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A SKIN-FRICTION GAGE FOR HYPERTHERMAL FLOW

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August 1974

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FOR THE COMMANDER:

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The development of a floating element skin-friction gage is described. The gage can be used in high temperature hypersonic flow of gases. The surface in contact with the flow is actively cooled to withstand heat transfer rates up to 300 BTU/ft^2-sec continuously. Linearity of output voltage and displacement with load are demonstrated graphically. The effect of input voltage on coil temperature and output voltage are shown. Water flow and mounting orientation have no effect on the calibration. A mechanical

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) hysteresis was found that is repeatable but could not be explained as to origin.

The friction gage was installed in a channel in which a two-dimensional viscous flow could be established. The friction force and flow conditions were measured. The data was within 1% of agreement with the established laminar flow theory.

Additional experiments were conducted to determine the effect of gage-surface alignment. Results are presented graphically.

Preliminary data from the nozzle wall of an arc-heated hypersonic wind tunnel are also presented.

FOREWORD

This report was prepared by Dr. James Van Kuren of the Analysis Group, Flight Mechanics Division, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio. The work was conducted by the author under Project 1426, "Experimental Simulation of Flight Mechanics," Task 142604, "Theory of Dynamic Simulation of Flight Environment." The friction gage was developed to make measurements for the author's Ph. D. Dissertation which was approved at The Ohio State University in December 1969.

The period of work covered by this report was from April 1966 to November 1969. This report was submitted by the author in March 1974 for publication.

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LIST OF SYMBOLS

A, A'	constant for hot wire anemometer
A_{gage}	area
a	channel half height
B, B'	constant for hot wire anemometer
C_f	friction coefficient
E_a	voltage
E_m	modulus of elasticity
F	force
I_a	current
I_m	moment of inertia
L	length
M	Mach number
P	pressure
R_a, R_{3a}	resistance
Re, R'	Reynolds number
T	temperature
$\overline{U}$	mean velocity in X direction
v_a	voltage
x	axial coordinate
Δ	displacement of floating element
μ	viscosity
ν	μ/ρ
ρ	density
τ	skin-friction stress

LIST OF SUBSCRIPTS

a, 3a	electrical variables
e	edge of boundary layer
exit	exit conditions of channel
gage	conditions at gage
Pressure	output pressure due to load
s	sensor
total	total output of gage
θ	boundary layer momentum defect thickness
0	stagnation conditions
2a	based on channel height

SECTION I

INTRODUCTION

Future tests planned for the Air Force Flight Dynamics Laboratory 50 Megawatt Hypersonic Test Facility and other possible applications such as a space shuttle have requirements to determine skin-friction drag at hypersonic speeds. The turbulent boundary layer in high enthalpy flows at hypersonic speeds is not amenable to a purely theoretical analysis. The previous history of the layer is important for determining local behavior and the problem may be complicated by the existence of chemical reactions and thermodynamic gradients in the fluid. In flows with negative streamwise pressure gradients such as found in hypersonic wind-tunnel nozzles, temperature and velocity profiles are not similar from point to point. To obtain a complete description of the boundary layer it is necessary to have the distributions of the velocity, temperature, and pressure, or the distributions of mass flux, total pressure, and concentration of the chemical species. Another approach is to measure skin friction at the surface directly. The most successful means of measuring surface skin friction has been the floating element gage. Other methods, such as the Preston tube, which are generally very successful, have not been tested in low Reynolds number hypersonic flow as found in the AFFDL 50 MW Hypersonic Tunnel. Floating element skin friction gages were developed and used successfully by Coles, Dhawan, and Korkegi (References 1, 2, and 3) in both subsonic and supersonic flows. These studies presented aspects such as the effect of dampening internal vibrations, the effect of flow through the gap around the surface element, and Reynolds number and Mach number effects on the flow over the gages. Later work at the University of Texas developed a simpler gage design for use in supersonic flows. In these investigations, Westkaemper, O'Donnell, and Young (References 4, 5, and 6) showed the effect of surface misalignment at different Mach numbers and Reynolds numbers and used the floating element gage in flows at high supersonic Mach numbers and varying Reynolds number with both smooth and rough surfaces. The skin friction balance used by Young was of simple design using constant cross-section flexures and a Schaevitz Linear Variable Differential Transformer (LVDT) sensing device. This basic design was essentially modified for the present development to a water-cooled gage for use in high temperature hypersonic flow.

The gage is shown in Figure 1. The essential new feature of the gage is its method of cooling. A continuous channel under the copper friction-surface contains water, flowing at high velocities. The water enters the floating surface through flexible tubing perpendicular to the direction of motion to minimize the force due to the momentum.

Gage output was recorded simultaneously on an oscillograph and in an Ambilog Data Processing System.

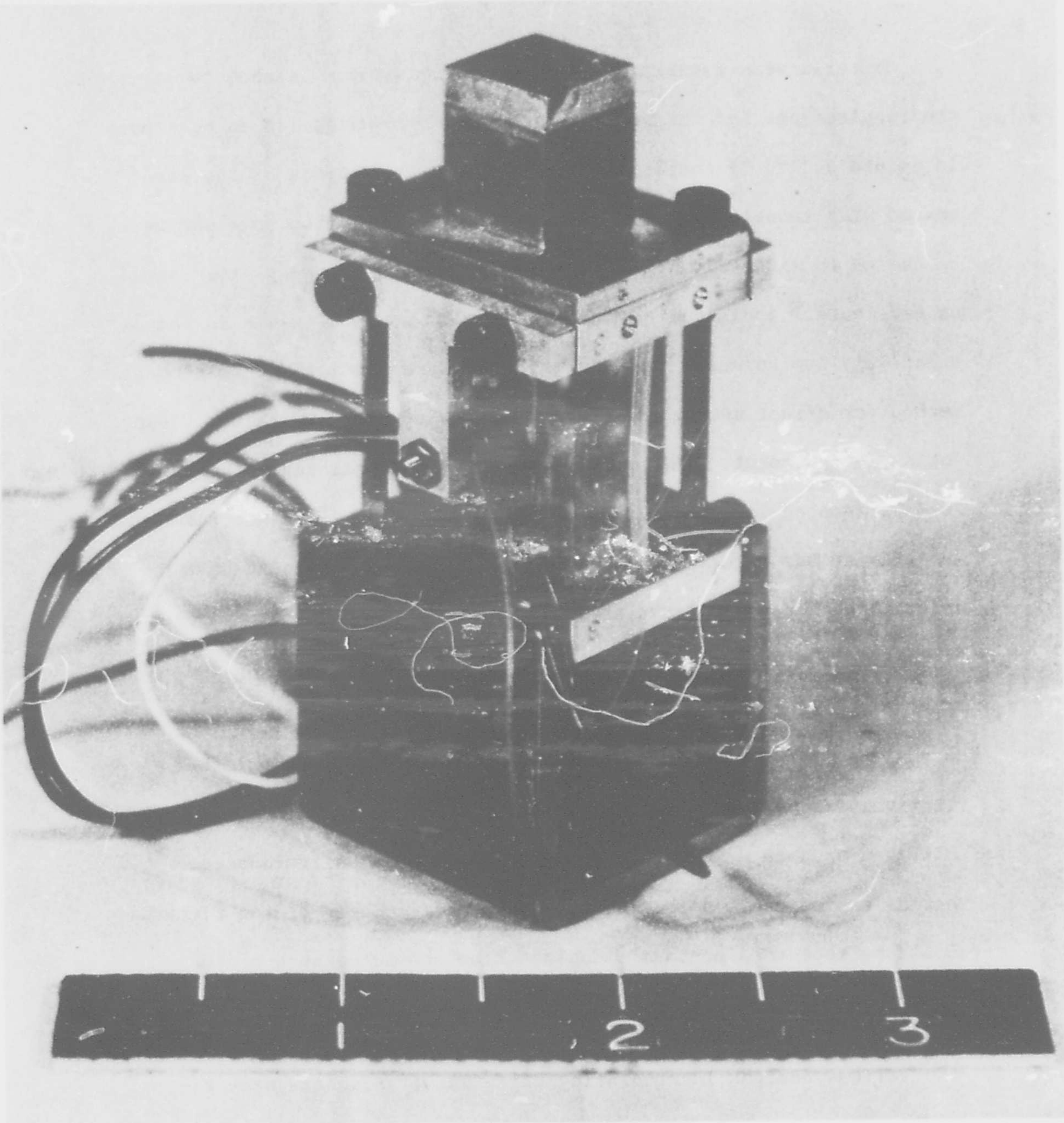


FIGURE 1. SKIN FRICTION GAGE

SECTION II

DESIGN

Criteria were established for the design of the balance to satisfy the requirements for the present problem. The design was to be simple in nature and to be compatible with the flow conditions of the arc-heated wind tunnels. The surface of the skin friction gage had to be cooled to withstand high heat transfer rates. A calculation based on Reference 7 indicated that a Preston tube was not usable in the relatively low Reynolds number flow of the arc facilities. The best method for direct measurement of shear load appeared to be the floating surface element. This gage consisted of a small segment of a test surface mounted level with the wall over which the fluid was flowing. The element was free to move in the streamwise direction against a restraining force such as a spring. A suitable transducer was used to measure the force or displacement of the element. It was desirable to have a balance configuration that was proven reliable, to eliminate some steps of the development. The motion of the gage should be relatively frictionless. Rotation of the surface could not be tolerated because unknown aerodynamic loads could be introduced. Thermal expansions and thermal stresses, particularly of the flexures, should be kept to a minimum. Coolant flow should cause a minimum disturbance in the direction of the skin friction shear.

Various designs incorporating different transducers were reviewed. Piezoelectric crystals were examined since these devices had proven successful in impulse facilities (Reference 8). For the high heat transfer rates and long run durations of the arc tunnel, use of these gages was not feasible. Different types of flexures incorporating bending or displacement of a coil spring were considered but none of these met the requirement for simplicity found in the gage used by Young.

In Young's gage four constant cross-section beam flexures become restrained beams for which the deflection is

$$\Delta = \frac{FL^3}{12E_m I_m} \tag{1}$$

The upper plate is free to move on the flexures and becomes the platform for the copper block containing the surface element. Figure 2 shows the various component parts of the gage. The Schaevitz LVDT is placed in a plexiglass block which is epoxy cemented to the base plate. The core of the transformer is threaded on a brass screw and fixed in place with a lock nut. The screw then is attached to rigid T-bars which are firmly fastened with allen screws to the top plate. The core therefore moves precisely the same amount as the surface elements. Water cooling was introduced into the friction surface through 1/16 inch channels in the copper block which forms the surface. The surface skin is 1/16 inch thick OFHC copper. Water enters the surface plate through 1/16 OD flexible teflon tubing extending from the lower plate to the top plate. The tubing is attached such that water enters and leaves the top plate perpendicular to the direction of airflow and to the displacement of the plate. This feature minimizes the dynamic loads of the water. Viscous damping of the surface plate

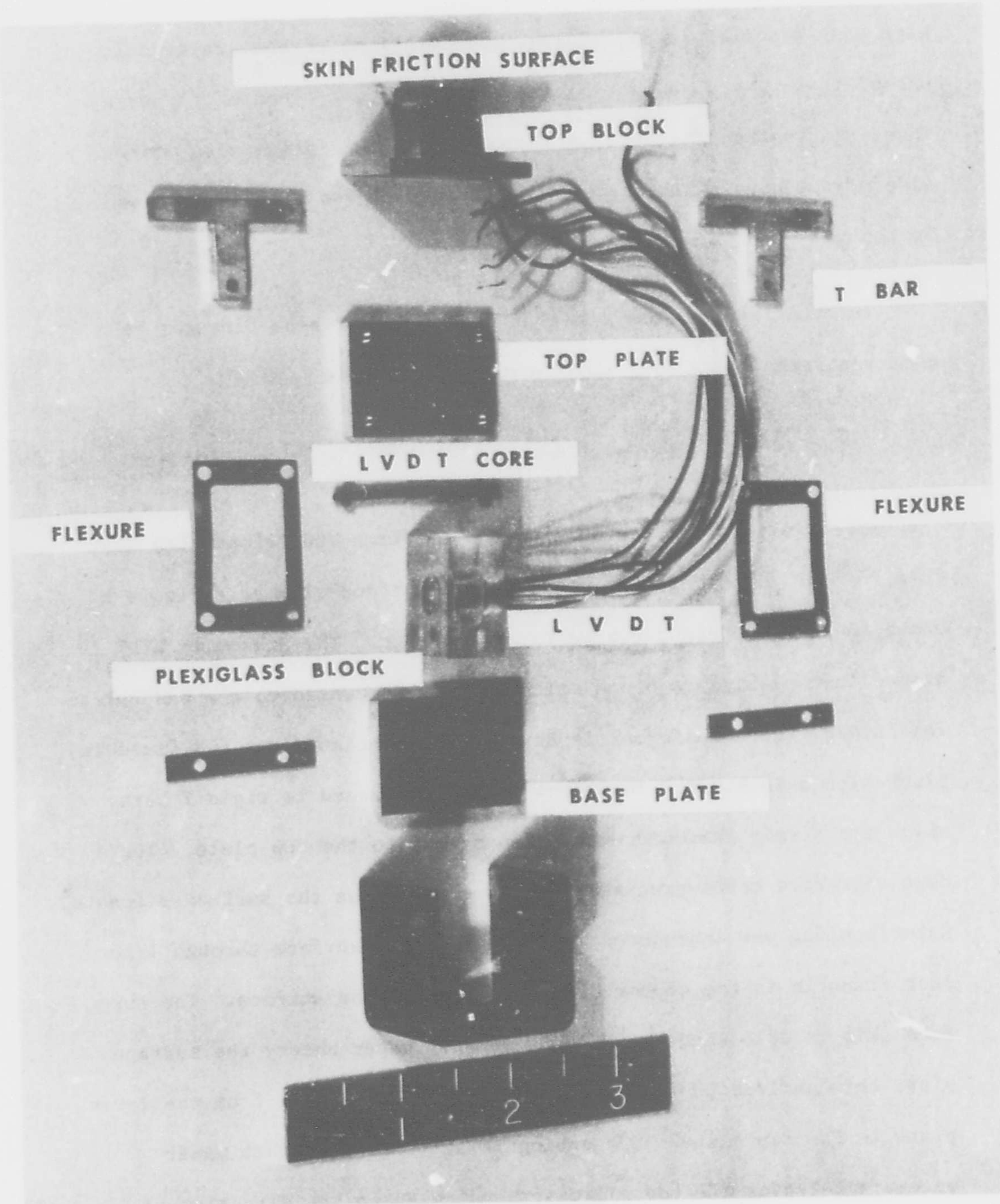


FIGURE 2. SKIN FRICTION GAGE COMPONENTS

is obtained by the use of silicon damping fluid placed in the small gap between the top plate and the transformer housing. The transformer contains one primary and two secondary coils. The primary was connected to an oscillator, set at 3000 cycles per second and initially 3 volts. The secondary was connected to an AC voltmeter. This circuitry, as recommended by the manufacturer, proved to have a very nonlinear and insensitive output of voltage versus displacement, and a high voltage at null or center position of the core (Figure 3). The circuit was modified by (Figure 4) adding a 10:1 transformer which magnified the output so as to make it appear to be more linear. The overall accuracy of this system was still less than desired and null could not be reduced to the required minimum of less than 1% of full scale voltage. A more sophisticated circuit was designed using a Wiancko oscillator with a steady 10 volt 3000 cycle per second output, an AC amplifier, and a rectifier bridge to form a large DC output. Rectification appeared to be more desirable in terms of recording accuracy because it permitted the use of a DC digital voltmeter. This circuit proved very satisfactory in terms of linearity, and by proper adjustment of potentiometers in the AC amplifier, the null was reduced to less than 1% of the full scale output of the Schaevitz transformer. For example, null voltage was less than 8 mv out of 900 mv full scale.

