion products 6-inch diameter ducting, flanged	Comfort Engineering Durham, N.C.
21	1	Tunnel insulation, 3-inch thick; fiberglass and mineral fiber blankets, secured with weld pins and galv. wire, finished with galv. poultry wire and 1/4 inch cement, 8-oz canvas sized, service temp = 650°F	Matls: Owens Corning Fiberglas Corporation Toledo, Ohio Forty-Eight Insulations, Inc. Aurora, Illinois Installation: Piedmont Insulation Durham, North Carolina
22	1	Control console, relays, switches, meters	Equipment: Various Assembly: Aerotherm Division Acurex Corporation

4. Design calculations were updated to final tunnel configuration requirements as the design progressed.

5. Final fan selection was made on factors of cost, delivery schedule, efficiency, noise, desired margin of safety, and compatibility with the potential drive systems.

Fans of this type may be slightly oversize or undersize and still meet delivery requirements. Thus, the 27-inch and 30-inch wheel diameter range could be shown to meet the tunnel delivery requirements.

Figure 6 presents the results of the fan characteristic analysis for the wind tunnel and the chosen vendor's fans. The preliminary analysis was based on a gas conditioning section of 6 ft x 6 ft cross section, with a 1-inch W.G. pressure drop. Calculations showed fan requirements to be approximately 7.4 inches W.G. (Point A, Figure 6). Based on these requirements, two fan sizes were appropriate, depending on horsepower available. Figure 6 shows that all fan/drive combinations would provide suitable margin.

The conditioning section design was subsequently modified to 4 ft x 4 ft, increasing velocity and pressure drop at that location. The new fan requirement appears as Point C in Figure 6, resulting in the elimination of the 40-horsepower drive option. The figure shows that the 40-horsepower drive provides only a 10-percent margin over the nominally calculated fan requirement at the calculated design point. Since the degree of conservatism in the analysis is not well defined, a 10-percent margin is inadequate. In addition, the 30-inch diameter fan offers the following advantages:

1. Lower rpm for a given fan requirement resulting in quieter and smoother operation

2. Slightly higher efficiency

3. A small price increase over the 27-inch diameter size

Consequently the 30-inch diameter, 50-horsepower fan was selected.

The original design study established the basic trade-off factors between types of variable-speed drives and the choice narrowed, for purpose of the actual design selection, to either SCR/dc or SCR eddy current clutch type drives. Since these drives were comparable from a systems standpoint, the final criteria was one of price. The choice was straightforward as the eddy-current coupling device with a constant speed ac motor proved to be about 20 percent less expensive.

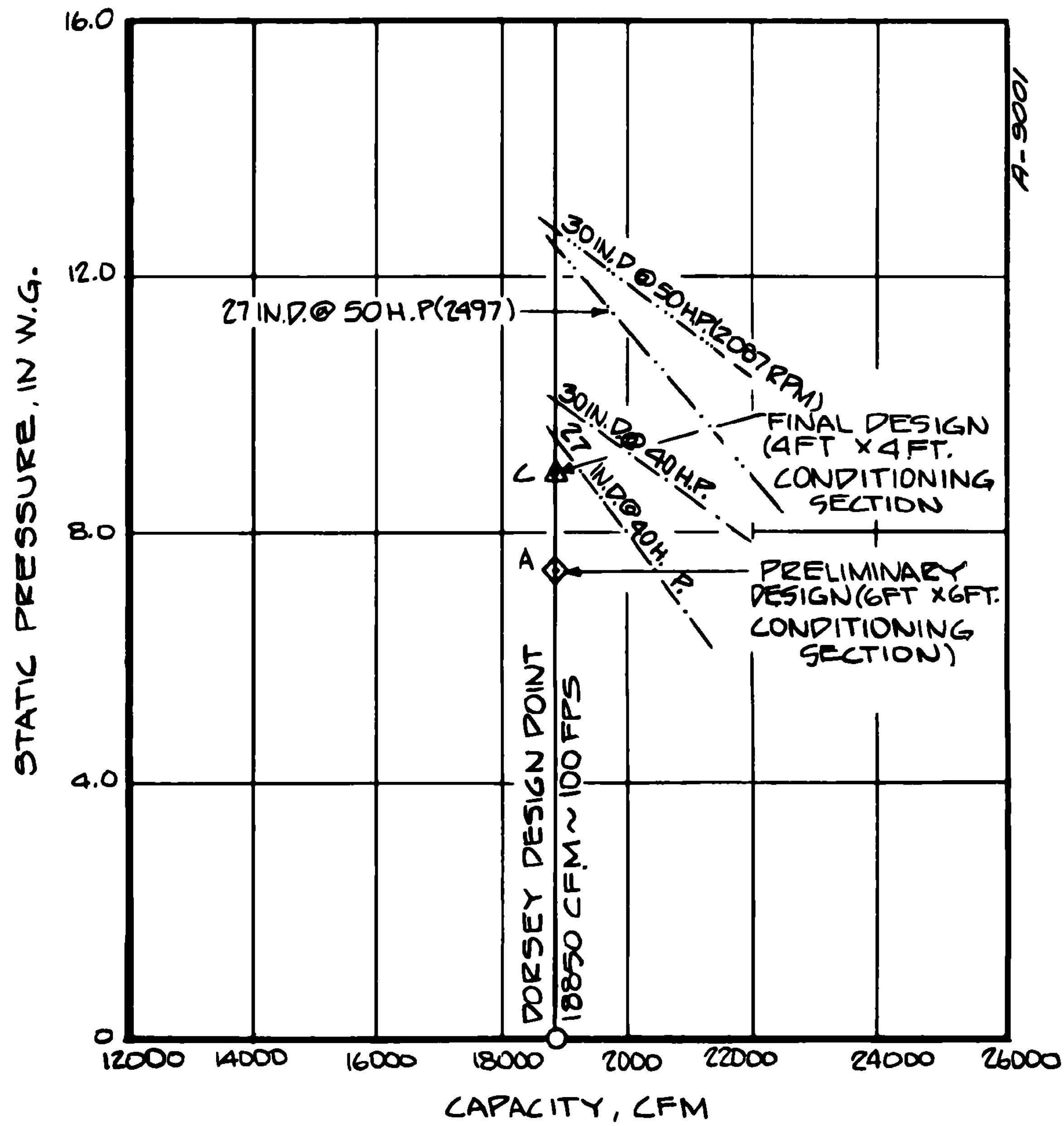

Figure 6. Fan Characteristic Curves

4.2 INSULATION

The external insulation performs three basic functions:

1. Reduces heat leaks from the tunnel at elevated temperatures,
2. Reduces the possibility of condensation on cold surfaces at high humidity levels, and
3. Protects facility personnel.

The basic choices when designing an insulation system involve optimizing performance (usually a function of thickness for a given material) vs. costs.

Actual material costs for insulation are relatively small compared to installation costs. Therefore, reasonable variations in insulation thickness do not appreciably perturb the total price of an insulation system within practical installation limits. However, such thickness variations do impact heating and cooling requirements with a resulting effect on the cost of these components.

The duct insulation must have a service temperature of 450°F at most locations and 500°F - 650°F in the region of the heater. Installed and finished, it must withstand occasional light impact and must have a clean, smooth appearance on both square and round ducting. The thermal conductivity must be as low as possible over the range of average operating temperatures. If possible, it should not contain asbestos, Cost and availability are also considerations.

Table III presents the major types of insulation considered. The selection narrowed to glass fiber or universal fiber blanket or both on the basis of service temperature, ease of handling (low density) and cost. Quotations were obtained from various insulation installers. The final selection was influenced by availability of material. The square ducting was insulated with mineral fiber batt and the round ducting was insulated with the less dense and more flexible glass fiber blanket.

The size of heater required to hold steady state conditions at the peak operating condition of 450°F depends on the insulation thickness. However, as will be discussed in the subsections on heaters, roughly 60 percent of the total heater capacity is governed by the tunnel heat-up requirement. So in this design, insulation thickness does not have great leverage on heater cost. Considering all factors, including heater requirements, heat load to the laboratory, insulation surface temperature, gas temperature decay between test section inlet and outlet, and insulation availability, an insulation thickness of 3 inches was selected.

TABLE III

CANDIDATE DUCTING INSULATION MATERIALS

Insulation Material	Form	Density (lb/ft^3)	Service Temperature (°F)	Thermal Conductivity (°F)	Thermal Conductivity ($Btu/hr-ft^3F$)	Typical Manufacturers
Glass fiber, bonded with thermosetting binders (without facing)	Blanket or batt	3-6	450-1000 depending on type	100	.020*	Owens-Corning
				200	.025	
				300	.032	Johns-Manville
				400	.040	
Mineral fibers, with various binders (without facing)	Batt	4-8	650	100	.020	Forty-Eight Insulations, Inc.
				200	.022	
				300	.027	
Polyurethane Foam	Board or foam in place	1.5-2.5	250	100	.013	
				200	.016	
Calcium Silicate Reinforced with small amounts of asbestos	Block	10-13	1200	100	.028	Owens-Corning
				200	.031	
				300	.034	
				400	.038	

*Data is for Owens Corning Intermediate Service Board and is typical of the glass fiber insulations.

Allowing for heat leaks at flanges and other penetrations, the effective normal conductivity for the insulation system can be taken as 0.04 Btu/hr-ft-°F. The total heat leak from a 450°F internal gas temperature condition is calculated to be approximately 54 Btu/hr-ft^2. Assuming 3000 ft^2 of tunnel surface, the incremental load on the laboratory air conditioning is 14 tons, the insulation surface exposed to personnel will run at 105°F maximum. Exposed metal surfaces will run hotter, of course. The worst case gas temperature decay between test section entrance and exit will be 10° - 15°, occurring at the hottest condition and minimum flow rate.

The insulation system was installed as shown in Figure 7. A 2-inch-plus-1-inch layup provides easier application over stiffness than a grooved 3-inch blanket. On flat surfaces, the insulation was impaled on welded pins. On cylindrical sections, wire bands were used in place of the pins. A covering of 18 gauge galvanized poultry wire was finished with insulating cement (1/4 inch thick) and covered with 8 oz canvas sized with lagging adhesive.

At bolted flanges, expansion joints, and test section windows, the insulation was beveled at an angle of approximately 45° for access to the bolts.

4.3 CONDITIONING SECTION

The conditioning section consists of a chilled water cooling coil, an electric heater and a steam humidifier. Its purpose is to achieve, in the test section, an operating set point within the ranges listed in Table IV for closed loop flow rates of 940-17,000 cfm.

TABLE IV

GAS CONDITIONING REQUIREMENTS

Condition	Set Point Range
Gas Temperature	70°F - 450°F
Humidity	"Typical" Stack Exhaust Product Moisture Content: Up to 14% - 15% Moisture By Volume 70° to 100° — Min: 0.008 lb H_2O per lb air Max: > 55% R.H. depending on velocity and temperature

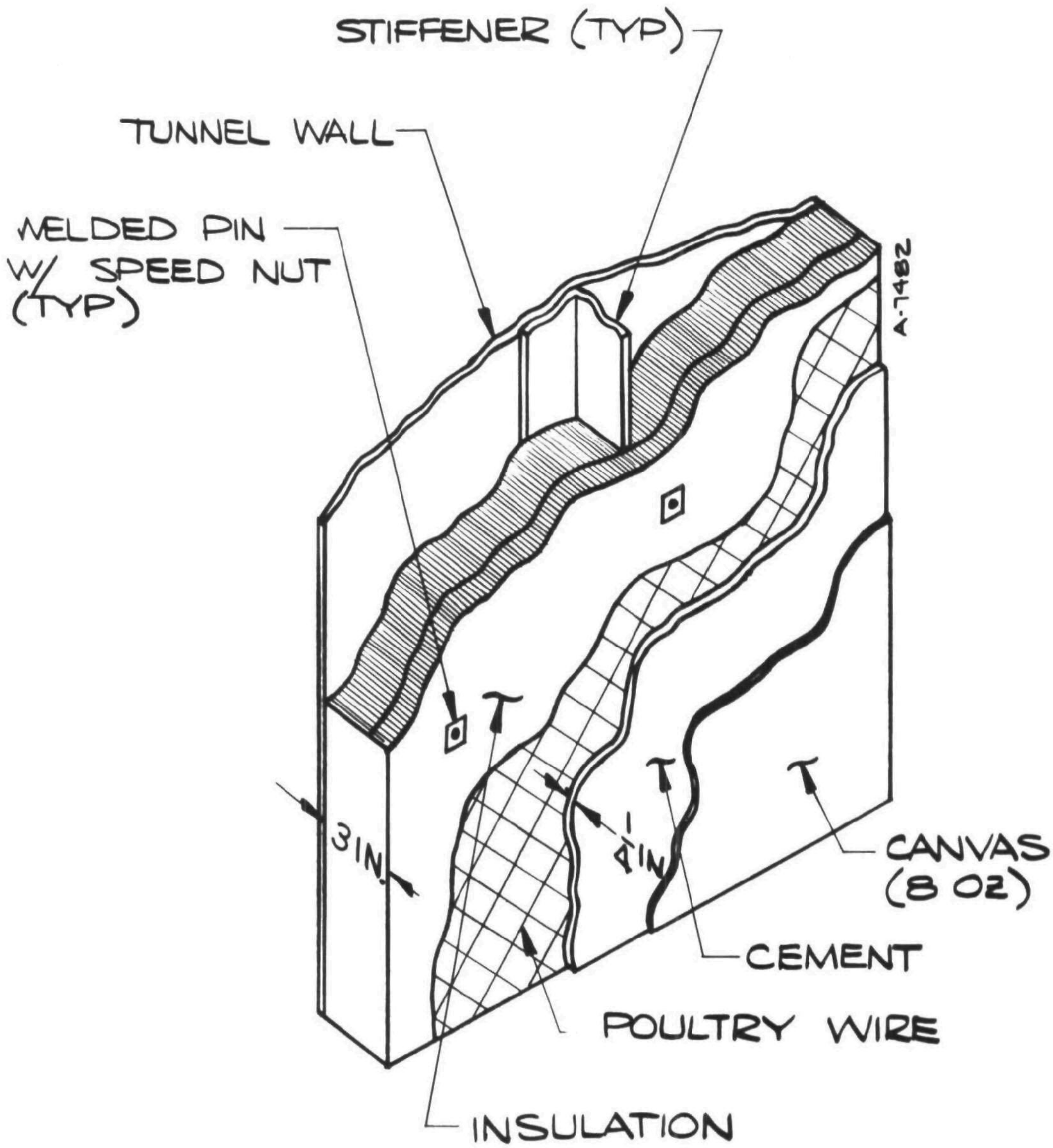

Figure 7. Wind Tunnel Insulation Detail

4.3.1 Heater

Based on the insulation effective thermal conductivity presented in 4.2, the system steady state heat leaks were computed at maximum temperature and maximum and minimum flow rates. The results were increased by 50 percent to allow adequate margin for uncertainty. Table III summarizes the resulting steady state heater power requirements. Blower power dissipation is considered negligible because, on the conservative side, it is less than 10 percent of the heater power required.

Heat-up power was sized on the assumption of a duct system weight of 25,000 pounds with a specific heat of 0.12 Btu/lb-°F and the insulation design of 4.2. On that basis, heat-up histories are presented in Figure 8 for various power inputs. It was concluded that the design study estimate of 200 kw of heating power was still valid, resulting in a maximum heat-up time of 2 to 3 hours when uncertainties are included. Thus, an elevated temperature test run could be easily initiated and completed in a single working day without designing timer-initiated start-up into the controls. Table V includes the heat-up power requirement for both tunnels.

TABLE V

HEATER POWER REQUIREMENTS

Steady State Power Required to Achieve Maximum Temperature (kw)	
@ Minimum Flow (kw)	60
@ Maximum Flow (kw)	75
Start-up Power for Elevated Temperature Operation (kw)	200

The heater selected consists of 90 Incoloy-sheathed hairpin resistance elements, suspended from a flanged terminal box. The heater power supply is 480 VAC-3ϕ-60 Hz. Two runs of heater elements are used only in heat-up and are wired in identical circuits of 62.5 kw each. Two rows are wired for 75 kw for steady state operation. Peak watt density on the heat-up elements is 24 watts/in^2, while the peak density on the steady state elements is 13 watts/in^2. Including the effect of radiation heat transfer to the duct walls, which is the dominant mode at low flow (1 ft/sec), the element surface temperatures should remain below 1000°F, which is roughly 500°F below maximum allowable.

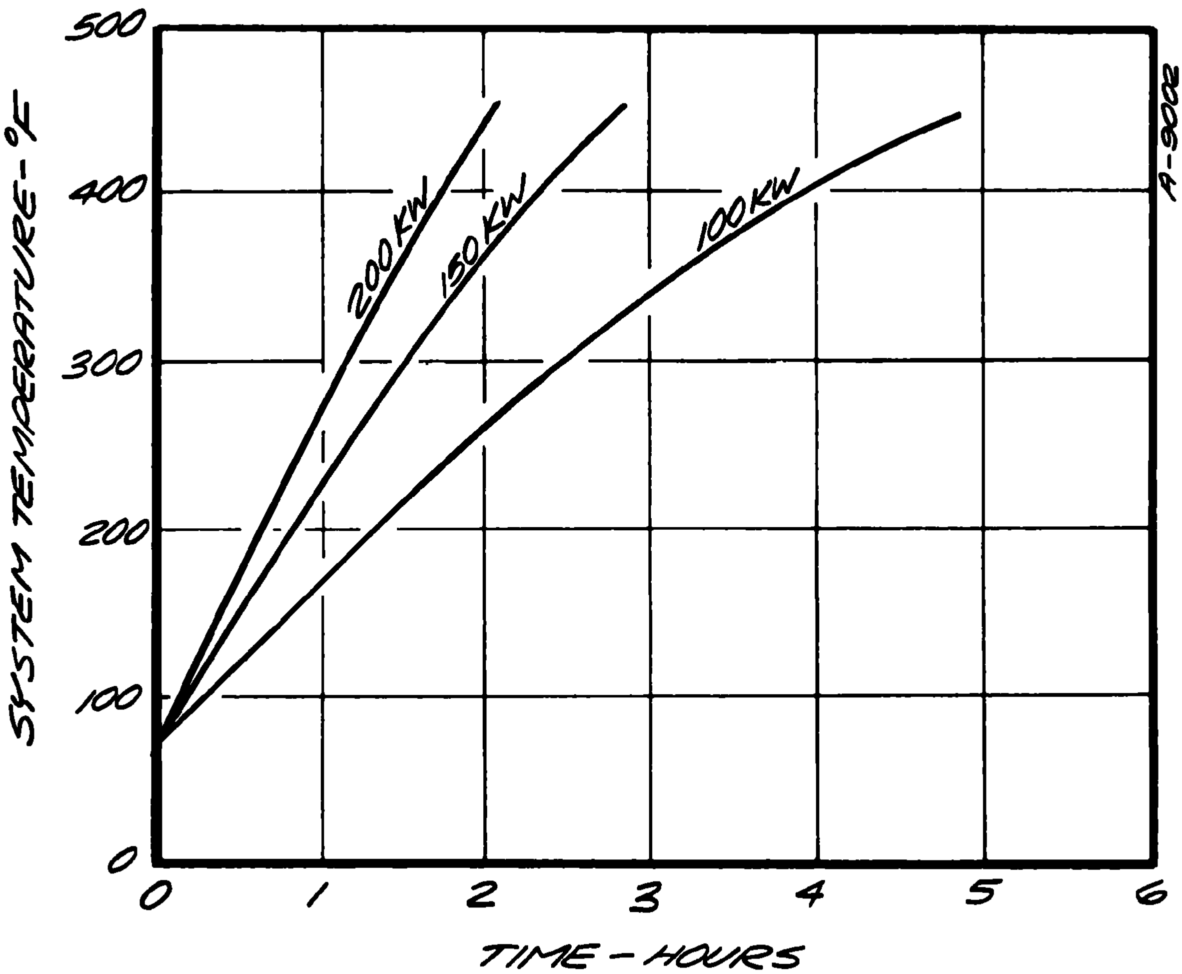

Figure 8. Heat-up Power Required for 3-Inch Insulation

4.3.2 Cooling Coil

The cooling coil is required to perform two main functions:

1. Remove blower power dissipation to maintain the ambient condition in the tunnel, and
2. Dehumidify the gas to meet specific humidity requirements.

The governing factor in the design of the chiller was the requirement to absorb blower power. If this was not done, the tunnel could achieve a steady state operation temperature approaching 200°F at maximum flow rate and horsepower input, just from the blower dissipation alone. Accordingly, the coil was designed to remove 50 hp from the gas at 70°F. It can be shown that dehumidification to a dew point of approximately 50°F can be achieved in a short start cycle with a cooling coil sized to remove fan power.

An optimization study of the coil based on gas pressure-drop limits and cost, in conjunction with vendor-recommended gas velocity across the coil, dictated a finned coil arrangement of roughly 16 square feet of face area. The coil is basically a counter-flow heat exchanger composed of straight plate vertical fins on horizontal tubes spaced on 1.5 inch centers in staggered rows. Condensed moisture flows down the fins to a drip pan and out a loop seal to a drain.

The Aerotherm analysis of coil size agreed within 25 percent of the analysis made by the prime vendor. (The Aerotherm design came out smaller.) To provide plenty of margin, the vendor enlarged his recommended size by 40 percent, resulting in a coil with four tube rows. For a 10°F water temperature rise the water flow rate must be 25 gpm to remove 50 hp. Under humid conditions, the latent heat removal will require greater water capacity, but this is not expected to exceed 75 gpm. Conversely, the temperature rise allowed may be greater than 10°F.

4.3.3 Humidifier

The basic design requirement that moisture content be typical of industry stack exhaust products implies that the tunnel dew point be in the range of 125°F - 130°F. For protection against condensation, an upper limit was set at 150°F. Actual total moisture requirements depends on gas temperature; but assuming 300°F as representative and a charging time of 20 minutes, the humidifier capacity required was calculated to be 66 lb/hr. Higher humidity levels at elevated temperatures could be achieved by extending the charging period.

The humidity level achievable in the ambient range of 70°F - 100°F will depend specifically on the temperature and velocity through the cooling coil which continuously removes moisture. The maximum attainable steady state relative humidity at a worse case condition in which maximum moisture removal occurs in the cooling coil will be approximately 55 percent. At lower temperature and higher and lower velocities, a greater R.H. can be achieved.

The humidifier consists of a manually-controlled pneumatically-activated dry steam injector, which utilizes 10 psi facility steam.

4.4 PURGE SECTION

The primary purpose of the tunnel purge section is to purge the system of test gases at the completion of a test run. In addition, the combustion products generator is ducted into the tunnel at the purge section.

The purge section consists of three valves located downstream of the blower. The valves include the 4 ft x 4 ft tunnel vane damper, the 12 inch diameter butterfly exhaust valve and the 12 inch butterfly inlet valve. The inlet valve draws laboratory conditioned air from the tunnel ambient environment. The exhaust valve couples the tunnel to an exhaust stack which extends through the roof above the building.

In the purge mode, gas is circulated around the tunnel loop, the duct damper is closed, and the inlet and exhaust valves are opened, effectively exhausting test gas outside the building and replacing it with fresh air from the room. During normal testing operation, the inlet valve is kept tightly closed, the duct damper is open and the exhaust valve is open to establish a pressure datum within the tunnel.

4.5 COMBUSTION PRODUCTS GENERATOR

4.5.1 System Selection

One of the few major differences between the design study conclusions and the actual as-built Particulate Aerodynamic Test Facility was in the area of combustion products generation.

The purpose of the combustion products generator (CPG) is to produce a tunnel gas constituency typical of a power plant. It was concluded in the design study that an external custom burner system would be the most effective technique for displacing tunnel air with combustion products, and presented a preliminary sketch of what such a burner might look like.

During the actual design phase, however, a thorough reevaluation of the various options discussed in the design study showed that a packaged boiler system would be both economically and performance competitive with a custom burner design, primarily because it was shown that design requirements could be met with an energy release system significantly lower than the 2,000,000 Btu/hr originally thought necessary.

Consequently the evaluation focused again on the following five alternatives, but only in the 500,000 Btu/hr range:

1. Firebox with dilution and gas-to-air heat exchanger
2. Firebox with dilution and gas-to-water heat exchanger
3. Hydronic boiler with water-to-water heat exchanger
4. Steam boiler with steam-to-water heat exchanger (closed loop)
5. Steam boiler with water softening system (open loop)

Considerations of cost, compactness of equipment, ease of installation, and ready availability of large quantities of chilled water narrowed the choices to 3 and 4. Table VI shows the various boiler designs and manufacturers investigated.

Natural draft boilers were eliminated from contention because excess air is high (40 percent) under normal operation and may become higher if an induced draft fan is included in the exhaust ducting. Modification of dampers in the natural draft boiler is possible to reduce excess air, but is risky because the outcome is presently not predictable.

Capacity requirements were analyzed from a tunnel leakage standpoint. Figure 9 shows how leakage affects final tunnel composition after completion of charging. The 20 hp boiler is a standard size and provided a significantly greater margin for leakage than the 10 hp boiler. The 30 hp boiler does not appear to make a major additional contribution. It was concluded then, that 20 hp was an optimum choice.

Final pricing of acceptable units showed a 20 percent variance; Cleaver-Brooks was lowest, and in addition uniquely included in its price prepaid shipping and services of a local service engineer to start, adjust, and test the boiler. The price trade-off between steam and hydronic was negligible. Since hydronic is safer because of the great expansion capability of steam, a water boiler was favored.

TABLE VI

BOILER MODELS STUDIED

Manufacturer	Boiler* HP	Configuration		End Product		Draft	
		Fire Tube	Water Tube	Steam	Water	Natural	Forced
Eclipse	20	✓		✓			✓
	20	✓			✓		✓
Raypak	20		✓		✓		✓
	12		✓		✓	✓	
Teledyne Laars	13		✓		✓	✓	
Fulton	10		✓		✓		✓
	20		✓		✓		✓
Cleaver-Brooks	20	✓			✓		✓

*1 boiler hp = 33,475 Btu/hr.

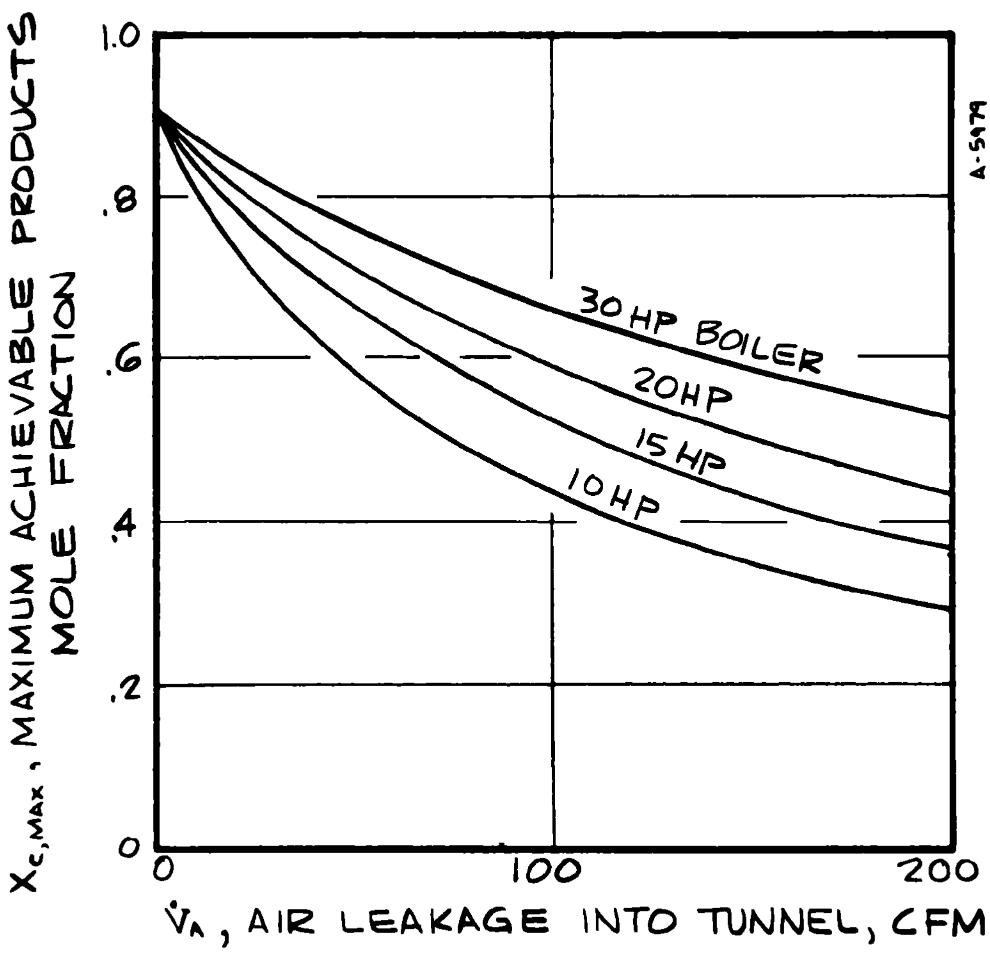

Figure 9. Tunnel Composition on Completion of Charging with 10 Percent Excess Air in 350°F CPG Exhaust

The Cleaver-Brooks system was selected on the basis of price, quality of exhaust products, relative simplicity of the system, and a good understanding of the problem by their personnel.

The combustion products system includes the hydronic boiler, an expansion tank, a recirculation pump, a heat exchanger, and various damper valves. Figure 10 is a schematic diagram of the system. The components are described in more detail below.

4.5.2 Hydronic Boiler

The boiler is a Cleaver-Brooks Progress Model 20 hp firetube boiler supplying hot water at 200°F and 20 psi. The boiler is a four-pass horizontal firetube boiler with 100 square feet of heating surface. The boiler is complete with integral forced draft burner, FIA burner safety controls, boiler trim and refractory. The boiler operates on natural gas. The gas pilot is the premix type with automatic electric ignition. The FIA-type gas train provides extra safety controls over the standard gas train. Water leaves the boiler at 200°F and the unit is equipped with a high limit water temperature cutout set at 240°F. Water is returned to the boiler at 170°F from the heat exchanger. Initial adjustment of the boiler firing rate and the heat exchanger hot and cold side flow rates will establish the optimum operating conditions in future runs.

Exhaust products exiting from the boiler at 300°F to 400°F are fed either to the tunnel exhaust stack or to the tunnel through a draft damper and diverter valve via a 6 inch duct (refer to Figure 10). The exhaust line joins the tunnel exhaust line above the tunnel exhaust damper. The combustion products generator fill line enters the tunnel fill line below the tunnel inlet valve (valve 4). Interlocks and control of the system will be discussed in Section 4.11.6.

4.5.3 Expansion Tank

Immediately above the boiler and connected to the feed water piping is a 15 gallon expansion tank to allow for heat-up of the system. Make-up water is automatically fed to the system if any loss of water occurs.

4.5.4 Pump

An in-line pump powered by a 1/2 hp, 1ϕ, 120 V motor circulates water through the boiler and a hot water-to-chiller water heat exchanger.

