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NASA CONTRACTOR REPORT

EXPERIMENTAL RESEARCH OF THE AERODYNAMICS OF NOZZLES AND PLUMES AT HYPERSONIC SPEEDS

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National Aeronautics and
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Ames Research Center
Moffett Field, California 94035

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16. Abstract

This study was conducted to experimentally characterize the flow field created by the interaction of a single-expansion-ramp-nozzle (SERN) flow with a hypersonic external stream. Data were obtained from a generic nozzle/afterbody model in the 3.5-Foot Hypersonic Wind Tunnel of the NASA Ames Research Center. The model design and test planning were performed in close cooperation with members of the NASP CFD team, so that the measurements could be used in CFD-code-validation studies. This final report presents a description of the experiment and the extent of the measurements obtained. The experimental results are presented in the cited references.

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ABSTRACT

This study was conducted to experimentally characterize the flow field created by the interaction of a single-expansion ramp nozzle (SERN) flow with a hypersonic external stream. Data were obtained from a generic nozzle/afterbody model in the 3.5-Foot Hypersonic Wind Tunnel of the NASA Ames Research Center. The model design and test planning were performed in close cooperation with members of the NASP CFD team, so that the measurements could be used in CFD code validation studies.

This final report presents a description of the experiment and the extent of the measurements obtained. The design and fabrication of the model, air-supply system, and jet-plume traversing-probe mechanism was completed. One major test entry into the 3.5 Ft Tunnel was completed. Most objectives of this test were met, including oil-flow and shadowgraph flow visualization photographs, ramp surface pressure measurements, ramp boundary-layer measurements, and probe-surveys the jet-plume pitot pressure and flow direction. Three papers were published presenting the test plans and preliminary computations and three additional papers were written to be published next year presenting experimental results from the test.

NOMENCLATURE

Moo	Freestream Mach number
Mj	Jet Mach number at combustor-exit station
P(t,oo)	Freestream total pressure
P(t,j)/Poo	Representative operational parameter, ratio of jet-total-pressure to freestream static pressure
Re/m	Freestream unit Reynolds number (per m)

INTRODUCTION

The next generation Transatmospheric Vehicles, such as the National Aero-Space Plane (NASP), will rely on airbreathing propulsion systems during all or part of their mission performance. These propulsion systems will be based on scramjet engine technology or some derivative thereof. The problems of propulsion and all the other major problems of hypersonic flight are intensified by the fact that major portions of the flight environment cannot be simulated by existing ground-test facilities at hypersonic velocities. Therefore, numerical simulations of aerodynamic and propulsion flow fields obtained from computational fluid dynamics (CFD) codes will be used extensively to complement data obtained from experimental facilities. Confidence in predictions of the codes can be developed only by making detailed computational/experimental comparisons at conditions for which experimental data are available. The data sets used for these comparisions should represent the best that are available from existing experimental facilities with respect to accuracy, level of detail, and simulation of the flight environment. Predictions of the validated codes should then provide the most reliable estimates of the increments in performance or design parameters associated with the differences between the available test conditions and the flight environment.

To contribute to the NASP research effort, NASA Ames Research Center has undertaken a comprehensive experimental and computational investigation of selected generic components of the NASP configuration. An important aspect of the NASP research is the propulsion system airframe integration. Accordingly, the capabilities of the Ames 3.5-Foot Hypersonic Wind Tunnel have been used to plan a series of tests on a generic nozzle afterbody configuration. One of the principal features of the 3.5-Foot Tunnel is a two-minute test time allowing time to survey the characteristics of the jet plume. The external flow is air, the same as flight. The available external Mach numbers of 5 to 10 cover a large part of the hypersonic, continiuum flight range. A relatively large, full span model can be tested that has the desired turbulent boundary layer over the forebody ahead of the jet plume. A relatively large ramp can be designed for flow measurements. The relatively large jet plume and the rather long test time available allows detailed surveys of the jet. Therefore a model was designed that would be acceptable for CFD code validation and hypersonic experimental research. The goals were to investigate the physical characteristics of one-sided nozzle jet flow (single expansion ramp nozzle - SERN) and the interaction of the jet plume with a simulated SERN afterbody and with an external hypersonic flow, and, most importantly, to make adequate measurements of the jet-plume flow field.

In the design of the model there were several significant departures from simulation of the flowfield associated with a flight vehicle:

- The generic geometry was highly simplified.
- The test gas was cold air (room temperature). Hence, the temperature and velocity was low and the density high relative to flight simulation requirements.
- The jet specific heat ratio was 1.4, which is higher than the values expected for a flight vehicle. The effect of specific heat ratio variation on the pressure distribution near the simulated combustor exit is highly significant.

However, the experimental values will provide a valuable "first step" validation for CFD codes.

The test plan included measurements of jet mass flow, pressure distributions, heat transfer, flowfield surveys, boundary-layer surveys, skin friction, flowfield visualizations (shadowgraph and oil flow) and (later) laser velocimetry. It was determined that "cold" air (room temperature) could be used without liquifaction condensation in the jet gas over much of the test range at Mach numbers of 5 and 7 and, maybe partially, at 10. "Cold" helium can be used for test conditions where air liquifaction condensation is encountered. Nozzle-pressure ratios (jet-total-pressure freestream-static-pressure) are to be similar to the flight values. The possibility of testing with a hot gas at temperatures up to 2400 deg R was incorporated by including the capability of installing hydrogen-gas generators (a test proposed by the General Applied Sciences Laboratory (GASL).

The primary objective of this research program is to conduct a carefully controlled and accurate experiment to provide high quality building-block and benchmark data that characterize nozzle flows in the hypersonic speed range under appropriate conditions to validate advanced computational methods. A second objective is to incorporate in the experimental-model design the capability of using the model to obtain design data of universal interest to the design teams by parametrically investigating and characterizing the dominant nozzle afterbody interactions that can affect propulsion and/or vehicle performance. Of particular importance will be to gain a basic understanding of how a jet functions at hypersonic speeds and how the jet plume interacts with the afterbody.

This final report summarizes the fundamental issues of the experimental and code-validation requirements; the design and construction of the model, the jet-plume-probe traversing unit, and the air/gas jet supply system; the test plan; the extent of the measurements obtained; and the status of the experiment, including deferred construction and tests. One test entry was accomplished at a Mach number of 7.3 using "cold" air (room temperature) as the jet gas. Preliminary test plans and computations were presented in references 1 to 3. The experimental results are published in references 3 to 6. Three internal reports were written summarizing previous research pertainent to this experiment (references 7 to 9). Fourteen other internal documents are listed in references 10 to 23, describing the fundamental issues, model design, and test planning of the experiment.

FUNDAMENTAL ISSUES

Flight Confirmation vs. CFD Code Validation

Flight confirmation tests and CFD code validation tests are different. Flight confirmation tests are more demanding. Jet flows must simulate high temperatures, high external Mach numbers, the correct ratio of specific heats and avoid tunnel and jet-gas liguifaction. CFD code validation tests are typified by simplified generic models and by flow similarity compromises.

Flight conditions.- Flight Mach numbers are high. The nozzle inlet flow is characterized by external compression by the wing from low free stream static pressure to a useable inlet static pressure. The nozzle internal flow is characterized by the addition of the maximum practical amount of heat by the process of combustion (hence, the use of hydrogen). The jet temperatures are high. There are losses in total pressure due to recompression shock losses and internal skin friction. Adding heat further decreases the total pressure (not obvious, but this has been concluded from engine studies), increases the static pressure, decreases the local Mach number, and increases the local speed of sound (potential of thermal choking). The nozzle flow expands to static-pressure equilibrium with the free-stream static pressure, forming a constant-pressure shear layer that is highly turbulent. The specific heats of the free stream and jet flows are different, which complicates the flow problem. Adding heat also increases the jet velocity. The jet ends up with a flow that has lower total pressure and Mach number but higher velocity, which translates to a higher static pressure, hence, thrust.

CFD-code-validation flow-similarity compromises.-
Thermal simulation:
It is generally agreed that, in most experiments, it is not necessary to simulate high temperatures in order to have a valid comparison with CFD codes.

Shear-layer dynamic simulation:
Dynamic simulation requires simulating the velocity and density ratios. It is generally agreed that it is not necessary to simulate the dynamics of the shear layer between the jet and freestream flows. The important similarity parameters are Mach number, nozzle-pressure ratio, and ratio of specific heats.

Ramp Mach number:
For air, a Mach number at the end of the ramp of about 4.5 is approximately the maximum value that can be achieved by expanding room-temperature air without oxygen-condensation fog. Higher Mach numbers require heated air or lighter gases. Inviscid methods indicate that the jet flow over a large part of the ramp is independent of the freestream flow, even at Mach 5.

Ratio of specific heats:
It has been previously determined the ratio of specific heats of the jet and the external flow do not have to be simulated for a valid "first step" comparison with CFD codes. Of course, the effect of specific heat must be validated with other experiments to "step up" as close as possible to the flight conditions.

"Cold" (room temperature) air:
Jet-plume tests with cold air are valid for a "first step" comparison with CFD codes.

FACILITY

The Ames 3.5-Foot Hypersonic Wind Tunnel is a closed-circuit, blow-down wind tunnel which has interchangeable, contoured, axisymmetric nozzles. Nozzles for test-section Mach numbers of 5.3, 7.3, and 10.3 are available. The test gas is air, which is heated by a storage heater containing aluminum oxide pebbles. Usable test time depends upon test conditions, and varies from 0.5 to 4 minutes. The test section is an open jet which is enclosed by a chamber 3.7 m in diameter by 14.6 m in length containing the model support system and instrumentation. The available ranges of stagnation pressure and stagnation temperature are 690 to 12,400 kPa (100 to 1800 psia) and 667 to 1922 deg K, respectively, although the usable ranges depend upon the Mach number. The tunnel is normally operated at the minium stagnation temperature which will prevent condensation of the test-section flow.

HYPERSONIC SERN MODEL

Generic Departures from Design-Like Configuration

Generic departures from a design-like configuration are as follows:

- A low-speed plenum is required for inlet flow from the nozzle-gas supply system.
- The internal nozzle configuration is a 2-D nozzle for first-step code-validation simplicity.
- There was an interest in testing with three "engine-like" compartments, and so provision was made for three nozzle compartments using splitter plates. This arrangement also allows generic representation of asymmetric-nozzle flow by constructing a nozzle that is asymmetric between compartments.
- The cross-sectional nozzle aspect ratio is a compromise: small enough that the nozzle-throat height is not intolerably small and the model span not too large for tunnel flow blockage, but large enough that the centerline flow is nearly 2D.
- The forebody is wedge shaped for hypersonic flow.

CFD Guide To Model Design

CFD-code-development results were also a good guide to the design of the SERN model . Two-dimensional computations of representative nozzle flow were used to design such components as -

ramp geometry: angle, length, curvature, width.
ramp flow conditions: boundary layer, induced thrust and moment
cowl length
cowl exit shear-layer profile
jet-plume characteristics: Mach no., static pressure,
low temperature (oxygen-condensation fog)
geometry interaction
instrumentation location

Boundary-layer transition on the internal walls of the nozzle is an important problem. Previous nozzle studies have shown that boundary-layer transition on the nozzle wall usually occurs at the throat section unless wall suction is applied maintain a laminar boundary layer.

It was found that at hypersonic speeds the external jet flow might not interact with the flow on the afterbody ramp due to the highly swept characteristic lines. Hence, the ramp surface flow conditions with tunnel wind on might be similar to tunnel wind-off tests, which might be useful and save some tunnel wind-on runs.

Model Design

The design procedure was an iterative process between the overall model size (length, height, and width), nozzle size, combustor station height and width (a selected representative internal nozzle station), nozzle-throat height, cowl exit height and width, and afterbody ramp size.

External design.- The development of the concept for the generic SERN model is shown in figures 1 and 2. Figure 1 shows a schematic of the engine-airframe integration design criteria for hypersonic flight. Figure 2 shows a schematic of the nozzle model approach. The area of research on the full configuration is circled - the nozzle afterbody region; the nozzle afterbody representation is shown below. The design objective was to provide a model that would create a nozzle-jet-plume flow over an afterbody that could be used to conduct experimental and computational reasearch into the nozzle afterbody interaction. The model had to have a forebody, which was chosen to be a hypersonic wedge. Since the model was not to have an inlet, compressed air was to be supplied to a plenum in the model from which the jet plume would emanate from a cowl through a nozzle section.

The primary features of the SERN model design and are shown in the schematics in figure 3 and in the photographs in figure 4. The model is designed to be the maximum size that can be accommodated by the facility at $M_\infty = 10.3$. The side view of the model is a parallelogram. The forebody is a hypersonic wedge whose upper surface is a flat plate with a nominally sharp leading edge (0.13 mm radius). This relatively short flat-plate configuration was chosen with the intent of providing a nearly uniform external flow above the cowl with a thin, turbulent boundary layer at the cowl trailing edge. A thin boundary layer at the cowl trailing edge, relative to a characteristic vertical dimension such as the combustor exit height, is representative of a realistic configuration in which the cowl length is small with respect to the vehicle length. The 20- deg included angle of the leading edge was chosen as a compromise between the conflicting desires to minimize both blockage and forebody length. A row of removable boundary-layer trips is provided for the upper surface of the plate, 10.2 cm (4.00 in) downstream of the leading edge (fig. 3a). The design and location of the trips are based on experimental data reported by Hopkins et al. (refs. 24 and 25). The leading edge of the model is made of invar, to avoid warping caused by thermal stress. Most of the remaining model parts are made of 17-4PH stainless steel. The model is supported from below on a swept strut with a wedge-shaped leading edge. The strut is attached to a box beam which is a part of the model support system of the tunnel. The test section is the free-jet type and the box beam is attached to an apparatus which can be translated to insert the model into the test section after the flow is established.

Internal design.- Air or helium is supplied to a low-velocity plenum through a supply pipe in the model support strut (fig. 3). A perforated choke plate is located at the entrance of the supply pipe to the plenum (see the internal schematic in fig. 3a, the exploded schematic in fig. 3b, and the exploded photograph in fig. 4b). The choke plate lowers the pressure in the supply pipe by 76% through 111 sonic sharp-edged orifices. Two screens are located in the plenum, designed using wind-tunnel flow-screen technology to smooth the flow from the choke plate with negligible loss in total head. The internal surface of the cowl is flat, and interchangeable nozzle blocks are mounted in the model between the plenum and the instrumented ramp. The internal nozzle exit was chosen to simulate a combustor exit station - a cross section of uniform flow, as would occur in the design of a jet engine. The height of the combustor exit station, 2.03 cm (0.800 in), was a compromise, dictated by the construction tolerences of the throat height, which can be quite small at high supersonic speeds. The combustor-station height was large enough that reasonable resolution of the flow at this station could be achieved by probe surveys and that the minimum internal nozzle throat height would not be excessively small, and small enough that a signigicant region of nearly two-dimensional flow would exist on the ramp.

