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NEAR-WAKE FLOWFIELD MEASUREMENTS
(Task 2.2 Experimental Flowfields -- REST Program)

Prepared by

A. Todisco
A. Pallone

RESEARCH AND ADVANCED DEVELOPMENT DIVISION
AVCO CORPORATION
Wilmington, Massachusetts

Technical Memorandum
RAD-TM-65-21
Contract AF04(694)-687

THIS REPORT WAS PREPARED IN ACCORDANCE WITH AIR FORCE CONTRACT NUMBER AF04(694)-687. IT IS SUBMITTED IN PARTIAL FULFILLMENT OF THE CONTRACT AND IN ACCORDANCE WITH AFBM EXHIBIT 58-1 (PARAGRAPH 4.2.1).

5 May 1965

Prepared for

BALLISTIC SYSTEMS DIVISION
DEPUTY FOR BALLISTIC MISSILE REENTRY SYSTEMS
AIR FORCE SYSTEMS COMMAND
Norton Air Force Base, California

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APPROVED

A. J. Pallone, Manager
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FOREWORD

This report represents work performed by Avco Research and Advanced Development Division, 201 Lowell Street, Wilmington, Massachusetts, as part of Task 2.2 (Experimental Flow Fields) of the REST Program, Contract AF09(694)-687. The REST Program is part of the ABRES Program (627A) sponsored by the Air Force Ballistic Systems Division, Air Force Systems Command.

This technical report has been reviewed and is approved.

Lt. T. Swartz, REST Project Officer
BSYDM
Air Force Systems Command
Norton Air Force Base, California

ABSTRACT

Measurements of the stagnation temperature field behind a 10-degree half-angle wedge and a 10-degree half-angle cone have been made in the Avco RAD hypersonic shock tunnel at Mach 16 and stagnation temperature of 2400°K, using a constant temperature hot-wire anemometer. The effect of Reynolds number and wall-to-stagnation temperature ratios was investigated. Reynolds numbers of 5.7×10^4/ft and 4.8×10^5/ft and ratios of wall-to-stagnation temperature of 0.0325, 0.125, and 0.155 were used. Experimental results showing wake centerline stagnation temperatures and some transverse stagnation temperature profiles are presented. For both the cone and wedge, a region of constant temperature exists for a distance of 0.3 to 0.75 base diameters from the model base. This region of constant temperature is then followed by a region of increasing temperature typical of far-wakes. For the models tested, the stagnation temperature in the near-wake was found to decrease with increasing Reynolds number and to approach a limiting value as the ratio of wall-to-stagnation temperature approaches zero. These limiting values are a function of Reynolds number. Schlieren photographs show that the time for wake formation is of the order of 1 millisecond.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

Symbols

D	=	base dimension
L	=	characteristic length
M	=	Mach number
Nu	=	Nusselt number
P	=	static pressure
q_J	=	joule heating
q_K	=	conduction to the supports
q_R	=	thermal radiation
q_C	=	convection losses
R	=	resistance
Re	=	Reynolds number
T	=	temperature
T_w	=	local wire temperature
$\overset{()}{T_w}$	=	average wire temperature
Kn	=	Knudsen number
a	=	exit conditions
l	=	hot-wire length
r	=	radial distance measured from model centerline
s	=	distance along model surface measured from wedge vertex
x	=	coordinate along wake centerline normal to base
y	=	coordinate normal to wake centerline

NOMENCLATURE (Concl'd)

Symbols

z	=	distance along wire
α	=	coefficient of thermal resistance
λ	=	mean free path

Subscripts

o	=	reference conditions
n	=	neck region
r	=	recovery conditions
s	=	local stagnation conditions
w	=	wall condition
z	=	zero heat transfer
∞	=	free stream

ACKNOWLEDGEMENT

This work was supported by the Air Force Ballistic Systems Division under Contract AF04(694)-687. The authors wish to acknowledge the Experimental Gasdynamics personnel for their assistance in carrying out the experimental program.

I. INTRODUCTION

The flowfield in the vicinity of the base of a moving body has again become of great interest, currently from the point of view of detection, tracking, and discrimination. Although a great deal of literature exists about the mechanism of the near-wake and its gross properties (references 1-10), a satisfactory theoretical approach for the determination of the near-wake profiles (enthalpy, species, etc.) for general classes of bodies is not yet available. More recently, Reeves and Lees[11] have developed a promising technique which makes use of local similar solutions and have applied it to flows about cylinders, obtaining good agreement with available experimental data. Their method has not yet been generalized to slender bodies, however, although in principle it is capable of generating sufficient detail to enable one to obtain initial profiles required for far-wake studies (see reference 12).

Most experimental investigations have been restricted to base pressure measurements, and only recently have investigators begun to probe the near-wake for details. Conditions of particular interest generated by advanced hypersonic vehicles are extremely difficult to achieve. For example, ratios of wall-to-stagnation enthalpy on the order of 0. 03 to 0. 12 and Reynolds numbers from 10^5 to 10^7 are required for flight simulation. Recently, Muntz and coworkers[13, 14] have carried out experimental investigations in which spatial distributions of density and stagnation temperature were obtained in the laminar wake of a 10-degree half-angle cone. The tests were performed in a shock tunnel using a free-flight technique at Mach 12 and 18. An electron-beam excitation technique was used to measure the density and temperature. The data so far presented has been limited to ratios of wall-to-stagnation temperature greater than 0. 2. Additional near-wake experiments have been performed by Avco/RAD personnel in the Jet Propulsion Laboratory Mach-6 wind tunnel. The main contribution has been careful measurements of the axial distribution of stagnation and static pressure which show the existence of low subsonic flow in the recirculating region. Other recent measurements in the wake of a 10-degree half-angle cone in laminar flow at Mach 11. 5 were reported by Cresci.[15] Static and stagnation pressure and stagnation temperature were measured in the region of x/D of 1. 5 to 3. 3. Centerline pressure measurements and Mach-number distributions are presented in addition to pressure and temperature radial distributions at several values of x/D. Here again, the ratio of wall-to-stagnation temperature was greater than 0. 25. However, a recent communication with the author indicated that the ratio of wall-to-stagnation temperature has been lowered and additional measurements have been obtained.

Some laminar near-wake temperature measurements were presented earlier by the authors in reference 16. In the present paper, stagnation temperature measurements in the laminar wakes of a 10-degree half-angle wedge and a 10-degree half-angle cone model were obtained in a Mach 16 hypersonic shock tunnel by a constant temperature hot-wire anemometer technique for a range of wall-to-stagnation temperature ratios of 0.0325 to 0.155 and Reynolds numbers of 5.7×10^4/ft and 4.8×10^5/ft. The test gas was air. Schlieren photographs showing wake formation are also presented.

II. EXPERIMENTAL EQUIPMENT

A. SHOCK TUNNEL

All measurements were performed in the Avco/RAD 20-inch hypersonic shock tunnel. The shock tunnel utilizes a 1.5-inch diameter straight double-diaphragm shock tube to provide a working gas of high-stagnation enthalpy and pressure. This gas is expanded from a 0.2-inch diameter throat through a 7-degree half-angle divergent conical nozzle to a 20-inch diameter test section.

A raster display of the output from thin-film platinum gages at known locations along the shock tube indicated the speed of the incident shockwave. The pressure level behind the reflected shock was determined by a Kistler PZ-14 pressure transducer. In addition, a direct measurement of "reservoir" temperature was made with a fast-responding thermocouple which has been recently developed at Avco/RAD*. A typical oscillogram of the thermocouple trace is shown in figure 1. These measurements are sufficient to determine all other reflected shock region conditions. The shock tube was operated near tailored operation, resulting in steady "reservoir" conditions of approximately 5 milliseconds.

The free-stream Mach number was determined by measuring the total pressure in the tunnel test section. Thus, the flow parameters were fixed by knowing the total pressure and the shock-tube reflected region conditions. The shock tunnel was operated with a free-stream Mach number of 16, Reynolds numbers of 5.7×10^4/ft and 4.8×10^5/ft, and a stagnation temperature of 2400°K ± 50 degrees. A 12-inch diameter test core was available in the test section with no significant drop in total pressure occurring with distance downstream (approximately 17 inches from the "upstream end" of the test section).[17] Test time was on the order of 4 milliseconds, with approximately 1-millisecond nozzle starting time. Table 1 lists shock tunnel conditions.

TABLE 1

TUNNEL TEST SECTION

M_∞	Re_∞/ft	P_∞ psi	$T_{s\infty}$ °K	λ (cm)
16.0	5.7×10^4	6.25×10^{-4}	2400	0.0089
16.0	4.8×10^5	5.3×10^{-3}	2400	0.000945

* To be fully described in a forthcoming Avco RAD technical memorandum.