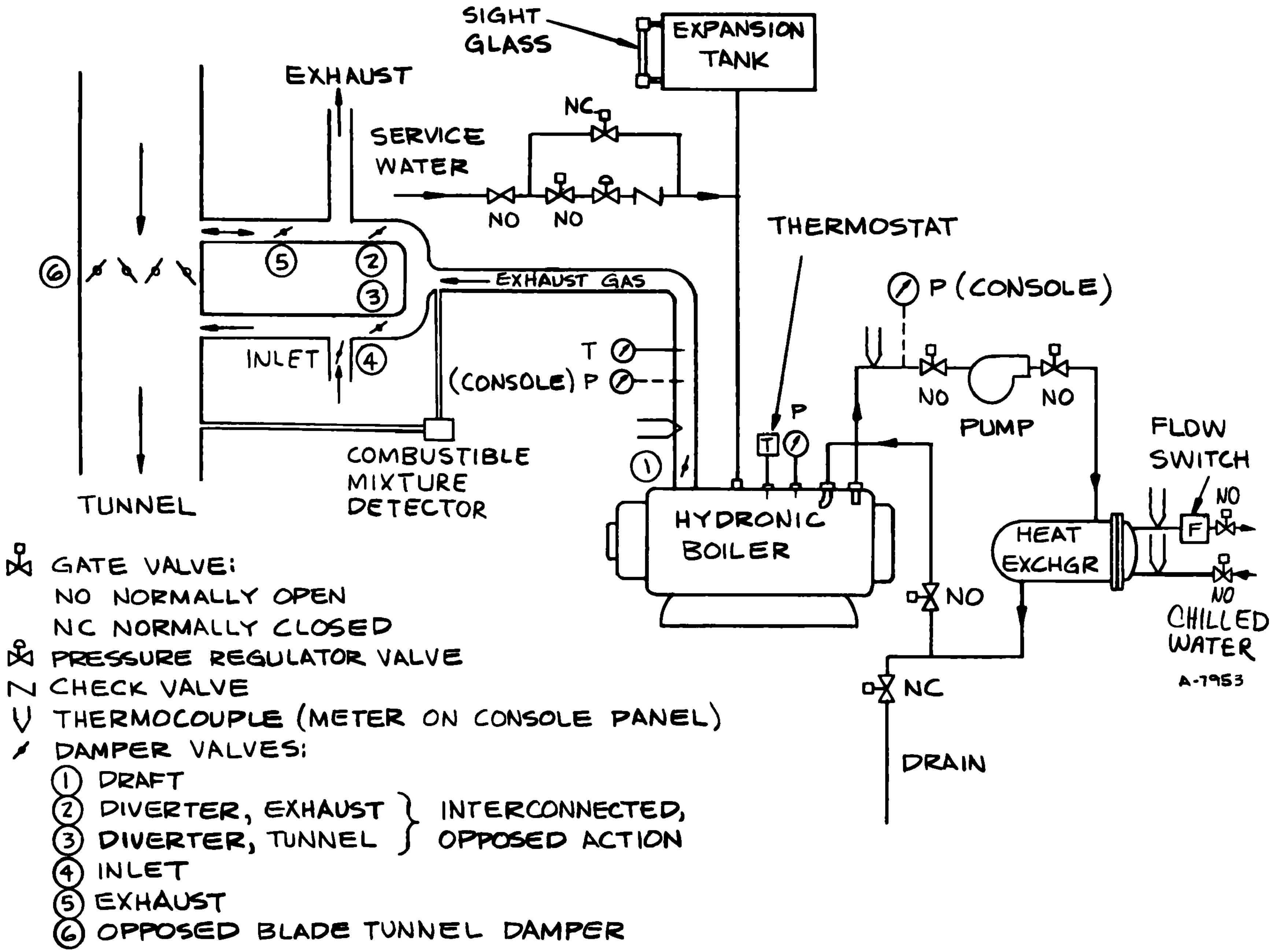

Figure 10. Combustion Products Generation System

4.6 DUST COLLECTOR

The bag-type, pulse-clean dust collector selected for the wind tunnel facility to filter the particulate from the gas was not significantly different from that recommended in original design study. However, the actual specification and dust collection procurement was not a straightforward process.

First of all, the potentially corrosive environment necessitated that the dust collector, like the ducting, be fabricated of stainless steel or be coated with acid resistant high temperature paints or an enameling process. Such coatings were investigated, but fabrication costs with coatings proved to more than outweigh any savings in basic structural material cost over all stainless steel construction. Coatings would have also required periodic and costly maintenance.

Secondly, and perhaps most important, envelope considerations virtually eliminated any standard design of the right capacity on the market. Height restrictions were severe and necessitated a shallow angle hopper; length restrictions virtually dictated an upper limit on number of bags and thus limited filter area to 2080 ft^2.

In addition, other considerations such as existing building penetrations (high bay door) required a custom combination modular/knock-down construction to allow the dust collector to be assembled in place. Figure 11 is an exploded pictorial view of the baghouse construction showing this modular construction. The major modules are the clear air plenum, the side panels, the hopper, the "tube sheet" (with nozzles and bag collars) and the structural support base. The last two items are not shown for clarity.

The baghouse was supplied by Miller Industrials, a division of Industrial Clean Air. All gas-side components are of stainless steel construction for corrosion protection. The filter bags are 14-ounce felted "Nomex" for high temperature serviceability on stainless steel cages. All exterior surfaces are insulated with Johns-Manville "1000" spun glass board protected by a galvanized steel sheathing.

Access to the interior of the baghouse is provided by eight 22-inch round ports on top of the unit (into the clean air plenum) and a 2-foot by 4-foot door at one end of the unit for bag inspection and servicing.

The screw feeder at the bottom of the hopper is driven by a 3/4-hp electric motor which brings the collected particulate to the outlet end at 15 rpm Because of severe height limitations which left no room for installation of a rotary air lock, the normal technique for removing the particulate out of baghouses, a penumatic dust box was installed instead for future pneumatic line connections to convey the collected material away as it is brought down by the screw.

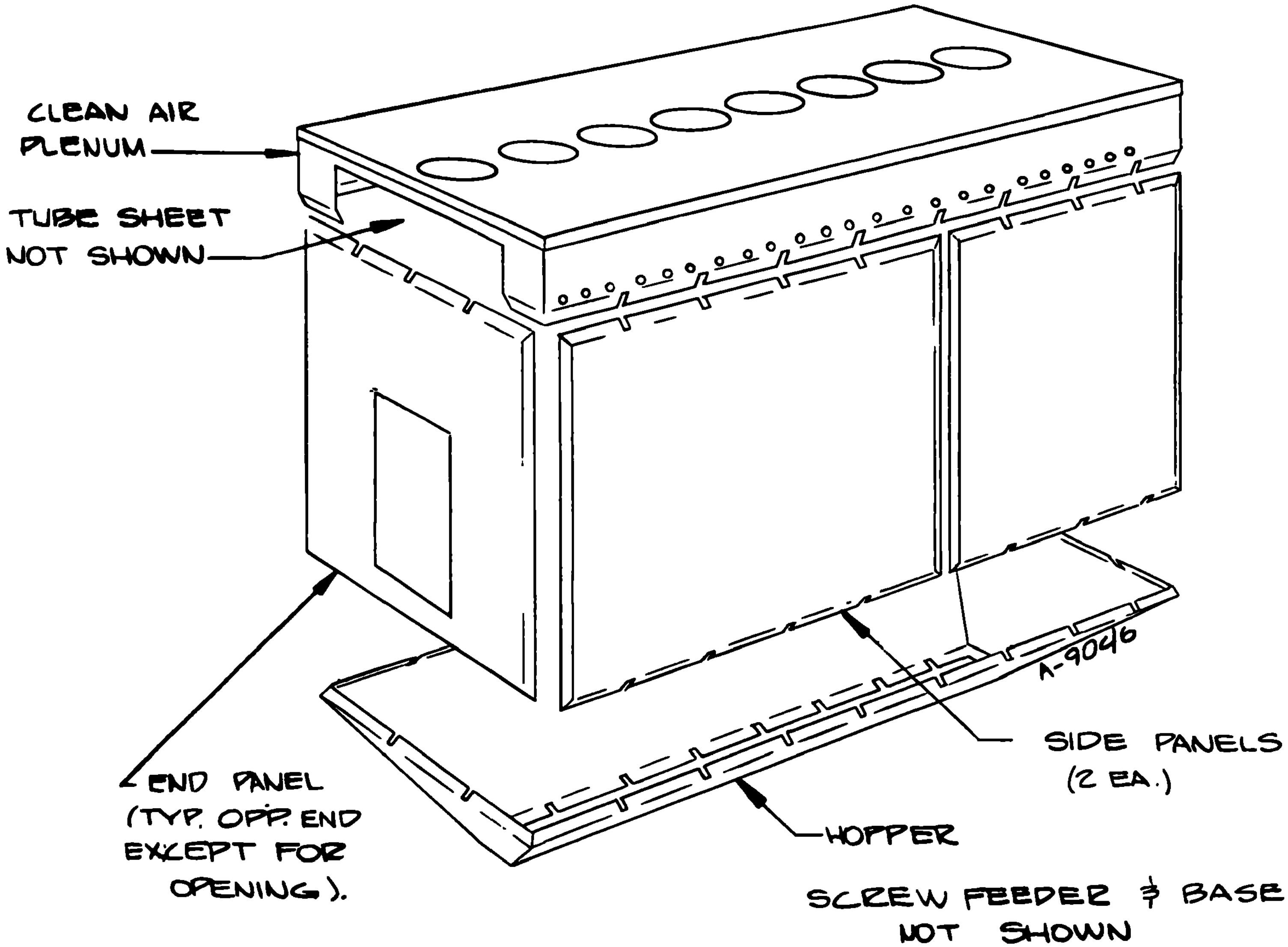

Figure 11. Dust Collector Modular Construction

4.7 DUCTING, GENERAL

Since there were some changes in the general tunnel ducting layout between the design study and the actual as-designed configuration, a few comments addressing the more obvious and important of these will be made in the following paragraphs.

4.7.1 Conditioning Section Cross-Sectional Area

The conditioning section cross-sectional area was changed from 36 ft^2 in the design study to 16 ft^2 due to engineering consideration of efficient cooling coil and heater design, already mentioned in the conditioning section discussion.

4.7.2 Dust Collector Entrance Elbow

In the interest of low pressure drop and good flow quality the dust collector entrance elbow was reconfigured to provide a more gradual right angle turn and in addition incorporate turning vanes. The turn was made rectangular in cross section (16 ft^2) for ease of fabrication. A transition from square to round was then incorporated to make the necessary interface with the diffuser outlet.

4.7.3 Expansion Joints

Because of the relatively high temperature achieved in wind tunnel operation, it was necessary to design into the ducting system means for controlled absorption of thermal expansion, primarily axial, but in some cases angular, without which large forces would be developed and have to be reacted by support structures and/or the ducting components themselves.

For this purpose, Aerotherm developed unique, custom expansion joints to be installed in strategic locations depending on the potential for thermal growth. Basically two types of flexible devices were developed; these are shown in Figures 12 and 13.

Figure 12 shows the basic expansion joint scheme. Expansion is accommodated by simply allowing the duct to which the joint is attached seek its own position, depending on its thermal growth characteristics, by "telescoping" into an adjacent duct. The joint is sealed by a rolling convolute of impervious fabric capable of operating at the elevated temperatures.

Figure 13 shows a custom metal bellows type design. It was necessary at the outlet of the diffuser to absorb not only axial thermal expansion, but also a thrust load developed in the diffuser itself due to the negative pressure inside the duct.

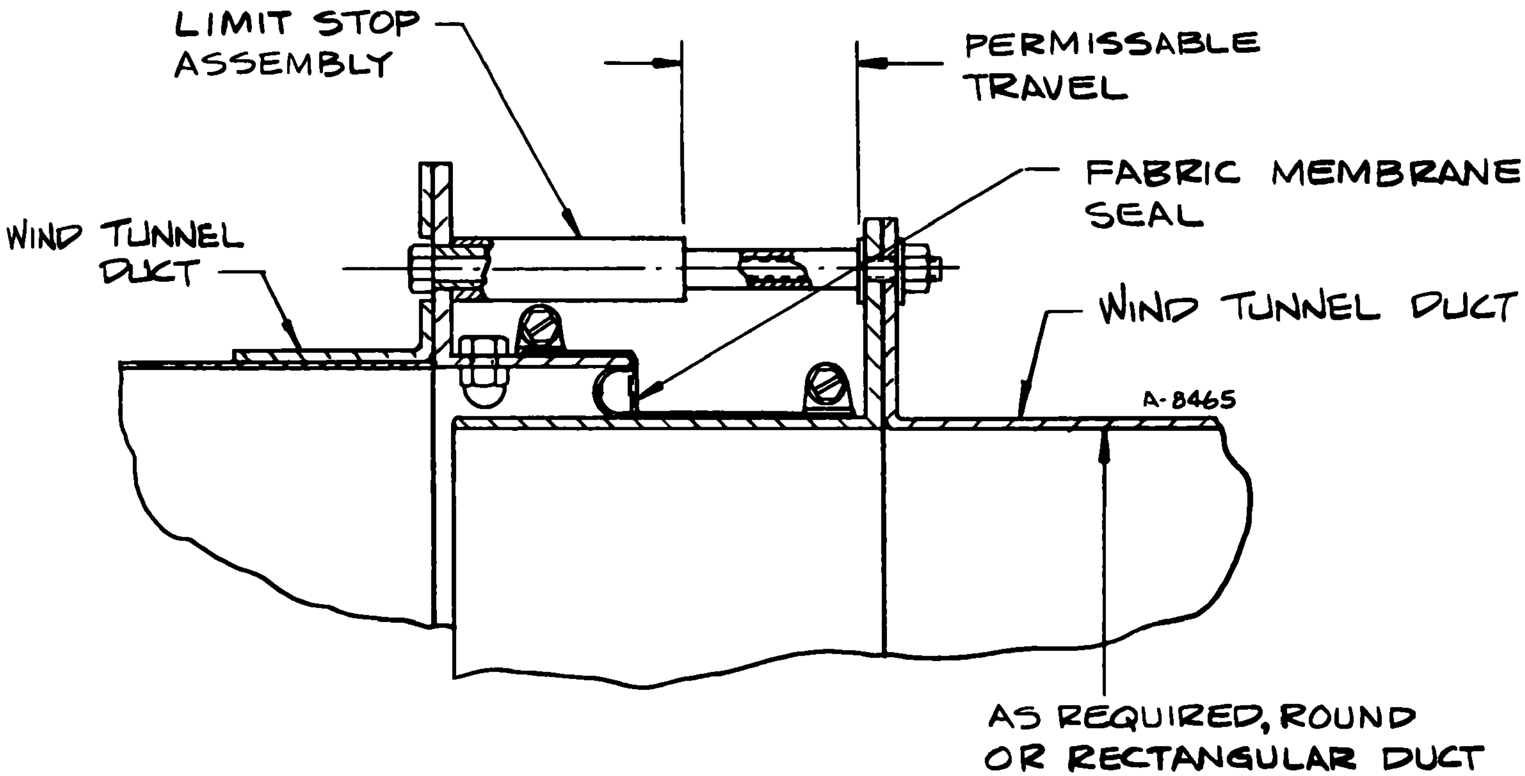

Figure 12. Basic Rolling Convolute Expansion Joint

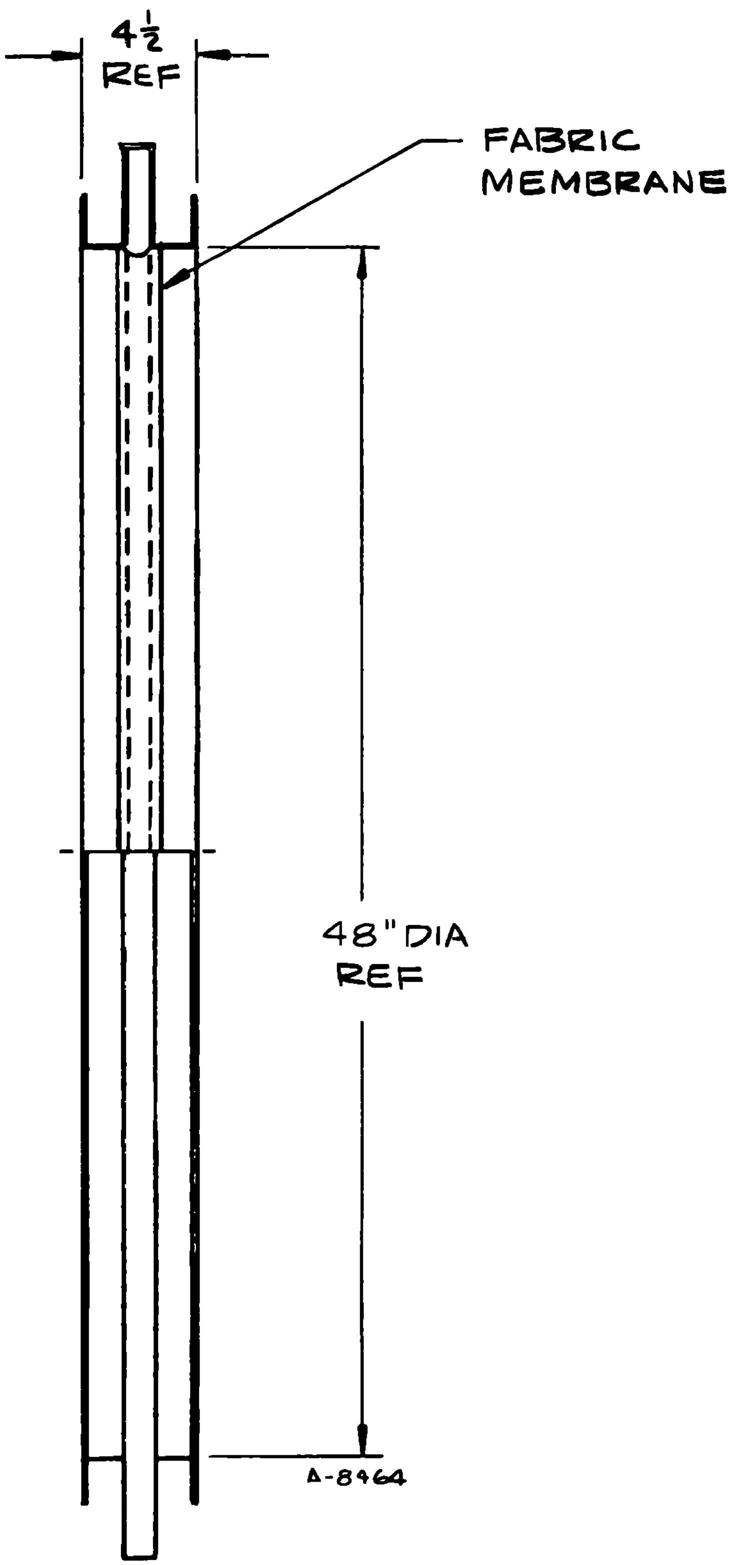

Figure 13. Bellow Expansion Joint

In addition, all of those expansion joints provide points where small amounts of angular misalignment arising from inherent fabrication and assembly tolerances could be accommodated.

4.8 CONTRACTION

The usual design condition for a contraction cone in a wind tunnel is that the velocity at the end of the cone be fairly uniform. The contours selected, of course, must avoid regions of an adverse pressure gradient to prevent flow separation from disturbing the core flow. The details of contraction design can be very complicated and will not be discussed here except to say that this particular contraction design was based on the method of Cohen and Ritchie, a method based on a radial expansion from an adopted axial velocity distribution, of a series solution of the Betrami differential equations in the Stokes stream function. If more specific details are desired, consult Reference 4 at the end of this report.

Of course, any contour design solution by such methods must allow for the realities of fabrication capabilities. In this case the contour was approximated by 12 "gore" strips developed on flat stock, shaped to the contour, and seam welded at the edges. Other methods such as spinning, or approximation by conical segments were not economically feasible.

4.9 DIFFUSER

The diffuser cone as presented in the design study was one of 3° included angle approximately 40 feet in length. As installed, the diffuser was shortened to 20 feet, 6° included angle preceded by 20 feet of 2-foot diameter straight ducting. The two configurations are shown in Figure 14.

This major design change was incorporated for two reasons, one practical and the other theoretical:

1. Diffusers are more costly to fabricate than equivalent lengths of constant area duct.
2. Straight lengths of duct immediately upstream of the diffuser enhances its performance whatever its angle by assuring the flow will be of good quality entering.

Pope and Harper (Reference 3) state conclusively that "with smooth flow entering a typical wind tunnel diffuser, 5° between opposite walls will yield satisfactory flow, as will 6°, possibly 7° and probably not 8° . . . Even 7° moves into the questionable category." Fortunately, the wind tunnel configuration conveniently allowed a 20-foot diffuser with 6° included angle, preceded

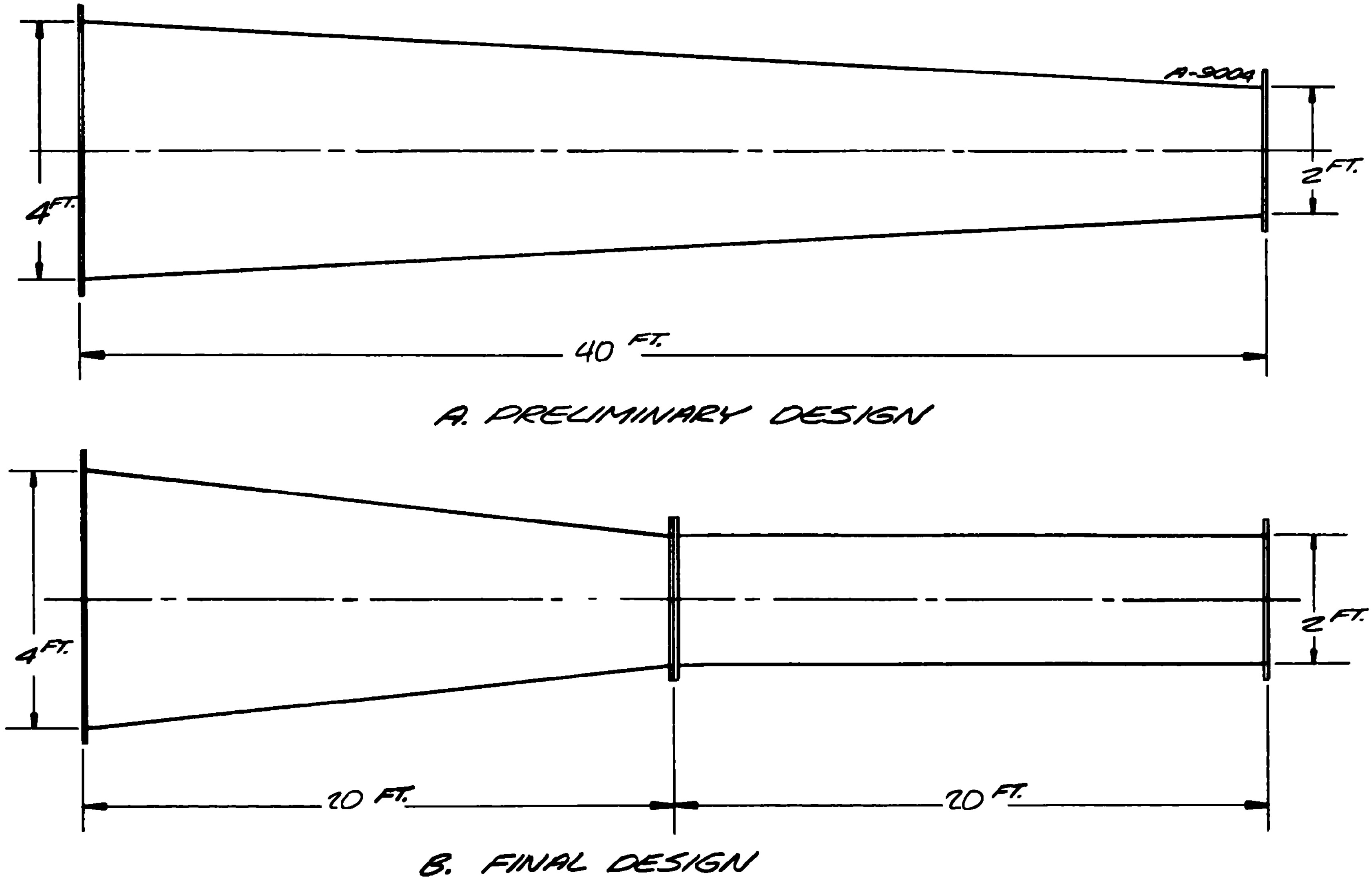

Figure 14. Diffuser Configurations

by the 20 feet (five diameters) of straight section. Considering the economic factors, the change was an ideal alternative to the original preliminary design layout.

4.10 AEROSOL GENERATOR AND INJECTION SYSTEM

The emphasis in the design of an aerosol generation system, or "dust feeder," from the design study to the final design and installation has been towards simplicity. A more sophisticated system is presently under design for future installation.

Even the present simple system has seen some developmental changes, however. The design study presented a system which created an aerosol by direct aspiration of the fly ash by an air ejector. The air ejector was fed directly by a live-bottom bin. Feed rate control was established by the manipulation of a variable size orifice at the bottom of the bin.

During the initial test and checkout of the tunnel, the above system was built and installed, modified from the original concept in that the dust feed rate was controlled by Acrison screw feeder rather than a variable orifice. Screw feeders have proven capable of providing very accurate feed rate control for fly ash; feed rates may be changed conveniently and are repeatable to better than 2 percent.

This system worked reasonably well for short durations, but had long term reliability problems. These were due to a number of reasons, but the primary problem was the slow accumulation of fly ash in the aspirator itself, a phenomenon associated with moisture condensation from the expanding air as it passed through the aspirator. Such accumulation eventually degraded the overall performance and so the system could not be used for long duration tests.

To eliminate this problem, the present system aspirates the dust by a crude fluidization technique. This solution, shown in Figure 15, should be considered interim until the more sophisticated system can be installed.

The dust is introduced into a "pressure pot" through which air is passing at a sufficient velocity to remove the particulates or agglomeration of particulates small enough to have terminal velocities lower than the internal air velocity. As a result, these particulates are carried away and transported to the tunnel by the approximately 5 psi potential in the fluidization container through a 3/4-inch vinyl tube. If the particulate agglomerations are too large to be carried away, they are "churned" inside the chamber until they are deagglomerated sufficiently well to be transported to the tunnel. This highly concentrated dust-laden flow is split into eight separate streams for injection into the stilling chamber.

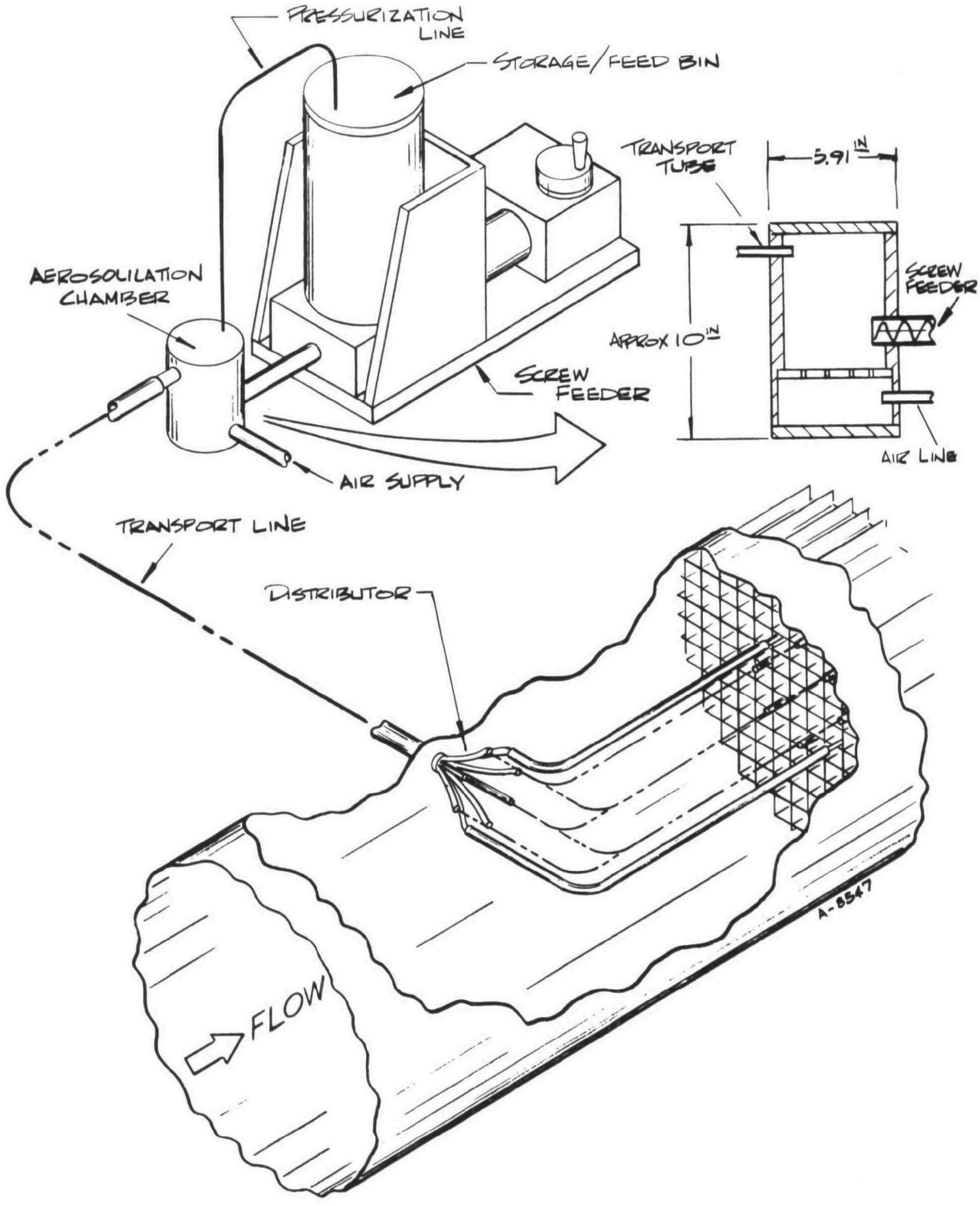

Figure 15. Aerosol Generation System

Actual sampler comparison tests have been conducted using this system and it has been shown to be repeatable and reliable. However, it should be pointed out that particle size distributions have not been investigated, so it is not known to what degree this system is capable of deagglomerating the bulk fly ash to its original constituent size distribution.

4.11 CONTROLS AND INSTRUMENTATION

The basic requirements for the controls and instrumentation system, defined in Reference 1, were followed in the final design. Complete control required for startup, regulation and shutdown of tunnel components is accomplished from the mezzanine. Parameters that are controlled from the operating console are the following:

- Test gas velocity
- Test gas temperature
- Inlet, exhaust and tunnel damper valve position
- Test gas humidity
- Combustion products injection
- Dust injection
- Dust collector pulse cleaning frequency

Control devices also on the mezzanine, but not a part of the console, are control valves for chilled water flow to the tunnel chiller, chilled water to the combustion products generator heat exchanger and the steam flow valve to the steam humidifier.

In addition to control functions, the console includes meters for monitoring tunnel velocity and temperatures and pressures that are critical to the proper operation of the wind tunnel. Indicator lights shown the operational status of the various system components. Safety interlocks are included in control operations to protect against potential hazards to personnel and equipment. A fault light display and alarm horn notify the operator if certain operating limits are being exceeded. A key switch on the console controlling power to all subsystems prevents tunnel operation by unauthorized personnel.

The console panel is shown in Figure 16. The controls and meters are on standard 19-inch wide panels mounted in vertical twin rack assemblies which are bolted together. Each panel is assigned to a specific subsystem, thus simplifying console operation and providing minimum disruption in the even maintenance or modification is required on a given subsystem.

