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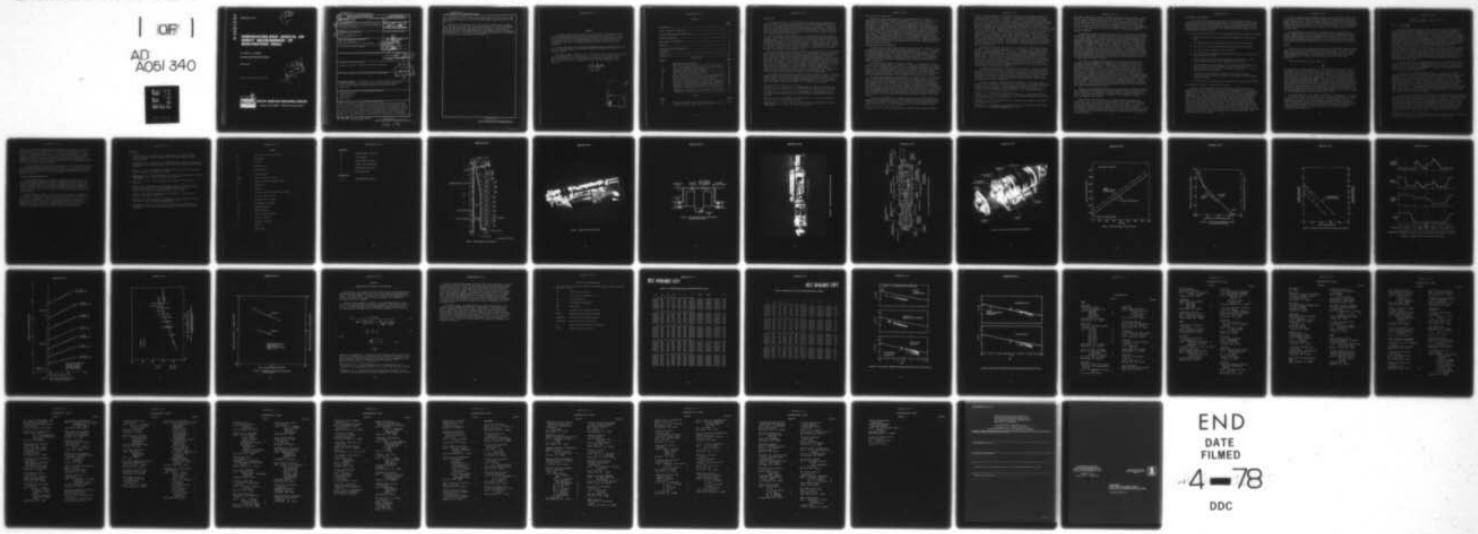

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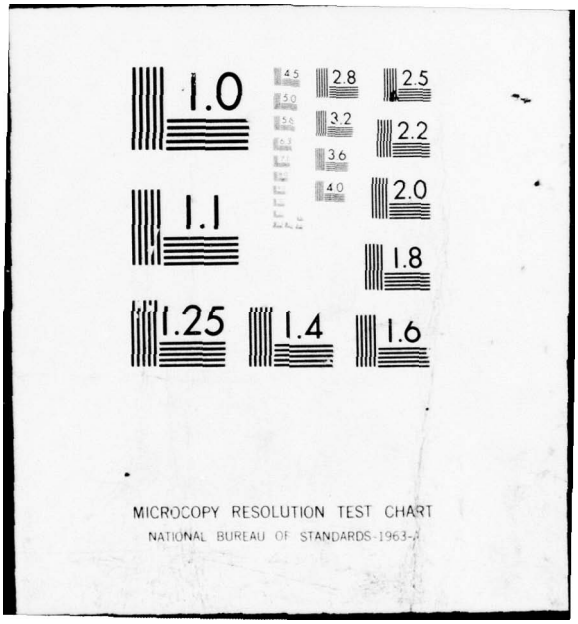
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TEMPERATURE-STEP EFFECTS ON DIRECT MEASUREMENT OF SKIN-FRICTION DRAG

BY ROBERT L. P. VOISINET

ADVANCED WEAPONS DEPARTMENT

7 JULY 1977

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Wall-temperature discontinuities can occur in skin-friction balance tests whenever a balance drag element is thermally insulated from the surrounding test surface. An experimental study was conducted to investigate the effects of such a temperature step on the local friction drag. A temperature step was produced by varying the temperature of the NSWC skin-friction-balance drag element above the temperature of the surrounding nozzle wall. Drag-element temperatures ranged from 100°K to 240°K with the surrounding wall maintained →

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at a temperature of 89°K. Nominal Mach numbers were 2.9 and 4.9 over a unit Reynolds number range of 2.6 to 20 million per meter (0.8 x 10^6 to 6.0 x 10^6 per foot).

The results show that the value of the measured shear stress is higher than the cold wall value for a drag element which is at a higher temperature than the surrounding wall temperature and the change in shear stress is proportional to the difference between the drag element and the surrounding wall temperatures. The data has been correlated and corrections to previously published skin-friction results are presented.

SUMMARY

This report documents the results of an experimental investigation of local surface-temperature-discontinuity effects on measured wall shear stress. The results are correlated and previously published skin-friction data are adjusted to compensate for this drag-element temperature effect. Design modifications and updated capabilities of the NSWC designed skin-friction device are also presented.

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The author wishes to thank Dr. W. J. Yanta and Dr. R. E. Lee for their support and consultation, Mr. J. R. Bruno and Mr. T. Young for their design efforts in improving the NSWC skin-friction balance to its present configuration, and Mr. F. W. Brown and Mr. F. C. Kemerer for their efficient operation of the facility.

C. A. Fisher

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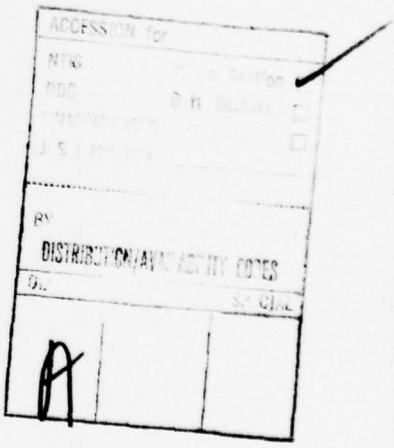

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INTRODUCTION

It is well known that a local discontinuity in the surface temperature of a body in motion will markedly influence the heat transfer from the fluid to the body over the region where the discontinuity exists. This effect is especially evident in plug-type calorimeters in high-speed wind-tunnel testing. A similar local "hot spot" condition can occur in skin-friction balance testing when a skin-friction balance drag element is thermally insulated from the cooled or heated main surface surrounding the element.

In the simulation of high-speed flight in a ground test facility where heat transfer is of consideration, the ratio of the wall-to-stagnation temperature is usually matched. The ratio can be attained in a wind tunnel either by raising the stagnation temperature of the facility or cooling the model surface. It has been the practice at NSWC to employ the latter approach in previous experimental studies of the turbulent boundary layer with heat transfer. Temperature ratios as low as 0.2 have been attained by the cryogenic cooling of the nozzle wall in the NSWC Boundary Layer Channel (see References 1 and 2).

From the inception of the cold-wall tests it was realized that a skin-friction balance would be needed which could operate in a cryogenically cooled environment. Such a balance was designed and built (see Reference 3) with a provision for cooling the drag element to the surrounding test-plate temperature just prior to data acquisition. This was to be done by clamping a cryogenically cooled manifold around the drag element. Unfortunately, this provision was not operational during the original tests and the drag element reached a temperature during each test run which was some 150°K hotter than the surrounding test-plate temperature. Since the effects of such a temperature step were unknown, the drag-element cooling capability had to be made operational in order to validate the previous test data. Through numerous balance design modifications and improvements, this cooling capability was made operational and validation tests were performed.

The present report describes the results of those validation tests. The drag-element temperature data are correlated and this correlation is applied to earlier published data. The data of Westkaemper (Reference 4) agree with the present results; however, the conclusion reached by that author; i.e., negligible temperature step effects, are not consistent with the findings of this study.

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[1] Voisinet, R. L. P., and Lee, R. E., "Measurements of a Mach 4.9 Zero-Pressure Gradient Turbulent Boundary Layer with Heat Transfer," NOLTR 72-232, Sep 1972.

[2] Voisinet, R. L. P., and Lee, R. E., "Measurements of a Supersonic Favorable-Pressure-Gradient Turbulent Boundary Layer with Heat Transfer," NOLTR 73-224, Dec 1973.

[3] Bruno, J. R., et. al., "Balance for Measuring Skin Friction in the Presence of Heat Transfer," NOLTR 69-56, Jun 1969.

[4] Westkaemper, J. C., "Step Temperature Effects on Direct Measurements of Drag," AIAA Journal, Vol. 1, No. 7, Jul 1963, pp. 1708-1710.

FACILITY AND TEST CONDITIONS

Wind-tunnel tests were conducted in the NSWC Boundary Layer Channel (Reference 5) at nominal freestream Mach numbers of 2.9 and 4.9. Skin-friction measurements were made on the flat nozzle-wall test plate of the facility (see Figure 1). The copper test plate was cryogenically cooled with liquid nitrogen to a temperature of 89°K. The supply temperatures were nominally 422°K and 403°K at the Mach 4.9 and 2.9 conditions respectively. The test conditions for the Mach 4.9 case were essentially the same as those reported in Reference 1 since the present tests were conducted for the purpose of validating the previous test data. The Mach 2.9 test conditions were similar except for a change in nozzle contour. The Reynolds number was varied by changing the supply pressure from 1 to 10 atmospheres at Mach 4.9 and 1 to 2 atmospheres at Mach 2.9. Data were obtained at several axial stations along the test plate. Typical wind-tunnel test runs lasted on the order of 90 minutes with half of that time being used for tunnel cool-down procedures.

BALANCE DESCRIPTION AND OPERATION

The skin-friction balance used in these tests is pictured in Figure 2. It is a redesigned version of the balance described in Reference 3. It is of the self-nulling type whereby a circular floating drag element is continually re-centered by a servo-feedback system. The unique feature of the balance design is the "clam-shell" mechanism used to cool the floating drag element to the temperature of the surrounding test plate. Although the basic design of the new balance is similar to the old, significant modifications have been made in the process of design optimization.

The balance drag element is sketched in Figure 3. It consists of a flat surface circular element which is 2.00533 cm. in diameter (surface area = 3.15836 $cm.^2$). The lip thickness is 0.00762 cm. and the clearance gap around the element is 0.0127 cm. The element edge is beveled at a 45° angle to minimize edge-pressure effects and the element surface is aligned flush with the surrounding flange surface to within $\pm$ 0.001 cm. Since the balance mechanism is of the self-nulling type, the clearance gap around the drag element does not change with loading.

The balance servo-feedback system operates in a manner similar to the previous design. The surface shear stress acting on the drag element causes the balance arm to rotate about a frictionless pivot (refer to the schematic in Figure 4). The movement of the arm is sensed by a translational Linear Variable Differential Transformer (LVDT). The LVDT null-offset signal is monitored by servo-feedback electronics and a DC motor is activated to produce a restoring force to the balance arm via a lead-screw, spring guide, and spring. The force exerted by the restoring spring opposes the shear force and restores the balance arm and drag element to a null or centered position. The magnitude of the restoring force is proportional to the shear force and is monitored by a potentiometer which is geared to the lead-screw.