The nozzles were designed by the method of characteristics with a boundary-layer correction, to provide uniform flow at the combustor-exit station, except for the wall boundary-layers. Nozzles have been designed for combustor-exit Mach numbers of 1.4, 1.75, 2.6, and 3.4, which are intended to be representative of scramjet operation at the wind-tunnel freestream Mach numbers of 5.3, 7.3, 10.3, and 14, respectively.

The cowl and ramp are defined to start where the combustor section ends. An arbitrary cowl length of 10.16 cm (4.00 in) was chosen as a representative configuration. The cowl-exit Mach number is about 2.6. A ramp angle of 20 deg was chosen from 2D computations to be a nominally representative configuration. An arbitrary radius of 7.62 cm (3.00 in) was chosen to prevent boundary layer separation. A ramp length of 61.0 cm (24.0 in) was chosen from 2D computations, which indicated that free-stream pressure would be recovered near the end of the ramp. Two interchangeable ramps were used downstream of the combustor exit station. one uninstrumented ramp for oil-flow studies and one instrumented ramp for surface pressures, two boundary-layer rakes, and preston tubes.

Alternative configurations.- Various alternate configurations of the model are illustrated in Fig. 3c. A number of variations on the basic model configuration are being considered because of the desire to obtain data corresponding to both two- and three-dimensional flows, and because the external flow along the sides and below the lower surface of the body alone will not be representative of the flow about a more realistic configuration, which would be considerably more slender. It was planned that flowfields associated with most of these configurations would be evaluated by CFD computations prior to testing. Surface-flow patterns will also be evaluated experimentally in the initial phase of the test by use of oil-flow visualization.

The first (and basic) configuration is the body alone. The 2D slot nozzle can be tested at lower plenum pressures where the

1.27 cm (0.50 in) thick cover plate does not deflect, changing the internal nozzle flow. For higher pressures and for multichamber tests, two streamwise splitter plates were designed to be installed in the nozzles, extending from the contraction section to the combustor exit station and dividing the nozzles into three equal-span passages. The splitter plates are 4.76-mm thick, and have rounded leading edges and sharp trailing edges. The splitter plates also permit the possibility of a jet flow in which the flow from one passage would have a different Mach number from that of the other passeges, thus testing for asymmetric nozzle flow. Lower-surface fences (fig. 3c) were designed to be added to the body to prevent crossflow from the high-pressure region on the lower surface from interacting with flow in the upper surface.

To create a nominally two-dimensional channel flow, a configuration including large upper-surface fences was planned. A significant complication in the design of the upper-surface fences is that the side walls of the jet-flow passage are 1.27 cm (0.50 in) thick, and the inner surfaces of the fences must be flush with the inner surfaces of the jet flow passage at the end of the cowl.

The computational baseline configuration that was desired for CFD code validation was chosen to be the body with symmetrical side extensions. This choice resulted because the nominal test conditions have pressure ratios for which the jet will be underexpanded at the cowl-exit plane. The configuration with the symmetrical side extensions were designed to provide lateral extensions of the ramp so that a larger portion of the lateral-plume expansion will take place above the ramp, rather than beyond the sides of the model. The side extensions also provide an alternative method for isolating the jet plume and the upper-surface external flow from highly compressed flow along the lower surface. However, the side extensions must be faired forward to the model leading edge. This geometry will result in expansion of the external flow along the sides of the jet plume from the freestream Mach number on the top of the forebody through the 20-deg angle of the ramp extension. The cross-section of each side extension was chosen to be rectangular at each streamwise station. Both side extensions probably cannot be used at Mach 10.3 because of tunnel blockage limitations; it should be possible to obtain useful data with a single side-extension at this Mach number because the flow on the side of the model with the extension should be independent of the flow along the opposite side.

The configuration with the symmetrical side extensions was sized by allowable tunnel blockage at Moo = 7.3. A semispan configuration having a larger effective span was planned. A large fence on one side would allow testing with a large side extension on the other side.

Hydrogen air combustor.- The model was designed to accommodate two hydrogen air combustors in a side-by-side arrangement (fig. 3d). This design avoided the necessity of building a separate model for the NASP program, which had been proposed. This design also required certain specified modifications to the tunnel to accommodate a two-pound bottle of liquid hydrogen, safety features, and blow-off valves at the top of each vacuum sphere to evacuate the collected hydrogen after a run. The plan was to test with combustion with considerably excess air (a ratio of 100/1, rather than 30/1 stoichiometric), giving a maximum design jet-gas total temperature of 2400 deg R. Use of the hydrogen combustors would allow testing at Mach numbers of 10.3 and 14 without the possibility of condensation fog in the jet plume. In addition, the hot jet will allow heat-transfer data to be obtained. A ramp surface instrumented for heat-transfer measurements will be designed and fabricated for this test phase. The use of hydrogen-air combustors appears to be a unique way to provide a simpler and less expensive method for providing a heated jet than does the use of an external electric heater, which would be prohibitively expensive to build and operate.

High-temperature hydrogen air combustors.- The jet total temperature of 2400 deg R does not allow the capability of obtaining real-gas chemistry effects in the jet. Accordingly, it was determined that it was within the current design technology to design special quick-acting hydrogen combustors that would allow testing at 4000 deg R for short periods. It is feasible that such testing could be done with this same model, eithor in the 3.5-Ft Tunnel or the Ames 16-in shock tunnel (in a specially-built test cabin).

Jet-Plume Traversing Mechanism.- It was essential for this test program that jet-plume flowfield measurements be obtained as part of the CFD code-validation experiment, particularly at inflow boundaries. Accordingly, a two-degree-of-freedom probe traversing mechanism was designed for this experiment to survey the jet plume (see schematic in fig. 5). The traversing unit mounts above the model ramp and consists of a probe holder attached to a horizontal circular tube that is in turn attached to a strut that has a wedge-shaped crossection and is air cooled. The lower part of the strut that is immersed in the tunnel flow is swept. The upper part of the strut attaches to a commercially-available positioning table, remotely driven vertically by a motor-encoder assembly. The vertical positioning table is mounted in turn on a horizontal positioning table that is remotely driven transversly to the flow. The mechanism is assembled inside of a rigid box structure. The motor-encoders are designed to be remotely driven from a VAXlab.

Air supply system.- The air supply to the nozzle is obtained from the Ames 3000 psi air supply system, through a regulator system. The system is remotely controlled to provide a short response time to quickly achieve a preset jet total pressure. Photographs of the system are shown in figure 6. Figure 6a shows the first leg of the system from the connection to the 3000 psi air source (in the background) followed by dome regulators (desired pressures are preset in the dome through a regulator-solenoid-control system). The next section is a 10.16 cm (4") diameter pipe (for low-speed, smooth flow) containing a mass-flow orifice plate section (figs. 6b and c) with a differential-pressure gage, a total-pressure gage upstream and a total-temperature gage downstream of the orifice plate. The air-supply pipe is then reduced to 5.08 cm (2") diameter pipe going up into the test cabin. Figure 6d shows the next section of the air supply, a high-pressure flexible hose to the model in the test cabin. A remote-control panel was located in the tunnel control room, from where the jet total pressure could be preset before the jet air was turned on. The regulator was remotely activated eithor before or after the model was injected into the tunnel air stream.

CFD EXPERIMENTAL ISSUES FOR THIS MODEL

The interaction with the CFD requirements in this design process has illuminated the fact that the design of a generic model can add complexity to computational modeling of the flowfield by requiring the modeling of regions of flowfield that are not of interest to the code validation, but require additional CFD code modeling. In the case of this model, there is the need to compute the flow about the forebody, and to treat the various configurations. The design process cannot perfectly satisfy the CFD code validation desires, but the experimental and computational efforts must make compromises. In-other-words, it might not be possible to plan the experiment in such a way as to provide data that contains no other effects than that desired to valid the code in question. This added complexity may introduce uncertainty in regions of the flowfield which are not of primary interest, and may degrade the overall accuracy of certain computed solutions; however, efforts must be made to minimize the impact of this complexity, and to accommodate the requirements of the computational effort. It is the experimenter's objective to simplify the model design to the simplest possible CFD representation, which requires working closely with those working on the code validation.

For example, for this model:
- The model required a forebody which was to subject the jet plume to a simplified external hypersonic flow; consequently, the induced flow around the forebody and afterbody sides must be modeled.
- There could be a problem with the side-edge flow effects. Therefore, a downward fence was designed to be used, if required, contain the forebody and strut induced crossflow.
- The flow fences, that were designed for each side of the ramp to create 2-D flow, could not be simply added to each side of the model. Since the cowl wall is 1.25 cm thick, the inside surface of the fence had to be flush with the inside edge of the cowl, which simplifies the jet-plume flow, but complicates the model construction.
- The trailing edges of the cowl cannot be blunt, as is usual for hypersonic trailing edges, or else the blunt trailing-edge wakes would have to be modeled. However, it is possible that the flow will separate off the tapered, producing a larger wake than desired.
- It was desired that the baseline configuration for jet flow computations be the the jet flow with an infinitely wide ramp.

This was accomplished in the model by designing extensions to the sides, however, these the extensions had to be faired forward to the model leading edge. Thus, the sides of the ramp had to be extended along side of the nozzle to the top of the model through a 20-deg arc.

- Extending the ramp sides farther than 7.5 cm (3 in) increases the tunnel blockage. However, one side edge (left side) can be extended to 15 cm (6 in) by using the semispan method, by putting one 2D fence on the right side of the basic body.
- The geometry of the extensions of the basic model was simplified to a rectangular shape at every cross section.
- The side-edge extensions probably cannot be used at Mach 10 due to tunnel blockage, although one side edge could be tried.

INSTRUMENTATION AND MEASUREMENTS

Two pitot tubes and a thermocouple probe are located in the plenum chamber, downstream of the screens, to measure jet stagnation pressure and total temperature, from which jet mass-flow rate can be obtained. An ASME orifice meter is located in the air supply pipe upstream of the model to obtain a second measurement of the jet mass-flow rate, obtained from the measured differential pressure across the orifice plate and the pipe total pressure and total temperature. Interchangeable ramp plates downstream of the combustor exit station were constructed. A noninstrumented ramp plate was intended for oil-flow visualization studies. A second ramp plate was extensively instrumented with static-pressure orifices. Locations of the static-pressure orifices on the ramp and on the forebody of the model are shown in a plan view in figure 7. There are 120 static-pressure orifices mostly on the ramp, but some on the forebody top and sides of the model. The static-orifice tubes are connected to arrays of electronically-scanned, solid-state transducers installed within the model (fig. 8). Three small, fixed pitot rakes are located off the centerline of the model; one at the midsection of the forebody, and two on the ramp. Skin-friction instrumentaion included three Preston tubes installed at the same ramp station as the first boundary-layer rake and two floating-element balances on the ramp. Values of skin friction can also be estimated from the velocity profiles obtained from the rake data, using the Clauser method.

To assure that the flow was uniform at the combustor-design station a pitot-survey apparatus was planned that mounts on the ramp so that pitot surveys can be made at the combustor exit with the cowl off and no tunnel flow. Miniature five-hole pitot/flow-direction probes were designed to attach to the probe holder of the two-degree-of-freedom traversing unit (figs. 5, 9 and 10). A miniture total-temperature probe, of the type described by Kussoy, et al. (ref. 26) is available. The probe position can be recorded from the position output of the drive-motor-encoder assemblies.

Shadowgraph and oil-flow visualization methods can be used in the tests.

DATA ACQUISITION

The NASA 3.5-Ft Tunnel data-acquisition computer was to be used to acquire test-section free-stream conditions, jet-stagnation conditions, jet mass-flow rate, rake-pressure data, Preston-tube data, and model static-pressure data. These data could be transferred to both a NASA VAX and a separate VAXlab for analysis. The traversing unit was to be remotely controlled, and the probe pressure and position data acquired, by the VAXlab. A high-speed link between the VAXlab and the NASA VAX allows access to all of the test data through either machine. Data analysis codes and graphics software on both machines provides extensive quick-look data, and allows data analysis to proceed in parallel with the data acquisition task.

TEST CONDITIONS

The complete test program included the following baseline test conditions. Off-design conditions were also to be included:

Moo = 5.3, 7.3, 10.3, and (maybe) 14
Mj = 1.4, 1.75, 2.6, and 3.4
Ptj/Poo = 100, 300, 5,000, and 50,000
Max. available Re/ft = 5, 7, 3, and 1 million
Jet gas: Cold air at Moo = 5.3 and 7.3
Cold air and/or helium at Moo = 10.3
Helium at Moo = 14

CONSTRUCTION

Figure 4 shows photographs of the hypersonic SERN model, as constructed. Not all model parts were constructed due to budgetary constraints. The basic model was constructed without side extensions, side fences, internal-splitter plates, and heat-transfer ramp. The traversing mechanism was constructed. Five 5-hole probes were constructed, three large-size probes with 1.1 mm (0.042 in) dia. tubes and two with 0.54 mm (0.022 in) dia. tubes (fig. 9). The smaller probes have less flow interference, but more pressure lag. The air-supply system was installed without an access pipe to helium. The hydrogen-gas generators were not built.

FIRST TEST

One test was completed with the model at a free-stream Mach number of 7.3. The primary objective of this experiment was to obtain a detailed set of data at the following baseline test conditions:

Moo = 7.33	Mj = 1.75
Ptoo = 6897 kPa (1000 psi)	Ptj/Poo = 300
Re/ft = 5 million	Jet gas: Cold air (Room temperature)

The combustor exit Mach number of 1.75 and pressure ratio of 300 are representative of scramjet operation at the freestream Mach number of 7.3 The details of the test are described in references 4 to 6.

Tunnel Installation

Figure 11 shows a schematic of the model and traversing unit installed in the tunnel test section. The model is supported from below on the swept strut. The strut is attached to a box beam which is a part of the model insertion system of the tunnel. The box beam is attached to an apparatus which can be translated laterally to insert the model into the test section after the flow is established. The whole apparatus can also be pitched to change the angle of attack of the model. The traversing unit is mounted as shown. on a box beam above the model. This beam is a counterpart to that which is used for supporting the model.

Figure 12 shows photographs of the model-alone installation in the 3.5-Ft Tunnel and figure 13 shows photographs of the model and probe traversing unit installation.

Test Procedures

In brief, detailed traverses were first made with a pitot tube at the combustor exit with the cowl removed and no tunnel flow, for the purpose of assuring that the flow was uniform. Surveys of the jet-plume cross section were made at several streamwise stations from the cowl exit rearward. The surveys generally consisted of a lateral survey at constant height above the ramp and a vertical survey at the centerline of the ramp. Some vertical surveys were made off center and also off the left side of the model. Some surveys extended through the model bow shock wave into the external tunnel flow field. The survey-point locations and spacing were selected to adapt to the flow field, so that more points were taken through the shock-wave and shear-layer regions.

