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HARDWARE AND INSTRUMENTATION OF THE DARPA SUBOFF EXPERIMENTS

by

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DTRC/SHD-1298-03 HARDWARE AND INSTRUMENTATION OF THE DARPA SUBOFF EXPERIMENT

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Experimental measurements of the flow field of an axisymmetric body will be used by the Defense Advanced Research Projects Agency (DARPA) to determine the current capabilities of the Computational Fluid Dynamics (CFD) community to assist in the development of advanced submarines. The design and construction of two geometrically similar DARPA SUBOFF models are outlined. The hardware and instrumentation used to collect the experimental data in the David Taylor Research Center (DTRC) Anechoic Flow Facility (AFF) are also summarized.

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ABSTRACT

Experimental measurements of the flow field of an axisymmetric body will be used by the Defense Advanced Research Projects Agency (DARPA) to determine the current capabilities of the Computational Fluid Dynamics (CFD) community to assist in the development of advanced submarines. The design and construction of two geometrically similar DARPA SUBOFF models are outlined. The hardware and instrumentation used to collect the experimental data in the David Taylor Research Center (DTRC) Anechoic Flow Facility (AFF) are also summarized.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The Defense Advanced Research Projects Agency (DARPA) has funded and coordinated a Computational Fluid Dynamics (CFD) Program to assist in the development of advanced underwater vehicles. The ultimate goal of the DARPA SUBOFF Project is to develop fully matured CFD codes that are user-friendly, cost effective, and fully verified by detailed experimental comparisons. At the present time however, experimental data for the flow field over an entire appended submarine are limited, making CFD validation difficult. Therefore, one task of the SUBOFF project is to conduct a series of detailed experiments to fill this void. Six configurations of two axisymmetric hulls with and without appendages will be tested, and the CFD predictions will be made without prior knowledge of the experimental results. This will better show the current predictive capabilities of the CFD community to solve problems confronting DARPA's Submarine Technology Program (STP).

Experiments will be conducted in wind tunnels and towing basins to obtain accurate measurements of the flow characteristics over:

1. an axisymmetric hull,
2. an axisymmetric hull with a fairwater,

3. an axisymmetric hull with four identical stern appendages,

4. an axisymmetric hull with a fairwater and four identical stern appendages,

5. an axisymmetric hull with a fairwater, at angles of attack and drift, and

6. an axisymmetric hull with two different ring wings.

Mean velocities, turbulence intensities, Reynolds stresses (radial and axial), static pressures (surface and freestream), wall shear stresses, forces, moments and the wake harmonics in the propeller plane will all be measured, although not all at the same time. The capability of the CFD codes to predict these quantities will be evaluated for the six test conditions.

An axisymmetric hull and appendages were designed by DTRC and two geometrically similar models were constructed. The models are identical except for the surface pressure tap locations and interior construction. The geometric offsets for the axisymmetric hull and appendages, two ring wings and ring wing support struts, along with the computer codes to generate them, are described by Groves, et al. [1]. (References are presented on page 29.) DTRC Model No. 5470 will be tested the DTRC Deep Water Model Basin (TMB) and the Tracor Hydronautics Ship Towing Basin (HSMB). Model No. 5471 will be tested in the DTRC Anechoic Flow Facility (AFF). All experiments will be conducted at a Reynolds number, based on the model length, of 1.2×10^7. A complete catalog of the experimental measurements, DTRC test numbers, and data presentation formats is in preparation. The following report presents details of the model construction and of the hardware and instrumentation used during the experiments in the AFF.

ANECHOIC FLOW FACILITY

The majority of the experimental measurements performed on the six SUBOFF configurations was conducted in the AFF. As shown in Figure 1, the AFF is a closed loop, atmospheric pressure wind tunel with a maximum air speed of 200 fps (61 mps). The tunnel has a 10 to 1 area contraction upstream leading to an 8 ft. (2.4 m) square by 13.75 ft. (4.2 m) long closed-jet test section. The contraction and closed-jet have 1.75 ft (0.53 m) fillets to reduce any secondary flows associated with the corners. The closed-jet opens into a large acoustically lined chamber 23.5 ft (7.1 m) square and 21 ft. long (6.4 m). The closed-jet, open-jet, and anechoic test sections of the AFF are shown in Figure 2.

DTRC Model No. 5471 is positioned with the nose and most of the parallel mid-body located within the closed-jet but the aft section of the model sticks into the open-jet anechoic chamber (see Figures 2 and 3). This position minimizes tunnel blockage effects on the flow around the stern region where the majority of measurements are made. The model is supported by two NACA-0015 shaped struts, each with a 6-in. (15 cm) chord and located 1.5 ft. (.4 m) and 7 ft. (2.1 m) from the end of the closed-jet. Each strut is rigidly mounted below the floor of the closed-jet section and laterally supported by cables, as shown in Figure 4. The struts are also hollow to allow instrumentation and pressure lines to connect inside the model.

Figures 2 and 3 also show the location of the primary traversing unit used for collecting both velocity and pressure measurements near the stern of the model. The following sections describe the design and construction of the two models, their various appendages and mounting struts, and the primary traversing unit.

SUBOFF MODELS

GENERAL MODEL CHARACTERISTICS

The detailed design and construction of the two models were contracted to Tracor Hydronautics, Inc. The models have movable appendages and two interchangable ring wings. The only differences between the two models are the locations of the surface pressure taps and interior construction details. The axisymmetric hulls and fairwaters are made of molded fiberglass and the stern appendages are made of Hysol, an epoxy and wood fiber-based compound that is both waterproof and easily machined.

The models are 14.3 ft. (4.3 m) long with a maximum diameter of 1.67 ft. (0.51 m). The detail design may be found in Groves et al. [1]. Figure 5 shows a schematic of these model components and stern configurations.

MODEL NO. 5471

An assembly drawing of this model is shown in Figure 6. The axisymmetric hull is constructed from two fiberglass shells. The joint connecting the upper and lower halves of the model is rotated 16° allowing a row of pressure taps to be placed on the port and starboard sides of the model. The lower shell contains three large hatches which allow access to the instrumentation inside the model and fit around the two support struts. The hatches are flush mounted and secured to an aluminum frame around the hatch perimeter. The struts are attached inside the model to the main support beam by a double gimble mount. Each gimble allows a ±2° change in the orientation of the model within the wind tunnel.

The main support beam inside the model is a 6 ft. (1.8 m) long, 6 in. (15.2 cm) aluminum channel located 3 in. (7.6 cm) above the centerline of the model. This beam is the backbone of the model and provides a base for attaching instruments. The fiberglass shell of the hull attaches to this platform by five bulkheads. The three stern appendage positions are fixed by a mounting block attached to the aft end of the beam. Two 1.5 in. (3.8 cm) wide hatches, covering a 90° arc across the top of the model, are cut through the upper fiberglass shell to allow a traversing unit to be mounted inside the model. This traversing unit will be described in greater detail later in this report. All the access holes in the surface of the model are plugged from the inside with flush mounted inserts to maintain a smooth surface.

Five identically shaped stern appendages exist for this model (only four are used at any one time). Four are made with removable sections to allow the appendages to be mounted at each of the three longitudinal positions (see Figure 5). The fifth has surface pressure taps on one side and can only be mounted in the baseline configuration. Each of the five appendages can only be varied in incidence angles when mounted in the baseline configuration.

There are 222 pressure taps flush mounted on the surface of the axisymmetric hull and appendages. The hull has 42 pressure taps along the upper, lower, port and starboard meridians, 72 in the fairwater region and 41 in the stern region. There are 30 taps on the surface of the fairwater and 33 located in the stern appendage mentioned earlier (see Figure 7). The pressure taps are made of 0.063 (1/16) in. outside diameter and 0.03125 (1/32) in. inside diameter stainless steel tubing sanded flush to the surface. The tubing extends inside the model to a point where it can be accessed comfortably from the hatch. Plastic tubing connects each pressure tap to a port on a pressure measurement system to be described later.

MODEL NO. 5470

Whereas Model No. 5471 is tested only in the AFF and attaches to two 6 in. struts, Model No. 5470 requires mounting on three different systems. Two of the three systems are shown in Figure 8. They include a planar motion mechanism (PMM) and a drag dynamometer system at DTRC. The third mechanism is a second PMM at HSMB. To accommodate these various mounting systems, the internal beam design and hatch covers differ slightly from Model No. 5471. The beam is an 8 in. (20 cm) wide aluminum channel 10 ft. (3 m) long and attached 5.44 in. (13.8 cm) below the centerline of the hull.

The 266 surface pressure taps are distributed over the axisymmetric hull and appendages. The pressure taps on the hull are located at eight axial locations covering 32 meridians. The fairwater contains 30 pressure taps on the port side and 20 on the starboard side. One of the four stern appendages contains 28 taps on the port and 18 on the starboard side. All tests on this model are conducted with the stern appendages mounted in the baseline configuration.

RING WING

Two ring wing assemblies can be interchangably mounted on the sterns of the two models. The ring wings are secured by four struts extending from the inside of the ring wing down to the stern hub of the model and the struts are rotated 45° with respect to the stern appendage locations. The ring wings, support struts, and stern hubs are machined from aluminum and anodized black.

Each ring wing has a diameter of approximately 13 in. (33 cm) and a length of 12 in. (30.5 cm). They differ only in their pitch angle. A stern assembly drawing of ring wing No. 1 is shown in Figure 9. When the wings are not in use, dummy hubs fit over the stern. Each ring wing has 37 surface pressure taps distributed axially along the wing in the four meridian planes.

A complete description of the geometric characteristics of these assemblies and the surface pressure tap locations is presented in Reference 1.

THE TRAVERSING UNIT

A traversing system was designed and constructed to collect velocity or pressure data very quickly. The unit, shown in Figures 2b and 10, allows a probe to be positioned anywhere within an annular volume 59 in. (1.5 m) long and from 3 in. (7.6 cm) to 28 in. (71 cm) in radius. Assembly drawings of this system are shown in Figures 10 and 11. The traversing unit is mounted inside the anechoic chamber directly behind the model, as shown in Figure 3. The unit is designed to concentrate on the model's stern region. The probe's position is controlled by three independent subsystems: axial, angular and radial.

The heart of the traversing unit is an assembly of telescoping aluminum pipes mounted to an axially-traversing table that is mounted on a tripod. The tripod attaches to beams in the floor of the anechoic chamber. The pipes rotate in bearings to allow angular movement of the probe which is fixed to the pipes through a rack and pinion assembly that provides radial movement.

The pipes are concentric with the model axis. Attached to the outside of the rear pipe is a ring gear which engages a second gear fixed to the end of a computer-controlled stepping motor. This controls the rotation of the pipe assembly and hence, the probe's angular location.