Since the servo-feedback is a dynamic system; spring, mass and damping components must be adjusted to obtain a stable response to the applied shear loading. The mass of the system is concentrated in the balance arm and counterweight and remains constant except for minor changes which are initially made for static

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[5] Lee, R. E., et. al., "The NOL Boundary Layer Channel," NOLTR 66-185, Nov 1966.

balance. Spring components in the system are found in the restoring spring and in the frictionless pivots, the flexures. These springs are matched to the drag loading expected in the test. Damping is introduced in the system using a dashpot. This is a change from the original design of damping discs which were developed by Durgin (Reference 6). The dashpot is composed of a small piston housed in a nonferrous cylindrical casing with a clearance gap between the two. The piston is made from a magnet and a magnetic damping fluid (References 7 and 8) is introduced into the clearance gap. The damping fluid (Dyester base, 10K centipoise viscosity) stays in the gap because of its magnetic attraction to the piston. The size of the piston and gap and the viscosity of the damping fluid determine the amount of viscous damping which is introduced in the system. Electronic damping (filtering) is also used to regulate the overall balance sensitivity and response. The final adjustments to the system are generally made to produce a critically damped response to an applied shear-stress loading. An underdamped system can cause undue oscillations of the balance arm about the null position and an overdamped system can respond too slowly to changes in the loading. The technique of system adjustment is generally one of trial and error.

Preliminary tests showed the balance to be sensitive to temperature changes around the critical balance components, i.e., the flexures, LDVT, springs and aft housing. Since the balance had to be used in a cyrogenically-cooled environment, special precautions were taken to insulate these sensitive components from the extreme cold. The mounting flange and drag-element cooling mechanism which are in direct contact with the cryogenic cooling were thermally insulated from the aft portion of the balance housing to minimize conduction effects. As an added temperature buffer, heater tape was applied to the mid-balance housing to compensate for the extreme cold at the mounting flange. As a result, the aft balance housing temperature remained relatively constant through each test run and thermal effects on the balance calibration were minimal.

The dimensional stability of the balance which relates to component expansion and contraction with temperature was minimized by using Invar and other materials having low coefficients of thermal expansion. Components such as the balance arm and balance housing had to be constructed of these materials otherwise the thermal expansion of the components would have changed the drag-element alignment with the surrounding surface. Maximum variation in surface alignment under cryogenic conditions was less than $\pm$ 0.0025 cm.

In a manner similar to that described in Reference 3, the present balance design has the capability of pre-cooling the drag element to the temperature of the surrounding wall by placing a coolant manifold, a "clam-shell" device, in direct contact with the drag element. The clamping action of the "clam-shell" is accomplished via a pneumatic cylinder, worm gear, and linkages (see Figure 5).

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[6] Durgin, F. H., "The Design and Preliminary Testing of a Direct Measuring Skin Friction Meter for Use in the Presence of Heat Transfer," Massachusetts Institute of Technology Report 93, Jun 1964

[7] Ezekiel, F. D., "Uses of Magnetic Fluids in Bearings, Lubrication and Damping," ASME Paper 75-DE-5, 1975

[8] Moskowitz, R., "Designing with Ferro-Magnetic Fluids," ASME Paper 74-DE-5, 1974 and reprinted in Mechanical Engineering, Feb 1975

The coolant flows from an external reservoir through an internal network of manifolds, flexible metallic bellows, and the "clam-shells." The mounting flange of the balance is cooled by conduction from the surrounding test plate. When liquid nitrogen was used as the coolant, the drag element could be cooled to within 15°K of the surrounding test-plate temperature. Since the drag element is made of copper and has a relatively large thermal capacity, its temperature did not rise at any significant rate after the release of the cooling manifold.

BALANCE CALIBRATION

The balance was easily calibrated because of its orientation when mounted in the vertical wind tunnel. Standard weights were directly attached to the surface of the drag element and the resultant force acted in a direction tangent to the drag-element surface. The balance response to the applied force was monitored by measuring the voltage output across the balance potentiometer. The balance was adjusted to accommodate loading as high as 3000 mg for the Mach 2.9 tests and 1500 mg for the Mach 4.9. Calibrations (as shown in Figure 6) were represented by straight lines with the "zero," no-load intercept, and "slope," voltage per milligram of loading, being the calibration constants. The calibration "slope" which was a function of the restoring spring constant and potentiometer voltage setting, changed very little between test runs, and proved to be very stable for a particular balance configuration. The calibration "zero" constant which relates to the no-load output of the balance varied with aft housing temperature and to a lesser degree with static pressure.

The effects of temperature and pressure on the balance calibration were evaluated in an environmental test chamber prior to wind-tunnel testing. By changing the ambient temperature of the balance, a calibration "zero" shift was measured as shown in Figure 7. This calibration shift was primarily a result of thermal effects on the sensitive balance components housed in the aft portion of the balance. As was noted earlier, the aft balance housing was maintained at a relatively constant temperature during a wind-tunnel test run to minimize the temperature change and the resulting errors. The balance housing temperature was monitored during each wind-tunnel test and if a temperature change occurred, appropriate corrections were made to the calibration "zero" constant. For the longest of wind-tunnel test runs the aft housing temperature changed by less than 3°K. The no-load "zero" reading was monitored just prior to and just after each air flow cycle allowing for a relatively short time and small temperature change between calibration checks.

Changes in the drag-element temperature did not affect the balance calibration. This was determined by obtaining no-load and loaded calibration checks before and after activation of the "clam-shell" cooling manifold. Both the calibration "zero" and "slope" were found to be unaffected by the temperature changes of the mounting flange and drag element.

The effects of static pressure on the newly designed balance were not significant. This is in contrast to the problems noted in Reference 3 where a sizable calibration "zero" shift resulted with pressure change. The reason for the previous problem related to the LVDT and the way in which it has been electronically excited. Present calibration results are shown in Figure 8. Since a calibration "zero" reading was taken before and after each wind-tunnel test run at a low pressure near the flow static pressure, a correction to the calibration was not necessary.

WIND-TUNNEL TEST PROCEDURE

The skin-friction balance was made to fit the instrumentation ports in the copper test plate of the Boundary Layer Channel. The aft portion of the balance projected back into the plenum chamber of the facility where associated wiring, liquid nitrogen supply lines, and pressure leads were attached. The aft portion of the balance was sealed, eliminating air leakage through the balance from the plenum of the test-plate surface.

For each wind-tunnel test run the following procedures were generally followed:

1. Prior to each run, a check of drag-element alignment and centering was made.

2. The balance was load calibrated while installed in the test plate.

3. The facility doors were closed and the test section was evacuated.

4. The test plate was cooled with liquid nitrogen.

5. Once the test-plate temperature was achieved uniformly, the balance "no load" output was recorded.

6. The air flow was started and drag measurements were obtained. Both Reynolds number and drag-element temperature were cycled.

7. At the completion of data acquisition, the tunnel was shut down and the liquid nitrogen cooling was stopped. A no-flow condition was established at a low test section pressure and temperature. A balance "no-load" output was recorded.

8. The test-section pressure was elevated to atmospheric pressure conditions, facility doors were opened, and a check of the drag-element alignment was made.

9. After a period of facility warmup, a post-test calibration was conducted.

This sequence of events is illustrated in Figure 9.

A number of test parameters were monitored during each wind-tunnel run. These included the wind-tunnel supply pressure and temperature, the test-plate temperature and static pressure, the balance internal pressure, the drag-element temperature, the balance aft-housing temperature, and the balance potentiometer voltage reading. These parameters established aerodynamic and heat-transfer conditions, allowed balance calibration checks, and provided the shear-stress data. The "slope" constant in the balance calibration was assumed constant through each run based on preliminary test results and the calibration checks which were taken before and after each test. The "zero" constant was evaluated from the "no-load" balance readings obtained just before and just after the air-flow cycles (at steps 5 and 7 and at times during step 6 in the procedure). Any changes in the "no-load" readings before and after the run were usually traced to aft housing temperature changes and appropriate corrections were made. This correction was usually minimal.

The shear stress variation with drag-element temperature was obtained in one of two ways; either the Reynolds number was cycled for progressively cooler drag-element temperatures or the drag-element temperature was cycled for set Reynolds number conditions (see Figure 9). Procedure steps 6A and 6B). The latter technique produced more consistent data; however, once the drag element had been cooled over one cycle it took a long time for it to warm up for a second cycle at a different Reynolds number.

The drag element of the skin-friction balance was not cooled during the initial stages of a test run and the drag element reached a temperature which was several hundred degrees above the temperature of the surrounding cooled surface. By obtaining wall shear-stress measurements at this temperature and for successively cooler drag-element temperatures using the "clam-shell" cooling mechanism, surface shear-stress data were obtained over a range of drag-element temperatures.

RESULTS

Typical plots of the surface shear stress versus drag-element temperature are shown in Figure 10 for both the Mach 4.9 and 2.9 conditions. An "ideal" cold-wall shear stress is obtained from an extrapolation of such data to where the drag-element temperature is equal to the surrounding wall temperature. The slope of this extrapolation line gives the shear error per degree of temperature difference.

Since the wall shear stress is defined as

$$\tau_w = \mu \frac{du}{dy} \qquad (1)$$

a discontinuity in surface temperature can influence the surface shear stress through the fluid viscosity and/or the velocity gradient at the wall. Figure 10 shows that the effect of a locally "hot" drag element is to increase the local wall shear stress in proportion to the difference between the drag-element temperature and the surrounding wall temperature. It is easy to see from Equation 1 that the higher the drag-element temperature, the higher the surface viscosity, and the higher the measured wall shear. The effects of a temperature step on the local boundary-layer velocity gradient at the wall cannot be analyzed as directly. Many factors can influence the velocity gradient at the wall, including the size and shape of the drag element, the boundary-layer thickness, the boundary-layer velocity and temperature profiles, the Mach number and the Reynolds number. Over the limited scope of these tests the drag-element geometry and size were unchanged and only the Mach number and Reynolds number were varied.

The shear-stress error per degree of temperature difference, i.e., the slope of the linear variation of shear stress with drag-element temperature, is shown in Figure 11 as a function of Reynolds number. The magnitude of the error is observed to decrease slightly with decreasing Reynolds number for the Mach 4.9 data. At Mach 2.9, only two Reynolds number conditions provided data and no trends could be determined other than the general agreement of the Mach 2.9 data with the Mach 4.9 results. A least-square fit of all the data provided a calibration curve of the form

$$\frac{\tau_{DE} - \tau_w}{T_{DE} - T_w} \left(\frac{N}{M^2\ {}^oK}\right) = A \log_{10} (Re/m) + B \qquad (2)$$

where: A = 0.0310988
B = 0.1795555

The data of Westkaemper (Reference 4) is often referenced on the subject of temperature-step effects. Westkaemper concluded that a moderate temperature mismatch (maximum of 34^oK) produced a negligible effect on the drag (less than 2 percent) over the range of test conditions covered in that study (Mach 5, Reynolds number per meter from 16.5 to 25 million). If the present correlation (Equation 2) is evaluated for the conditions of Westkaemper's tests (Mach 5, $Re/m = 20. \times 10^6$), a wall shear stress error of 0.0475 N/m^2 per ^oK is indicated. For a 34^oK maximum temperature step and a nominal wall shear stress of 82.1 N/m^2 (C_f assumed equal to 0.0015), the wall shear stress variation which might be expected from the present correlation would be of the order of 1.96 percent. This low percentage error is within the observed drag variation and stated experimental accuracy noted by Westkaemper. As such, if the present correlation were to hold for those tests, the expected error would be small, it would be very difficult to evaluate and could easily be over-shadowed by the accuracy limitations of the experiment. The temperature-step effects might be considered negligible for those tests; however, the inference that the temperature-step effects are generally negligible must not be made.

It has been shown that the absolute magnitude of wall shear-stress error per degree of temperature mismatch is not a strong function of the wall shear stress (see Figure 11). As such, the percentage error will be small if the absolute magnitude of the wall shear stress is large. However, the opposite will be true for small values of wall shear stress.

The magnitude of the temperature-step effects in these tests is better realized in Figure 12 where the calibration results are presented in terms of the percentage error. Errors as high as 0.45 percent per degree (K) of temperature mismatch are indicated. The percentage errors are higher at the higher Mach number conditions because the wall shear stress is lower for the same Reynolds number (the absolute error showed no dependence on Mach number). For a constant Mach number, the percentage error increases with decreasing Reynolds number. Again the magnitude of the percentage errors tends to reflect the magnitude of the wall shear stress. It is important to note that the percentage errors can become very large as the value of the wall shear stress becomes small; i.e., for high Mach numbers and/or low Reynolds numbers.