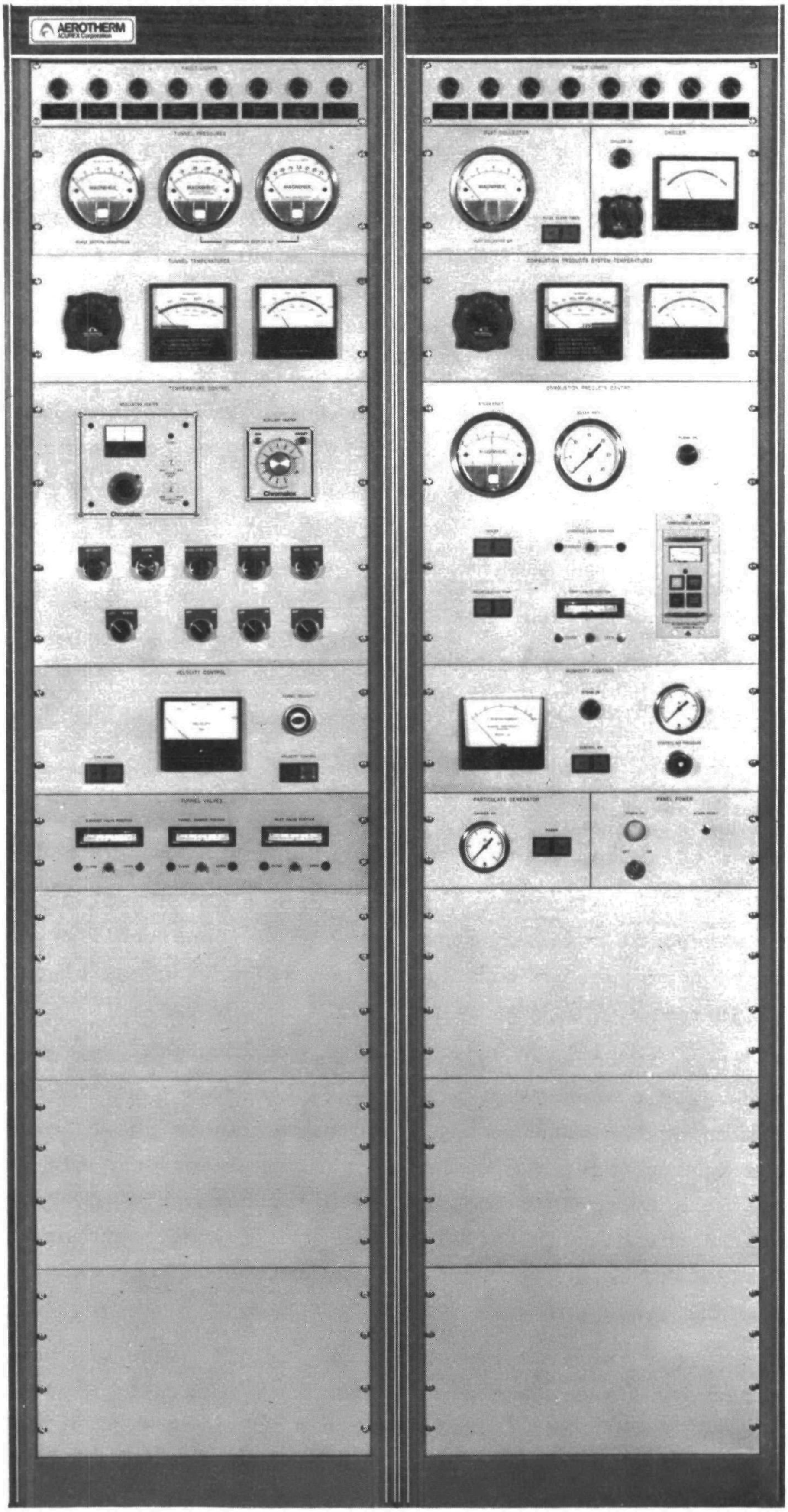

Figure 16.   Test Facility Control Console

A complete description of how the tunnel is controlled is contained in Reference 2. All control systems are electrically operated except for the combustion products diverter valve and the steam humidifier control valve, which operate pneumatically.

This section summarizes how each subsystem is controlled, with block diagrams for clarification where necessary. Appendix A outlines the basic procedure for operating the particulate wind tunnel.

4.11.1 Fault Lights

The design study identified a tentative list of tunnel conditions that should be flagged by an alarm or fault system. A summary of the faults designed into the control console is presented in Table VII. Each fault operates a light allocated to that fault as well as an alarm horn. Certain faults interlock with other parts of the control system for automatic control of a potential hazard; other faults only alert the operator to take action or monitor the situation.

4.11.2 Velocity Control

Velocity control is maintained primarily by fan speed control with the tunnel damper as an auxiliary control. A block diagram of the fan speed control system appears in Figure 17. The fan control was designed so that the tunnel velocity may be controlled by operator adjustment of the clutch coupling through the adjustment dial on the console or in the automatic mode by feedback control employing a built-in analog computer[1]. In either mode of operation tunnel velocity is computed automatically from the tunnel contraction section static pressure drop and absolute temperature.

The velocity computer has three prime tasks:

1. Conversion of a thermocouple voltage to an absolute temperature analog.
2. Computation of the velocity by implementing a preprogrammed formula.
3. Interfacing to the pressure transducer and to the clutch controller.

In the automatic mode, the velocity computer serves as the summing point in the velocity control system. As such, it compares the set point defined by the velocity control (console dial) to the computed value and applies the error (residual) to maintain the difference at a minimum. Additionally, the initial conditions of the controller are set by the velocity computer in manual mode so that relatively "bumpless" transfer occurs when switching to automatic mode.

[1]The computer was designed by the Products Division of Acurex Corporation.

TABLE VII

FAULT LIGHTS AND HORN ALARM

Title	Actuated By	Interlocked Control Functions
Tunnel over temp.	Test sect. inlet exceeds 500°F	Shuts off heater system
Heater over temp.	Modulating or Aux. heater elements exceed overtemp. setpoint (1200°F recommended)	
Chiller over press.	Chiller exceeds 120 psi	
Low tunnel velocity	Tunnel velocity not adequate for operation of auxiliary heaters	No effect on tunnel systems
Tunnel inlet valve open	Tunnel inlet (from laboratory) not closed; fault not operative if tunnel damper closed for purging	
Low air press.	Compressed air press. is too low to operate explosive mixture detector, humidifier, and diverter valve	
Tunnel temp. low	Tunnel temp. below 170°F (combustion products dewpoint), when boiler is on	
Boiler fuel limits	Boiler fuel press. exceeds the range of 5.5" to 20" W.G.	Shuts off boiler and swings diverter valve to exhaust
Boiler flame failure	Boiler flame failure	
Boiler water low	Boiler water level below safe level	
Boiler over temp.	Boiler water temp. exceeds 250°F	
Boiler heat exchanger off	Recirculation pump off or chilled water not flowing in boiler heat exchanger, when boiler is on	No effect on tunnel systems
Explosive mixture	Gas mixture approaching explosive level in boiler exhaust stack (with diverter to exhaust) or in tunnel (with diverter to tunnel)	20% lower explosive limit swings diverter valve to exhaust 40% lower explosive limit shuts off boiler

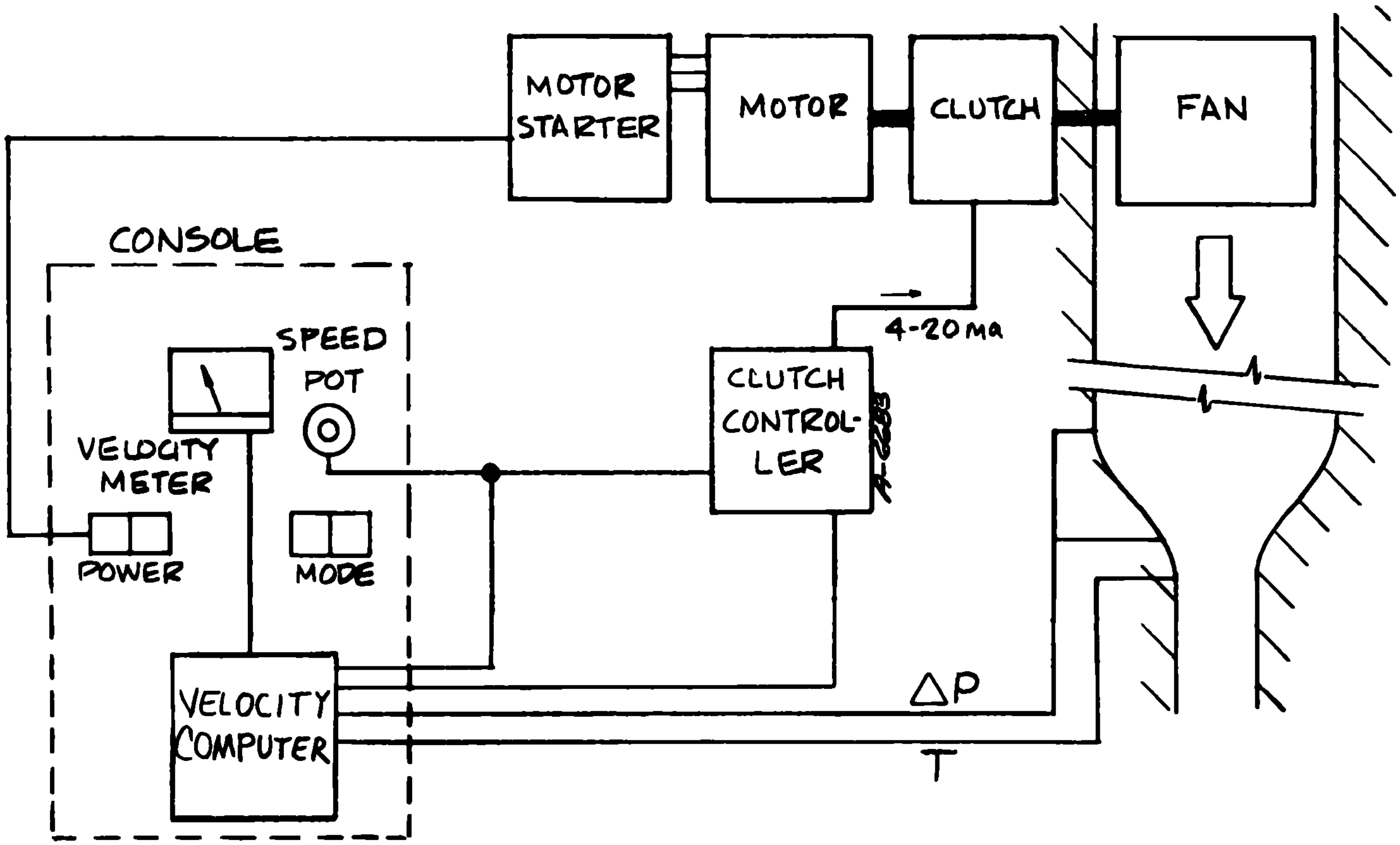

Figure 17. Velocity Control System

4.11.3 Temperature Control

Feedback control of the tunnel heater power is employed to achieve any temperature set point between the limits of 70°F and 450°F. The cooling coil is manually throttleable and is intended to be used as a cooling element for test conditions near ambient temperature. Its purpose in temperature control is to remove dissipated fan power. Reheat will be required to maintain accurate temperature control.

The heater power supply is 480-3ϕ-60 Hz. The two auxiliary (heat-up) heater modules are wired in identical circuits of 62.5 kw each and are operated by a set point controller which deactivates the heaters when set point is reached in heat-up. The third heater module is the modulating heater, wired in a 75 kw circuit, which is controlled by an SCR controller package to continuously maintain accurate set point. Thermocouples located at the test section inlet are connected to the modulating heater controller and the auxiliary heater controller.

A thermocouple is welded to a heater element of auxiliary heater no. 1 and to an element of the modulating heater, providing a means of sensing excessive element temperatures. A pressure switch (in the console) coupled to the contraction section ΔP manifold provides for signalling the operator with a fault light if tunnel velocity is too low to safely use the high watt density auxiliary heaters.

Temperature measurements at the following locations in the tunnel are displayed on meters on the console tunnel temperatures panel.

1. Test section inlet
2. Test section outlet
3. Dust collector outlet
4. Temperature control (gas conditioning) section inlet
5. Temperature control section outlet
6. Humidity sensor

For tunnel startup to an elevated temperature, the normal mode of operation is to operate the fan at nearly full velocity in order to maximize the effectiveness of the heater elements. Set points will be adjusted on the modulating heater control and the auxiliary heater control. Auxiliary heater power may be cut in half by operating auxiliary heater no. 1 only. Auxiliary heater no. 2 will not operate independently. When set point is achieved, the auxiliary heaters will cut out and not reactivate unless the manual reset button is depressed. Tunnel velocity may then be adjusted to the desired set point. The modulating heater functions throughout the test run as required on Thyristor (SCR) control to maintain set point.

A schematic of the chiller is shown in Figure 18. Chilled water flow is controlled by hand-operated valves located on the mezzanine. A drain valve provides capability for emptying the coil when test conditions exceed 180°F. Compressed air applied to the vent valve can be used to force all water from the coil. Safety features to handle the possibility of steam forming in the coil include an over pressure switch which shuts down the heater system at 120 psi in the coil and a relief valve which opens at 140 psi. The preceding settings may be adjusted. A system fault is announced at the 120 psi level.

The chiller section of the control console includes 1) a status light coupled to the water flow switch shown in Figure 18, and 2) a meter showing the chiller inlet and outlet water temperatures.

4.11.4 Humidity Control

A schematic diagram of the humidifer system is shown in Figure 19.

Steam is supplied to the humidifier control unit by means of a manual valve on the mezzanine. The steam controller is a pneumatically actuated valve attached to the humidifier. The penumatic controls are operated from the control console. Air is supplied to these controls via the manual laboratory air valve on the mezzanine.

Operation consists of the following procedures:

1. Upon achievement of temperature set point and after the tunnel is charged with combustion products (if required), the humidifier is turned on by manually opening the steam valve and electrically opening the control air solenoid valve.

2. Adjustment of the control air pressure by means of the pressure regulating valve (venting type) controls the diaphragm-actuated steam regulating valve from closed at 3 psig to maximum position at 10 psig.

3. An aspirator, operating on laboratory air, draws tunnel gases past a humidity sensor that will operate up to 120°F. (The measurement system was designed for the range 70°F - 100°F.) The humidity measurement appears on the console meter. Since the tunnel gas may have cooled in transit to the detector, a temperature measurement must also be made and the relative humidity corrected to the tunnel temperature at the test section inlet.

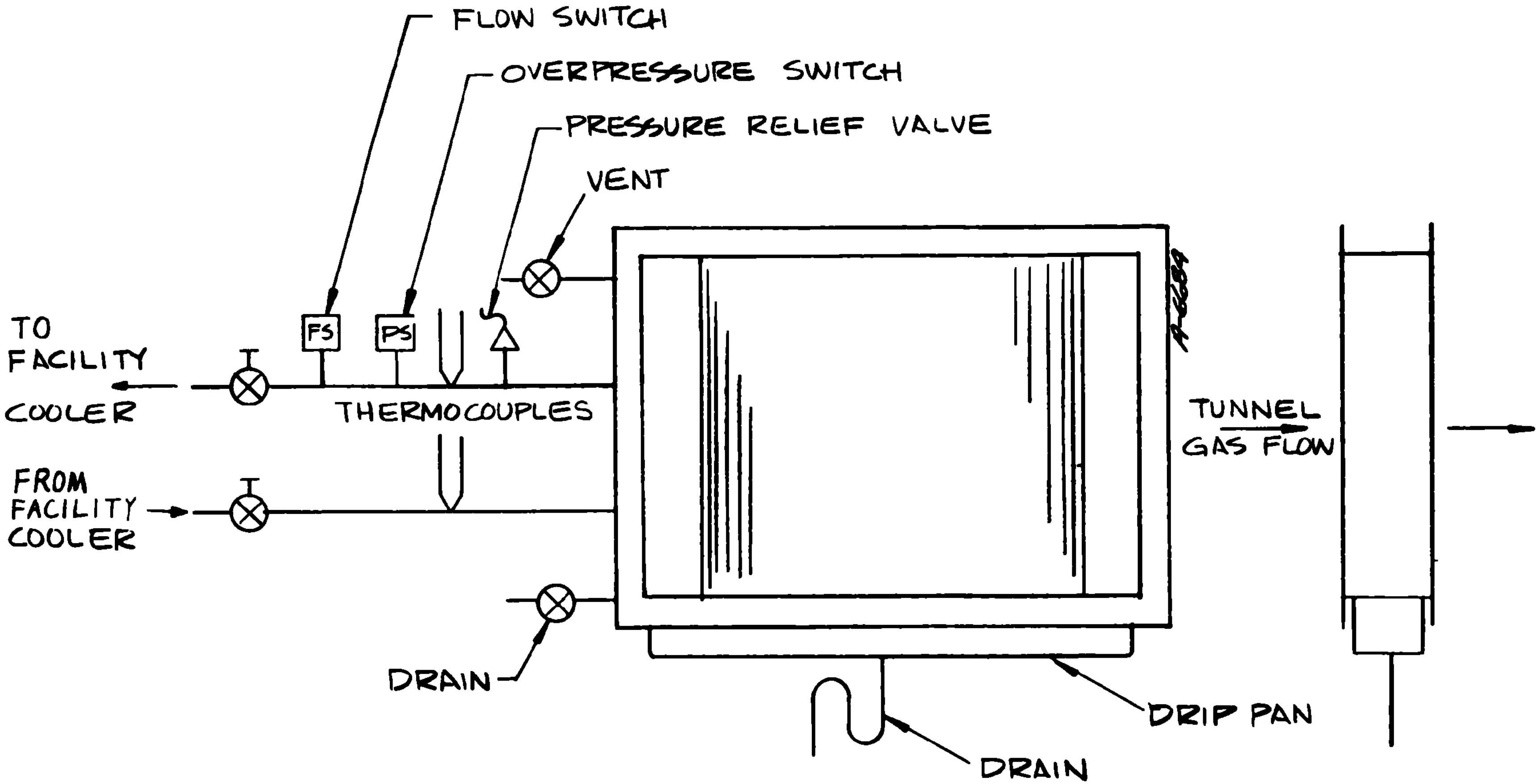

Figure 18. Chiller Schematic

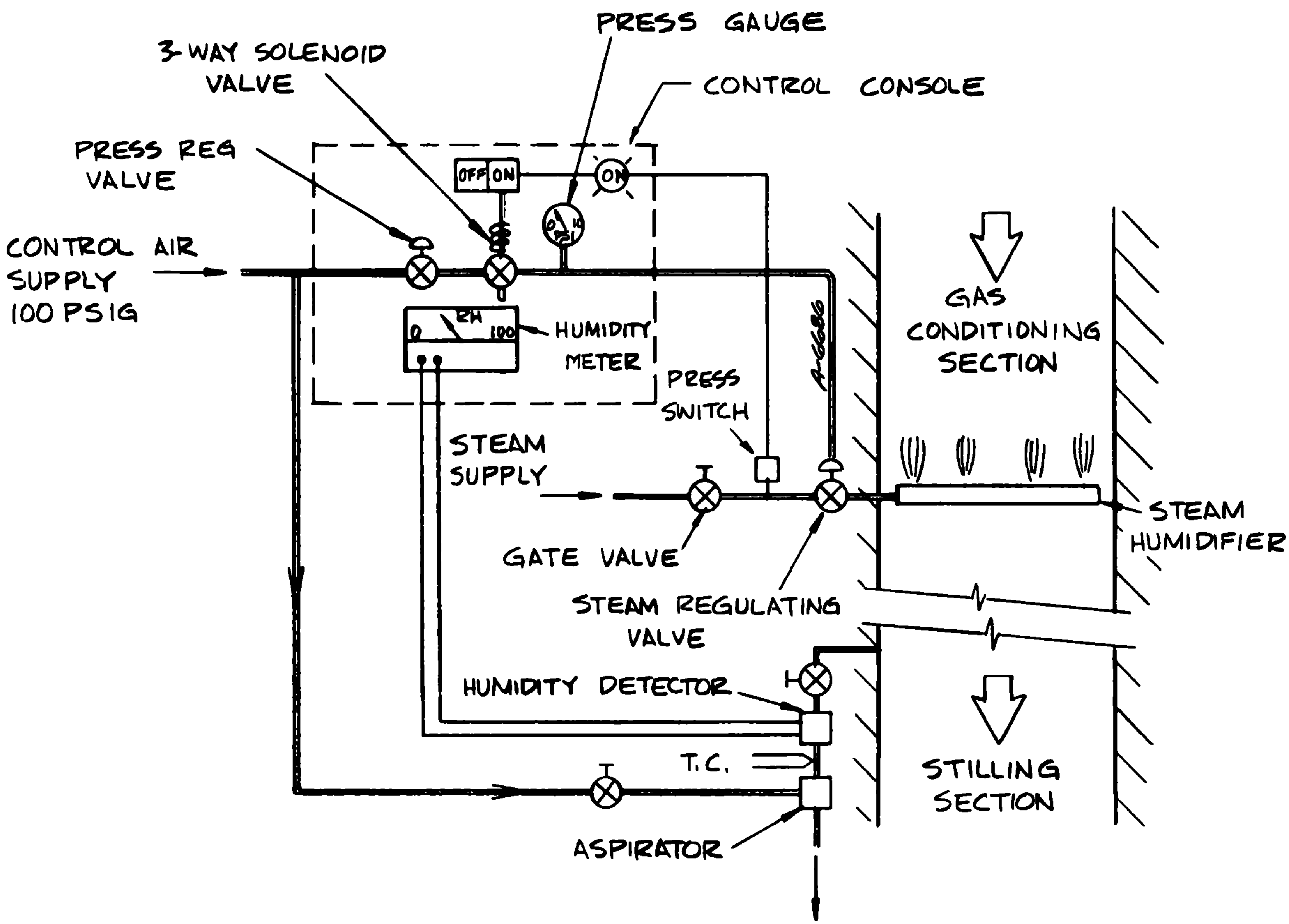

Figure 19. Humidity Control System

4. As the humidity set point is approached, the air pressure regulating valve will be adjusted to achieve a smooth approach.

5. If humidity exceeds set point and the chiller is operating for temperature control, the humidifier flow is reduced with the pressure regulating valve. The chiller will continue to condense moisture from the gas.

6. The humidifier is shut off from the console pushbutton which vents the solenoid valve, closing the steam valve.

4.11.5 Purge Section Control

Control of the purge section valves is maintained from the console by means of toggle switches. A position potentiometer on each valve is read out on a panel meter indicating percent of full open position. Limit switches on the tunnel damper and the inlet valve actuate the panel limit lights indicating the valves are either fully closed or fully open. The limiting positions of the exhaust valve are not critical and therefore not indicated with lights. It is important to insure the closed status of the inlet valve so that test gases do not enter the laboratory area. Therefore, a fault light indicates when the inlet valve is not closed. The fault light is automatically deactivated during purge by means of the closed switch on the tunnel damper.

4.11.6 Combustion Products Control

The combustion products system is controlled from the console. Refer back to Figure 10 for the combustion products system schematic diagram. The system is started by 1) opening the flow valves to the coolant side of the heat exchanger (located on the mezzanine), 2) starting the boiler recirculation pump, and 3) activating the "boiler on" switch at the console. There will be a fault signal if the boiler is activated without coolant flow or recirculation pump on. Until the boiler is turned on, the combustion products diverter valve is unpowered and, therefore, cannot be moved from the exhaust position. Boiler ignition activates the console flame-on light on the console.

Controls in the boiler-mounted control package automatically proceed through a normal start sequence with the appropriate interlocks and flame safeguard features. Wind tunnel control console relays are connected to the following switches internal to the boiler:

1. Low water cutoff

2. High water temperature cutoff

3. High and low gas pressure limits

4. Flame failure

Any one of the above problems will shut the boiler down and alert the operator to the situation by fault alarms (light and horn) at the console.

To guard against the hazard of an explosive mixture of gas forming in the wind tunnel, a combustible mixture detector, calibrated for natural gas, is connected to the tunnel and the combustion products 6-inch duct by means of an aspirating draw system. The aspirator begins drawing air automatically with boiler turn-on. The detector control package is mounted on the console and provides two alarm levels, 20 percent of the lower explosive limit (LEL) and 40 percent LEL. The console fault light operates on signal from the detector electronics. In the "exhaust" mode, the detector sample is drawn from the 6-inch duct. When the combustion products are diverted to "tunnel," a three-way solenoid valve in the detector draw line automatically switches the measurement to the tunnel. To insure that the aspirator is properly powered by laboratory compressed air, an air pressure switch signals a console fault alarm if the compressed air pressure is low. (The alarm also indicates that the diverter valve pneumatic actuator and the humidifier pneumatic valve will not operate effectively until laboratory air pressure is increased.) As well as actuating the fault alarm, the 20 percent LEL alarm diverts boiler gases to exhaust. At 40 percent LEL, the boiler is shut down.

Due to the risk of moisture condensation, the tunnel temperature, particularly at the baghouse, should be above approximately 170°F before combustion products are allowed to enter the tunnel. Therefore, when the boiler is on, a temperature switch located at the baghouse exit, will signal a console fault alarm until the tunnel temperature exceeds 170°F. The diverter valve is not interlocked to the temperature switch so operator judgement is required here.

In order to operate the boiler at optimum combustion efficiency, the draft damper position is controlled by the operator from the console. This valve is normally open, and is operable from the console only during flame-on condition. A pressure gauge is included on the console to provide direct readout of draft pressure. During boiler operation, the gauge should indicate + 1/2 inch to 1 inch W.G. To assist in monitoring the boiler exhaust, a second pressure gauge measures tunnel pressure at the purge section outlet (that is; the boiler exhaust back pressure).

Measurements on the console assigned to the combustion products system temperatures panel include the following temperatures:

1. Combustion products gas (at the boiler exhaust)

2. Boiler water inlet

3. Boiler water outlet

4. Boiler heat exchanger inlet

5. Boiler heat exchanger outlet

Boiler water pressure is also displayed on the console. Normal operating pressure is about 20-25 psig. To avoid moisture condensation in the stack, the combustion products gas temperature should be kept between 300°F and 350°F.

When the boiler achieves steady state operation (about 20 minutes) and tunnel temperature exceeds 170°F at the dust collector exit, the diverter valve is actuated to the tunnel position.

When tunnel charging is completed (as determined by a detection system external to the control console) the operator will swing the diverter valve to exhaust and probably continue boiler operation in preparation for recharging as required due to dilution from tunnel leaks.

4.11.7 Dust Collector Control

There are two functions on the dust collector which are controlled: the bag cleaning function and the hopper cleanout. Only the former is initiated from the control console. Hopper cleanout will be achieved when the tunnel is not operating by activating a motorized screw in the hopper at an adjacent circuit breaker.

The switch on the control panel activates the bag cleaning controller located on the baghouse. This controller performs the following functions:

- Controls the duration of the cleaning air pulse (adjustable)
- Controls the period between pulses (adjustable)
- Controls the cleaning air in a prescribed manner to 12 groups of bags via 12 solenoid valves

The baghouse pressure drop is displayed on the control panel with a differential pressure gauge.

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2. "Particulate Aerodynamic Test Facility, System Description and Operations and Safety Manual," Aerotherm User's Manual, UM-73-39, March 1974.

3. Pope, Alan and Harper, John J., Low Speed Wind Tunnel Testing, John Wiley and Sonse, Inc., 1966.

4. Cohen, M. J. and Ritchie, N. J. B., "Low Speed Three Dimensional Contraction Design," Journal of the Royal Aeronautical Society, Vol. 66, April 1962, p. 231.

APPENDIX A

TEST FACILITY OPERATION PROCEDURE

This section outlines the basic procedure for operating the test facility. It is presented in enough detail to provide a working knowledge of tunnel operation.

Figure A-1 shows the locations on the tunnel of the hatches, breaker boxes, thermocouples, and pressure taps. Table A-1 is the key to Figure A-1.

Table A-2 contains the test facility startup and operation procedure. The startup description begins with the circuit breaker boxes and proceeds through all of the facility subsystems. In the text, words consisting of all uppercase letters denote labels as they appear on the control console or elsewhere.

Under normal circumstances the shutdown procedure for individual subsystems is the opposite of the steps in Table A-2. There is, however, a correct order in which the subsystems should be deactivated, as delineated in Table A-3. The normal shutdown procedure assumes as an initial condition that all tunnel subsystems are activated.

There are several instances during which a malfunction in a tunnel subsystem will require a specialized operation procedure. These activities are briefly outlined below:

- If the fan becomes disabled during a test run, the tunnel should remain sealed off from the room, all subsystems deactivated, and the test gas purged from tunnel by the repaired fan or other means.
- If one or more of the heater modules overheat, and the automatic heater over-temperature control fails to operate, deactivate the system and operate the fan for a length of time sufficient to cool the modules.
- If condensation occurs on the dust collector bags, purge the tunnel in conjunction with the heater system until the filter media are fully dry.

This is not an exhaustive list, since straightforward solutions to such difficulties are usually discovered when operator judgement and discretion are applied.