The probe is fixed to the end of a sharp-edged flat bar with an in-laid gear rack. This bar rolls radially in four pulley wheels attached to the front of the telescoping pipes. The gear rack engages a spur gear attached to the end of a shaft that is centered in the pipes. This shaft couples to a computer-controlled stepping motor inside the pipe itself. This system, fixed to the forward telescoping pipe, controls the probe's radial location.

The probe support is restricted to radial translation only and is aerodynamically shaped. Four V-notched pulley wheels engage sharp leading and trailing edges of the probe support and provide lateral support. Attached to the end of the probe support is the probe holder and the holder remains attached to the actual probe from calibration through the end of the test. This insures the probe is always properly aligned. When the holder is attached to the probe support it positions the probe directly over the central axis of the traversing unit. The various types of probes will be discussed later.

The axial location of the probe is set up using tape measures, plumb bobs,etc. in conjunction with the axial traversing table. This location is fixed while the probe surveys this axial plane in radius and angle. The radius and angle locations are fed into the computer as encoder readouts of the motors that move the probe. These motors are usually controlled in closed loop fashion.

A number of measurements are planned for locations along the parallel mid-body of the model. To reach these measurement planes, the radial traversing subsystem is remounted inside the model, as shown in Figure 12. A 1.5 in. (3.8 cm) slot cut through the surface and main support platform allows the probe support to pass outside the model. The slot allows a measurement area of $-45° < \theta < 45°$, and $1.0 < r/R_{max} < 2.8$ (R_{max} = 10in. (25.4 cm)). In this configuration, the internal size of the model and the large radial distance to be traveled require a second probe support to be made in pieces. By varying the number of pieces, the probe can be positioned in overlapping radial positions.

THE DATA ACQUISITION SYSTEM

The data acquisition system, as shown in Figure 13, consists of four sub-systems: the traversing system, the velocity and pressure measuring systems and the computer. The traversing system is described in the previous section. The computer controls data acquisition reduction, storage and the other subsystems. The velocity measuring system is a 16 channel hot-wire anemometry unit. The pressure measuring system uses five rotary pressure scanners and transducers. These sub-systems interact to provide accurate, efficient and easily documented data on the flow characteristics.

Because of schedule and hardware requirements, the velocity and pressure data are collected at different times.

THE COMPUTER

The computer serves many functions. For velocity measurements, it controls the stepping motors of the traversing system and collects and analyzes the hot-film anemometry data. For pressure measurements, it steps the rotary pressure scanner, collects and analyzes the data.

The data acquisition and reduction of hot-film measurements are computationally intensive involving the solution of three non-linear simultaneous equations for each velocity component. High data collection rates are also required to provide adequate frequency response. The combination of these requires a high-speed computer capable of direct access to a large main memory.

A MASSOMP MC 5450-01 Scientific Laboratory System, shown in Figure 14, was selected as the data acquisition computer. The 5450-01 uses a Motorola MC 68020 CPU operating at 20 MHz with an eight MIPS Data Acquisition Control Processor (DACP) and a five slot STD + Bus. All data acquisition routines run from a dedicated processor in real time with direct access to the main memory. Direct memory access allows non-buffered data sampling, up to 1 mega-samples per second, with the proper modules.

Residing on the SDP + Bus are a multi-function data acquisition module, a 16-channel simultaneous sample and hold module, and an IEEE-488 interface card. The sample and hold module is required for the time varying wake harmonic and the multi-component velocity measurements. These measurements require 10 to 14 single-component hot-film anemometer signals to be recorded at the same instant with a data rate of 10-20 KHz for each channel. The IEEE-488 interfaces with the stepping motor controls of the traversing system and it reads the tunnel temperature, and a programmable clock controls the stepping of the pressure scanner.

VELOCITY MEASUREMENT SYSTEM

The velocity measurement system utilizes standard hot-film techniques to obtain the magnitudes and directions of the velocity vectors. These velocities are then used to calculate mean velocities, turbulence intensities, and Reynolds stresses in the wake of the model.

A TSI Model IFA-100 (Intelligent Flow Analyzer), computer-controlled, hot film anemometer is used and each component of a probe is connected to a separate anemometer. These anemometers include signal conditioners with computer settable DC offsets (0-9v), gains (1-900), anu low pass filters (0-900 kHz). Figure 13 shows a typical setup. Typically the velocity data are sampled at 150 Hz for 10 seconds for each channel with no filtering. The conditioned analog signal goes to the analog to digital converter in the MASSCOMP and then the digital voltages are converted to velocities in probe coordinates. These velocities convert to velocities in model coordinates through an intricate program. The actual data analysis software will be described in a later report.

A variety of hot-film probes are available to match the type of measurement required. Probes were selected to optimize frequency response and voltage range to accurately measure the turbulence quantities within the expected velocity ranges. Figure 15 shows the various probes used during these tests. In all cases, thin, cylindrical, hot-film sensors have been chosen for their rigidity, calibration repeatability and high angular sensitivity. They are constructed of fine quartz rods with a platinum film bonded to the surface. Platinum provides a stable, anti-corrosive film that can tolerate high temperatures. The film is coated with alumina to protect it from abrasive particles in the flow, giving the sensor a longer operational life.

A TSI Model 1210-20, single sensor hot-film probe, shown in Figure 15a, is used when the direction of the flow is known: first, to measure the velocity and turbulence quantities of the boundary layer; second, as a group of 10 to 14 single sensor probes mounted in the wake harmonic probe rake, at a constant radial position, as shown in Figure 16. These measurements are in a plane where the full velocity distribution is known. A more detailed description of these measurements will be presented in a later report.

When the flow is two-dimensional or in a boundary layer, a TSI Model 1249A-10 miniature "X" probe, shown in Figure 15b , is used. The "X" probe measures two components of velocity, turbulence intensity and Reynolds stress.

A special, three sensor probe is used for most of the flow measurements. The probe, TSI Model 1299-20-18, has three orthogonal film sensors as shown in Figure 15c. The geometry of the probe is new and more compact, yielding better spatial resolution.

PRESSURE MEASUREMENT SYSTEM

The heart of the pressure measuring system is a set of five rotary pressure scanning units, operating in parallel. Each unit has a silicon diaphragm, differential pressure transducer attached to 48 mechanically scanned measurement ports. The analog output signal is conditioned, amplified, filtered, and finally connected to the A/D converter of the MASSCOMP. The Laboratory Workbench data aquisition software is then used to record, analyze and store the pressure data. The pressure data are low pass filtered at 10 KHz and sampled at 1 KHz for 100 ms on each tap. A layout of the equipment used in the pressure system is shown in Figure 17. Most of these components, the solenoid controller, pressure scanning units, signal conditioners, and calibration transducers are located inside the model. This reduces the length of the pressure lines from each of the surface pressure taps, decreasing the response time required for a measurement, and thus increasing the allowable scanning rate. Each of the five scanning units is set for a scanning rate of 1 measurement port every 2 seconds.

Connected to the measurement side of each of the transducers are static pressure, calibration pressure, two pitot-static tubes, and the pressure taps, as shown in Figure 18. Pressure manifolds distribute the total, calibration, and static pressures to the five scanning modules (only a single scanner is shown in Figure 18). The two pitot-static tubes located at the exit plane of the closed-jet, see Figure 3, measure the tunnel velocity and pressure. All pressure coefficients are normalized by these reference values. The two static pressure lines connect together and provide reference pressure on the back of each of the transducers. The pressure scanning system, therefore, measures the pressure coefficient directly by comparing each port's pressure to the static reference pressure and dividing by the dynamic pressure measured by that transducer. The average static pressure is also connected to the measurement side of the scanner as a zero check of the transducer.

A high accuracy, temperature controlled pressure transducer is used to calibrate the transducer in each scanner module. The calibration transducer is connected between the average static pressure line and a calibration pressure line connected to a measurement port. The calibration pressure is externally controlled by a bellows chamber located in the control room. The remaining measurement ports are connected to the models' surface pressure taps. Therefore, each scan of each module measures two reference velocities, a known calibration pressure, static presure and the models' surface pressures. This reduces bias errors of the system. A complete error analysis of the pressure measurement system will be presented in a later report.

This pressure system is also used for measuring surface shear stresses. Small blocks (1/16" x 9/64" x 9/32") placed downstream of the pressure taps stagnate the flow near the wall and produce a pressure rise. The pressure rise is measured by recording the pressure at the tap with and without the block. The calibrations of these blocks and an error analysis of their use are also presented in the aforementioned report.

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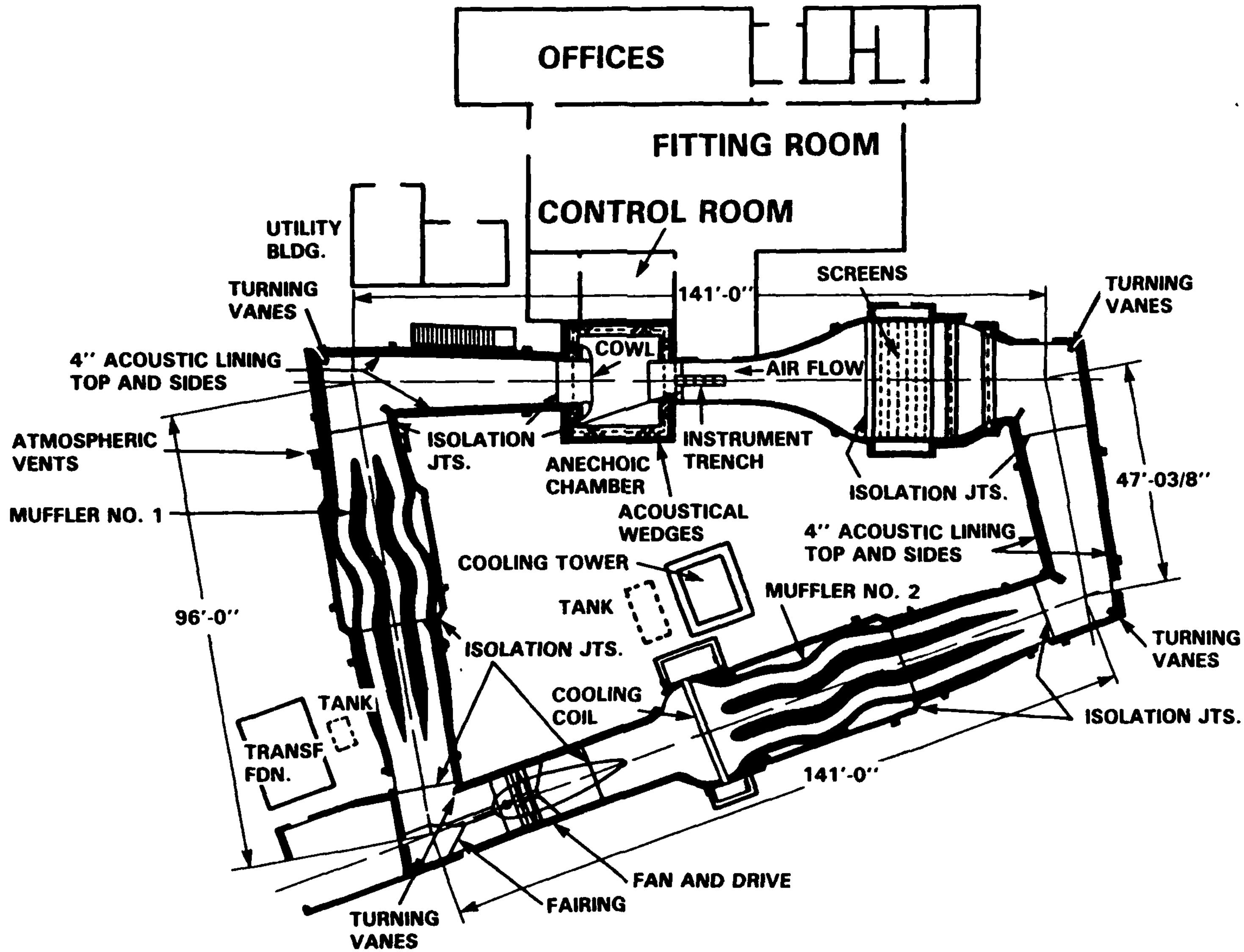