As a final note, some comment should be made as to drag-element misalignment and the possibility of errors resulting from such misalignment. Several precautions were taken to minimize this problem as discussed in the text and, for the most part, the steps taken were successful. The drag-element misalignment was less than $\pm$ 0.0025 cm, and based on the data of O'Donnell (Reference [9]) an error in shear stress of less than $\pm$ 4 percent could be expected. Between duplicate test runs and for certain long test runs where the temperature of the drag-element was cycled several times, the level of shear stress was slightly different between temperature cycles. These shifts could not always be explained in terms of

[9] O'Donnell, Francis B., Jr., "A Study of the Effect of Floating Element Misalignment on Skin-Friction-Balance Accuracy," DRL Report 515, CR-10, Mar 1964

calibration shifts and a drag-element misalignment was suggested. It should be noted, however, that the data showed a consistent trend of decreasing shear stress with decreasing temperature for each of the temperature cycles. Also, the shift in shear stress which was due to suspected misalignment of the drag element was always less than the change in shear stress due to drag-element temperature effects. Since the data were analyzed for single temperature cycles, changes in the shear-stress value between cycles were not considered and effects on the analysis were considered minimal.

Since the purpose of these tests was to obtain a calibration which could be used to verify previously published skin-friction data, it is appropriate that the calibration now be applied to that data. Refer to Appendix A for a listing and description of corrections which were applied to the skin-friction data of References 1 and 2.

CONCLUSIONS AND RECOMMENDATIONS

An experimental study was conducted to determine the NSWC skin-friction balance drag-element temperature effects on measured wall shear stress. The results of the study indicate a friction-drag variation which is proportional to the difference between the drag-element temperature and the temperature of the surrounding wall. The percentage change can become very large when the value of the wall shear stress is low, i.e., for high Mach numbers and/or low Reynolds numbers.

Additional work is needed to gain a better understanding of temperature-step effects. The present study has shown that an effect exists and this effect can be significant. Other experimentalists must now consider this fact and evaluate the effects for their balance configuration and flow-field conditions. Of equal importance to experimental results is the need for analytic modeling of the effect. Hopefully from an analytic approach, the important parameters which influence the effect may be determined.

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SYMBOLS

C_f	local skin-friction coefficient
M	Mach number
P	pressure
P_s	static pressure
P_{t_2}	Pitot pressure
r	recovery factor
Re/m	Reynolds number per meter
Re_θ	momentum thickness Reynolds number
T	temperature
u	velocity
x	distance along plate from nozzle throat
y	distance normal to plate
δ	boundary-layer thickness
δ^*	displacement thickness
θ	momentum thickness
θ_E	energy thickness
θ_H	total enthalpy thickness
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
τ	shear stress

Subscripts

aw	adiabatic-wall conditions
DE	drag element
e	free-stream conditions
o	tunnel supply conditions
t	stagnation conditions
w	wall conditions