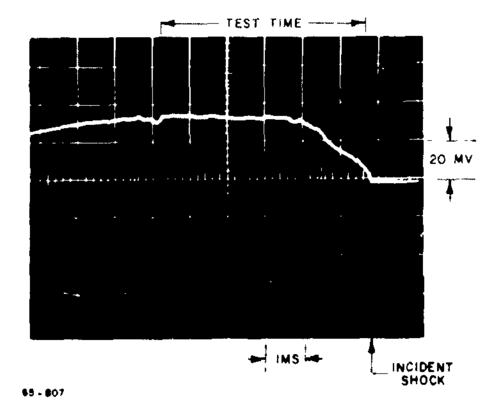

Figure 1 THERMOCOUPLE OSCILLOGRAM IN REFLECTED SHOCK REGION

B. MODELS

A 10-degree half-angle wedge with base height of 1.5 inches was used. The wedge was mounted to span the 12-inch test core. The wedge was constructed of 0.125-inch brass plates with a coolant feed and exhaust line mounted at the edges. Liquid nitrogen at 78°K and stream at 373°K were used as the working fluid to provide the various model temperatures. In order to check for uniformity in wall temperature, several thermocouples were inserted on the surface and base of the model. A photograph of the wedge in the test section with the hot-wire probe in measuring position is shown in figure 2.

A 10-degree half-angle cone with a base diameter of 3.26 inches was also tested. The cone was suspended with several 0.016-inch diameter wires. Check runs were also made with 0.025-inch diameter suspension wires to see if the support wires disturbed the flowfield. No noticeable effect was observed.* This type of suspension coupled with the fact that the tunnel static pressure, even for the higher pressure case, is low (5.3×10^{-3} psi) held the model firmly during the test time. This was confirmed by a comparison of no-flow and flow schlieren photographs. A photograph of the suspended cone with the hot-wire probe is shown in figure 3.

C. HOT-WIRE PROBE

A photograph of a typical hot-wire probe is shown in figure 4. The sensing elements were 0.00025 and 0.0004-inch diameter platinum-20-percent iridium wires.** Knudsen numbers, based on the wire diameter and free-stream density, varied from 0.93 to 14. However, it must be pointed out that Knudsen numbers based on local densities in the wake are larger by factors of 10 or more. Two wire lengths were used, 0.035 inch for the cone model and 0.08 inch for the wedge model. The wires were attached by welding to 0.01-inch diameter, 0.150-inch length copper-plated steel pin supports. The joints were also plated in order to minimize their electrical resistance. Because of the low pressure in the test section, wire breakage presented no problem, so that many runs could be obtained with the same wire. All new wires were heated to a dull glow and left there at this temperature for several minutes to eliminate any change in wire cold resistance from run to run.

The hot-wire probe was made as small as possible to eliminate any probe interference with the flowfield. The dimensions of the probe strut were 0.03 x 0.08 inch and entered the wake inclined at an angle. Schlieren photographs with the probe at three locations and a schlieren photograph without the probe in the wake of the wedge are shown in figure 5. Although the schlieren is not the most sensitive technique of detecting the effects of probes, it does give some assurance that the wake structure is essentially unchanged.

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* One may note that the boundary layer thickness for the highest Reynolds number is approximately an order of magnitude larger than the wire diameter. This may account for the negligible effect of wire interference.

** Sigmund Cohn Co., Mt. Vernon, New York.

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Figure 2 EXPERIMENTAL ARRANGEMENT IN THE TEST SECTION OF THE SHOCK TUNNEL SHOWING 10-DEGREE WEDGE MODEL AND HOT-WIRE PROBE

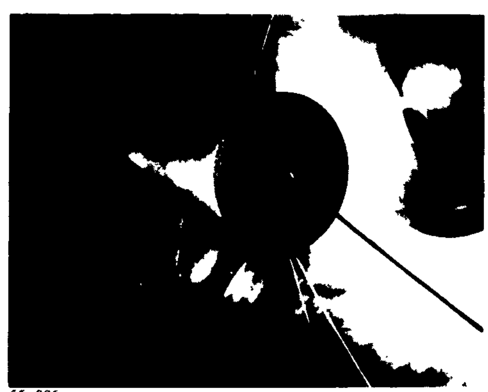

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Figure 3 EXPERIMENTAL ARRANGEMENT IN THE TEST SECTION OF THE SHOCK TUNNEL SHOWING 10-DEGREE CONE MODEL AND HOT-WIRE PROBE