However, in this design noticeable voltage variations were picked up over a period of time. These variations were caused by temperature changes in the transistor and resistors in the amplifier,

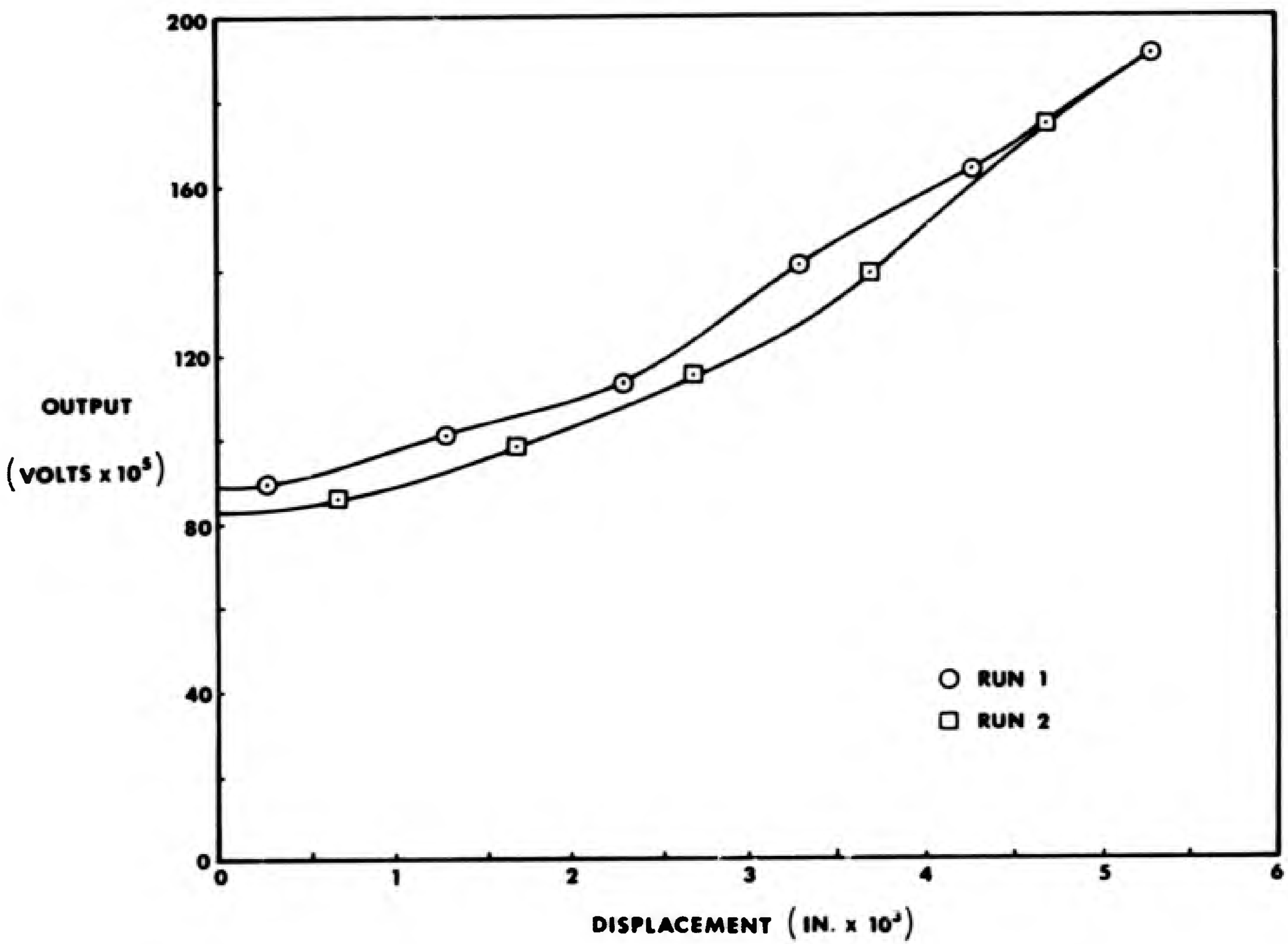
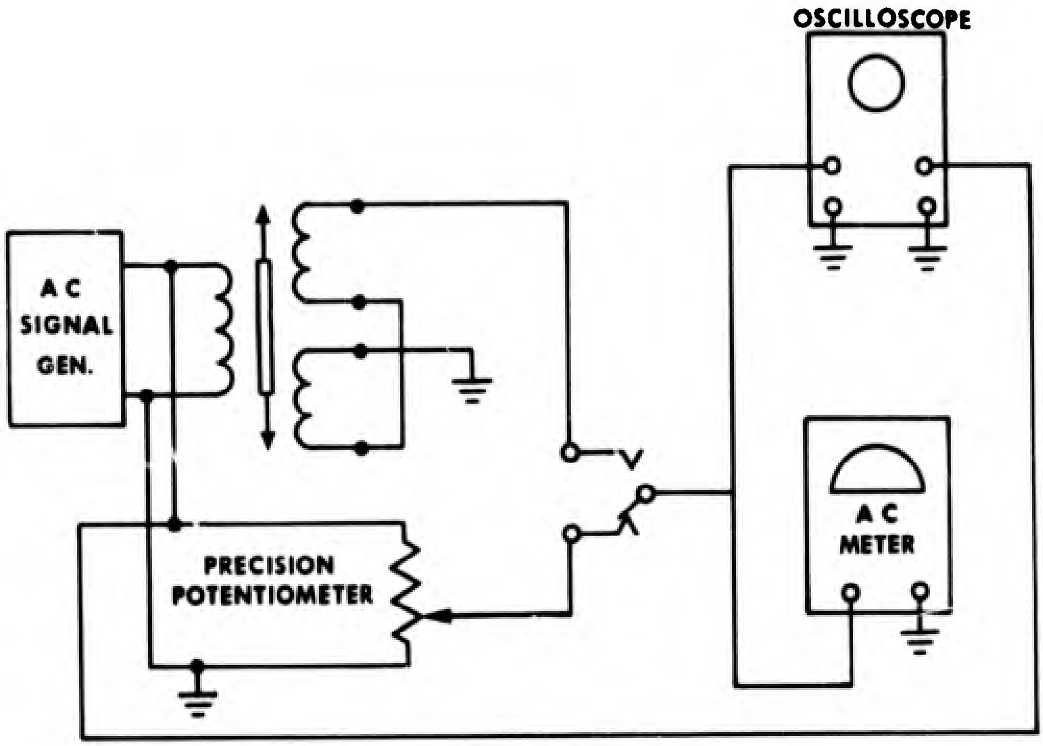
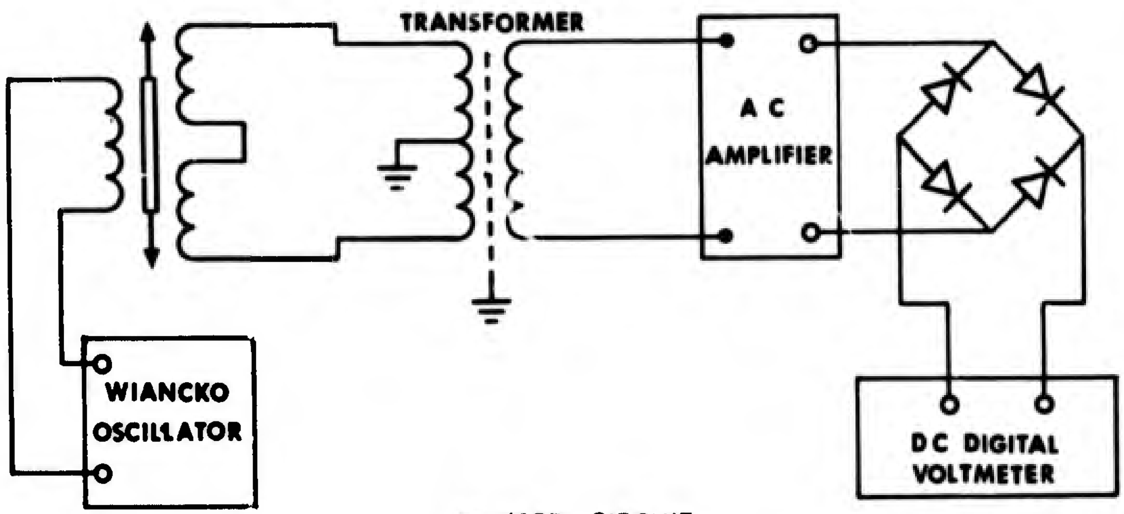


FIGURE 3. NONLINEAR OUTPUT



ORIGINAL CIRCUIT



REVISED CIRCUIT

FIGURE 4. CIRCUIT DIAGRAMS

due to convective air currents in the room. The problem was corrected by adding a copper heat sink to the transistor and by using variable resistors. However, even with these modifications the rectifier circuit and the DC digital voltmeter left much to be desired in accuracy and were replaced with an AC digital voltmeter which connected directly to the AC amplifier (Figure 5), a combination which proved to be the most successful of all. Accurate linear output was achieved with a very low null. The system was quite sensitive and could pick up small disturbances of the skin friction balance. It was noticed that joule heating of the Schaevitz gage caused its temperature to increase, producing changes in the voltage output. Air cooling was added to the Schaevitz gage to keep its temperature relatively constant. This would be particularly desirable in the temperature environment in which the balance would be used.

During the last bench tests it was noticed that mechanical shift of the gage caused a permanent set in its displacement. Core drag and pulley friction were eliminated as possible causes. It was thought that the flexures were shifting in their attachment points causing an elastic instability in the overall system of four flexures. This was minimized by using allen-head screws and tightly clamping the aluminum bars over the copper flexures. (Later, it was discovered that the flexure material was slightly curved due to the rolling process by which it was manufactured. This means that the flexures did not share the load evenly and that one pair went through a neutral position during loading.)

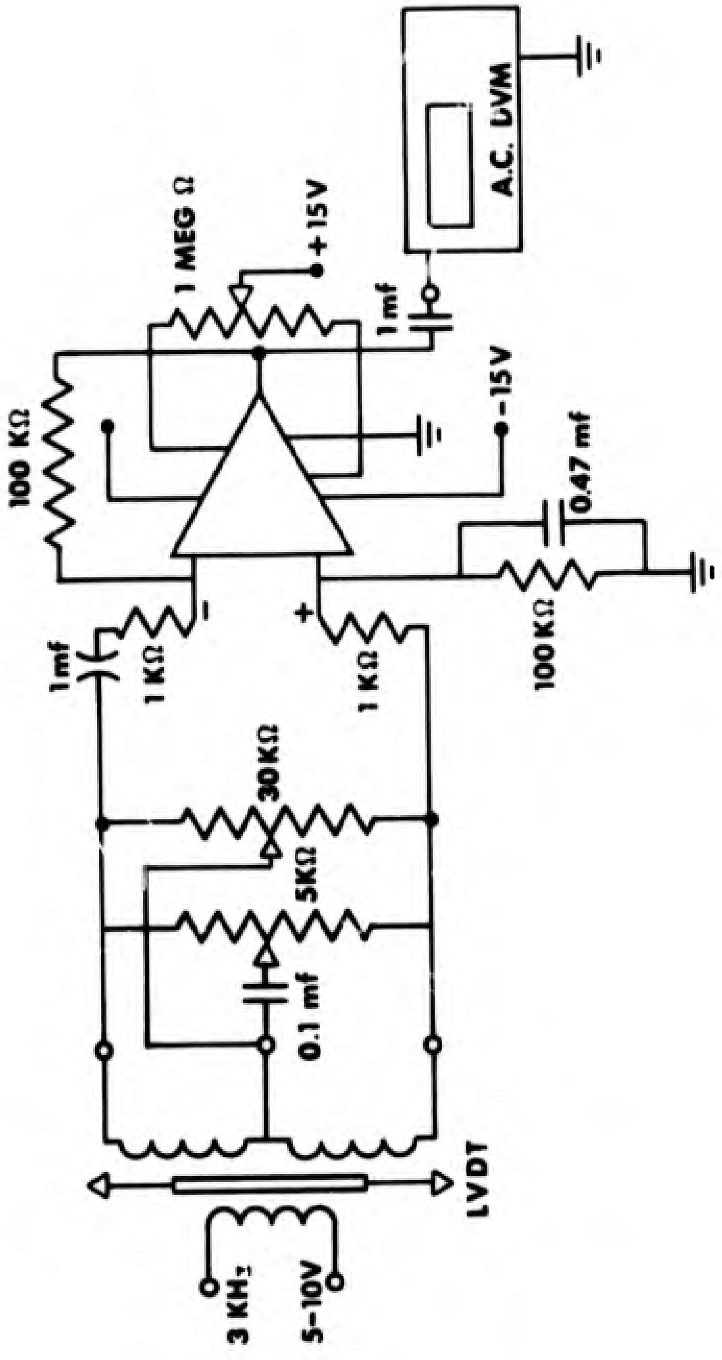


FIGURE 5. FINAL CIRCUIT

SECTION III

EXPERIMENTAL RESULTS

1. Bench Calibration

First an uncooled version of the skin friction balance was assembled. The assembly was attached to a bracket with a micrometer screw to displace the upper surface of the gage. This apparatus was used to develop the appropriate circuitry and instrumentation to get a linear output of relatively large amplitude. Output versus displacement is shown in Figure 6. The Schaevitz transformer proved to be more accurate than the micrometer.

Water-cooling passages were added to the skin friction balance. Water flow and load due to water flow were measured by using a water flow calibration rig designed by Greyrad Corporation. The loads and vibration could then be measured under the flowing condition. The water-cooled version of the balance was incorporated into the circuit calibration rig so that output versus displacement could be obtained with the water flow on.

A loading mechanism consisting of a hook, string, pulley, and pan was added to the calibration apparatus so that voltage output versus actual load or force could be obtained with the water flow on. It appeared that pulley friction was causing a hysteresis in the calibration curve. The gage was mounted with the motion vertical to enable direct application of the weights. The null position of the core was adjusted to allow for the tare weight of the gage itself. The hysteresis still appeared. A possible

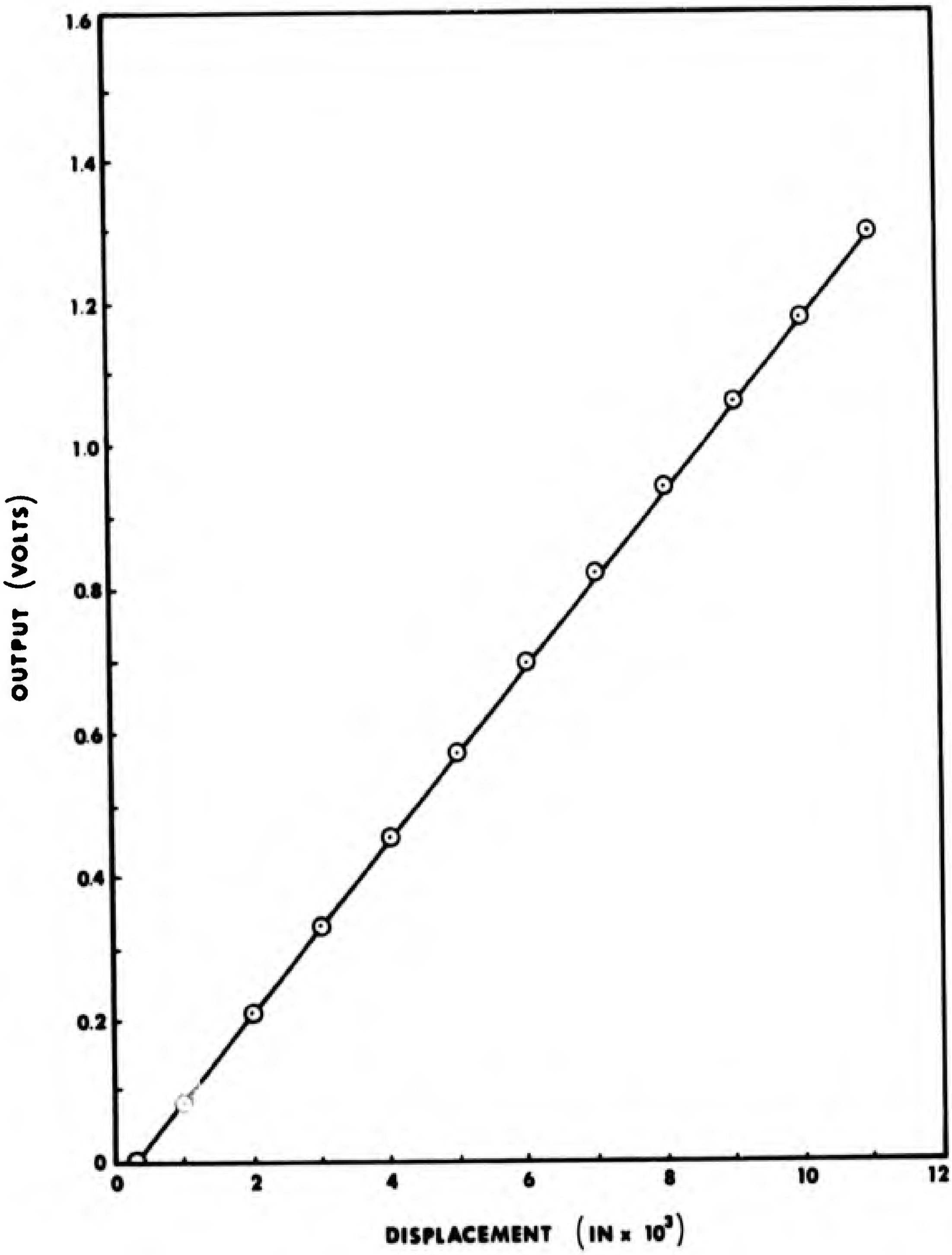


FIGURE 6. OUTPUT VS DISPLACEMENT

explanation is that this was characteristic of the BeCu sheet used in the flexures. Regardless of this anomaly the data were repeatable (Figure 7). Other figures in this section are shown only for positive loading rates. In measuring skin friction, care must be exercised to ensure that the gage has been loaded in the positive direction. Data were taken at 3 kc with various input voltages from 4.5 to 9.