Superscripts

$\overline{\quad}$	transformed quantities

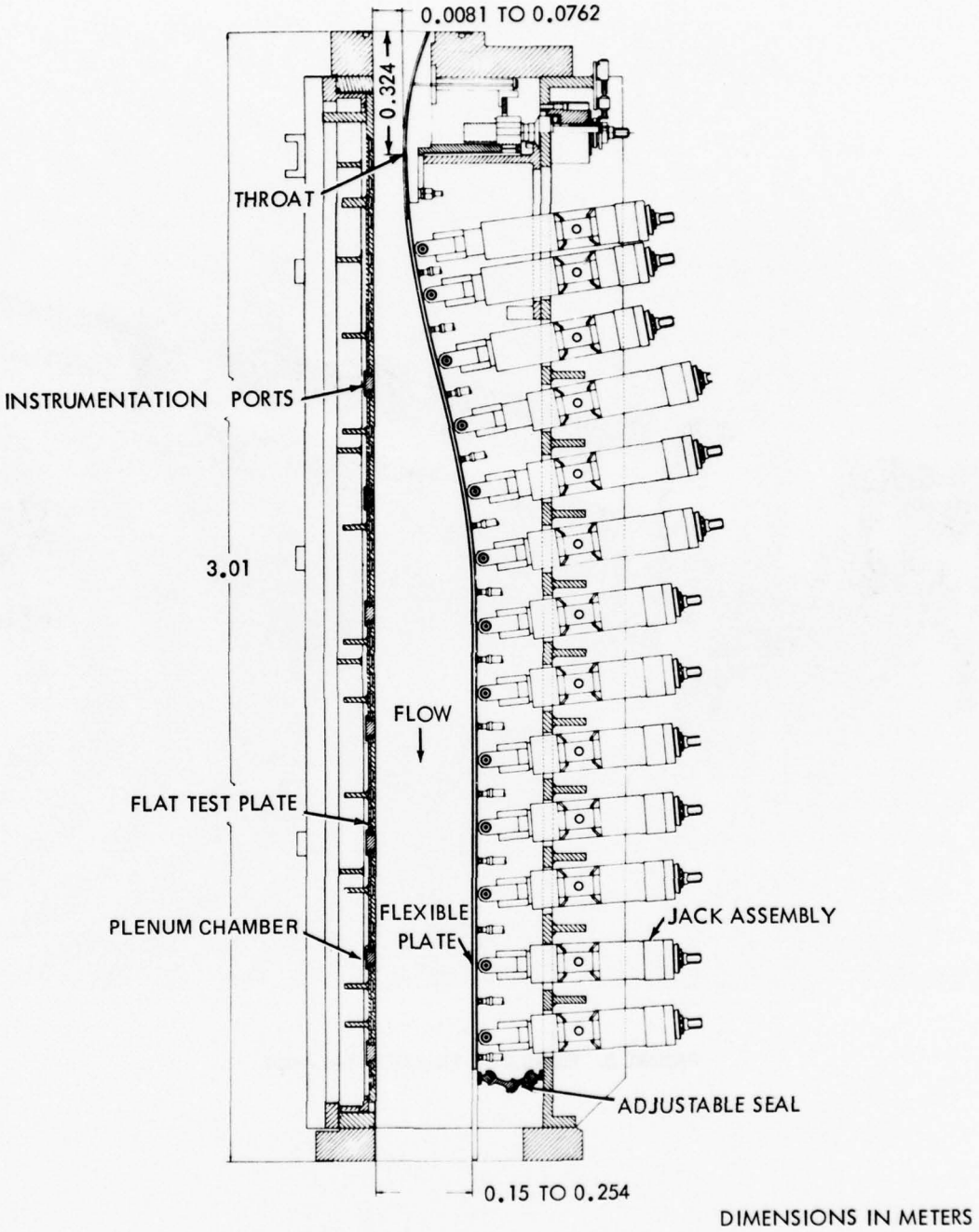

FIGURE 1 NSWC BOUNDARY LAYER CHANNEL

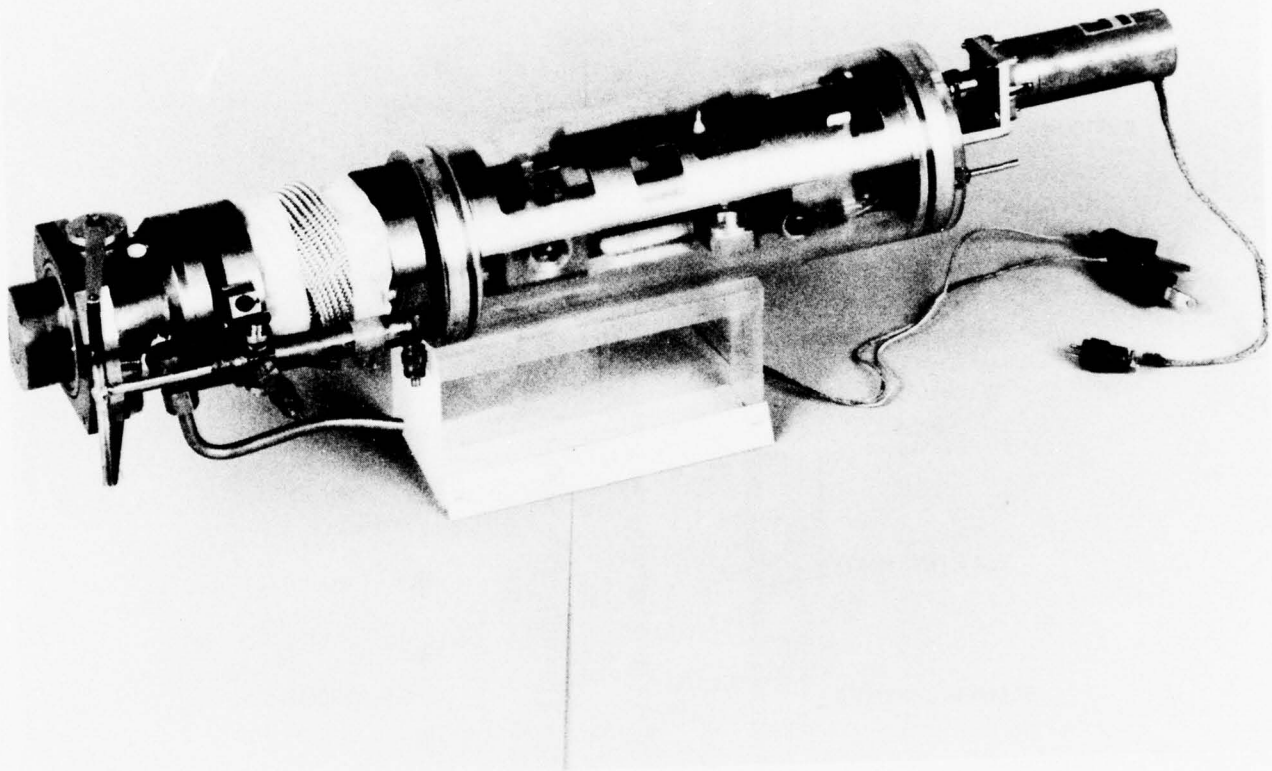

FIGURE 2 NSWC SKIN-FRICTION BALANCE

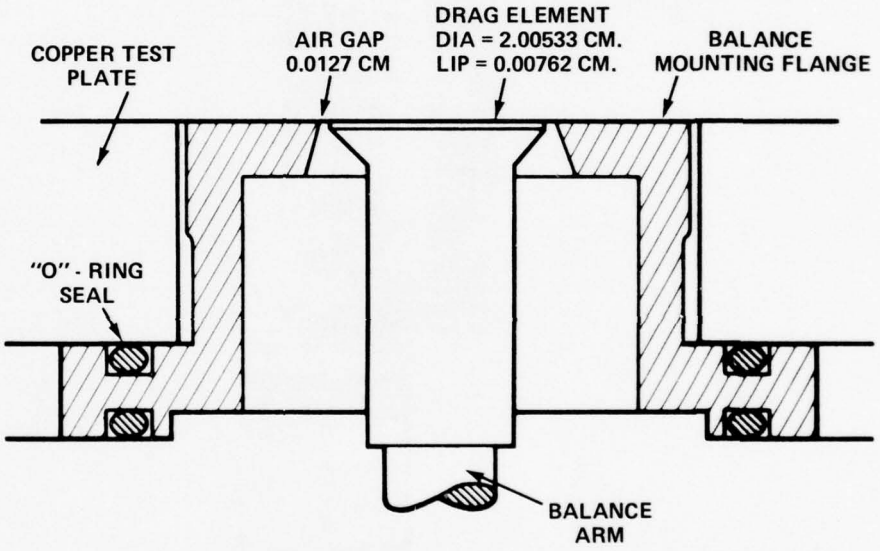

FIGURE 3 SKIN FRICTION BALANCE DRAG ELEMENT AND MOUNTING FLANGE

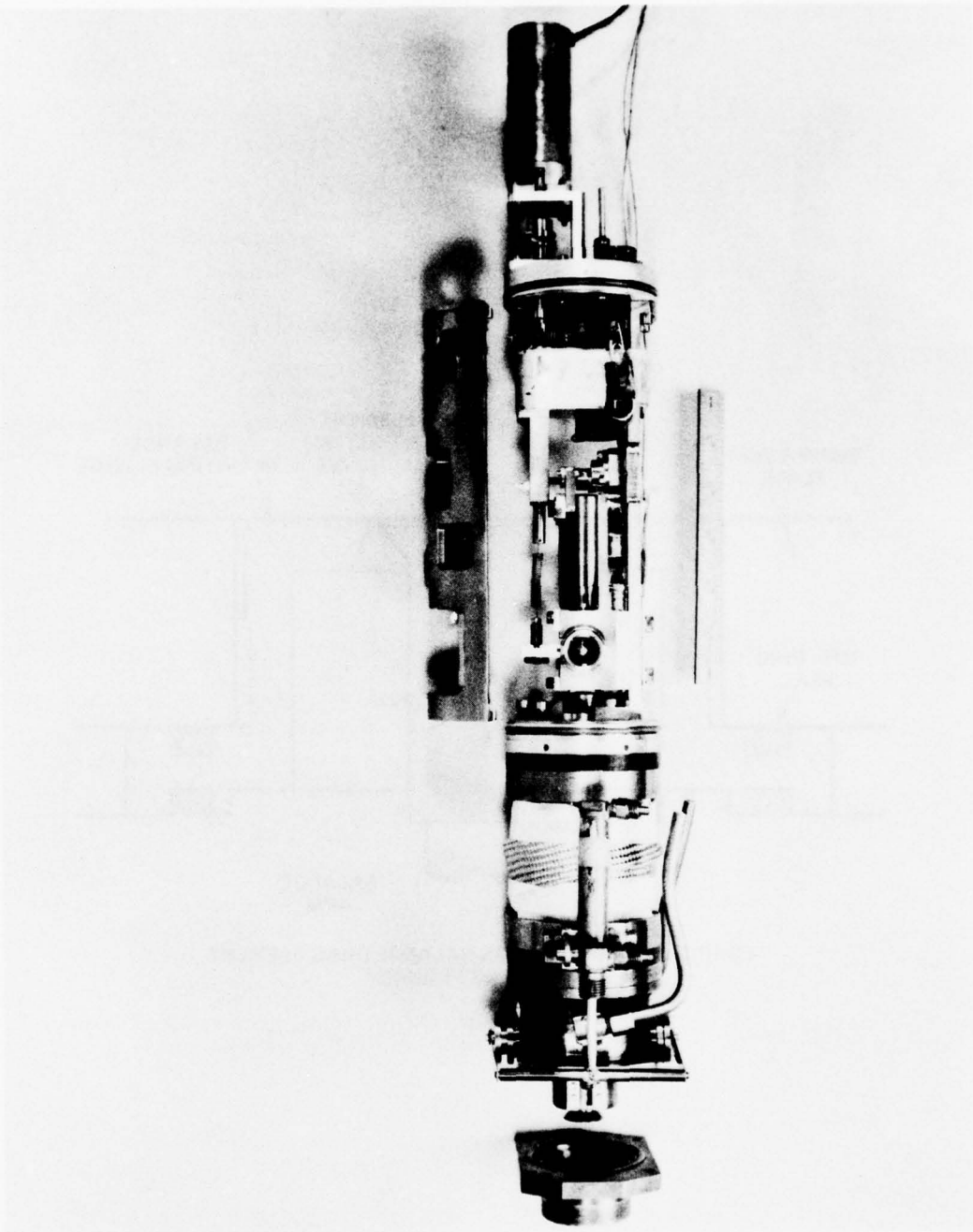

FIGURE 4(a) PHOTOGRAPH, NSWC SKIN-FRICTION BALANCE

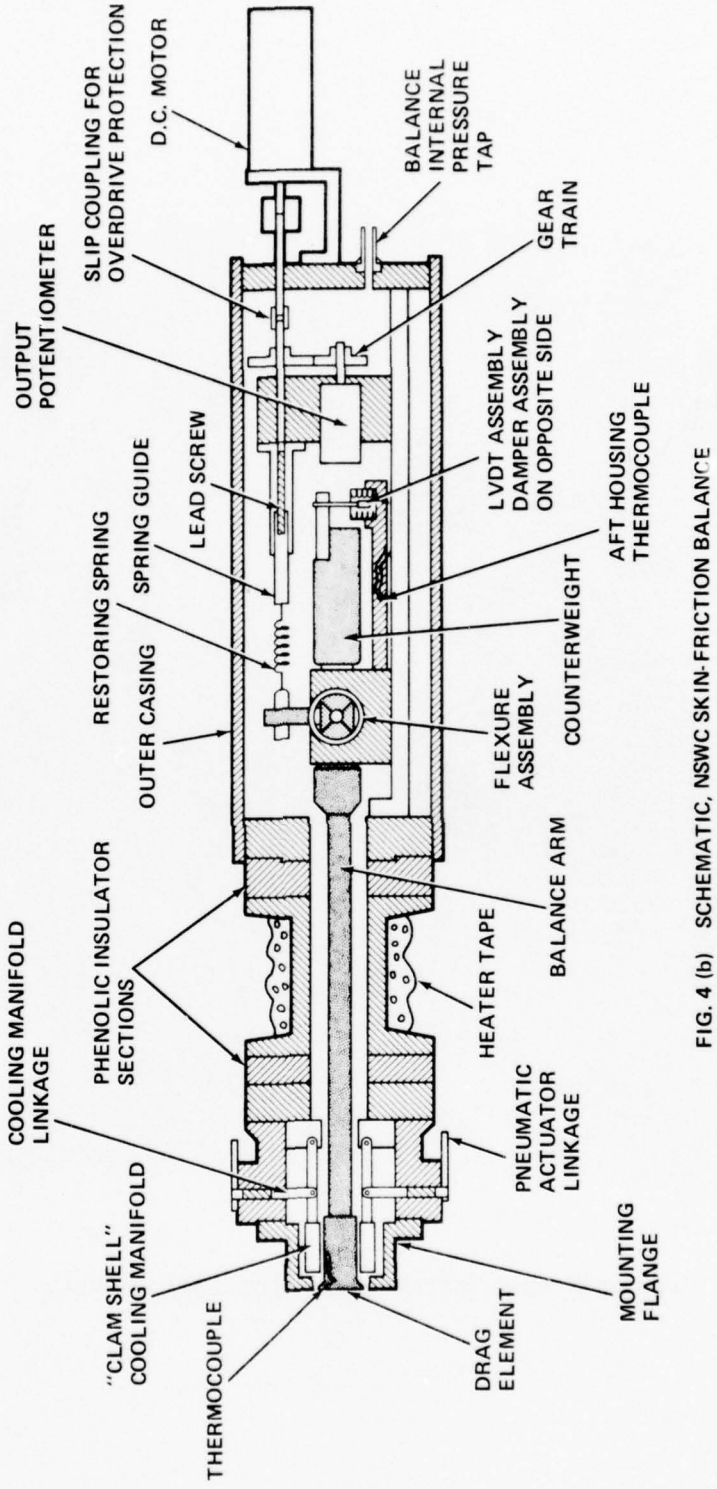

FIG. 4 (b) SCHEMATIC, NSWC SKIN-FRICTION BALANCE