Fig. 1 Schematic of Anechoic Flow Facility (AFF)

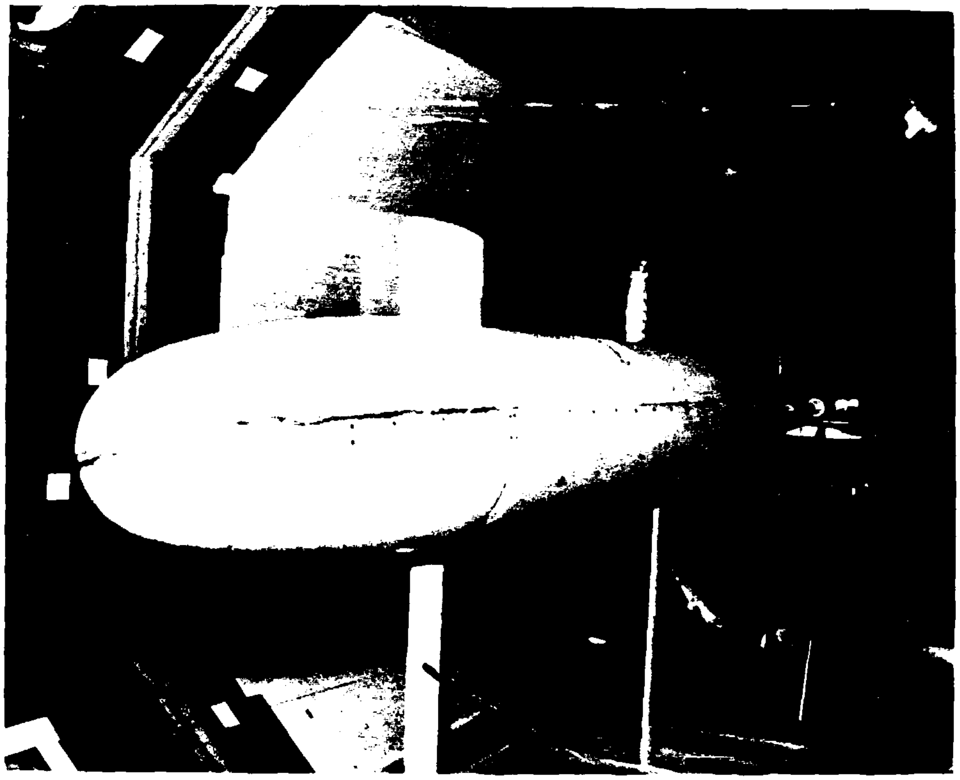


Fig. 2a Front view of Model No. 5471 in closed-jet test section (looking downstream)

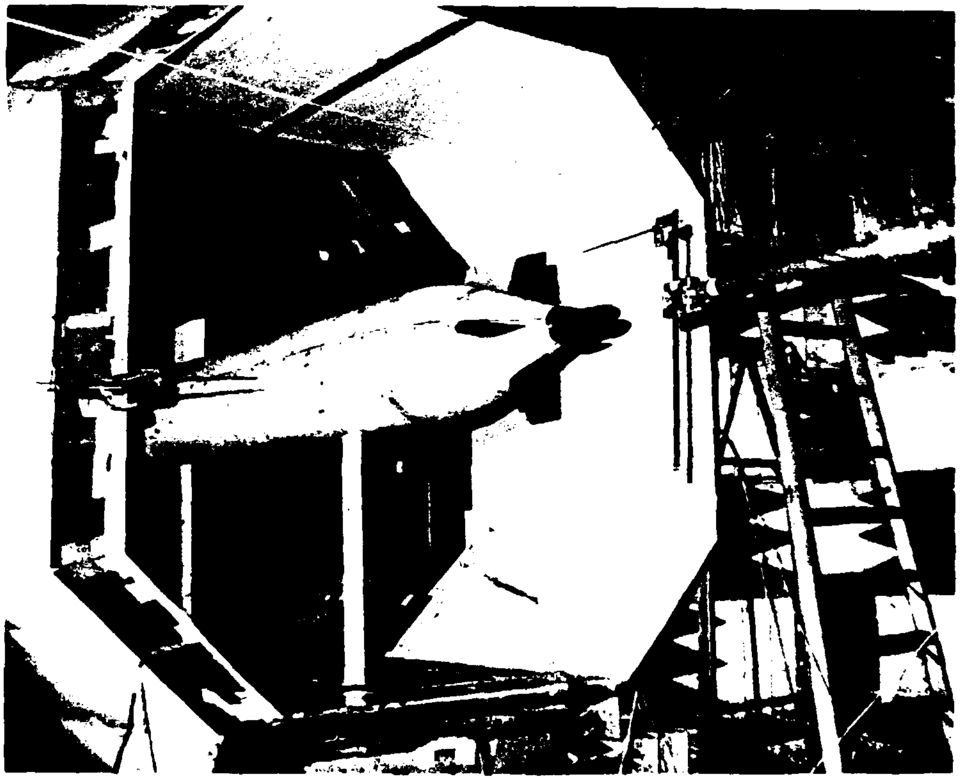


Fig. 2b Aft view of Model No. 5471 in open-jet anechoic test section (looking upstream)

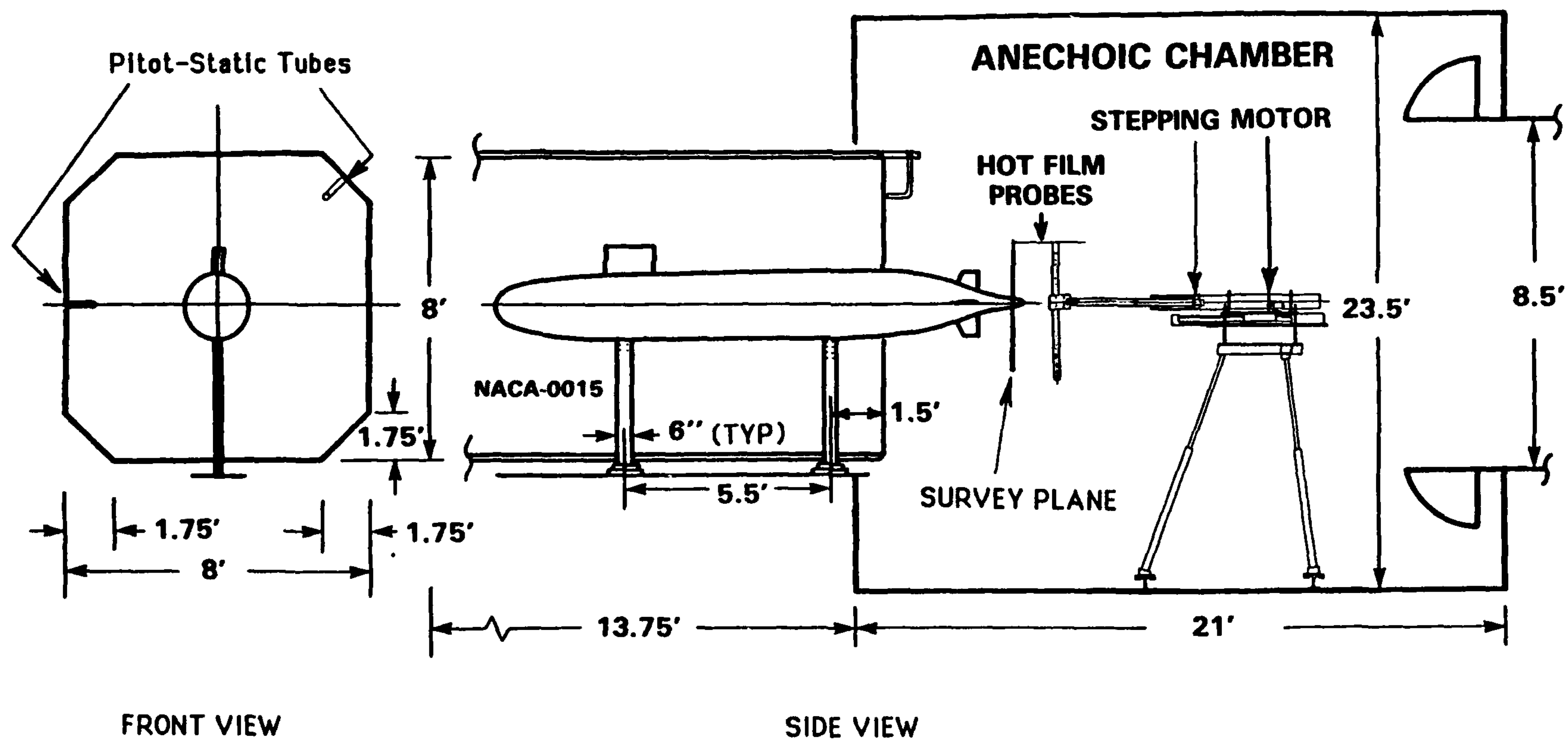


Fig. 3 Front and side views of Model No. 5471 in AFF.