Test Conduct

The test installation started on October 2, 1991 and the first part of the test was conducted. The model was removed starting December 8 for several weeks to accommodate another test. On February 6, 1991, the reinstallation of the model started. On February 14 the traversing unit was installed. Wiring and pressure tubing installation took until March 5, when the first run was recorded. Four model stations were surveyed with the traversing mechanism and 5-hole probe with some surveys with a total-temperature probe. The last survey runs were on March 28. Both the model and the survey mechanism were then removed and the 5-hole probe was mounted in the tunnel for calibration. Two unused 5-hole probes were also mounted in the

3-probe holder. Calibration runs were made over an angle range of 30 deg. The test ended on April 5. The 5-hole probes were subsequently calibrated at additional Mach numbers of 2.5 and 3.5 in a probe-calibration wind tunnel.

PROJECT TEST PLAN OUTLINE

An outline of the total Project Test Plan is given below with the Status of each item.

PART	STATUS
I. NOZZLE JET FLOW CONTROL SYSTEM CHECK	2/90
II. NOZZLE FLOW SURVEYS: WIND OFF, COWL OFF	3/90
TWO SLIDE TABLES ATTACHED TO RAMP OR C-STRUT	
III. BOUNDARY LAYER TRANSITION	
FOREBODY TOP SURFACE	SHADOWGRAPH
RAMP	?
IV. FLOW VISUALIZATION	
OIL FLOW	11/90
RAMP, SIDES, TOP	
SHADOWGRAPH	11/90
V. RAMP MEASUREMENTS	
PRESSURES, BOUNDARY LAYER RAKES, PRESTON TUBES	11/90
VI. JET PLUME SURVEYS;	
5-HOLE PROBE	3/91
TOTAL TEMP. PROBE	3/91
VII. 5-HOLE PROBE CALIBRATION	
Moo = 7.3	4/91
Moo = 2.5, 3.5 (MDRL)	4/91
VIII. RAMP BOUNDARY-LAYER SURVEYS	
3-HOLE PROBE WITH JET TRAVERSING MECHANISM	NO
3-HOLE PROBE WITH B.L. TRAVERSING MECHANISM	NO
IX. REPEAT WITH SIDE EXTENSIONS	DEFERRED
Moo = 5.3 & 7.3	
X. OFF DESIGN NOZZLES	DEFERRED
M = 1.5 & 2.6 NOZZLES AT Moo = 7.3	
ASYMMETRIC NOZZLE WITH SPLITTER PLATES	
M = 1.5 ON LEFT, M = 1.75 IN CENTER & RIGHT	
ALT: M = 1.5 IN CENTER	
XI. NOZZLE INTERNAL DISTURBANCES	DEFERRED
XII. RAMP HEAT TRANSFER	DEFERRED
HYDROGEN COMBUSTION	

TEST CONDITIONS:

AIR	
Moo = 7.3	YES
Moo = 5.3	DEFERRED
Moo = 10: LIMITED DATA NEAR COWL	DEFERRED
Moo = 14 (maybe)	DEFERRED
HELIUM	DEFERRED

Moo = 10

I. WIND OFF SURVEYS, HELIUM — DEFERRED
II. WIND ON SURVEYS, HELIUM — DEFERRED

TEST RESULTS

One paper was published during the test period, presenting preliminary results from the current Test entry (Ref. 3). Three more papers are expected to be published in 1991, presenting the results (Refs. 4 to 6).

FUTURE PLANS ON HOLD

The 3.5-Ft Tunnel is scheduled for a major modification, which will take it out of operation for a period of up to two years. It was proposed to test the model during the down time by using the test cabin as a vacuum chamber, however, the test cabin is now unavailable. Therefore, the continuation of the following test program for this model is on hold:

(1) Conduct vacuum-chamber tests in 3.5-Ft Tunnel test cabin.
Ramp boundary-layer measurements.
Modify remote control system for air/helium supply to record orifice-plate mass flow instrumentation with the tunnel data processing system.
(2) Finish fabricating the second priority model parts.
Side extensions.
Splitter plates and nozzle for asymmetric-nozzle test.
(3) Conduct helium gas tests at Mach 10.
Install helium pipe line.
(4) Conduct hydrogen-combustion tests.
Modify the tunnel for hydrogen-jet testing.
Fabricate and bench test GASL hydrogen combustors (GASL).
Modify the model for the GASL hydogen combustors.
(5) Design and construct the heat-transfer ramp.
Conduct ramp heat-transfer test.

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1. Spaid, Frank W., Keener, Earl R. and Ruffin, Stephen M.: Design Aspects of a Hypersonic Nozzle/Afterbody and Code Validation Experiment. Paper No. 50, 5th National Aero-Space Plane Symposium, NASA Langley Research Center, Hampton, Va., October 19, 1988.
2. Ruffin, S. M.; Venkatapathy, E.; Keener, E. R.; and Nagaraj, N.: Computational Design Aspects of a NASP Nozzle Afterbody Experiment. AIAA Paper No. 89-0446, 27th Aerospace Sciences Meeting, Reno, Nev., January 9-12, 1989.
3. Spaid, Frank W., Keener, Earl R., and Ruffin, Stephen M.: Experimental Results and CFD Code Validation for a Hypersonic Nozzle Afterbody Flow Field. Paper No. 123,

9th National Aero-Space Plane Technology Symposium, Orlando, FL, November 1-2, 1990.

4. Ruffin, S. M.; Venkatapathy, E.; Keener, E. R.; and Spaid, F. W.: AIAA Paper No. 92-0387, 30th Aerospace Sciences Meeting, Reno, Nev., January 1992.
5. Spaid, F. W., and Keener, E. R.: Experimental Results for a Hypersonic Nozzle/Afterbody Flow Field. AIAA Ground Testing Conference, Nashville, Tenn., July 1992.
6. Spaid, Frank W., and Keener, E. R.: Experimental Results for a Hypersonic Nozzle/Afterbody Flow Field. NASA TM, 1992.

Internal Documents

7. Keener, Earl R.: Comments on Proposed Experiment to Determine Reynolds Analogy Factor. NASA Internal Memo, Feb. 1989.
8. Keener, Earl R.: Review of the Flat Plate Boundary-Layer Data of Hopkins and Keener and Heat Transfer Data of Polek from the Ames 3.5-Ft Hypersonic Wind Tunnel. NASA Internal Memo, March 1989.
9. Keener, Earl R.: Review of Preston-Tube and Velocity-Profile Correlation Methods for Indirectly Obtaining Surface Shear Stress at Supersonic and Hypersonic Speeds. NASA Internal Memo, June 1989.
10. Project LOG.
11. Fundamental Issues of Hypersonic Sern Model Experiment.
12. Design Development of Hypersonic Sern Model.
13. Design of Internal Nozzles for Hypersonic Sern Model.
14. Coordinates of Internal Nozzles for Hypersonic Sern Model.
15. Design of choke plate for Hypersonic Sern Model.
16. Design of Internal-Flow Screens for Hypersonic Sern Model.
17. Computation of Ramp-Boundary Layer from Nozzle Throat Using Schnoz plus Cebeci/Smith CFD programs.
18. Work Statement for Design of Hypersonic Sern Model.
19. System Operating Procedures for Air Supply System.
20. Instrumentation for Hypersonic Sern Model.
21. Research Tasks for Hypersonic Sern Model.
22. Test Plan for Hypersonic Sern Model.
23. Data Processing for Hypersonic Sern Model.
24. Hopkins, Edward J., Keener, Earl R. and Louie, Pearl T.: Direct Measurements of Turbulent Skin Friction on a Nonadiabatic Flat Plate at Mach Number 6.5 and Comparison With Eight Theories. TN D-5675, 1970.
25. Keener, Earl R. and Hopkins, Edward J.: Turbulent Boundary-Layer Velocity Profiles on a Nonadiabatic Flat Plate at Mach Number 6.5. NASA TN D-6907, August 1972.
26. Kussoy, M. I.; Horstman, C. C.; and Acharya, M.: An Experimental Documentation of Pressure Gradient and Reynolds Number Effects on Compressible Turbulent Boundary Layers. NASA TM 78488, 1978.

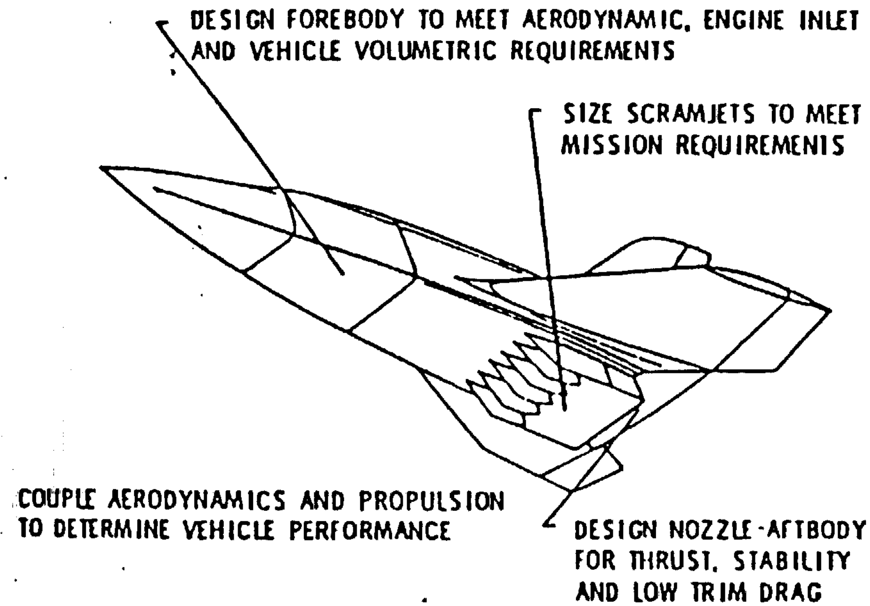


Figure 1.- Engine-airframe integration design criteria for hypersonic flight.