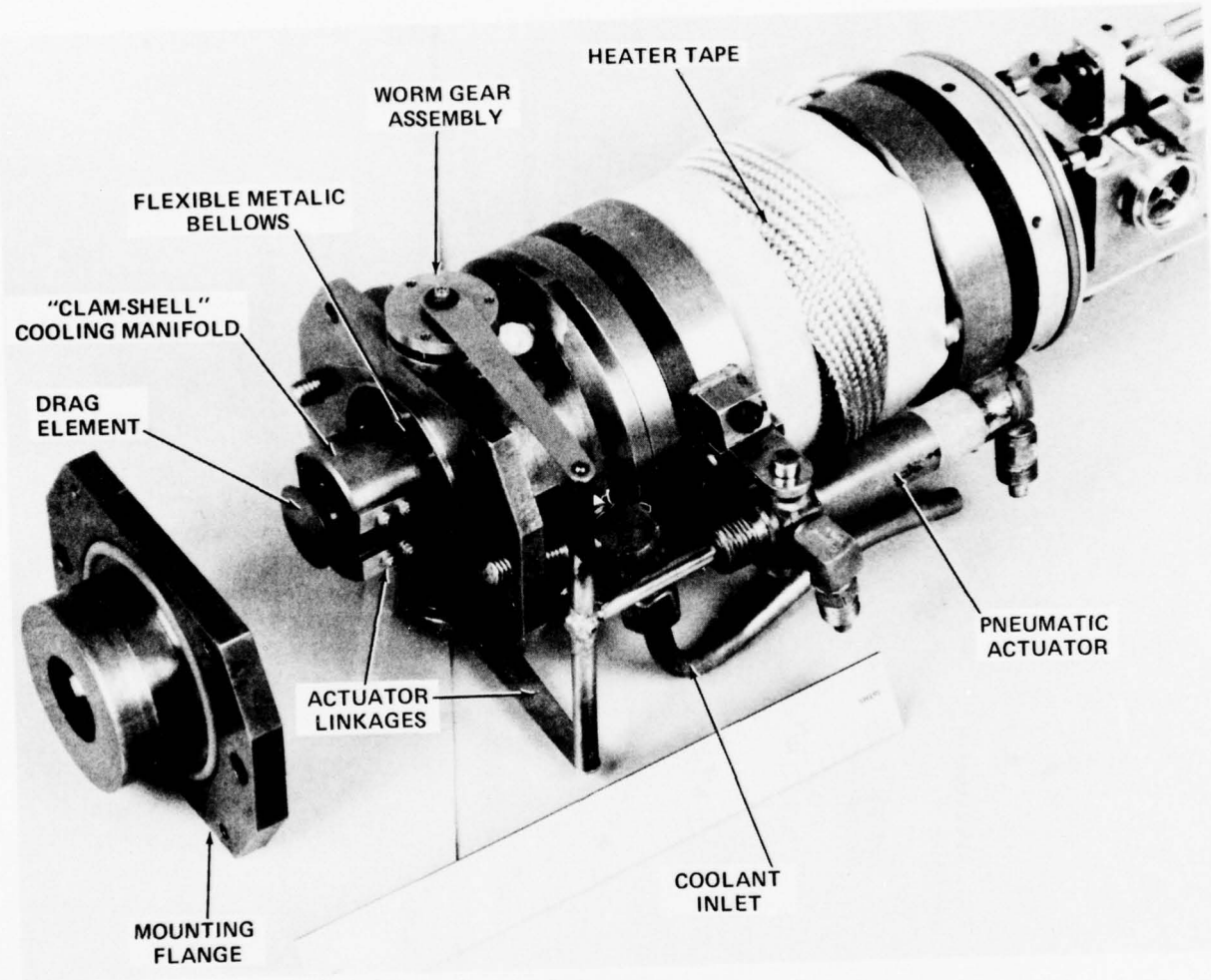

FIGURE 5 SKIN FRICTION BALANCE COOLING ASSEMBLY

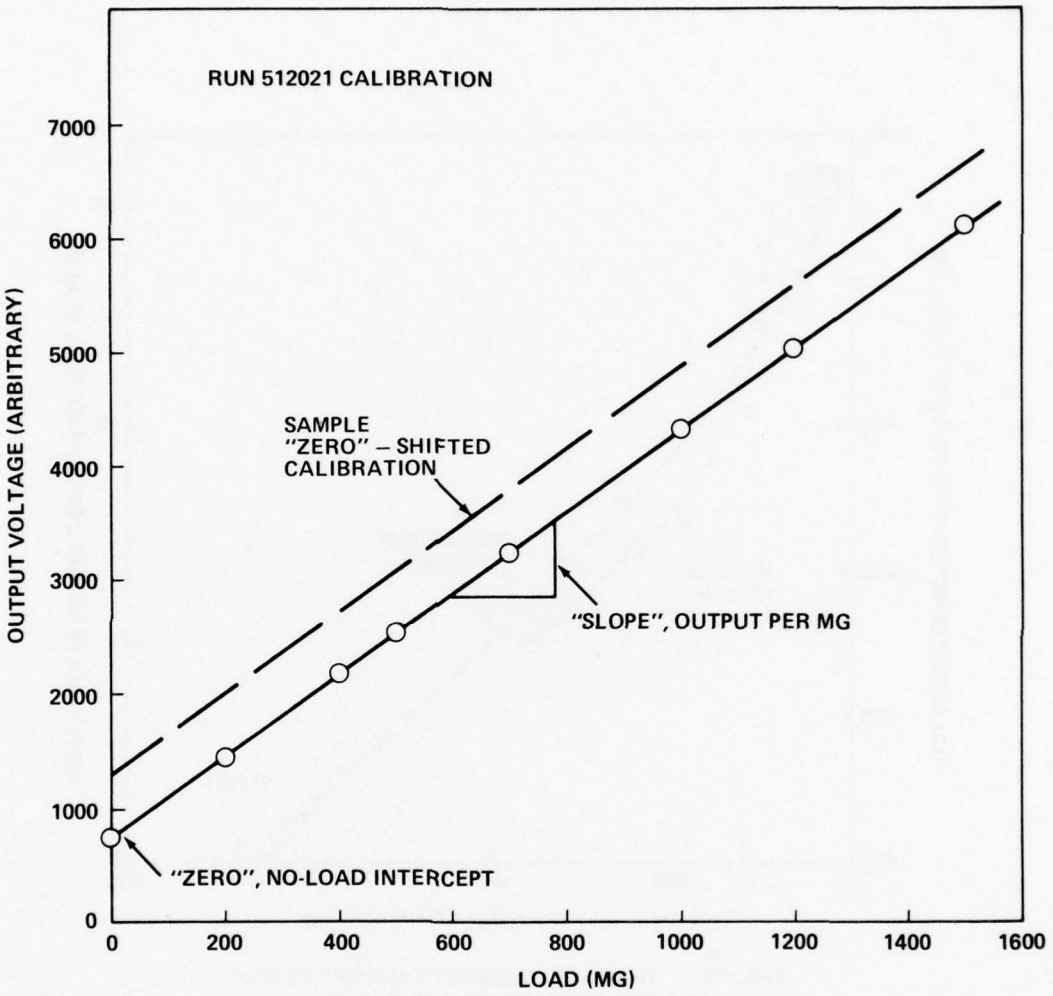

FIGURE 6 SAMPLE BALANCE LOAD CALIBRATION

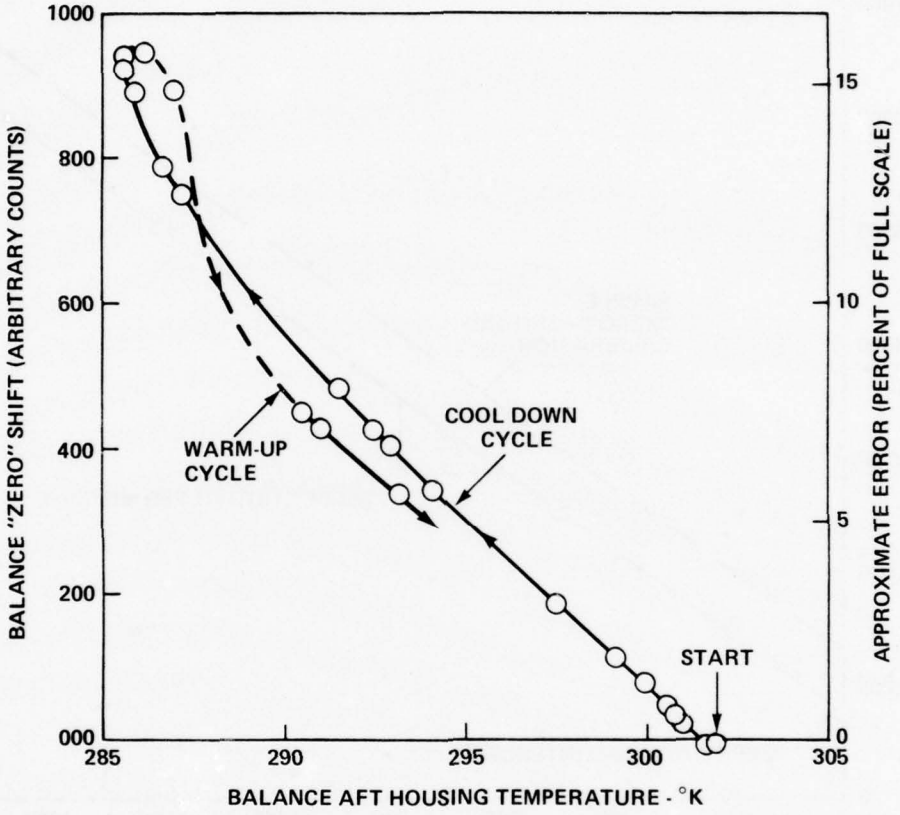

FIGURE 7 BALANCE CALIBRATION SHIFT VERSUS AFT HOUSING TEMPERATURE

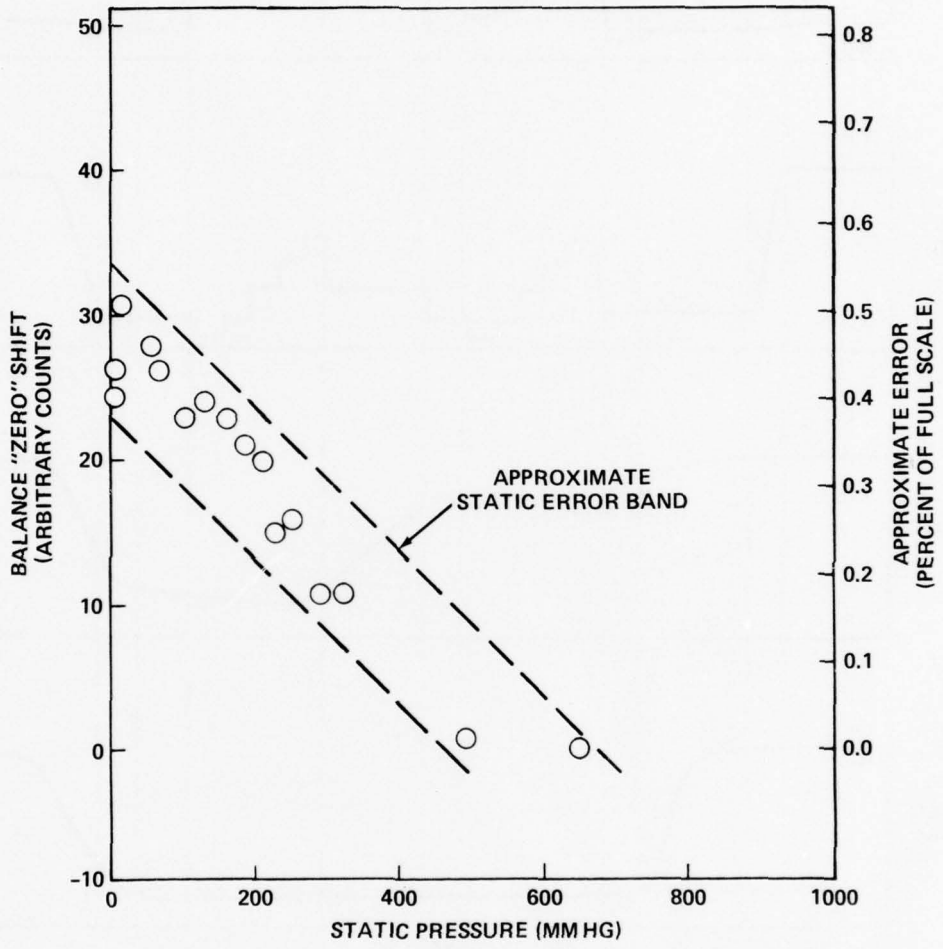

FIGURE 8 BALANCE CALIBRATION SHIFT VERSUS STATIC PRESSURE

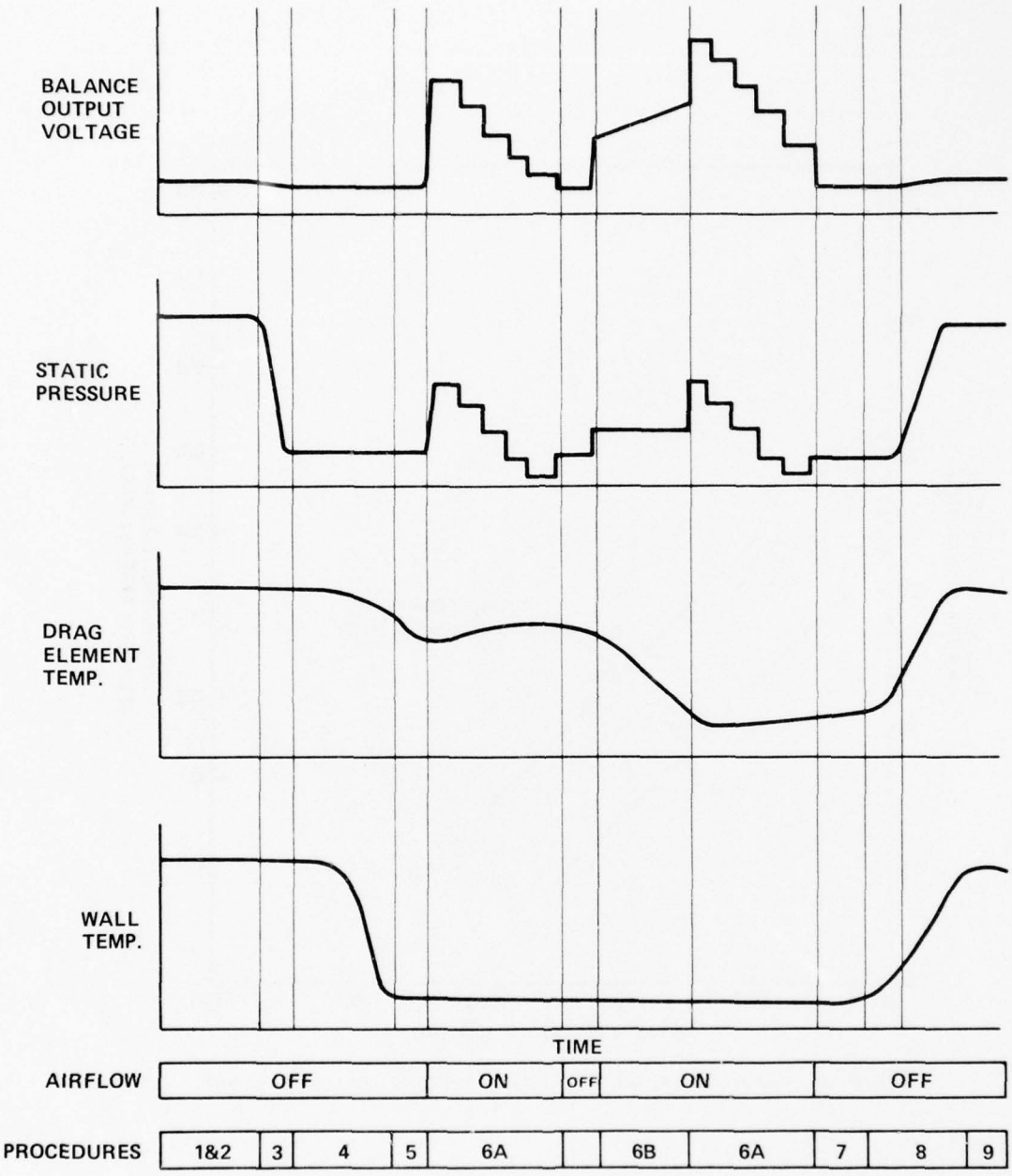

FIGURE 9 SEQUENCE OF EVENTS DURING TEST (NOT TO SCALE)