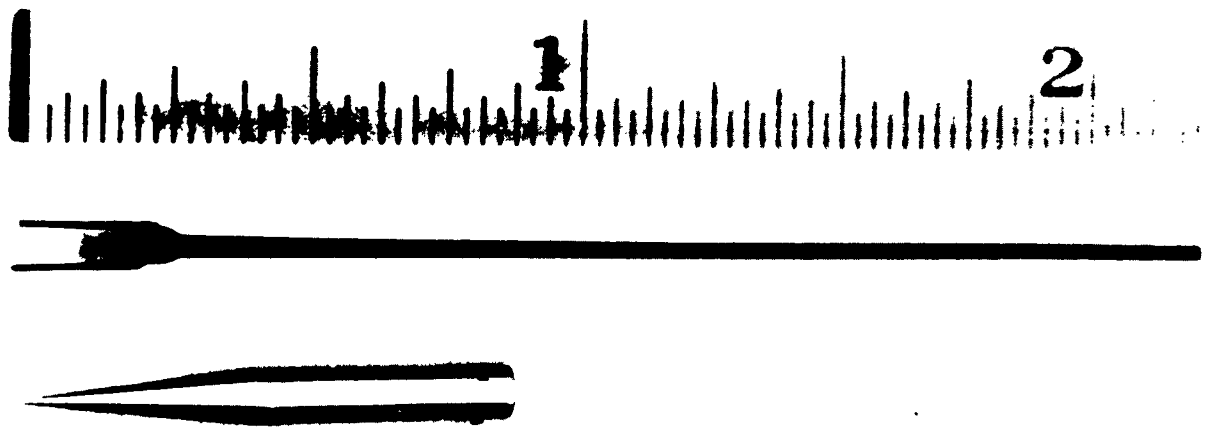

Figure 4 HOT-WIRE PROBE

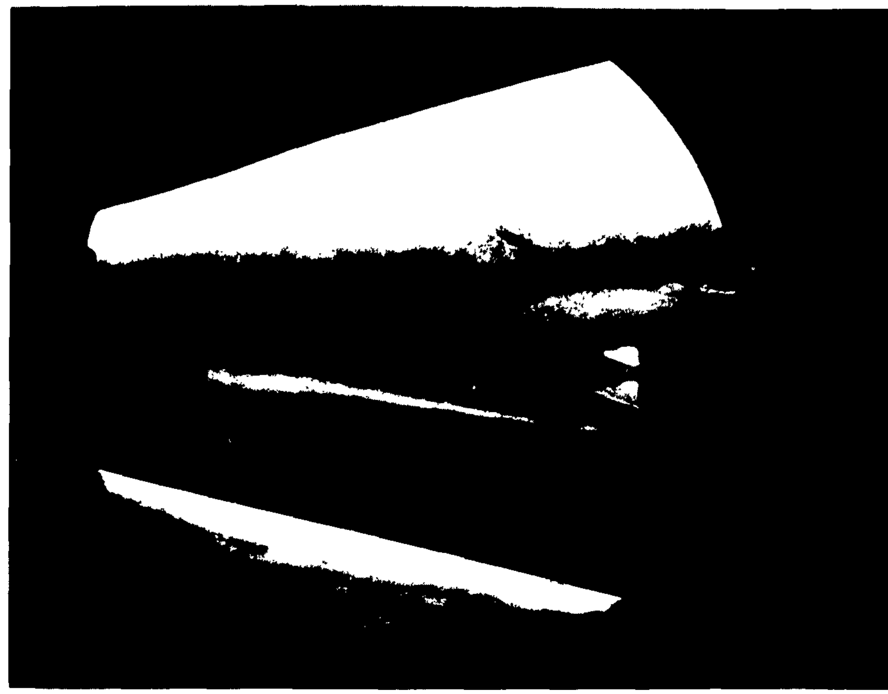

Figure 5a SCHLIEREN PHOTOGRAPH OF THE WAKE OF THE 10-DEGREE WEDGE FOR Re_∞/FT = 4.8 X 10^5

Figure 5b SCHLIEREN PHOTOGRAPH OF THE WAKE OF THE 10-DEGREE WEDGE FOR Re_∞/FT = 4.8 X 10^5, PROBE AT x/D = 0.333

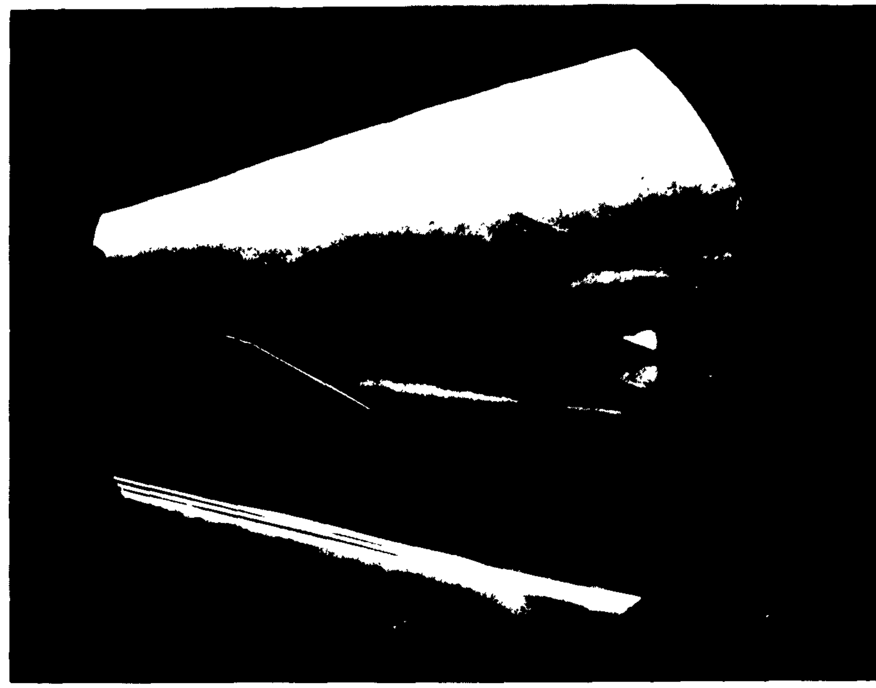

Figure 5c SCHLIEREN PHOTOGRAPH OF THE WAKE OF THE 10-DEGREE WEDGE FOR Re_{∞}/FT = 4.8 X 10^5, PROBE AT x/D = 0.667

Figure 5d SCHLIEREN PHOTOGRAPH OF THE WAKE OF THE 10-DEGREE WEDGE FOR Re_{∞}/FT = 4.8 X 10^5, PROBE AT x/D = 1.667

D. HOT-WIRE ANEMOMETER

A constant-temperature, hot-wire anemometer was used.* Measurement of the cold and operating resistance of the wire could be made with an accuracy of 0.5 percent. Response time of the hot-wire electronics varied from 15 to 100 microseconds depending on the chosen operating temperature. Constant-temperature operation minimizes the effect of thermal lag with the use of a null-seeking device. This is a loop system incorporating a bridge circuit, in which the hot wire forms one arm of the bridge, and a dc amplifier. Wire resistance, and hence temperature, is controlled by the amount of current flowing through the bridge. The bridge is fed by an amplifier whose input voltage is controlled by the bridge unbalance. There will be a condition of balance at which the bridge deviation is small because of the high loop gain. Therefore, the instrument will automatically adjust itself so that the desired temperature of the hot wire can be set by adjusting the resistance of the variable bridge arm.

* DISA Constant-Temperature Anemometer 55-A-01.

III. TEST TECHNIQUE

The hot-wire technique used in the present investigation requires the knowledge of the wire resistance when the integral of the convective heat transfer is zero. In order to ensure this, before the run one must require that the joulean heating will exactly balance the heat loss by conduction to the supports and the thermal radiation. Moreover, if the heat losses due to conduction and radiation remain a constant during the run (4 milliseconds), then the change in wire voltage (ΔW) is solely due to the convective heat transfer. Calculations show for 0.01-inch diameter supports in a shock tunnel with run times up to 6 milliseconds and conditions within the range of the present experiment changes of less than 1°K will occur in support temperature. In addition, changes in the local wire temperature are less than 2 percent of the average wire temperature. Thus, if one interpolates the voltage output to zero, then it follows that the integrated convective heat transfer is equal to zero. From the wire resistance at the point where $\Delta W = 0$ and the physical properties of the wire one can readily calculate an average wire temperature and show it to be equivalent to the recovery temperature.

The resistance of the wire at the point where $\Delta W = 0$ can be obtained with either a constant temperature or a constant current hot wire by operating the wire at various temperatures. If the constant temperature method is used, one plots the voltage output versus operating resistance and picks off the resistance at $\Delta W = 0$. For the constant current method, plotting voltage output versus operating current will yield the current (hence, resistance) at $\Delta W = 0$.

The difference between this technique and the previously used technique (see reference 18) is as follows. In reference 18, the wire resistance was obtained at zero-input current and an average equilibrium wire temperature was calculated from the wire properties. However, this average equilibrium wire temperature is not equal to the recovery temperature where the integrated convective heat transfer is equal to zero, but is the temperature obtained from the balance of the convection, conduction, and radiation-heat transfer. Therefore, the recovery temperature was determined by correcting the average equilibrium wire temperature for the conduction and radiation losses.

In the present paper, a constant temperature hot-wire technique was used. To find the wire resistance where $\Delta W = 0$, the hot-wire outputs were plotted against operating resistance. Figure 6 is a plot of probe outputs for one location. The intercept at zero output with the resistance axis determines the "zero heat-transfer" resistance. If the coefficient of thermal resistance is a constant for a given wire material over the testing range of temperatures, then the average wire temperature is given by the simple relation

$$R_z = R_0 \left[1 + \alpha (T_w - T_0) \right] \qquad (1)$$

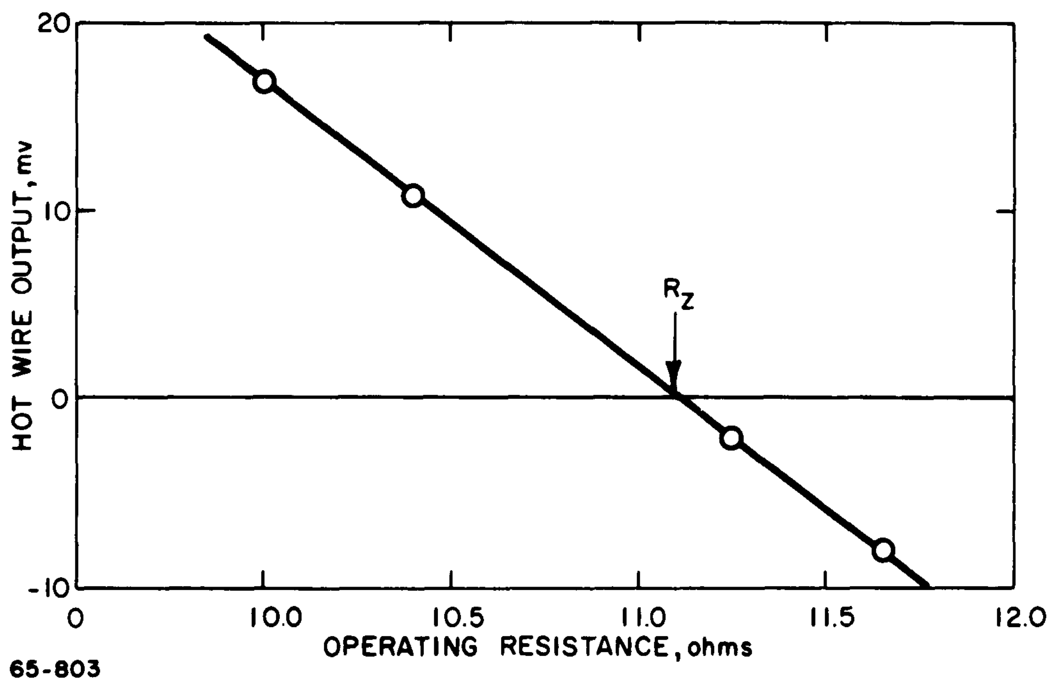

Figure 6 HOT-WIRE OUTPUT AS A FUNCTION OF OPERATING RESISTANCE

For our test conditions platinum -20-percent iridium wire was found to exhibit a constant coefficient of thermal resistance over a substantial temperature range. This coefficient was checked in a calibration oven. The resistance of the wire was found to be linear with temperature (see figure 7), so that a constant coefficient of thermal resistance could be used. If the coefficient of thermal resistance is nonlinear, however, the average wire temperature must be obtained by solving the nonlinear differential equation obtained by requiring a steady-state energy balance for an element of hot wire which is losing heat by conduction to the supports and by thermal radiation as follows:

$$q_J - q_K - q_R + q_C = 0 \tag{2}$$

This results in the following differential equation:

$$\frac{d^2 T}{dz^2} - \beta_2^2 T^4 + \beta^2 T + \beta_1^2 = 0 \tag{3}$$

where β^2, β_1^2, β_2^2 are coefficients involving the coefficient of thermal resistance, thermal conductivity, and emissivity. This equation can be solved using a standard "predictor-corrector method" on an IBM 7094 computer.*

A comparison between the two above methods of determining the average wire temperature was made for the platinum -20-percent iridium wire at one location. The temperature distribution obtained by solving the differential equation and the two values of average wire temperature are shown in figure 8. It is important to note that this difference in average wire temperature is about 8 percent. This is well within the uncertainties of knowing exactly the physical properties of the wire.

Typical oscillograms of hot-wire outputs at various operating resistances (hence, temperatures) for one centerline location are shown in figure 9. Note that as the temperature of the wire is increased the output drops, changing sign as the wire temperature is made higher than the local stagnation temperature. It is interesting also to note that the hot-wire output remains fairly constant most of the test time.

In order to show that the local stagnation temperature is approximately equal to the average wire temperature when the integrated convective heat transfer to the wire is zero, one may note that in free-molecule flow the convective heat transfer is

$$Q \sim (T_r - T_w) \qquad \text{(see reference 18)} \tag{4}$$

*A calibration technique may also be used if conditions of interest are available.