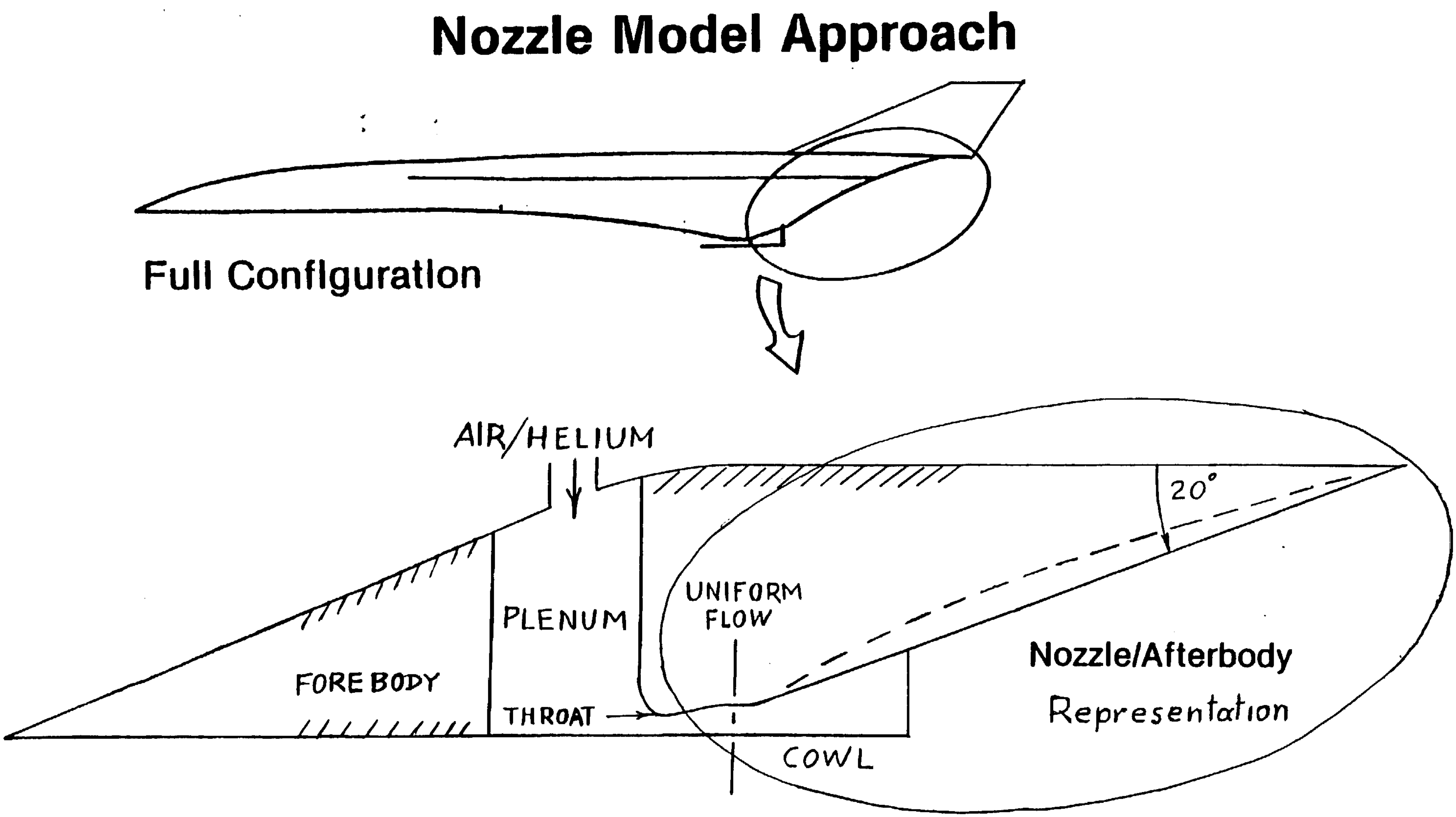
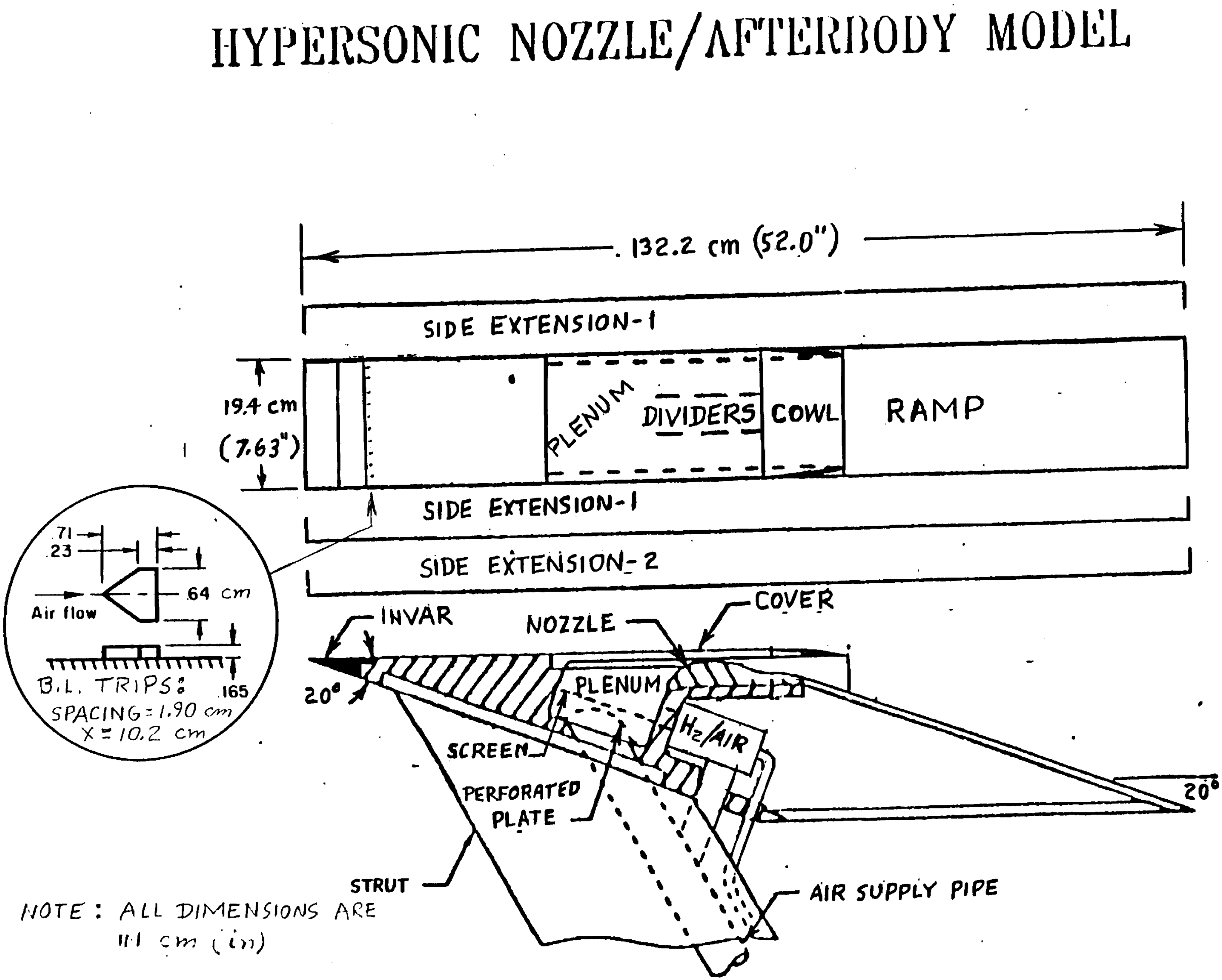
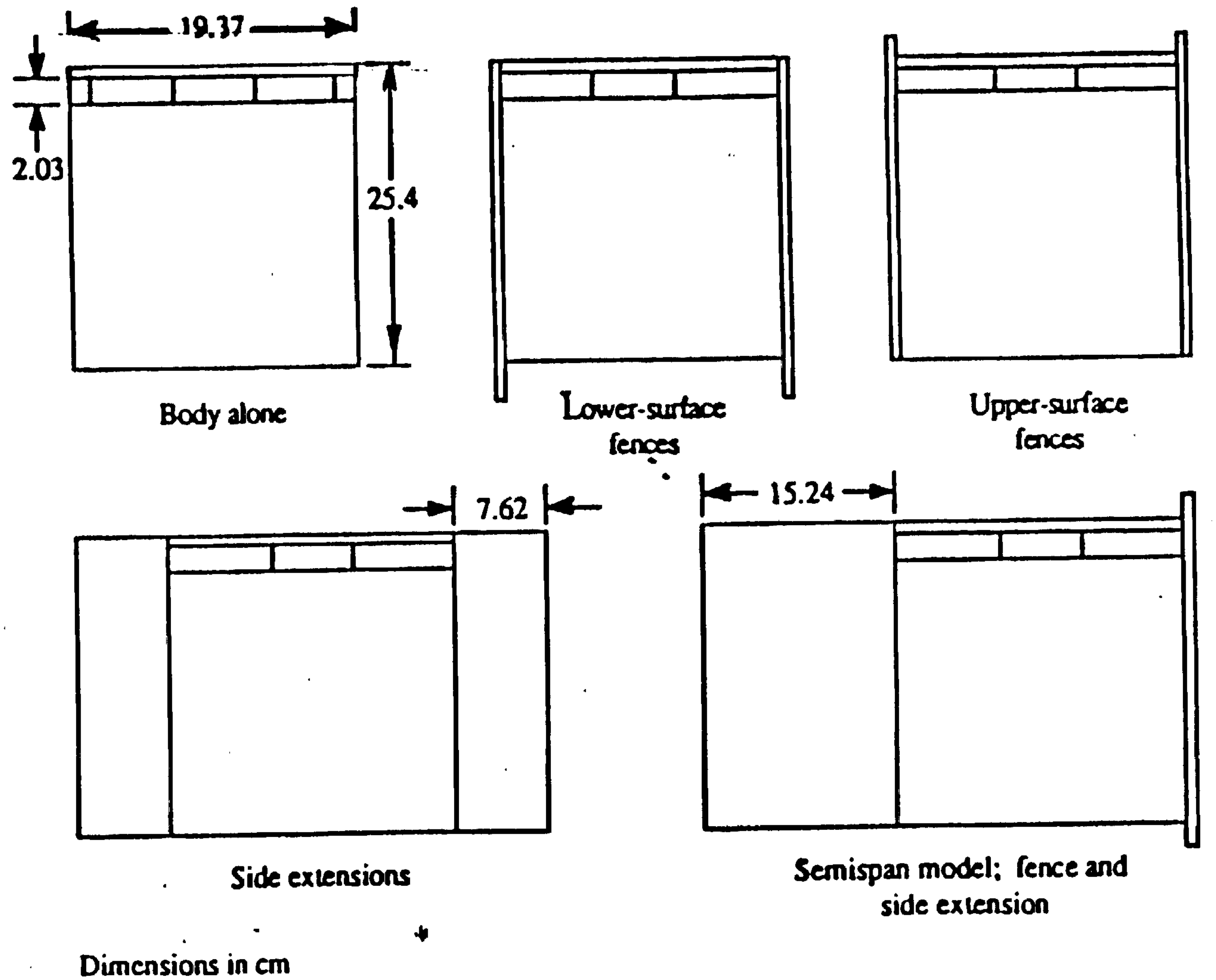


Fig. 2. Schematic of the development of the nozzle/afterbody model approach.



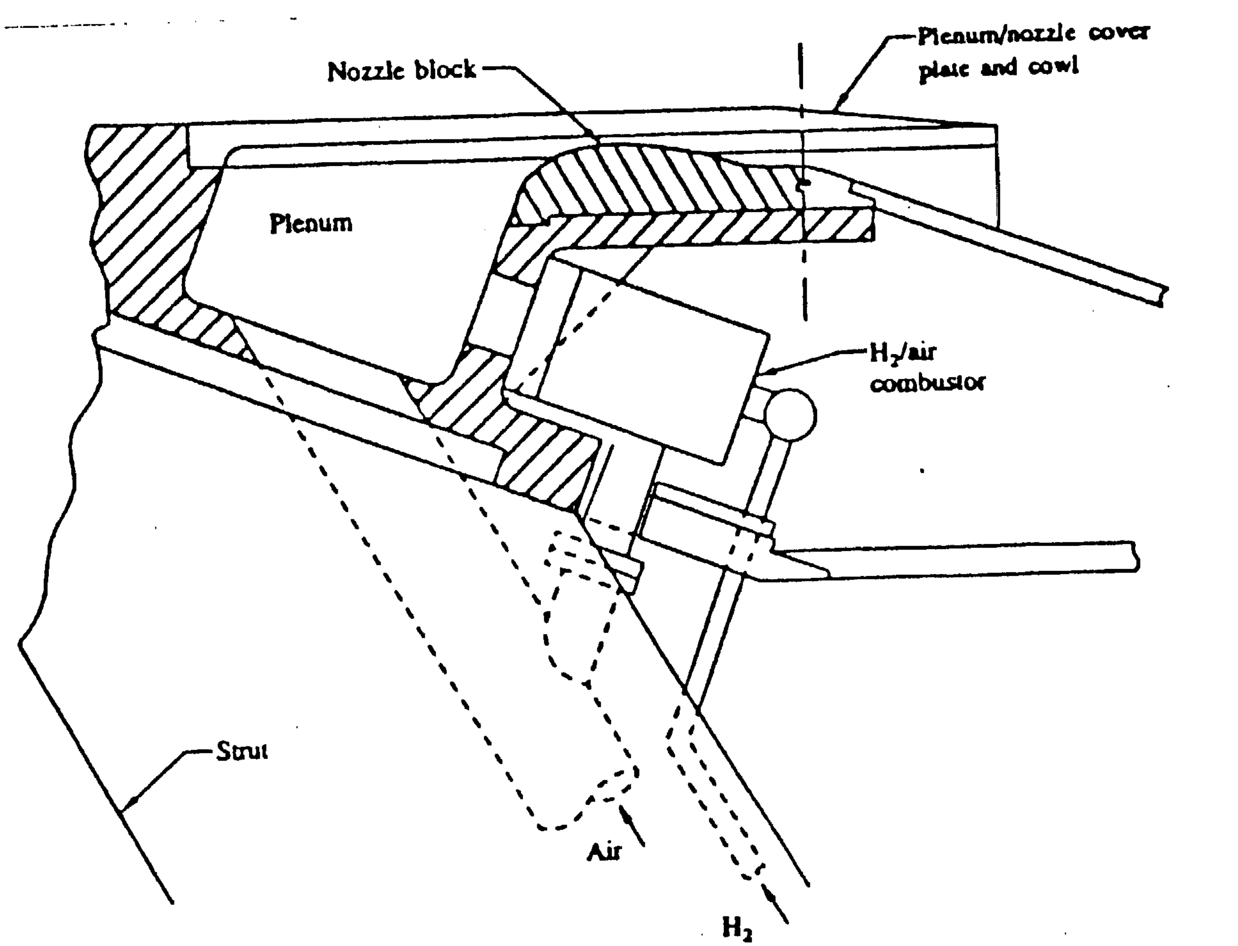
a. Basic model and side extensions.
Fig. 3. Schematic of hypersonic SERN model.

ALTERNATE CONFIGURATIONS, REAR VIEWS

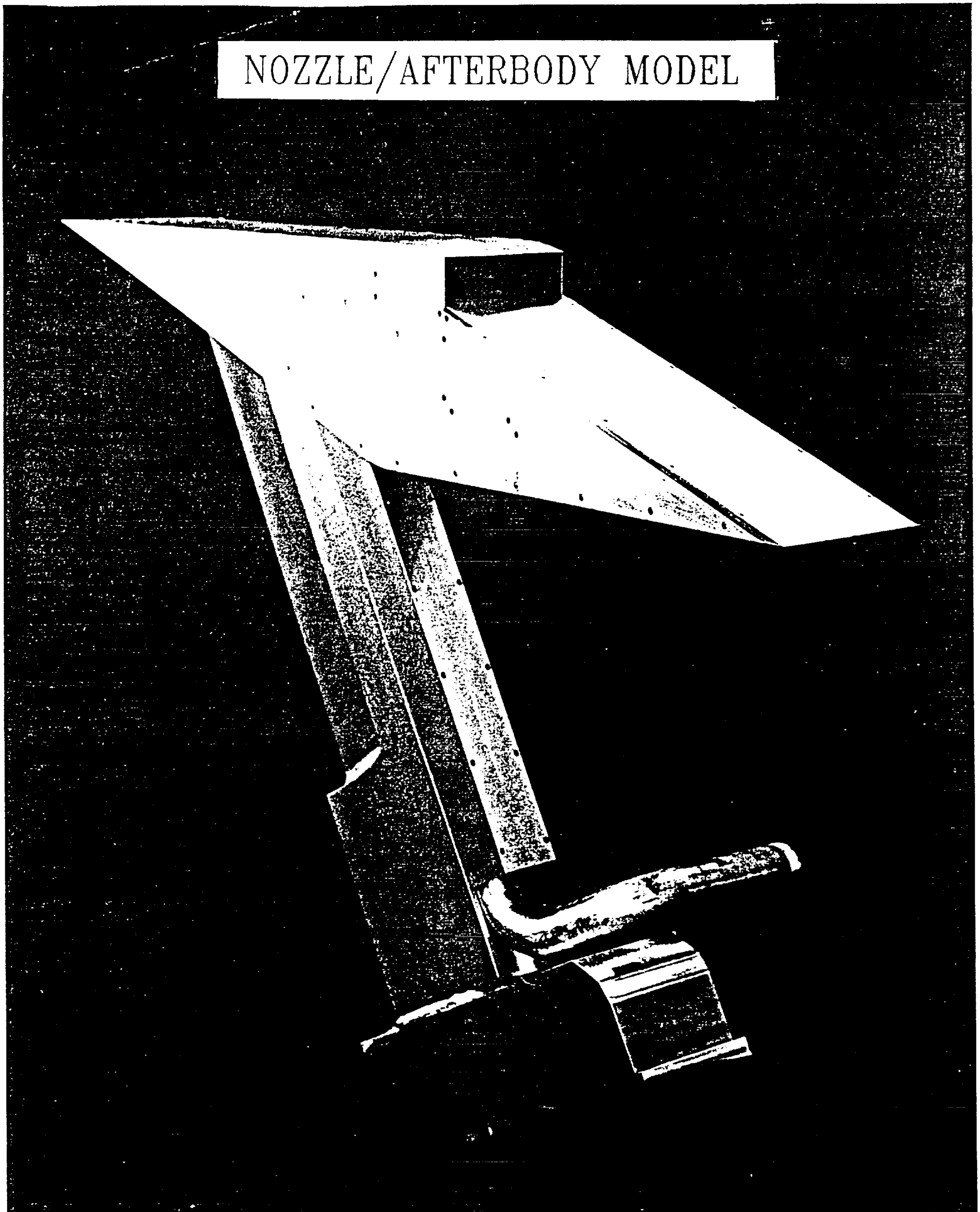


c. Alternate configurations, rear views.
Fig. 3. Schematic of hypersonic SERN model.