Fig. 4a Front view of Model No. 5471 with floor of closed-jet removed

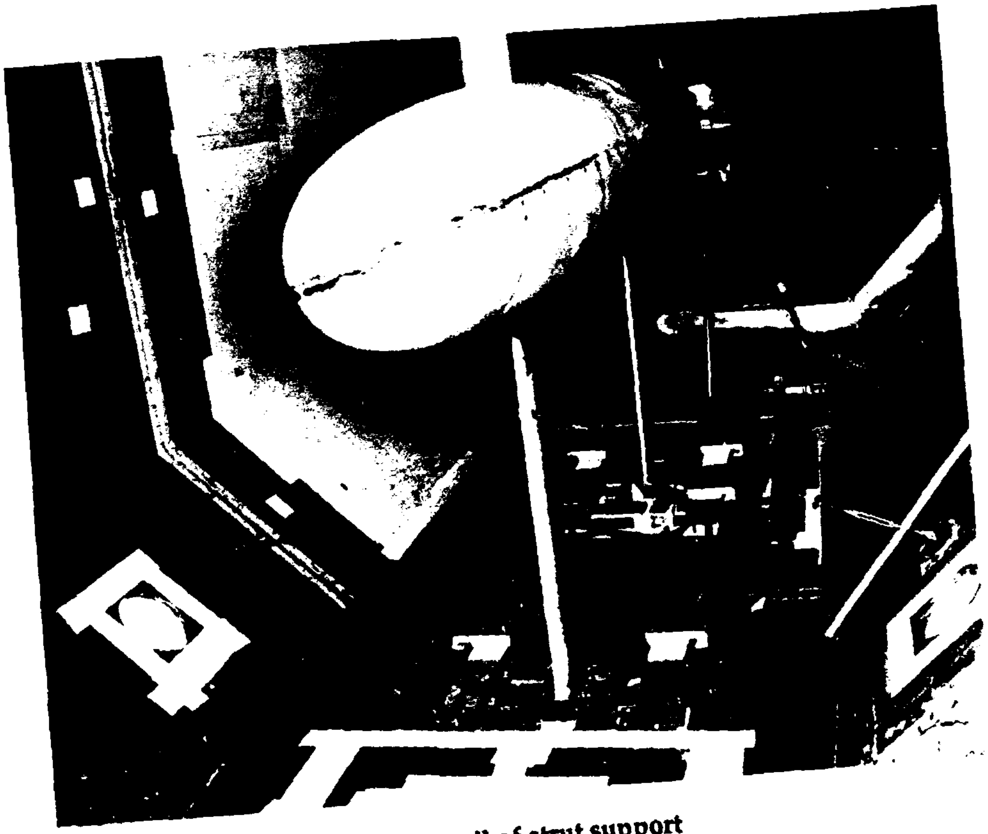


Fig 4b Detail of strut support

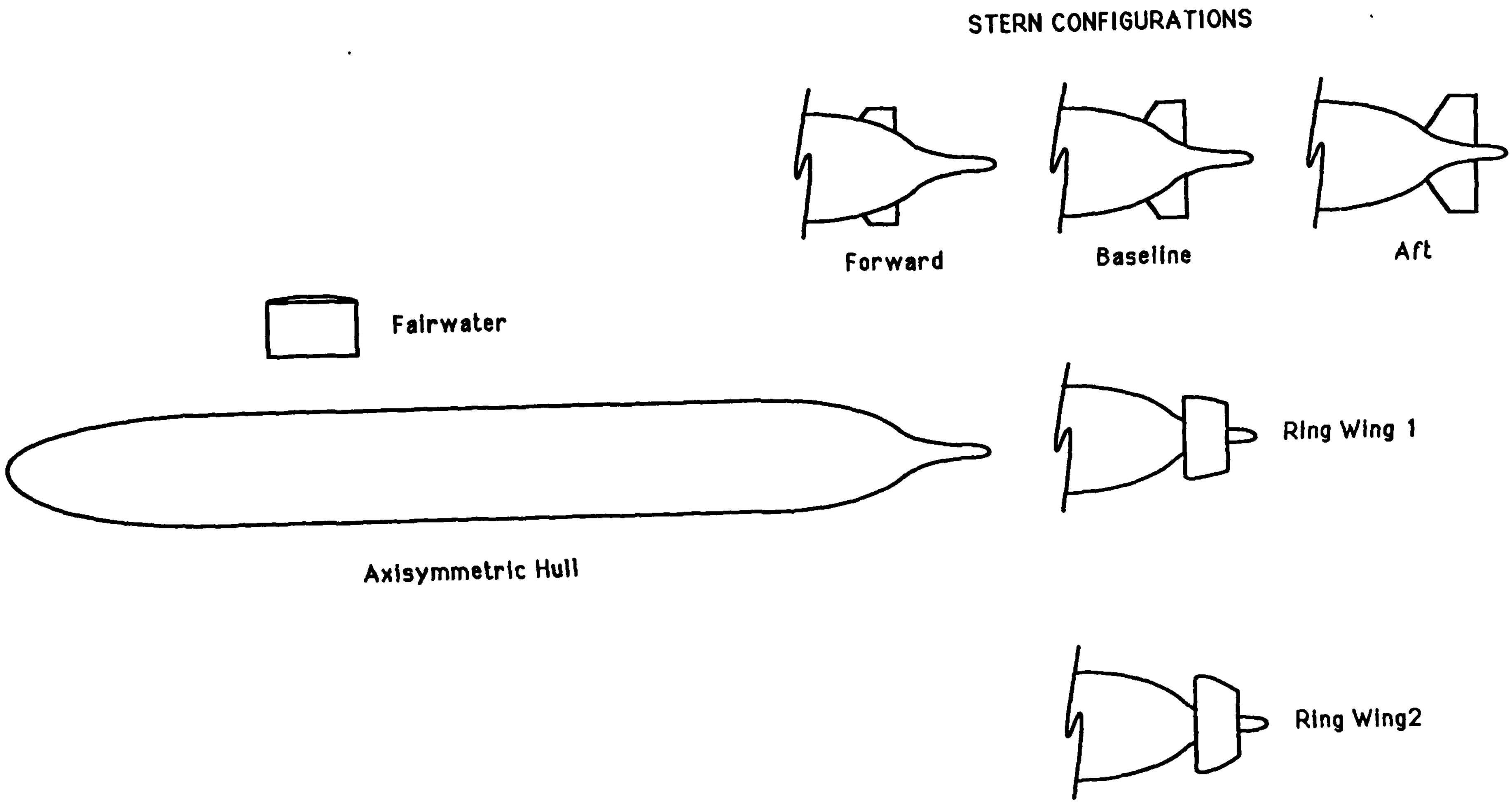


Fig. 5 Schematic of DARPA SUBOFF model components and stern configurations

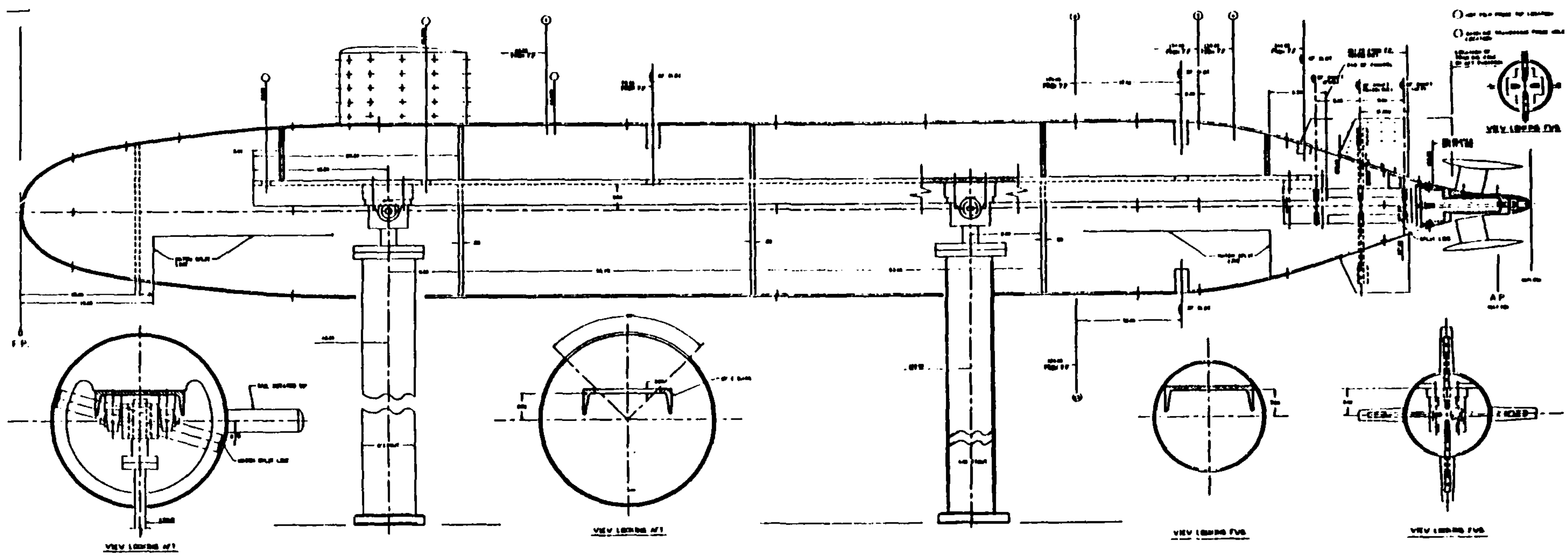


Fig. 6 Assembly drawing of DARPA SUBOFF model (DTRC Model No. 5471)