As mentioned previously it was necessary to cool the transformer body. Thermocouples were added to the coil and mounting block to ascertain the severity of ohmic heating. Temperatures were monitored for various input powers. Results are shown in Figure 8. The coil temperature was at an acceptable level of less than 200°F at the available voltages.

Water pressure drop through the gage coolant circuit was much higher than calculated. A restriction caused during fabrication of the gage, probably exists in the water circuit. At 335 psig inlet, the flow rate through the gage was 0.015 lbs/sec, which gave an average water velocity of 11 feet/sec. At this flow rate the gage was capable of absorbing about 300 BTU/ft^2-sec.

A single-point check was made of the gage performance under a condition where a hot gas was actually flowing over the friction surface. The apparatus consisted of a metal shield with a square hole for the gage surface, a commercial resistance type of heat gun, and thermocouples mounted at the edge of the friction surface

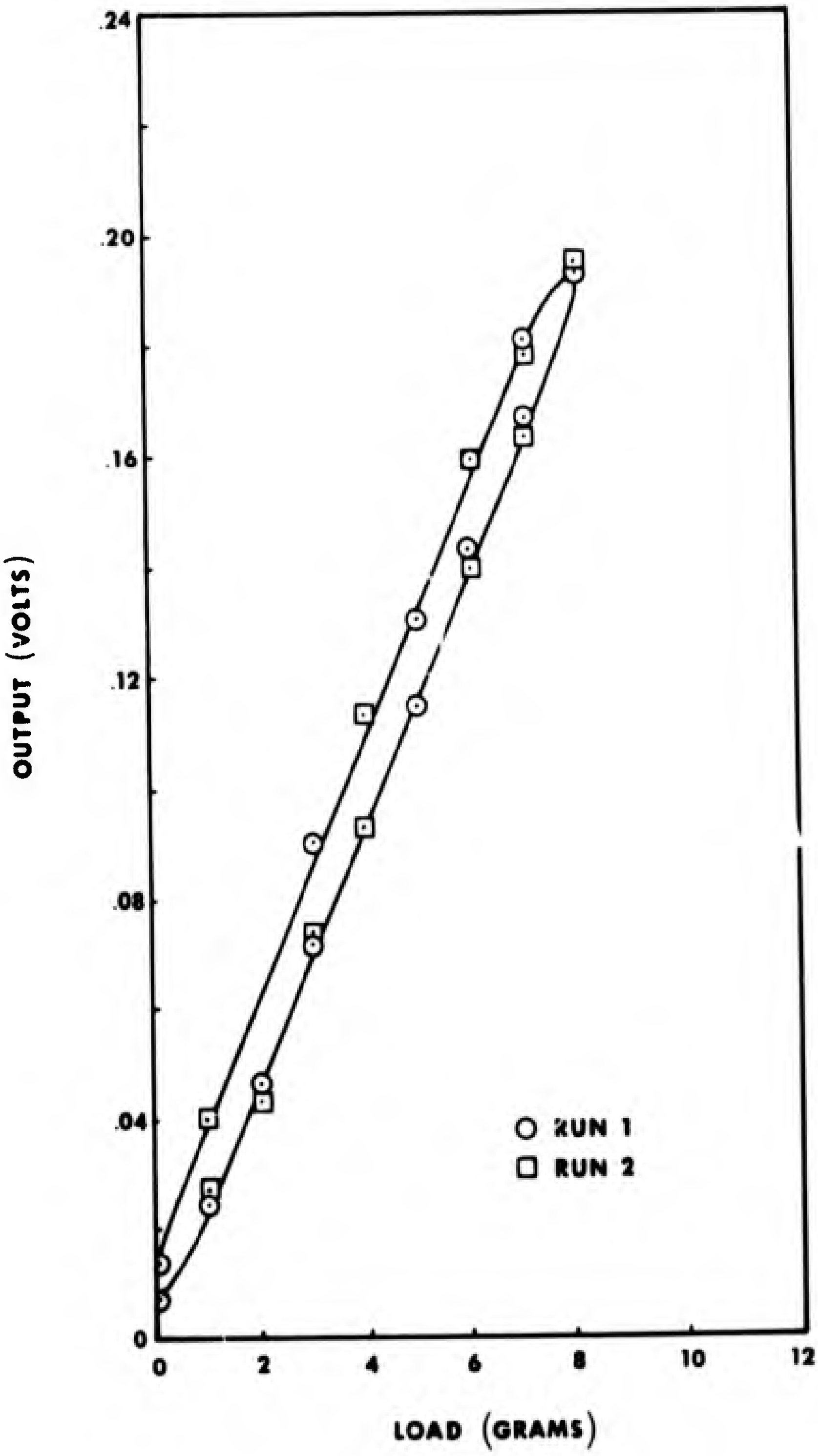


FIGURE 7. GAGE HYSTERESIS

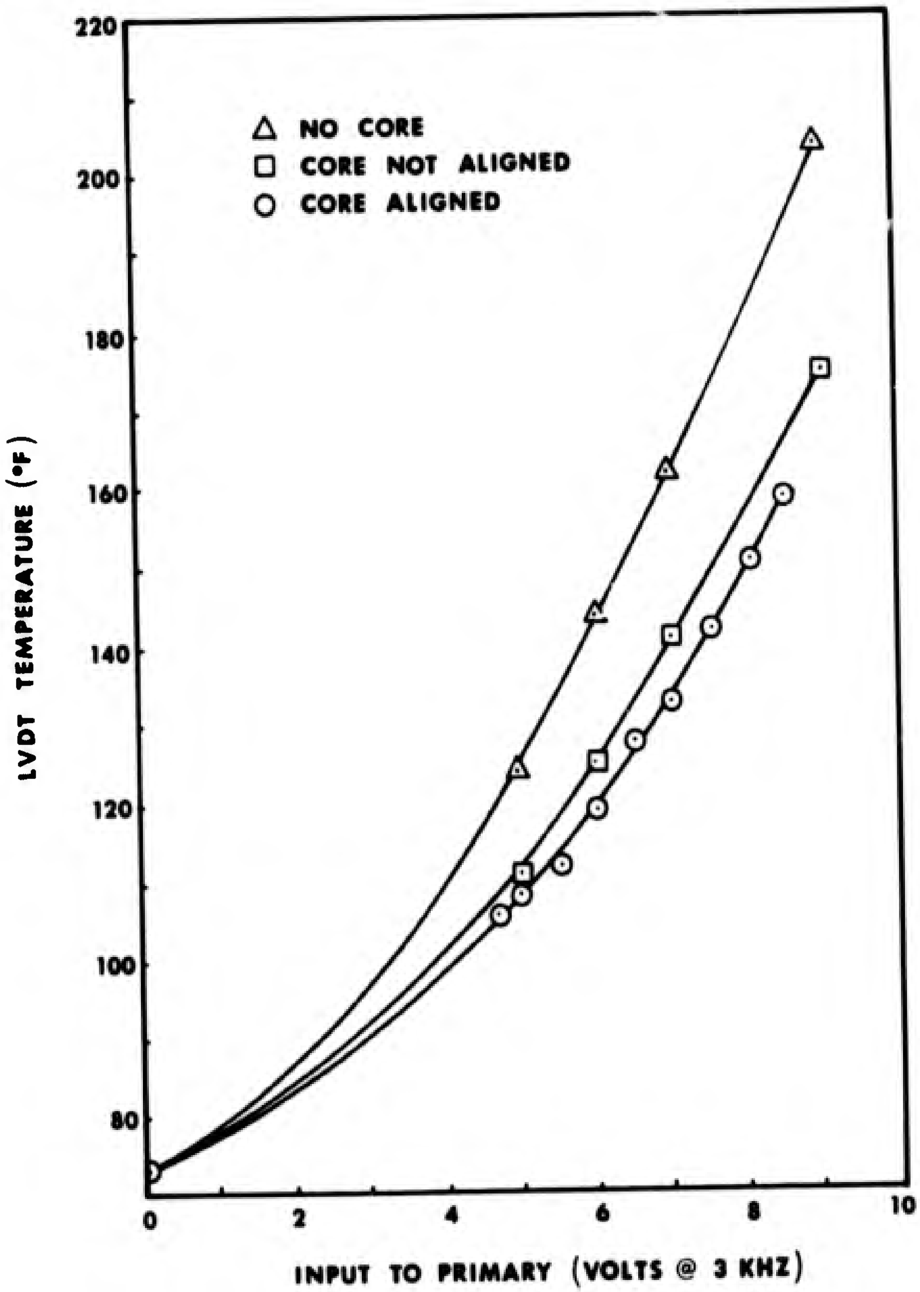


FIGURE 8. LVDT TEMPERATURE

and at the base of the top block. Temperatures at the Schaevitz transformer and mounting block were also monitored. The gun was held so that the hot jet flowed over the gage surface. After an initial thermal transient, relatively steady temperatures (±2°F) were observed. For a water flow rate of 0.0082 lbs/sec, the top surface temperature was 236°F and the base of the top block was less than 84°F. The LVDT had a 10°F rise in temperature to a value of 111°F. The average heat transfer rate to the gage surface under these conditions, calculated from the water temperature rise, was 26 BTU/ft^2sec.

The calibration of the skin friction balance showed that the Schaevitz transformer when properly connected to an oscillator and an AC digital voltmeter, could give a large and very linear output for displacements of the skin friction balance as low as 10^{-4} inch.

A sample curve of voltage output versus displacement has been presented as Figure 6. The output was linear and repeatable within 1% of the reading over a range of +0.004 inch displacement. In place, in a model or nozzle, the gage could measure up to 5 grams load with a total displacement less than 0.001 inch (Figure 9).

Figure 10 shows the voltage output for various load inputs to two different gages. By taking the ratio of output to input voltage these curves collapse onto one line as shown in Figure 11.

Additional checks of the effect of gage orientation were made. The data for the gage mounted in vertical and horizontal positions is shown in Figure 12. The effect of the column loading on the