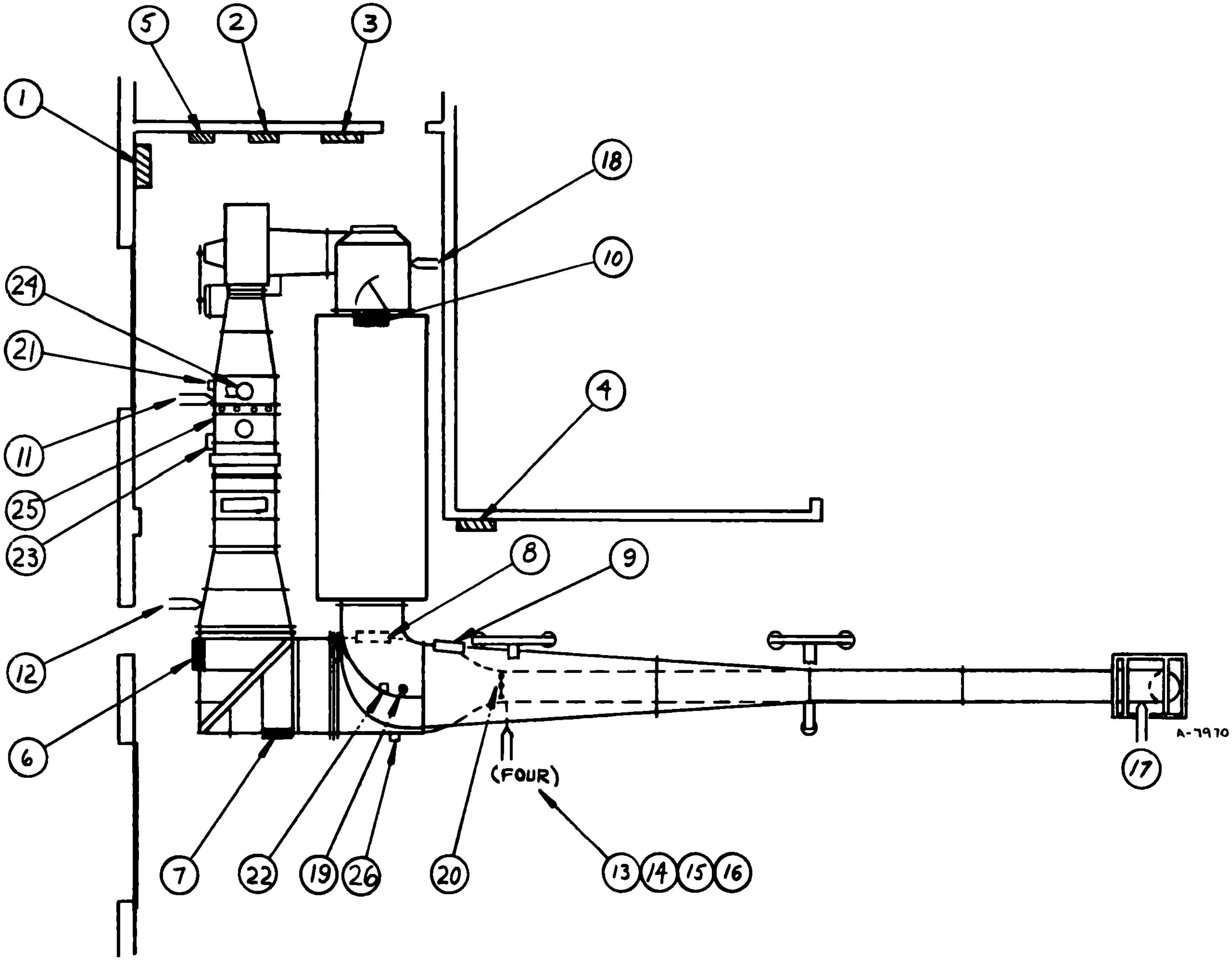


Figure A-1. Plan View of Installation

TABLE A-1

KEY TO FIGURE A-1

ITEM	DESCRIPTION
1	Breaker box 1
2	Breaker box 2
3	Breaker box 3
4	Breaker box 4
5	Breaker box 5
6	Turning box hatch, before vanes
7	Turning box hatch, after vanes
8	Stilling section hatch
9	Diverging section hatch
10	Baghouse access door
11	Conditioning section inlet thermocouple
12	Conditioning section outlet thermocouple
13	Test section inlet thermocouple
14	Velocity computer thermocouple
15	Auxiliary heater controller thermocouple
16	Modulating heater controller thermocouple
17	Conditioning section outlet thermocouple
18	Baghouse outlet thermocouple
19	Contraction section ΔP tap, low velocity
20	Contraction section ΔP manifold tap, high velocity
21	Tunnel low temperature switch
22	Tunnel over-temperature switch
23	Combustible gas detector
24	Combustible gas detector tap, exhaust
25	Combustible gas detector tap, tunnel
26	Humidity detector tap

TABLE A-2

TEST FACILITY START-UP AND OPERATION PROCEDURE

ITEM	COMMENTS
1. Breaker and Junction Boxes	Refer to Figure A-1
A. Box 1, Switches ON:	
1) Unnumbered	Heater, 440V
2) Unnumbered	Fan motor, 440V
3) Unnumbered	Baghouse auger, 220V
B. Box 2, Switch outside lever ON:	Fan motor, 440V
C. Box 3:	Heater Overtemp Control Box
1) Switch outside breaker lever ON	
2) Dial overtemp controls to desired setpoints	Recommended maximum setpoints: Modulating heater: 1200°F Auxiliary heaters: 1200°F
3) Reset both heater overtemp controls	
D. Box 4, Switches ON:	Marked "PF"
1) # 30	Console and boiler, 220V
2) # 32	Boiler, 110V
2. Verify secured hatches	
A. Turning box, before vanes	
B. Turning box, after vanes	
C. Contraction section	
D. Diverging section	
E. Baghouse access door	
3. Manually rotate fan one revolution by the fan belt	Check for obstructions
4. Open compressed air supply valve.	Supplies air to all pneumatically-operated subsystems.
5. If tunnel is to be operated above 180°F and tunnel chiller will not be used, drain chiller.	
6. Activating console panel:	
A. Turn panel POWER switch ON with key	
B. Panel initial conditions	
1) All subsystem power switches should be off.	All switches except those for the heaters normally have defaulted to the OFF or MANUAL positions before initial console activation.
2) All fault lights, unlit	Correct any indicated faults before proceeding

ITEM	COMMENTS
7. Tunnel Fan	
A. Set TUNNEL VELOCITY dial to zero	
B. Adjust TUNNEL DAMPER POSITION to OPEN	
C. Turn FAN POWER switch ON.	
D. For automatic velocity control, switch VELOCITY CONTROL to AUTO at this time.	A slight fan speed surge will be noted if control mode is switched to AUTO above ~ 10 fps tunnel velocity
E. By monitoring the test section VELOCITY meter, approach the desired velocity by slowly increasing the dial setting	
F. Inspect fan for smooth, quiet rotation and that downstream pressure readings are steady.	Lubricate bearings after every 200 hours of operation.
8. Tunnel Chiller	If humidifier is on at this point, chiller may cause condensation in the tunnel
A. Open chiller water inlet and outlet valves	
B. Verify illumination of CHILLER ON lamp	
C. During operation, keep CHILLER WATER OUTLET temperature below ~ 65°F.	If this is impossible, tunnel is operating too hot for the chiller. Close valves and drain the chiller before continuing.
9. Heater System (Note: Procedure assumes breaker box 3 is activated)	Max. Tunnel Temp. 450°F; Tunnel velocity must be above ~ 50fps before heater activation
A. Turn No. 1 or both auxiliary heaters ON	Heater No.2 will not operate independently of No. 1
B. Dial in desired tunnel temperature setpoint	
C. Press auxiliary heater RESET button	Verify ON lamp, illuminated
D. Turn modulating heater switch ON	Used to maintain tunnel temperature during testing
E. Dial in desired tunnel temperature setpoint	Glowing intensity of OUTPUT L.E.D. is proportional to power supplied to the heater.
F. At setpoint attainment:	Refer to Chromalox mannual for modulating heater proportional band and manual reset adjustment.
1) DEGREES DEVIATION meter reading ≅ 0	
2) Auxiliary heaters turn off and must be manually reset for further operation	
3) Power supplied to modulating heater diminished	
G. During tunnel shutdown, always deactivate heaters before fan	
10. Humidity Control System	
A. If tunnel is to be operated below 120°F, open humidity detector aspirator and toggle valves.	
B. Open steam inlet valve	

ITEM	COMMENTS
C. On HUMIDITY CONTROL panel:	
1) Verify illumination of STEAM ON lamp	
2) Turn CONTROL AIR switch ON	
3) Modulate control air pressure until desired humidity is reached	Calculate tunnel relative humidity by converting meter RH at humidity detector temperature to RH at tunnel temperature employing a psychrometric chart
11. Combustion Products Generator System	
A. Open heat exchanger and boiler water inlet and outlet valves.	
B. Verify:	
1) Operation of lab facility chiller	
2) Proper water level in expansion tank sight glass: Just above lower end of glass tube.	
3) Shutoff Cocks in burner and pilot gas lines, open	
4) Proper pressures in pilot gas line: Before regulator, ~ 5 psig; after regulator, ~ 15" W.G.	
5) High and low gas pressure switches, reset	
6) Low boiler water switch, reset	
7) BOILER HEAT EXCH. INLET temperature ~ 45°F	
C. On COMBUSTION PRODUCTS CONTROL panel:	
1) Verify DIVERTER VALVE POSITION = EXHAUST and DRAFT VALVE POSITION =OPEN	Valves should be inoperable from console during flame-off
2) Test COMBUSTIBLE GAS ALARM system	Recalibrate system every 3 months
3) Turn RECIRCULATION PUMP switch ON	
4) Turn BOILER switch ON	Subsequent automatic start sequence: 1. 15 second boiler pre-purge by blower 2. Combustion Air Proving Switch, activated 3. Igniter spark, activated 4. Pilot gas line solenoid valve, open 5. Pilot flame, on 6. Burner gas line motorized valves, open. 7. Flame on 8. Pilot gas line solenoid valve, closed
5) Verify FLAME ON lamp, illuminated	
6) Verify BOILER DRAFT = 1/2" to 1" W.G.	If necessary to attain proper draft, modulate DRAFT VALVE POSITION
7) During operation be sure that:	
a. BOILER WATER pressure < ~ 20 psig	
b. BOILER WATER INLET temperature > 170°F	
c. BOILER WATER OUTLET temperature < 200°F	
d. BOILER HEAT EXCH. OUTLET temperature < 65°F	

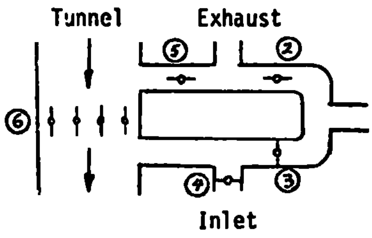
ITEM	COMMENTS
11. (continued)	
e. COMBUSTION PRODUCTS GAS temperature above 300°F, by adjusting heat exchange and boiler water inlet and outlet valves	Prevention of condensation in the the stack.
G. Visually inspect flame for stability and color--yellow with blue tinge	Marginal adjustment can be made by varying position of combustion air damper plate
H. Verify combustible mixture detector rotometer setting: ~ 1.75 - 2.0 scfh when boiler is operating.	
I. Verify Combustible mixture detector aspirator pressure: ~ 10 - 15 psig	
J. Combustion Products Generator System Operating Modes	
(note: procedures assume fan is operating)	
1) Boiler off; valve positions	Refer to Figure A-2 (a)
a. Draft, open	
b. Diverter, exhaust	
c. Inlet, closed	
d. Exhaust, open	Pressure datum
e. Tunnel damper, open or modulated	
2) Boiler on, exhaust to stack	Refer to Figure A-2 (b)
a. Initially, operate tunnel in mode 1)	
b. Implement new valve positions:	
(1) Draft, open	
(2) Diverter, exhaust	
(3) Inlet; open	Pressure datum
(4) Exhaust, closed	
(5) Tunnel damper, open or modulated	
c. Activate combustion products generator system.	
3) Boiler on, exhaust to tunnel	Refer to Figure A-2 (c)
a. Initially, operate tunnel in mode 2)	
b. Raise DUST COLLECTOR OUTLET temperature to steady state 170°F, minimum. Monitor thereafter.	Prevention of condensation in tunnel and baghouse
c. Implement new valve positions:	
(1) Draft, open or modulated	
(2) Diverter, tunnel	
(3) Inlet, closed	
(4) Exhaust, open	
(5) Tunnel damper, open or modulated	
d. When tunnel is fully charged with combustion products, return to modes 1), or 2)	

ITEM	COMMENTS
11. (continued)	
4) Tunnel Purge	Refer to Figure A-2 (d)
a. Initially, operate tunnel in mode 1)(or, mode 2) with boiler off)	
b. If water vapor is judged to be present in the tunnel, keep DUST COLLECTOR OUTLET temperature above 170°F	Prevention of condensation in the tunnel
c. If operating, close down humidifier	
d. Turn on boiler blower motor switch	
e. Implement new valve positions (1) Draft, open (2) Diverter, exhaust (3) Inlet, open (4) Exhaust, open (5) Tunnel damper, closed or modulated	
f. When tunnel is judged fully purged, return to mode 1)	
12. Aerosol Generator and Dust Collection System	
A. Prepare aerosol generator for operation (procedure to be supplied later)	
B. Breaker Box 5; Switches ON: 1) Outside breaker lever 2) Power pushbutton switch	Dust auger control box; Heater overtemp box must be on for this box to activate (Operate dust auger in conjunction with bulk handling system)
C. On DUST COLLECTOR panel, turn PULSE CLEAN TIMER to ON.	
D. On PARTICULATE GENERATOR panel, turn power ON	
E. Adjust reading on CARRIER AIR meter from dust generator location	
F. Keep DUST COLLECTOR ΔP meter reading < 8" W.G.	
G. Operate tunnel and dust generator in conjunction with combustion products generator system as shown in Figure A-2.	

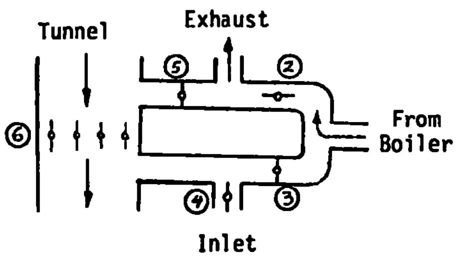
TABLE A-3

TEST FACILITY NORMAL SHUT-DOWN PROCEDURE
(Assumes All Subsystems Are Initially Activated)

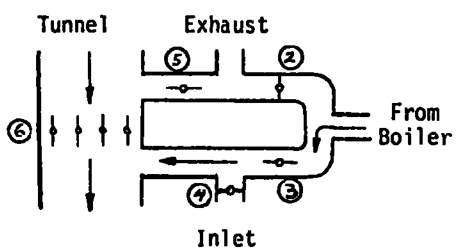
Item	Item Referenced in Table 9-2
1. Turn off aerosol generator system	12
2. Turn off boiler and heat exchanger pump, manually turn on boiler blower	11
3. Shut off chilled water supply to tunnel chiller and boiler heat exchanger	8, 11
4. Turn off humidity control system	10
5. Deactivate humidity detector	10
6. Shut off steam supply	10
7. Turn off heater(s)	9
8. Reduce test gas velocity to <30 fps in test section	7
9. Proceed to purge tunnel	11
10. Upon completion of purge, reset tunnel valves to normal positions and shut off boiler blower	11
11. Reduce test gas velocity to zero	7
12. Shut off tunnel fan	7
13. Shut off control console	6
14. Shut off compressed air supply	4
15. Turn off circuit breakers	1



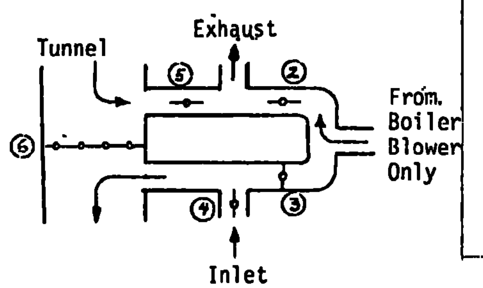
(a) Boiler Off



(b) Boiler On, Exhaust to Stack



(c) Boiler on, Exhaust to Tunnel



(d) Tunnel Purge, Boiler Off

Valve Positions				
(1) Draft (not shown)	(2) & (3) Diverter	(4) Inlet	(5) Exhaust	(6) Tunnel Damper
Open	Exhaust	Closed	Open	Open or Modulated
Open or Modulated	Exhaust	Open	Closed	Open or Modulated
Open or Modulated	Tunnel	Closed	Open	Open or Modulated
Open	Exhaust	Open	Open	Closed or Modulated

Figure A-2. Combustion Products Generator System Operating Modes

APPENDIX B

Aerotherm Final Test Report 74-107

TEST PHASE OF PROJECT 7086 ENGINEERING SERVICES SUPPORT OF PARTICULATE AERODYNAMIC TEST FACILITY

Aerotherm Project 7086

July 15, 1974

Aerotherm Final
Test Report 74-107

TEST PHASE OF PROJECT 7086 ENGINEERING SERVICES SUPPORT OF PARTICULATE AERODYNAMIC TEST FACILITY

by

Dale R. Blann
Hans J. Dehne
L. W. Anderson

Contract No. 68-02-1318
Task Order No. 1

Prepared for

U. S. Environmental Protection Agency
Research Triangle Park
North Carolina 27711

AEROTHERM
ACUREX Corporation

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (concluded)

SECTION 1

INTRODUCTION

In response to Task No. 1 under Contract 68-02-1318, Aerotherm Division of Acurex Corporation has provided engineering services to plan and conduct preliminary tests in the Particulate Aerodynamic Test Facility to establish its utility as a basic test bed for Control Systems Laboratory research programs.

Three subtasks were accomplished:

1. Establish invicid core flow zones at four axial stations and three operating conditions
2. Conduct particulate sampling tests at typical facility operating conditions to establish particulate loading profiles across the duct
3. Conduct an experimental comparison of isokinetic particulate sampling instruments.

Modifications were made during the testing, as necessary, to improve system performance.

Subtask 1 is described in detail in Section 2 below. Subtasks 2 and 3 were closely related and were carried out together; thus they will be described in conjunction in Section 3.

SECTION 2

SUBTASK 1: VELOCITY PROFILES

2.1 OBJECTIVE

The objective of Subtask 1 was to establish the invicid flow core regions in the wind tunnel test section at four axial positions and at three operating conditions.

2.2 APPROACH

The approach to meeting the objectives was to make pitot tube traverses vertically and horizontally at each of the axial stations and at each of three operating conditions, and to calculate, based on the measured static and stagnation pressure data, the local air velocity at each of the profile grid points. The calculated velocity data was then plotted graphically to obtain "velocity profiles" at each axial station in both the vertical and horizontal directions.

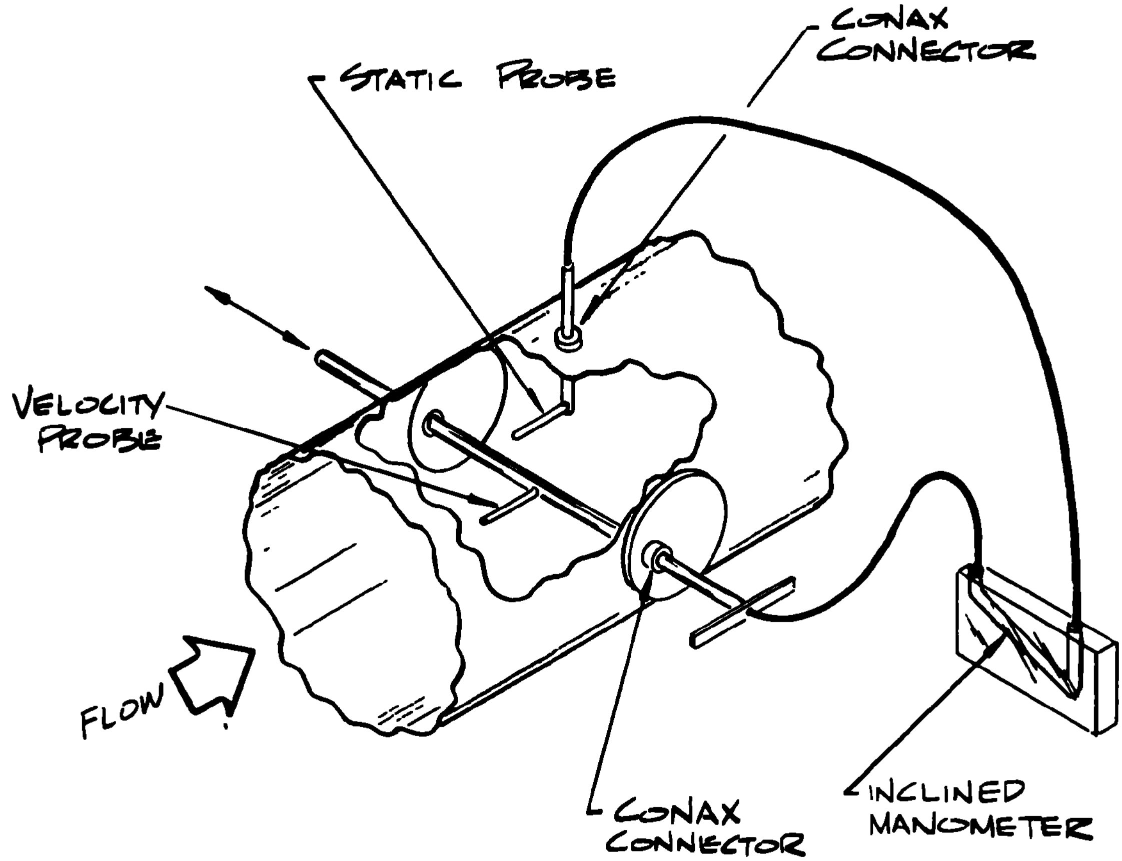
2.3 APPARATUS

The test set-up for taking the velocity pressure data is shown in Figure 1: the details of the probes are shown in Figures 2 and 3. Two probes were used: 1) a total pressure probe which measured stagnation pressure and 2) a static pressure probe which indicated local duct static pressure.

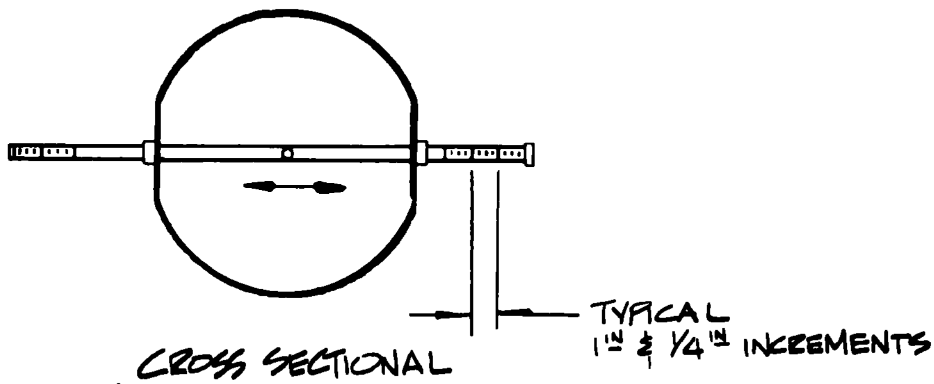
The static probe was stationary. It was mounted through one of four ports located at each axial station. The stagnation probe was attached to an aluminum tube which penetrated the test section through conax fitting installed into diametrically opposed prot holes. It was of sufficient length to allow the probe to be positioned at any point across the duct.

Manometer tubing was attached to each probe. For greater sensitivity a 3 inch inclined manometer was used to measure differential pressures between the static and stagnation probe, which by definition, is velocity pressure.

The basic layout of the Particulate Aerodynamic Test Facility is shown in Figure 4. The fan is an airfoil centrifugal type driven by a 50 H.P. variable speed drive. The air (or combustion products, if desired) is "conditioned"



TYPICAL VELOCITY SAMPLING SECTION



CROSS SECTIONAL VIEW LOOKING DOWNSTREAM

FIGURE 1 VELOCITY PROFILE PROBE AND GRID

A-8466

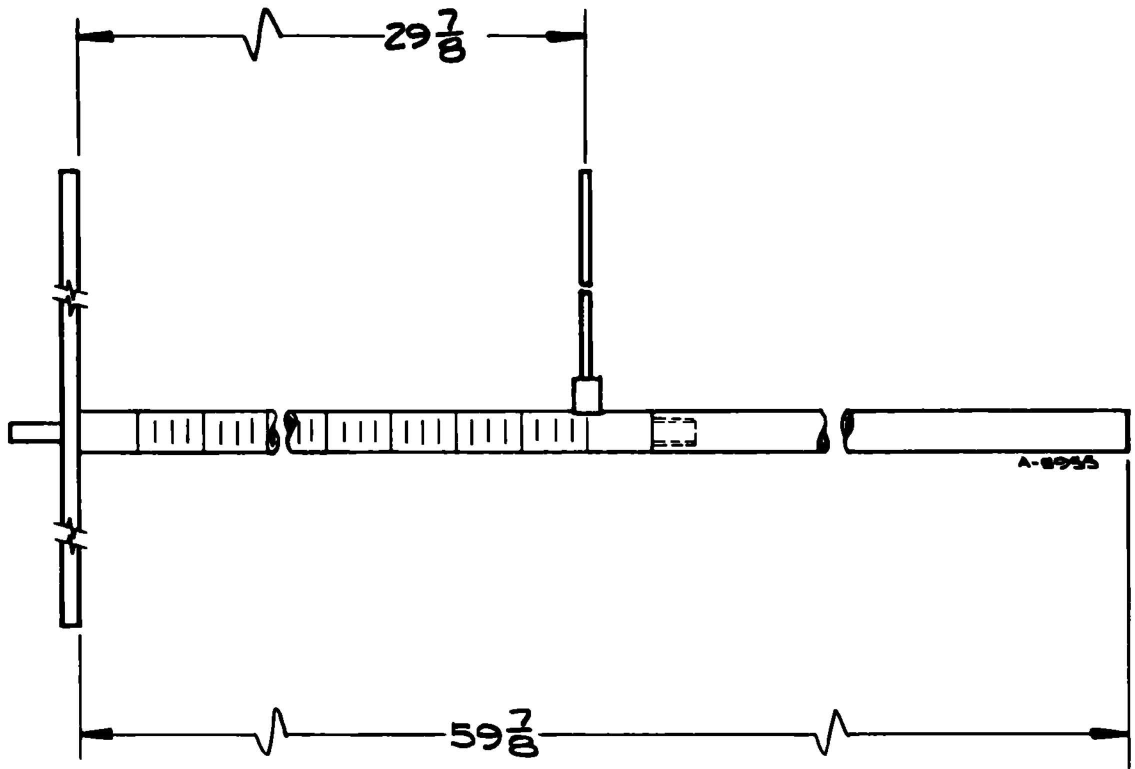


Figure 2. Stagnation Pressure Probe and Traverse Bar

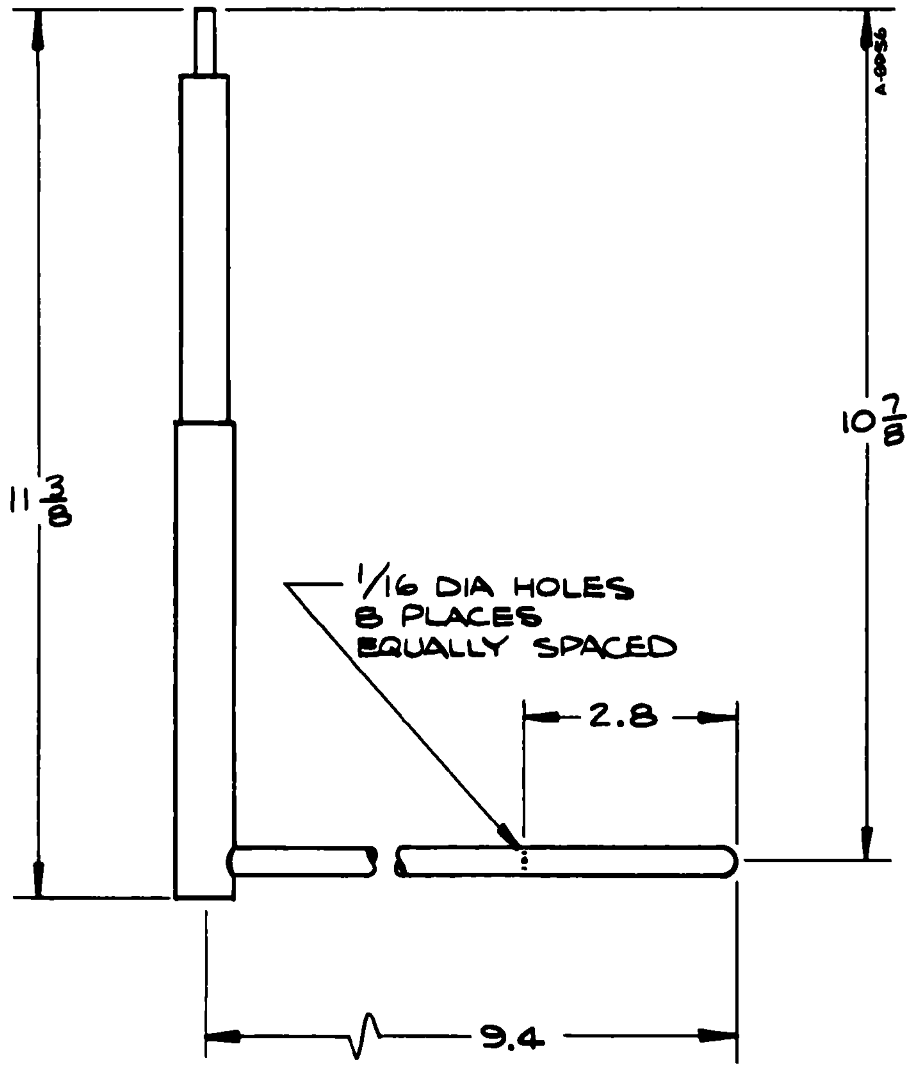


Figure 3. Static Pressure Probe

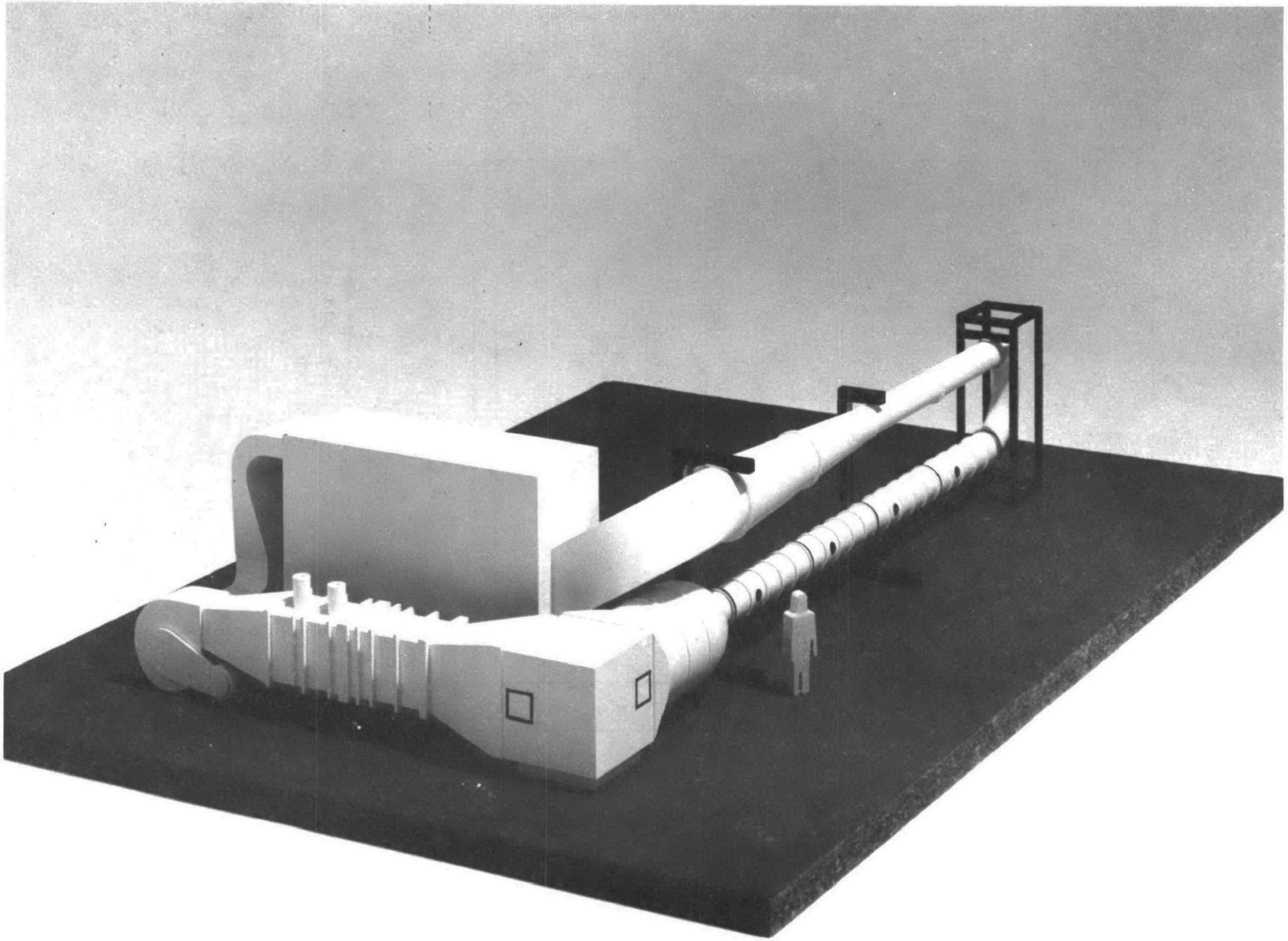


Figure 1. Model of Particulate Aerodynamic Test Facility

downstream of the fan prior to the first turn. The conditioning section consists of a duct heater (resistance heating), duct chiller (air-to-water heat exchange), and humidfier (steam).

The test section is 2 feet in diameter which gives a contraction ratio of 9 to 1. Particulates may be injected (as described in sections below) which are subsequently removed by a bag-type dust collector. The gas returns to the fan to complete the circuit.

2.4 TEST PROCEDURES

The test program was straightforward. Both probes were installed into a given test section axial location and the tunnel air velocity adjusted at the control console to indicate a given nominal test section velocity. The tunnel velocity controller was switched to AUTO in order to hold that velocity, and the tests were conducted. Three nominal test section velocities were used: 30, 60, and 90 fps. The probes were kept in position at each axial location until all data at the three different velocities were attained; then they were moved to a new axial location.

The stagnation probe was sequentially positioned across the duct at pre-determined intervals by scribe marks on the traverse road. These scribe markes were made to provide 1/4 inch increments for a distance of 3 inches from each wall and 1 inch increments in between (core region).

2.5 TEST RESULTS

The velocity profile data is plotted in Figures 5 through 28 for each nominal velocity, sequentially by test section. A single data point at a given "x" location indicates that the pressure reading from the manometer was steady; two points indicate a measureable fluctuation could be observed, so max-min was recorded. No attempt was made to average over the test time-increment at such points.