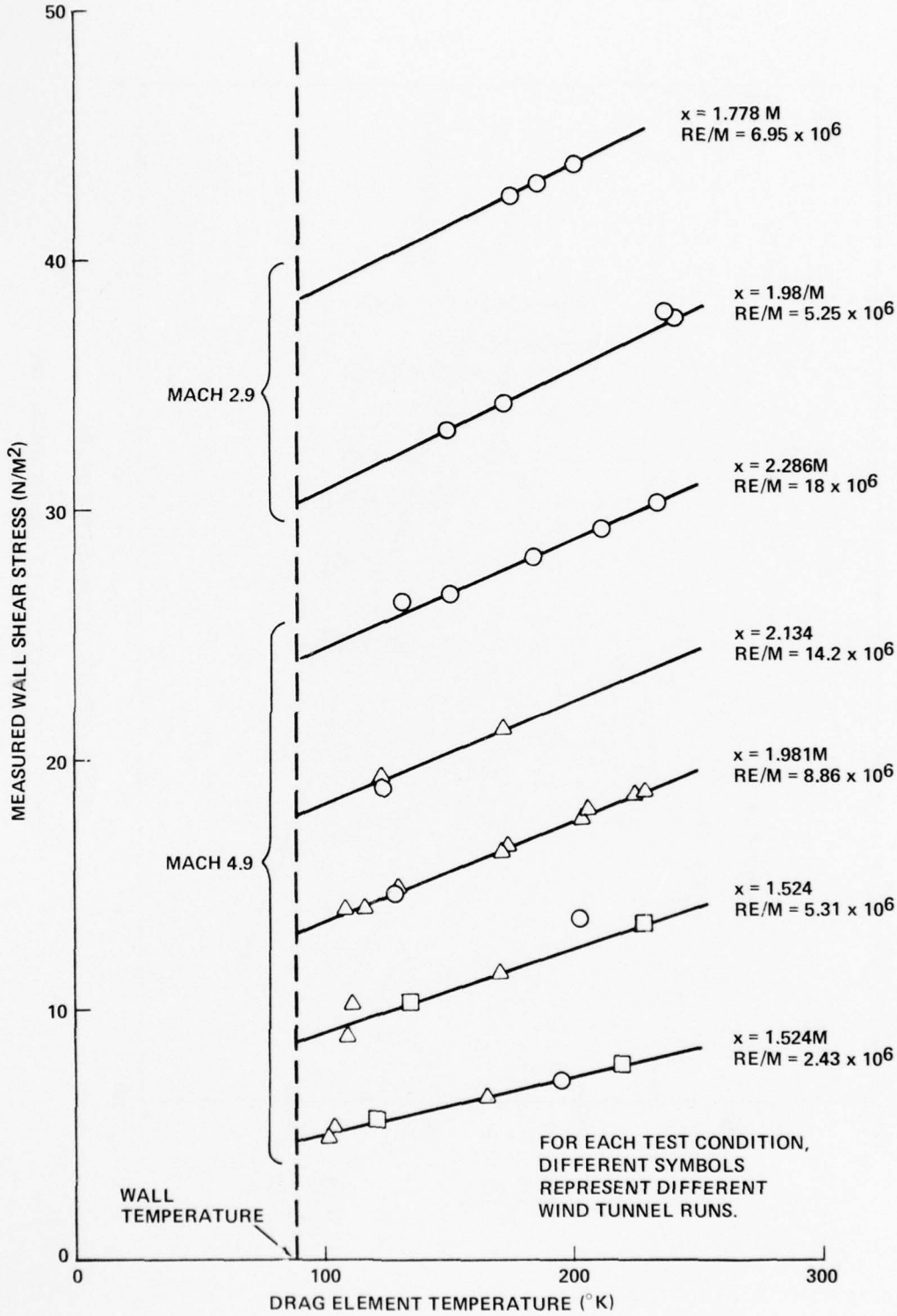

FIGURE 10 WALL SHEAR STRESS VARIATION WITH DRAG ELEMENT TEMPERATURE

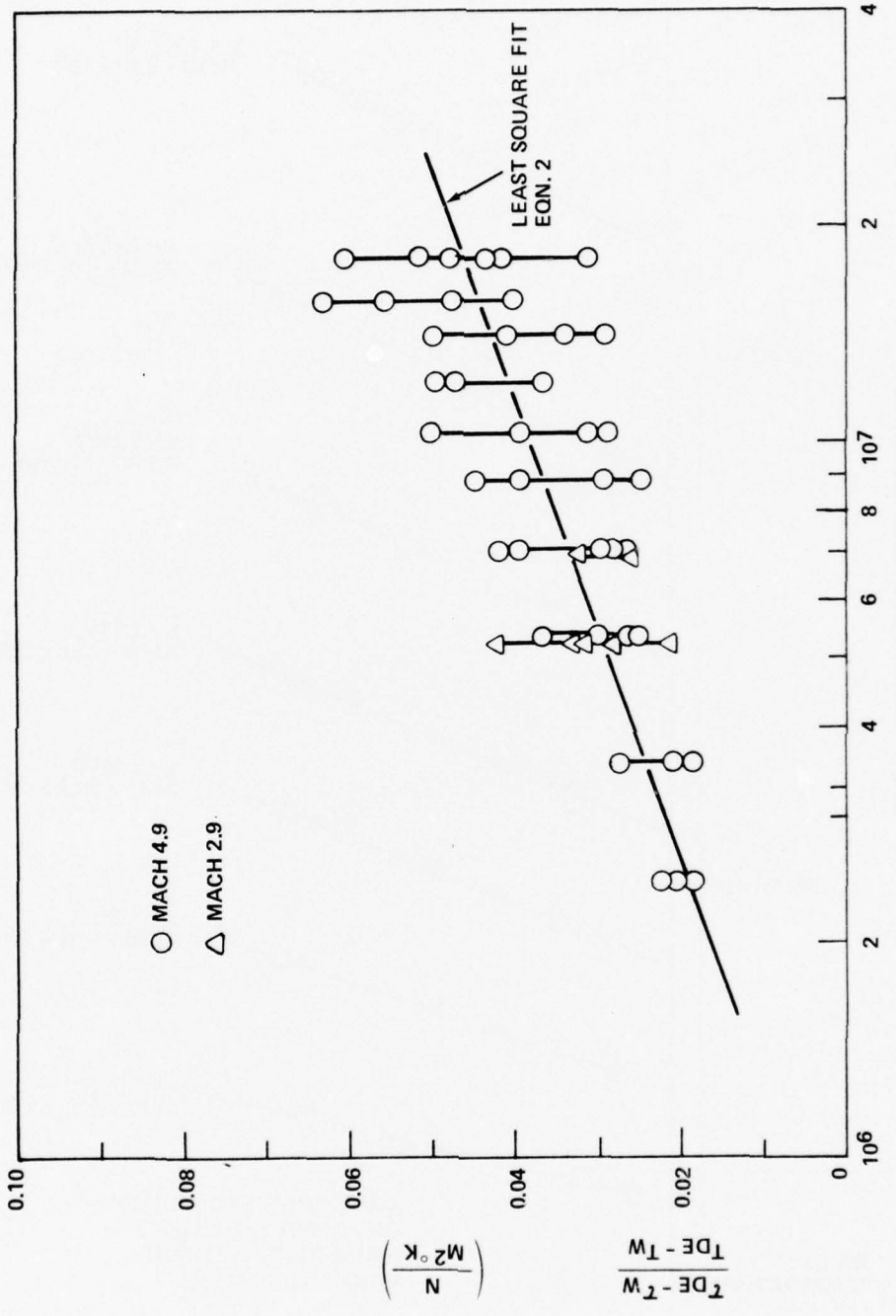

FIGURE 11 INFLUENCE OF REYNOLDS NUMBER ON TEMPERATURE STEP EFFECT.

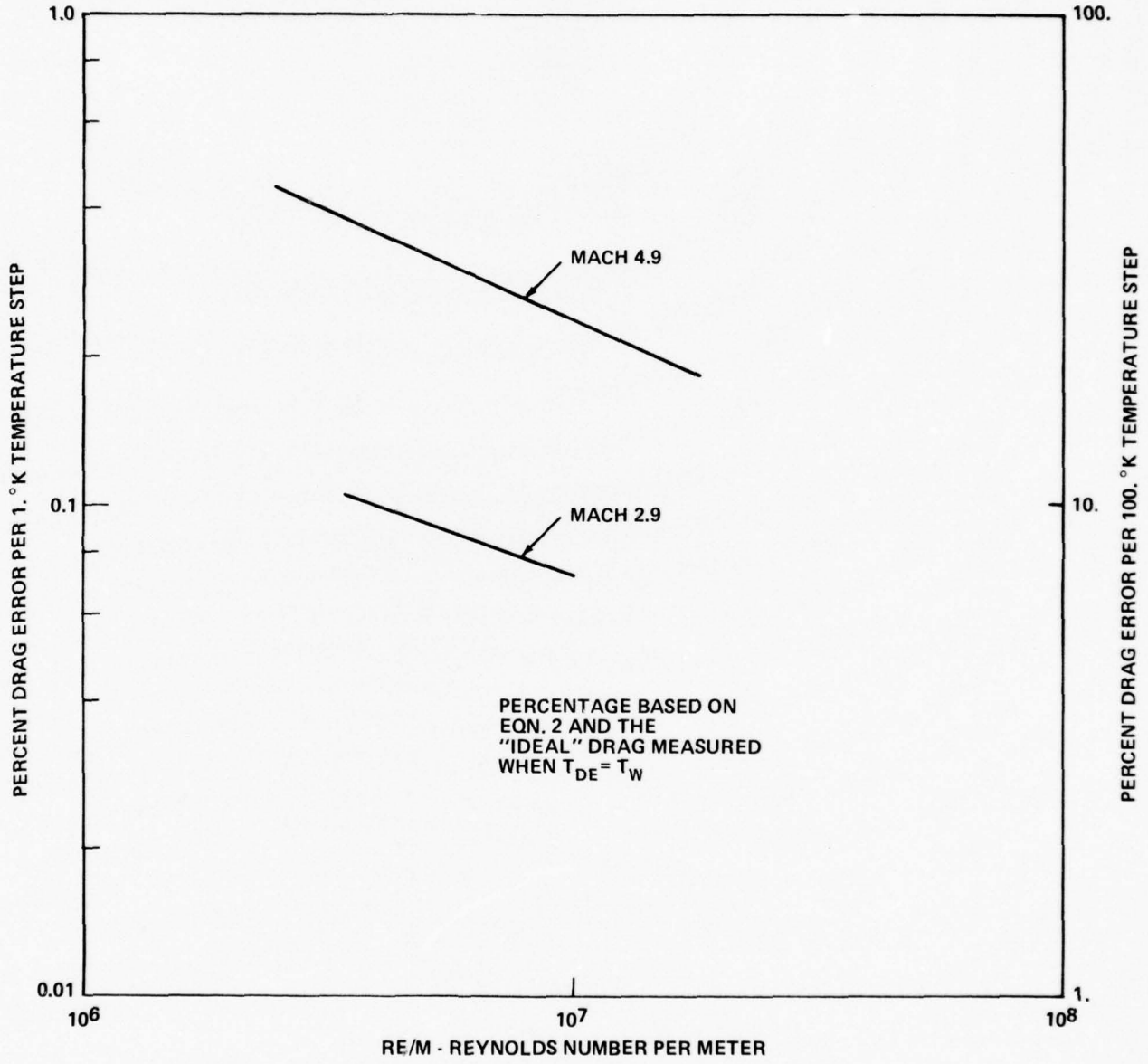

FIGURE 12 TEMPERATURE STEP EFFECTS IN PERCENT OF "IDEAL" DRAG.