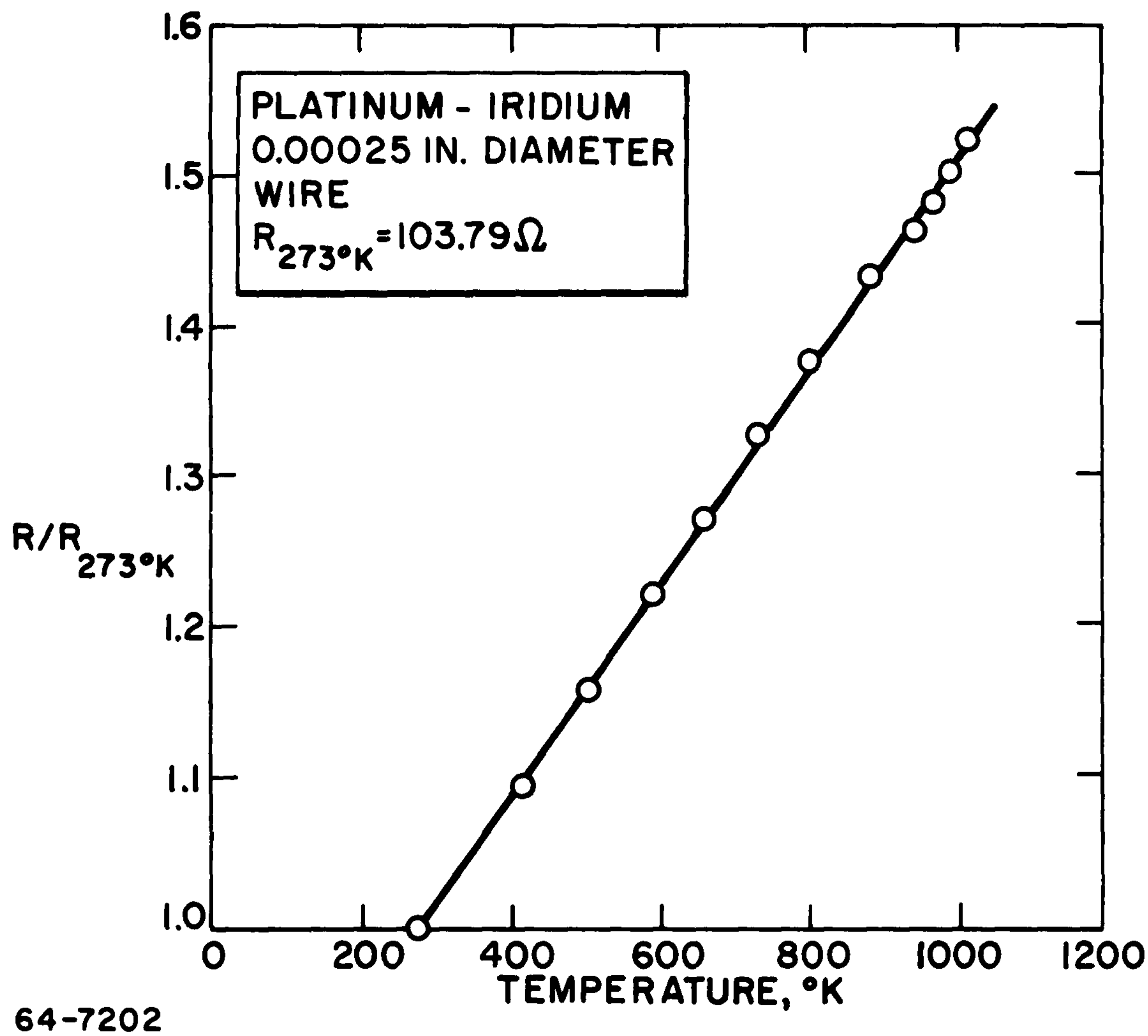

Figure 7 RESISTANCE RATIO AS A FUNCTION OF TEMPERATURE FOR PLATINUM-20-PERCENT IRIDIUM WIRE

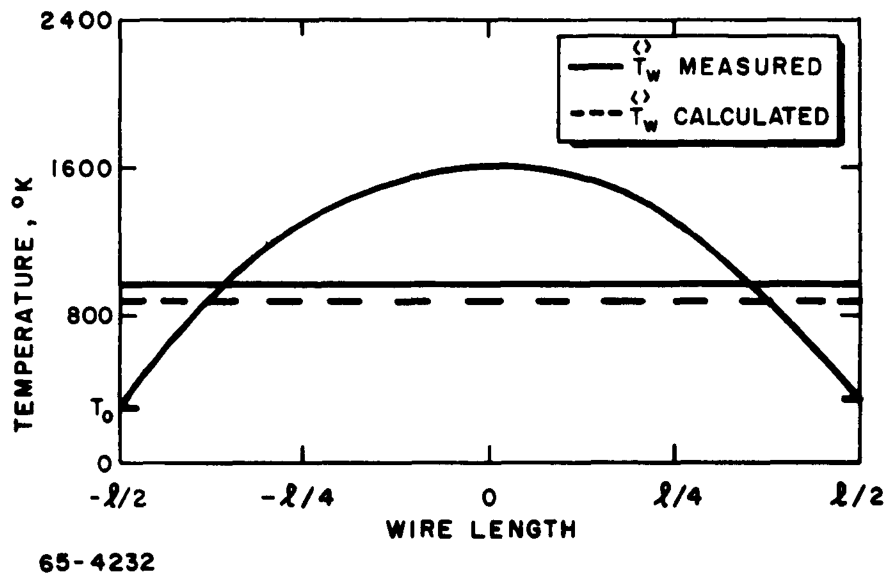

Figure 8 TEMPERATURE DISTRIBUTION OF PLATINUM-20-PERCENT IRIDIUM WIRE

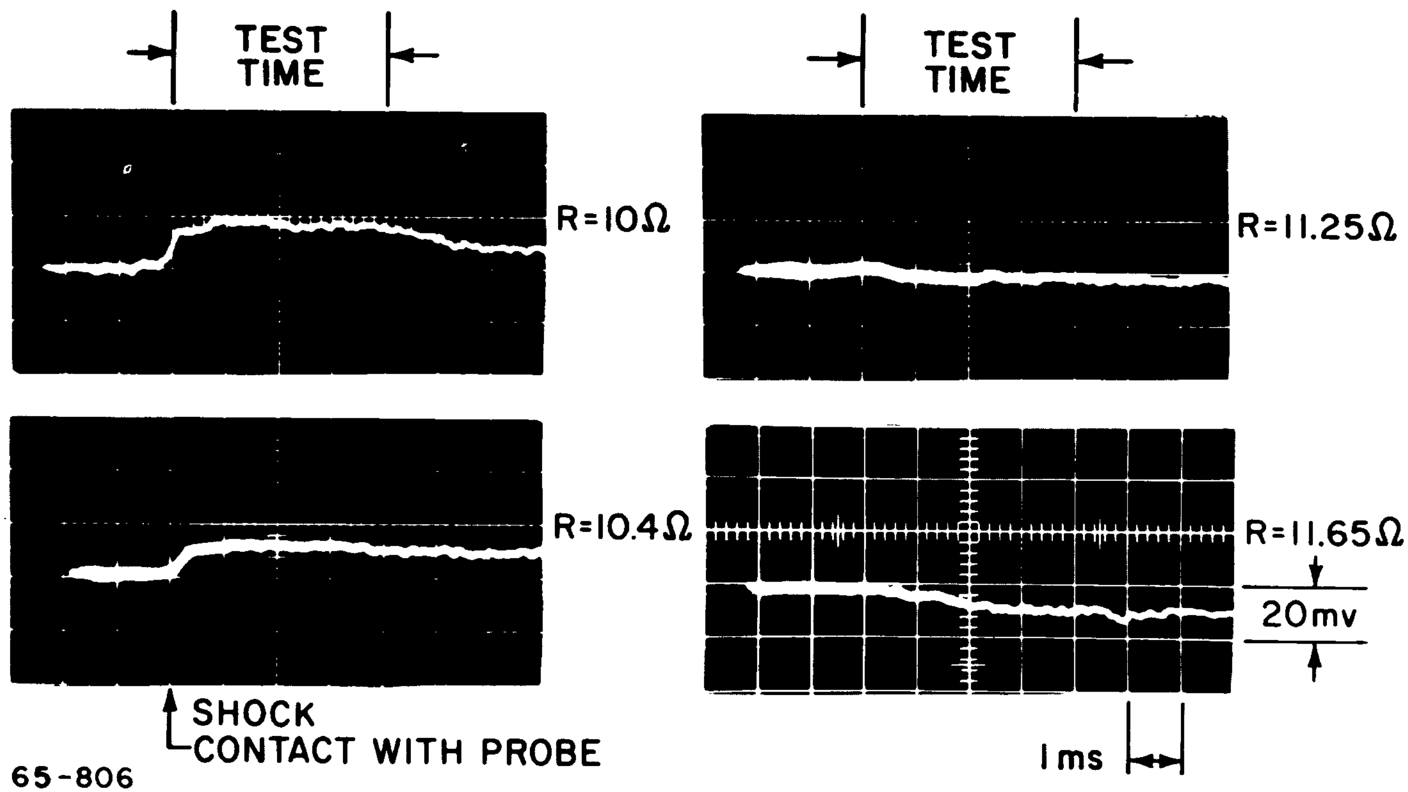

Figure 9 TYPICAL HOT-WIRE OSCILLOGRAMS

In our case the integral

$$\int_0^l Q\,dz = 0 \tag{5}$$

specifies the condition where "zero heat transfer" resistance is obtained. Then:

$$\int_0^l Q\,dz \sim \int_0^l (T_r - Tw)\,dz = 0 \tag{6}$$

If T_r is assumed constant* over the length of the wire (0.035 inch for the cone and 0.08 inch for the wedge), then the recovery temperature is equivalent to the average temperature of the wire

$$T_r = \frac{1}{l} \int_0^l Tw\,dz = \overset{\langle\rangle}{Tw} \tag{7}$$

Free-molecule flow theories and experiments show, however, that the recovery temperature of cylindrical wires depends on the Knudsen number as shown in figure 10 (see reference 20). For the present experimental conditions, an approximate correction to the centerline measured values can readily be made using a computed centerline Mach number (from reference 12). This correction is shown in figure 11. It is interesting to note that subsonic flow exists at the centerline for at least four base diameters (which is beyond the limits of present tunnel experiment). Moreover, similar tests conducted in the Jet Propulsion Laboratory wind tunnel indicate low subsonic flow in the recirculating region. Thus, negligible error is expected in the recirculating region, and a maximum error of 8 percent (if no corrections are applied) is expected for the highest Knudsen number and the farthest point on the centerline in the present tests. For the transverse profiles without correction, we can expect a maximum of 12-percent overestimate of the actual stagnation temperature for the point farthest from the wake centerline. These estimates were made from computed wake profiles. From figure 10, one can also observe

* For the conical model this dictates the maximum resolution of the measurement. However, for the wedge model the length is not critical because of the two-dimensionality of the flow.

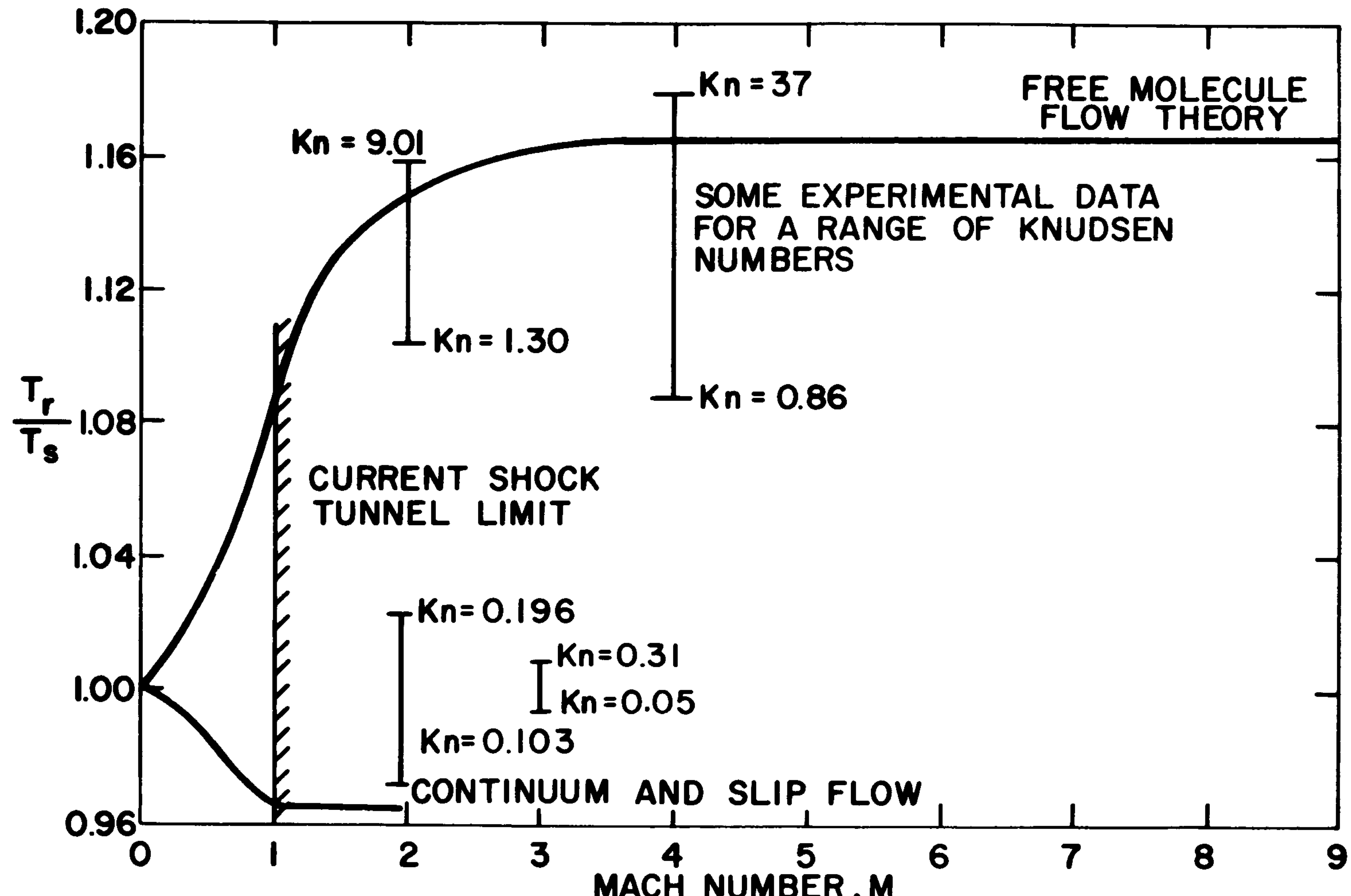

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Figure 10 RECOVERY TEMPERATURE RATIO AS A FUNCTION OF MACH NUMBER

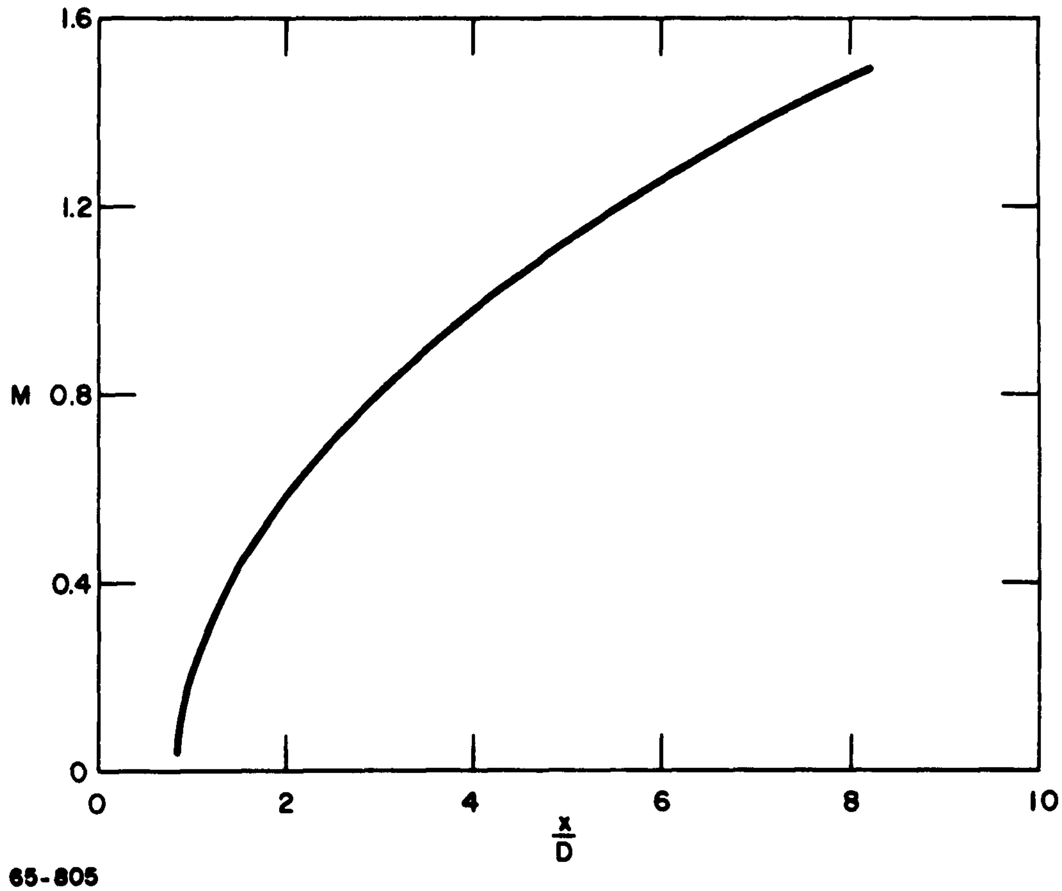

Figure 11 MACH NUMBER GRADIENT IN THE WAKE OF A 10-DEGREE HALF-ANGLE CONE

that for Knudsen numbers in the range 0.05 to 0.3 the recovery temperature of the wire is approximately equal to the stagnation temperature for all Mach numbers of interest. The capacity of the present hot-wire anemometer is limited to a certain resistance range (0-50 ohms) and current range (0-250 milliamperes), however, so that limited ranges of Knudsen numbers can be obtained.