The horizontal profiles show the expected uniform core flow in the center with a boundary layer developing along the wall. Boundary layer thicknesses range from 1/2 to 4 inches depending on velocity and axial position. Test section 1 does show, for both 60 and 90 fps, some local distortion in the profiles, but since it disappears by test section 2, it is attributed to the presence of the dust injector nozzles in the stilling chamber.

The vertical profiles, however, present more difficulty in interpretation. As one scans the vertical velocity profiles from test section 1 to 4, it is apparent, particularly at the higher velocities, that the flow is being

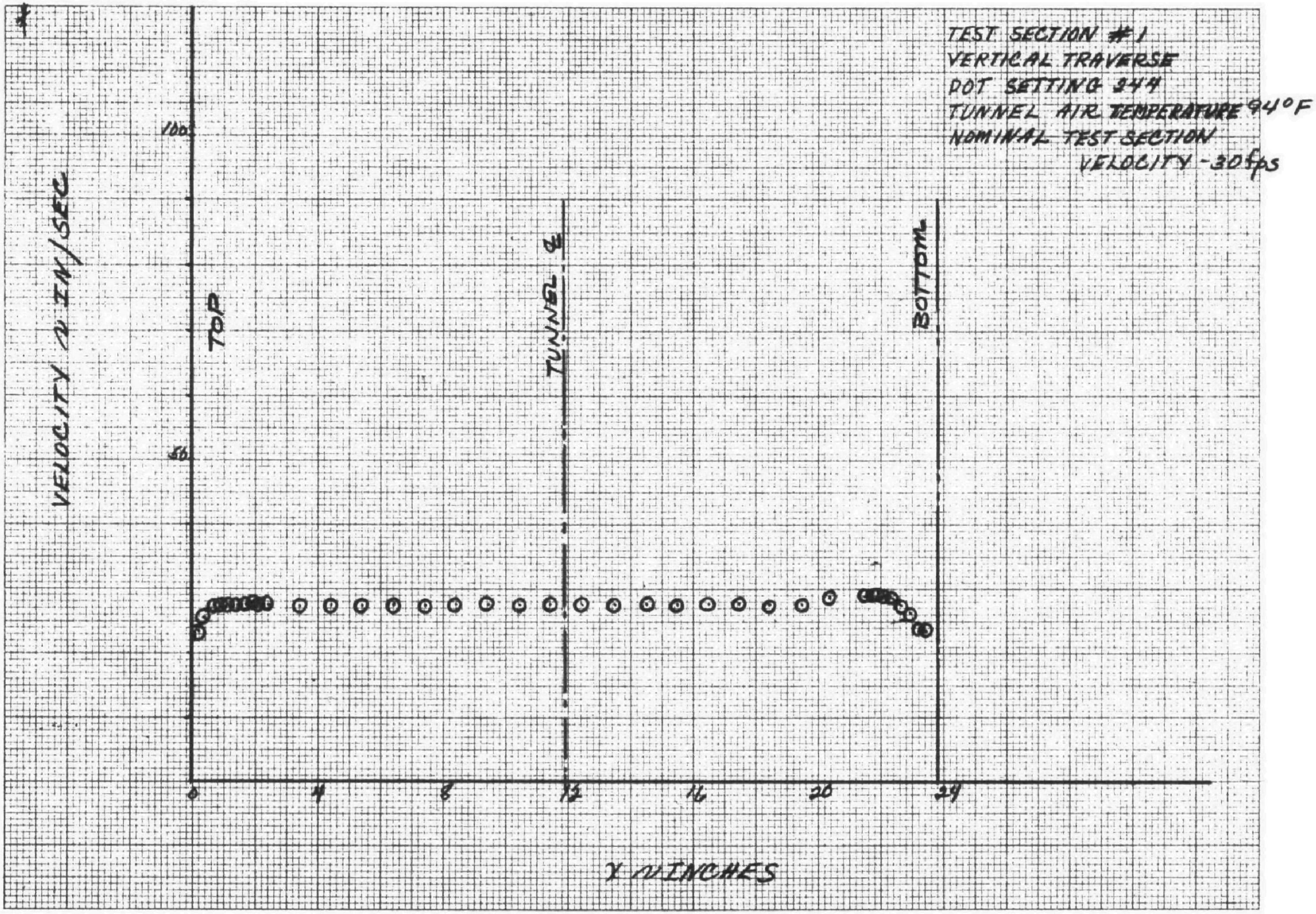


Figure 5. Velocity Distribution

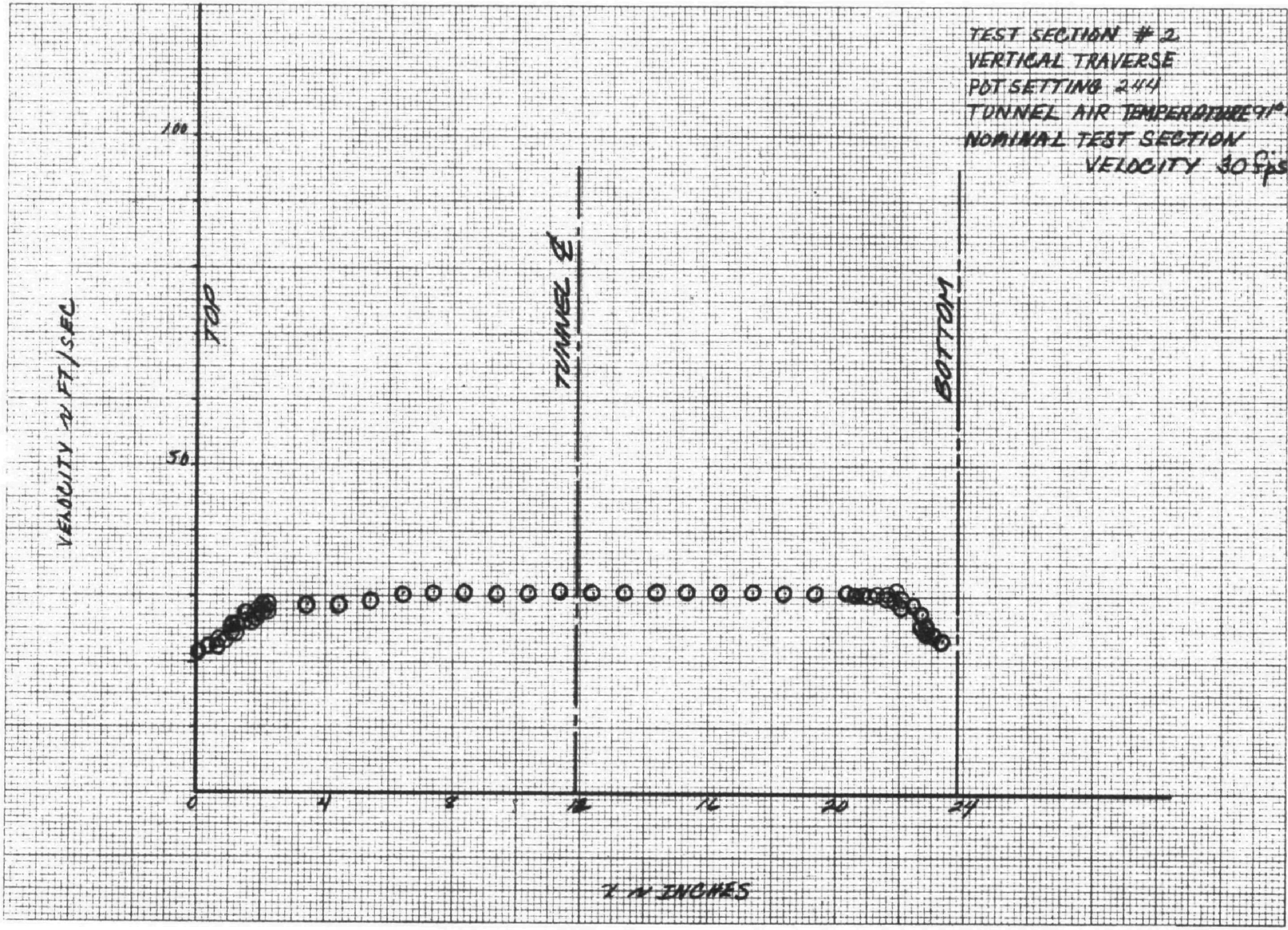


Figure 6. Velocity Distribution

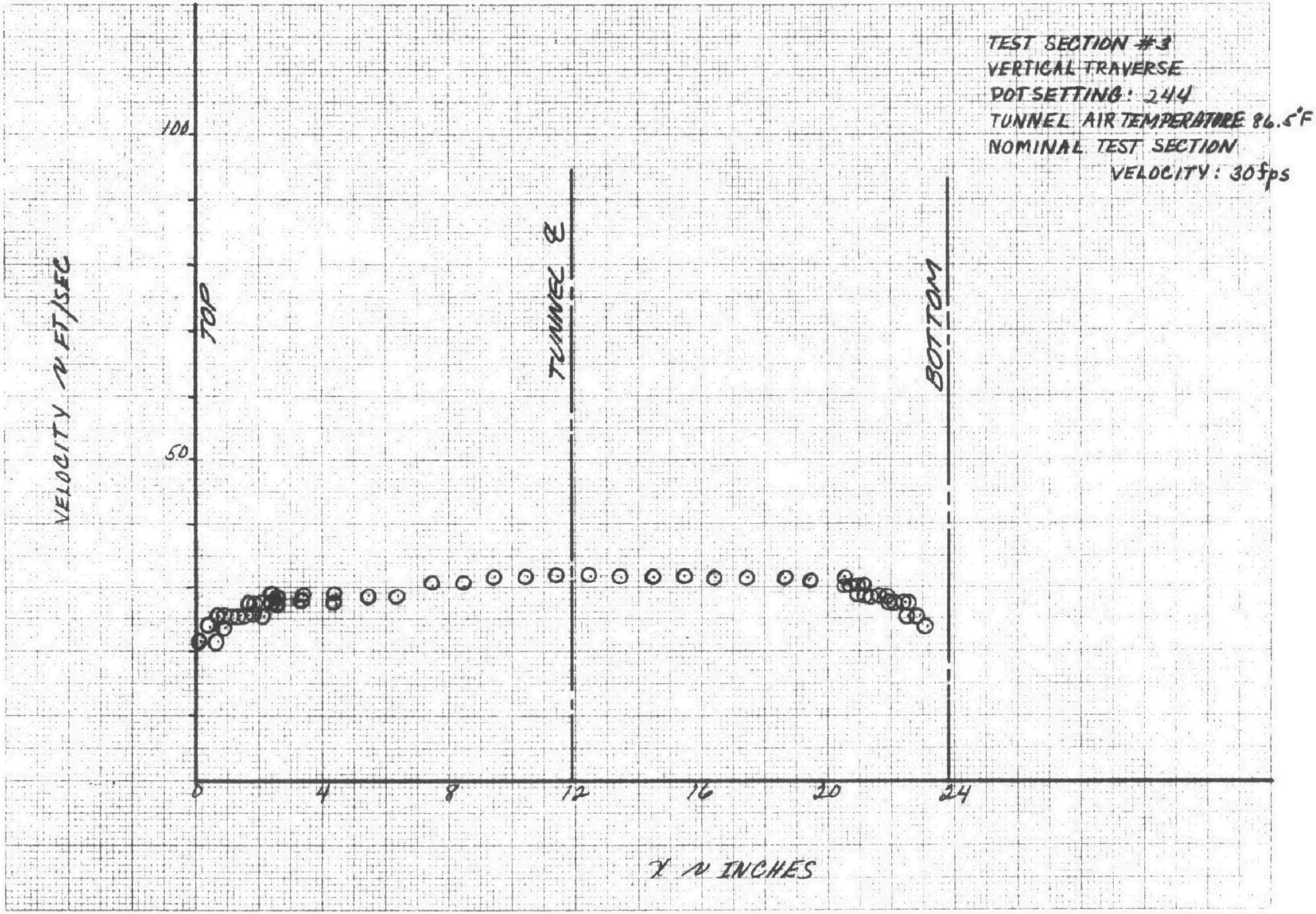


Figure 7. Velocity Distribution

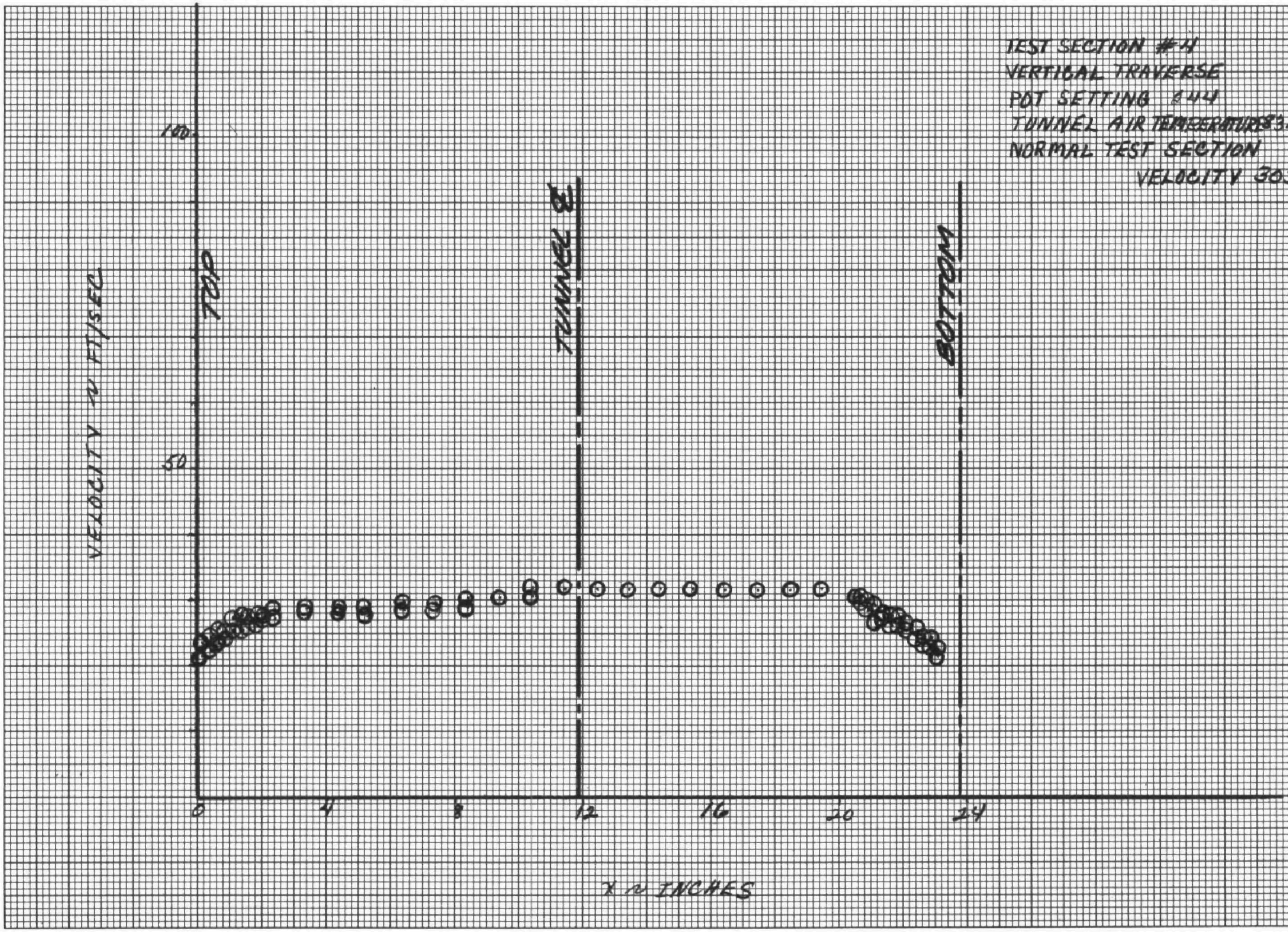


Figure 8. Velocity Distribution

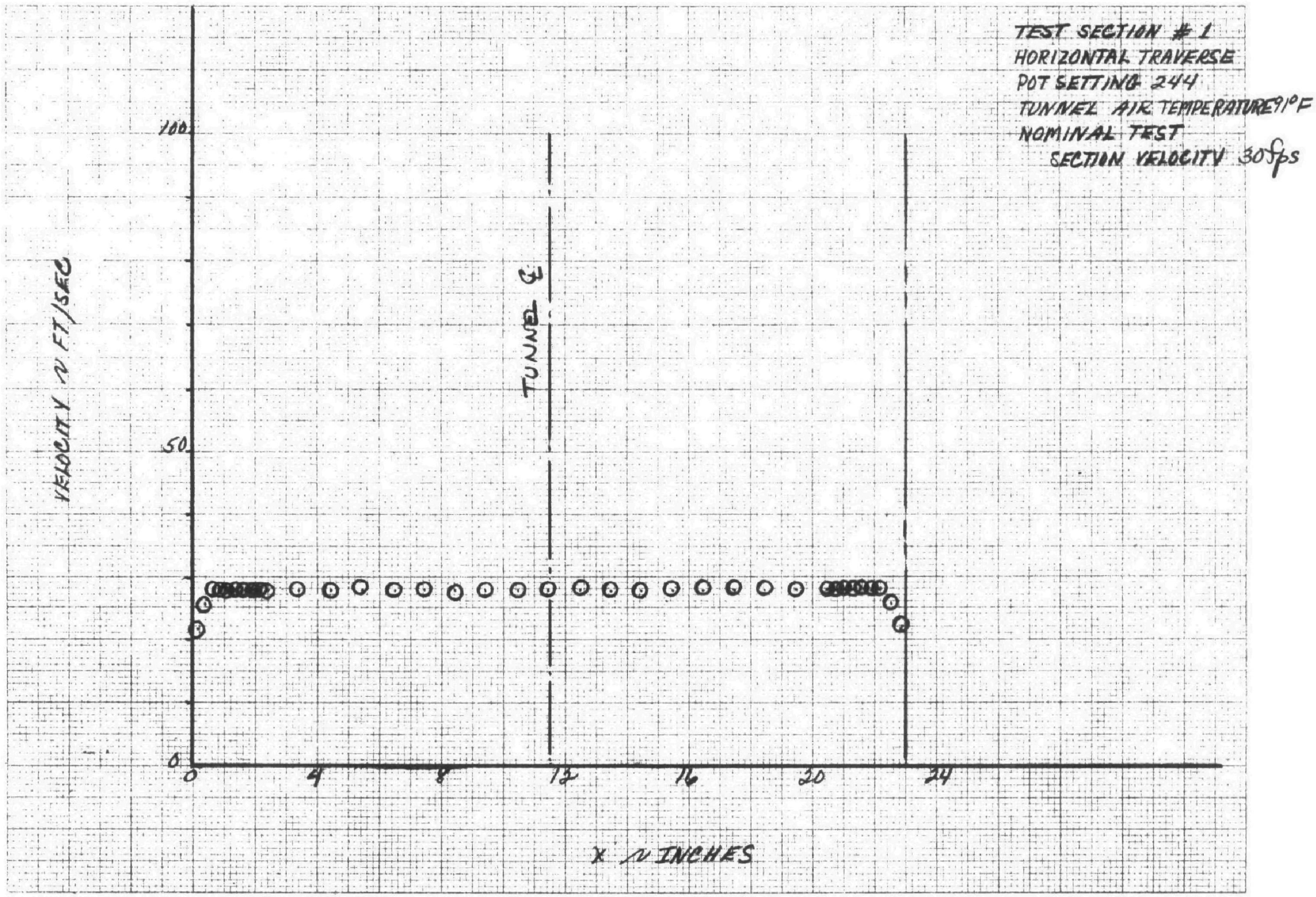


Figure 9. Velocity Distribution

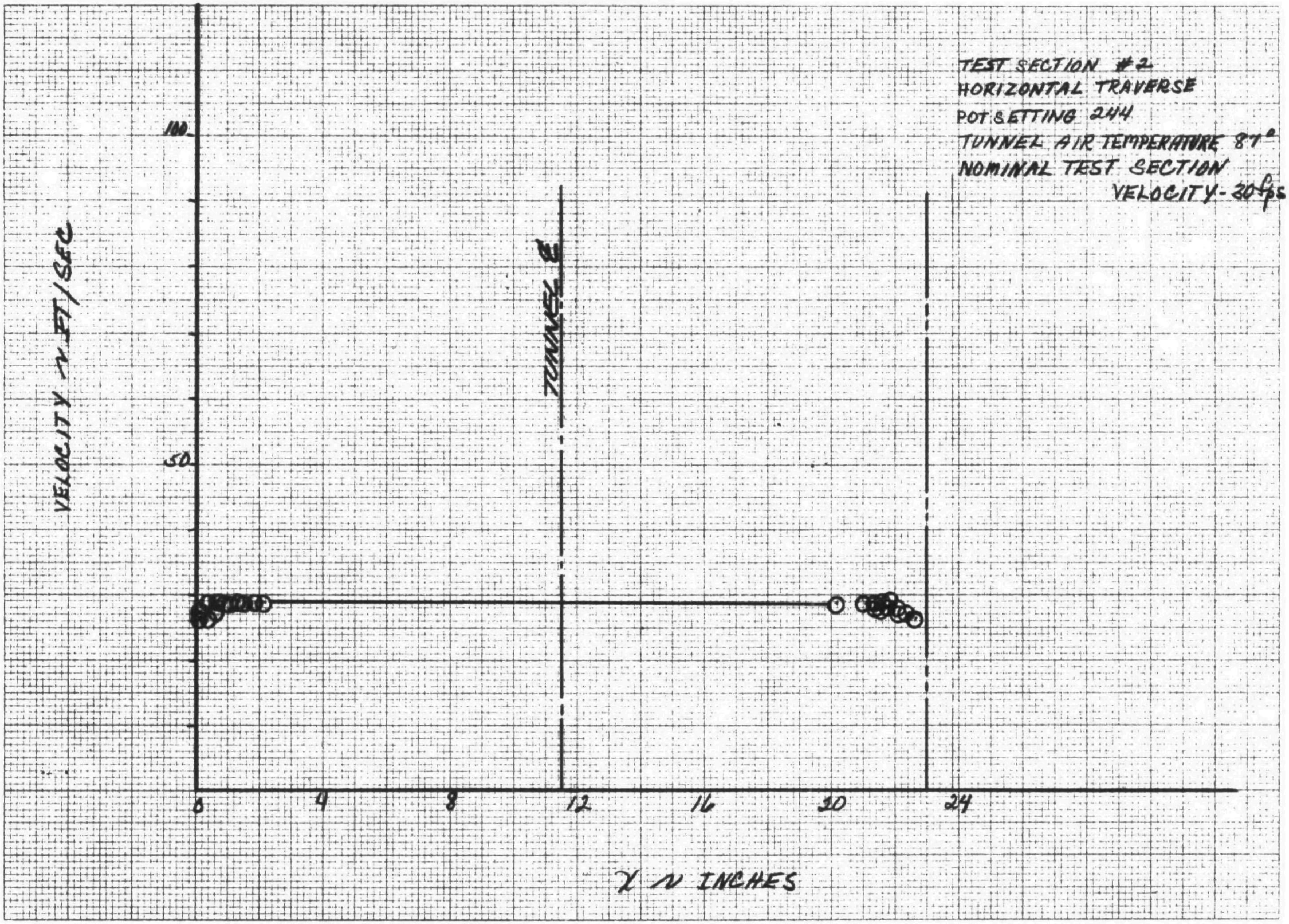
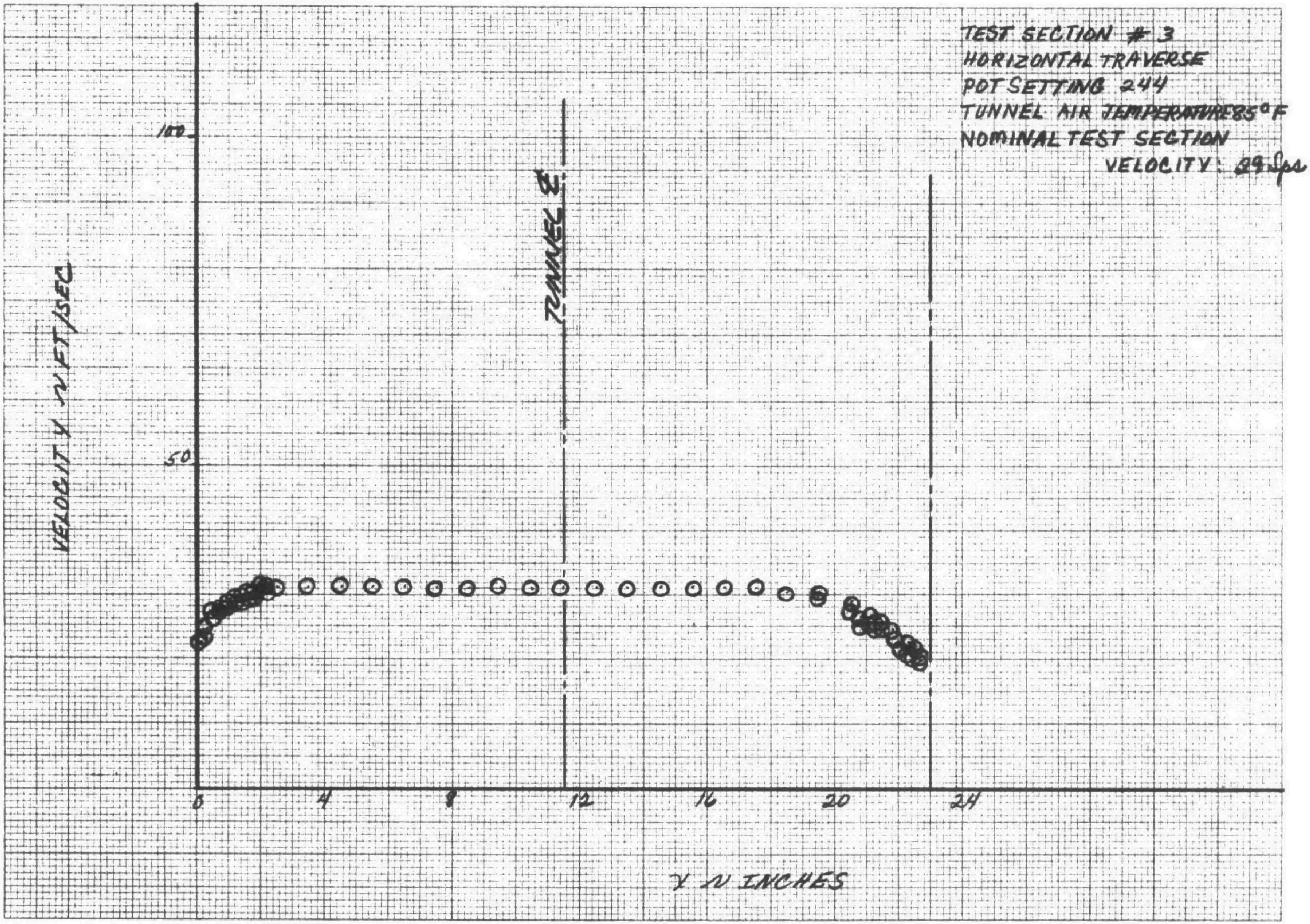


Figure 10. Velocity Distribution



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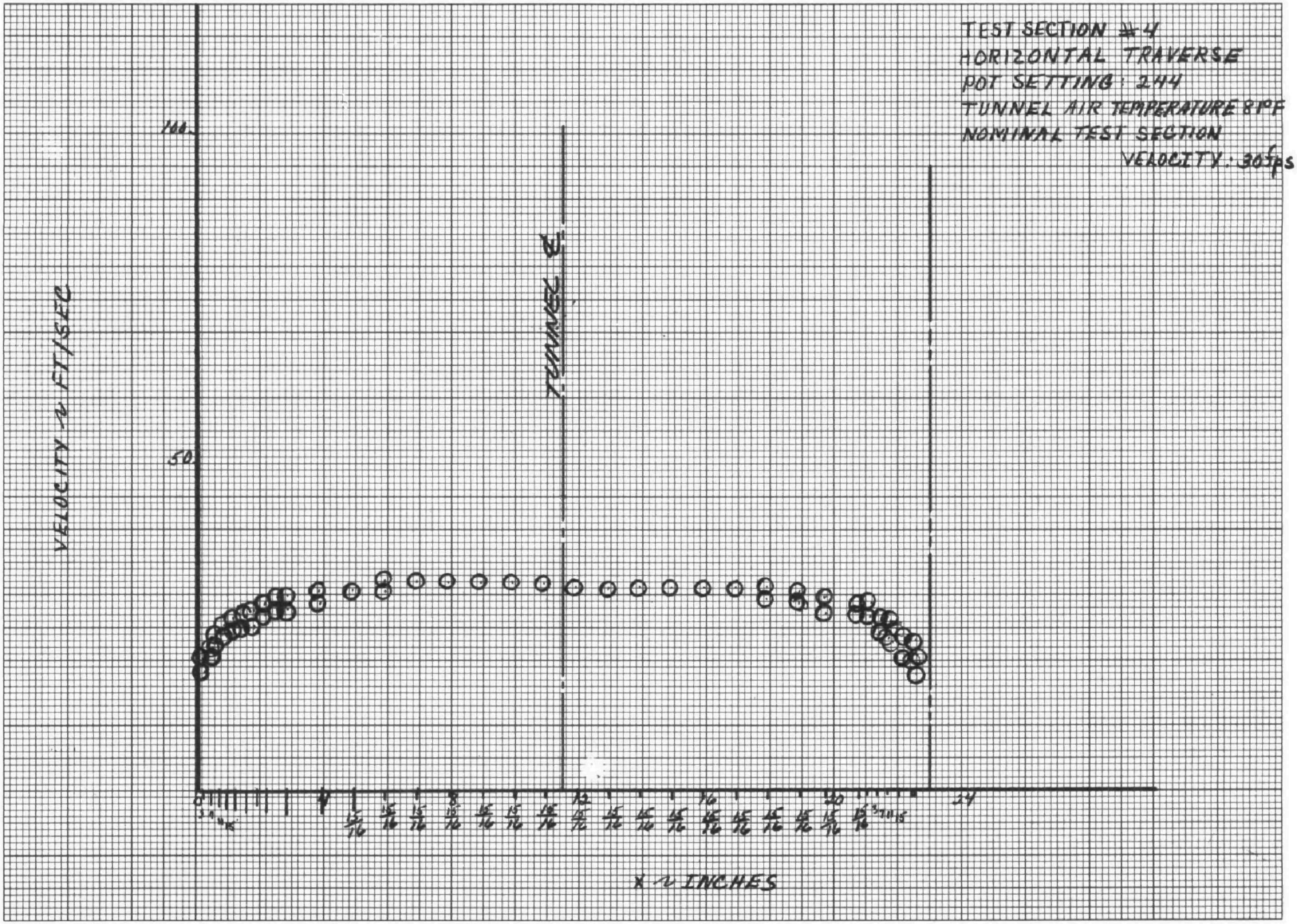