APPENDIX A

CORRECTIONS TO PREVIOUSLY PUBLISHED DATA

In References 1 and 2 cold-wall skin-friction results were presented and a statement was made to the effect that the cold-wall data were obtained with a locally "hot" drag element. By applying the correction for temperature-step effects as derived in this study, significant changes to the previously published results are indicated.

Figure A1 shows a summary of the Mach 4.9 zero-pressure-gradient (ZPG) skin-friction data which was presented in Reference 1 together with corrected results. The data are shown in an incompressible frame of reference using the compressibility transformation of Van Driest (Reference A1) in the form:

$$\overline{C_f} = C_f \frac{r\,(0.2\,M_e^2)}{\left\{\sin^{-1}\left(\frac{2A^2 - B}{B^2 + 4A^2}\right) + \sin^{-1}\left(\frac{B}{\sqrt{B^2 + 4A^2}}\right)\right\}^2} \tag{A1}$$

$$\overline{R_{e_\theta}}' = \frac{\mu_e}{\mu_w} R_{e_\theta}' \tag{A2}$$

where:

$$A = \sqrt{\frac{T_e}{T_w} r\,0.2\,M_e^2} \qquad r = 0.89$$

$$B = \frac{T_{aw}}{T_w} - 1$$

Using this transformation, the effects of Mach number and heat transfer on the skin-friction coefficients are eliminated and the trends in the data are more easily noticed. Shown for comparison to the data is the incompressible, zero-pressure-gradient relation of Karman-Schroenherr (Reference A-2).

A1 Van Driest, E. R., "Turbulent Boundary Layer in Compressible Fluids," Journal of the Aeronautical Sciences, Vol. 18, No. 3, Mar 1951, pp. 145-160.

A2 Schoenherr, K. E., "Resistance of Flat Surfaces Moving Through a Fluid," Society of Naval Architects and Marine Engineers, Vol. 40, 1932, pp. 279-313.

Figure A1 shows the uncorrected cold-wall (CW) data of Reference 1 to have a trend which is quite different from the adiabatic-wall (AW) and moderate-heat-transfer (MHT) results. The AW and MHT skin-friction data are consistently (from 15 to 20 percent) below predicted values and vary inversely with the 0.25 power of Reynolds number. The higher skin-friction values and increased power relationship of the CW data could not be explained prior to the recent tests. Only when the temperature step correction, equation (2), is applied to the CW data do the CW results fall in line with the AW and MHT results. The values of CW skin-friction are reduced by the correction and the reduction is greater at the lower Reynolds numbers resulting in a change in the C_f vs. Re_θ power trend.

In a similar manner, the temperature-step correction was applied to the favorable-pressure-gradient (FPG) data of Reference 2. These results are shown in Figure A2. The trends of lower skin-friction values and reduced power exponent relationship with Reynolds number are again present, however, the magnitude of the correction is not as pronounced due to the higher values of wall shear stress which were experienced in the FPG flow field. Corrected tabulations of the ZPG and FPG data of References 1 and 2 are presented in Tables A1 and A2. These data listing should be considered as addendum to the previous data reports.

TABULAR OUTPUT NOMENCLATURE

The nomenclature used in the computerized tabular output (Tables A1 and A2) is defined as follows:

PO	tunnel supply pressure
TO	tunnel supply temperature
TW	wall temperature
TDE	drag-element temperature
MPW	Mach number
THP	boundary-layer momentum thickness
RTHPW	momentum thickness Reynolds number
TAUW(UNC)	wall shear stress (uncorrected)
TAUW(CORR)	wall shear stress (corrected)
CF	skin-friction coefficient (corrected)
BETADS	pressure-gradient parameter

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TABLE A1 CORRECTED COLD-WALL SHEAR STRESS DATA OF REF. 1

PO N/M2	TO DEG.K	TW DEG.K	TDE DEG.K	MPW	THP CM	RTHPW	TAUW(UNC) N/M2	TAUW(CORR) N/M2	CF	BETADS
RUN NO. 110191, ZPG-CW, 1.524 M STATION, NOL BALANCE										
1.034E+06	426.7	90.0	201.7	4.968	.2771	4.718E+04	3.885E+01	3.379E+01	9.642E-04	0.000
9.308E+05	431.1	90.0	202.2	4.960	.2854	4.317E+04	3.642E+01	3.152E+01	9.92EE-04	0.000
8.274E+05	422.2	90.0	201.7	4.956	.2914	4.059E+04	3.369E+01	2.893E+01	1.022E-03	0.000
7.239E+05	424.4	90.0	201.1	4.961	.3022	3.644E+04	3.019E+01	2.568E+01	1.041E-03	0.000
6.205E+05	418.3	90.0	199.4	4.967	.3125	3.297E+04	2.660E+01	2.235E+01	1.062E-03	0.000
5.171E+05	422.2	90.0	197.2	4.961	.3281	2.850E+04	2.289E+01	1.901E+01	1.079E-03	0.000
4.137E+05	420.6	89.4	193.9	4.959	.3464	2.425E+04	1.921E+01	1.573E+01	1.114E-03	0.000
3.103E+05	421.1	88.9	190.0	4.937	.3717	1.966E+04	1.545E+01	1.246E+01	1.157E-03	0.000
2.068E+05	425.2	87.8	187.2	4.922	.4125	1.441E+04	1.131E+01	8.929E+00	1.229E-03	0.000
1.034E+05	423.3	87.8	178.3	4.871	.4874	8.769E+03	6.291E+00	4.936E+00	1.306E-03	0.000
RUN NO. 110181, ZPG-CW, 1.778 M STATION, NOL BALANCE										
1.034E+06	424.4	90.0	206.1	4.922	.2845	4.986E+04	3.864E+01	3.333E+01	9.173E-04	0.000
9.308E+05	425.6	90.0	204.4	4.917	.2927	4.606E+04	3.612E+01	3.106E+01	9.463E-04	0.000
8.274E+05	428.9	90.0	203.9	4.914	.3028	4.188E+04	3.299E+01	2.815E+01	9.627E-04	0.000
7.239E+05	421.1	90.0	202.8	4.916	.3112	3.877E+04	2.934E+01	2.471E+01	9.667E-04	0.000
6.205E+05	420.6	90.0	200.0	4.919	.3241	3.462E+04	2.606E+01	2.176E+01	9.963E-04	0.000
5.171E+05	424.4	90.0	197.2	4.919	.3413	2.954E+04	2.283E+01	1.893E+01	1.040E-03	0.000
4.137E+05	423.3	90.0	194.4	4.915	.3613	2.551E+04	1.909E+01	1.560E+01	1.068E-03	0.000
3.103E+05	423.3	88.9	191.7	4.899	.3890	2.074E+04	1.517E+01	1.213E+01	1.093E-03	0.000
2.068E+05	427.5	88.9	188.3	4.886	.4339	1.527E+04	1.113E+01	8.743E+00	1.171E-03	0.000
1.034E+05	421.1	87.8	181.7	4.836	.5143	9.476E+03	6.718E+00	5.282E+00	1.361E-03	0.000
RUN NO. 110141, ZPG-CW, 1.981 M STATION, NOL BALANCE										
1.034E+06	419.4	91.7	206.7	4.885	.2892	5.249E+04	3.639E+01	3.108E+01	8.314E-04	0.000
9.308E+05	426.1	91.7	205.6	4.902	.3003	4.747E+04	3.338E+01	2.833E+01	8.530E-04	0.000
8.274E+05	424.4	91.7	203.9	4.899	.3094	4.380E+04	3.098E+01	2.617E+01	8.849E-04	0.000
7.239E+05	423.3	91.1	201.7	4.902	.3205	3.982E+04	2.785E+01	2.331E+01	9.02BE-04	0.000
6.171E+05	421.7	90.6	198.9	4.895	.3339	3.568E+04	2.442E+01	2.019E+01	9.125E-04	0.000
5.171E+05	419.4	90.0	196.7	4.895	.3494	3.157E+04	2.092E+01	1.700E+01	9.166E-04	0.000
4.137E+05	422.2	88.9	192.8	4.891	.3721	2.666E+04	1.757E+01	1.408E+01	9.459E-04	0.000
3.103E+05	422.2	88.9	189.4	4.886	.4020	2.165E+04	1.417E+01	1.117E+01	9.970E-04	0.000
2.068E+05	418.3	88.9	184.4	4.874	.4462	1.635E+04	1.058E+01	8.233E+00	1.092E-03	0.000
1.034E+05	422.2	88.9	176.7	4.830	.5378	9.852E+03	6.320E+00	4.980E+00	1.277E-03	0.000
RUN NO. 110131, ZPG-CW, 2.134 M STATION, NOL BALANCE										
1.036E+06	418.9	91.7	204.4	4.861	.2924	5.382E+04	3.716E+01	3.192E+01	8.368E-04	0.000
9.308E+05	424.4	91.7	204.4	4.908	.3047	4.834E+04	3.457E+01	2.957E+01	8.945E-04	0.000
8.274E+05	420.6	91.1	203.3	4.906	.3135	4.491E+04	3.198E+01	2.716E+01	9.22BE-04	0.000
7.239E+05	424.4	90.6	201.1	4.903	.3266	4.039E+04	2.891E+01	2.438E+01	9.448E-04	0.000
6.205E+05	426.7	90.0	198.3	4.899	.3415	3.596E+04	2.554E+01	2.133E+01	9.617E-04	0.000
5.171E+05	422.2	89.4	194.4	4.895	.3574	3.195E+04	2.223E+01	1.838E+01	9.912E-04	0.000
4.137E+05	427.2	89.4	190.0	4.887	.3819	2.650E+04	1.876E+01	1.540E+01	1.031E-03	0.000
3.103E+05	427.8	88.9	185.0	4.866	.4130	2.157E+04	1.487E+01	1.202E+01	1.056E-03	0.000
2.068E+05	432.8	88.9	180.0	4.859	.4643	1.621E+04	1.107E+01	8.885E+00	1.165E-03	0.000
1.034E+05	412.8	88.9	171.1	4.794	.5470	1.060E+04	7.206E+00	5.893E+00	1.469E-03	0.000
RUN NO. 110151, ZPG-CW, 2.286 M STATION, NOL BALANCE										
1.034E+06	426.7	91.7	212.8	4.823	.2989	5.424E+04	3.783E+01	3.223E+01	8.215E-04	0.000
9.308E+05	431.1	91.7	209.4	4.876	.3114	4.888E+04	3.457E+01	2.936E+01	8.664E-04	0.000
8.274E+05	422.2	91.7	206.7	4.868	.3186	4.612E+04	3.093E+01	2.597E+01	8.570E-04	0.000
7.239E+05	423.3	91.7	203.9	4.849	.3305	4.204E+04	2.785E+01	2.321E+01	8.624E-04	0.000
6.205E+05	421.7	91.1	200.6	4.857	.3450	3.771E+04	2.478E+01	2.047E+01	8.931E-04	0.000
5.171E+05	418.3	90.0	196.7	4.846	.3615	3.351E+04	2.137E+01	1.742E+01	9.041E-04	0.000
4.137E+05	418.3	88.9	192.8	4.846	.3851	2.856E+04	1.766E+01	1.412E+01	9.163E-04	0.000
3.103E+05	422.2	88.9	188.9	4.837	.4190	2.306E+04	1.405E+01	1.104E+01	9.481E-04	0.000
2.068E+05	422.2	88.9	183.9	4.820	.4691	1.733E+04	1.025E+01	7.901E+00	1.005E-03	0.000
1.034E+05	422.2	88.9	177.2	4.818	.5706	1.056E+04	6.263E+00	4.907E+00	1.246E-03	0.000

