THE DEVELOPMENT OF A LOW VELOCITY WIND TUNNEL

WITH

INSTRUMENTATION FOR BOUNDARY LAYER INVESTIGATIONS

A Dissertation

By

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INTRODUCTION

This project originated through meetings with Warren Rice, principal investigator of National Science Foundation grant G-2770 entitled "Transfer Coefficients at Low Velocities," and Professors R.M. Wingren and E. S. Holdredge, Department of Mechanical Engineering, The Agricultural and Mechanical College of Texas. The need for such a project was originally suggested by Maurice H. Halstead, principal investigator of The Agricultural and Mechanical College of Texas Project 93 entitled "Forecasting Micrometeorological Variables" (1).

The primary task was to devise an experiment to simulate the atmospheric condition existing when air moves over a wet surface at uniform temperature, but the final experimental equipment lends itself basically to the investigation of boundary layers at low velocities. The boundary layers investigated herein are contained in that region adjacent to a wet heated surface of uniform temperature in which a potential exists for the transference of momentum, heat, and water vapor. For momentum to be transferred there must be a velocity gradient; for heat, a temperature gradient; and for water vapor, a vapor concentration gradient. These three requirements can exist separately but only under abnormal conditions. In the case under consideration they exist as simultaneous layers, each in the presence of the other two.

The thickness of each of these layers has been defined as that perpendicular distance from the surface to the point at which ninety-nine percent of the potential difference has been reached.

In the case of momentum transfer it has been universally accepted that the velocity of a fluid in contact with a fixed surface is zero and that the velocity increases linearly from the surface through the laminar layer, the region where the viscous forces predominate. Immediately above this layer neither the viscous forces nor the inertia forces predominate, and this overlapping region is referred to as the transition zone. From the transition zone to the top of the momentum layer the inertia forces predominate, and this region is designated the turbulent zone.

In recent years it has become more apparent that the processes by which momentum, heat, and water vapor are transferred are intimately related and that a more complete understanding of the flow conditions near phase boundaries may be expected ultimately to provide a sound basis for the development of a description of interphase transfer as a single subject whether it be momentum, heat, or water vapor that is transferred. The purpose of this investigation therefore, was to devise a highly instrumented experiment to obtain data which will contribute to the development of the analogy between momentum transfer, heat transfer, and water vapor transfer.

REVIEW OF LITERATURE

The concept of boundary layer was announced by Prandtl in 1904 (2). It was not generally accepted, however, until the inner structure of the boundary layer was explored by Burgers and his assistant van der Hegge Zijnen in 1924 (3). Their experiments were made over a highly polished glass plate mounted vertically in the plane of symmetry of an 80-cm square wind channel having a test section 400 cm in length. Velocity was measured with hot-wire anemometers. Hansen (4) repeated the experimental measurements of velocity distribution in the laminar boundary of a plate in 1928, using very small glass pitot tubes. Elias (5) used the same tunnel as Hansen and made velocity measurements in the boundary layer over a hot plate. Elias also employed very small glass pitot tubes.

In 1929, when greater attention was given to turbulent flow, the National Bureau of Standards published their first results concerning that subject in a paper by H. Dryden and A. M. Kuethe (6). This was mainly a paper on hot-wire anemometers. It was followed in 1936 by a full report of experimental results on boundary layer flow near a flat plate (7).

In 1935 Powell and Griffiths (8) published the results of experiments to determine evaporation rates above a plane surface. They used a wind tunnel 330 cm in length and a cross section 54 cm square.

The maximum center-line velocity was 300 cm per sec. This investigation aimed primarily to determine the evaporation rates; it made no attempt to investigate the boundary layer aspects of the results. In 1940 Powell (9) carried out experiments to determine evaporation rates from surfaces of various shapes, and some attempt was made to correlate evaporation data with heat transfer data.

Others (10) (11) (12) (13) performed extensive experiments in evaporation between 1940 and 1950. Cermak and Lin (14) investigated evaporation from a wet, porous surface without supplying heat to increase the vapor concentration potential. Velocity profiles were obtained by using a hot-wire anemometer, temperature profiles by using a probe-mounted thermocouple, and vapor concentration profiles by using wet and dry bulb thermocouples. They reported difficulties with the wet and dry bulb thermocouples.

Spengos (15) investigated the diffusion of momentum and heat above a dry plane boundary. Klebanoff (16), Klebanoff and Diehl (17), and Corrsin and Kistler (18) performed experiments on the boundary layer above a dry flat surface. Many other articles discussed by Dryden (19) have been published on boundary layer studies, and the problem of transference of mementum, heat and water vapor is receiving much attention, but to date very little data exist concerning simultaneous measurement of velocity, temperature, and vapor concentration profiles.

PRELIMINARY CONSIDERATIONS OF TUNNEL DESIGN

The problem of developing experimental facilities for boundary layer studies was of an engineering nature. The balance between desired conditions and acceptable conditions was governed mainly by available funds and allotted time. Before the final tunnel design was approved a balsa wood scale model was constructed, and discussions were held regarding the usefulness of the design. The tunnel had to satisfy two main conditions: (1) to approximate two-dimensional flow and (2) to have flexibility for future studies. Based upon the Nikuradse data on flow in channels, it was decided that a 2- by 4-ft cross section tunnel would closely approximate a two-dimensional flow condition along a one-foot-wide central vertical section. The cross-sectional size was considered adequate for any contemplated future investigations.

The length and general design of the tunnel were influenced by the location and size of the housing facilities. Wood construction was chosen chiefly because excellent wood working facilities existed and future modifications could be made locally. Except for the exhaust diffuser section the entire tunnel was located in one room. The air was exhausted into a large plenum chamber and returned to the entrance section through two large openings. The ambient conditions of the room were considered and found to be relatively stable over a three-hour period.

The location of the test section was made so that a well developed turbulent boundary layer would exist over its entire length. The greatest possible thickness of the momentum layer was insured by a triggering section installed near the tunnel entrance. A complete description of the final design follows.

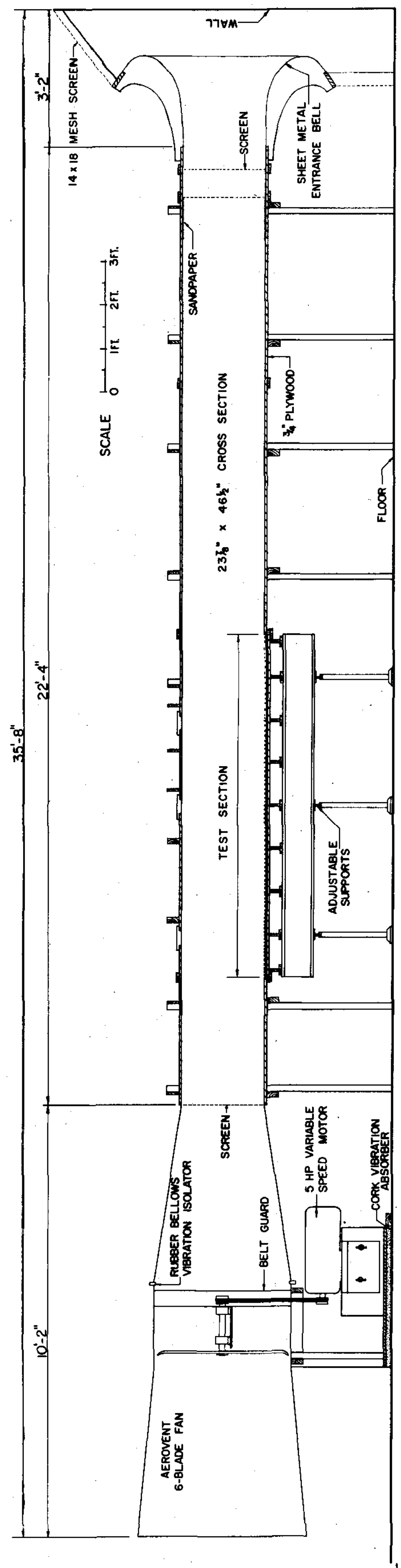
THE LOW VELOCITY WIND TUNNEL

The housing facilities for the tunnel were provided by the Texas Engineering Experiment Station at their Cooling Tower Laboratory in the Mechanical Engineering Shop Building located on the campus of the Agricultural and Mechanical College of Texas.

An estimate of the power required to obtain a maximum center-line velocity of 35 fps in a 32-ft-long tunnel with a 2- by 4-ft cross section indicated that a 5-HP motor would be adequate. The Mechanical Engineering Department furnished a 5-HP variable speed electric motor. Fan performance curves were surveyed and a 6-blade "macheta" airfoil axial flow fan selected. With adequate power available and fan selected, it was decided to build the tunnel as shown in Figure 1.

The entrance bell was installed to minimize entrance losses and to direct the air into the tunnel in a uniform manner. Screens were placed around the entrance bell and in the tunnel entrance to eliminate large scale fluctuations of tunnel entrance conditions and to stabilize the flow. Rough sandpaper was placed immediately after the entrance screens to trigger the boundary layer so that a well developed turbulent boundary layer would exist over the test section. Another screen was placed at the fan inlet to prohibit any vortexing action from forming over the test section. The tunnel vibration problem was solved by mounting the fan and motor assembly on a cork foundation and joining this assembly to the tunnel proper with a rubber bellows. Sufficient bracing was provided to maintain a constant rectangular cross section. All of the inside surfaces were shellacked and rubbed with steel wool prior to being painted. The paint was then carefully coated with clear varnish, a very smooth surface resulting. All joints were glued to eliminate air leakage into the tunnel. Except for the sheet metal used in the entrance bell section, the fan section and the exhaust section, the entire tunnel is of wood construction.

Drawings and photographs of the tunnel are shown in Figures 1, 2, 3, 4, 5, and 6.