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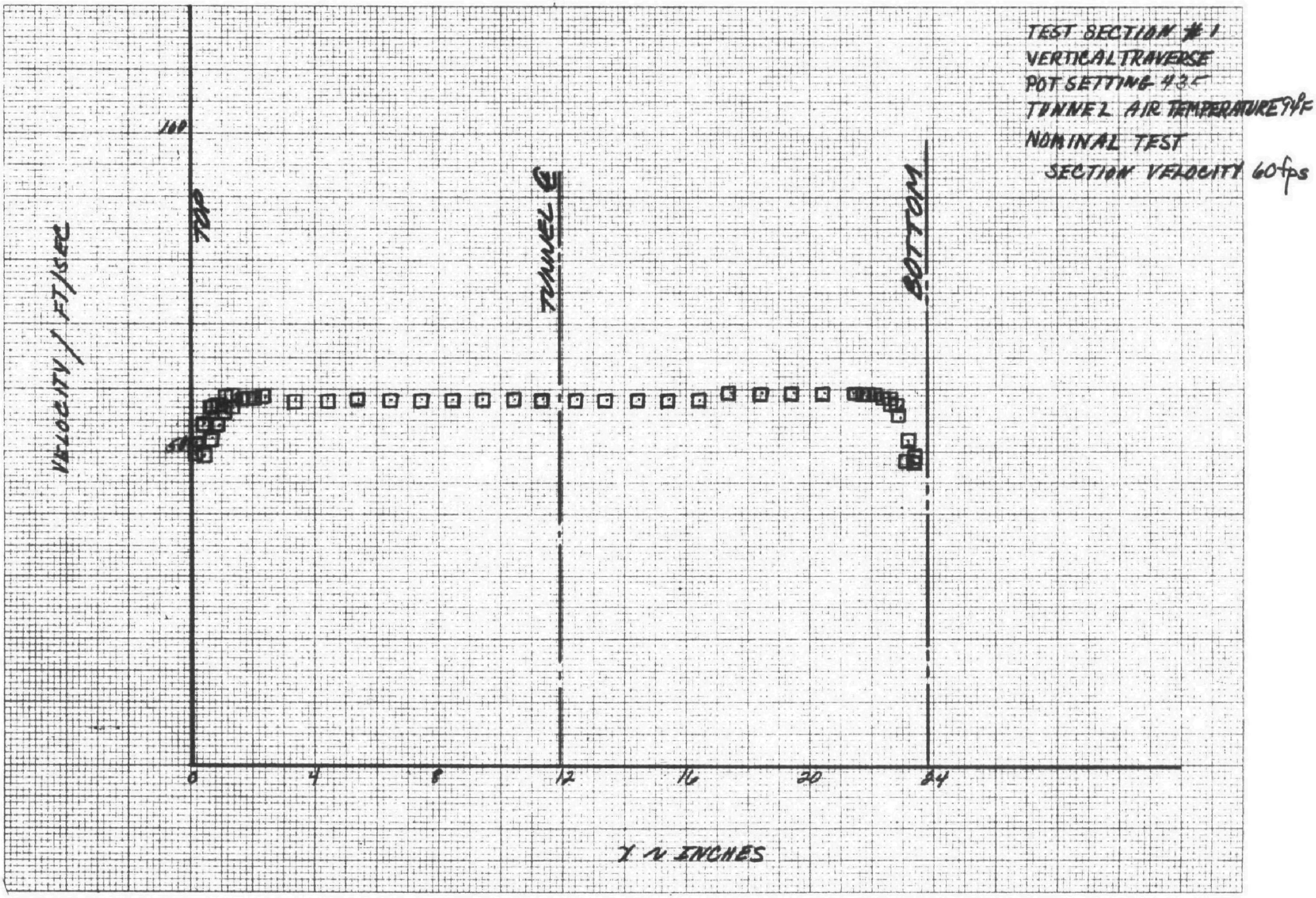


Figure 13. Velocity Distribution

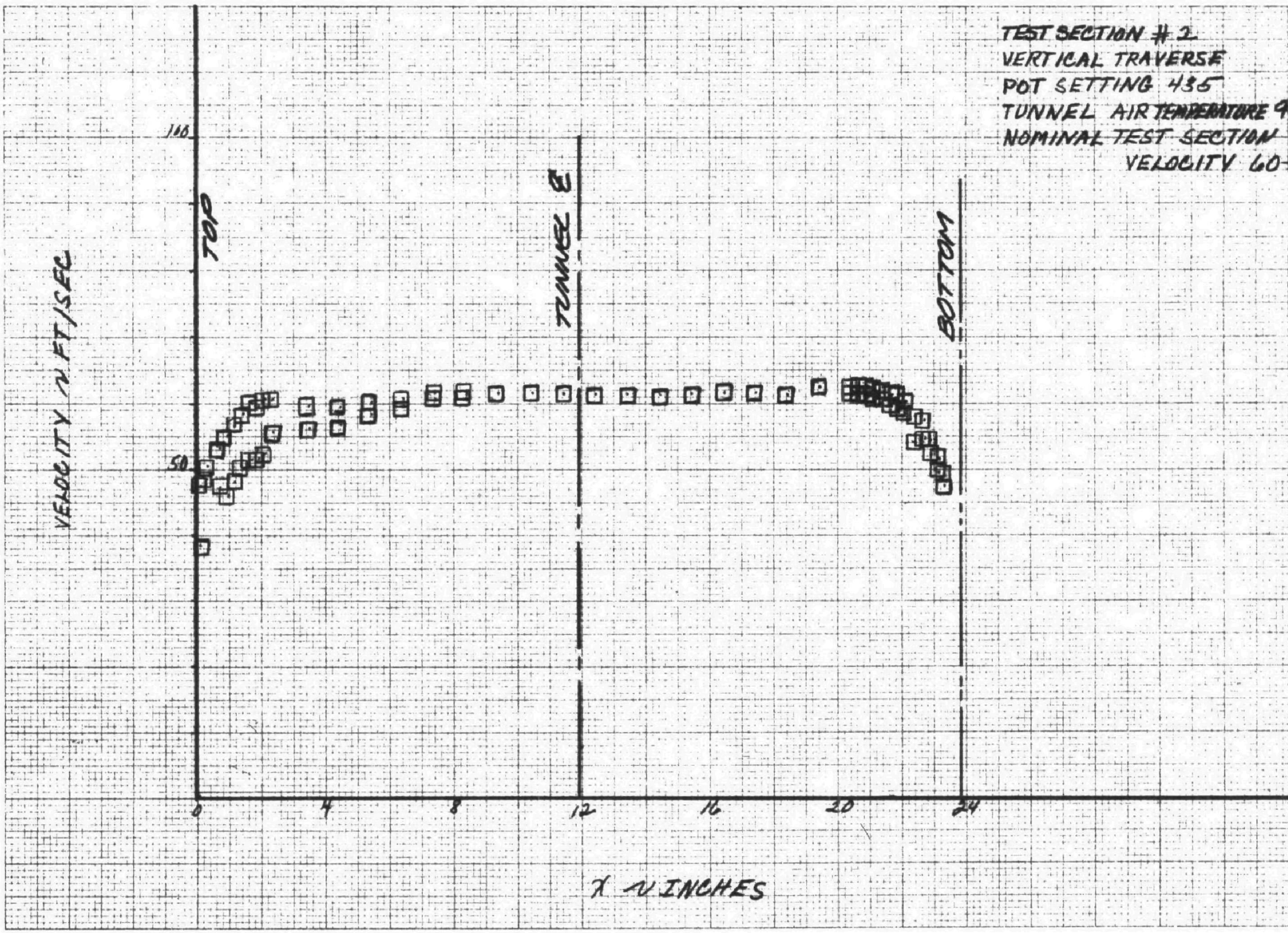


Figure 14. Velocity Distribution

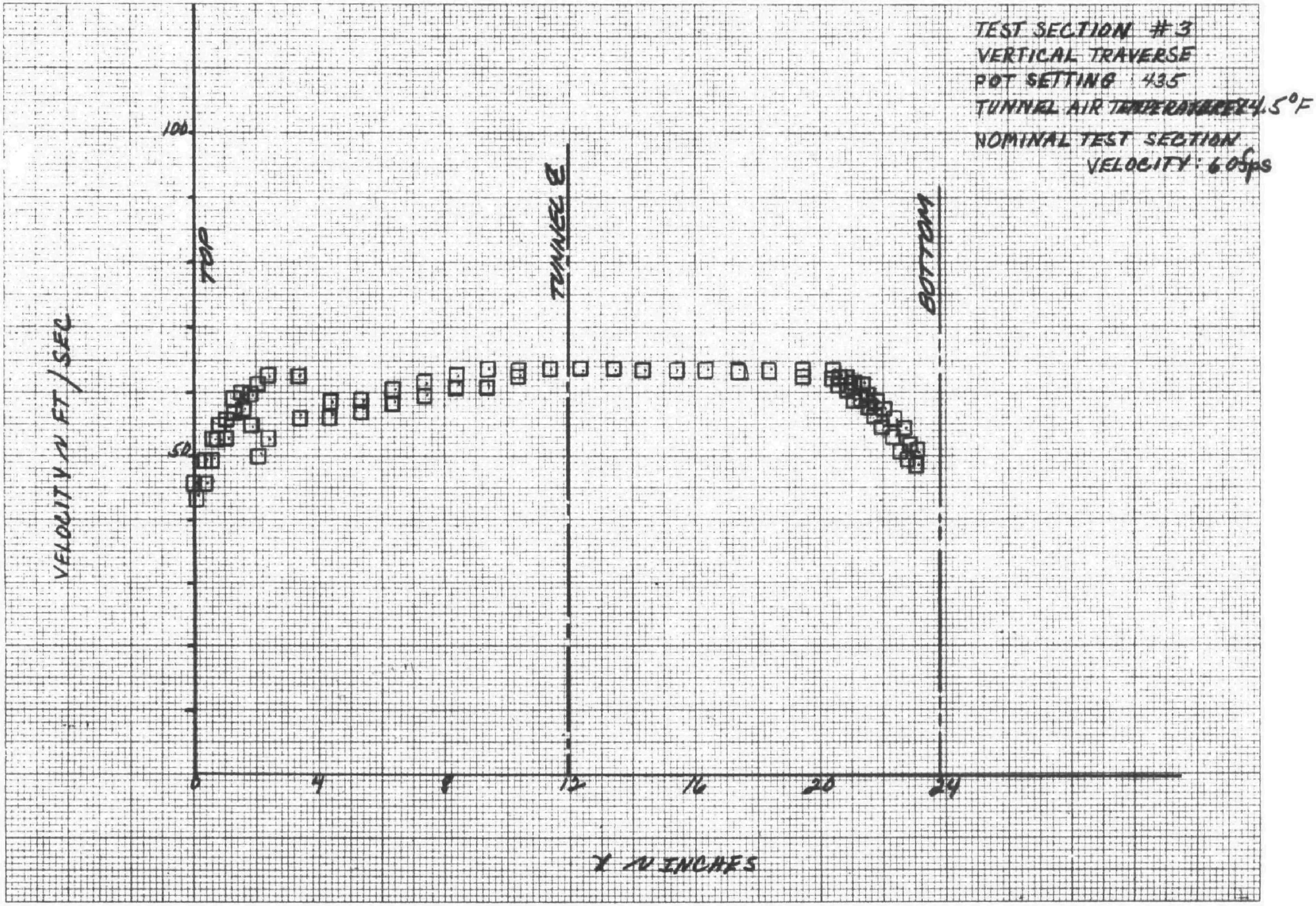
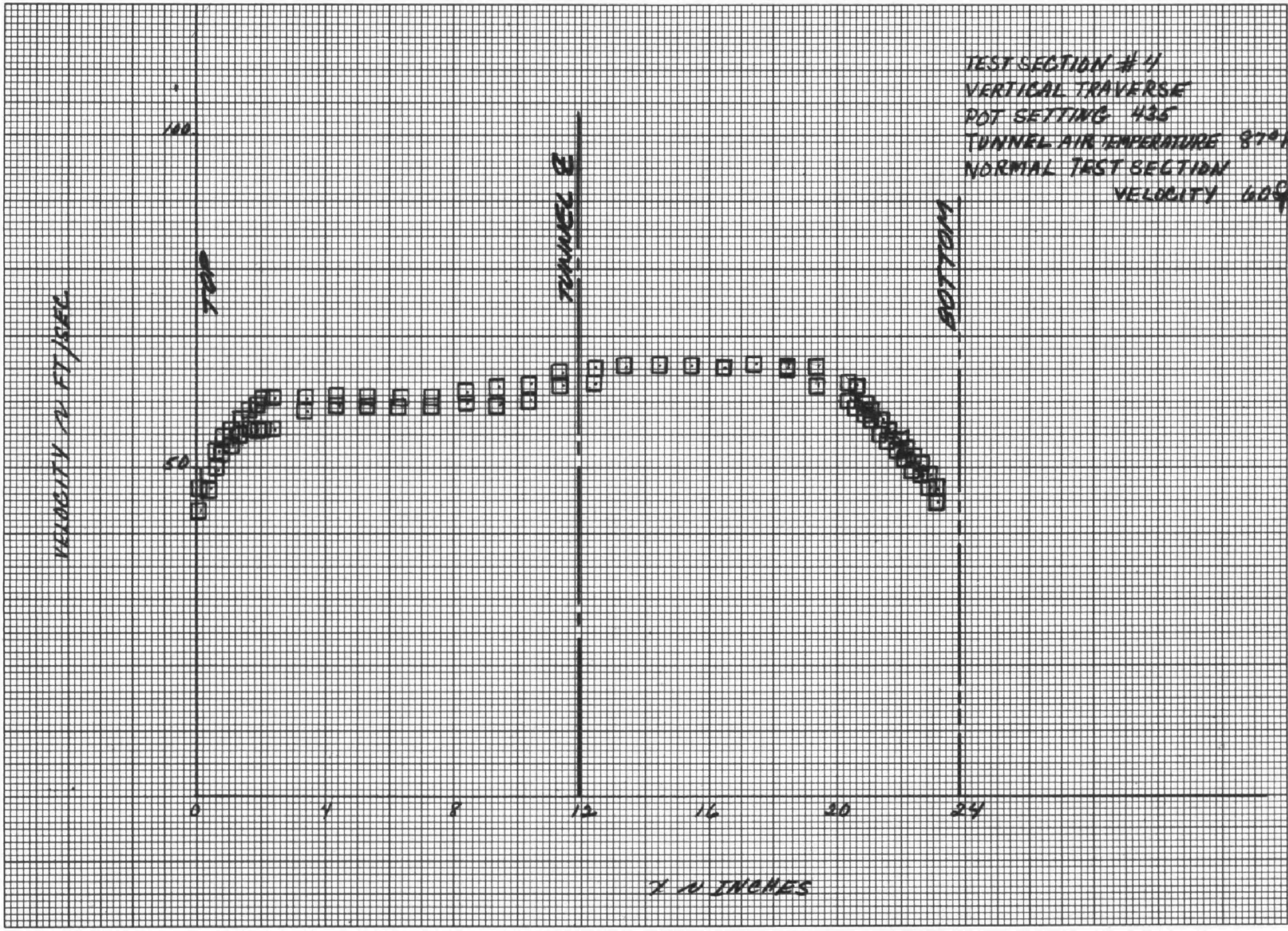


Figure 15. Velocity Distribution



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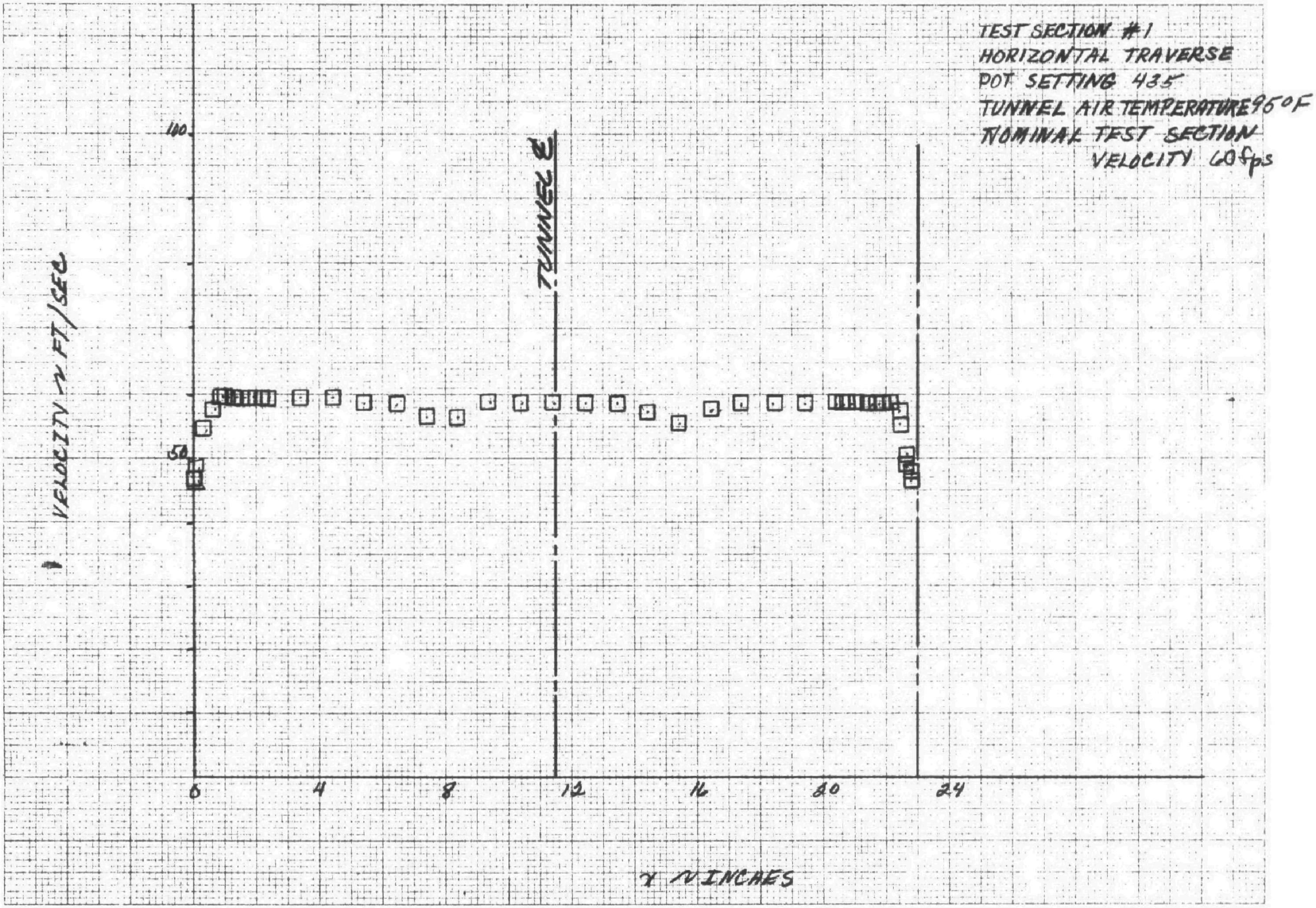


Figure 17. Velocity Distribution

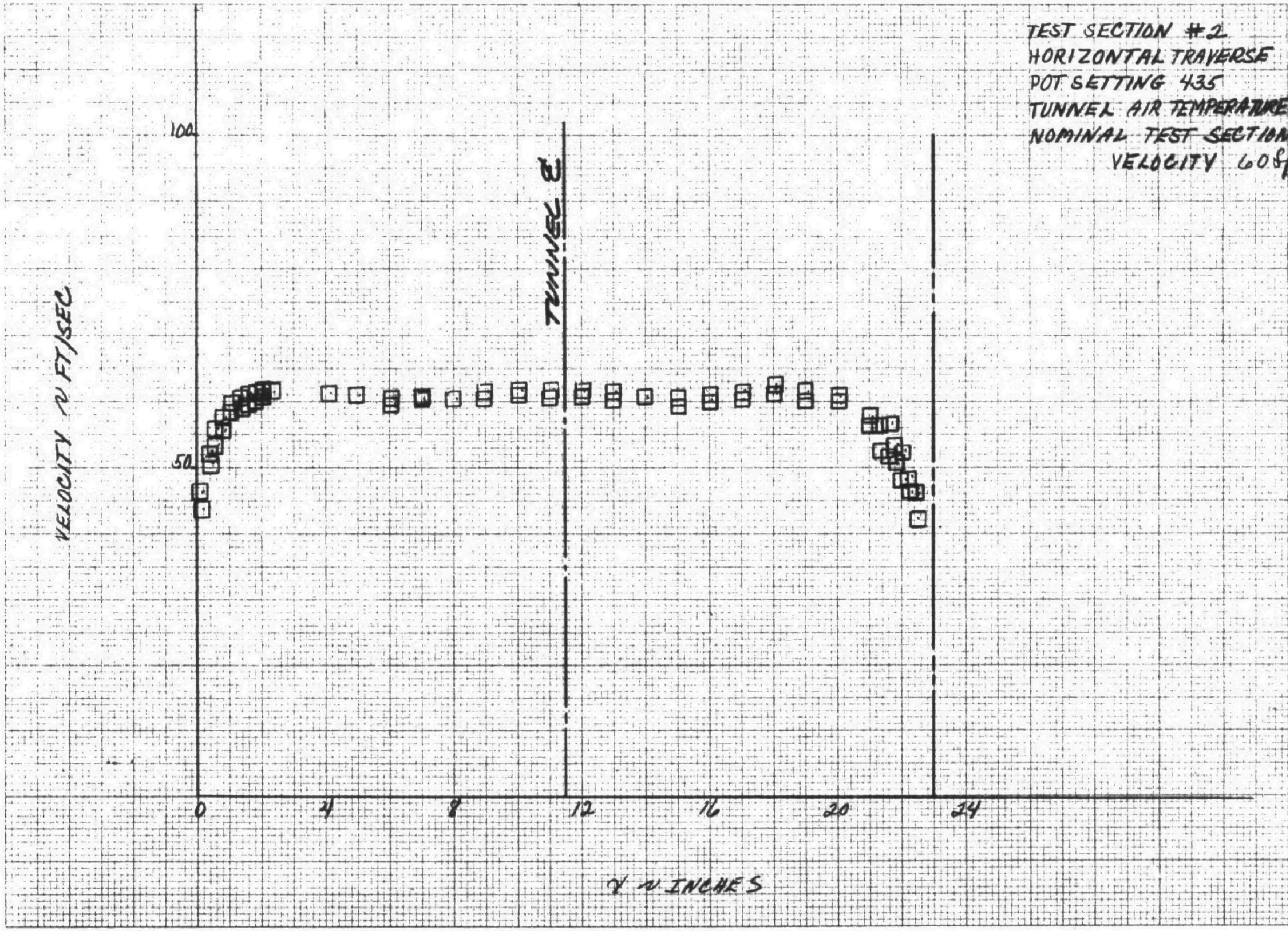
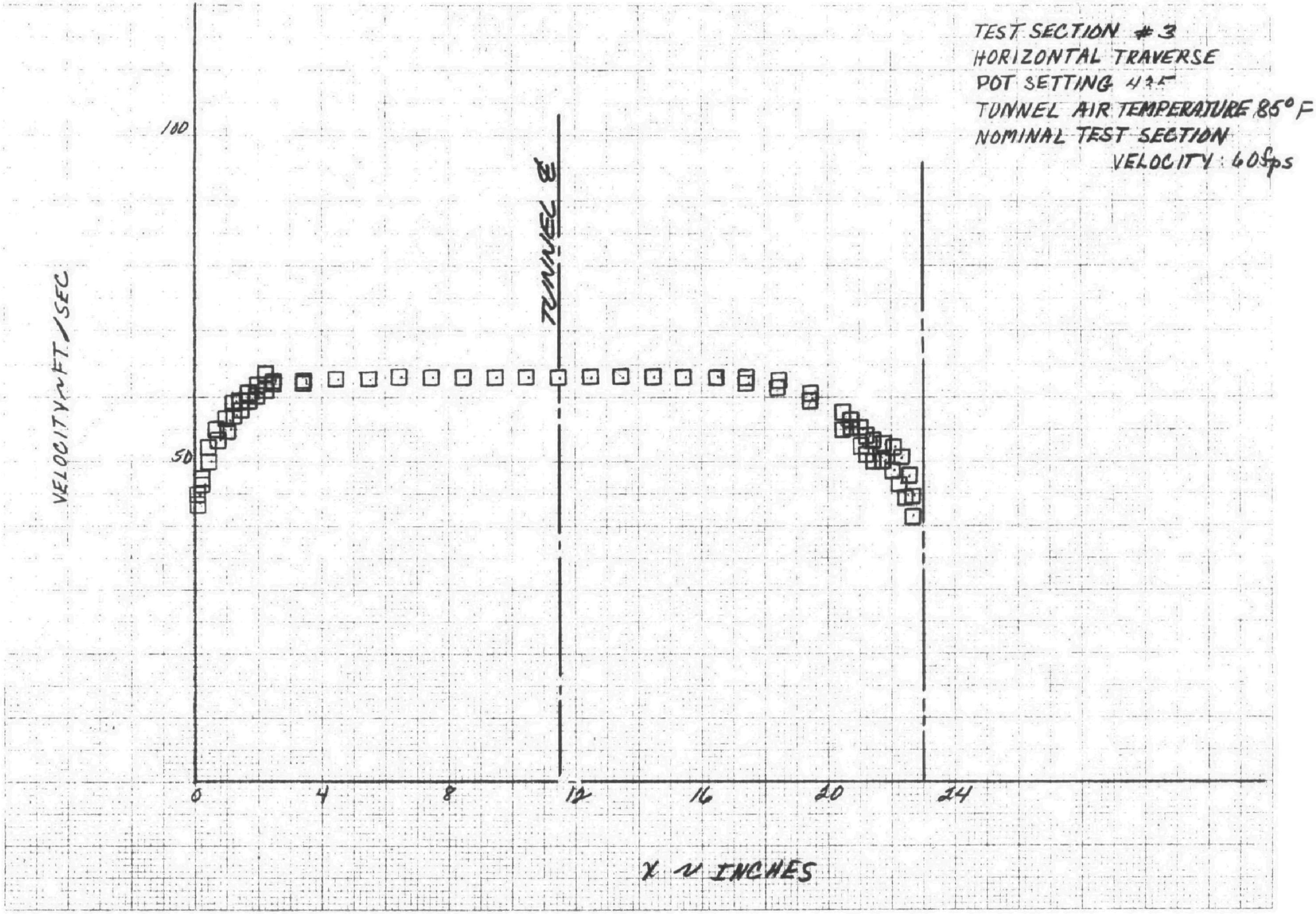


Figure 18. Velocity Distribution



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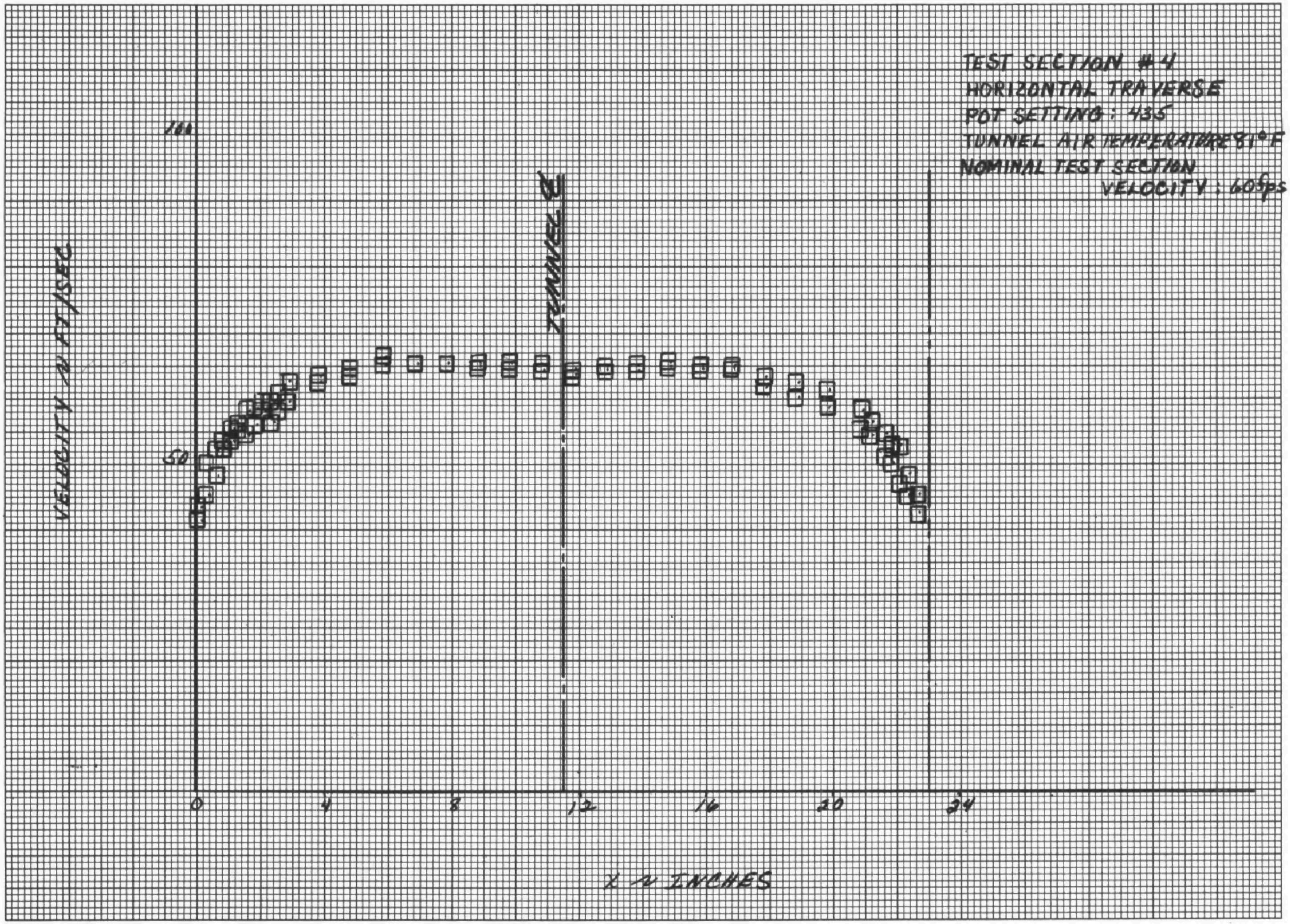

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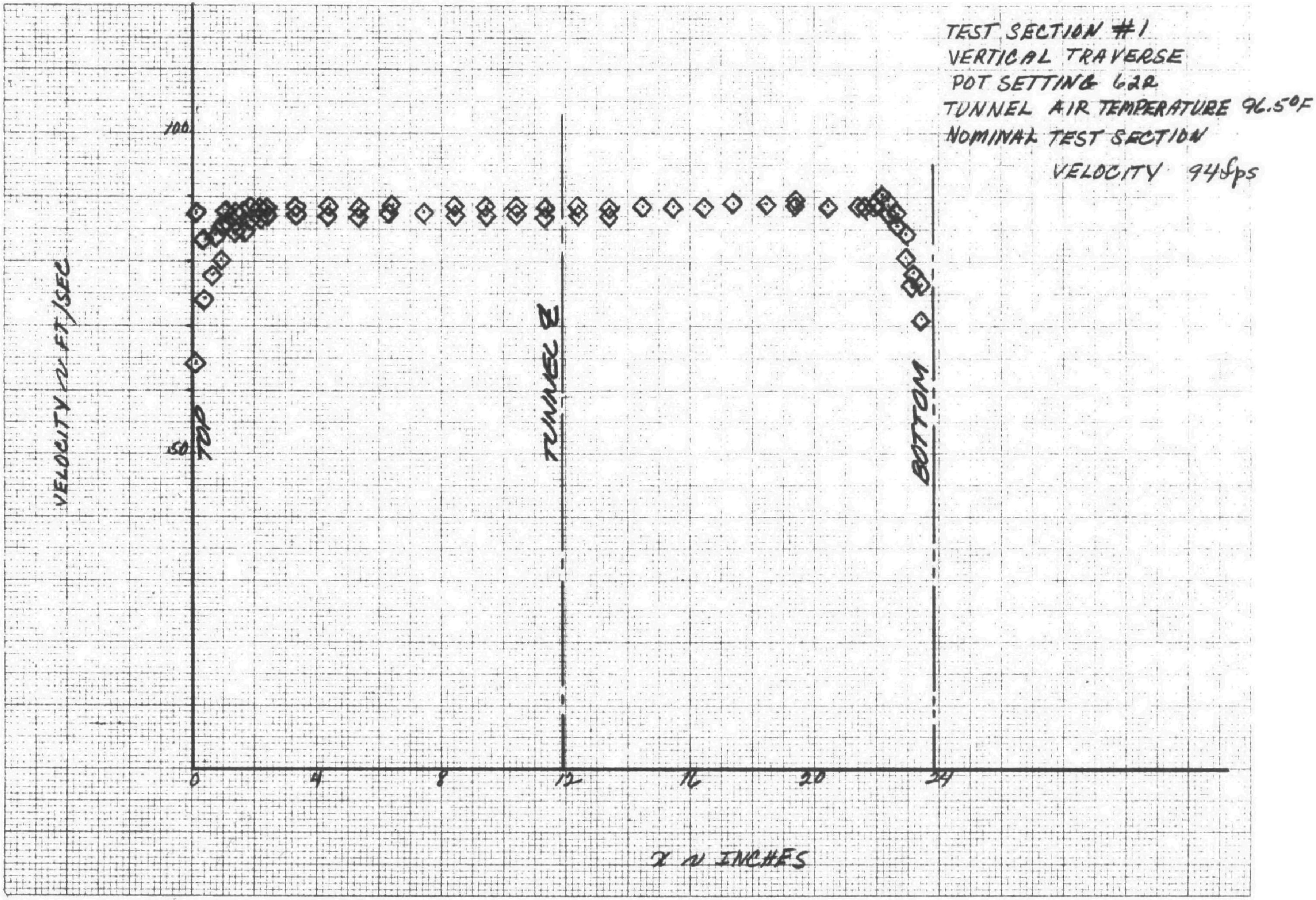