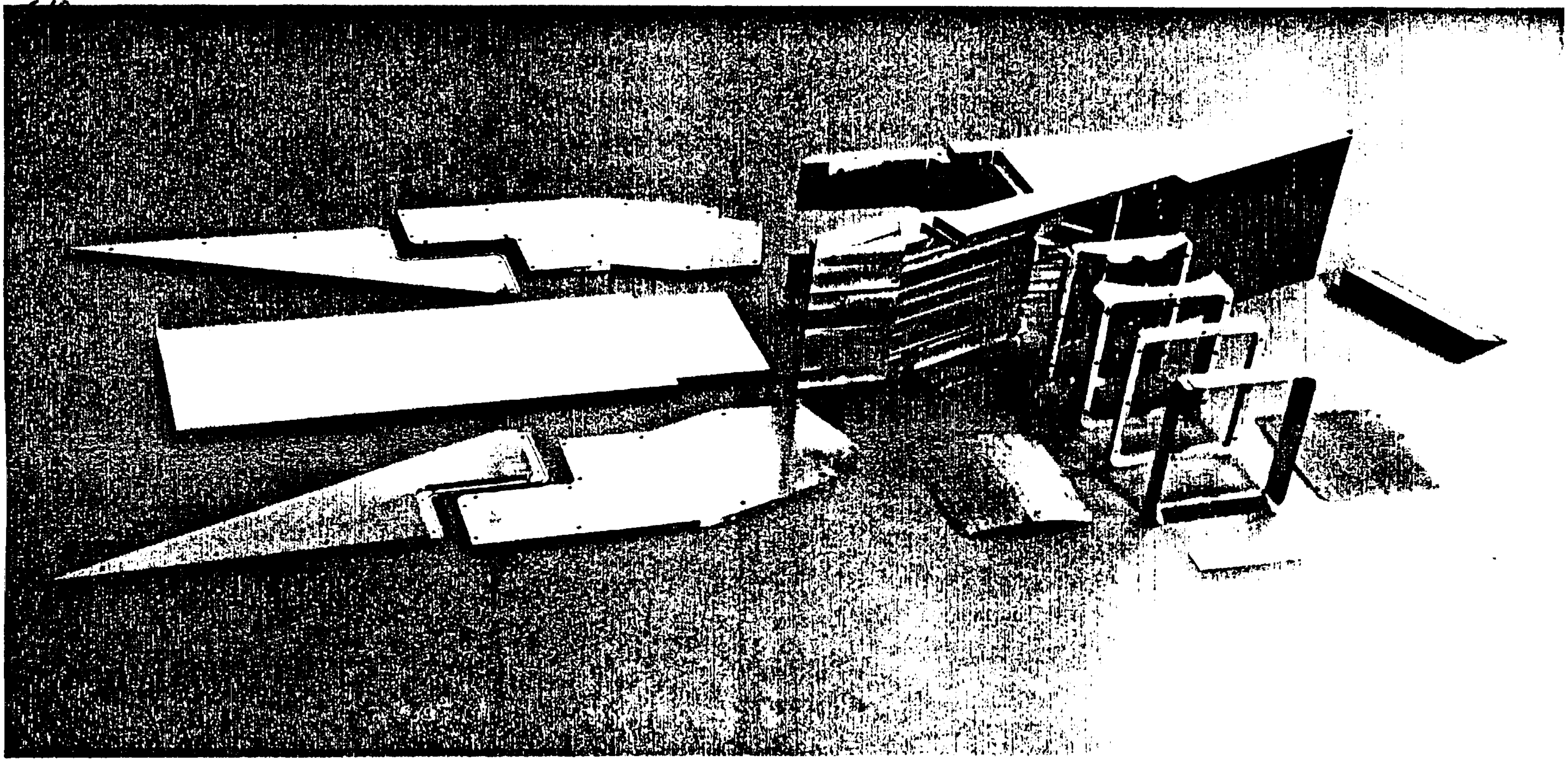
HYDROGEN/AIR COMBUSTOR INSTALLATION



d. Hydrogen/air combustor installation.
Fig. 3. Schematic of hypersonic SERN model.



a. 3/4 rear view of model and strut.
Fig. 4. Photographs of hypersonic SERN model.



b. Exploded view of the model parts
Fig. 4. Photographs of hypersonic SERN model.

JET PLUME TRAVERSING UNIT

5-HOLE PITOT-PRESSURE AND FLOW-DIRECTION PROBE

STATIC PRESSURE AND TOTAL TEMPERATURE PROBES

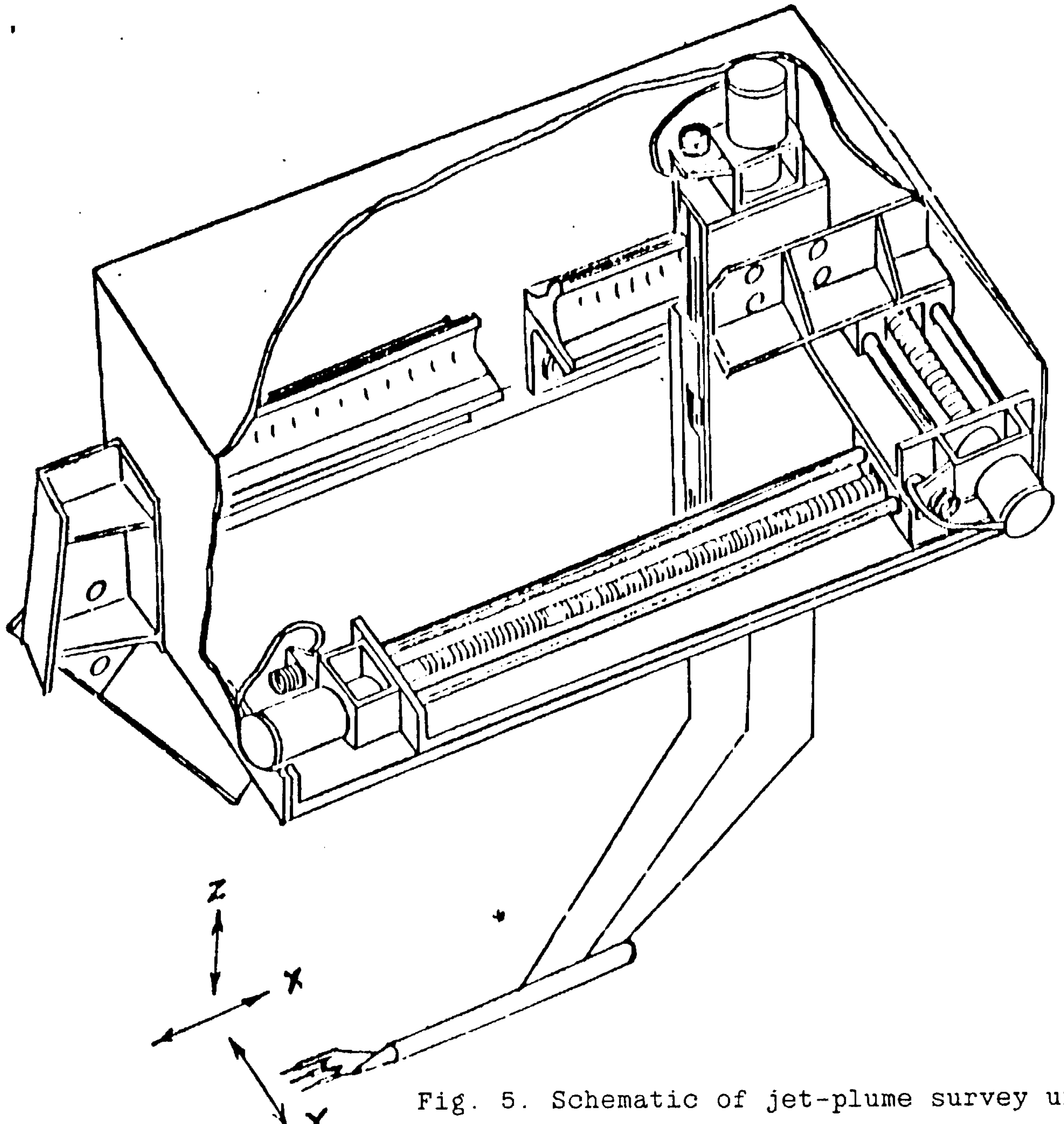
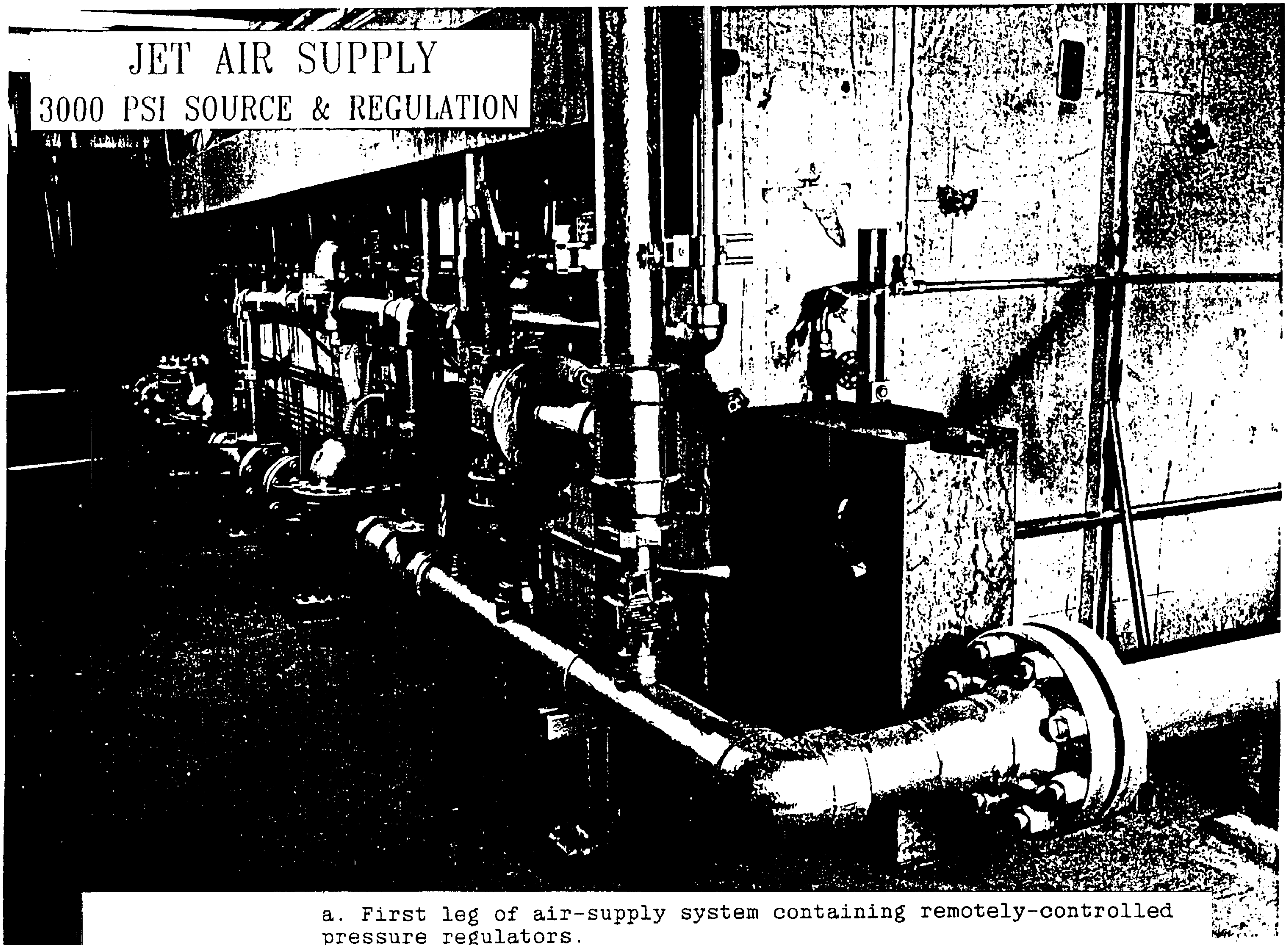
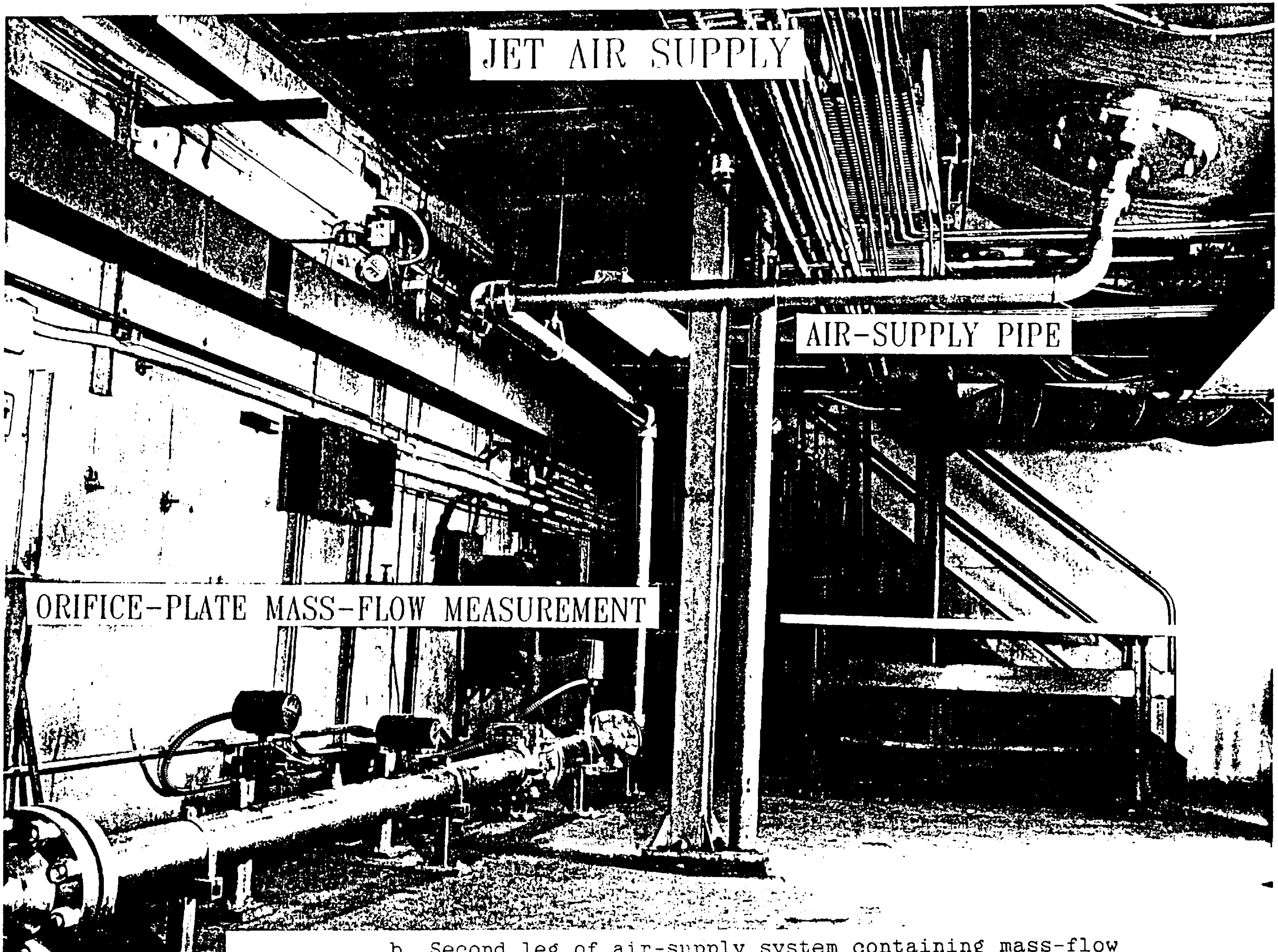


Fig. 5. Schematic of jet-plume survey unit.