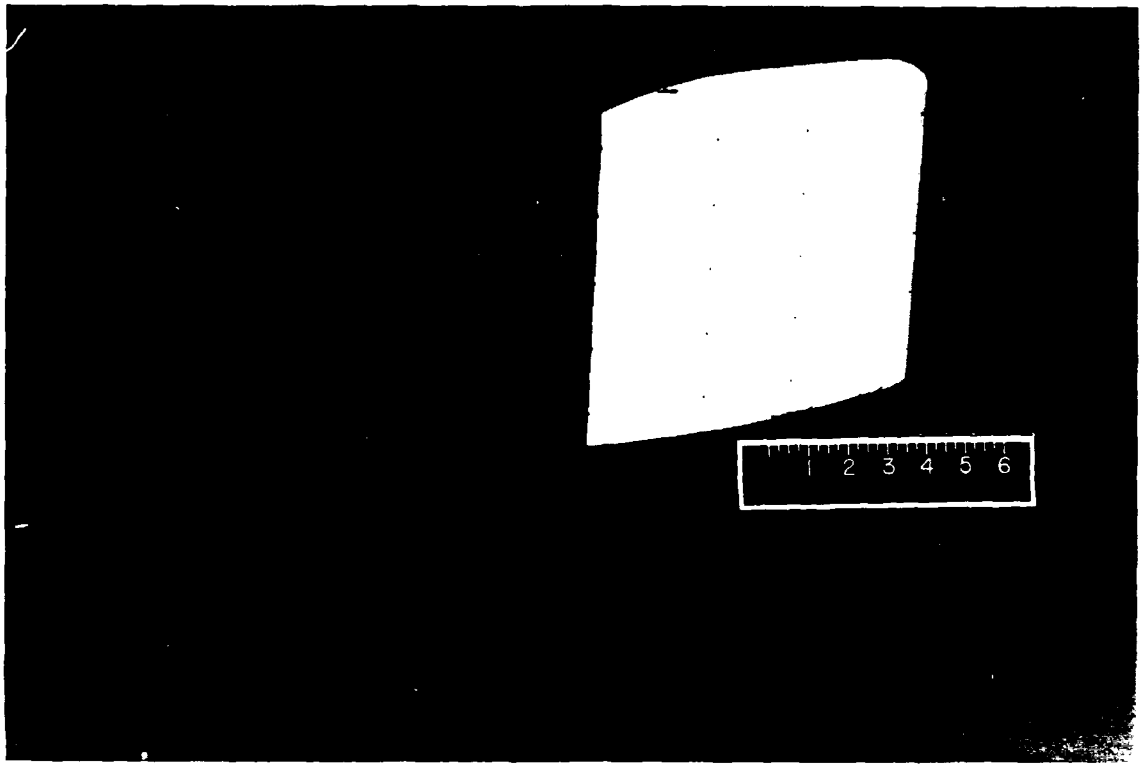


Fig. 7 Fairwater and stern appendage with pressure taps for Model No. 5471

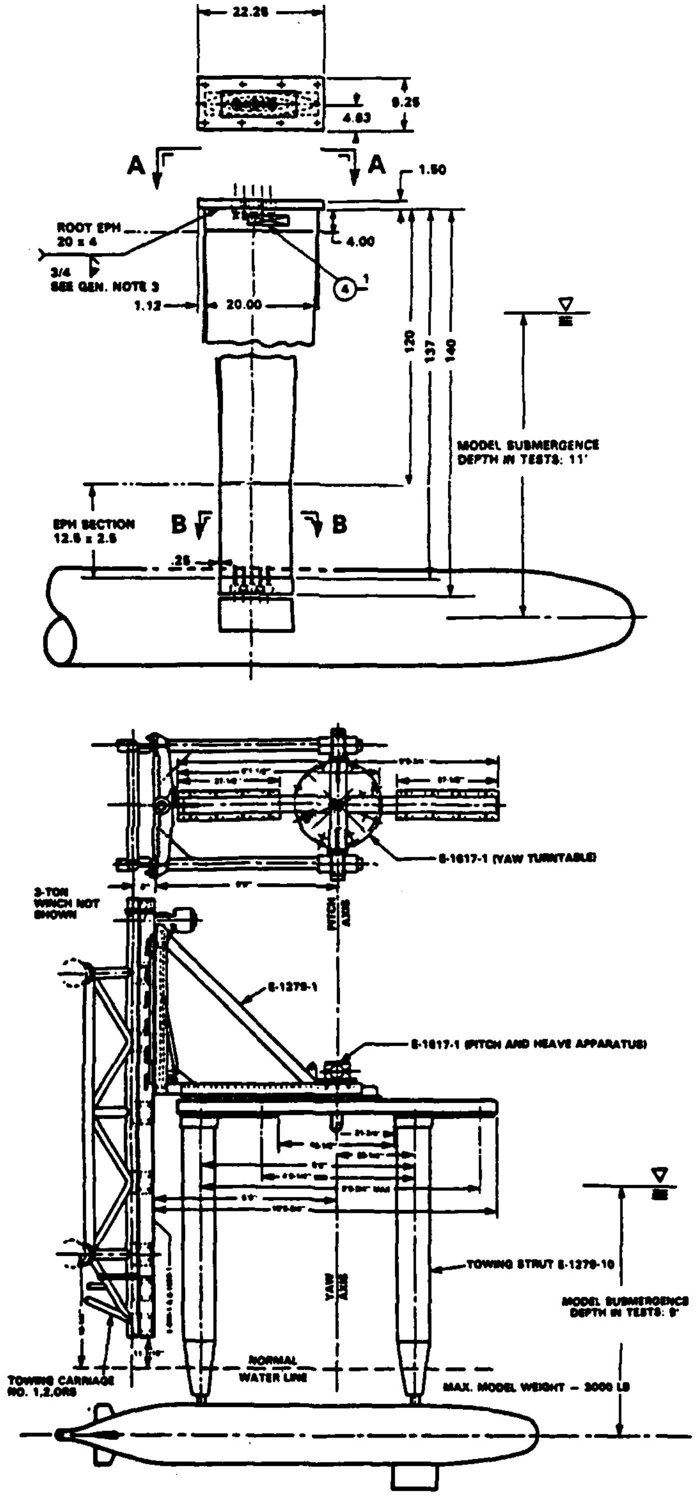


Fig. 8 Mounting systems for Model No. 5470

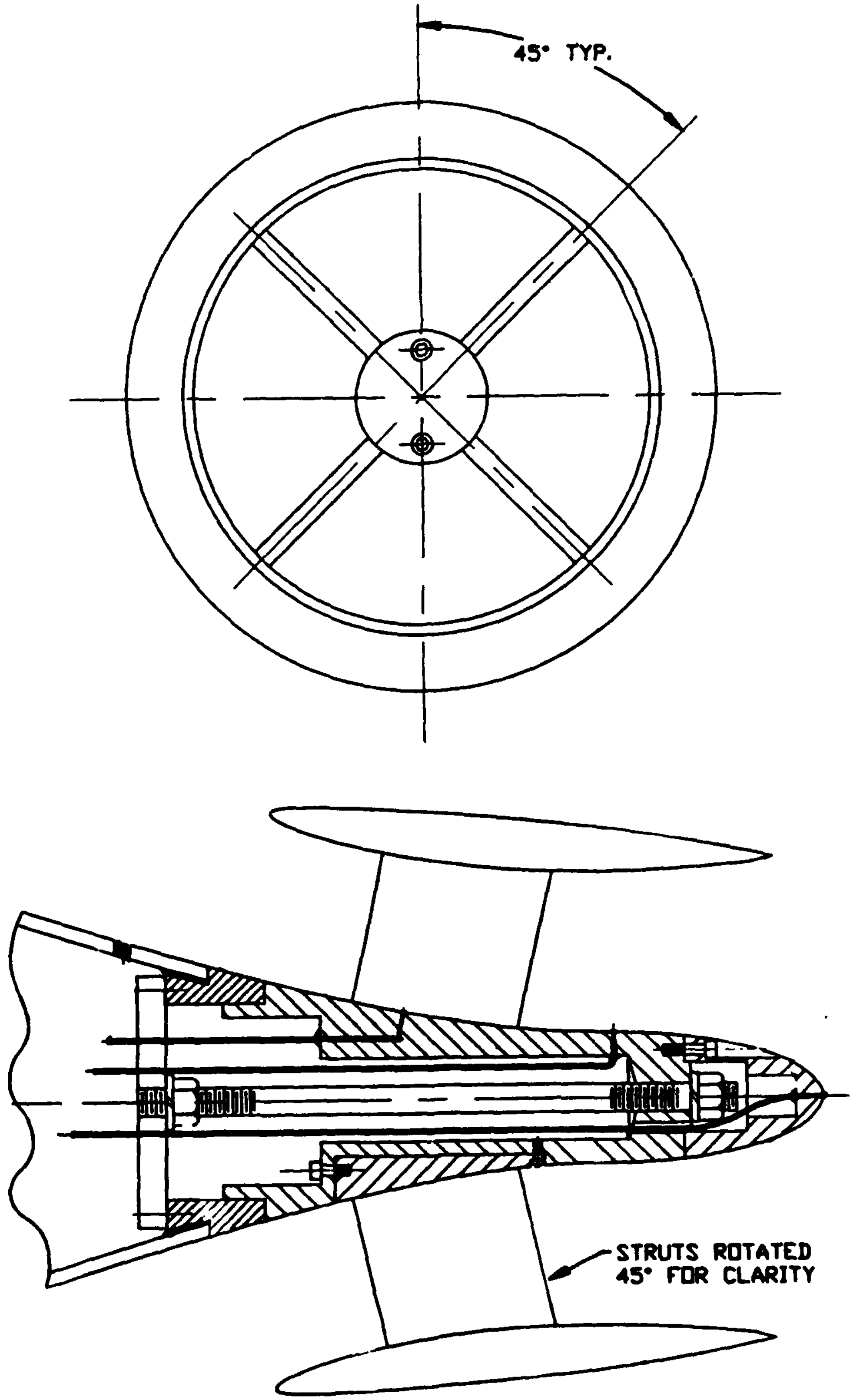


Fig. 9 Assembly drawing of ring wing No. 1

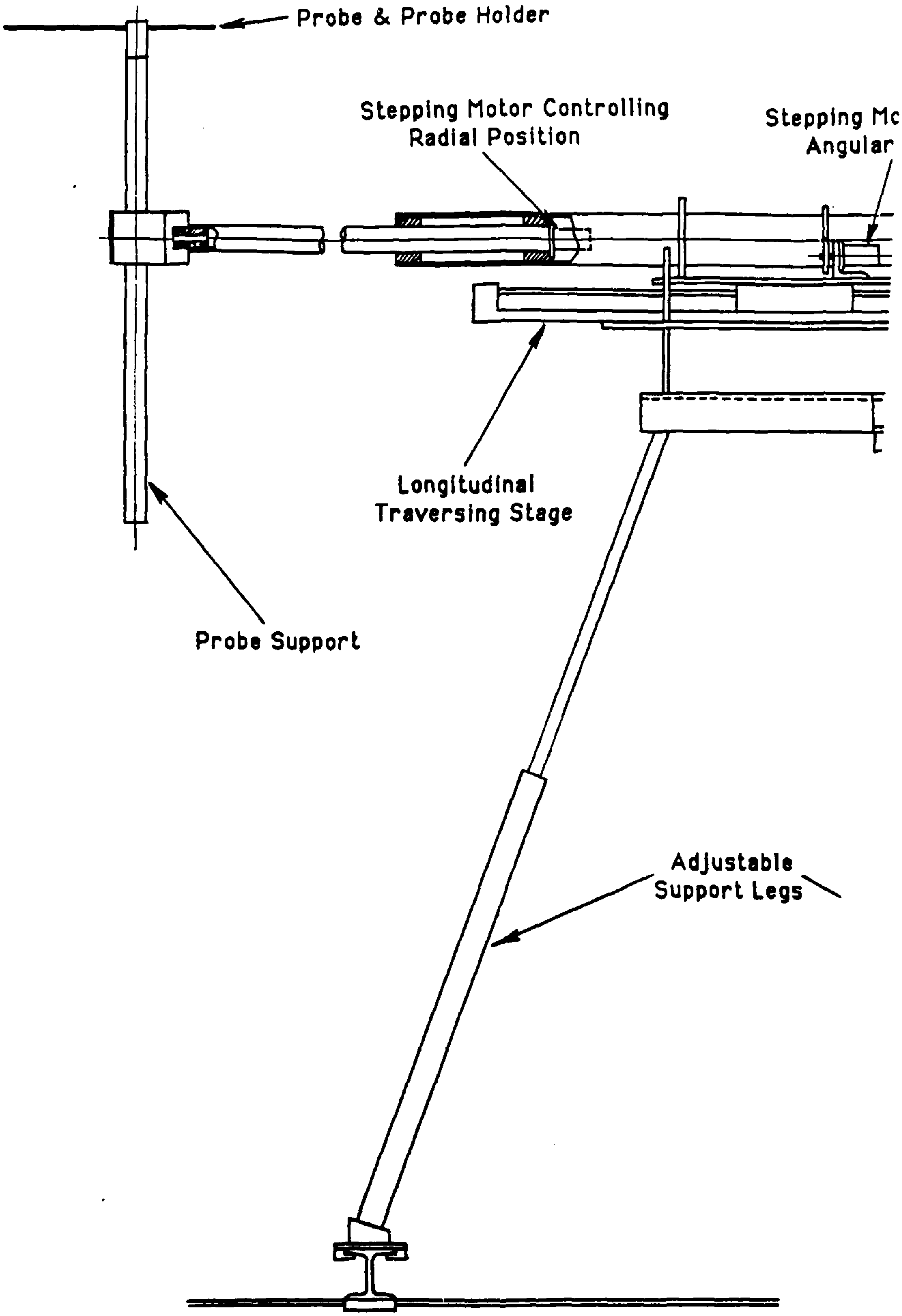


Fig. 10 **Assembly drawing of the traversing unit**