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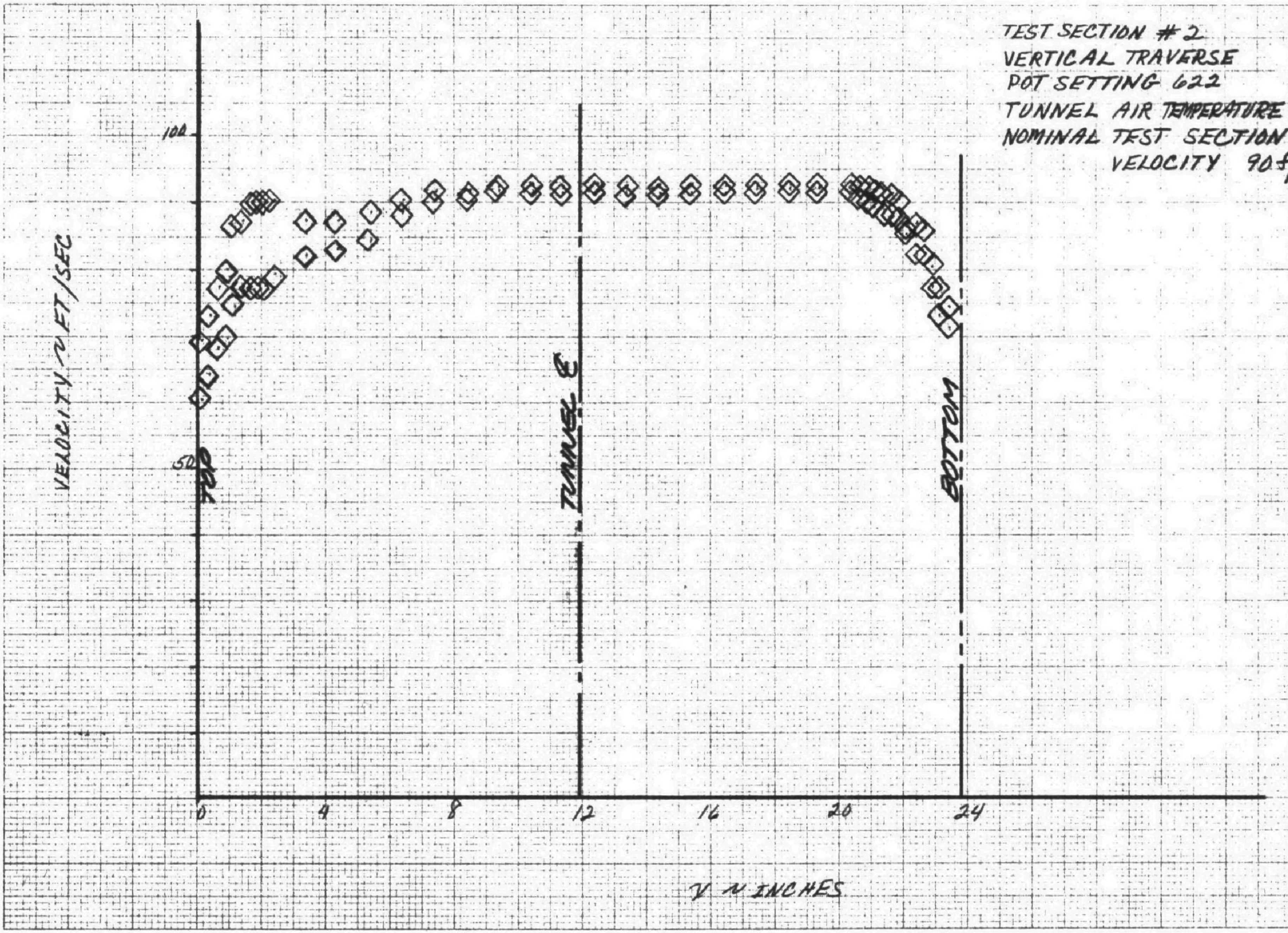

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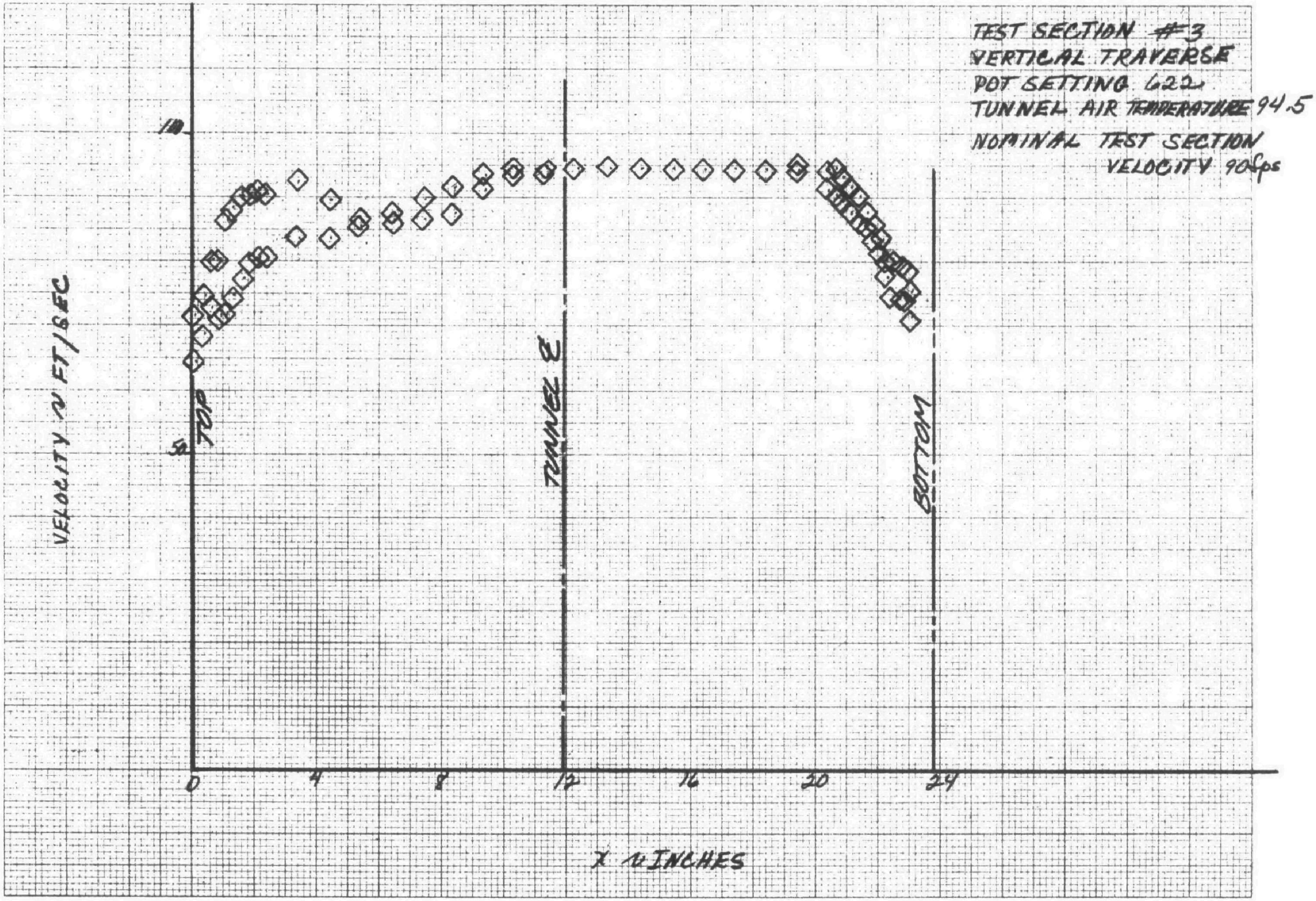

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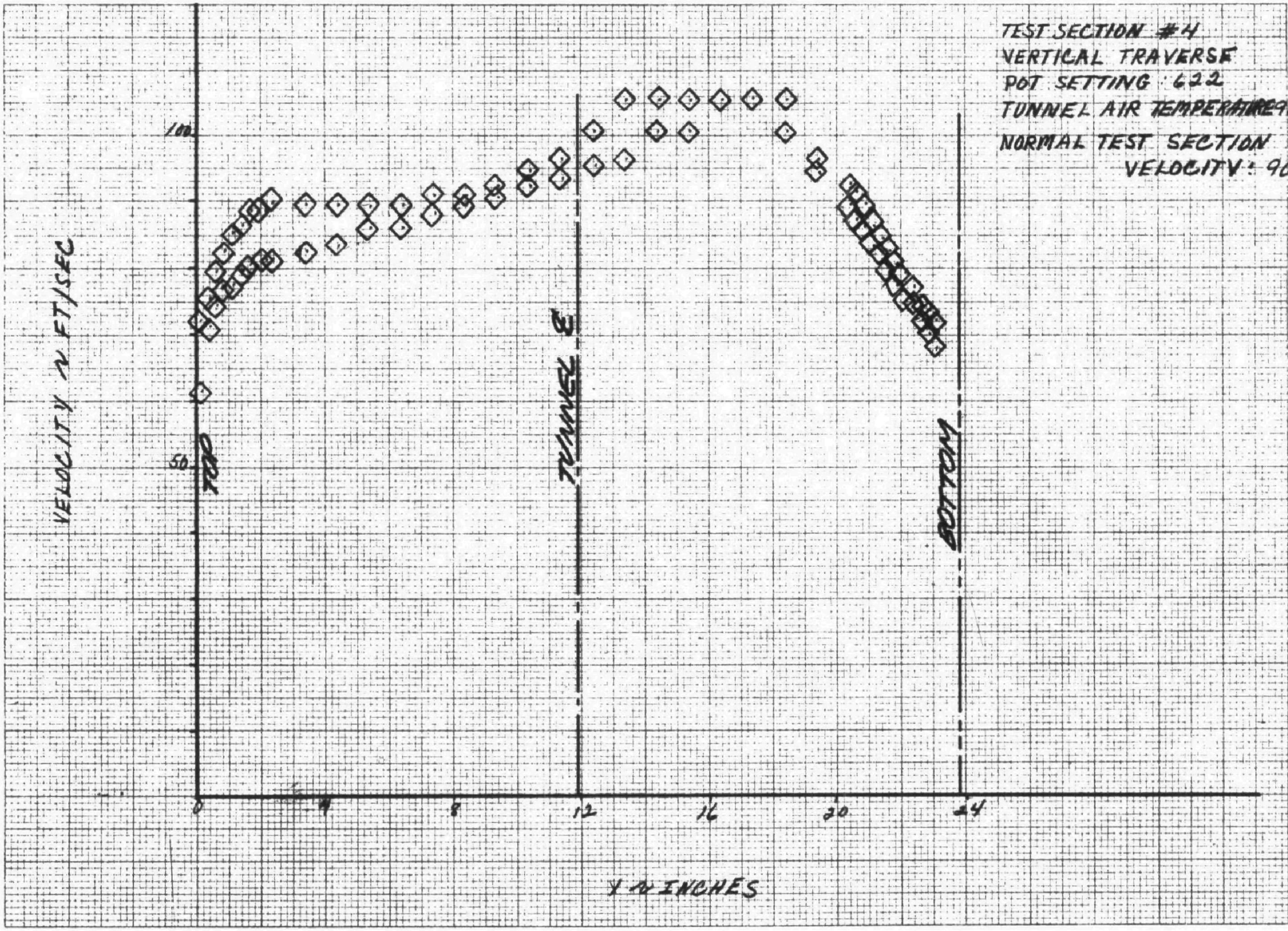

Figure 24. Velocity Distribution

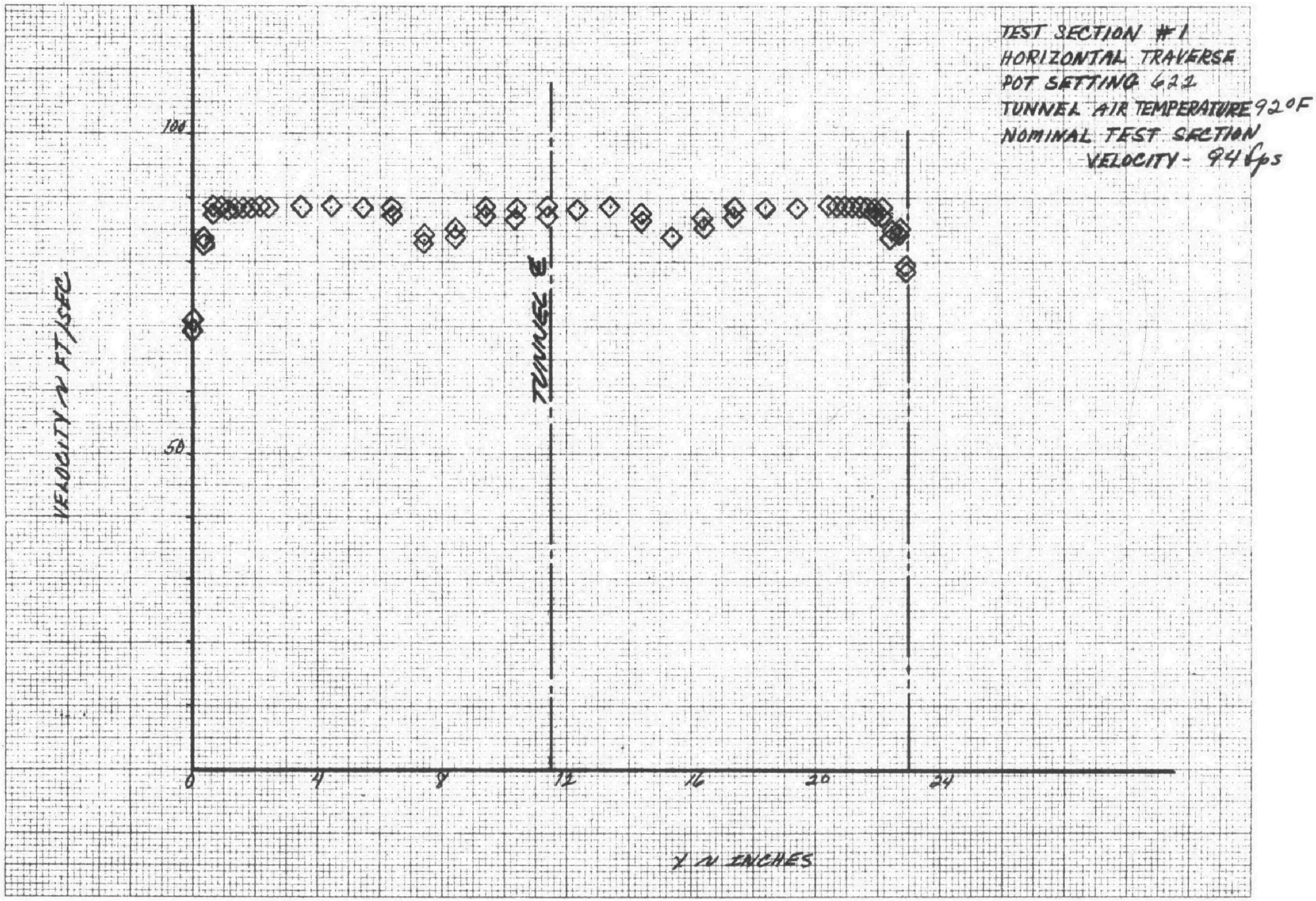

Figure 25. Velocity Distribution

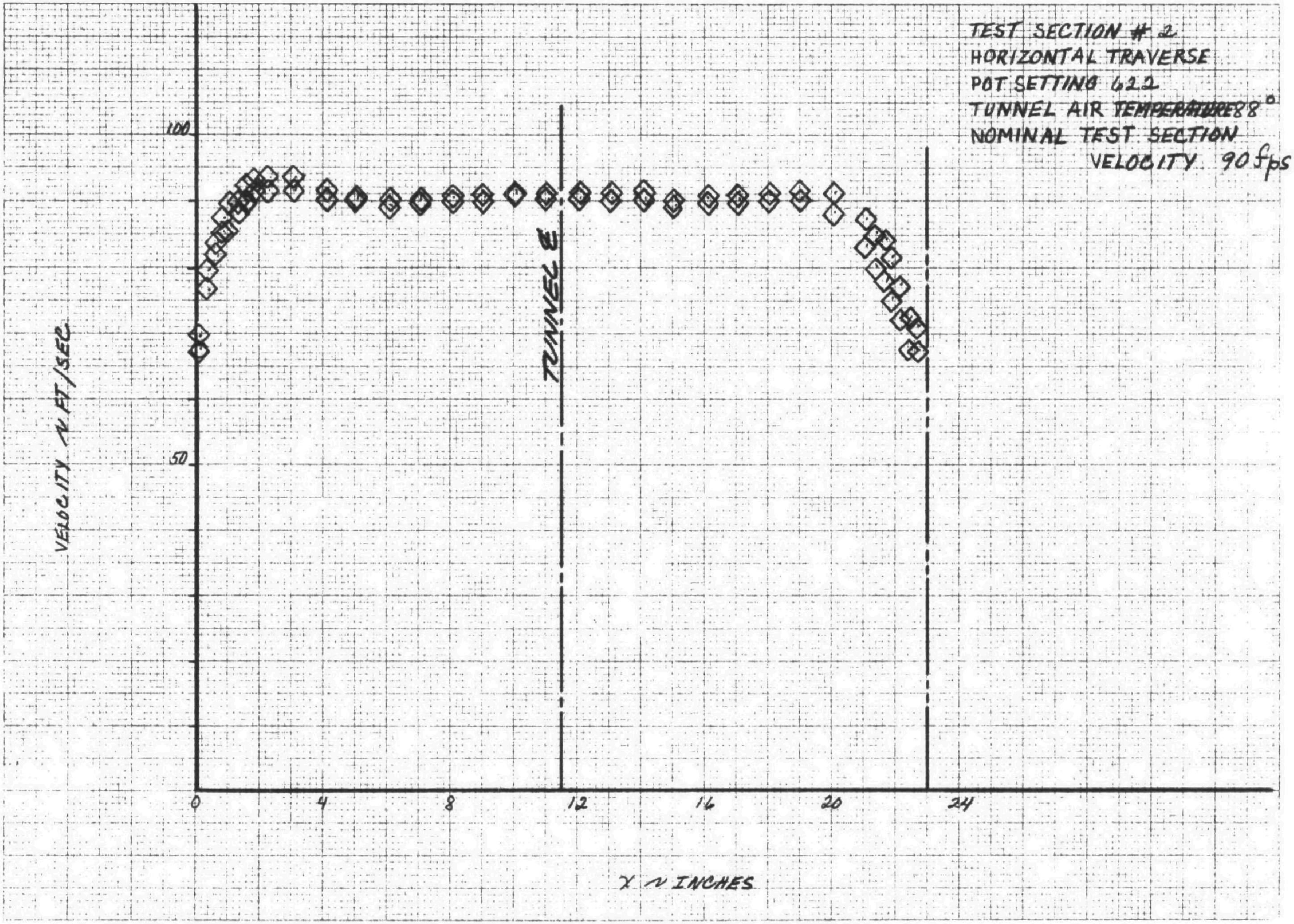

Figure 26. Velocity Distribution

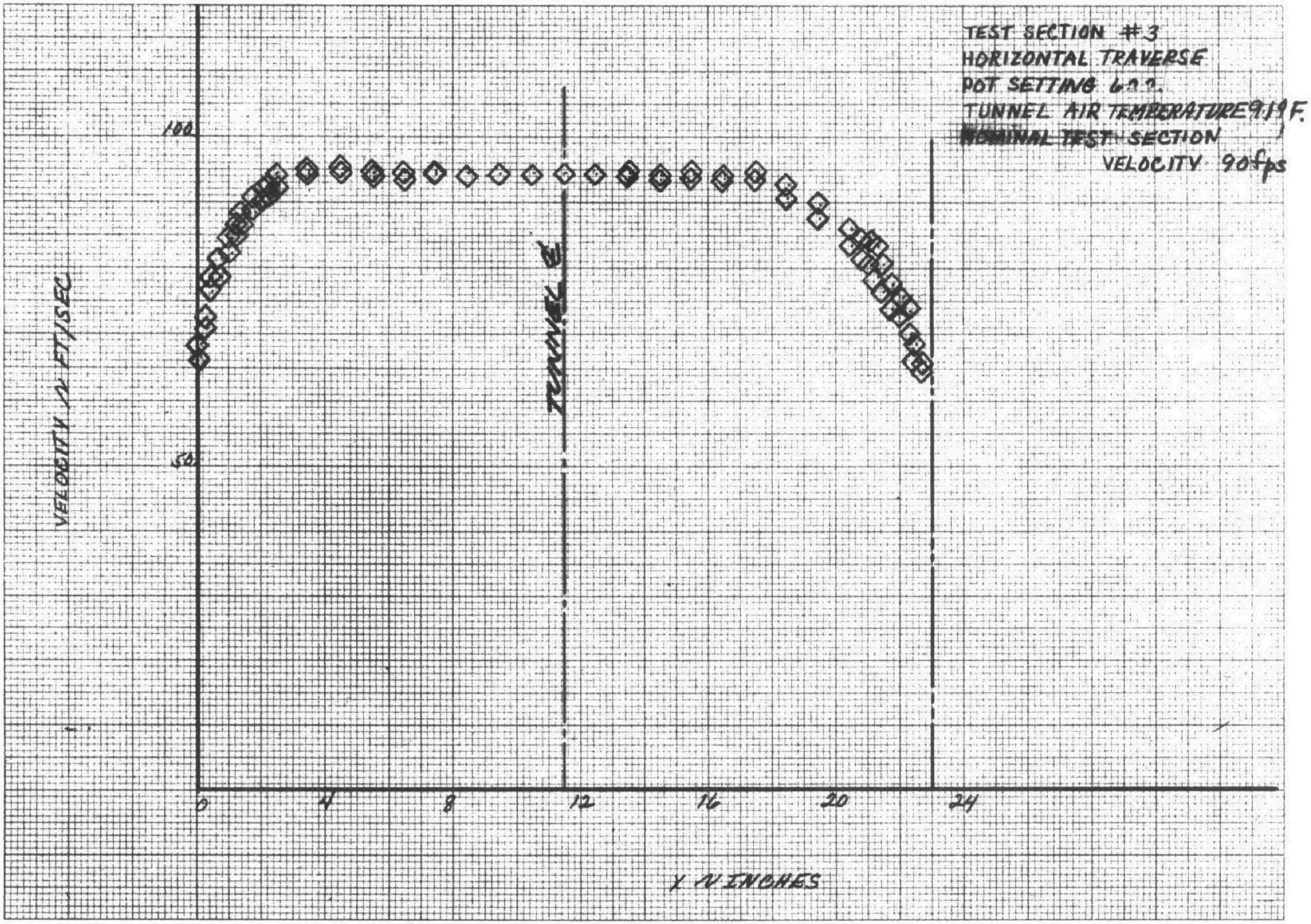

Figure 27. Velocity Distribution

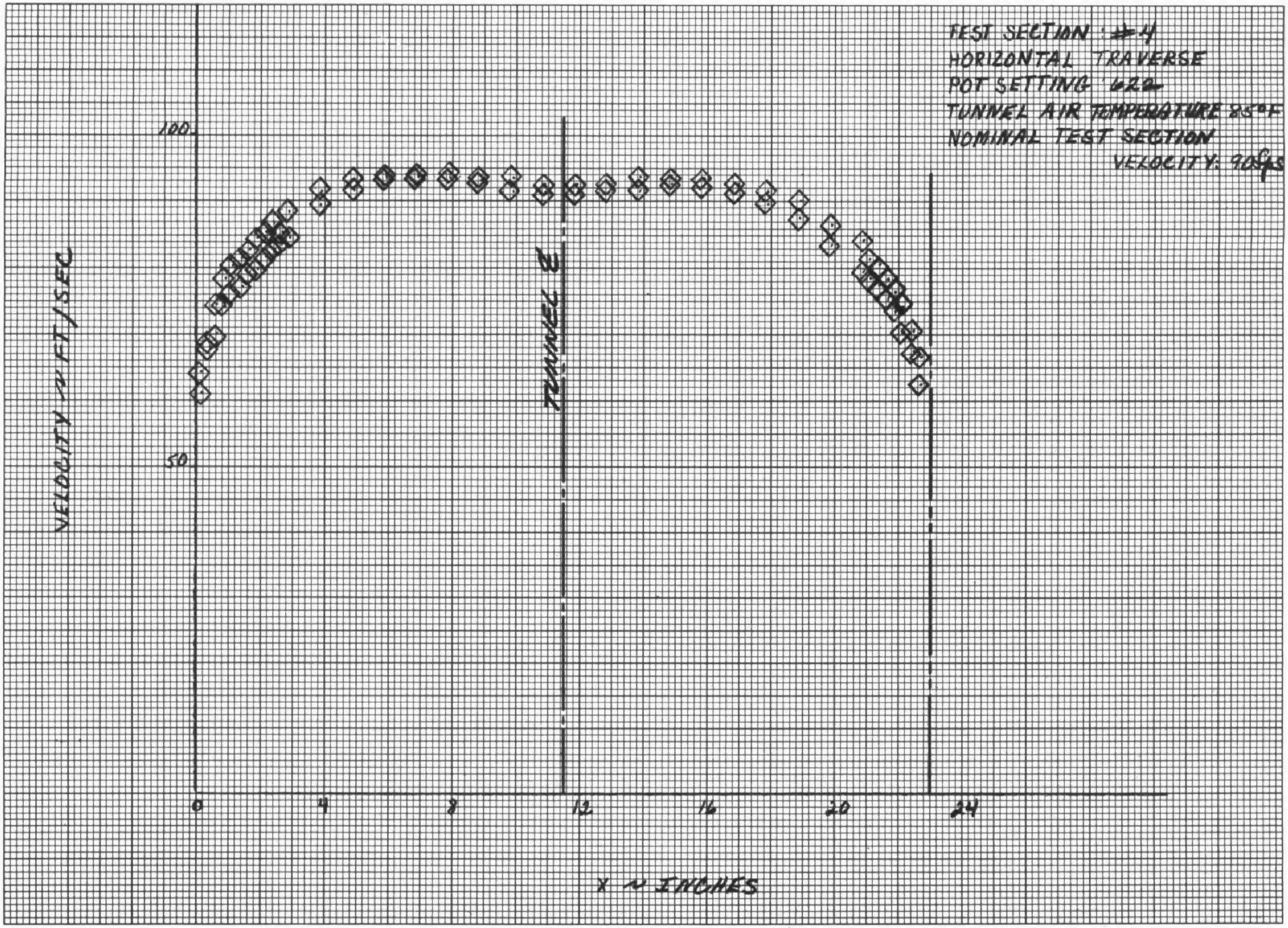

Figure 28. Velocity Distribution

skewed towards the bottom of the tunnel. Also, the upper portion of the tunnel, in addition to being of lower average velocity, seems, as indicated by the scatter in the max-min data points, to possess greater turbulence.

The exact reason for this behavior is unclear, but the most likely explanation (without benefit of further testing) is that it is related to the 180° turn at the end of the test section. The flow seems to be adjusting itself to go around the turn. The disturbance may be caused by a stall in the turn at higher velocities; it is well known that flow disturbances in subsonic flow can be propagated well upstream of the actual cause of the disturbance.

It was observed during testing that the presence of a 3 inch diameter probe in test section 3 partially alleviated the problem, probably due to the vorticity added to the flow by its presence. Consequently, in an attempt to artificially create this vorticity, some hastily made vortex generating tabs were inserted into the turn at the end of test section 4. This technique was not completely successful, but did indicate that the problem could be solved with further testing and minor equipment changes.

2.6 CONCLUSIONS

Basically, the velocity profiles of the Particulate Aerodynamic Test Facility show good quality flow and should provide the basis for many interesting experiments in the particulate flow research. Good quality flow is available in all but the last test section, and tests can be run in either uniform or shear flows.

The solution to the problem of poor flow quality in the last test section could be approached in a number of ways. The method that is most direct and has the greatest probability of success with minimum expenditure of time and money is to install one or more turning vanes in the turn. Other methods would include experimenting further with the installation of vortex generators or swirl generators in the turn to redirect the higher energy flow into the "stalled" regions. More elaborate methods might include boundary layer suction on the inside turn radius of the elbow.

SECTION 3

SUBTASKS 2 and 3: PARTICULATES TESTING AND ISOKINETIC SAMPLER COMPARISONS

3.1 OBJECTIVES

The objective of subtask 2 was to first document the concentration profiles that were being obtained with the aerosol generation system as it was initially installed*, and secondly, modify the system as required to obtain dust concentration profiles as uniform and repeatable as possible for use in reaching the objectives of subtask 3.

Subtask 3 has the primary objective of obtaining comparative test data between a commercially available low volume "Method 5" isokinetic stack sampler and a newly developed high volume isokinetic sampling train. The low volume unit was typical of most currently available mass sampling systems which sample at rates less than one CFM. The primary drawback of these low volume sampling rate devices is that, in regions of low particulate loading, they necessitate excessively long sampling periods in order to gather measurably significant quantities of pollutants and thus achieve acceptable accuracy. As a consequence of these long sampling cycles, short term operating conditions, which can vary widely during the sampling process, can be completely masked.

A secondary objective of subtask 3 was to demonstrate the utility of the recently completed Particulate Aerodynamic Test Facility in simulating repeatably, on a steady state basis, a condition or range of conditions typical of industry stack sampling environments.

3.2 THE APPROACH

The approach to accomplishing subtask 2 was to make horizontal traverses with the sampling probe of a direct-reading (IKOR) dust sampler at various test sections to determine the kind of profiles being obtained with a given aerosol generatory test set-up. The most important variable in

*An interim system, pending the design and installation of more sophistication and higher mass flow rate.

adjusting the dust profiles was, of course, the location of the injector lines themselves.

Objective 3 was achieved by injecting dust and simultaneously sampling a given axial location by the two sampling devices to be compared. Concentrations during the tests were monitored for constancy on a real time basis by the direct reading sampler located downstream. Figure 29 shows the basic test arrangement.