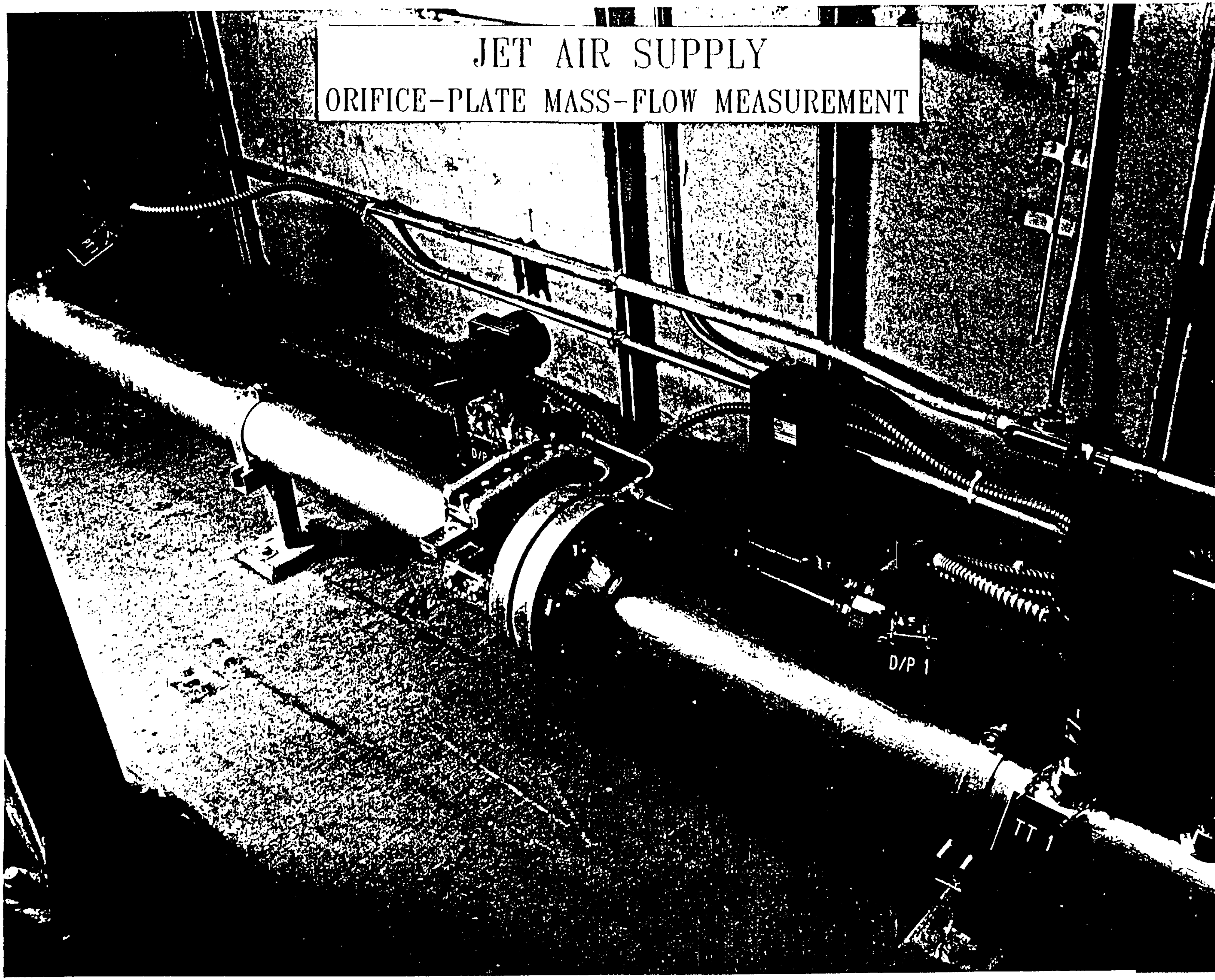
a. First leg of air-supply system containing remotely-controlled pressure regulators.

Fig. 6. Photographs of model air-supply and orifice-plate mass-flow measuring system.



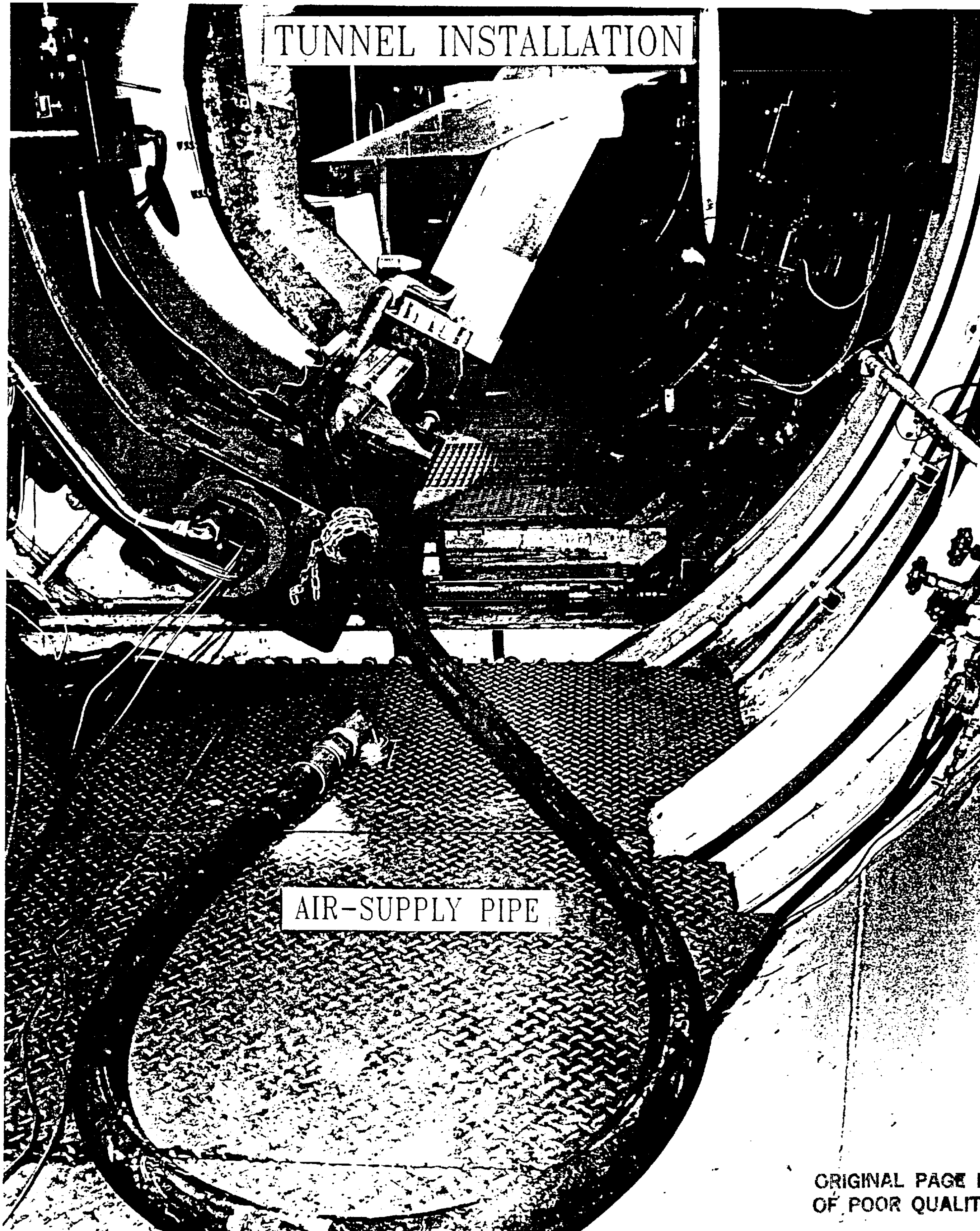
b. Second leg of air-supply system containing mass-flow orifice-plate system and pressure and temperature transmitters.

Fig. 6. Photographs of the model air-supply and orifice-plate mass-flow measuring system.



c. Orifice-plate section and pressure and temperature transmitters

Fig. 6. Photographs of model-alone installation in Ames 3.5-Ft Hypersonic Wind Tunnel



d. Model and air supply pipe

Fig. 6. Photographs of model-alone installation in Ames 3.5-Ft Hypersonic Wind Tunnel.

HYPERSONIC NOZZLE/AFTERBODY MODEL

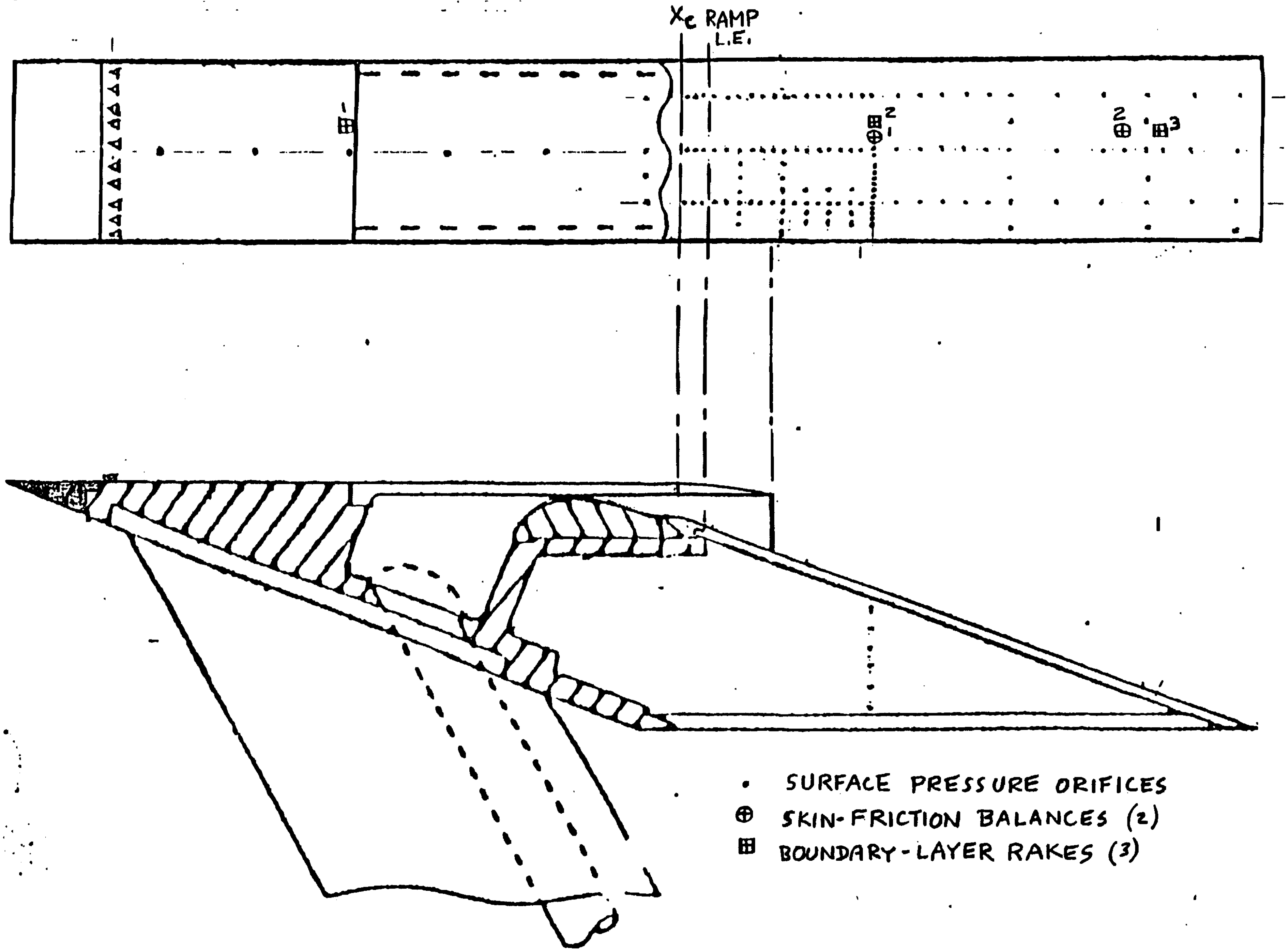


Fig. 7. Plan view of model instrumentation locations

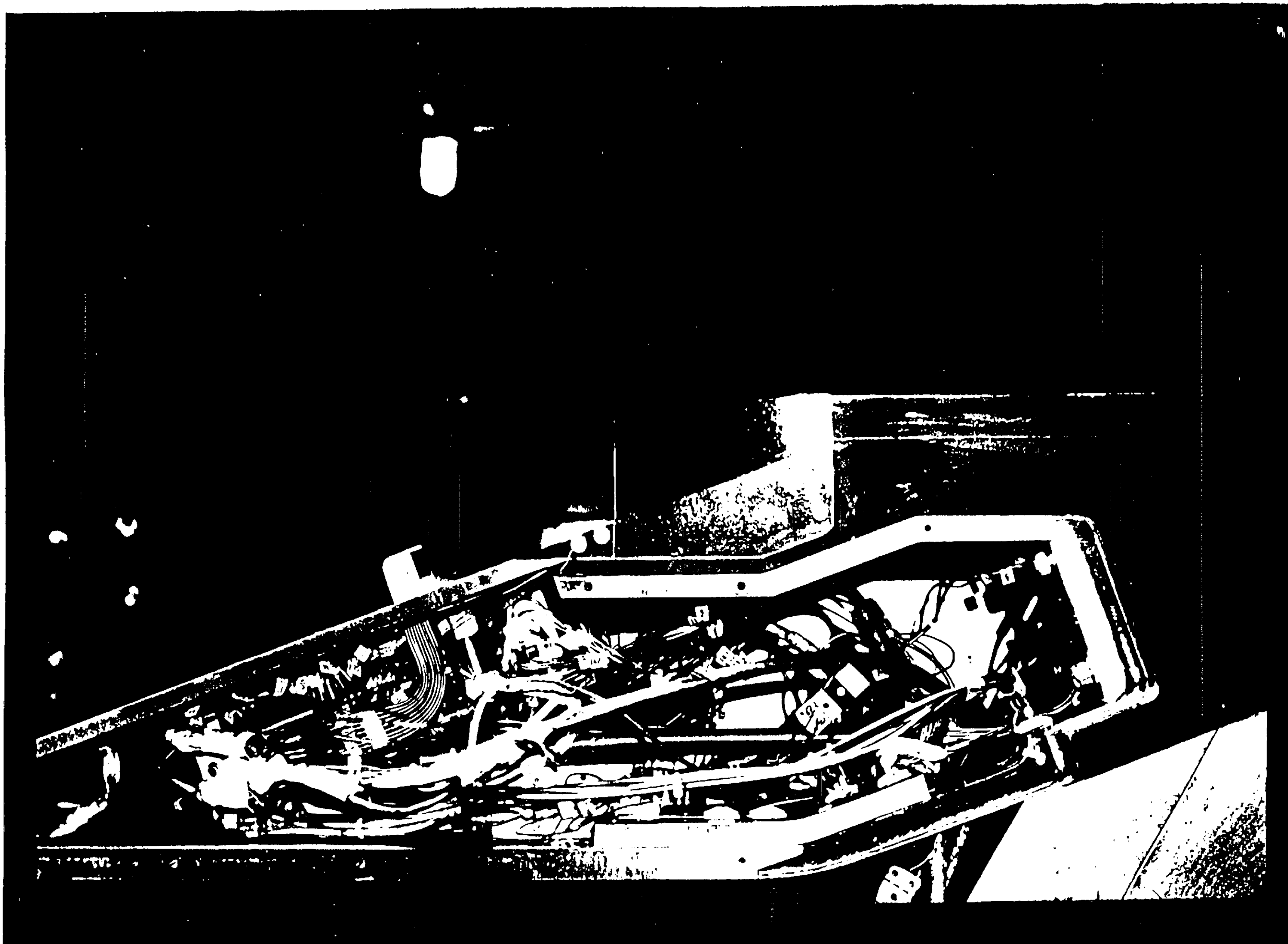


Fig. 8. Photographs of model instrumentation compartment.