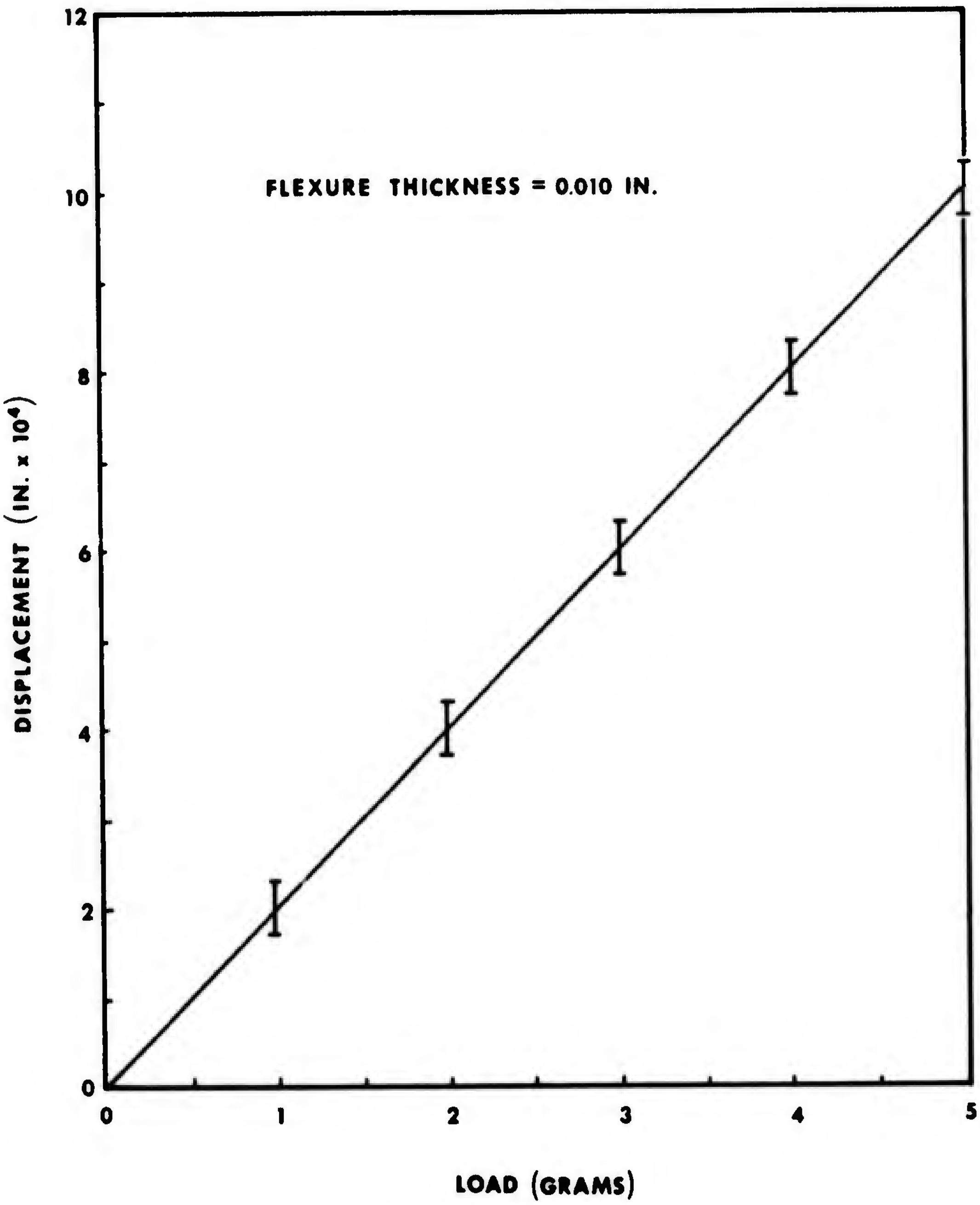


FIGURE 9. DISPLACEMENT VS LOAD

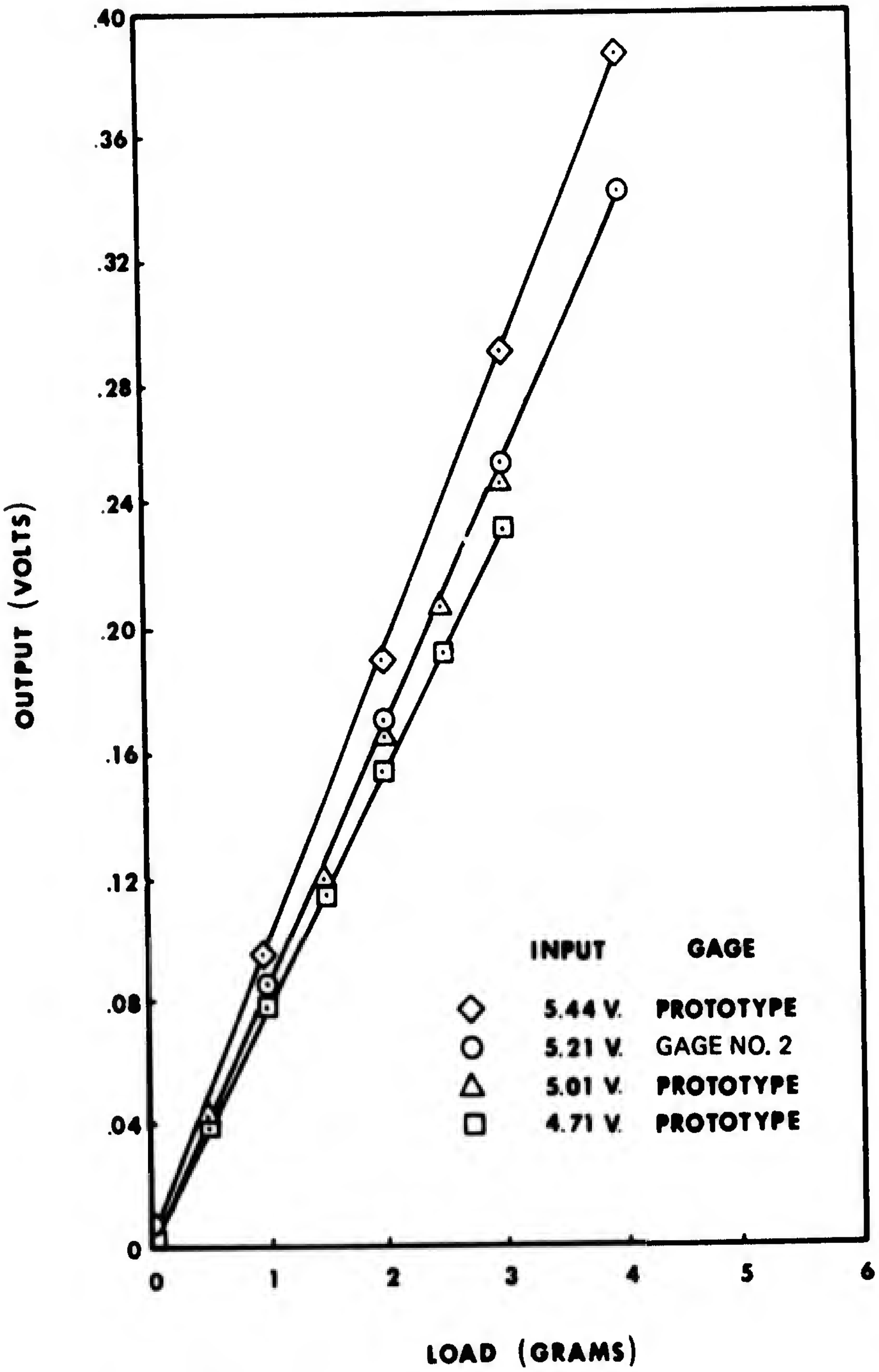


FIGURE 10. GAGE CALIBRATION

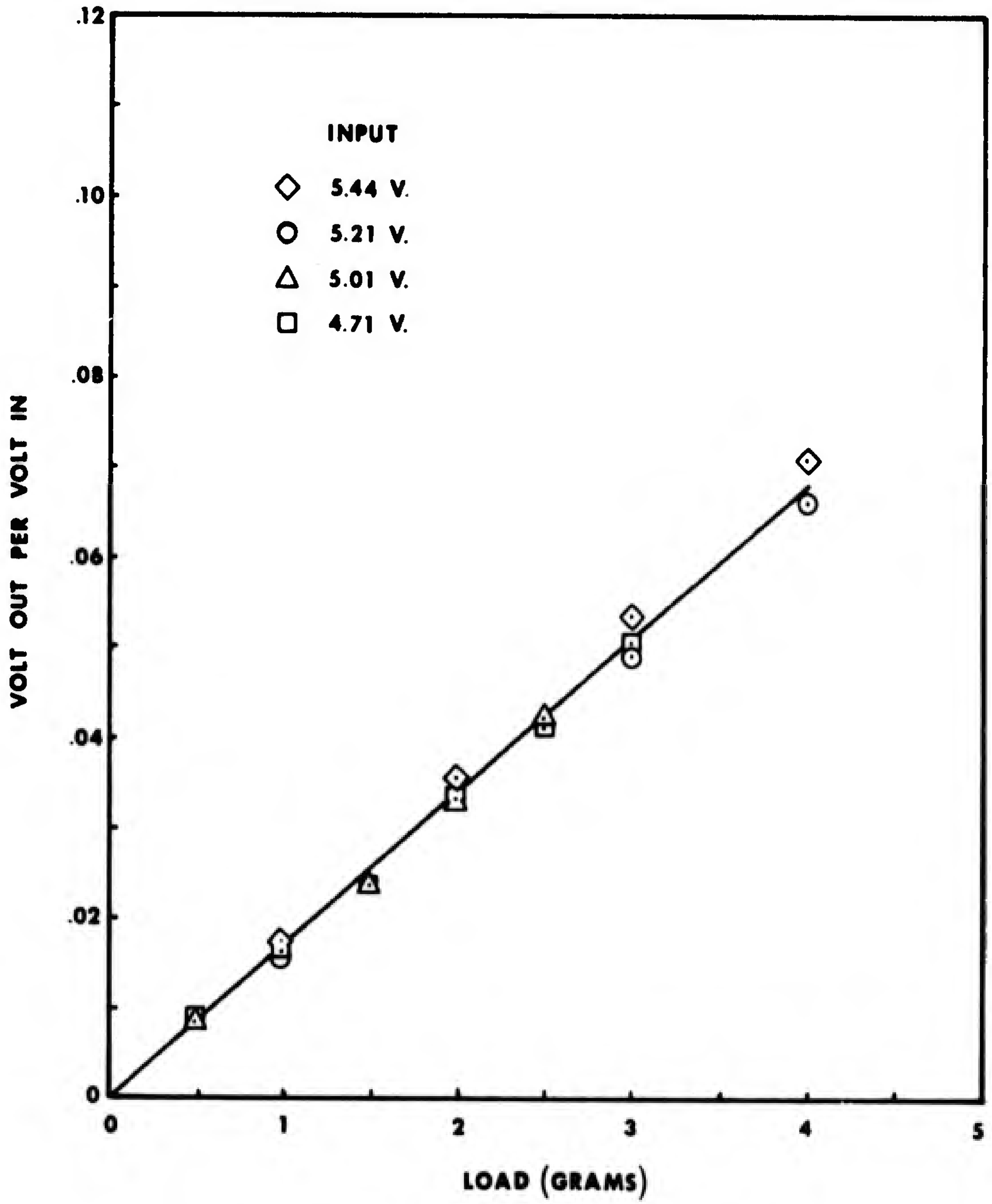


FIGURE 11. NORMALIZED CALIBRATION

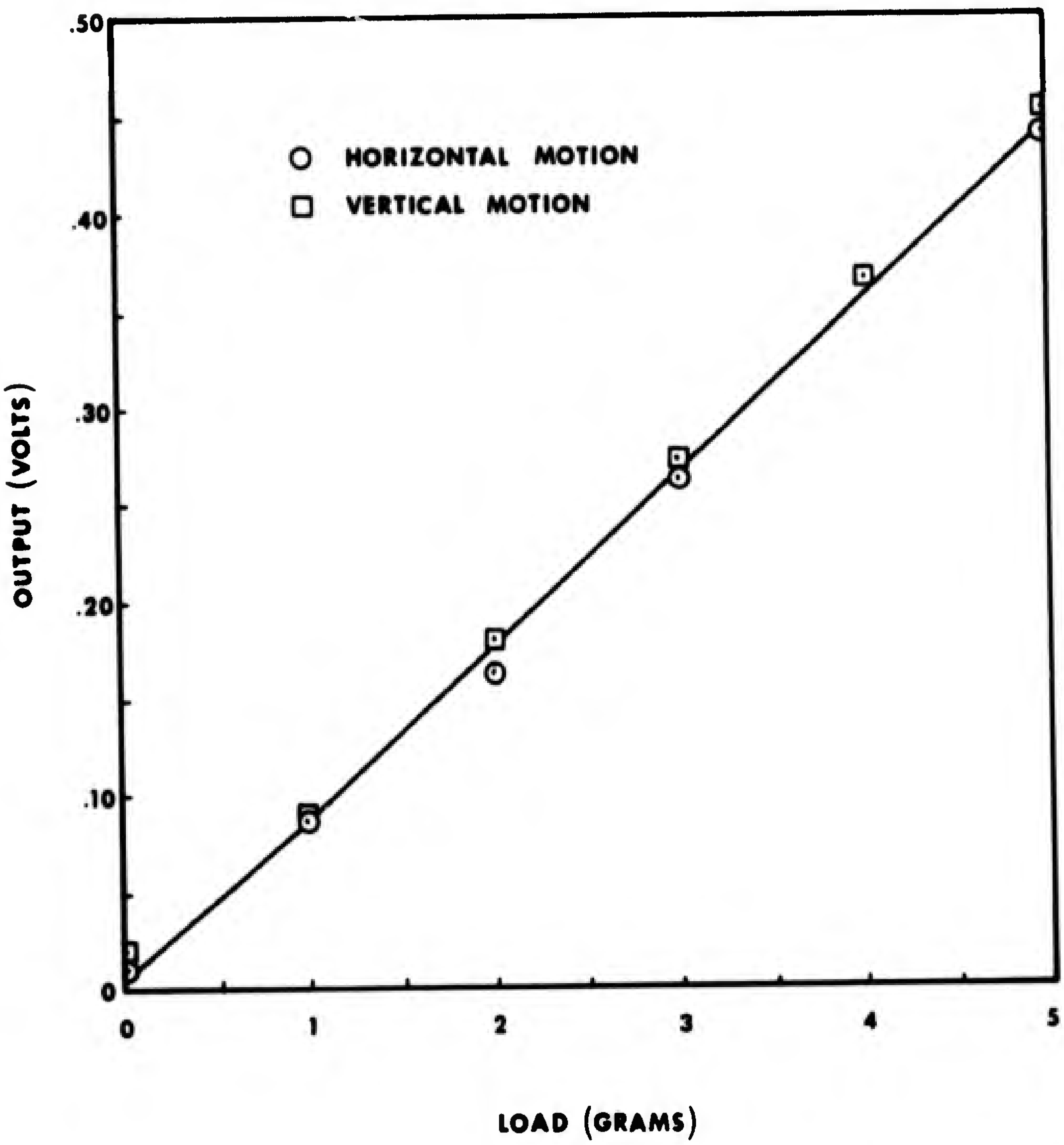


FIGURE 12. EFFECT OF ORIENTATION

flexures due to pressure normal to the friction surface was calculated to be negligible.

The final result of a typical calibration with various coolant flow rates is shown in Figure 13. The load-displacement relationship is linear for loads of 1/2 to 5 grams for all water-flow rates within the capacity available. There is no consistent measurable effect due to water flow. Scatter of the data is within the noise of the system, which was ±4 mv under quiet conditions and ±7 mv when machinery was running in other parts of the building. The zero offset in the calibration curve is characteristic of the LVDT and was consistently of the same value as the noise from external sources.

2. <u>Operation in Incompressible Viscous Flow</u>

The friction gage was installed in a channel in which a two-dimensional viscous flow could be established. The objective of this experiment was to obtain operating experience with the gage under conditions of known friction.

The channel was designed to produce, as accurately as possible, an ideal two-dimensional viscous incompressible flow. The basic channel was designed to satisfy three criteria: (1) the value of the friction load should be the same as that expected at the wall of the hypersonic nozzle of the 50 MW Electrogasdynamic Facility, (2) the flow must be incompressible, thereby limiting the maximum Mach number of the air to less than 0.3, and (3) the flow must be

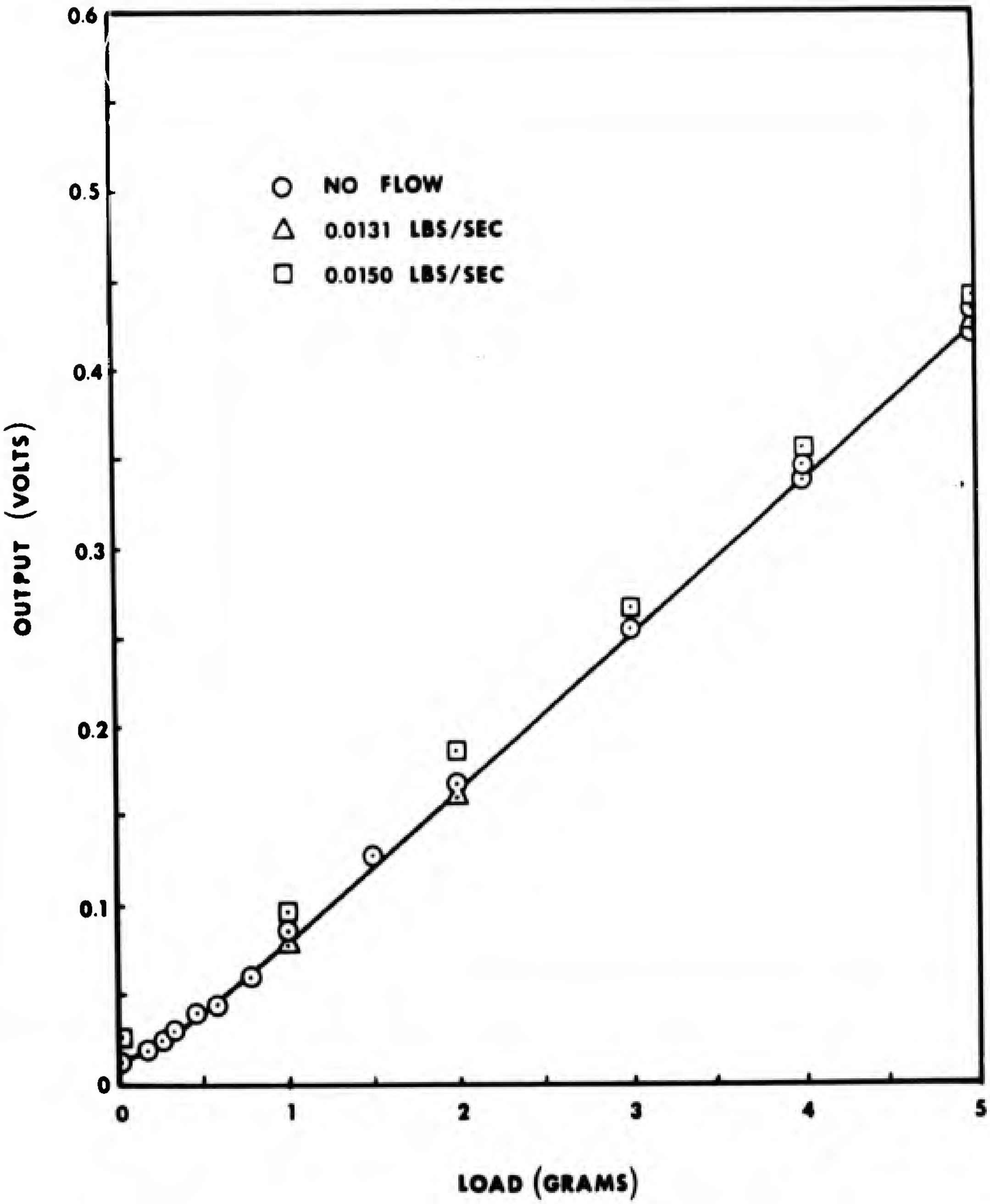


FIGURE 13. EFFECT OF WATER FLOW

laminar, thereby limiting Reynolds number to less than 2000, based on channel height.