LOW VELOCITY WIND TUNNEL

FIGURE I

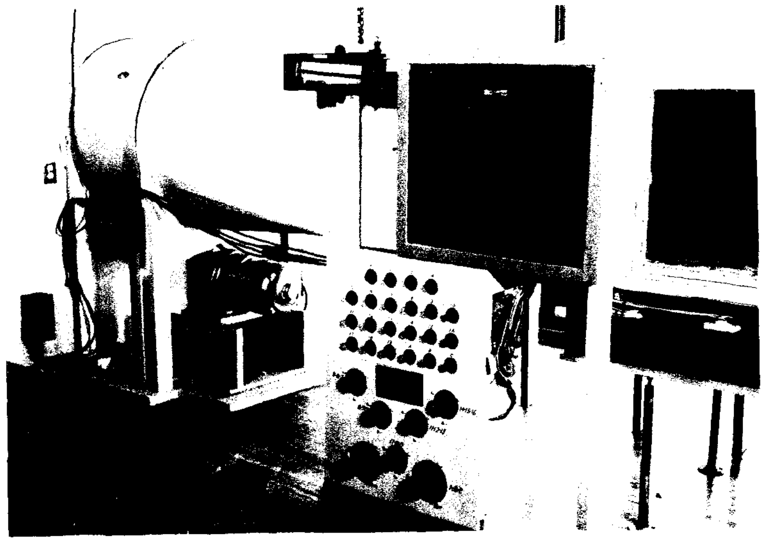


Figure 2. Tunnel Exhaust Section - Exterior

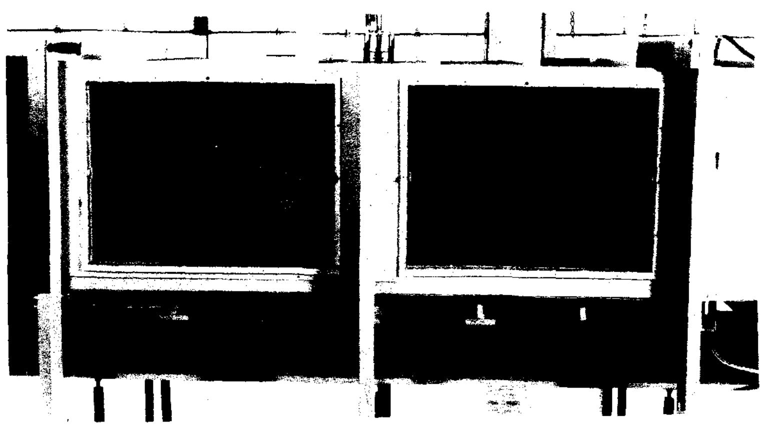


Figure 3. Tunnel Test Section - Exterior

Figure 4. Tunnel Entrance Section - Exterior

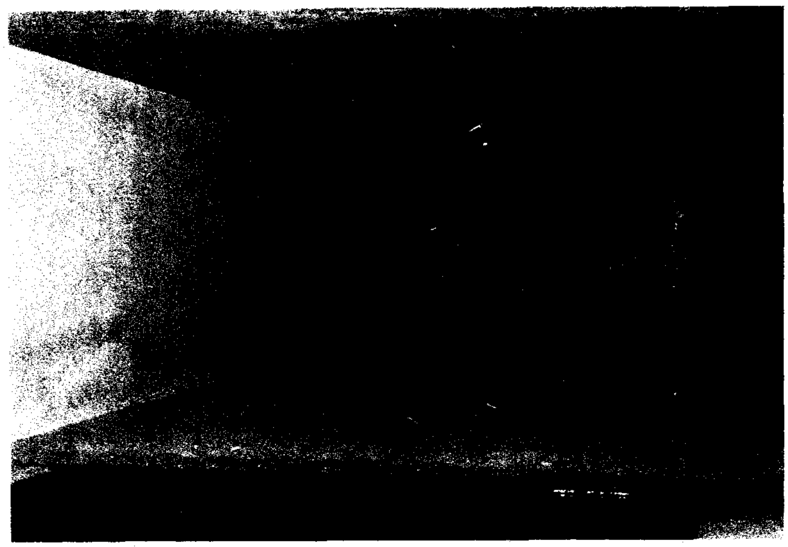


Figure 5. Tunnel Entrance - Interior

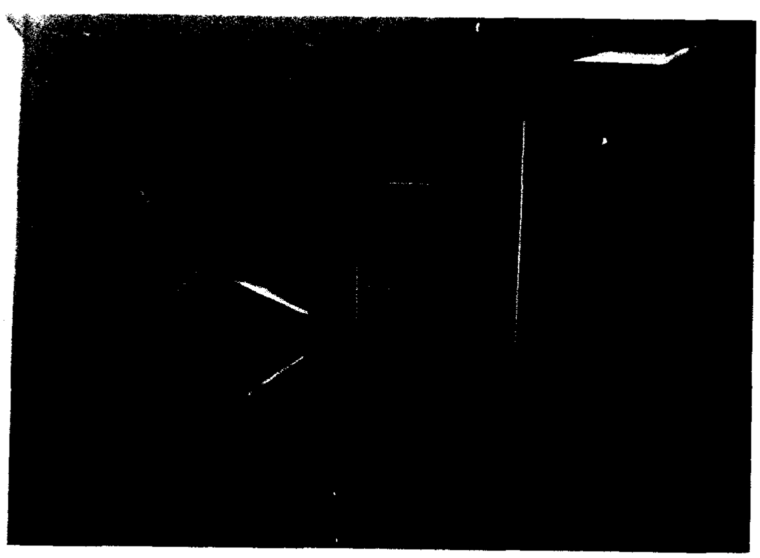


Figure 6. Tunnel Exhaust - Interior

THE TEST SECTION

The test section of the tunnel is designated herein as that region in which the desired data were to be taken. It is an integral part of the wind tunnel and the details of construction and instrumentation follow.

Preliminary Considerations of Design

Several attempts have been made to construct a surface of uniform temperature when that surface is subjected to a tangential air stream. The first, reported by Elias (5) in 1930, consisted of electric heaters submerged in oil so as to tend to maintain a dry surface having constant temperature. Liepmann and Fila (20) attempted to construct a constant-temperature dry surface by wiring heaters according to an assumed heat load. They reported a $\pm 5^{o}C$ variation in surface temperature. Spengos (15) used flat strip heaters of various sizes and attained a $\pm 6^{o}F$ variation from the desired surface temperature.

The problem becomes more complicated when the surface is to be wet. Powell and Griffiths (8) submerged electric strip heaters in water and stretched linen across the water surface to keep the surface at zero velocity. They reported obtaining a surface of uniform temperature but gave no surface temperature distribution. Cermak and Lin (14) used porous porcelain plates as a wet surface but applied no heat. In this case the surface tends to reach thermal equilibrium at the ambient wet-bulb temperature. Maisel and Sherwood (12) used fire bricks covered with a single layer of rayon cloth and placed the thermocouples immediately below the cloth to measure the surface temperature. They reported a surface temperature variation of the order of 2 of 3°C. They made no attempt to heat the surface.

For this investigation it was initially thought that the water could be heated by passing electric current directly through the water. This method was proved impractical because of unstable contact resistance of the submerged bus bars. The next attempt consisted of submerging nichrome wire heaters in water and covering them with a one-quarter-inch layer of very smooth airfoam rubber. This method also proved unsuccessful because of uninsulated heaters and the aging effects of the rubber. Since it was wet for several days, the rubber surface became distorted and rough.

After considerable deliberation, the decision was made to submerge the heaters in oil and install an artificial interface above which was positioned a one-quarter-inch layer of water. Muslin cloth was stretched very tightly to form a wet smooth surface. The description of the final test section design follows.

The Design Used

The problem of designing a wet heated surface of uniform temperature when the surface is subjected to varying wind velocities is in no way elementary. The final design, illustrated in Figures 7 and 13, is the result of several preliminary efforts.

Based upon methods described by Jakob (21), an estimate of the sensible heat load was made. The vapor heat load was estimated from data presented by Cermak and Lin (13). With the total heat load estimated (sensible heat load plus vapor heat load), the test section was divided into nineteen heater sections, and nichrome wire heaters wound to approximate the estimated total heat load. A plot of the estimated sensible heat load, vapor heat load, and total heat load is shown in Figure 8. The heaters were designed for a tunnel center-line velocity of eighteen fps and a temperature difference of 15^{o}F between the tunnel center line and wet surface. The heaters were constructed using a voltage of 110 VAC, which could be raised to 140 VAC as the heat and vapor loads increased at high velocities. A variable resistor was placed in series with each heater area to compensate for errors in heater design. The test section control panel is shown in Figure 2.

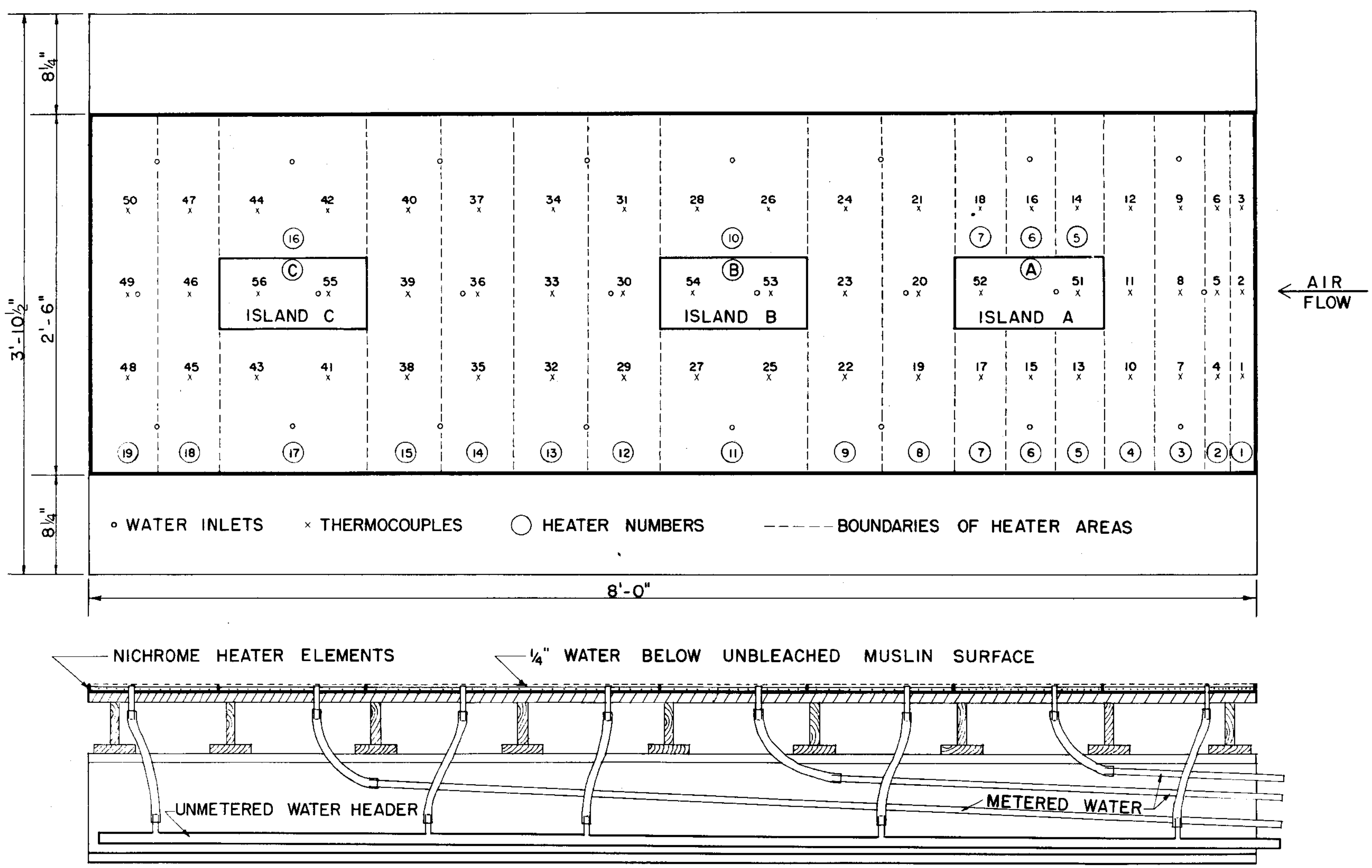
The nichrome heaters were submerged approximately one-eighth inch in one-quarter inch of a silicone liquid (Dow Corning No. 200). The density and viscosity of the silicone liquid are stable within the temperature range used, and it is an excellent electrical insulator. A thin layer of celluloid was placed above the silicone liquid to separate the heater sections and the water. The celluloid served as an artificial interface as illustrated in Figure 9. The base and sides of the test section were made of one-quarter-inch Plexiglass.