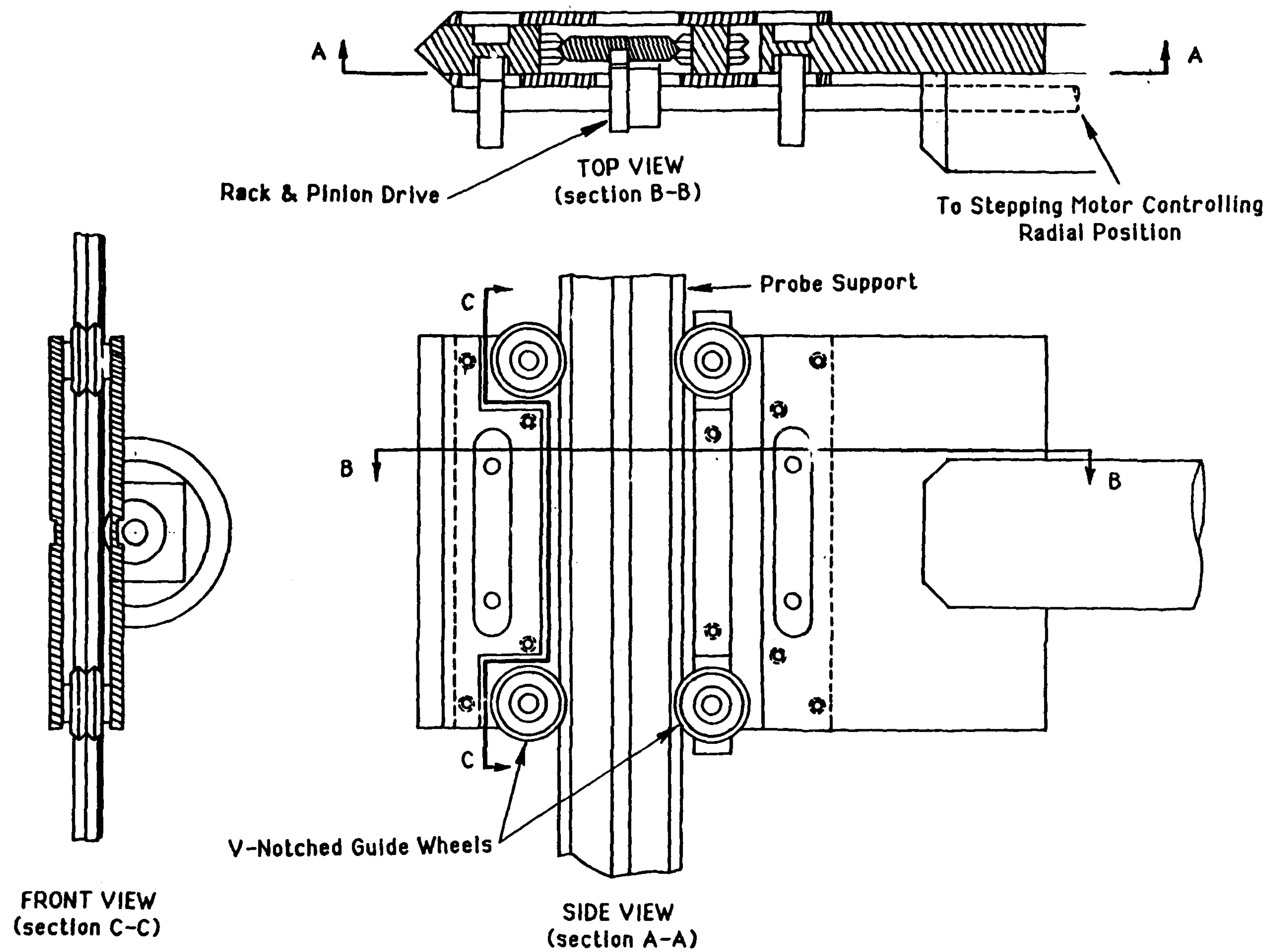


Fig. 11 Detailed assembly drawing of the radial traversing unit

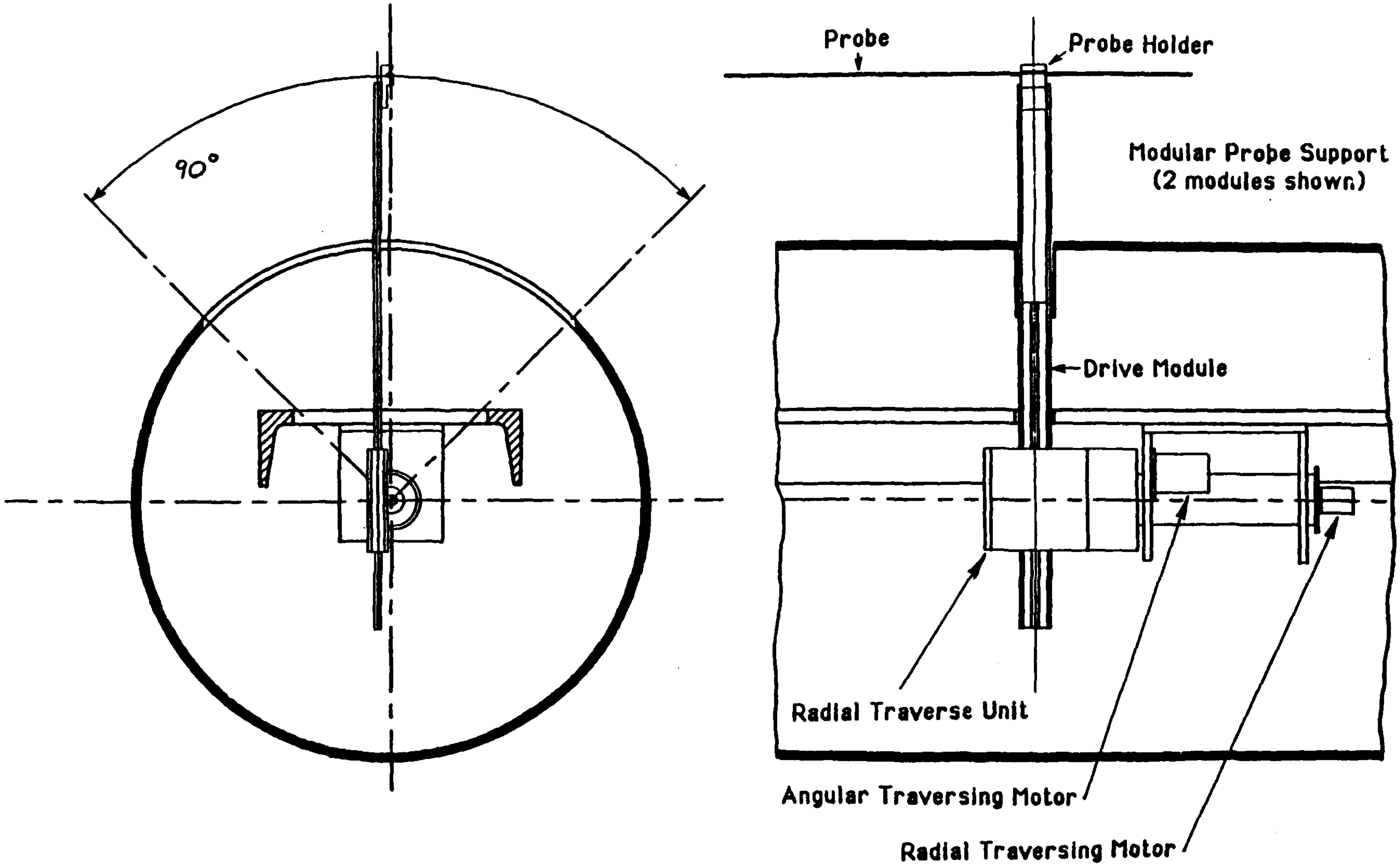


Fig. 12 The traversing unit mounted inside the model

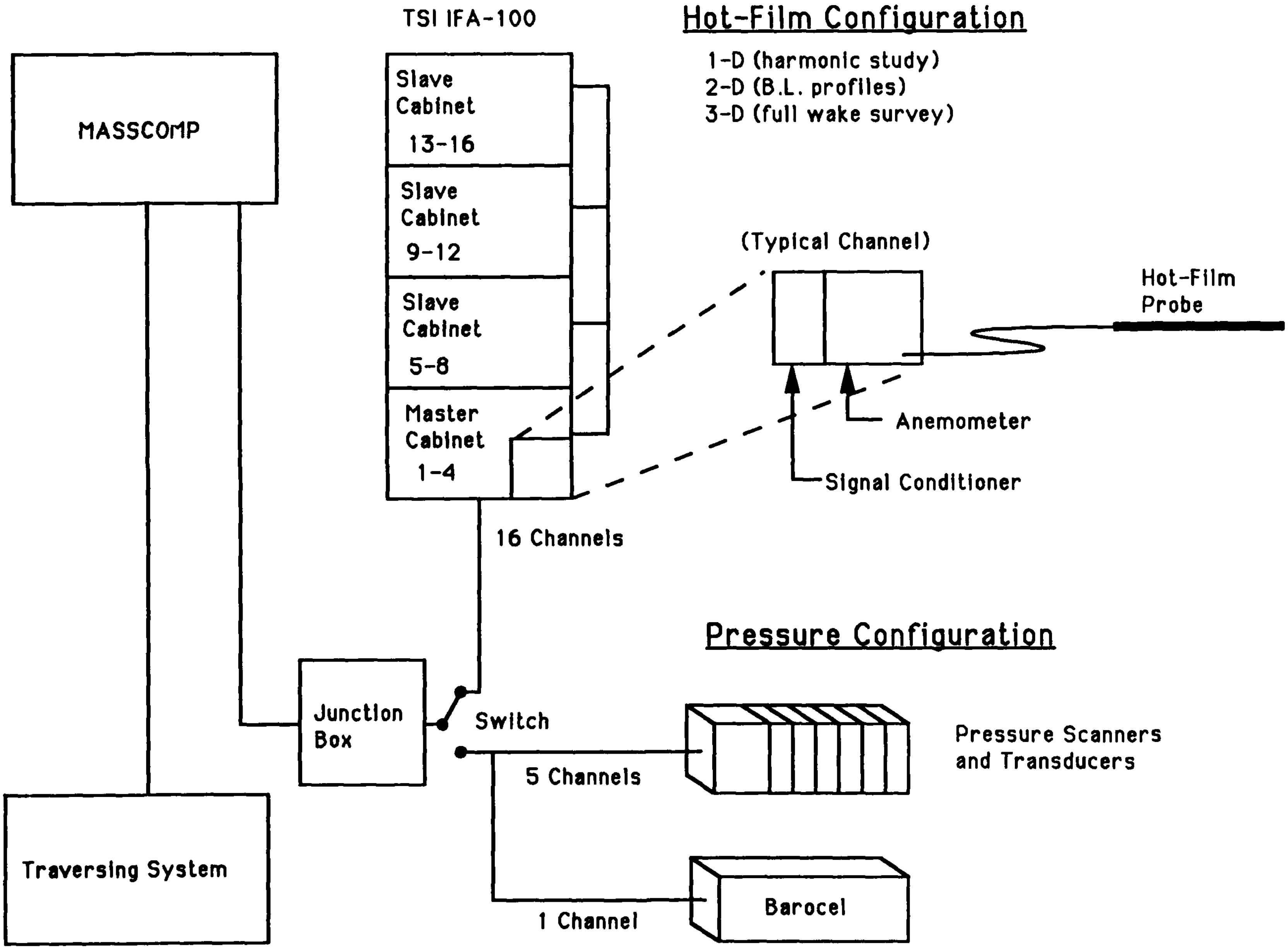


Fig. 13 Schematic of the data acquisition system

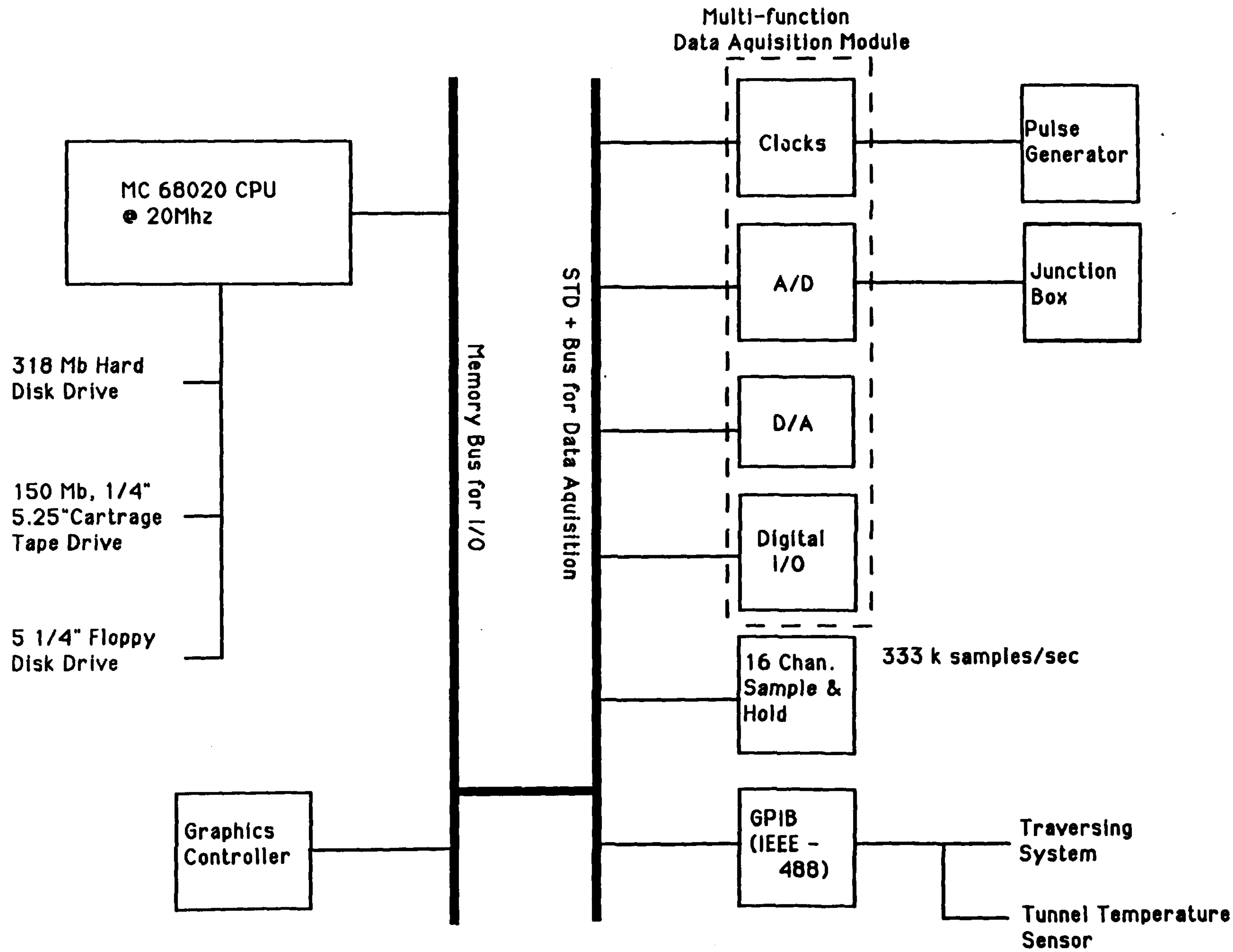
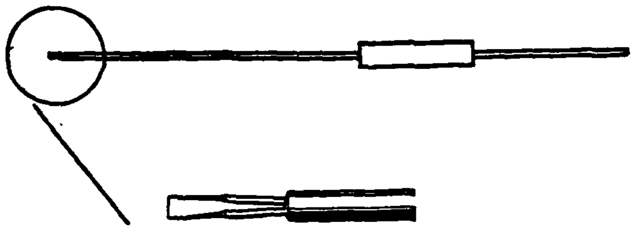