A crude experimental check of the capabilities of the hot wire to measure the local stagnation temperature was made by measuring the temperature in the reflected region of a shock tube. A 1.5-inch-diameter shock tube with 20 feet of driven section and a 3-foot driver was used. The shock-tube gas temperature covered a large portion of the temperature range obtained in the tunnel. Measured hot-wire temperatures are shown on the plot of reflected region equilibrium temperature for air as a function of shock Mach number in figure 12. The hot-wire technique indicated the reflected region temperature[21] to within 10 percent. This agreement is, in fact, as good as one can expect considering the uncertainty of the calculation. Thermocouple measurements for the same conditions were not available due to limited test time for these nontailored conditions (very low-shock Mach numbers).

Schlieren photographs of the wake behind the wedge have also been obtained to assure flow formation within the testing time. Typical schlieren photographs using a double-pass schlieren system at 3 milliseconds into the flow and at $Re_\infty = 4.8 \times 10^5$/ft. were shown in figure 5. Similar schlierens were obtained down to 1 millisecond after the tunnel started. Additional evidence of steady flow after 1 millisecond can also be observed from the hot-wire traces.

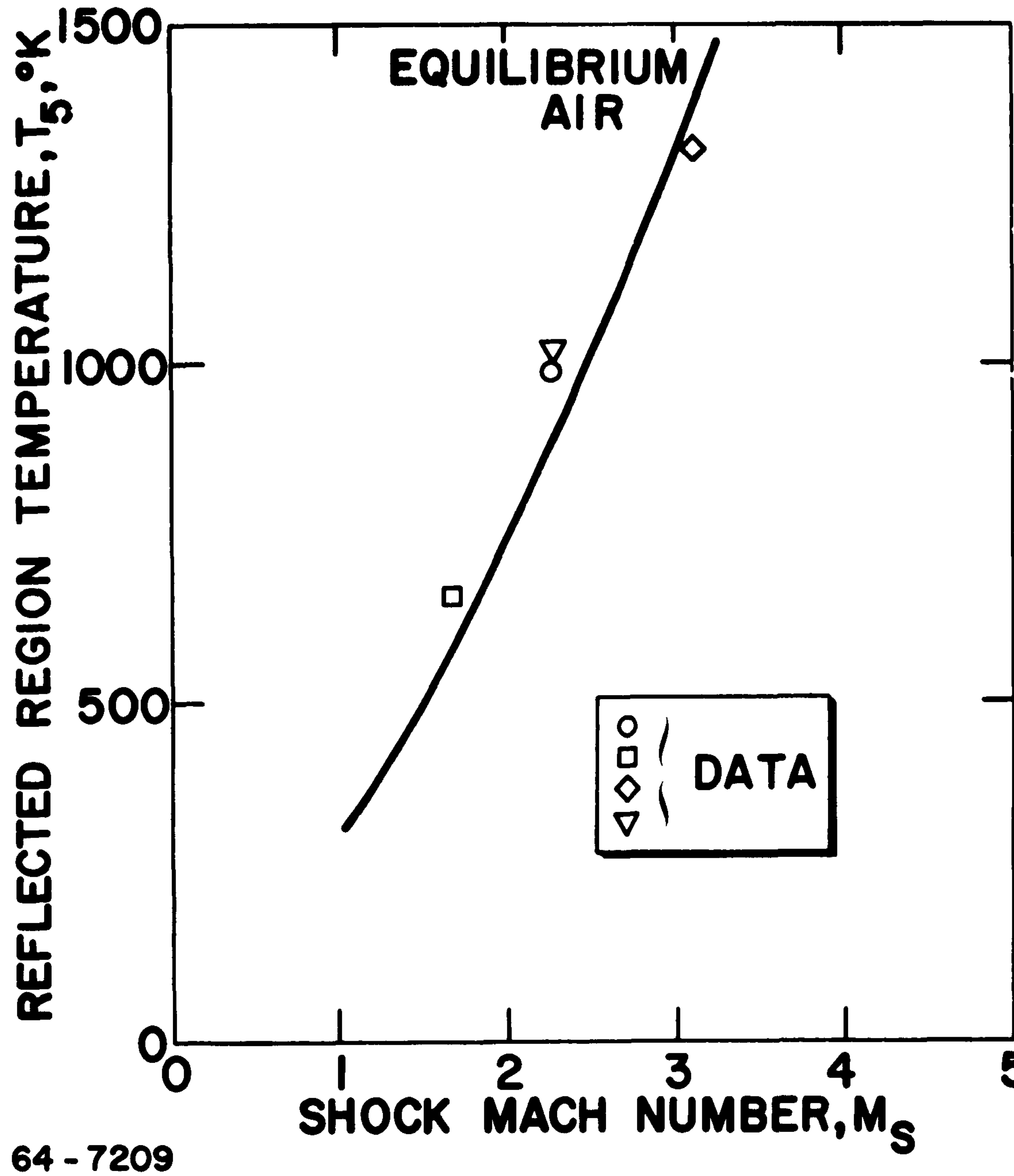

Figure 12 PLOT OF REFLECTED REGION GAS TEMPERATURE VERSUS SHOCK MACH NUMBER

IV. RESULTS AND DISCUSSION

In order to extend the results of the present experiment to flight and other laboratory conditions and to geometrically similar bodies, these measurements must be interpreted in terms of suitable parameters. In the literature on wakes, several parameters governing the base flowfield have been proposed (see references 2, 22, 23, 24). The more appealing parameters have been based on shoulder or exit conditions (see reference 24), i.e., based on the properties as the flow turns parallel to the model axis, such as Ma and Rea. In addition, for slender bodies the characteristic length is taken as the wetted distance from the leading edge. This length scale, although deemed reasonable by the authors, is by no means unique. For example, reference 2 has successfully used the base diameter as the characteristic length. In that case, however, only blunt bodies were treated where the ratio of L/D was of order 1.

The ratio of the wake centerline temperature to the free-stream stagnation temperature for distances from the wedge base from 0.1 D to 3.5 D is shown in figure 13 for two Reynolds numbers. The ratio of wall-to-free-stream stagnation temperature is 0.125. It is interesting to note that a substantial Reynolds number effect exists. In the recirculating region (extending to approximately 0.75 base diameters) for Rea = 2.05×10^4 the temperature approaches a level between 0.275 $T_{s\infty}$ and 0.29 $T_{s\infty}$ while for Rea = 1.73×10^5 the temperature level is between 0.215 $T_{s\infty}$ and 0.225 $T_{s\infty}$. From the stagnation point downstream, one notes the typical far-wake stagnation temperature characteristics (see reference 12). Note also that the Knudsen number based on the wire diameter has a relatively small effect on the measured temperature, as was discussed in the previous section. This can be explained as being due to the low Mach number, and confirms our previous discussion on the probable error due to Knudsen number effect.

The effect of the wall-to-free-stream stagnation temperature ratio is shown in figures 14 and 15. For the wedge, liquid nitrogen under pressure at 78°K provided the lower wall temperature. A drop of 20 percent in temperature in the recirculating region is associated with this wall temperature. Additional wall-temperature effects on the temperature of the recirculating region can be seen from figure 16, where the wedge model was heated to 373°K. This figure can be readily extrapolated to obtain limiting values of $T_{sn}/T_{s\infty}$ as T_w approaches zero. These values are a function of Reynolds number and are approximately 0.15 and 0.2 for Rea = $1.7^3 \times 10^5$ and 2.05×10^4, respectively.

The ratio of wake centerline temperature to the free-stream stagnation temperature for distances from the cone base of 0.1 D to 2.5 D is shown in figure 17. The ratio of wall-to-stagnation temperature is 0.125. The length of the recirculating region is roughly the same as for the wedge. However, the temperature level is definitely higher and again a Reynolds number effect