A layer of unbleached muslin was stretched very tightly across the top of the section to form the smooth wet surface as illustrated in Figure 10.

Instrumentation of Surface Temperature

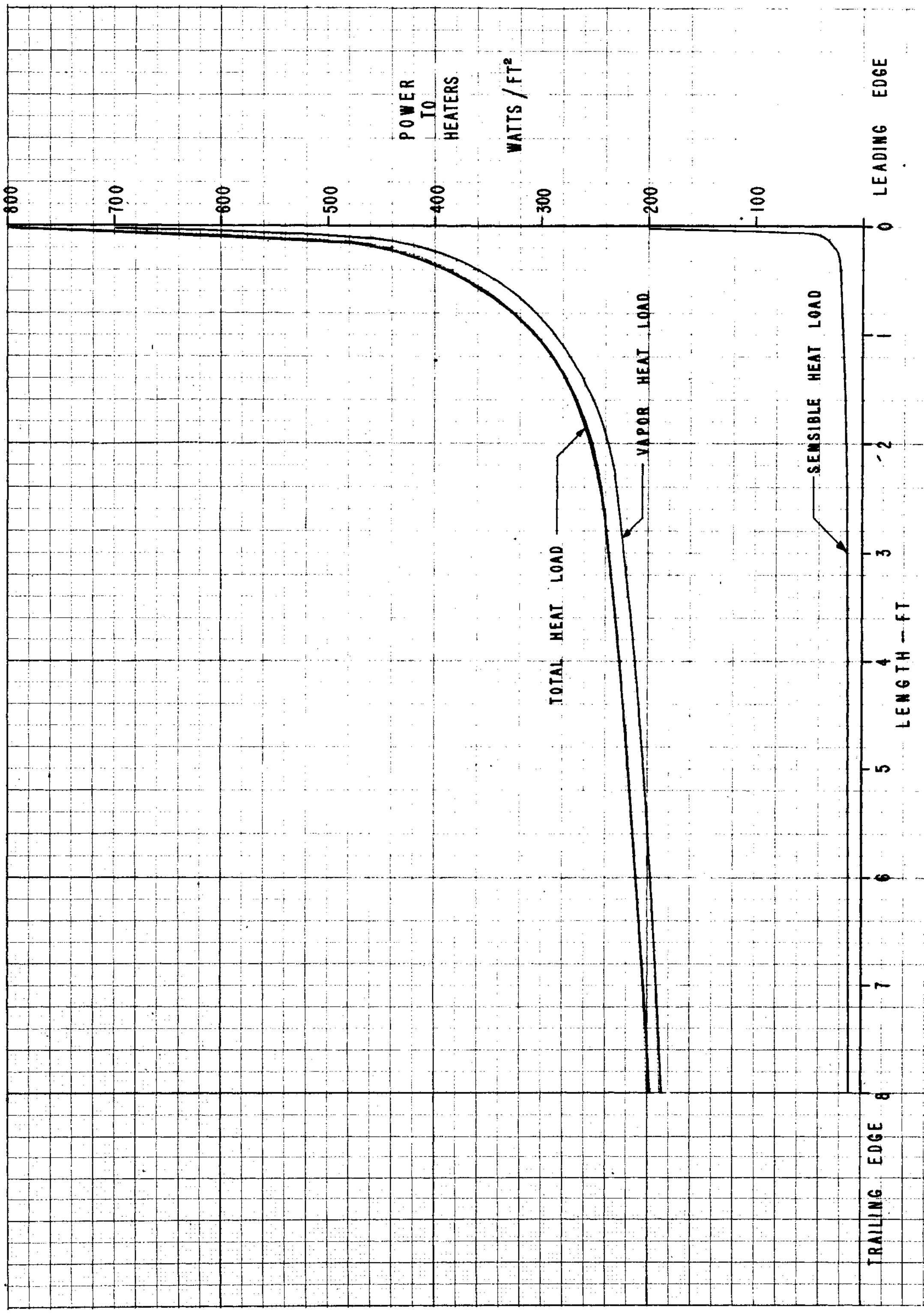
The surface temperature was measured at locations shown in Figure 7. The copper-constantan thermocouples were mounted in contact with the lower side of the cloth surface on cloth tapes stretched tightly across the test pan. The thermocouple wires were kept in the same plane to minimize conduction errors. Details are shown in Figure 11.

The thermocouples were dipped repeatedly in Glyptal to insulate them electrically from the water. A common cold junction was used and placed in a one-quart thermos bottle mounted in an insulated box. The thermocouples were connected to silver contact wafer switches which permitted the selection of any desired thermocouple. The emf of the thermocouples was measured with a potentiometer.



TEST SECTION

FIGURE 7



ESTIMATED HEAT LOADS

FIGURE 8

The thermocouples and switch box are shown in Figure 12. Standard calibration curves were used with these thermocouples. With the surface dry and at room temperature the maximum difference among the thermocouple readings was approximately $1^{o}F$. With the surface wet and air flowing, the surface temperature stabilized near the ambient wet bulb. The maximum difference among the thermocouple readings was again approximately $1^{o}F$. This one degree of variation was accepted as the range of the thermocouple indications, i.e., each thermocouple indication was assumed to be accurate to $\pm 0.5^{o}F$.

Water Metering System

All water used was distilled and was furnished by the Department of Chemistry of the A & M College of Texas.

The water to the test islands was measured by using calibrated burettes. It flowed from the burette automatically as the water level of the test island was lowered. A schematic diagram of this system is shown in Figure 13. The buffer-zone water system (water outside the test islands) operated similarly to the test island system, but the water rate was not determined. As shown in Figure 7, each test island had one water inlet, the buffer-zone 21. This arrangement assured uniform water distribution. A thermocouple was provided in the water system to determine the water inlet temperature. A photograph of the water system is shown in Figure 4. A Glyptal water

Figure 9. Test Section Heaters

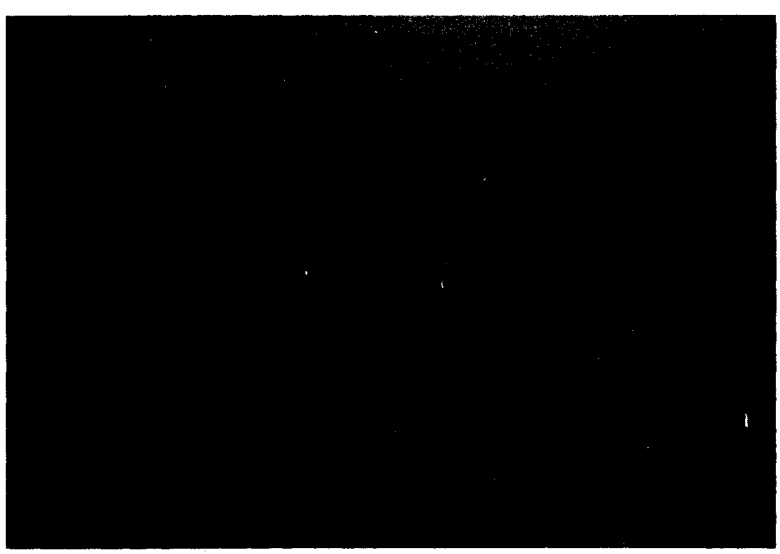


Figure 10. Test Section Surface

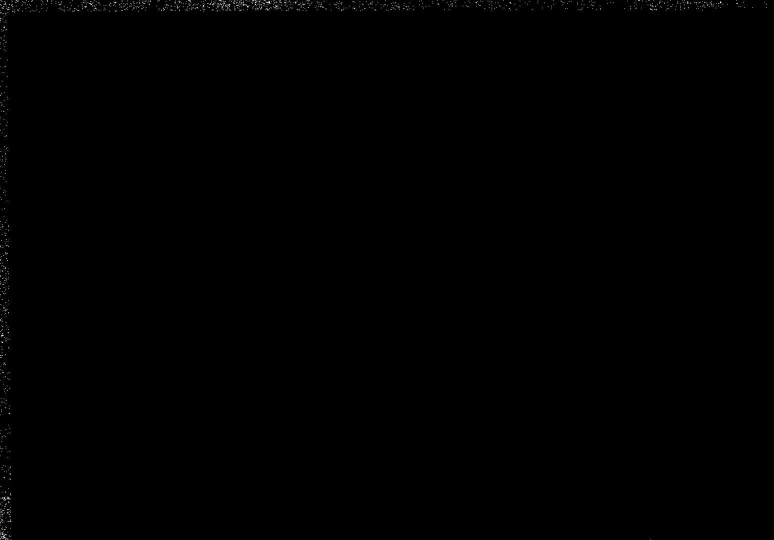


Figure 11. Surface Thermocouples

Figure 12. Surface Thermocouples and Switch Box

barrier was made around the top edge of the test islands to prevent mixing of metered and unmetered water.