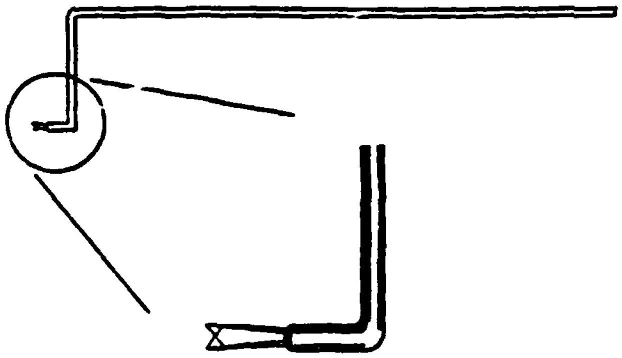


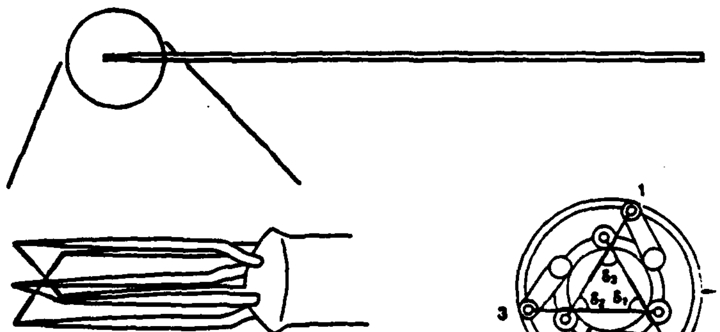
Fig. 14 Schematic of the MASSCOMP MC5450-01 Scientific Laboratory System

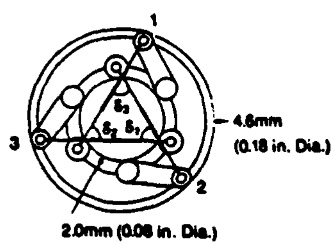


a. Typical single-component probe and holder
(TSI-Model 1210-20)



b. Two-component 'x' probe
(TSI-Model 1249A-10)





c. Three-component probe
(TSI-Model 1299-20-18)