Air at 40 psi was piped to the gage through approximately 20 feet of 3/8 inch copper tubing in which a metering valve was installed for regulation and control of the mass flow. The air entered a 1.50 high by 8 inch wide stilling chamber and passed through a copper mesh to produce uniform properties at the channel entrance. The entrance had 0.5 inch radius ramps into the 0.01 high by 5.50 inch wide two-dimensional flow channel (Figure 14). Channel surfaces were ground flat to increase the probability that constant flow properties would be produced. Based on the theory given in Reference 11 (1955 Ed., P 147, Schlichting) for the development of this flow, no changes in profile should occur after a certain length.

$$100 \frac{\nu\lambda}{a^2\overline{U}} = 16 \qquad (2)$$

or

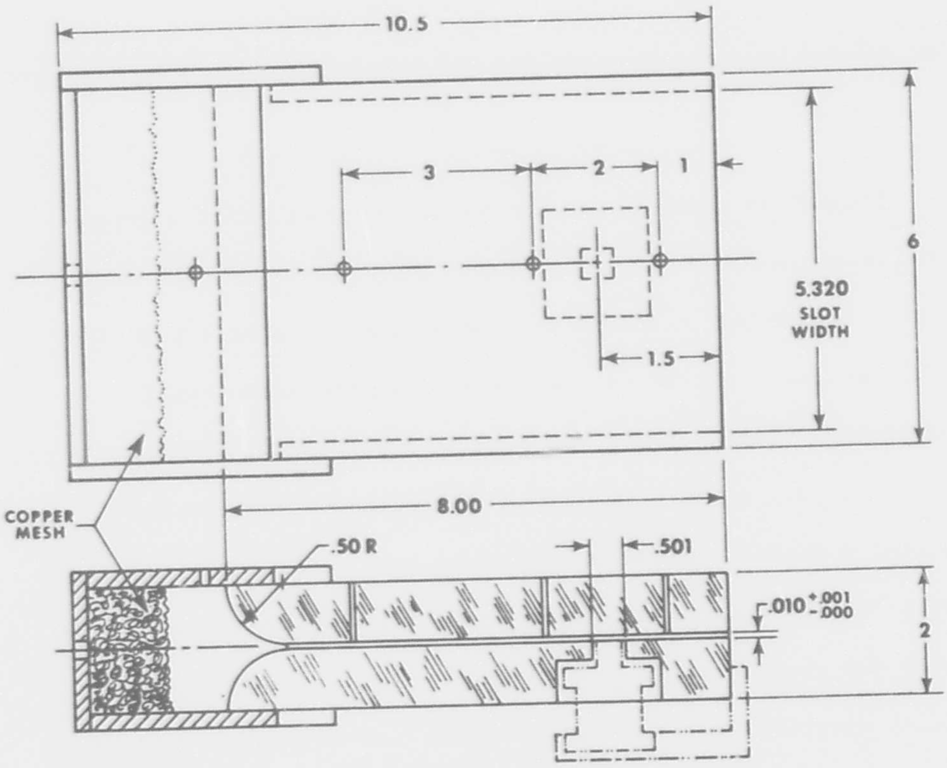
$$X = 0.16\ a \frac{\overline{U}a}{\nu} \qquad (3)$$

or

$$X = 0.04\ (2a)\ Re_{2a} \qquad (4)$$

For $Re_{2a} = 2000$ and $2a = 0.01$, $X \approx 0.8$ inch. The flow is fully developed veyond this location; velocity profiles are identical and the pressure gradient is constant, being exactly balanced by the friction force, so that

$$\frac{dP}{dx} = \frac{\tau}{a} \qquad (5)$$



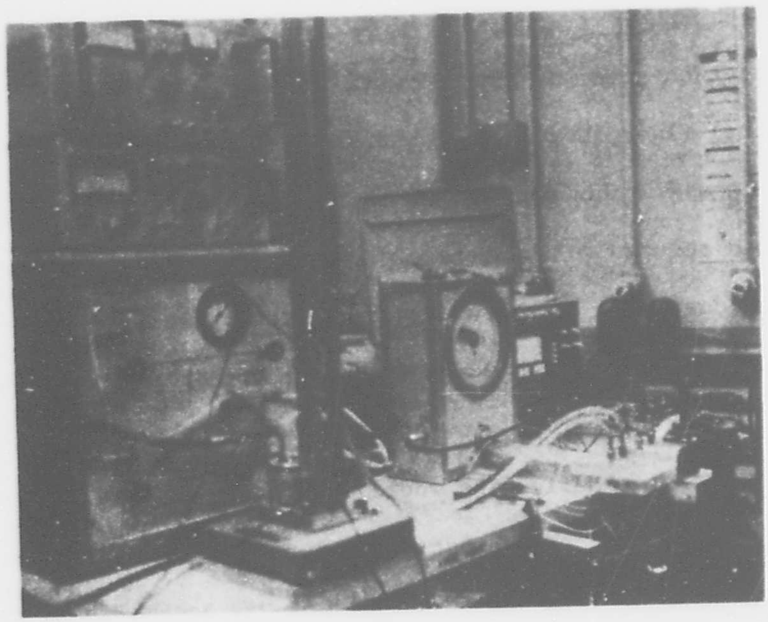


FIGURE 14. FLOW CHANNEL

The channel was instrumented for one temperature and four pressure measurements.

Stagnation chamber temperature was measured with a copper-constantan thermocouple and recorded on a CEC Data-Graph strip chart. Stagnation pressure was taken from a static tap in the stilling chamber where the mean air speed was less than 1 foot per second. The pressure was read on a Wallace-Tiernan gage with a 0 to 35 psig range. The gage was checked, at one pressure, against a mercury column and found to read 1% high at 4 psig. Three static pressure taps were located in the upper channel wall above the channel axial centerline at 1 inch, 3 inches, and 6 inches upstream from the exit. Static pressures were read using a mercury manometer with a vernier scale to allow reading to 0.05 mm.

The friction gage was mounted with the friction surface centered in the channel floor, two inches upstream from the exit. The floating surface was 1/2 inch square (as in the nozzle tests) but the clearance was reduced to an average of 0.001 inch on all sides. A pulley was connected to the underside of the channel assembly for calibration of the gage with weights and for preloading the gage to extend its usable range. This was necessary at the higher flow conditions when the gage deflection would be great enough (0.001 in.) for the gage to contact the downstream side of the hole. Vertical alignment of the gage with the channel floor was accomplished by placing shim stock in the channel over the gage hole, then installing the gage until it touched the surface of the stock.

Various degrees of channel interference could be obtained by using thinner shim stock. Location of the gage below the surface was only done by visual observation and comparison with the edge of the shim stock. A ten-power magnifier was used for this purpose. Final visual check of the gage was made with a stereo microscope. For some of the data runs, a hot wire anemometer was used at the gage exit to detect turbulence. The wire was 0.0005 inch in diameter and was mounted on prongs approximately 0.25 inch apart. The wire was placed in cross flow parallel to the large dimension of the channel exit slit, as close to the exit as possible (estimated to be about 0.02 inch). With air flowing in the channel, the wire was moved across the flow until peak output was observed. This was assumed to be the center of the flow and, correspondingly, the locus of maximum velocity; the wire was fixed at this position. Wire output was manually recorded from the bridge voltage meter of a Thermo-Systems Inc. constant temperature anemometer circuit.

Gage input was supplied by the Wiancko 3 K-Hz oscillator used in the bench tests and nozzle flow tests. The input was held at 5 volts RMS to within 0.02 volts. Gage output was balanced, amplified, and filtered by the identical circuitry used in the bench tests and the tunnel tests. An oscilloscope was used across the amplifier output to aid in balancing the circuitry to minimize the null voltage. The scope trace was also very useful in determining whether the friction gage was freely mounted. There was a noticeable difference in the response of the free gage to an impulsive input such as a tap on the mounting bracket, compared to the case when the gage was touching one of the four sides of the hole. The output was recorded manually from a digital voltmeter which was accurate to 0.001 volt.

Before the flow was started the friction gage output was balanced by two potentiometers in the output circuit (Figure 5). Normally a null voltage of less than 0.012 volts could be achieved. (Midway through the series of experiments this was found to be unnecessary since the output remained linear regardless of initial voltage.) The metering valve was opened until the desired pressure was reached. All instrument readings were recorded and the pressure was increased to the next value. When the gage reached its downstream limit the range was extended by preloading in the upstream direction with the pulley-weight arrangement. The free range of the gage corresponded to about 0.7 psi supply pressure change. By adding weights up to 15 grams, the gage range was extended over the full incompressible limit which corresponded to 5 psig. For example with 1 gram the gage could be used between 0.7 and 1.4 psig, with 2 grams between 1.4 and 2.1, etc. During one run, polaroid photographs were taken of the anemometer output displayed on an oscilloscope. The crude hand-triggering technique used on the scope resulted in multiple traces on the film for some data points.

The basic force calibration of the gage is given in Figure 15. When the gage is not in contact with the slot the output is 0.240 volts per gram of force, as shown by the solid line with the scale given to the left. The calibration of the gage in the nozzle

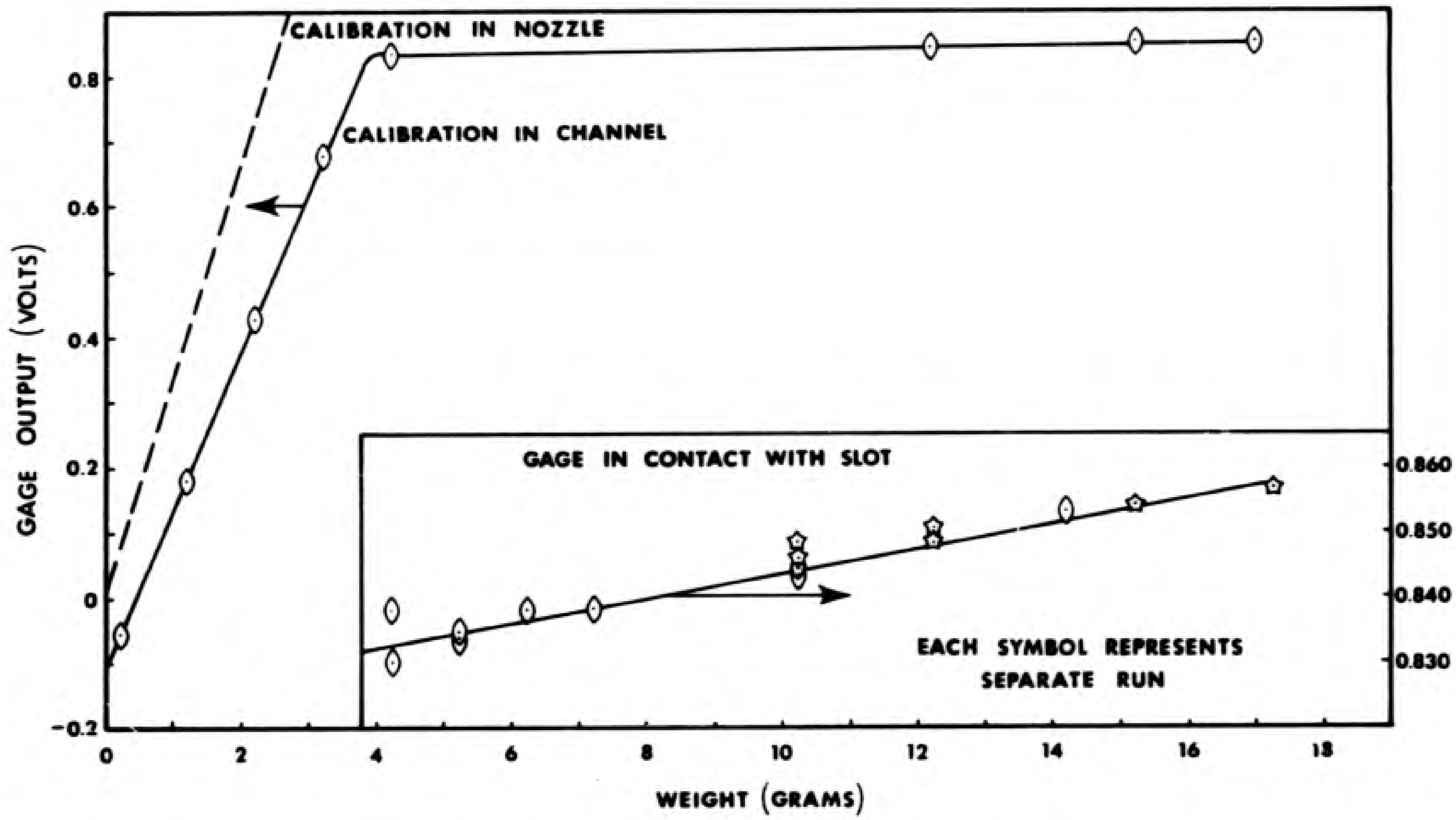


FIGURE 15. GAGE CALIBRATION IN CHANNEL

side wall is given as the dashed line with slope of 0.338 volt per gram. The change in output is attributed to an effective change in spring constant due to the flexures being vertical in the channel and horizontal in the nozzle wall. When the gage touches the end of the slot the displacement is restricted and the spring constant becomes very large. The system does not become absolutely rigid because a point contact is probably achieved at first and there is some rotation of the floating surface and compression of the copper material as more load is applied. The slope of the gage in contact is given on the lower curve which has an expanded scale to the right. The data shows more scatter because of unknowns in the contact geometry but the slope is approximately 0.002 volts/gram.

Friction force was converted to shear stress by dividing by the exposed gage surface.

$$\tau = \frac{F}{A_{gage}} = \frac{F}{454 \cdot \frac{1}{4} \cdot \frac{1}{144}} = 1.27F \qquad (6)$$

where τ is in lbs/ft^2 and F is in grams. The shear stress voltage relation is obtained by substituting the gage calibration, v_a = 0.240F to give

$$\tau = 1.27F = 1.27 \frac{v_a}{0.240} = 5.29\ v_a \qquad (7)$$

The friction coefficient is formed by dividing the shear stress by the dynamic pressure.

$$C_f = \frac{\tau}{1/2\rho\bar{u}^2} \qquad (8)$$

Density was assumed constant at the atmospheric value since the flow was maintained at incompressible levels. Originally it was thought that either the dynamic pressure would be obtained from measurements of supply pressure and friction pressure loss or that velocity would be derived from the supply pressure. The hot wire tests, however, give a more direct and accurate method of obtaining velocity. King's equation is recommended by the manufacturer as representing the velocity, voltage, temperature relationship of the hot wire.

$$\frac{E_a^2 R_a}{(R_a+R_{3a})^2} = \left| A' + B' \sqrt{\overline{u}} \right| (T_s - T_e) \tag{9}$$

E_a = bridge voltage

R_a, R_{3a} = bridge resistances

A', B' = constants for a given wire

$\overline{u}$ = velocity of fluid in front of the wire

T_s = sensor temperature

T_e = fluid temperature

Temperatures and resistances are constants so that the equation reduces to

$$E_a^2 = A+B \sqrt{u} \tag{10}$$

The constants were obtained experimentally for the particular wire used in this experiment. It was assumed that the wire measured the maximum velocity in the channel. Making use of the fact that the average velocity, $\overline{u}$, in a laminar channel is 2/3 of the maximum velocity, and rearranging terms to solve for $\overline{u}$, the resulting equation is;

$$\bar{u} = \frac{4}{3}\,(E_a^2-1.75)^2 \qquad (ft/sec) \tag{11}$$

The friction coefficient now reduces to an equation in the measured quantities v_a and E_a.

$$C_f = \frac{5.29\ v_a}{1/2\cdot 0.0023[4/3(E_a^2-1.75)^2]^2} \tag{12}$$

$$C_f = \frac{2587.5\ v_a}{(E_a^2-1.75)^4} \tag{13}$$

For laminar flow in a channel the theoretical value of the coefficient is

$$C_f = \frac{16}{R'} \tag{14}$$

where R' is the Reynolds number based on channel height.

$$R' = \frac{\rho\bar{u}(2a)}{\mu} = Re_{2a} \tag{15}$$

At standard atmospheric pressure and temperature $\mu/\rho = \nu = 1.66 \times 10^{-4}$ ft^2/sec.