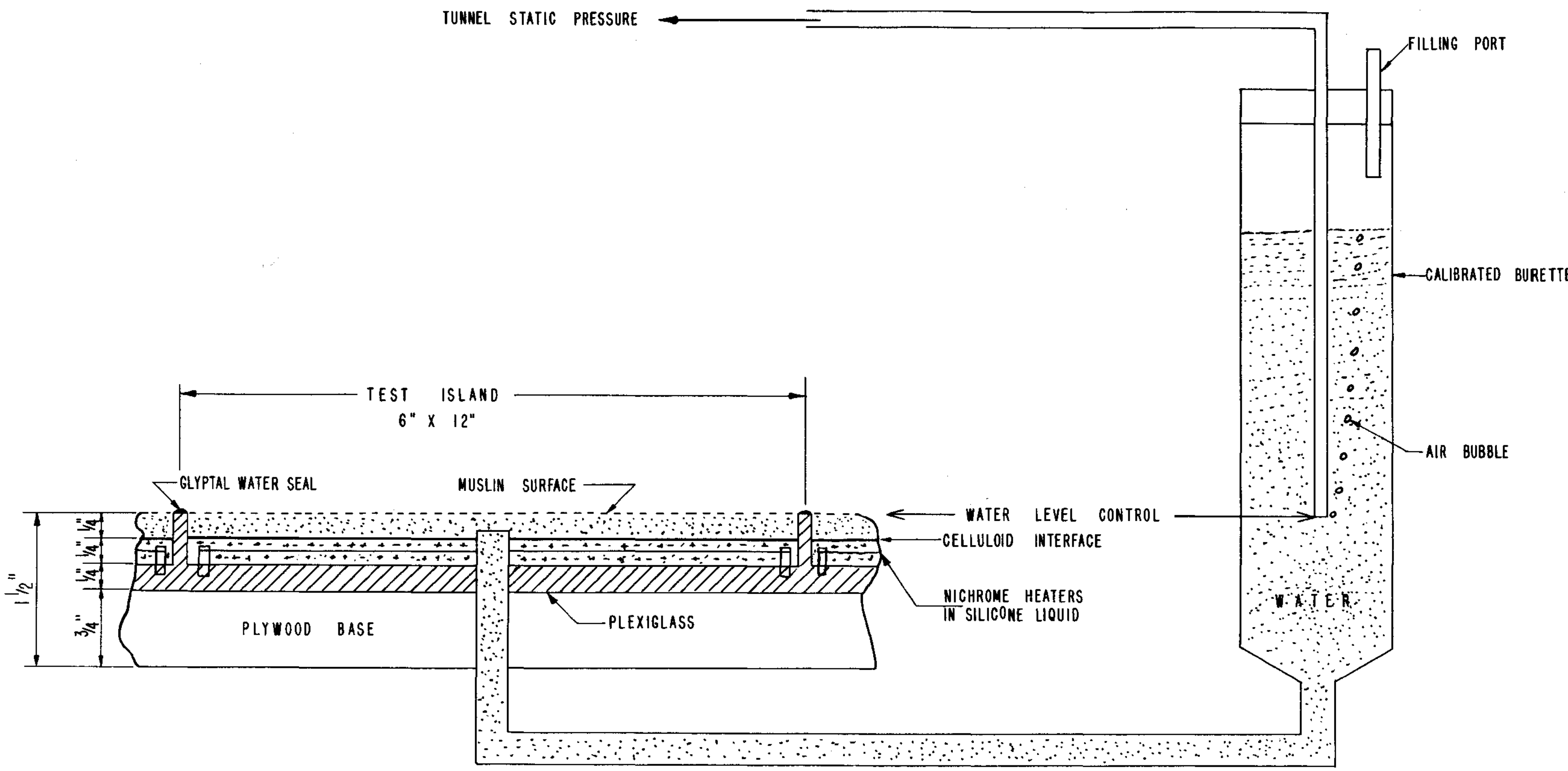
Electric Heater Instrumentation

The electrical power supplied to the test islands was measured by a wattmeter furnished by the Department of Electrical Engineering of the A & M College of Texas. The meter was connected into the circuit so that either continuous or intermittent readings could be taken for test islands A, B, and C. No measurements were made of the electrical energy supplied to the buffer zone.

Velocity Measuring Instrument

Pitot tube techniques were used in measuring velocity profiles. As shown in Figure 14, a total pressure tube was made by mounting on the probe hollow wire having an outside diameter of 0.016 inches. A survey of static pressure variation at the test section revealed that as long as the air was made to flow perpendicular to the static pressure opening, no measurable static pressure variation could be obtained. The static pressure pick-up had an inside diameter of 0.0625 inches and was mounted flush in the tunnel roof at the center of the test section.

Because of the experience of the Texas Engineering Experiment Station (22), it was decided to use a Statham pressure transducer to measure the pressure difference between the total and static



Schematic Diagram of Metered Water System and Test Island

Figure 13

pressure pickups. The Statham Laboratories built and calibrated a pressure transducer with a 0 to ± 0.015 psi range. Essentially, the transducer is a wheatstone bridge made from strain gages mounted in a diaphragm in such a manner that a linear output is produced corresponding to the differential pressure exerted on the diaphragm. The transducer was compensated for temperature changes. To eliminate the vibration pickup from the tunnel fan and from other mechanical equipment in the building, the transducer was mounted inside an air-foam rubber-lined case supported by flexible cords from the ceiling of the room.

The output of the pressure transducer was recorded with a Model 127 Sanborn recorder, which was also mounted on an airfoam base to minimize vibration pickup.

Profile Measuring Instrument

All temperature profile measurements were made by means of a copper-constantan thermocouple. The temperature measuring system consisted of (1) an unshielded air temperature measuing junction, (2) a modulated carrier-type d-c amplifier, (3) a milliameter, (4) a reference junction, and (5) a reference temperature compensator.

The thermocouple junction was made by tinning the ends of No. 36 B&S-gauge copper and constantan wires, by bringing them

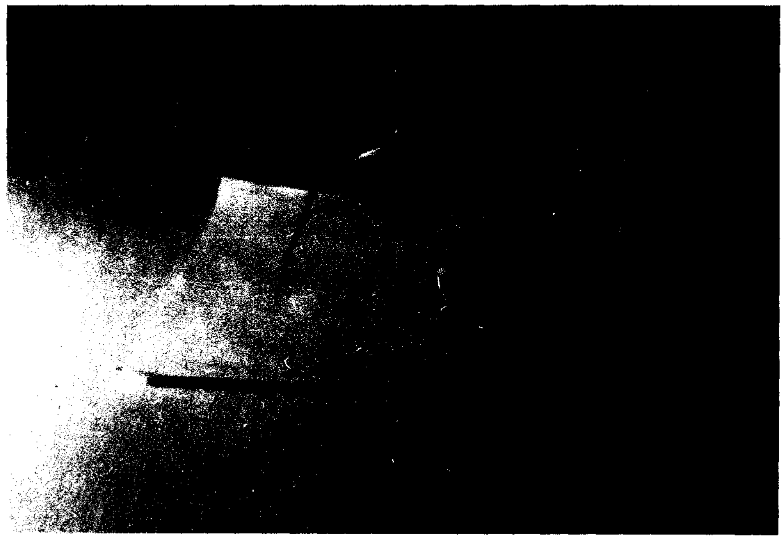


Figure 14. Probe

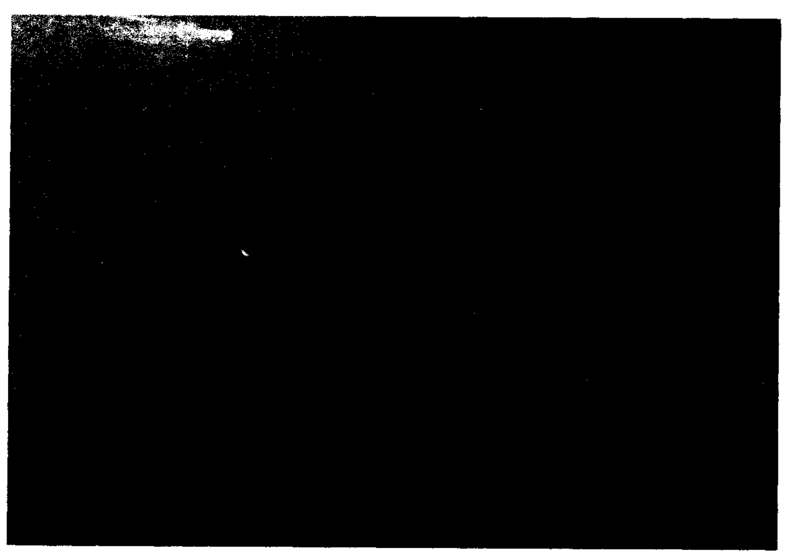


Figure 15. Probe

into end-to-end contact with the aid of a glass capillary tube, and by soldering them. A junction formed in this manner is uniform and not significantly larger in diameter than the bare wire. A thermocouple of this type has a low heat capacity and relatively low lead conduction.

The thermocouple was soldered to lead wires made from a twisted pair of rubber-covered No. 16 B&S-gauge copper and constantan. These wires were enclosed by a weatherproof neoprene covering. The lead wires formed part of the probing mechanism. To minimize the effect of thermal conduction along the lead wires, each lead was formed in the same plane as that of the thermocouple for a distance of approximately three inches. Figure 15 illustrates the arrangement of the lead wires and thermocouple junction.

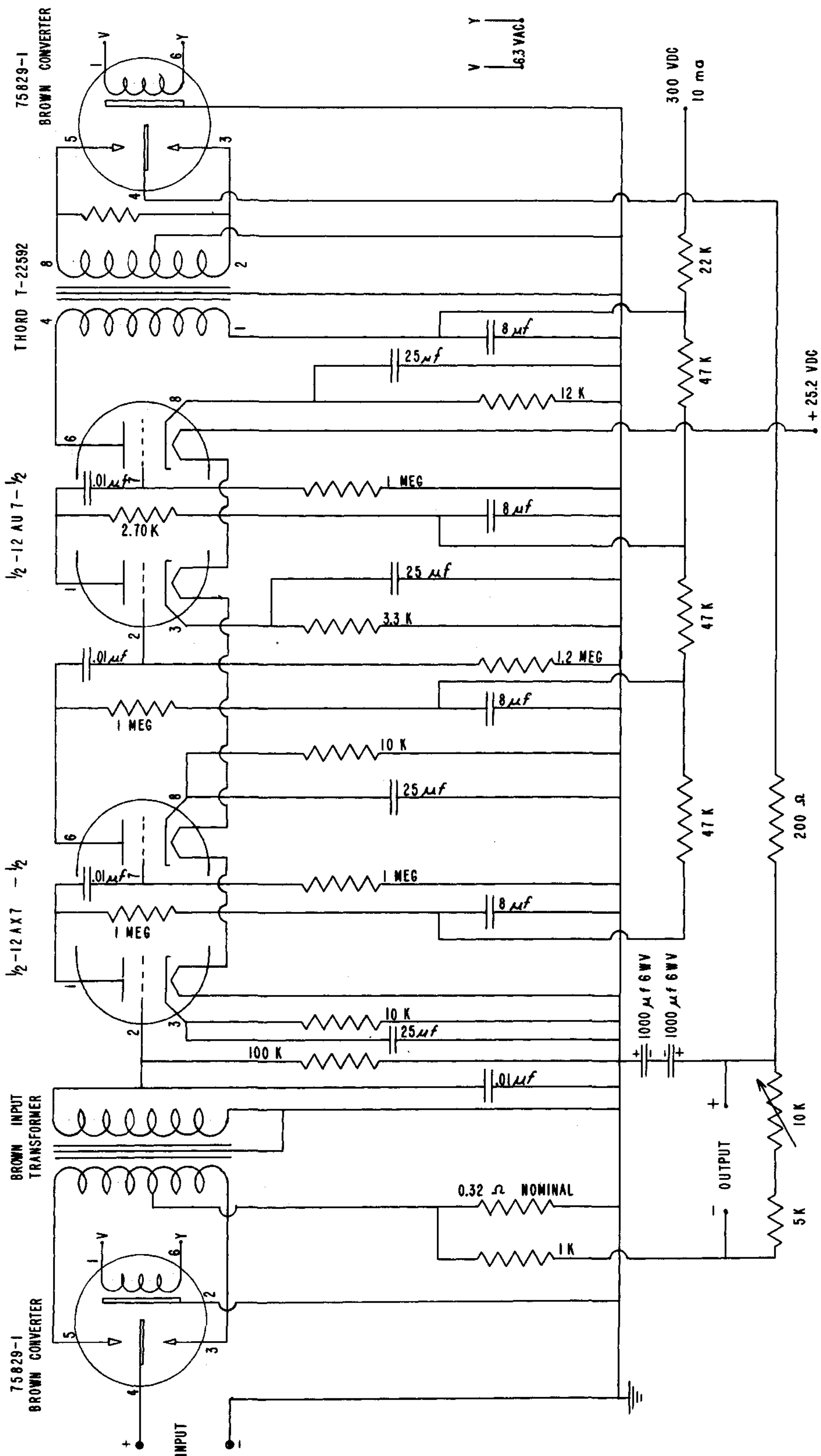
The reference junction was formed with No. 16 B&S-gauge copper and constantan wires and was electrically insulated and waterproofed by a thin layer of polyethelene. The reference junction was immersed in a quart thermos bottle filled with a mixture of distilled water and crushed distilled water ice. To prevent conduction of heat to the junction by the lead wires, approximately two feet of the lead wires were immersed with the junction. The thermos bottle was mounted in a glass-wool-lined container to further reduce the melting rate of the ice. The reference junction was assumed to be at $0^{o}C$. The copper loop of the thermocouple circuit was cut to form the junctions at the copper input connections of the instrument.