Fig. 15 Hot-film anemometry probes

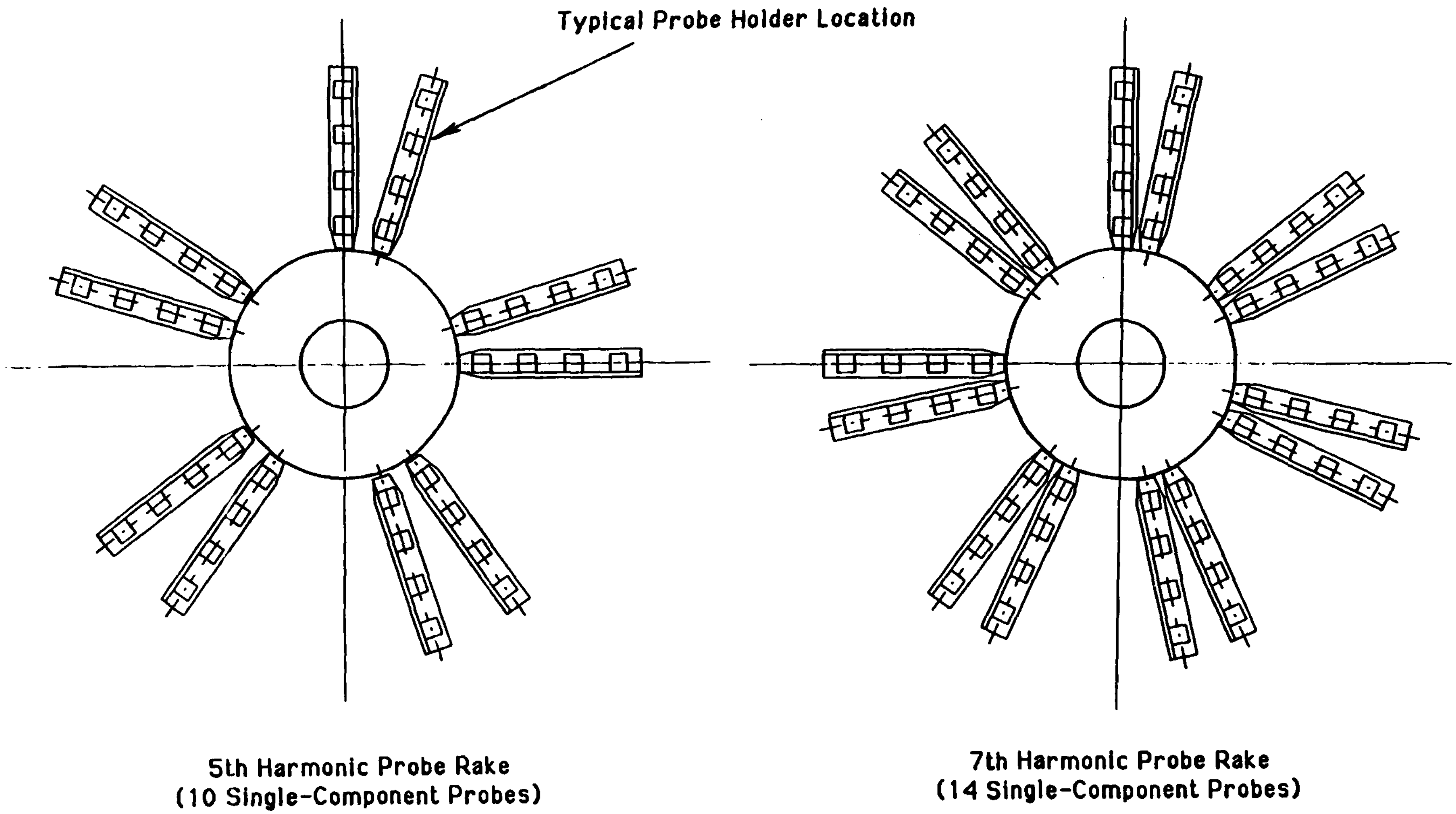


Fig. 16 Probe rake for 5th and 7th harmonic measurements

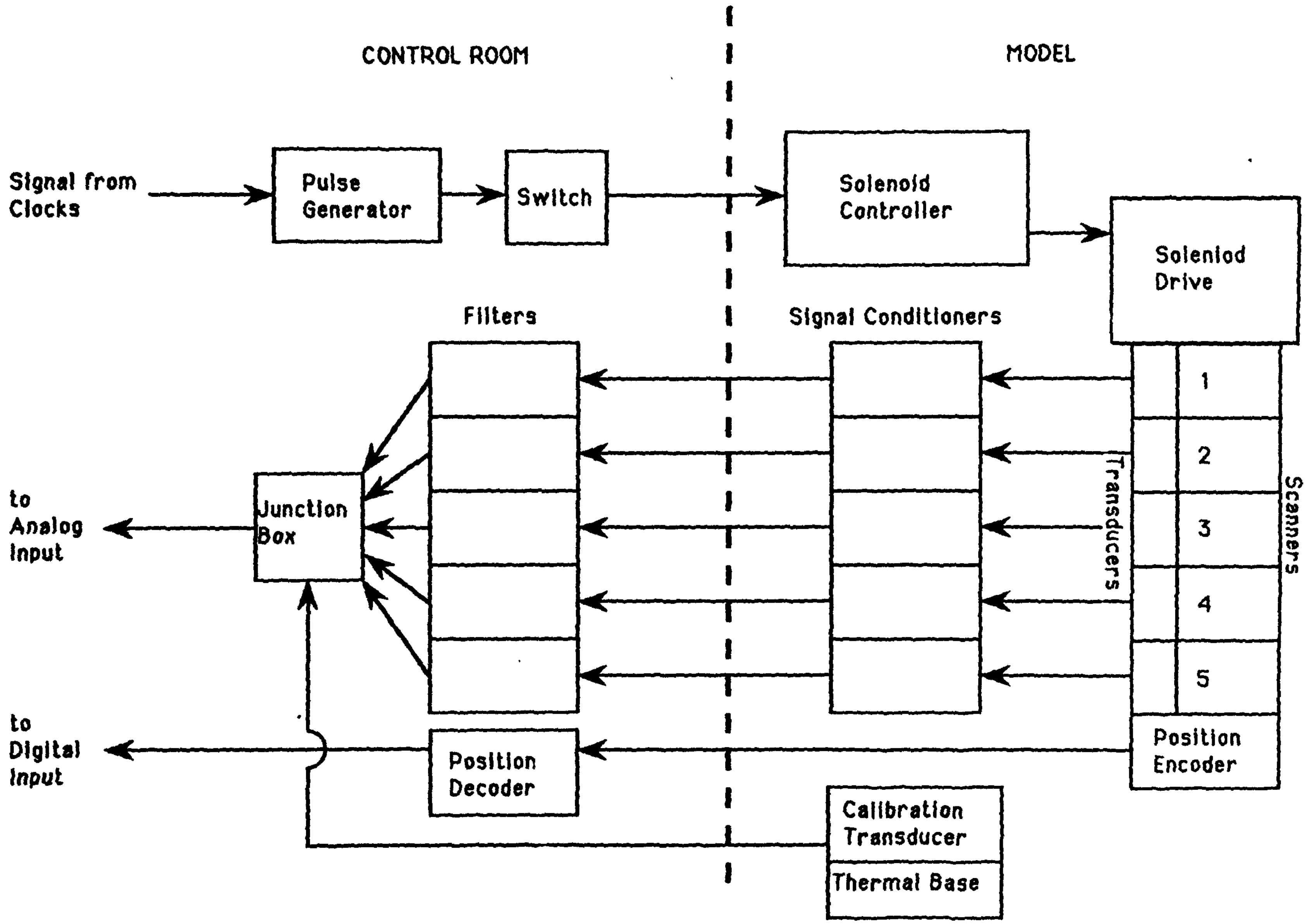


Fig. 17 Schematic of pressure measuring system

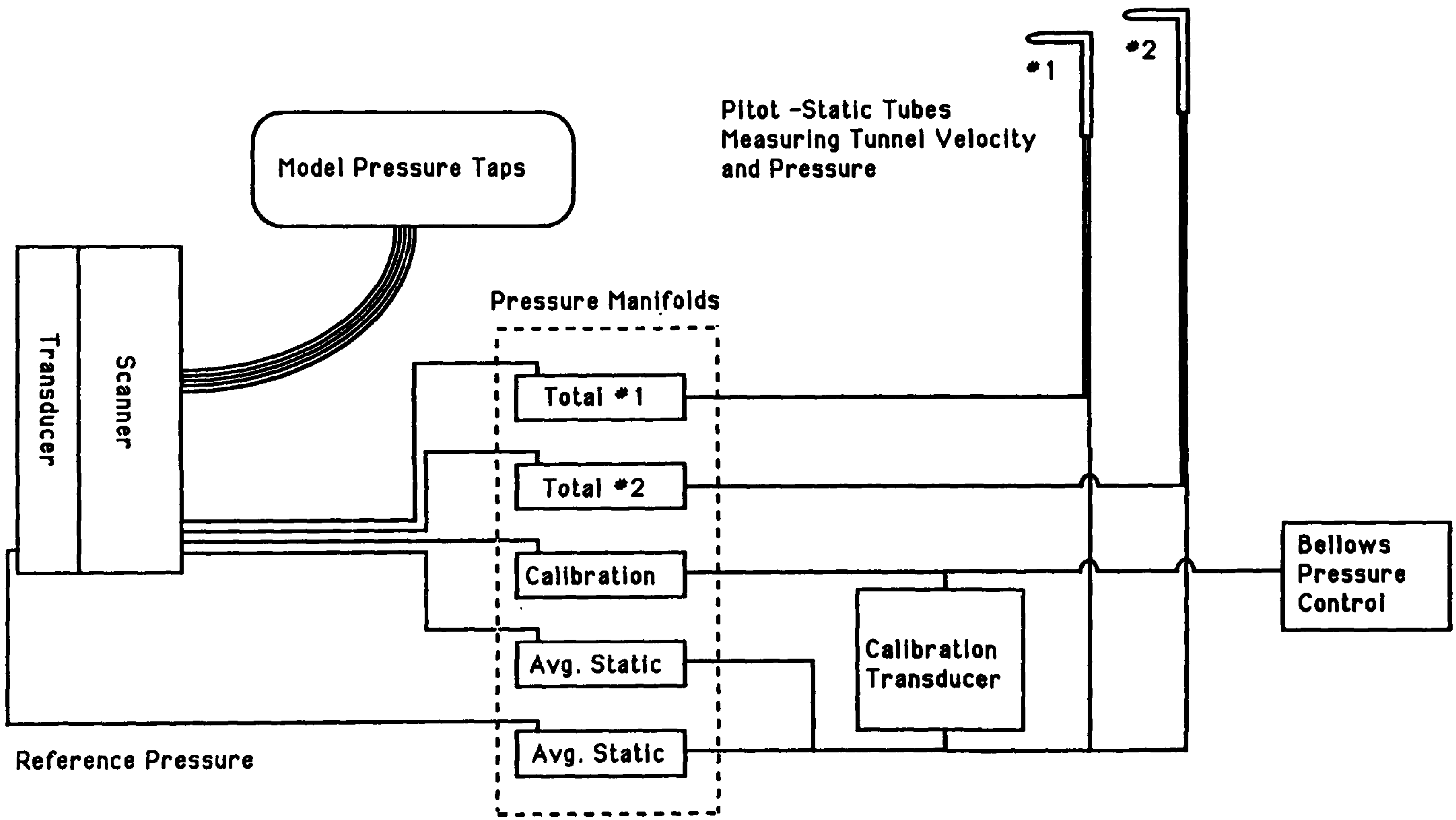


Fig. 18 Pneumatic connections made to each scanning module

REFERENCES

1. Groves, N.C., T.T. Huang, and M.S. Chang, "Geometric Characteristics of DARPA SUBOFF Models (DTRC Model Nos. 5470 and 5471)," Report DTRC/SHD-1298-01 (March 1989).