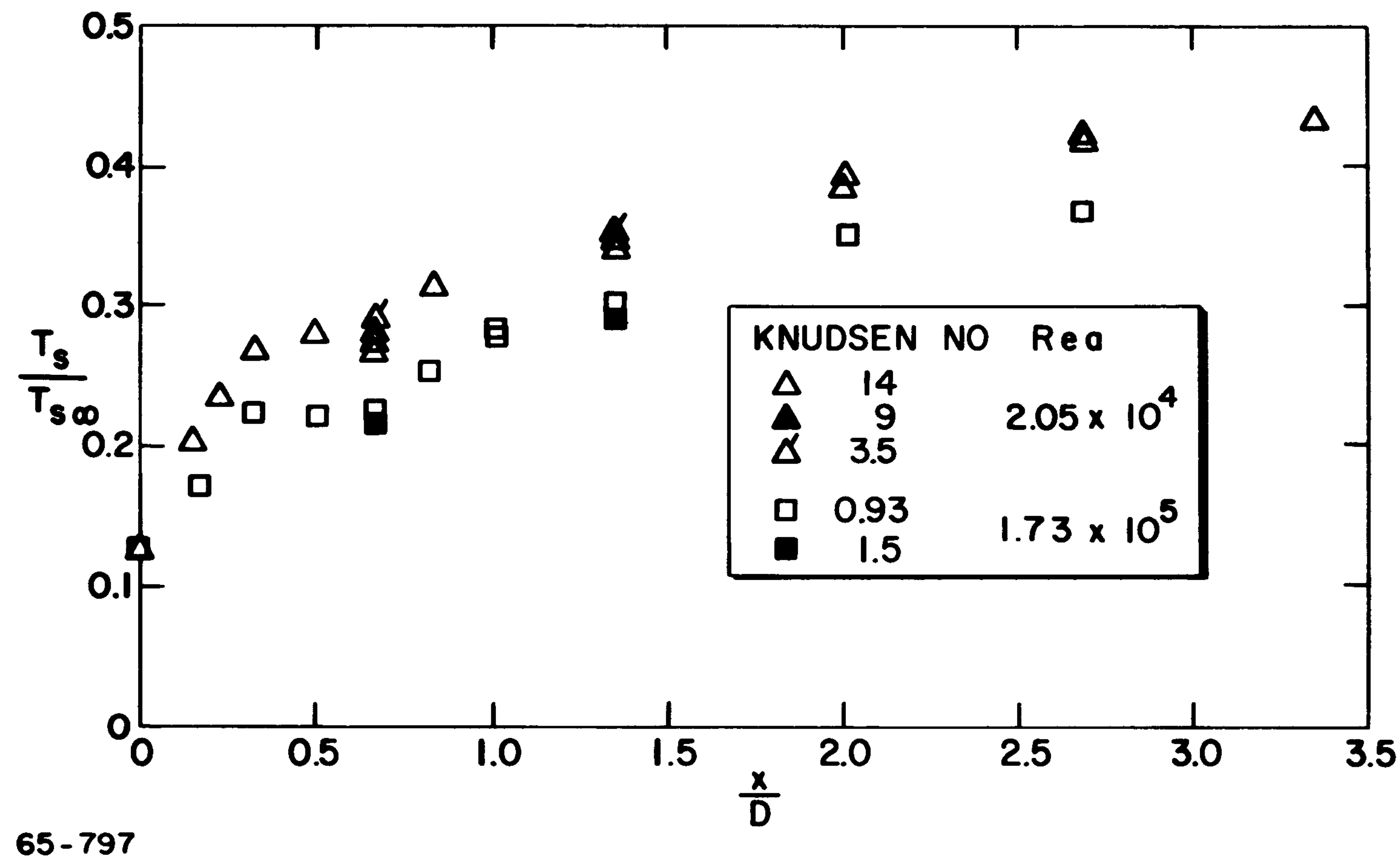

Figure 13 CENTERLINE TEMPERATURE IN THE WAKE OF A 10-DEGREE HALF-ANGLE WEDGE FOR $T_w/T_{s\infty} = 0.125$

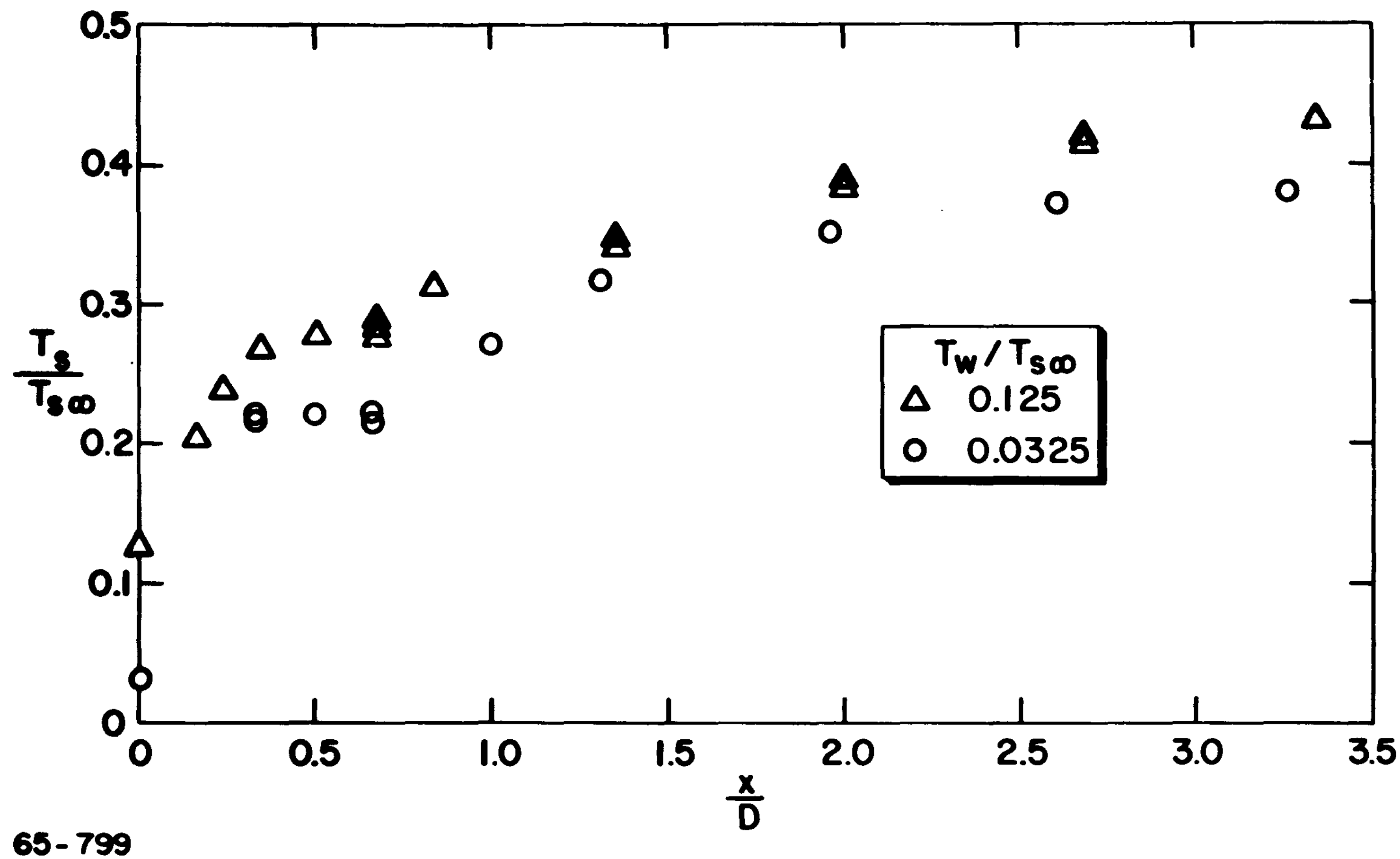

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Figure 14 CENTERLINE TEMPERATURE IN THE WAKE OF A 10-DEGREE HALF-ANGLE WEDGE FOR $Re_a = 2.05 \times 10^4$

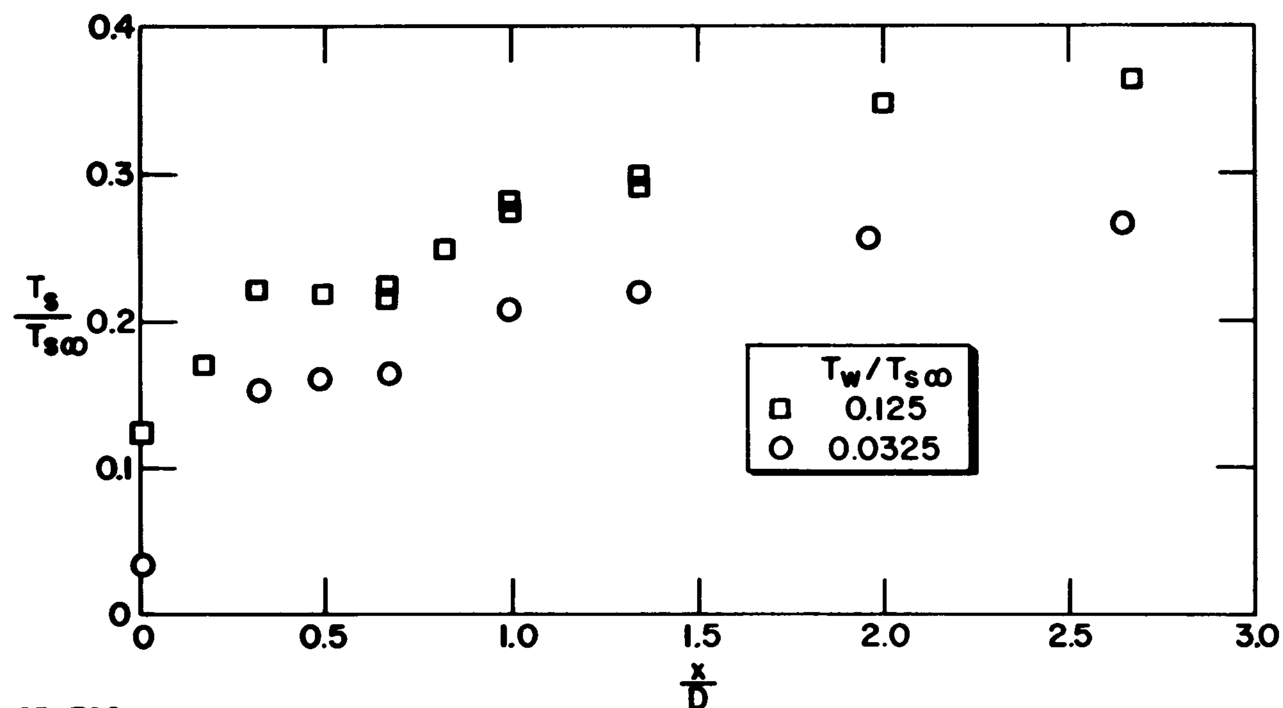

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Figure 15 CENTERLINE TEMPERATURE IN THE WAKE OF A 10-DEGREE HALF-ANGLE WEDGE FOR $Re_a = 1.73 \times 10^5$