The circuit diagram for the modulated carrier-type DC amplifier is shown in Figure 16. The prominent characteristics of this amplifier are high sensitivity, virtually no zero drift, high gain stability, relatively high input impedance, and a high degree of linearity. The amplifier used for temperature profile measurements had a nominal input range of 0 to 400 microvolts, which corresponds to the output of a copper-constantan thermocouple for a 10°C temperature difference. A control was provided for precise setting of amplifier gain. The amplifier power supply circuit is shown in Figure 17 and an auxiliary voltage source in Figure 18.

The amplifier output was indicated on a meter (Weston, model 273) which had a range of 0 to 1 milliampere and an internal resistance of 1400 ohms in order to be electrically similar to other recorders. The meter scale was 5.8 inches in length, had 100 divisions, and was marked to read a temperature range of 0 to 10°C. This meter was equipped with a knife-edge pointer and a mirror scale, devices which eliminated reading errors due to parallax. The meter mount was provided with levels to insure consistent orientation.

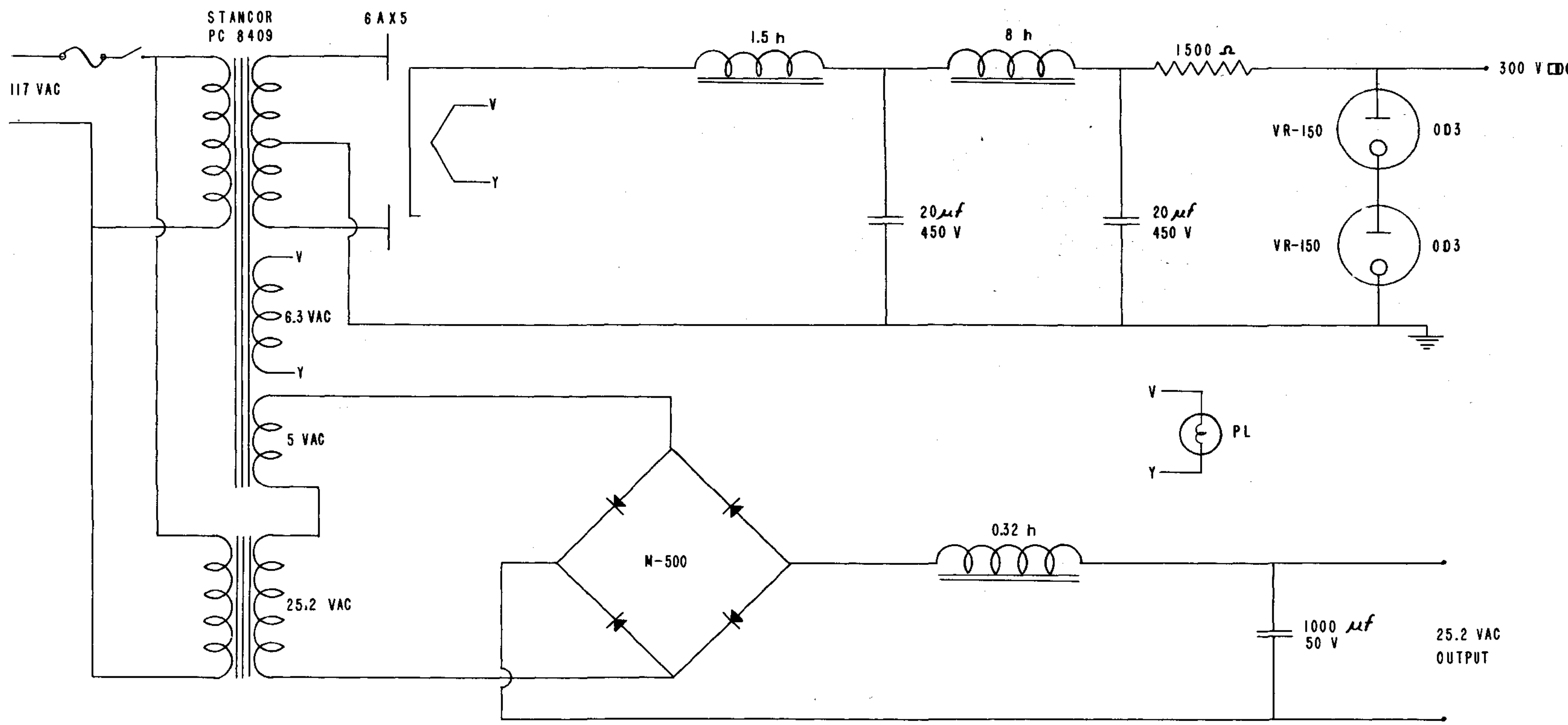
The reference temperature compensator circuit is shown in Figure 19. This unit is a calibrated variable microvoltage source. By setting the dial of the 500-ohm precision helipot and regulating the voltage across the precision resistor network consisting of the 500-ohm helipot, 1361-ohm, 1248-ohm and 1678-range selector resistors, 1200-ohm and 1-ohm resistors, a voltage equivalent to that produced by the copper-constantan thermocouple for any temperature in the range of 5°C to 70°C could be obtained. In this circuit the output voltage is made dependent only on the setting of both the 500-ohm helipot and the selected range resistor by maintaining a constant voltage across the precision network. This constancy is accomplished by comparing the voltage across the network with the emf of a standard cell and varying the resistance in series with the 1.5-volt dry cell until a condition of balance is obtained as indicated by a zero reading of the null indicator.

Since the input range of the amplifier was limited to a 10°C increment and the reference temperature junction maintained at 0°C, the reference temperature compensator was employed in measuring temperatures which exceeded 10°C. The connection of the compensator into the measuring circuit was such that its output voltage was subtracted from the voltage produced by the thermocouple. The net voltage was then amplified and indicated on the meter.



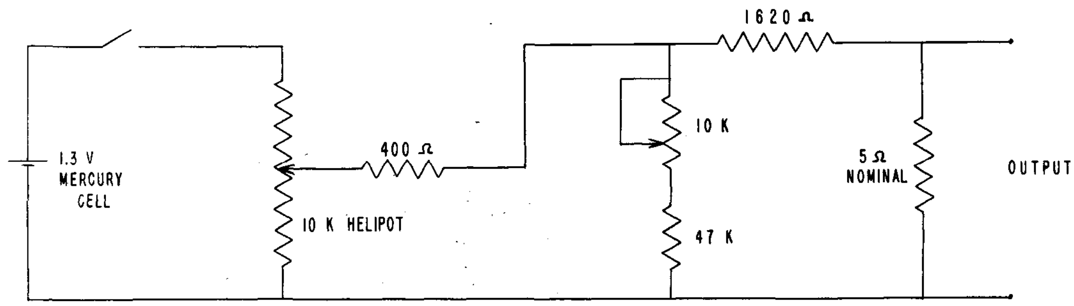
THERMOCOUPLE AMPLIFIER

FIGURE 16



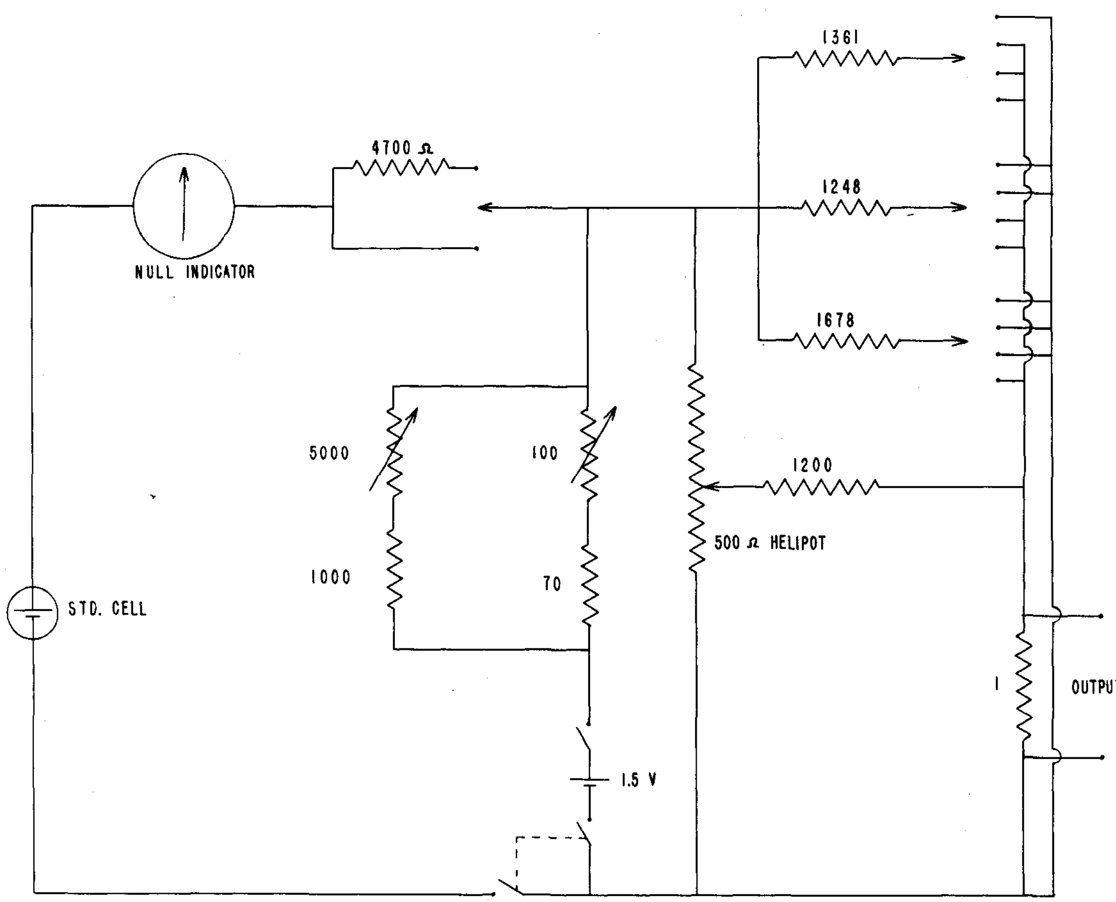
AMPLIFIER POWER SUPPLY

FIGURE 17



AUXILIARY VOLTAGE SOURCE

FIGURE 18



COMPENSATOR

FIGURE 19

THERMOCOUPLE WIRE AND INSTRUMENT CALIBRATION PROCEDURE

A platinum resistance thermometer (Leeds and Northrup), which had been calibrated by the National Bureau of Standards, and a Mueller Bridge were used to calibrate the copper-constantan thermocouple wire. A thermocouple circuit was constructed from a length of No. 16 B&S-gauge copper-constantan lead wire. One junction was placed in a 0^{o}C reference bath, and the other junction was immersed in a large thermos flask filled with water (approximately five gallons). A Beckman differential thermometer and the resistance thermometer were immersed in this calibrating bath. The thermocouple junction, Beckman thermometer bulb, and resistance thermometer bulb were placed in close proximity near the center of the bath. A motor-driven stirring mechanism was used to agitate the water. The thermocouple wires were connected in a circuit with an amplifier, meter, and reference temperature compensator as shown in Figure 20. Since the amplifier and meter served merely as a sensitive null indicator, their calibrations had no influence on the wire calibration.