Probe Tip Details

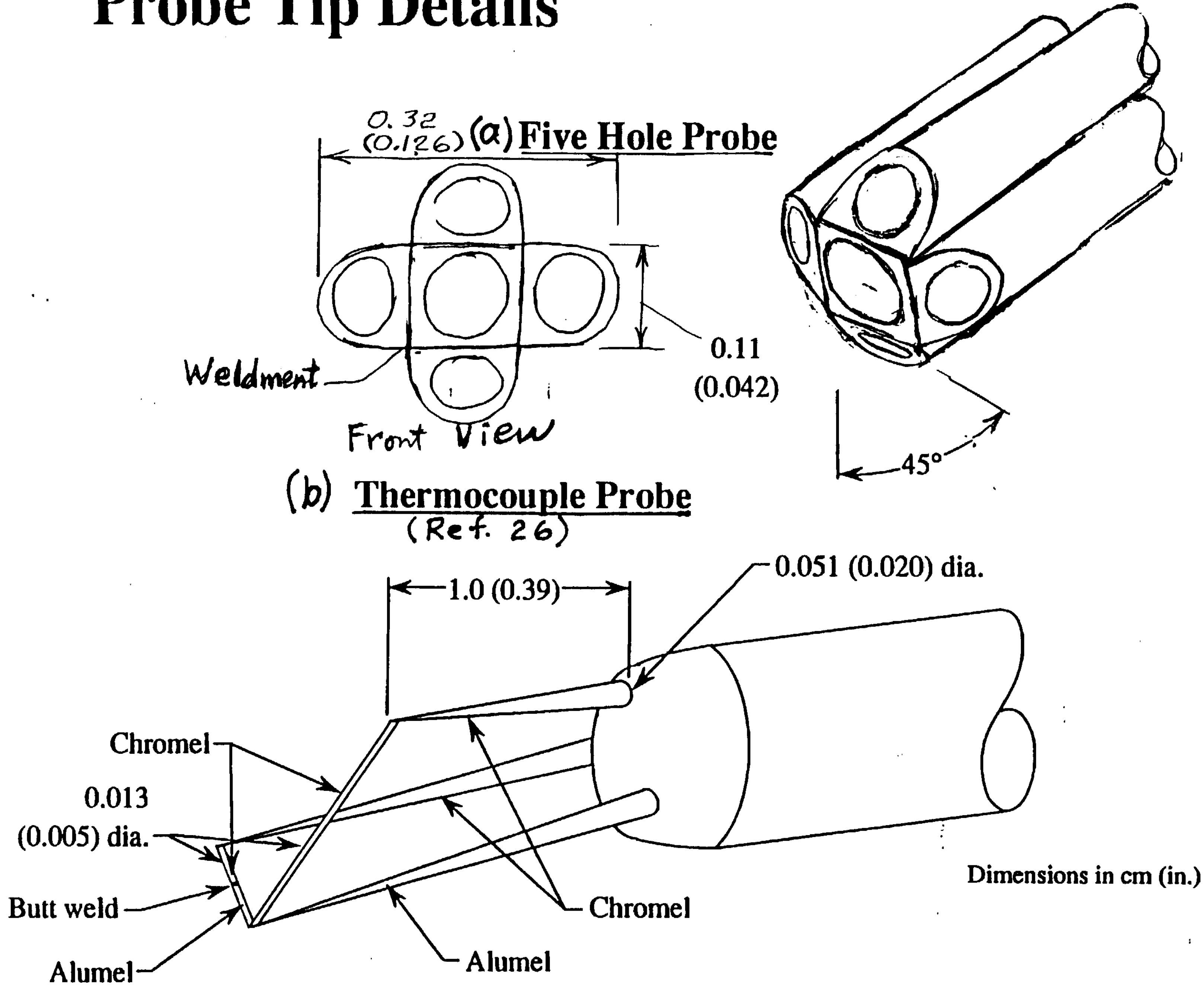
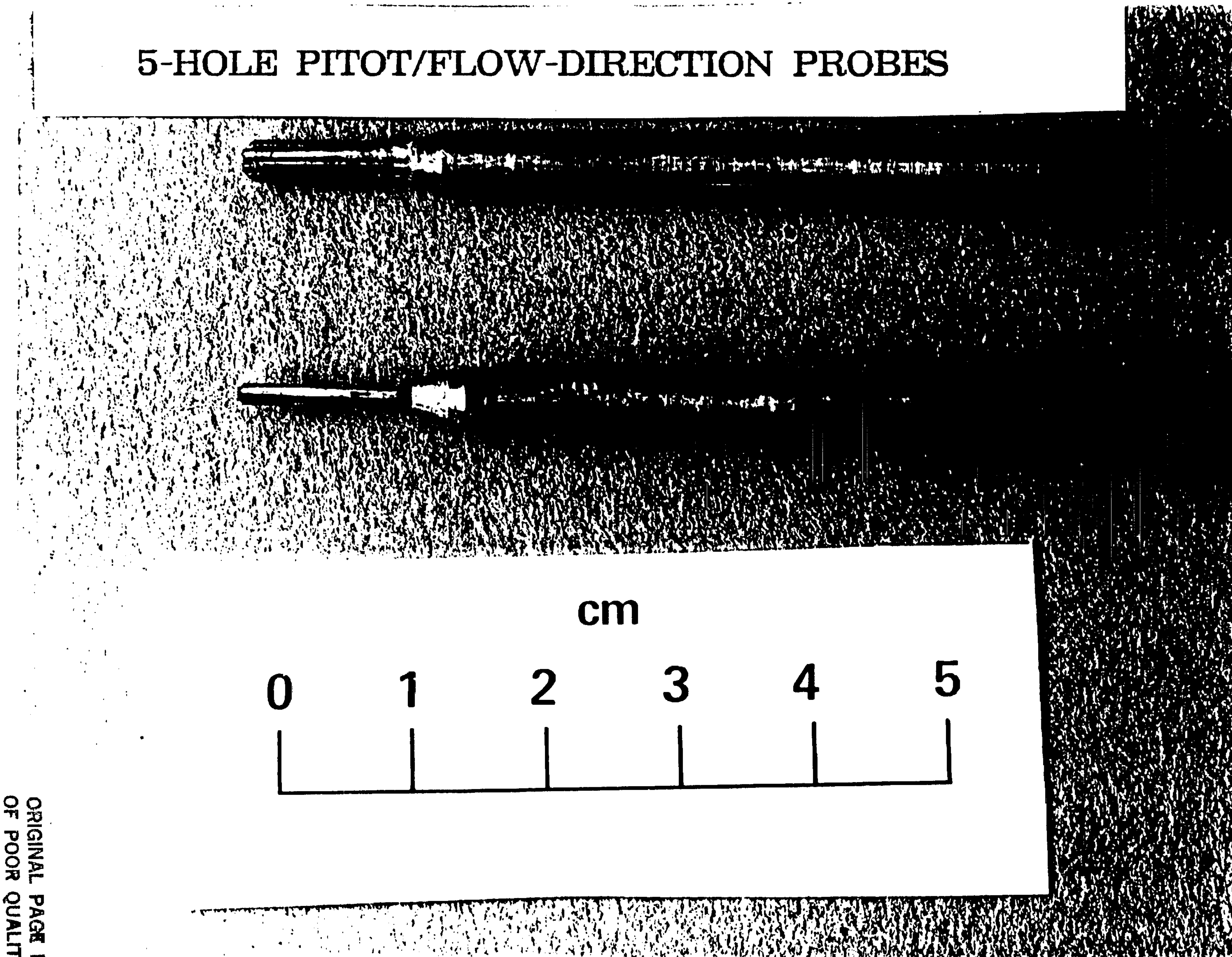


Fig. 9 . Sketches of probes.



(a) Top view.

Fig. 10. Photographs of 5-hole probes.

5-HOLE PITOT/FLOW-DIRECTION PROBES

(b) End view

Fig. 10 Photographs of 5-hole probes.