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TABLE A2 CORRECTED COLD-WALL SHEAR STRESS DATA OF REF. 2

PO N/M2	TO DEG.K	TW DEG.K	TDE DEG.K	RRW	THP CM	RTHRW	TAUW(UNC) N/M2	TAUW(CORR) N/M2	CF	BETACS
RUN NO. 202071, FPG-CW= 1.270 M STATION, NOL BALANCE										
1.032E+06	420.8	97.2	223.9	4.021	.1783	4.819E+04	9.495E+01	8.842E+01	1.181E-03	-.797
9.280E+05	423.3	97.8	227.2	4.006	.1830	4.440E+04	8.808E+01	8.159E+01	1.197E-03	-.789
8.274E+05	430.7	98.9	229.4	4.016	.1895	3.973E+04	8.255E+01	7.626E+01	1.266E-03	-.769
7.226E+05	427.8	97.8	229.4	4.015	.1953	3.615E+04	7.516E+01	6.904E+01	1.311E-03	-.755
6.219E+05	429.1	96.7	228.9	4.013	.2026	3.216E+04	6.753E+01	6.166E+01	1.358E-03	-.745
5.178E+05	422.2	96.7	226.1	4.017	.2106	2.846E+04	5.917E+01	5.370E+01	1.426E-03	-.729
4.116E+05	422.8	96.7	222.8	3.997	.2221	2.405E+04	5.056E+01	4.562E+01	1.499E-03	-.704
3.103E+05	425.6	95.6	216.7	3.996	.2382	1.927E+04	4.077E+01	3.650E+01	1.590E-03	-.692
2.068E+05	426.1	92.2	211.1	3.994	.2627	1.415E+04	3.016E+01	2.662E+01	1.736E-03	-.671
1.027E+05	417.8	87.8	200.6	3.949	.3069	8.654E+03	1.733E+01	1.496E+01	1.892E-03	-.652
RUN NO. 202031, FPG-CW= 1.778 M STATION, NOL BALANCE										
1.034E+06	426.1	112.2	227.8	4.423	.2330	5.086E+04	5.762E+01	5.199E+01	9.649E-04	-.762
9.284E+05	427.6	127.8	230.0	4.421	.2395	4.680E+04	5.260E+01	4.778E+01	9.845E-04	-.751
8.274E+05	423.3	117.8	231.1	4.423	.2455	4.333E+04	4.886E+01	4.367E+01	1.013E-03	-.737
7.205E+05	424.0	102.2	228.9	4.418	.2540	3.905E+04	4.475E+01	3.919E+01	1.039E-03	-.723
6.178E+05	422.2	138.9	227.2	4.415	.2633	3.457E+04	3.779E+01	3.408E+01	1.052E-03	-.720
5.171E+05	421.1	138.9	227.2	4.405	.2745	3.079E+04	3.265E+01	2.915E+01	1.066E-03	-.714
4.130E+05	422.9	105.6	222.8	4.409	.2907	2.582E+04	2.937E+01	2.509E+01	1.152E-03	-.674
3.096E+05	425.0	92.2	211.7	4.492	.3156	2.006E+04	2.417E+01	2.035E+01	1.333E-03	-.638
2.068E+05	426.1	91.7	203.3	4.372	.3440	1.540E+04	1.766E+01	1.462E+01	1.301E-03	-.609
1.034E+05	427.8	91.7	190.0	4.342	.4071	9.191E+03	1.052E+01	8.746E+00	1.520E-03	-.536
RUN NO. 202021, FPG-CW= 1.981 M STATION, NOL BALANCE										
1.034E+06	427.2	92.2	224.4	4.553	.2529	5.177E+04	5.439E+01	4.807E+01	9.898E-04	-.680
9.287E+05	427.8	94.4	222.8	4.540	.2595	4.789E+04	5.114E+01	4.518E+01	1.025E-03	-.663
8.274E+05	417.8	93.3	217.8	4.536	.2645	4.522E+04	4.780E+01	4.215E+01	1.070E-03	-.627
7.267E+05	424.4	94.4	215.6	4.550	.2753	4.007E+04	4.326E+01	3.803E+01	1.112E-03	-.616
6.205E+05	419.4	93.3	213.3	4.535	.2846	3.628E+04	3.797E+01	3.300E+01	1.116E-03	-.610
5.171E+05	423.3	92.2	208.9	4.531	.2988	3.134E+04	3.335E+01	2.883E+01	1.166E-03	-.589
4.102E+05	425.6	92.2	204.4	4.510	.3164	2.637E+04	2.770E+01	2.369E+01	1.189E-03	-.576
3.096E+05	424.2	92.2	200.0	4.517	.3393	2.138E+04	2.140E+01	1.797E+01	1.201E-03	-.583
2.062E+05	423.6	91.7	195.6	4.491	.3742	1.592E+04	1.566E+01	1.290E+01	1.268E-03	-.553
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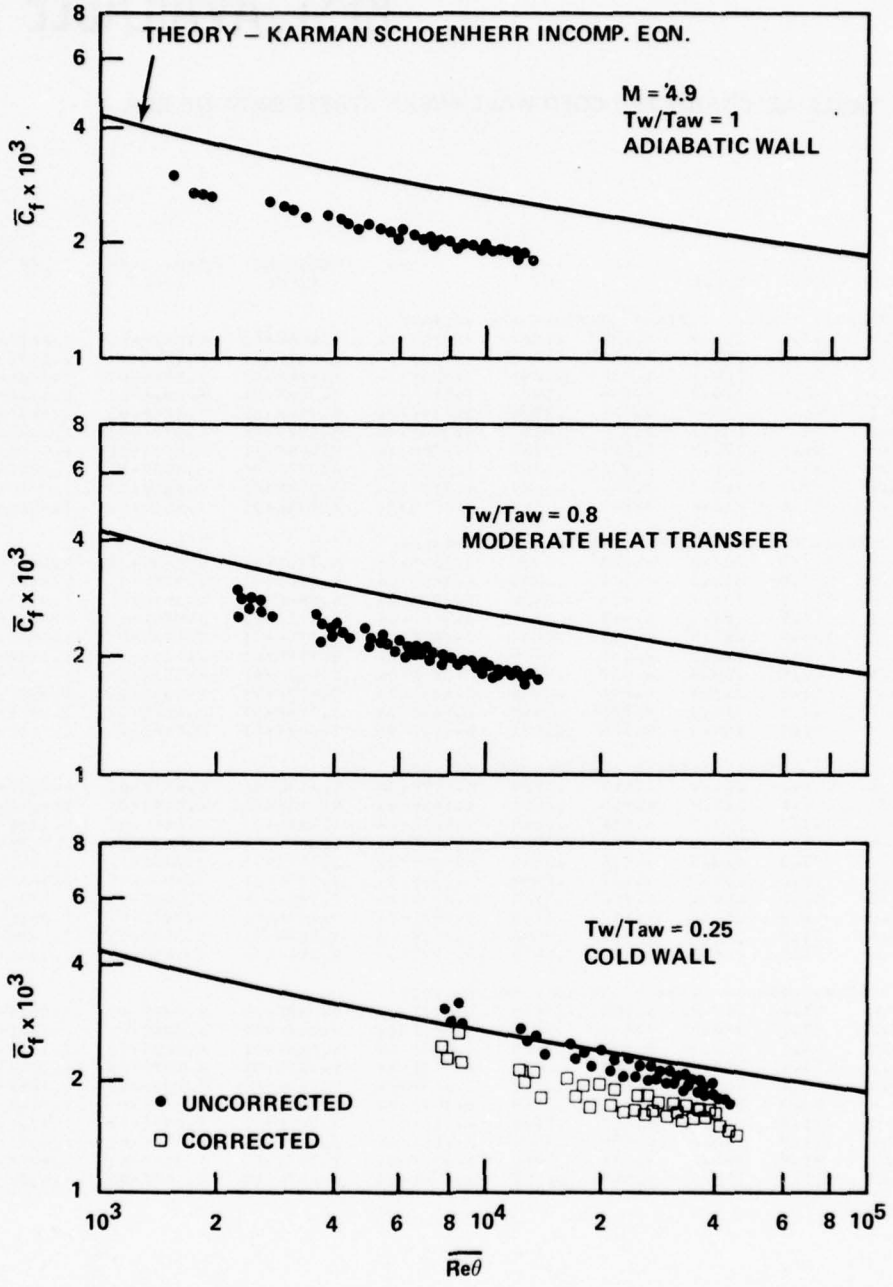

FIGURE A1 INFLUENCE OF TEMPERATURE STEP CORRECTION ON THE DATA OF REF. 1

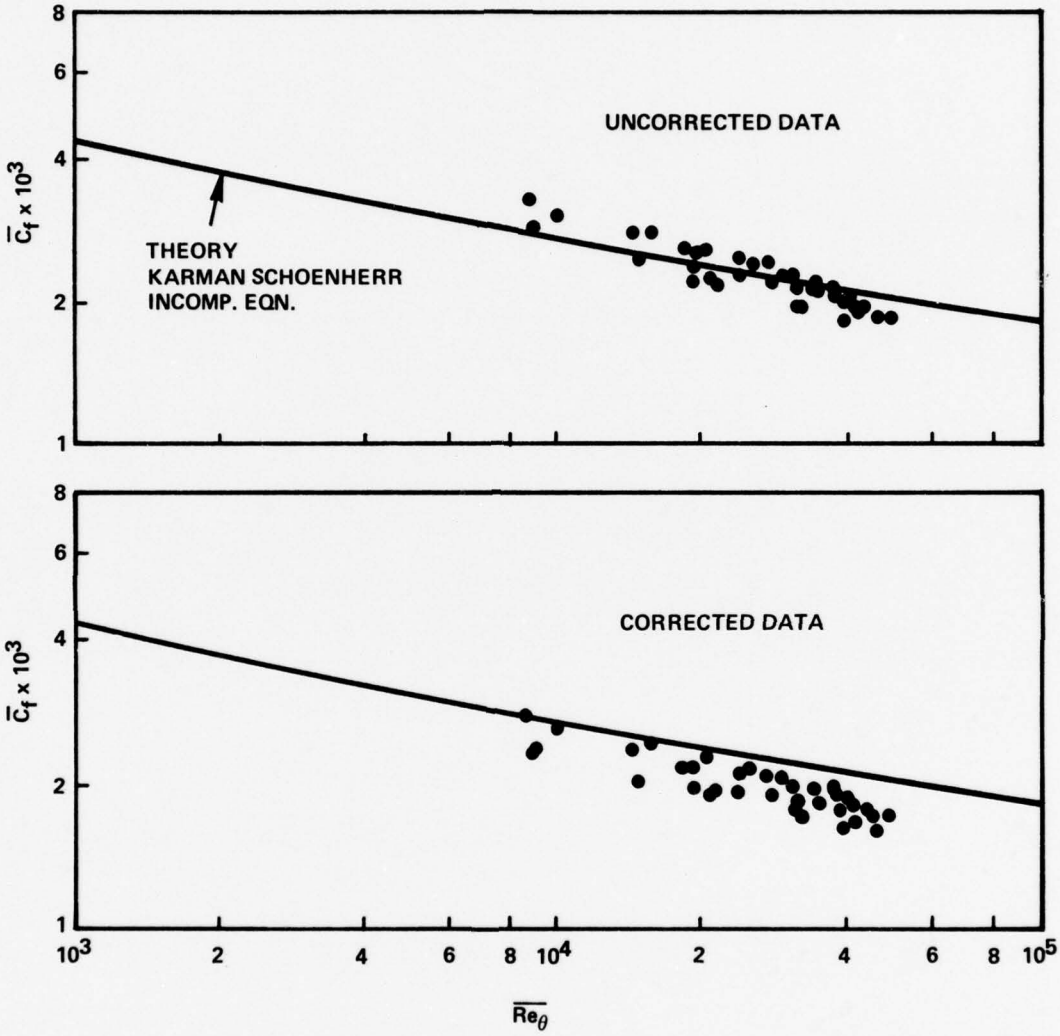

FIGURE A2 INFLUENCE OF TEMPERATURE STEP CORRECTION ON THE CW DATA OF REF. 2

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