The temperature of the calibrating bath was varied through the range of 20^{o}C to 50^{o}C, and fifteen evenly distributed calibration points were obtained. Methanol anti-freeze was added to the bath water for temperatures lower than 0^{o}C. The temperature of the bath was determined by means of the resistance thermometer, and the rate of change of temperature was monitored by means of the Beckman differential thermometer. At each claibration point, a reference temperature compensator setting was determined which produced a zero current flow in the measuring circuits as indicated by the amplifier meter null detector, i. e., a setting was determined which caused the compensator output to be equal in magnitude to the emf produced by the thermocouple junctions. The emf temperature characteristic of the copper-constantan wire was then determined by measuring the output of the compensator for each of the dial settings. A potentiometer (Leeds and Northrup type K), a precision voltage divider, an amplifier-meter null detector, and an auxiliary emf source were employed for these measurements as shown in Figure 21.

Errors caused by loss of calibration due to change in characteristics of the system components, particularly a change in the emf temperature characteristics of the thermocouple wire, can be considered insignificant. A comparison of this wire calibration (conducted in April 1956) with a calibration conducted in May 1953 shows an average difference of 0.05°C. An unknown but supposedly small fraction of this difference is probably due to a change in the emf temperature characteristic of the wire.

The emf temperature characteristic of the No. 36 B&S-gauge copper-constantan thermocouple wire had been established to be virtually the same as that of the No. 16 B&S-gauge thermocouple wire manufactured by the Leeds and Northrup Company. This was verified by experimentation. A series circuit was constructed from lengths of No. 16 B&S-gauge copper wire, No. 16-gauge constantan wire, No. 36 B&S-gauge copper wire, and No. 36 B&S-gauge constantan wire.

Four junctions were formed: (1) No. 16 B&S-gauge copper to No. 36 B&S copper, (2) No. 36 B&S-gauge copper to No. 36 B&S-gauge constantan, (3) No. 36 B&S-gauge constantan to No. 16 B&S-gauge constantan, and (4) No. 16 B&S-gauge constantan to No. 16 B&S-gauge copper. This circuit was connected to an amplifier-meter null detector. The No. 16 B&S-gauge copper-constantan junction and the No. 36 B&S-gauge copper-constantan junction were maintained at the same temperature by immersing them in a thermos flask filled with water. The No. 16 B&S-gauge to No. 36 B&S-gauge copper junction and constantan junction were heated separately. No thermoelectrical emf was obtained.

A very similar procedure was used in the calibration of the instrument used in obtaining data for presentation in this dissertation. A water bath, resistance thermometer, Beckman thermometer, and similar technique were used, but the compensator settings were determined at 5°C intervals for each temperature from 5°C to 60°C. It was not necessary to calibrate at lower or higher temperatures since it would be impossible to attain them in the existing tunnel.

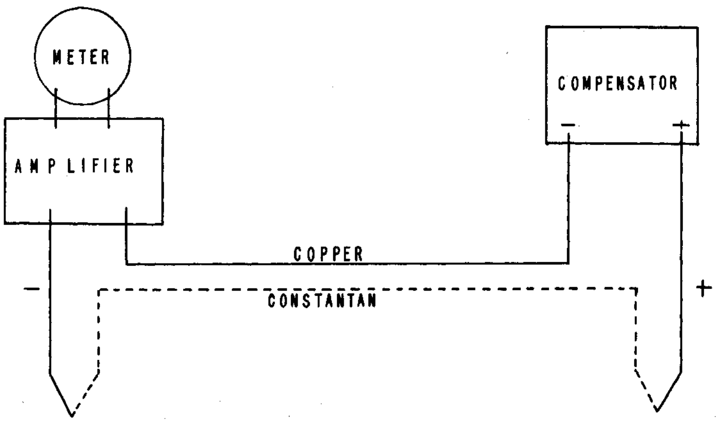
The compensator settings required to balance out the emf produced by the thermocouple were determined. The temperature of the water bath was maintained constant by tempering with cold or hot water as required. The values for the resistance thermometer were computed and set on a bridge. As the temperature drifted very slowly up and down through the set points, dial readings of the compensator which produced zero readings on the meter were taken. These readings produced dial-settings-vs-temperature data. Subsequently, the voltage-vs-temperature data were obtained by measuring the voltage at various dial settings and comparing it with the dial-setting-vs-temperature data.

After the compensator was calibrated, the amplifier-meter combination had to be calibrated, i. e., the settings had to be found which made the meter read an interval of 10°C at the various ranges. The amplifier and meter were calibrated by means of the circuit shown in Figure 22. In this circuit, the compensator serves as a calibrated voltage source which simulates the output of the thermocouple. With the auxiliary voltage set at zero output, the compensator was set for 10°C, and the setting of the amplifier gain control which produced full-scale meter deflection was then determined. The output of the auxiliary voltage source was next adjusted until it was equal in magnitude to the compensator output. Since the two voltage sources were connected so that their polarities were in opposition, a condition of equality was indicated by a reading of zero on the meter. The setting of the compensator was then changed to 20°C, and the amplifier gain setting for full-scale meter deflection was determined. The auxiliary voltage source was again adjusted for a condition of equality and the process repeated. By this method, amplifier gain settings were established for a series of overlapping operating ranges between 5°C and 70°C.

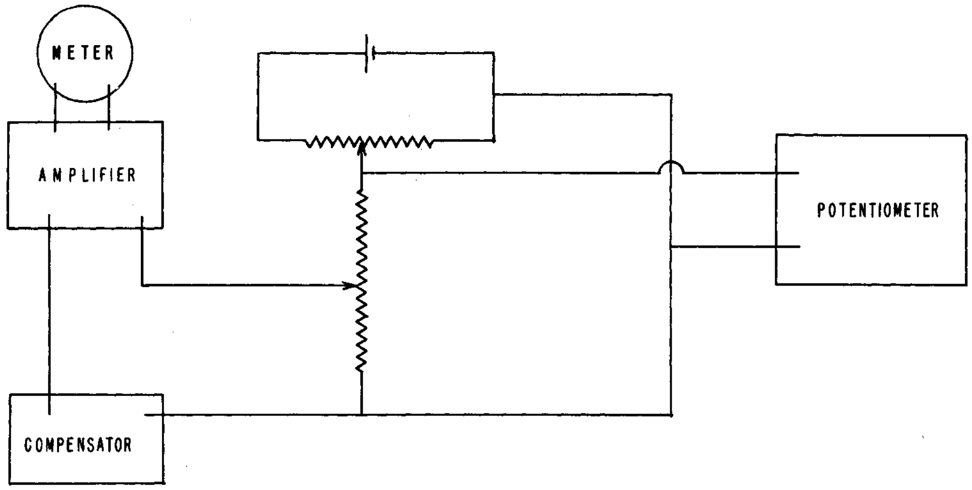
Points were taken from the voltage-vs-temperature curve and fitted by the method of least squares to the thermoelectric power equation. This calculated curve was plotted and compared with a straight line. A representative 10°C increment was selected, and correction factors were obtained to correct for nonlinearity of the thermocouple wire.

By determination of the transfer characteristic of the amplifier-meter combination, it was found that deviations from linearity were due primarily to meter movement and scale irregularities, and corrections to be applied to meter readings were established which corrected for the irregularities in the amplifier-meter transfer characteristic. The corrections for nonlinerarity and meter characteristics are shown in Figure 23. The total or final correction curve is shown also.

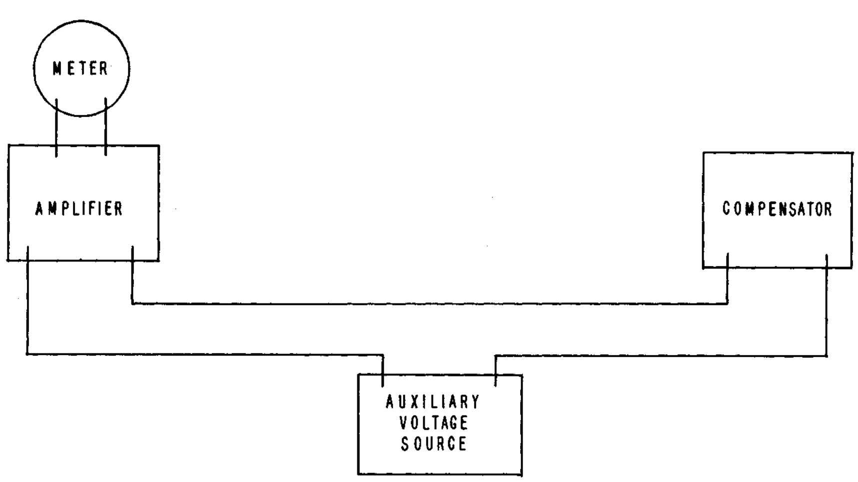
The accuracy of the thermocouple wire calibration is difficult to evaluate. However, the calibration was conducted with extreme