The channel height is 0.01 inch.

$$R' = \frac{4/3(E_a^2-1.75)^2(0.01/12)}{1.66\cdot 10^{-4}} \tag{16}$$

$$R' = 6.70(E_a^2-1.75)^2 \tag{17}$$

The measured gage output includes a component due to the pressure force on the sides of the gage in the slot.

$$v_a \text{ total} = v_a + v_a \text{ pressure} \tag{18}$$

This force is usually negligible for boundary layers on flat plates, slender bodies, or hypersonic nozzle walls but is large in the channel flow. The pressure force is directly related to the friction force for a fully developed channel so that the following simple ratio can be derived.

$$v_a = 0.03\ v_{a_{total}} \tag{19}$$

Substituting this into the equation for the firction coefficient and rounding off to 3 places gives the final relationship to be used in data reduction

$$C_f = \frac{77.6\ v_a}{(E_a^2-1.75)^4} \tag{20}$$

Channel data for C_f vs R' are plotted in Figure 16. The measured values are consistently about 5% high compared to the theoretical line, which can be attributed to any combination of the following: (1) the pressure force was underestimated, (2) the channel thickness was greater than specified, (3) the hot wire was not on the exact channel centerline, thereby measuring a low velocity, or (4) the temperature of the air in the channel was higher than that used in the data reduction.

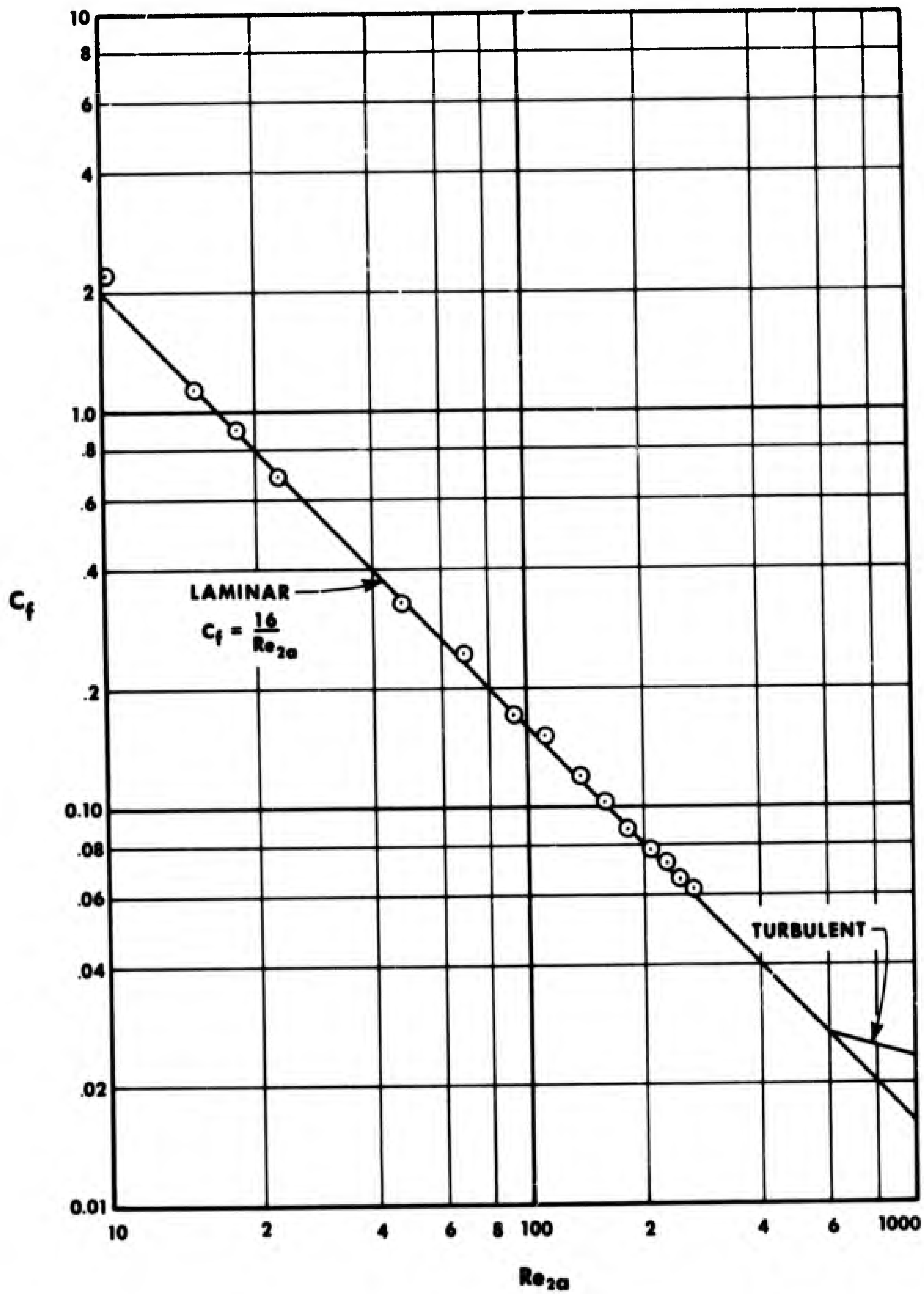


FIGURE 16. CHANNEL FLOW FRICTION COEFFICIENT

The results shown in Figure 16 confirm the validity and usefulness of the water-cooled floating element skin friction gage. Additional comparisons can be made to further substantiate that the channel was operating at known laminar incompressible flow conditions. As previously stated for a fully developed flow, the pressure loss is uniquely related to the friction.

$$\Delta P = \frac{\tau \Delta X}{a} \tag{21}$$

Substituting for the distance between pressure taps, X, and the channel half height, a, gives a linear relationship between P and τ, which is given as the solid line in Figure 17. For incompressible flow with friction the supply pressure P_0', is related to the friction loss ΔP_f by the equation

$$P_0' = \Delta P_f + 1/2\ \rho \bar{u}^2 + P_{exit} \tag{22}$$

If the exit pressure, which is atmospheric, is substracted for the absolute supply pressure, the gage pressure P_0 can be used directly. The dynamic pressure $1/2\ \rho \bar{u}^2$ can be shown to be less than 1% of the supply pressure for pressures less than 3 psig, and the equation reduces to the simple approximation

$$P_0 = \Delta P_f \quad +1\% \text{ at } P_0 = 3 \text{ psig.} \tag{23}$$

Figure 18 shows that the data deviate from this linear expression at the higher pressures, where the corrections become larger. For example at 5 psi about 3% of the total reading is due to the dynamic pressure, 1% is due to the pressure gage error, and 4% is due to leakage through the gage gap.

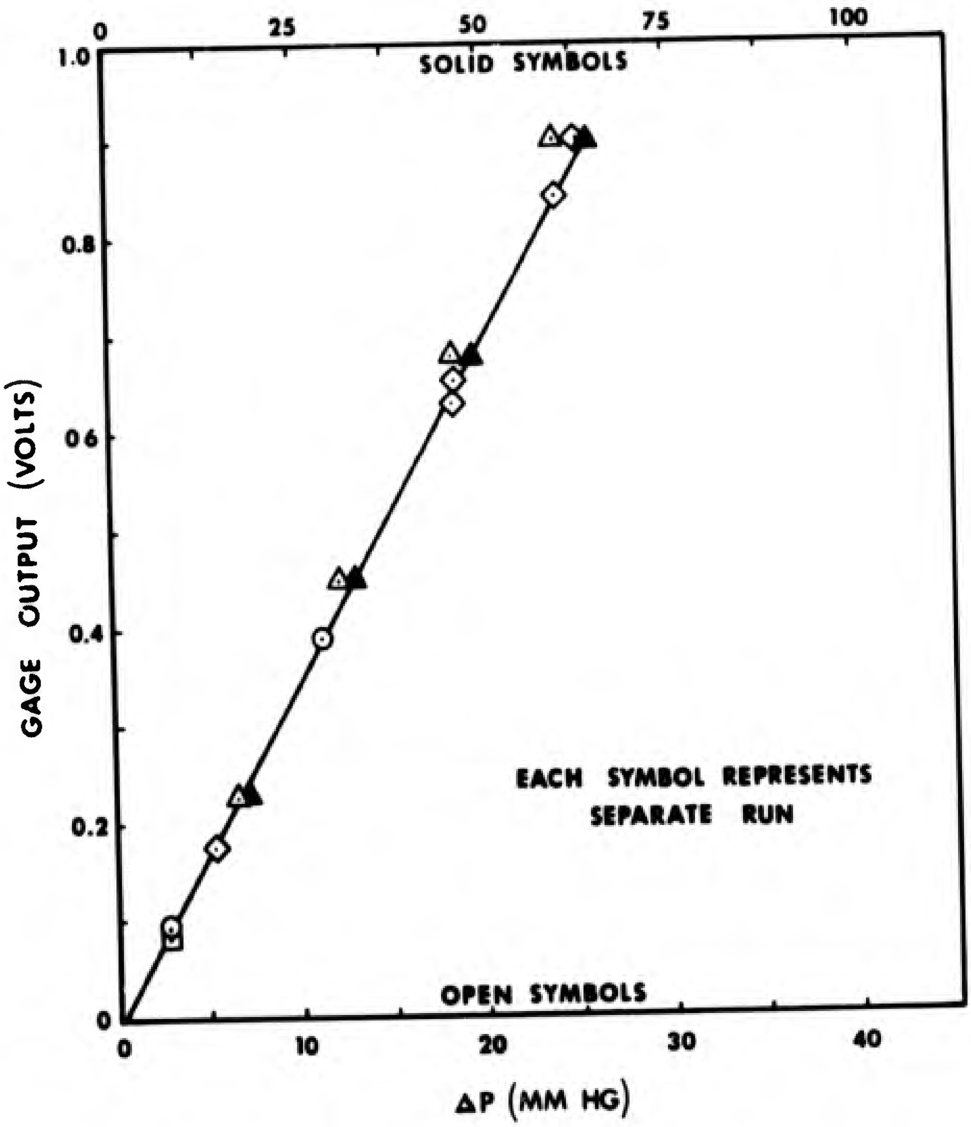


FIGURE 17. CHANNEL PRESSURE LOSS

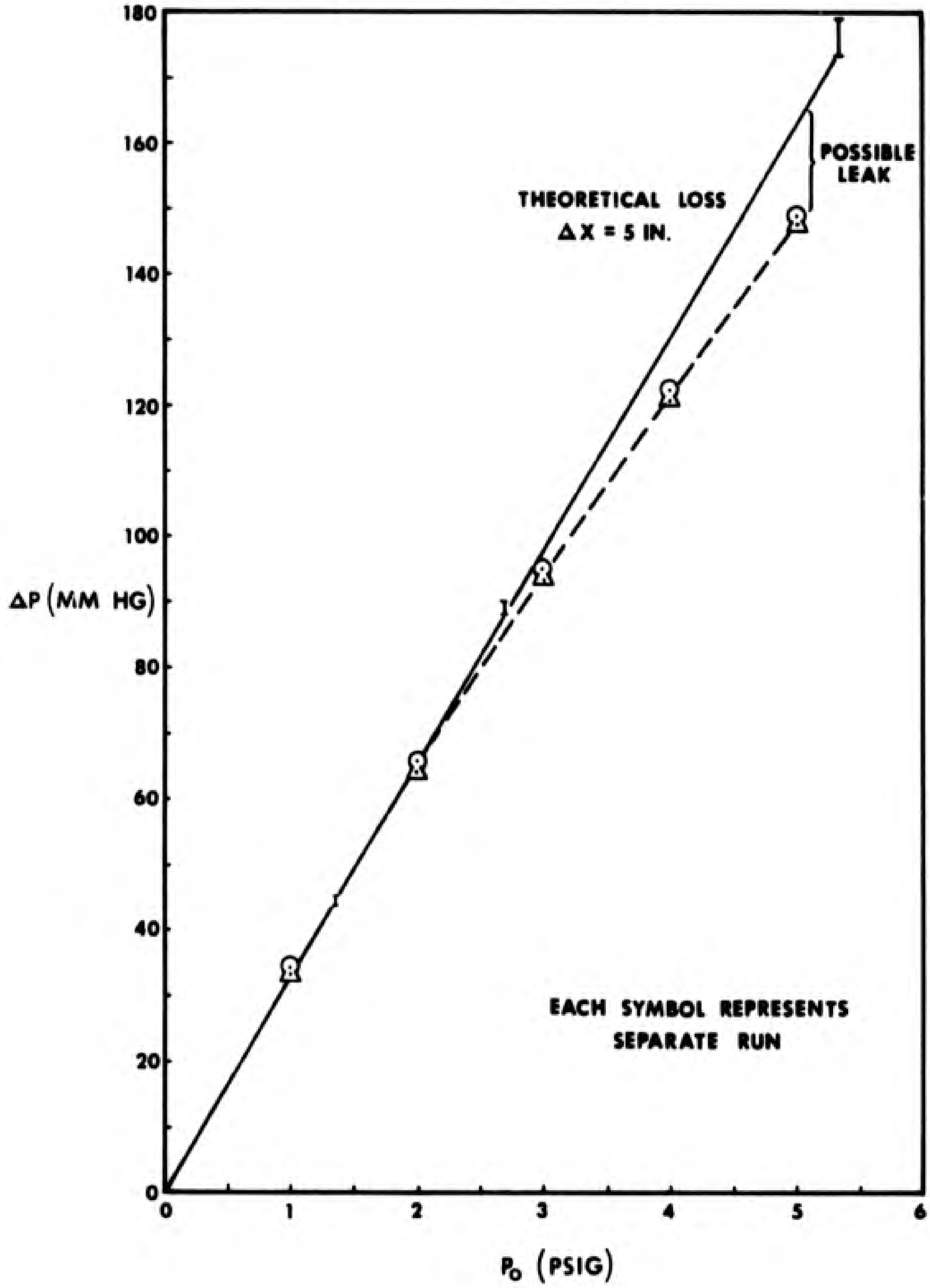
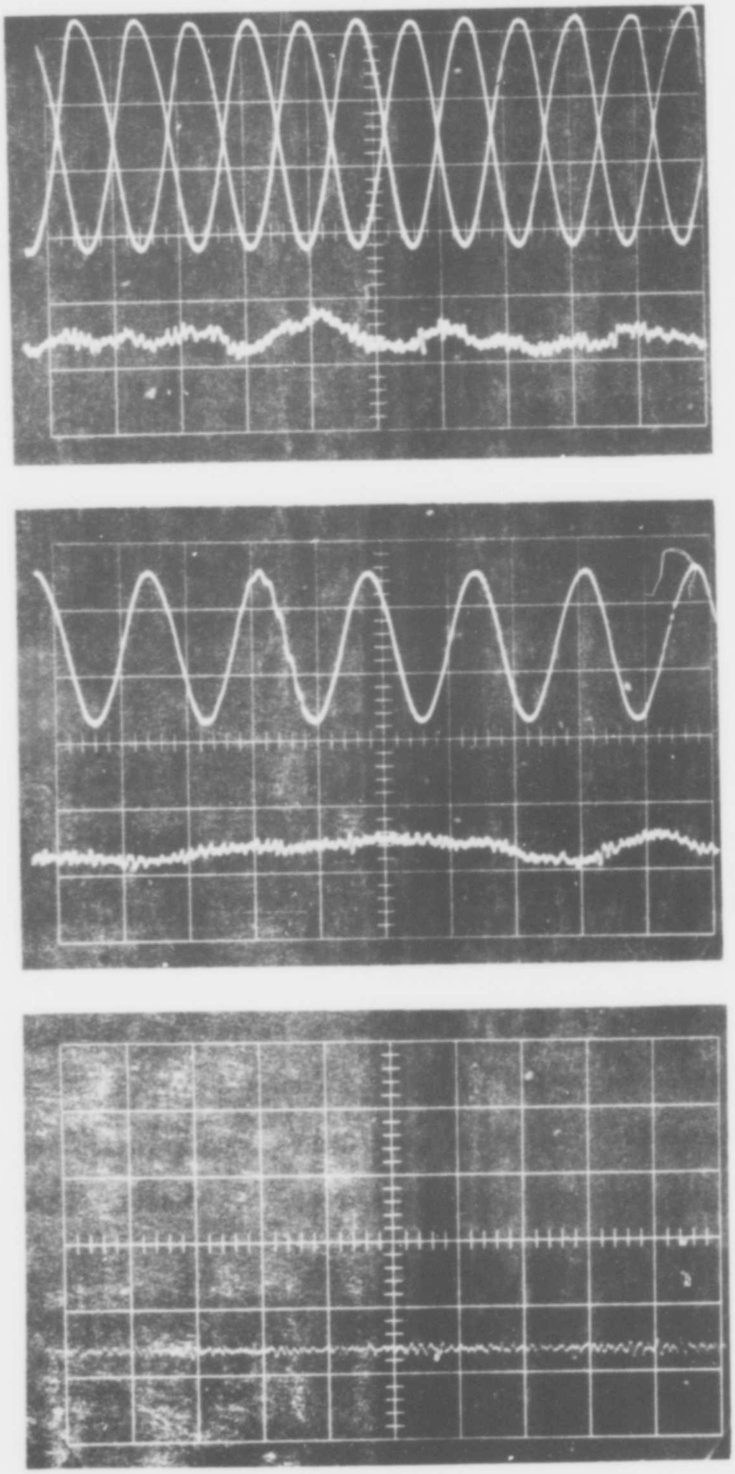