3.3 TEST APPARATUS

The test apparatus for subtasks 2 and 3 consisted of:

- Aerosol generation system
- Real-time concentration monitor:
  IKOR Model 206 Portable Air Quality Monitor
- Low volume sampler:
  Lear Siegler Model 31 Stack Sampler
- High volume sampler:
  Aerotherm High Volume Stack Sampler

The final configuration of the aerosol generation system is shown pictorally in Figure 30. The system consists of six major components:

- Pressurized storage/feed bin
- Modified Acrison Model 120-D screw feeder
- Aerosolization chamber
- Transport line
- Distributor
- Injection tubes

The aerosolization chamber may be roughly characterized as a fluidized bed, but it should be pointed out that high quality fluidization is not generally attained due to the agglomerated condition of the dust and the relatively high superficial air velocities through the chamber. The incoming dust, the bulk of which is highly agglomerated and too heavy to be entrained in the air flow through the chamber directly, drops down to a churning bed of dust where it is broken up and de-agglomerated to the point where it may be carried away to the tunnel. Further dispersion is accomplished by impact and shear forces as the dust is transported at high velocity to the tunnel.

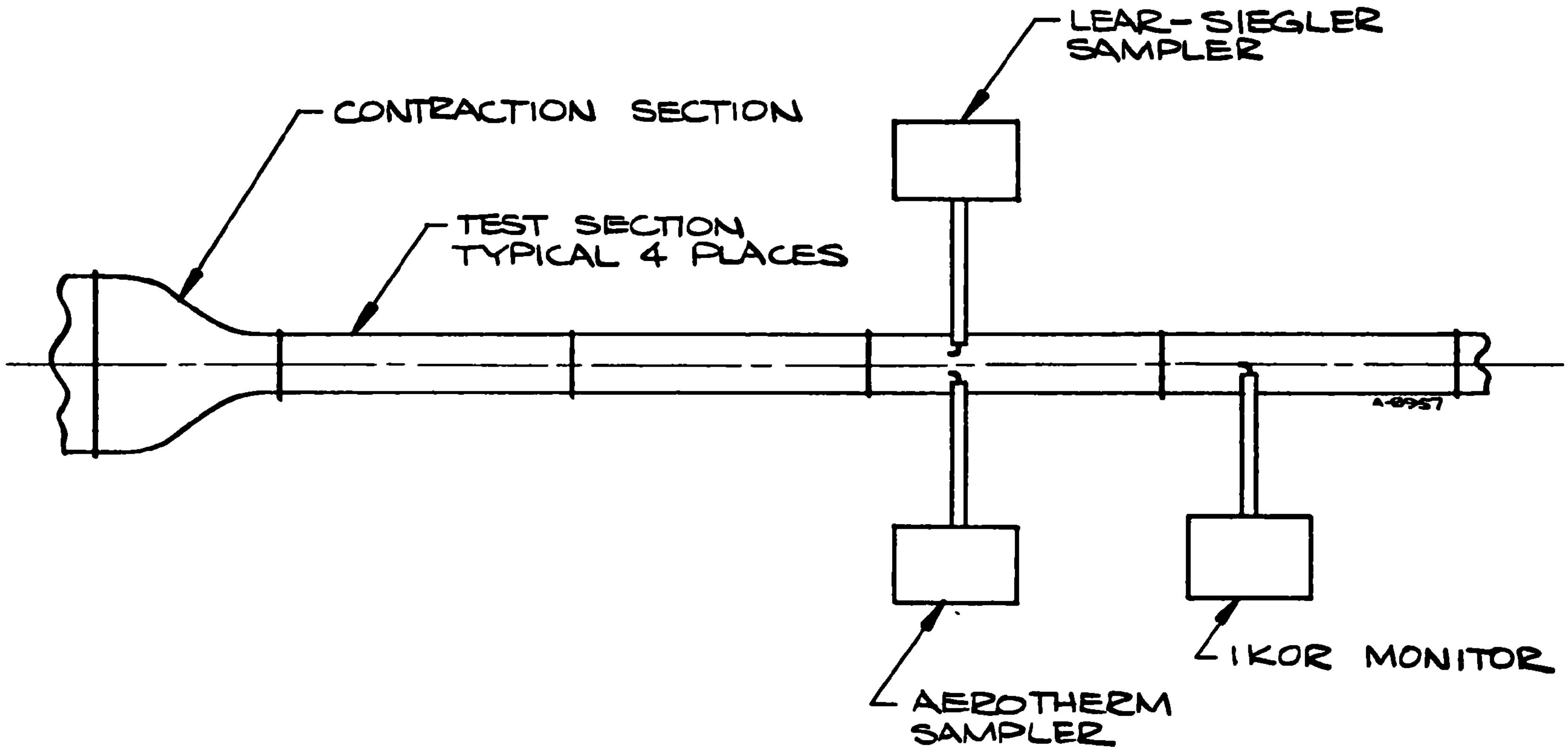

Figure 29. Basic Task 3 Test Arrangement

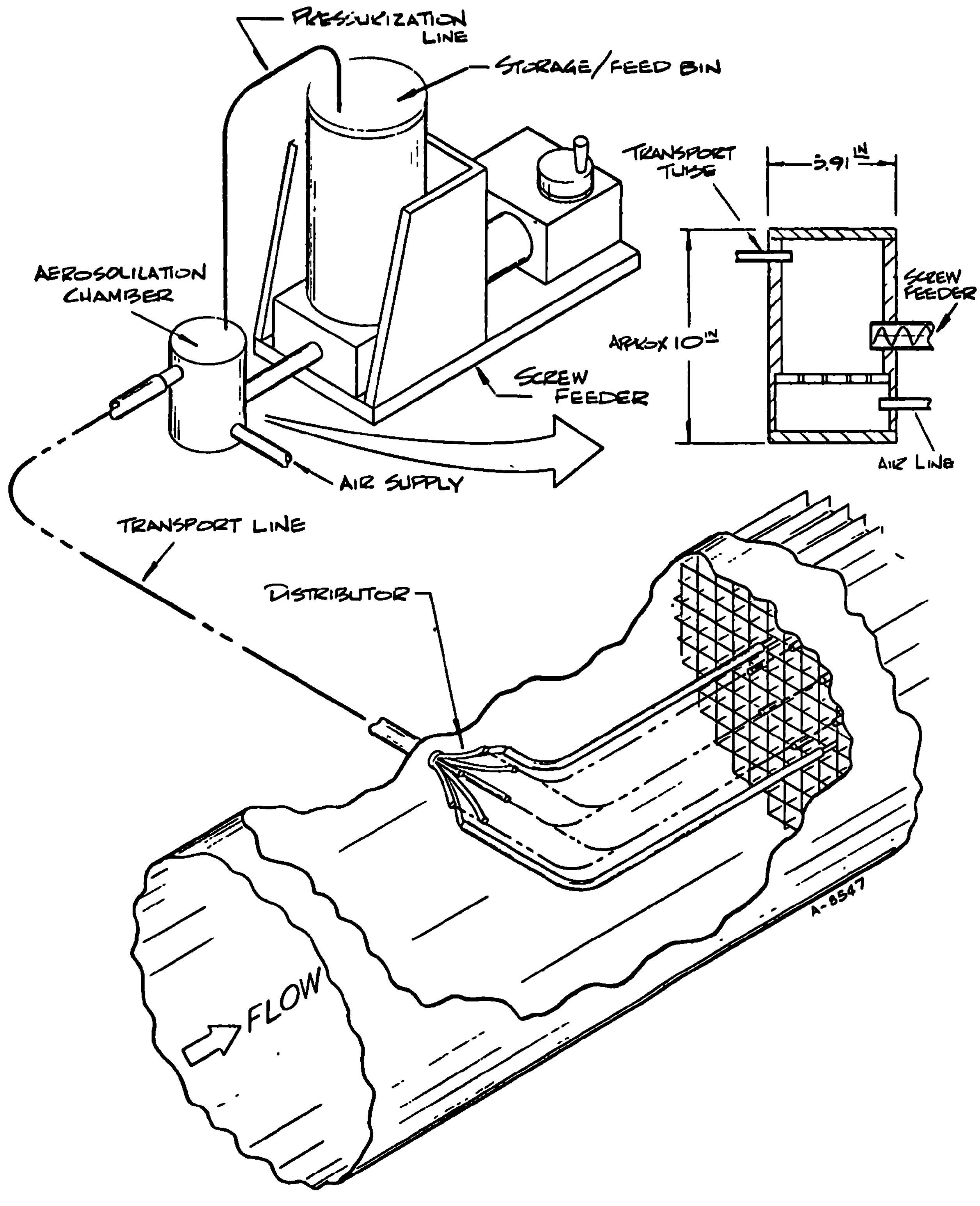

FIGURE 30. AEROSOL GENERATION SYSTEM

Actual redispersion and de-agglomerization efficiency was not of importance in these subtasks, and consequently was not determined quanitatively. Qualitatively (by visual observation) however, the de-agglomeration appeared to be excellent.

Feed rate control was achieved with an Acrison screw feeder modified by installation of a cylindrical bin which is pressurized at the same pressure as in the aerosolization chamber. Pressurization was necessary because the screw feeder was not designed to feed against pressure.

The transport line was 3/4 inch vinyl tubing. The distributor split the aerosol flow from the transport line into eight individual injection lines which were routed through the stilling chamber straightening vanes to appropriate injection points.

The real time concentration monitor was an IKOR Model 206 Portable Air Quality Monitor. A sample is continuously drawn through an electronic sensing head where the particulates generate an electric current by charge transfer. This feature, combined with a strip recorder output, allowed continous real-time monitoring of any point of interest and relatively rapid traverses of the tunnel duct to be made to obtain concentration profiles. The features and dimensions of the unit are given in Table 1.

TABLE 1

MODEL 206 PORTABLE AIR QUALITY MONITOR
IKOR INCORPORATED
BURLINGTON, MASSACHUSETTS

1. Weight and Dimensions

a. Stack Unit	18 x 11 x 17	25 lbs
b. Control Unit	26 x 11 x 20	28 lbs
c. Stack Probe	5 ft length	13 lbs

2. Particulate Emission Mass Flow Range, 0.001 - 100 Grains/SCF
3. Particulate Size Detection, 0.1 - 100 microns
4. Stack Temperature Range, 30°F - 2000°F
5. Ambient Operating Temperature Range, -20°F - +160°F

The two manual samplers to be compared were basically equivalent sampler units (except for sampling rate and certain commercial features) based on EPA Method 5 particulate sampling technique. The low volume sampler was a Lear Siegler Model 31 Manual Stack Sampler, and the high volume was an Aerotherm HVSS Stack Sampler.

3.4 TEST PROGRAM AND RESULTS

The test program consisted of setting up the tunnel flow environment to simulate conditions typical of stack environments. The parameters selected were:

- Air as the gas stream
- Temperature: 300°F
- Velocity: 60 fps
- Dust concentration: approximately 0.5 grains/cu.ft.

Profiles were taken horizontally with the IKOR sampler at various stations. The data was automatically recorded on a strip chart recorder in real time. The data presented in this report is replotted from these strip chart records for clarity.

The initial injection line arrangement was as shown in Figure 31. The eight injection lines were equidistant from one another on a circle of approximately 40 inches diameter. The plane of injection was approximately 4 feet forward of the wind tunnel straightening vanes - essentially at the entrance of the contraction. These positions correspond to those originally designed into the tunnel.

Typical profiles obtained by this arrangement are shown in Figure 32 which shows max-min data from traverses at test sections 2 and 4. The data shows a fairly high degree of scatter and extremely nonuniforn profile (definite injector "spikes") at station 2; by test section 4, however, enough mixing has occurred that the profile is more uniform bell shape, as would be expected, and with less data scatter between max-min points.

The effect of velocity was explored in this same configuration; the results are shown in Figure 33, which presents the data from traverses at test section 4 at three different velocities. It demonstrates that at the higher velocities, the dust tends to migrate more toward the center to cause a steeper concentration gradient across the duct. This is probably attributable to the imbalance of aerodynamic forces acting on the particles in a nonuniform velocity field; in other words "lift" towards the center of the duct is being generating on the particles.

To obtain more uniform profiles across the duct for the entire length of the tunnel test section, the injection line arrangement was modified to that shown in Figure 34. This was necessary to provide a more reliable basis for the comparison tests of subtask 3. The plane of injection in this case

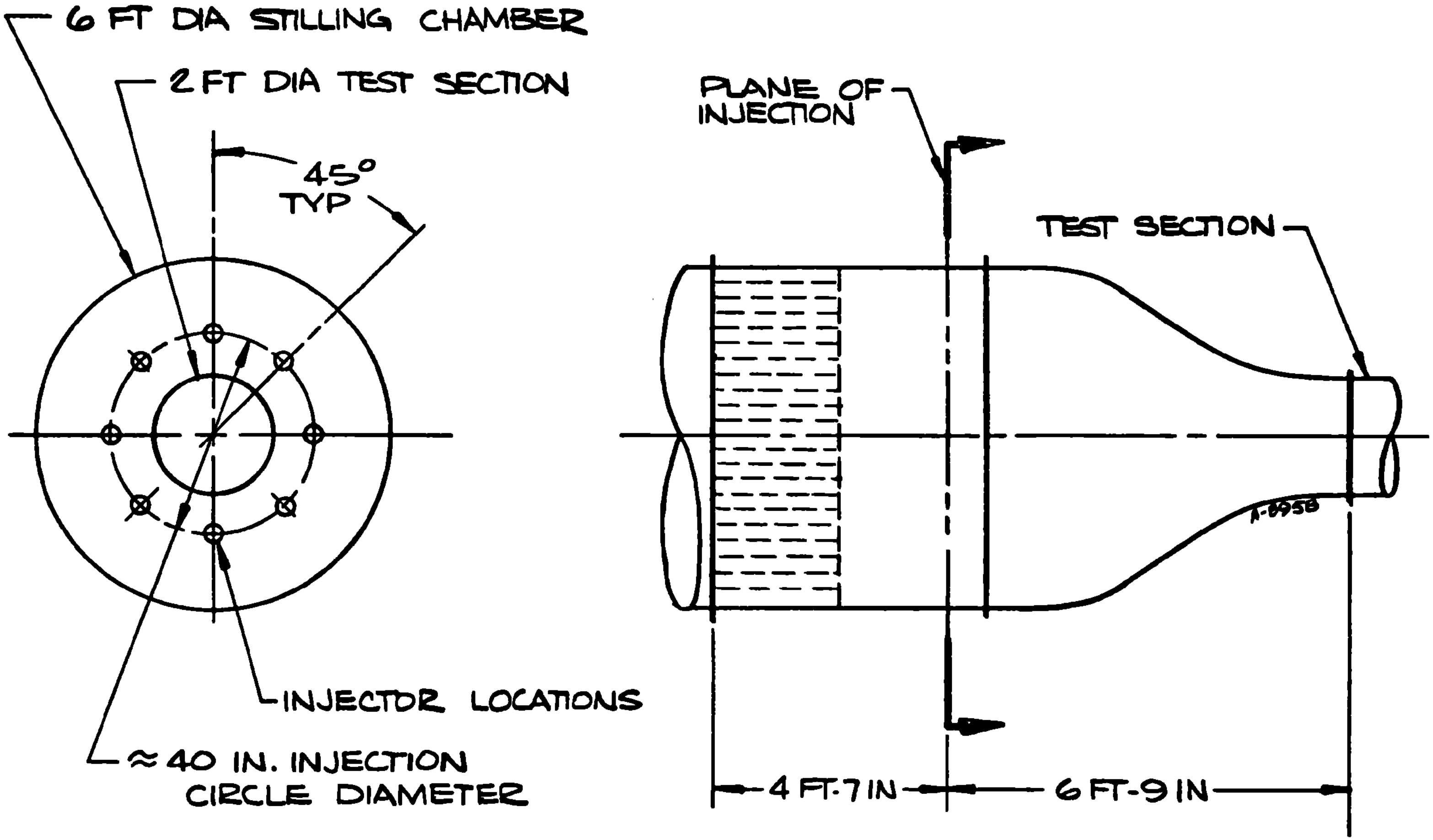

Figure 31. Initial Injection Line Arrangement

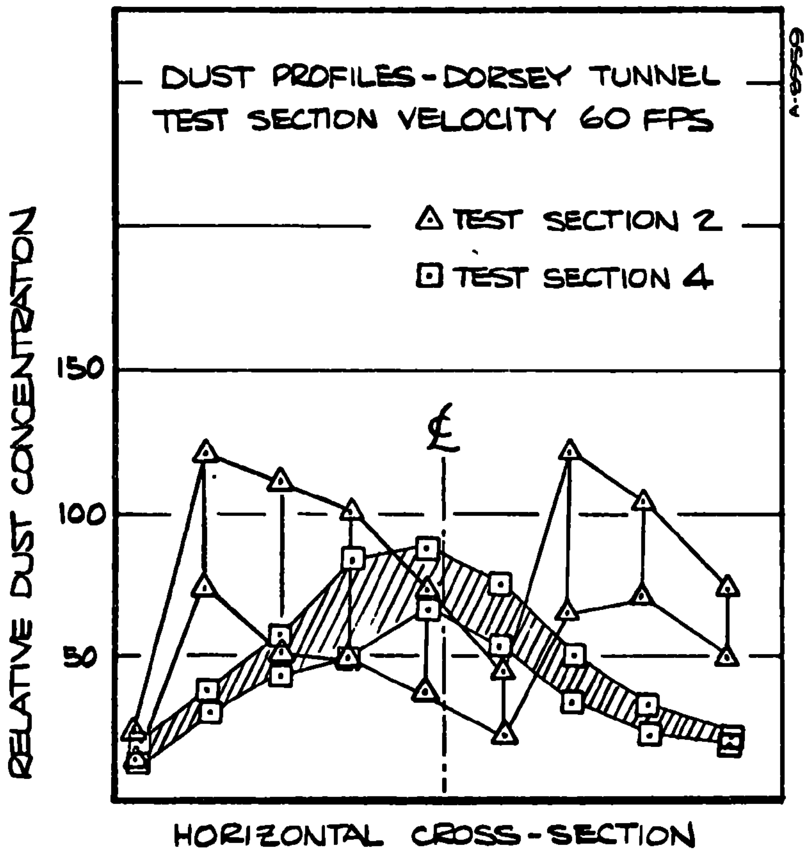
DUST PROFILES - DORSEY TUNNEL
TEST SECTION VELOCITY 60 FPS
TEST SECTION 2
TEST SECTION 4
RELATIVE DUST CONCENTRATION
150
100
50
HORIZONTAL CROSS-SECTION

Figure 32.

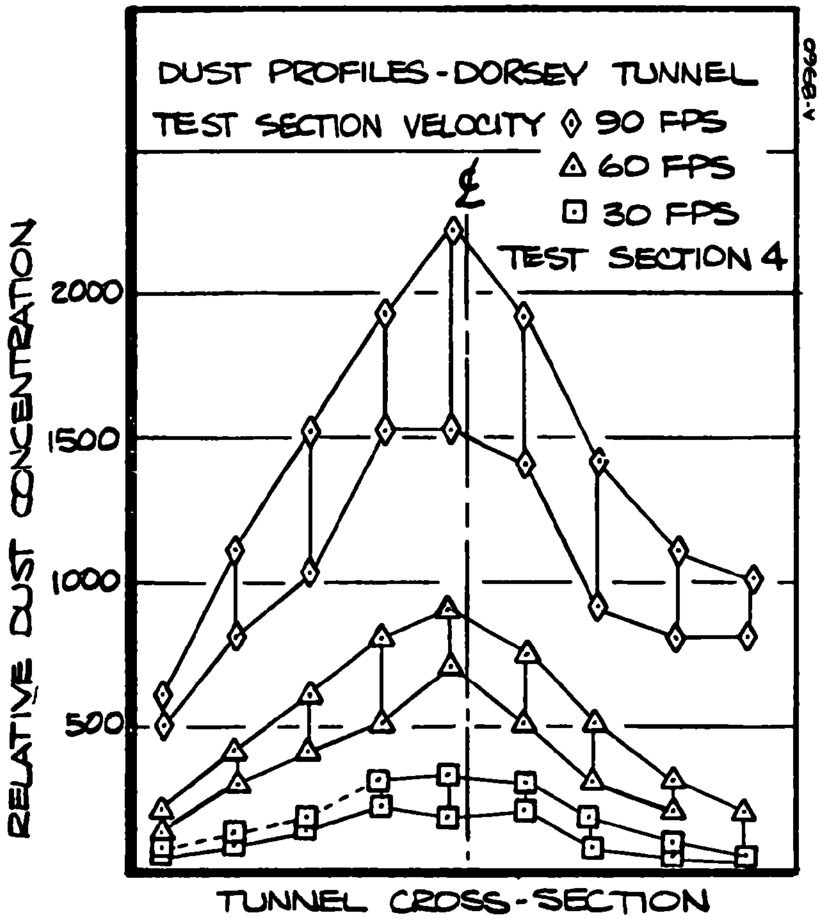
DUST PROFILES - DORSEY TUNNEL
TEST SECTION VELOCITY ◊ 90 FPS
△ 60 FPS
□ 30 FPS
TEST SECTION 4
A-8960
RELATIVE DUST CONCENTRATION
2000
1500
1000
500
TUNNEL CROSS-SECTION

Figure 33.

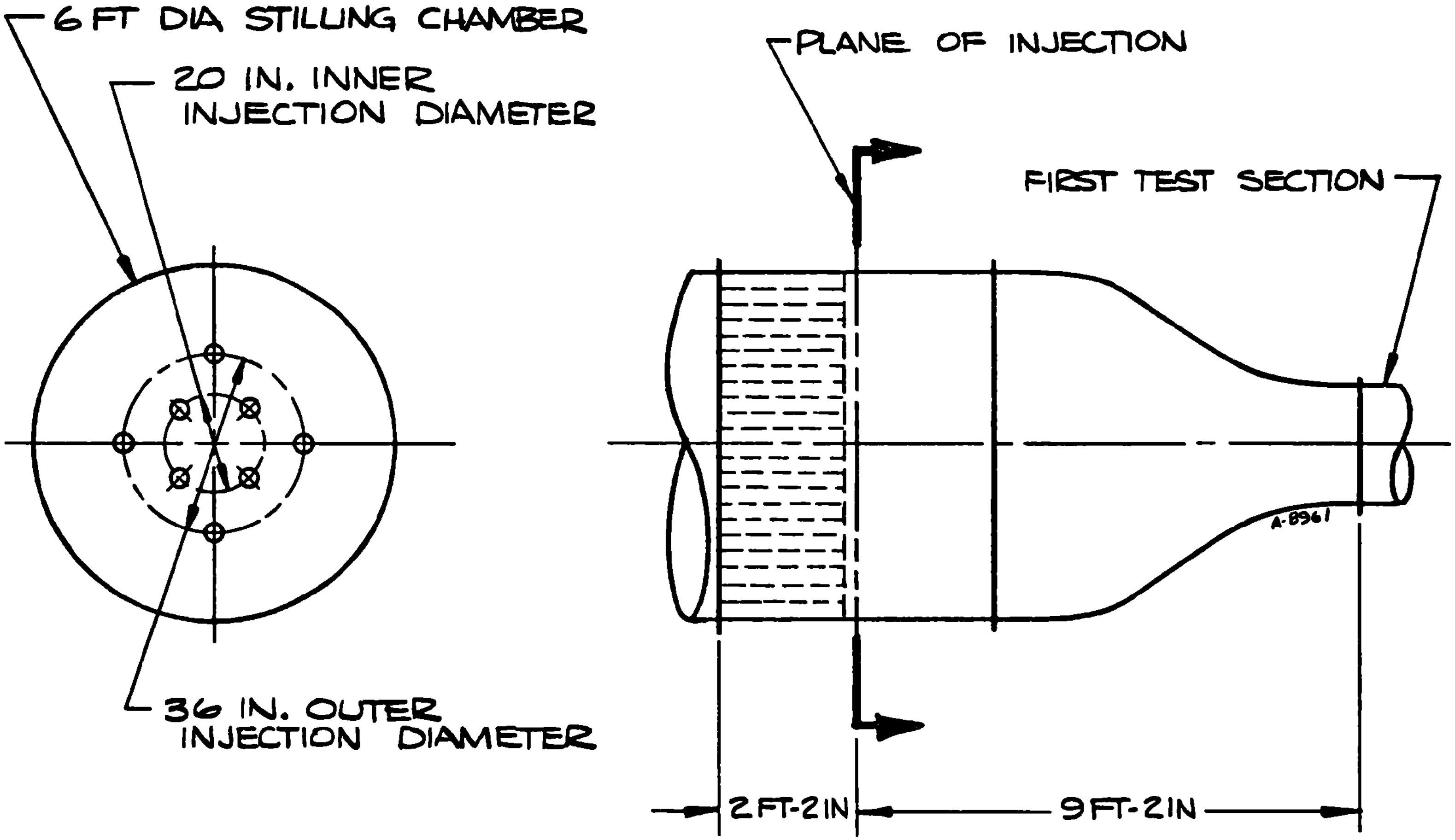

Figure 34. Final Injection Line Arrangement

was 2 inches forward of the straightening vanes. Figure 35 shows the profile that resulted from this arrangement after final tuning of the injection lines to achieve near equal distribution of the dust between them. The profile is relatively flat and exhibited only a ±10 percent concentration variation; time-averaged over a few minutes these fuctuations were of negligible importance.

The two samplers were placed in test section 2 from opposing sides at approximately equal concentration points. Test durations of 4 hours for the low volume sampler and 1 hour for the high volume sampler were selected for the data comparisons. Even with this 1 to 4 time ratio, the total sample volume ratio was 2 to 1 in favor of the high volume sampler because of its 8 to 1 sampling rate ratio over the low volume sampler. This meant that allowing for wind tunnel and aerosol generater set-up time each day, it was possible to obtain only one sampler per day with the low volume sampler and as many as 3 5o 5 per day with the high volume sampler. In addition sample twice the volume of particulate-laden flow in any given test.

Table 2 presents the data of three days of testing. The concentrations measured by both samplers are in close agreement in each case; averages over the three days are exactly the same. Because of its capability for higher sampling rate, however, the high volume sampler was able to detect slight variations in concentration that could not have been detected by the low volume sampler.

Another test result of interest is that a negligible amount of particulates settled in the probe of the high volume sampler. The high velocity in the probe assures that nearly all the sample is carried into the cyclone or filter; accuracy is enhanced.

3.5 CONCLUSIONS

The present aerosol generation system can deliver a range of dust concentrations with a variety of profiles, depending on placement of injection lines. The system exhibits good de-agglomeration efficiency and provides reasonably long term operation with constancy of output. At present, however, the system is capable of only a few hours operation without shut-down to replenish the bin (1 cu.ft.). This capability is soon to be extended under another program.

High volume sampling trains were demonstrated to be superior to low volume sampling trains for at least three reasons:

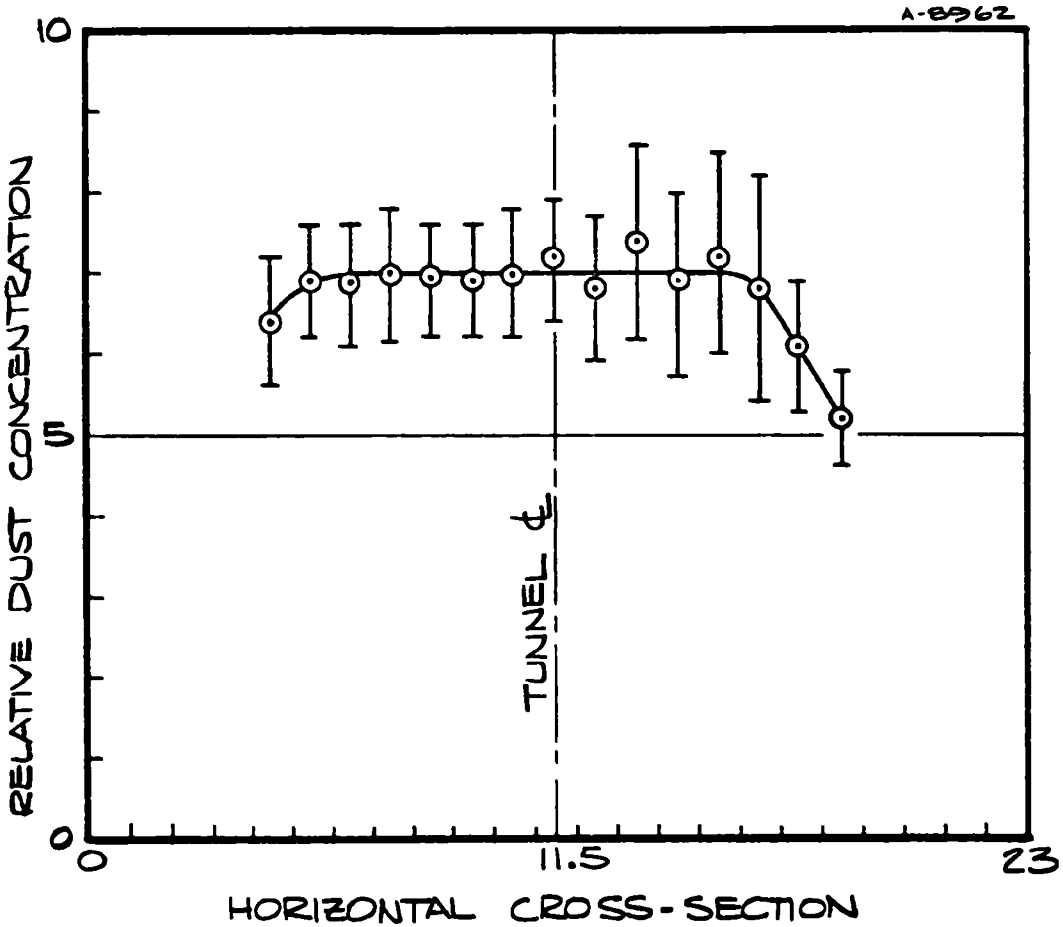

Figure 35. Final Concentration Profile for Subtask 3

TABLE 2

Date	Low Volume			High Volume		
	Time	Volume (scf)	Conc. (gr/scf)	Time	Volume (scf)	Conc. (gr/scf)
3-18	10:53	128.7	0.045	11:30	232.7	0.047
	14:53			12:30		
				13:45	236.4	0.046
				14:45		
					Avg.	0.0465
3-19	10:30	136.4	0.038	10:30	238.4	0.043
	14:45			11:30		
				13:15	240.5	0.035
				14:15		
					Avg.	0.039
3-20	9:22	128.5	0.038	9:30	231.8	0.036
	13:22			10:30		
				11:02	231.7	0.039
				12:02		
				13:00	236.8	0.032
				14:00		
					Avg.	0.036
Average			0.040			0.040

- Sampling time is reduced for equivalent volume sample. This means reduced time investment in the sampling task.
- More samples/day on short turn-around are possible. This means it is possible to detect variation of short duration during a typical 8 hour testing period.
- Negligible sample loss due to settling in the probe. This means increased accuracy.

TECHNICAL REPORT DATA *(Please read Instructions on the reverse before completing)*		
1. REPORT NO. EPA-650/2-74-103	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Design, Fabrication, and Installation of a Particulate Aerodynamic Test Facility		5. REPORT DATE October 1974 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Dale D. Blann, Ken A. Green, and Larry W. Anderson		8. PERFORMING ORGANIZATION REPORT NO. 74-108
9. PERFORMING ORGANIZATION NAME AND ADDRESS Aerotherm/Acurex Corporation 485 Clyde Avenue Mountain View, California 94040		10. PROGRAM ELEMENT NO. 1AB012; ROAP 21ADJ-080 11. CONTRACT/GRANT NO. 68-02-0625
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development NERC-RTP, Control Systems Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; Through 7/25/74 14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

The report presents the trade-offs and design considerations, component selection criteria, and final design details for a particulate aerodynamic test facility. The design meets a range of performance specifications for the test gas, including test section gas velocities to 90 ft/sec, temperatures to 450F, and variable humidity and gas composition, including particulates.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Installing	Air Pollution Control	13B
Aerodynamics		Stationary Sources	20D
Test Facilities		Particulates	14B
Wind Tunnels			
Design Criteria			14A
Fabrication			13H

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Unlimited	Unclassified	122
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)