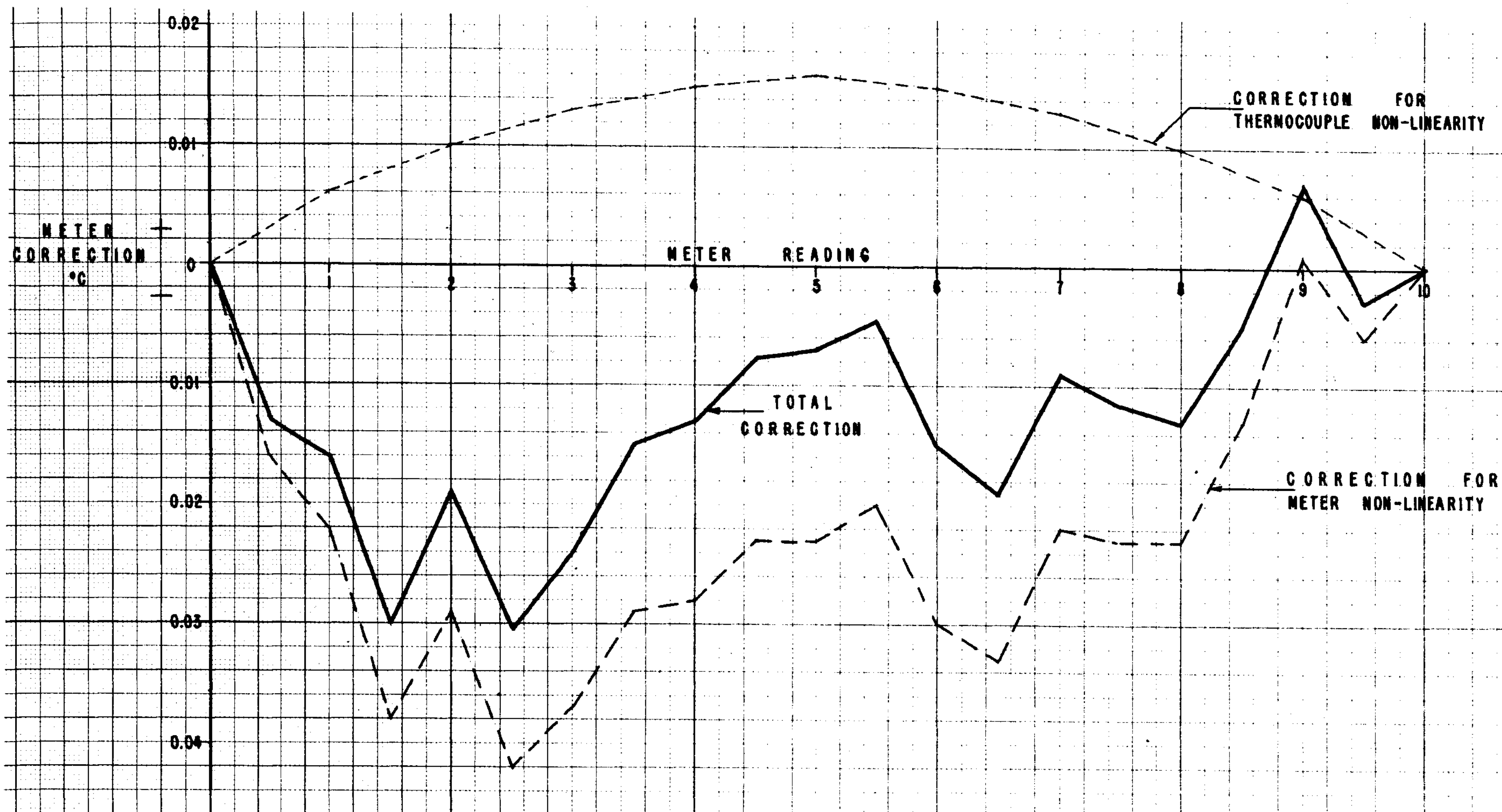
THERMOCOUPLE WIRE CALIBRATING CIRCUIT
FIGURE 20



CALIBRATING CIRCUIT
FIGURE 21



AMPLIFIER CALIBRATING CIRCUIT
FIGURE 22



METER CORRECTION CURVE

FIGURE 23

care, and several determinations of each measured value showed the calibration to be reproducible. A conservative estimate of the error due to calibration inaccuracies is 0.05°C for an absolute measurement (deviation from true temperature) and 0.02°C for a relative measurement (deviation from true temperature difference).

OPERATING INSTRUCTIONS FOR PROFILE TEMPERATURE INSTRUMENT

1. Fill cold jug with mixture of crushed distilled water ice and distilled water.
2. Turn on amplifier power supply and allow at least a thirty-minute warm-up period.
3. Place thermocouple at desired location.
4. Estimate temperature and then select range. Assume 20°C to 30°C as an example; then range setting would be 2.
5. Set compensator dial for 20°C compensation. In this example the dial would be set at 0646.
6. Set and lock amplifier gain dial to setting given in the table, which would be 3015 for this example.
7. Read the meter. Assume for this example a reading of 6.35.
8. Apply correction from curve in Figure 23. In this case the temperature would be the compensation 20°C plus the meter reading 6.35°C plus the meter correction -0.018°C or an approximate total of 26.33°C.

TABLE I

TEMPERATURE INSTRUMENT DATA

Temperature °C	Compensation Setting	Range Setting
5-15	0633	1
10-20	1293	1
15-20.75	1900	1
20-20.75	2404	1
20-30	0646	2
25-35	1330	2
30-35.25	1948	2
35-35.25	2456	2
35-45	0038	3
40-50	0722	3
45-55	1430	3
50-55.25	2058	3
55-65	0414	4
60-70	1150	4

PROCEDURE TO DETERMINE AMPLIFIER GAIN NUMBERS

1. Turn power supply on and allow a thirty-minute warm-up period.
2. Remove thermocouple lead wires and attach copper wire frames as shown in Figure 23 wired as in Figure 22.
3. To obtain gain setting for 0 to 10°C, set compensation for 10°C.
4. Adjust amplifier gain for full-scale deflection.
5. Balance out this output with auxiliary voltage until meter reads zero.
6. Set compensation for 20°C compensation and repeat procedure until desired gain numbers are determined.

The gain numbers used were

Temperature °C	Gain Setting
10-20	4040
20-30	3015
25-35	2535
35-45	1595

These values were checked periodically during the tests, and no appreciable deviation was observed.

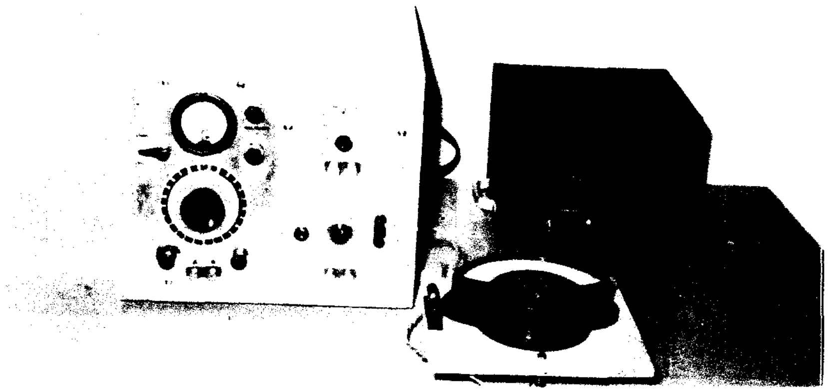


Figure 24. Profile Measuring Instrument

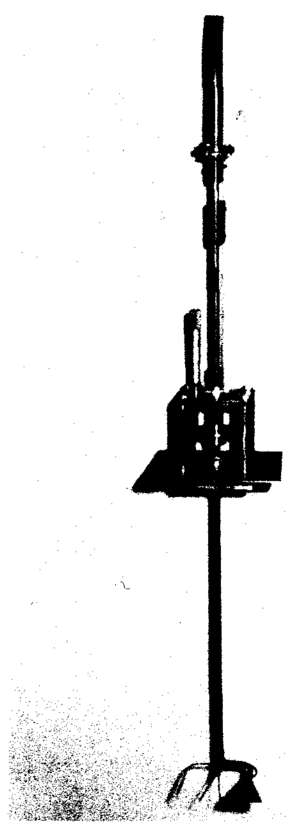


Figure 25. Probing Mechanism

THE PROBING MECHANISM

The probing mechanism shown in Figure 24 was designed to obtain simultaneous readings of velocity, temperature, and humidity above the wet surface. Besides the described velocity and temperature pickups, the probe contains an air sampling pickup at the same elevation as the other pickups. It was originally planned to obtain humidity profiles, but the dew-point measuring device was not available as planned.

The probe-mounted pickups can be positioned above the surface with micrometer accuracy by using the micrometer mounted on the probe frame. The thermocouple lead wires, total-pressure tube, and air-sampling tube extend through the inside of the three-eighths-inch steel tubing support. The bottom of the support was sealed with castable plastic.

EXPERIMENTAL PROCEDURE

Many preliminary tests were required to verify the tunnel instrumentation. Time-consuming difficulties were experienced with the pressure transducer after the transducer vibration problem was solved.

Since the first velocity profiles were inconsistent and not reproducible, the tunnel was checked for leaks which would cause unstable boundary layer conditions. Some very minor leaks were discovered and repaired.

Then tests were made with the room heater fans on and off. The result was enough variation in room static pressure to be detectable with the pressure transducer. It was decided to make all test runs with the heater fans off. Because the results remained inconsistent, the outside ambient conditions were considered. A ventilator in the ceiling of the plenum chamber and a door to the roof of the building were open during some of these preliminary tests. The tunnel room and plenum chamber were closed to outside effects. These corrective actions failed to produce completely positive results.

Close attention was then given to the total and static pressure leads. Complete leakage tests were made, and the leaks so detected were sealed with Glyptal. Though closing the leaks greatly improved the results, unacceptable differences remained in velocity measurements. For example, the recorder continued to have appreciable zero drift. After some discussion the pressure transducer was compared with two similar but greater-range transducers belonging to the Texas Engineering Experiment Station. These two transducers gave almost identical results when compared with each other, but no comparison existed with the special transducer purchased for this investigation.

After being discussed with the manufacturer by telephone, the transducer was returned for calibration. The manufacturer stated that over-ranging the transducer had affected its zero reading and linearity. The transducer was therefore repaired and recalibrated at no charge. The Sanborn recorder was sent to a manufacturer's representative for complete maintenance check.

With these corrective actions taken, later results were found to be consistent and reproducible except for a slight low frequency oscillation of tunnel conditions which was eliminated by symmetrically blocking part of the tunnel entrance screens.

The following procedure was employed during all accepted transducer output measurements:

1. The input connections of the transducer were connected with a short perforated jumper. This jumper had to be connected very carefully to avoid over-ranging the instrument. The jumper insured a constant zero pressure difference on the transducer diaphragm.

2. After an hour warm-up period the recorder was balanced and the calibration adjusted to give the desired scale deflection with pressure.
3. The transducer jumper was removed and the total and static pressure leads connected to the transducer. Again this was accomplished very carefully to avoid over-ranging the transducer.
4. The tunnel speed was increased slowly until the desired stable tunnel conditions were attained. The probe was near mid-stream for the tunnel speed adjustments.
5. The total tube was indexed by setting the tube 0.025 inches above the surface by using a mirror-finished bar; then the probe was placed close to the surface with the micrometer attachment. The pressure difference measurements were taken at the desired distances above the surface.
6. After the desired readings were taken the tunnel fan was stopped and the jumper connected across the transducer to check for recorder zero-drift.