FIGURE 18. PRESSURE LOSS VS STAGNATION PRESSURE

During the hot wire tests, unsteadiness of the wire output was noticed at pressures above 1.8 psig. Figure 19 shows oscilloscope traces at several pressures. This unsteadiness was originally attributed to transition to turbulent flow. However, the Reynolds number was only 180 for flow conditions in which the unsteadiness was first noted and no abrupt increase in friction was observed. The scope traces of the hot wire output with a 3 K-Hz signal for reference can be compared with traces by Schubauer and Skramstad (page 333, Schlichting, Reference 11), which have a 1/30 sec timing mark. In Figure 19, the total span of the photograph must be compared with the patterns between two of the timing marks in this other work. It appears that, at 2.75 psig, the fluctuations were much less intense than the fully turbulent case of these authors. They (see page 350, Schlichting) conducted similar experiments for various pressure gradients and found the flow to be very stable under a negative gradient, such as that which exists in the channel flow. From this information it is concluded that the onset of laminar flow instability was observed in the channel and that actual transition to turbulence, would occur at supply pressures two to three times higher than the maximum used in these tests.

An additional experiment was performed to obtain information on the effect of floating-element misalignment on channel pressure gradient and skin-friction balance accuracy. The misalignment problem was investigated previously for a flat plate in supersonic flow and the results were reported in Reference 5.



2.75 PSIG

1.81 PSIG

0.75 PSIG

FIGURE 19. OSCILLOSCOPE TRACES

The change in channel pressure drop due to the increased or decreased drag of the gage is shown in Figure 20. The data are plotted in the top of Figure 20 as the deviation from the pressure drop of a smooth channel at a given supply pressure. Both channel pressure loss and gage voltage (shown in Figure 21) are increased when the gage protrudes into the channel. These data should not be used as accurate values for the effect because of the crude way in which the displacements were determined. For the positive settings the gage was located with respect to the upper surface of the channel by placing pieces of shim stock of known thickness between the gage surface and the upper plate. For negative displacements the location was observed with a stereo microscope and compared with a known height. Leakage around the gage also has a strong influence on the output. Leakage would probably be at a minimum when the gage is flush and the momentum of the air carries it over the small gaps. When the gage is misaligned the air stagnates on the protruding edge or flows into the cavity and has a tendency to follow the vertical walls into the gap. A rough comparison of the present data with that of Reference 5 for the flat plate is given in Figure 22. For these experiments, the friction gage output was slightly more sensitive to alignment than in the flat plate tests, due to the channel flow becoming restricted.

The two-dimensional channel is a simple and useful means of calibrating floating element skin friction gages. Practically any flow condition such as compressibility, heat transfer, or positive pressure gradients could be designed into a similar channel. The gage performed as predicted within the incompressible regime. Thermal drifts

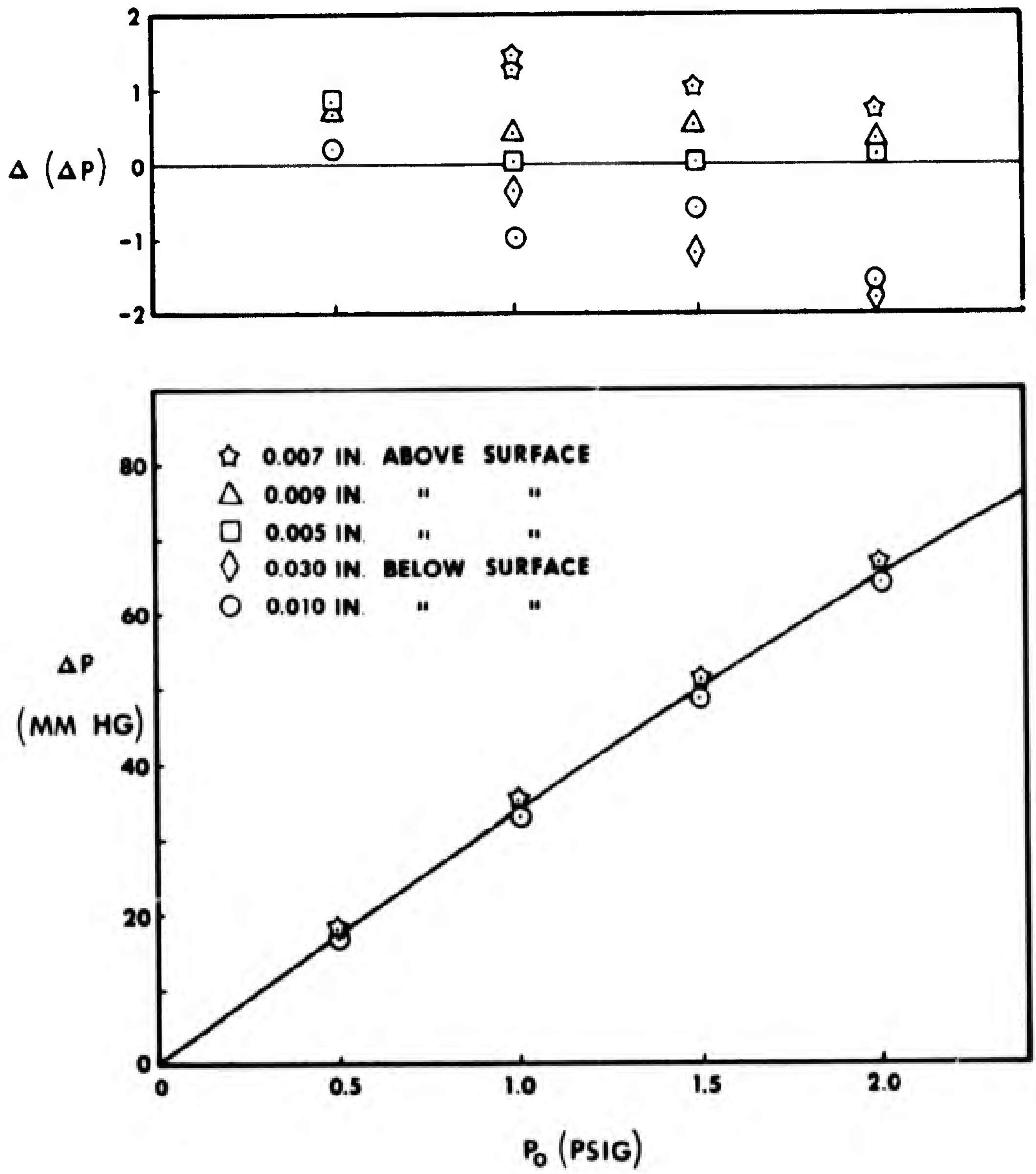


FIGURE 20. EFFECT OF MISALIGNMENT ON PRESSURE LOSS

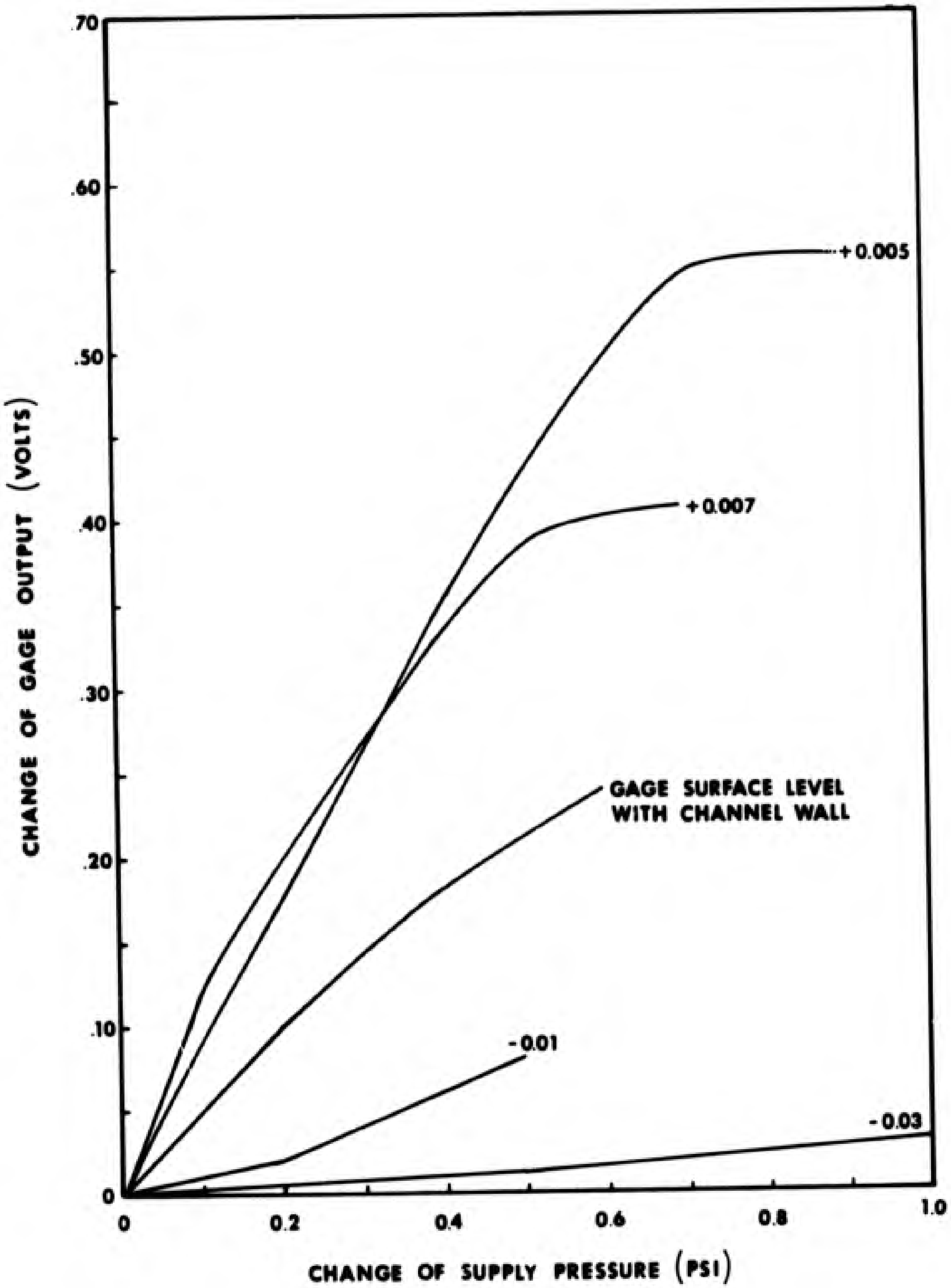


FIGURE 21. EFFECT OF ALIGNMENT ON GAGE OUTPUT

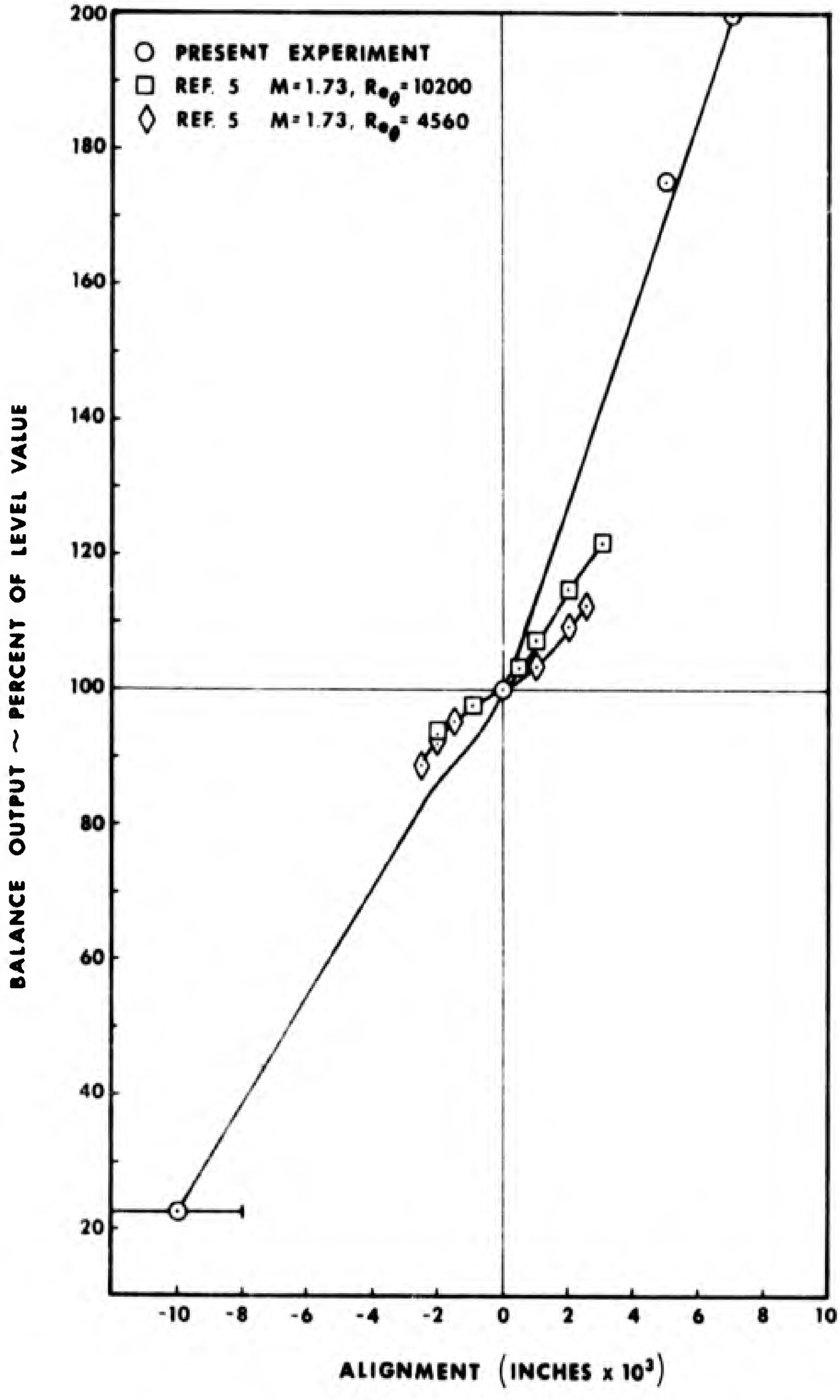


FIGURE 22. PERCENTAGE EFFECT OF ALIGNMENT

of the gage output were as great as 10% but were predictable and could be properly taken into account. All data presented here have been corrected for thermal drift. Gage output was experimentally determined to be accurate to within 2% of the reading for all channel tests.