MODEL AND TRAVERSING UNIT INSTALLATION

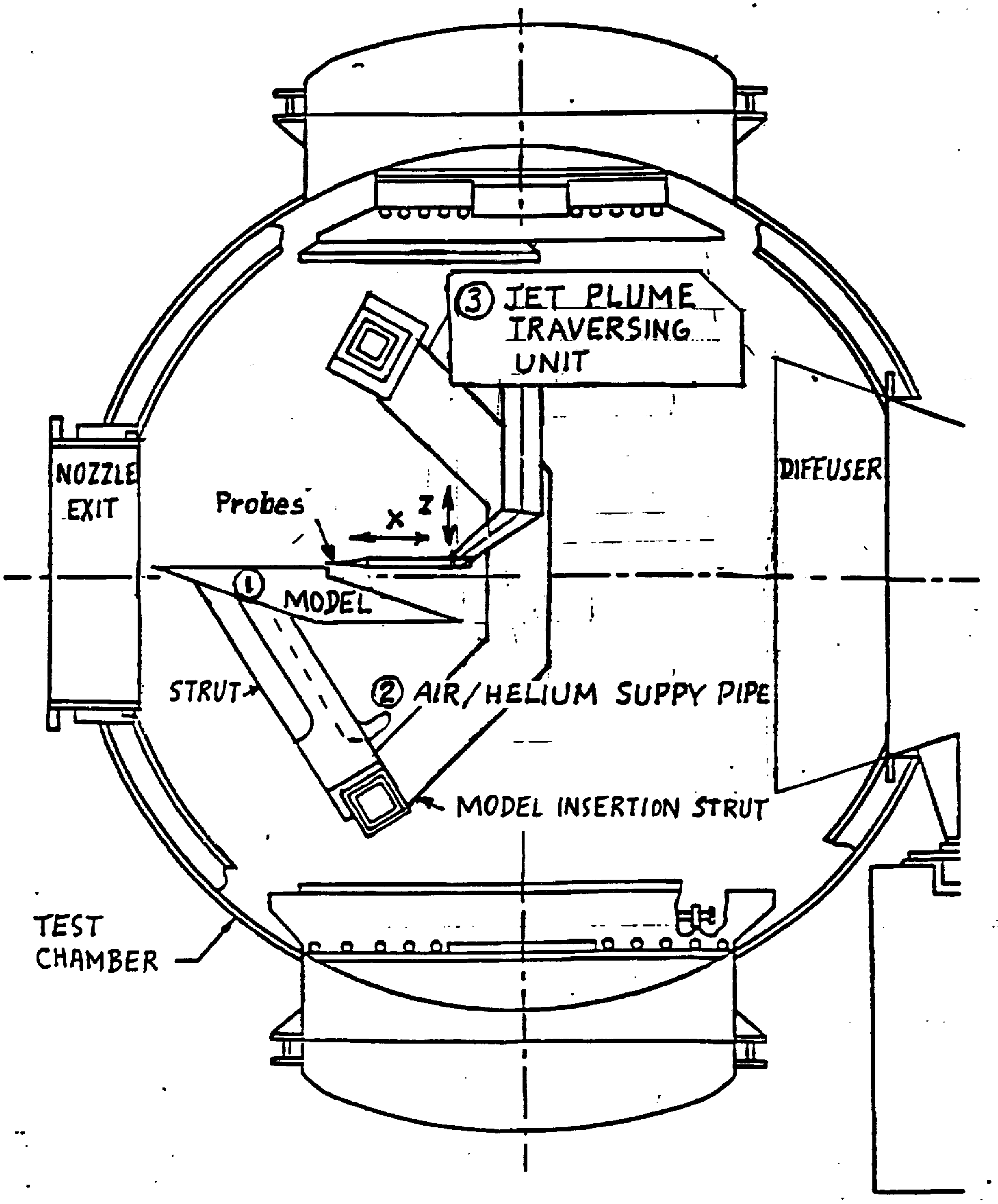
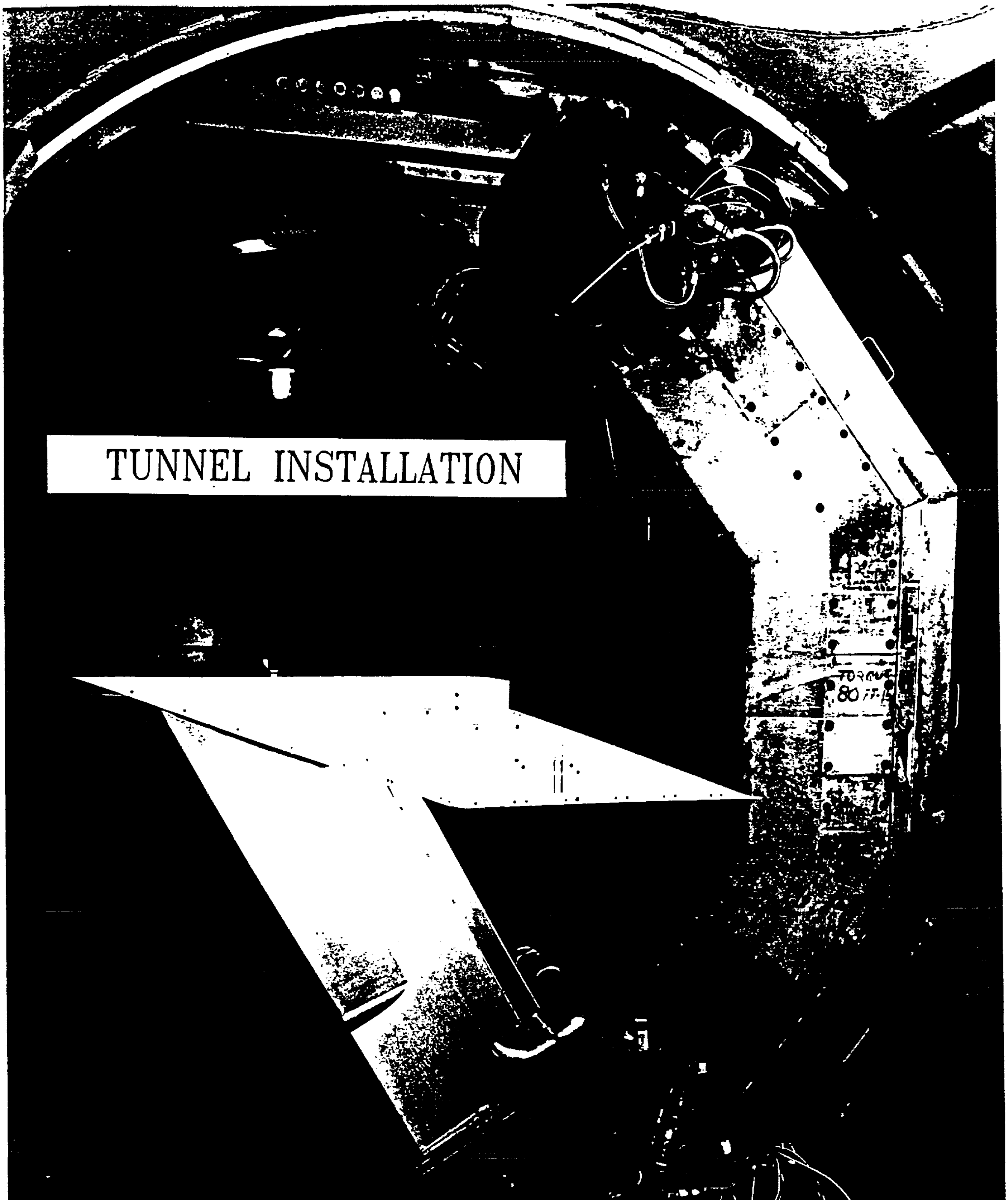
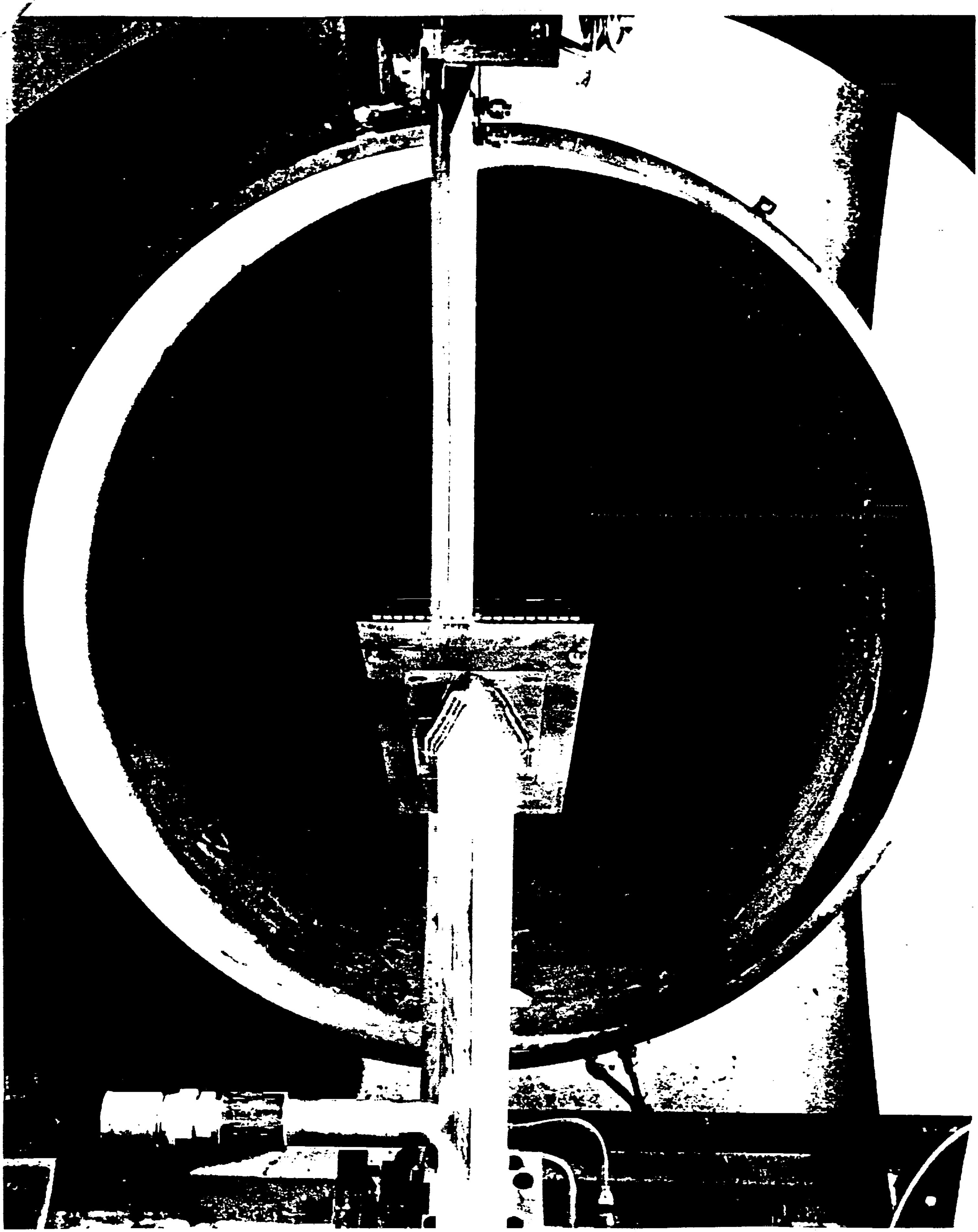


Fig. 11. Schematic of model and jet-plume survey unit installed in test section of Ames 3.5-Ft Hypersonic Wind Tunnel.

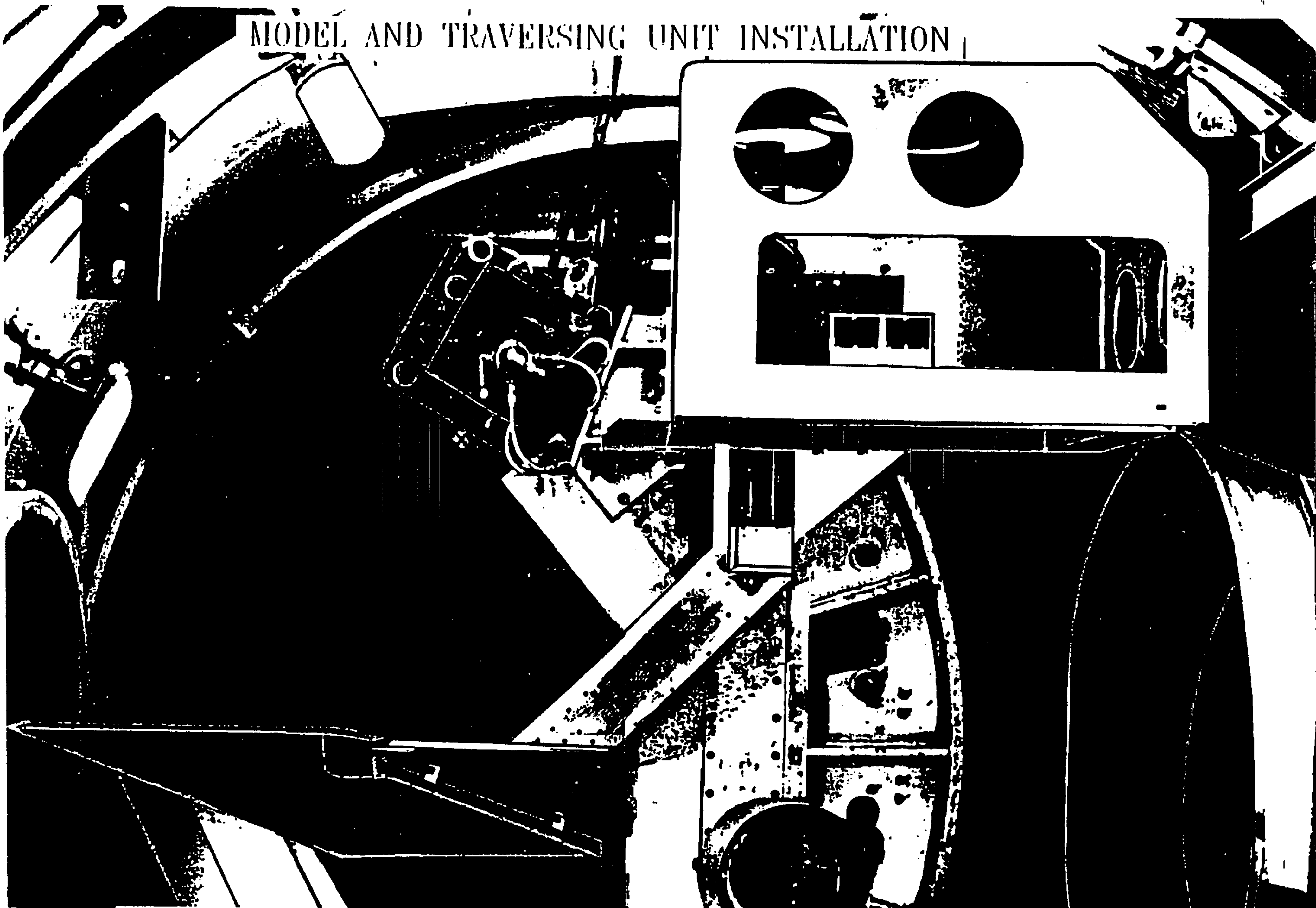


a. Side view.

Fig. 12. Photographs of model-alone installation in Ames 3.5-Ft Hypersonic Wind Tunnel.

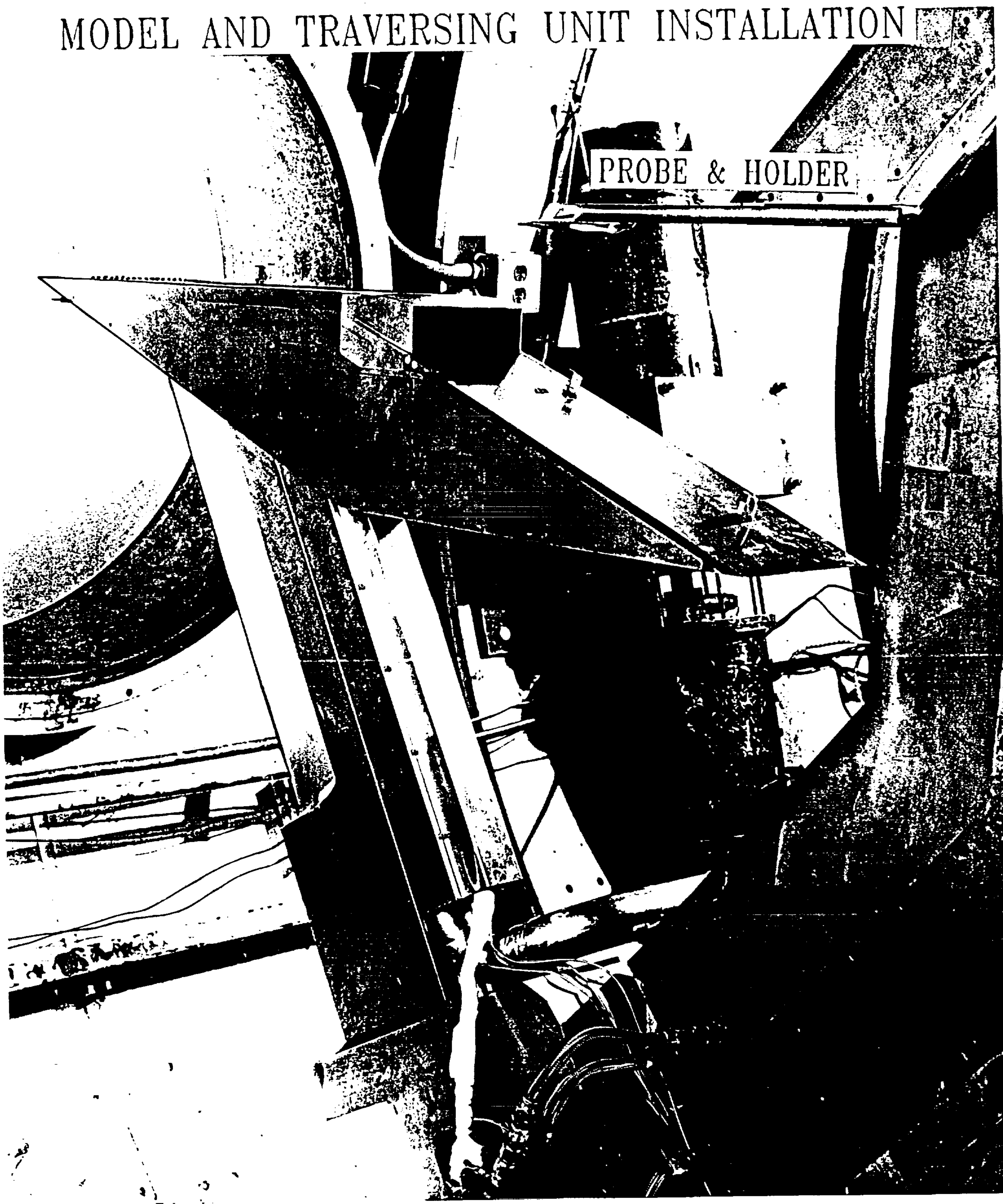


b. Front view.
Fig. 12. Photographs of model-alone installation in Ames 3.5-Ft Hypersonic Wind Tunnel.



a. Model and traversing unit

Fig. 13. Photographs of model and probe traversing unit installation in Ames 3.5-Ft Hypersonic Wind Tunnel.



b. Model and traversing-unit probe holder

Fig. 13. Photographs of model and probe traversing unit installation in Ames 3.5-Ft Hypersonic Wind Tunnel.