This procedure was repeated for each profile determination. Data were taken over Test Island C at tunnel center-line velocities of approximately 15, 25, and 35 fps and without supplying water to the test section. The muslin surface was dry, and a one-quarter-inch air space existed below the porous muslin surface. A profile for this condition is shown in Figure 25. No temperature profiles were taken for this condition because very small temperature difference existed, i.e., the tunnel was close to thermal equilibrium with the room air.

With the technique of obtaining data developed, water was added to the surface. Slight leveling of the test section was required to obtain a uniformly saturated surface.

At first the water feed system did not operate properly because of very small air leakages. With the system air tight, a steady stream of air bubbles bled into the buffer-zone water bottles as water evaporated. The test island meter system was periodic and water would feed into the system in small equal-batch quantities.

The water system operated on a self-control basis after the test surface water level was initially determined.

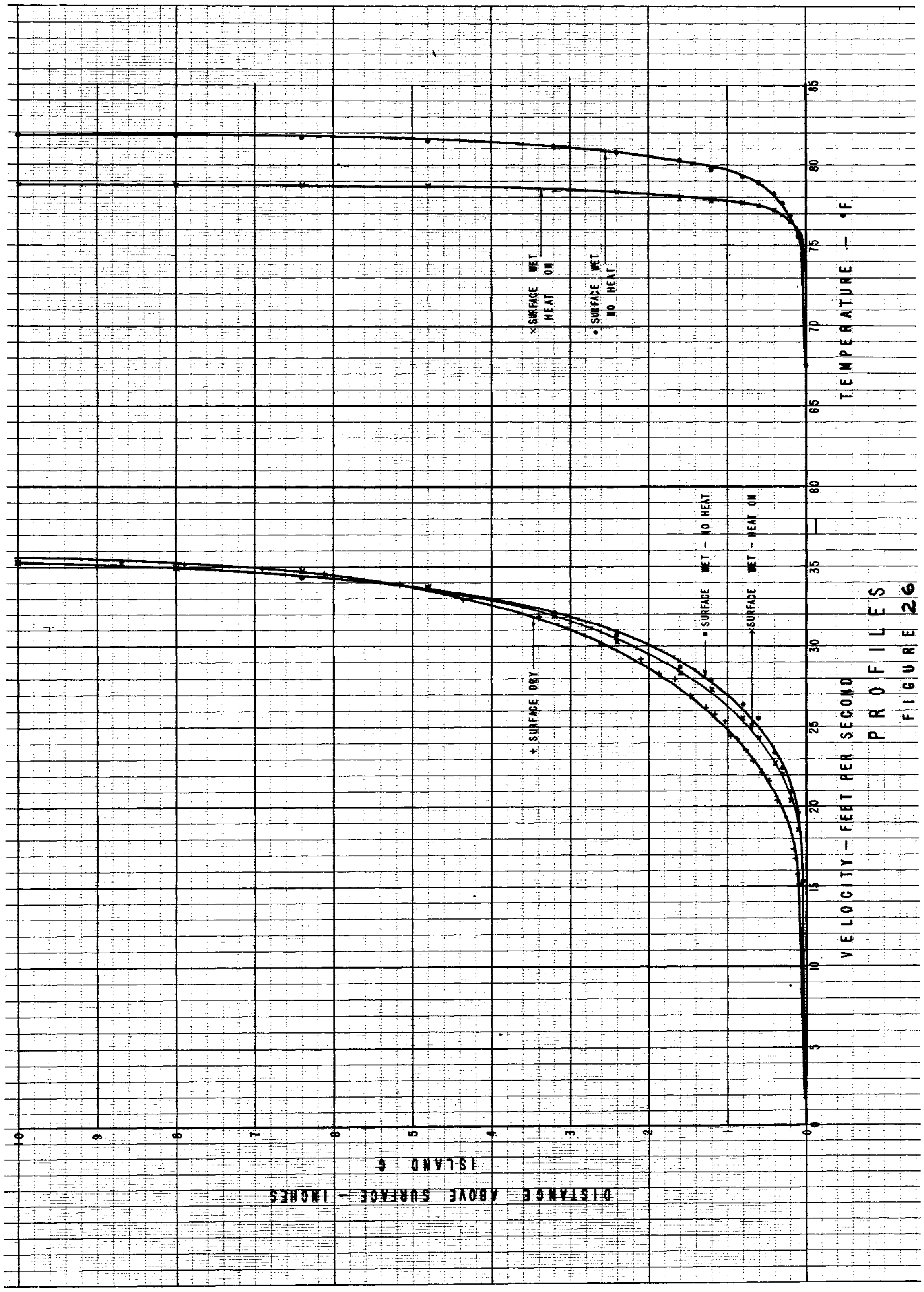
Velocity and temperature profiles taken over Test Island C with the surface wet and with no heat added by the electrical heaters are shown in Figure 25. These data were taken after the surface temperature stabilized at approximately room-air, wet-bulb temperature.

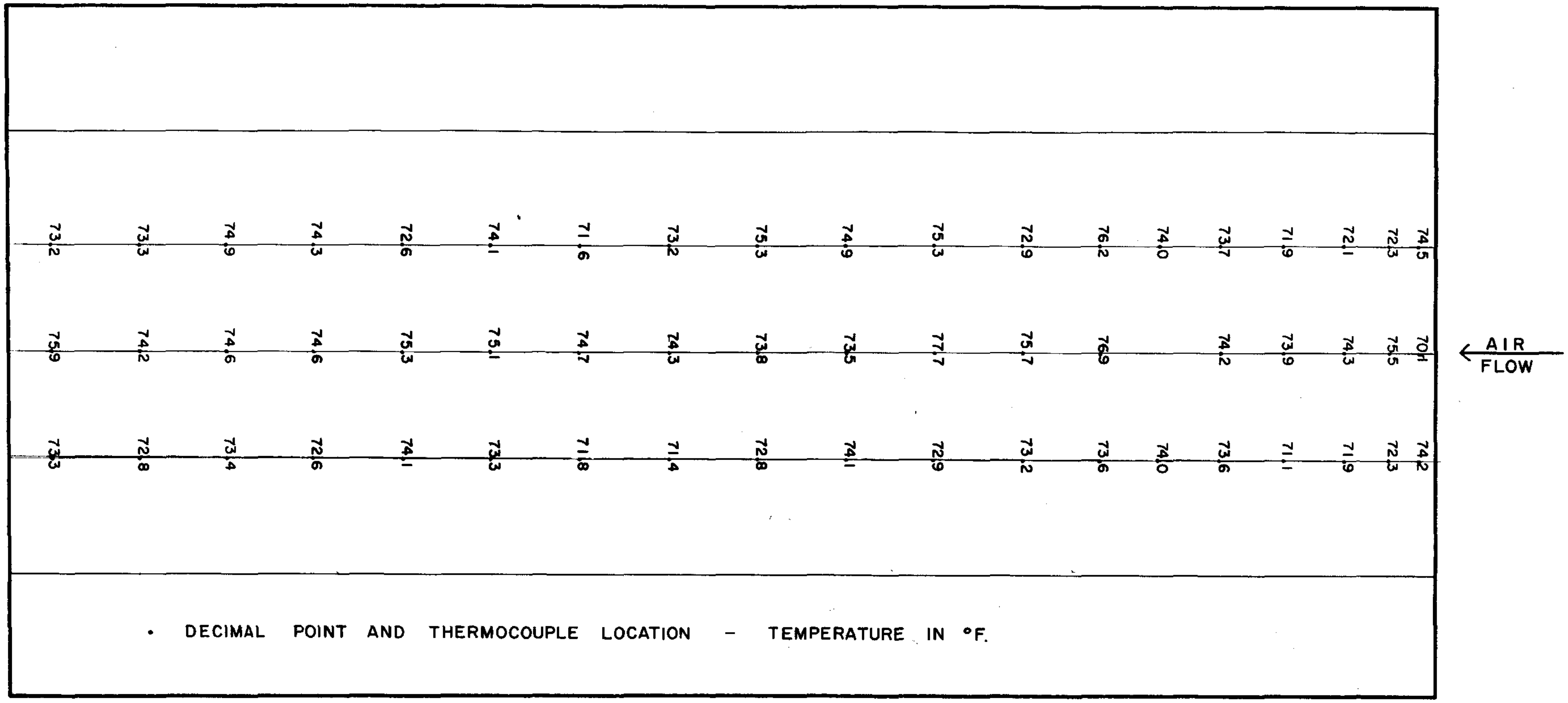
The addition of heat to the surface required no additional technique of instrumentation except that considerable time was required to bring the surface to a reasonably uniform temperature. A recorded surface temperature distribution is shown in Figure 26.

A continuous manual check of all the surface temperatures was made during all tests with the heaters on, and particular attention was given the center-line thermocouples.

Velocity and temperature profiles taken with the heaters activated are shown in Figure 25.

The test-section heaters shorted out and failed during one test run when the temperature of the surface was greater than that of the incoming air. The development of several oil leaks rendered further experimentation impossible.


VELOCITY — FEET PER SECOND
TEMPERATURE — °F
DISTANCE ABOVE SURFACE — INCHES
ISLAND 6
+ SURFACE DRY
• SURFACE WET — NO HEAT
× SURFACE WET — HEAT ON
× SURFACE WET HEAT ON
• SURFACE WET NO HEAT
PROFILES
FIGURE 26



TEMPERATURE DISTRIBUTION-WET SURFACE
HEATERS ON

FIGURE 27

COMPUTATION OF PROFILES

Although the flow was not one-dimensional, the velocity was computed by using the equation

$$V = \sqrt{\frac{2\Delta P}{\rho}}$$

The pressure difference ΔP was measured with the transducer, and the density ρ was computed at the various locations by using the equation

$$\rho = \frac{p}{RT},$$

in which p represents the tunnel pressure, T the absolute dry-bulb temperature, and R the gas constant. No correction was made for the variation of density with vapor concentration because the vapor concentration profiles could not be obtained above the surface. The temperature was read directly from the meter as described previously.

CONCLUSIONS

1. The general design and construction of the wind tunnel are satisfactory for studies of "Boundary Layers at Low Velocities."

2. The test-section surface and heater design are satisfactory in principle, but automatic surface temperature control, monitoring and a more flexible distribution of heat are desirable. Experience with the tentative design leads to the belief that an extremely flexible, heated, wet, and durable surface of uniform temperature could be designed and instrumented.

3. The method of obtaining mean velocity profiles is satisfactory and economical for this type of investigation.

4. The temperature profiles could be improved by providing an integration of the meter reading of the profile temperature-measuring instrument.

5. The positioning device of the probing mechanism should be automatic and of such a design as to permit a complete profile traverse in five minutes.

6. If the proposed dew point instrument is proved and if suggested design changes are made, accurate simultaneous velocity, temperature, and vapor-concentration profiles can be measured under controlled conditions.

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