3. Operation of the Skin-Friction Gage in Hyperthermal Flow

The 24 inch exit diameter nozzle of the 50 Megawatt Electrogasdynamic Facility was constructed with double walls to form a coolant channel. This construction made it difficult to install the skin-friction gage into the wall. To facilitate the installation of the skin-friction gage and other instrumentation for this study a 4 inch extension was added to the nozzle exit. The extension was made of carbon steel and was not actively cooled. Two orifices were located 2 1/8 inches apart on a generatrix at each of two diametrically opposite positions and a slot and bracket were incorporated to accommodate a boundary layer pitot probe. A precision window was machined 0.501 inch square on the horizontal generatrix, centered 0.75 inch from the downstream edge of the ring. The downstream edge became the nozzle exit of 25.2 inches. The nozzle extension ring is shown in Figure 23.

The fixed surface of the floating element skin-friction gage was bolted to a bracket with adjusting screws that allowed alignment of all six degrees of motion. The bracket was bolted to a 1/4 inch plate which in turn was bolted to the exit face of the extension ring.

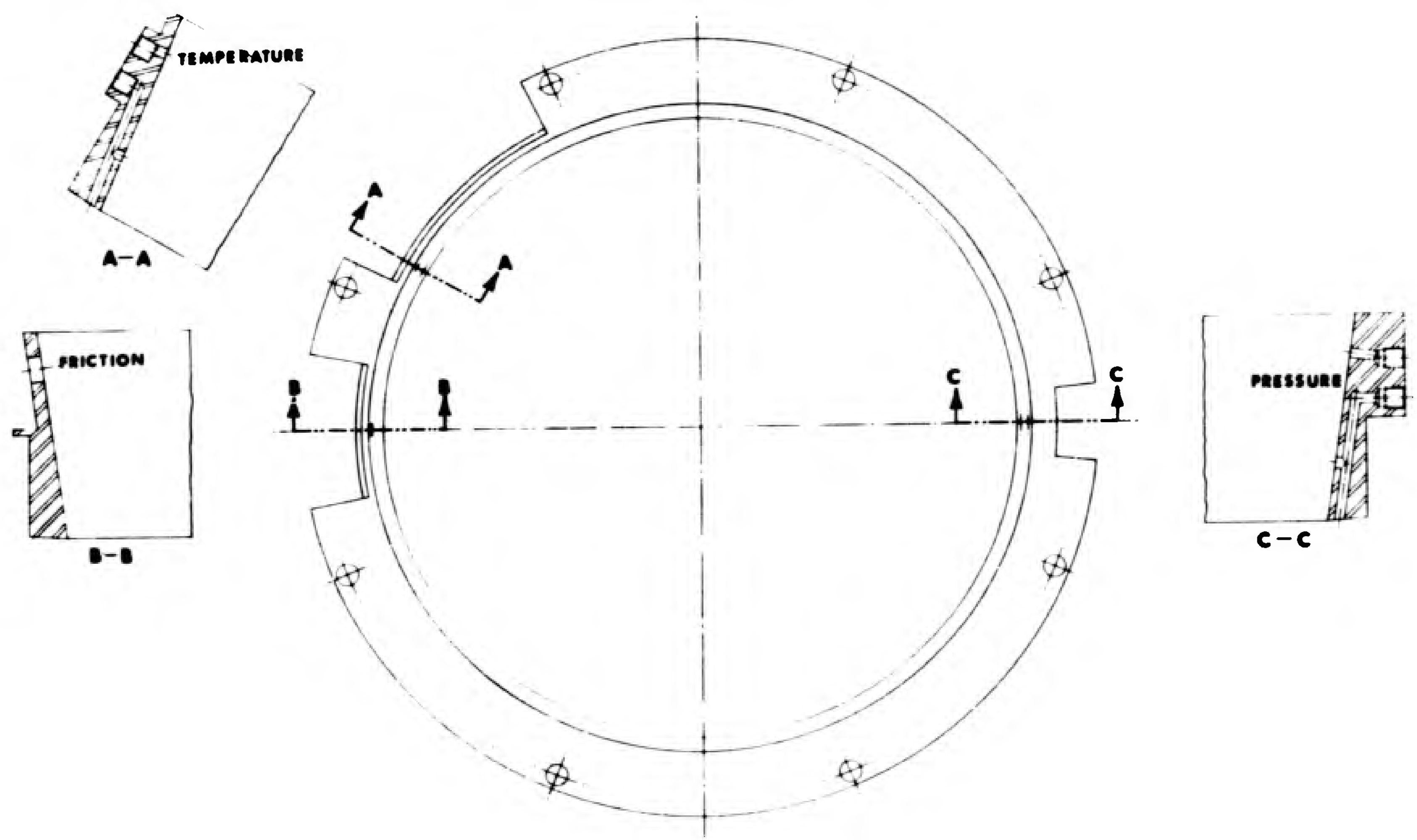
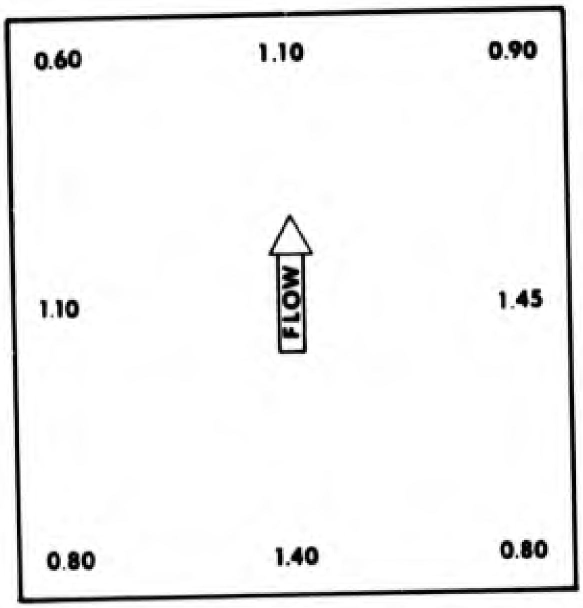


FIGURE 23. NOZZLE EXTENSION RING

Originally the back side of the gage was unprotected from the test cabin environment. This was found to be a detriment when large models caused flow blockage with large amounts of hot gas circulating in the area of the gage. A temporary protective shroud was added after the first few runs.

The floating element was installed aligned in the square window and free to move approximately 0.0006 inch upstream and 0.0011 inch downstream. The results of surface alignment are given in Figure 24, with the maximum displacement of 0.00145 inch below the nozzle wall.

The gage was calibrated in place with a pulley and weight arrangement similar to that used in the bench tests. The string was carefully glued or taped to the center of the surface of the floating element and stretched over the pulley so as not to rub against the nozzle surface and add unwanted friction. Weights in increments down to 10 mg were placed in a foil pan (which itself had been weighed in an analytical balance) and the pulley was vibrated to reduce bearing friction. The output was hand recorded from a digital voltmeter. For later runs output records were made on an oscillograph. An oscilloscope was used to monitor the wave-forms of the input and output signals. Numerical values of the RMS voltage for the input/output were recorded from the digital voltmeters and simultaneously recorded in the Ambilog Data Processing System. The rectifier and amplifier used for the nozzle experiments were the identical ones used in the bench tests.



NUMBERS REPRESENT 10^{-3} INCHES
BELOW SURFACE

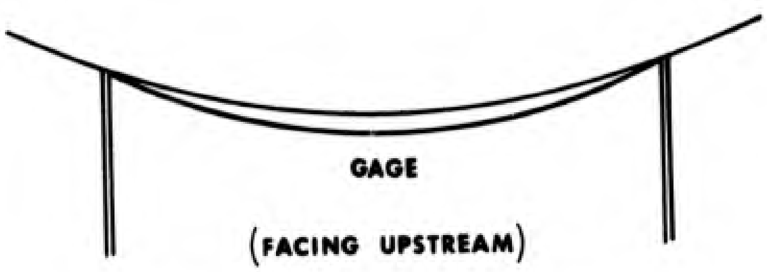


FIGURE 24. SURFACE ALIGNMENT OF FRICTION GAGE

The floating element skin-friction gage was used to measure the aerodynamic friction at the nozzle wall. The fluid dynamic and thermodynamic conditions at which the friction was being recorded were not always well defined. The friction gage had been designed for larger loads than were encountered in these tests; consequently the gage operated at the low end of its calibration curve where it was less accurate. The data were limited by the tunnel mass flow to approximately a decade range of Reynolds number. Figure 25 presents the data reduced to friction-coefficient form and plotted versus Reynolds number based on length from the throat. Laminar and turbulent flat plate theories and Coles (Reference 1) data are shown for comparison. The data is evidently of a mixed nature containing points taken in laminar flow, transitional flow, and turbulent flow. There is an apparent separation of the data into groups according to enthalpy. The solid symbols represent tunnel flow total enthalpy <2000 BTU/lb, in which case early transition is indicated. The open symbols are for total enthalpy between 2000 and 2500 BTU/lb. These data are preliminary and are presented here only as an indication that the gage was operating properly under hyperthermal flow conditions. No other experiments have been reported at similar conditions. Interpretation of the data is very difficult due to the necessity to evaluate such factors as boundary layer transition, flow history, pressure gradients, Mach number, and wall temperature effects. The gage did perform successfully in an extremely destructive environment. Over 60 runs were made with total temperature equalling approximately 4000°K. After these tests the gage was used in another facility without refurbishment.

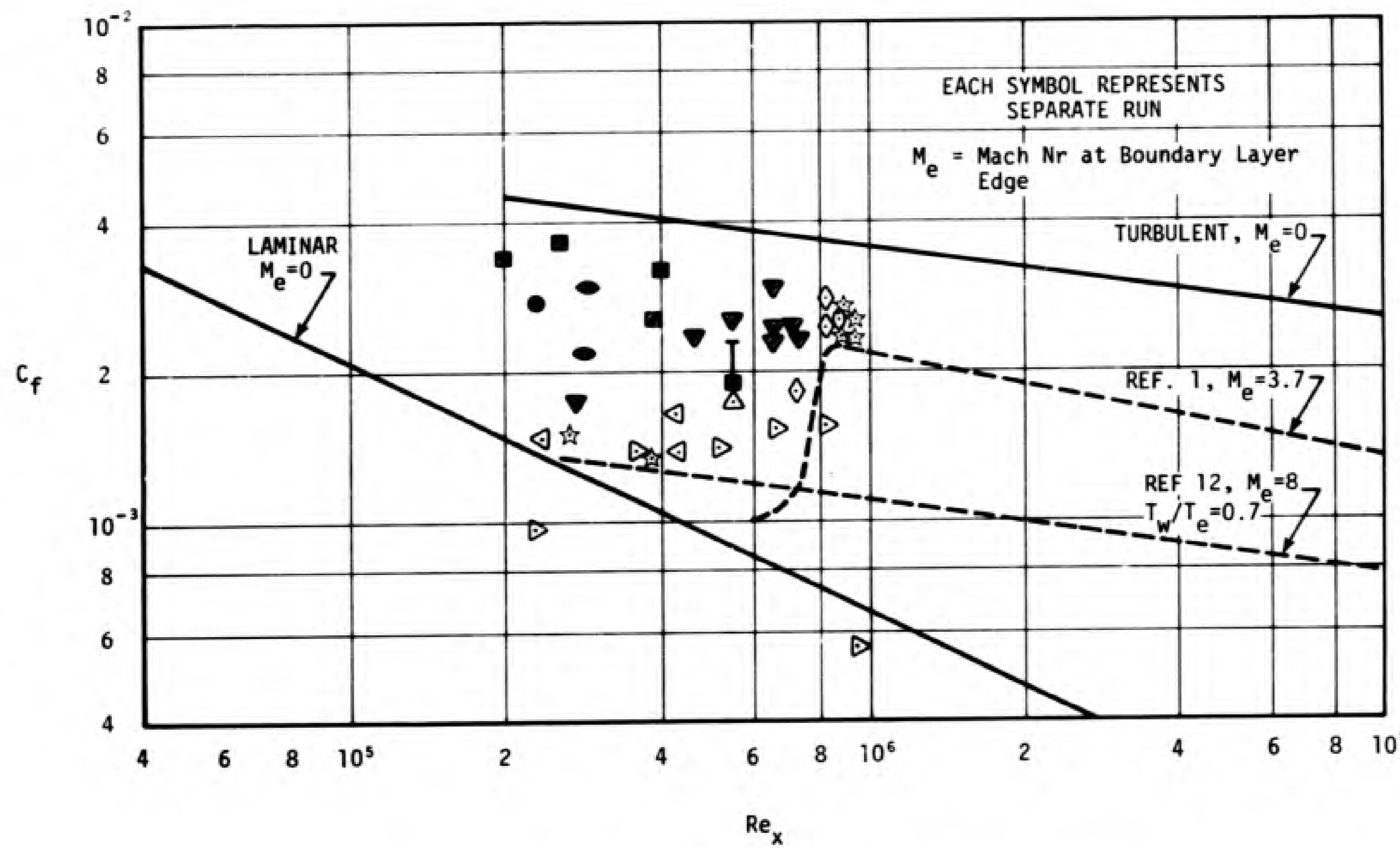


FIGURE 25. NOZZLE FRICTION COEFFICIENT

SECTION IV

CONCLUSIONS

A cooled floating element skin-friction gage was designed, fabricated, calibrated in bench tests and in known flow conditions and operated in hyperthermal flow. The gage is suitable for loads from 10 milligrams to 5 grams and can be used for higher loads by changing the flexures according to a prescribed formula. The gage can be used in high temperature flows with heat transfer rates up to 300 BTU/ft^2-sec. Friction surfaces of various materials or shapes can be utilized by spray-coating, plating, or machining the floating element surface.

Bench tests demonstrated that output voltage and displacement varied linearly with applied load. The effect of excitation voltage on induction coil temperature and on output voltage are shown. Water flow, for cooling, and mounting orientation have no effect on the calibration. A mechanical hysteresis was found that is repeatable but its origin could not be explained.

The friction balance was installed in a channel in which a two-dimensional incompressible viscous flow could be established. The friction force and flow conditions (pressure, temperature, and velocity) were measured. Data presented in the form of friction coefficient versus Reynolds number based on channel height was within 1% of agreement with classical fully developed laminar flow theory.

The floating element skin-friction balance has been successfully used in the nozzle wall of a high temperature hypersonic wind tunnel.

SECTION V

RECOMMENDATIONS

The gage should be miniaturized for use in models. The gage mounting and alignment system should be redesigned to conserve space. Adjustment screws should permit fine adjustments.

A feedback loading system should be designed to return the surface to the original (no load) position to help minimize gap effects.

The damping mechanism should be improved by adding grooves to increase the area over which the viscous force acts. A rim or trough should be added to retain the silicone fluid.

A comparison should be made with Preston Tube measurements in the low Reynolds number range.

The gage should be exploited for making skin-friction measurements of a fundamental nature in hyperthermal flows, since there is a dearth of information available on flat plates and cones in hypersonic flows at temperatures representative of flight conditions.

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