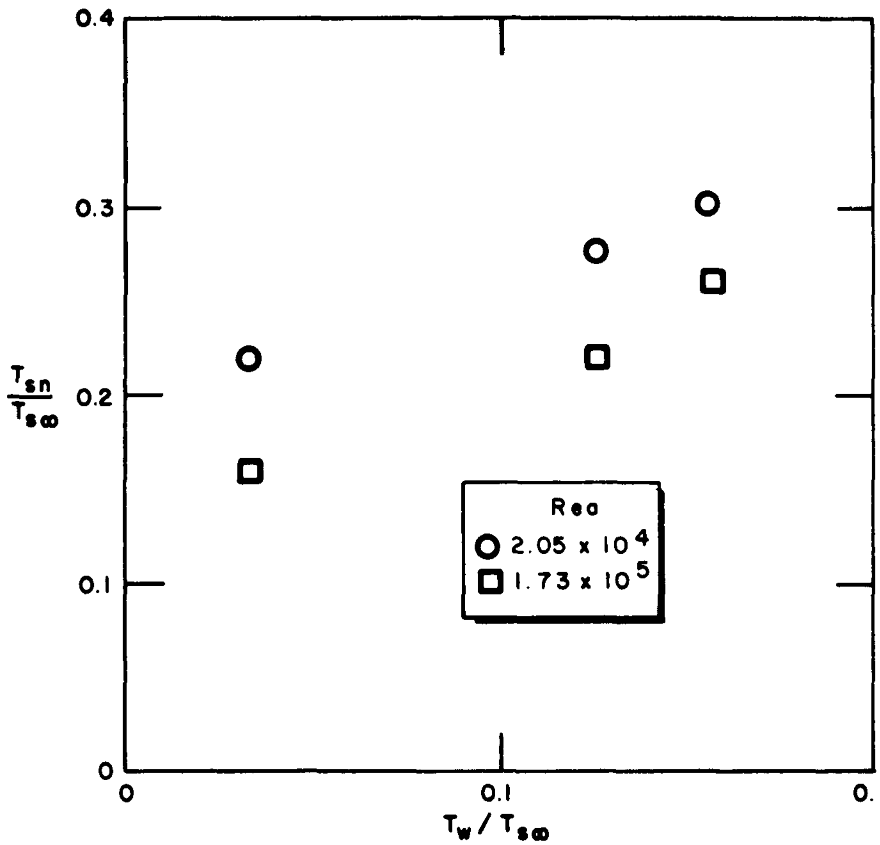

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Figure 16 WAKE-NECK TEMPERATURE AS A FUNCTION OF WALL TEMPERATURE FOR A 10-DEGREE HALF-ANGLE WEDGE

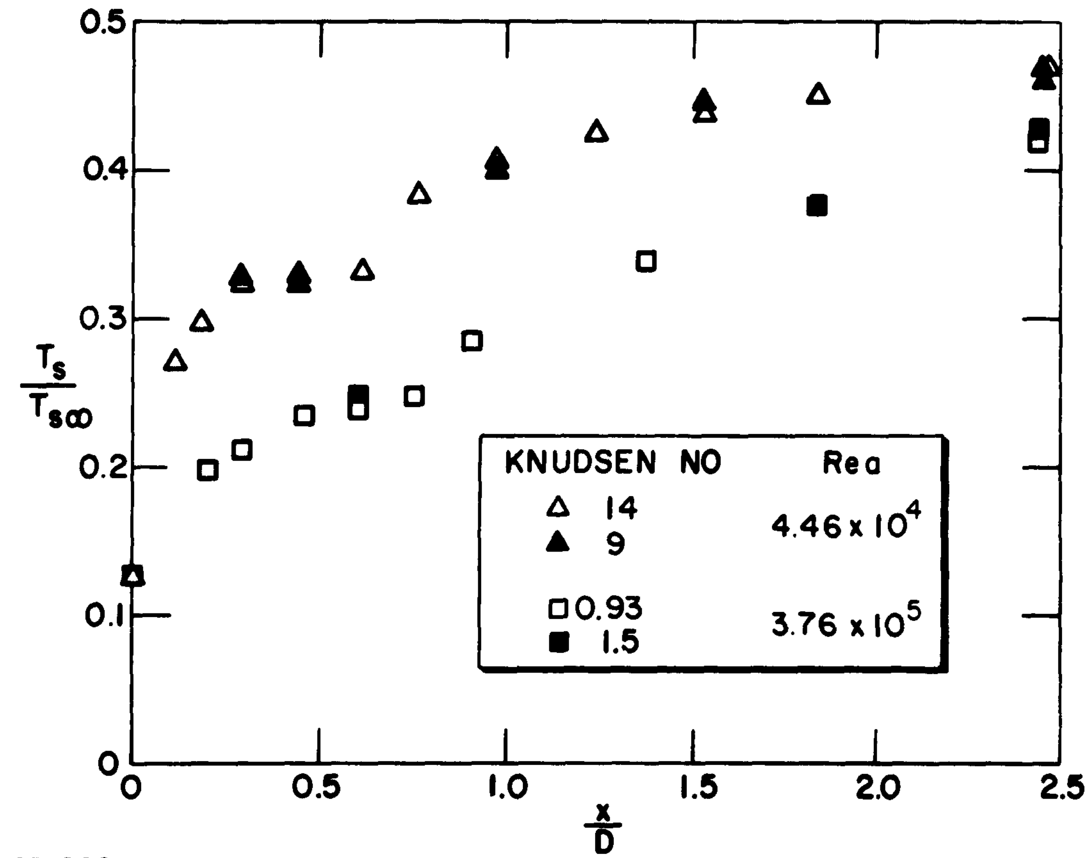

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Figure 17 CENTERLINE TEMPERATURE IN THE WAKE OF A 10-DEGREE HALF-ANGLE CONE FOR $T_w/T_{s\infty}$ = 0.125

exists. In the recirculating region for $Re_a = 4.46 \times 10^4$, the temperature level is between $0.32\ T_{s\infty}$ and $0.33\ T_{s\infty}$, while for $Re_a = 3.76 \times 10^5$ the temperature level is between $0.23\ T_{s\infty}$ and $0.24\ T_{s\infty}$. The negligible effect of Knudsen number may again be noted.

Variation of the base configuration from an abrupt (flat base) to a more gentle expansion had no effect on the temperature level. However, translation of the axial distribution was noted. This result tends to confirm the choice of shoulder parameters.

Transverse temperature profiles in the wake of the wedge model at one location are shown in figure 18 for $x/D = 0.645$. The temperature gradient seems to exist well outside the viscous wake that one observes from schlieren photographs. The external gradients in stagnation temperature may be a result of rapid expansion and compression as the boundary layer separates from the body and forms a wake.

Transverse temperature profiles in the wake of a cone at two locations (x/D = 0.609 and 1.75) are shown in figure 19. One may note that these profiles are similar to those observed for the wedge when plotting stagnation temperature as a function of y/r.

Unfortunately direct comparison with other available experimental data for slender bodies, such as that obtained by Muntz and coworkers (references 13, 14) and Cresci (reference 15), cannot be made because of the difference in test conditions, i.e., Mach number and wall-to-stagnation temperature ratio. However, an examination of their temperature data shows rough agreement with the temperature levels obtained in the present investigation and reveals a similar Reynolds number and wall-to-stagnation temperature dependence.

Preliminary stagnation temperature measurements were obtained in another Avco/RAD shock tunnel at $M_\infty = 5.5$, $Re_\infty = 8.71 \times 10^6/\text{ft}$, and $T_w/T_{s\infty} = 0.231$ in the near-wake of a 10-degree half-angle wedge. The shock tunnel consists of a 4-inch diameter shock tube terminated by a contoured nozzle with a 30-inch diameter test section. A 25-inch diameter test core was available in the test section.*

Thin-film, heat-transfer gages were located along the surface of the wedge. The heat-transfer distribution is shown in figure 20. The data agrees reasonably well with the turbulent theoretical prediction of the flat-plate reference enthalpy method described in reference 25. Thus, a turbulent boundary layer is present for all locations on the wedge surface where heat transfer was measured.

* A complete description of this facility will be made in a future Avco/RAD Technical Memorandum.

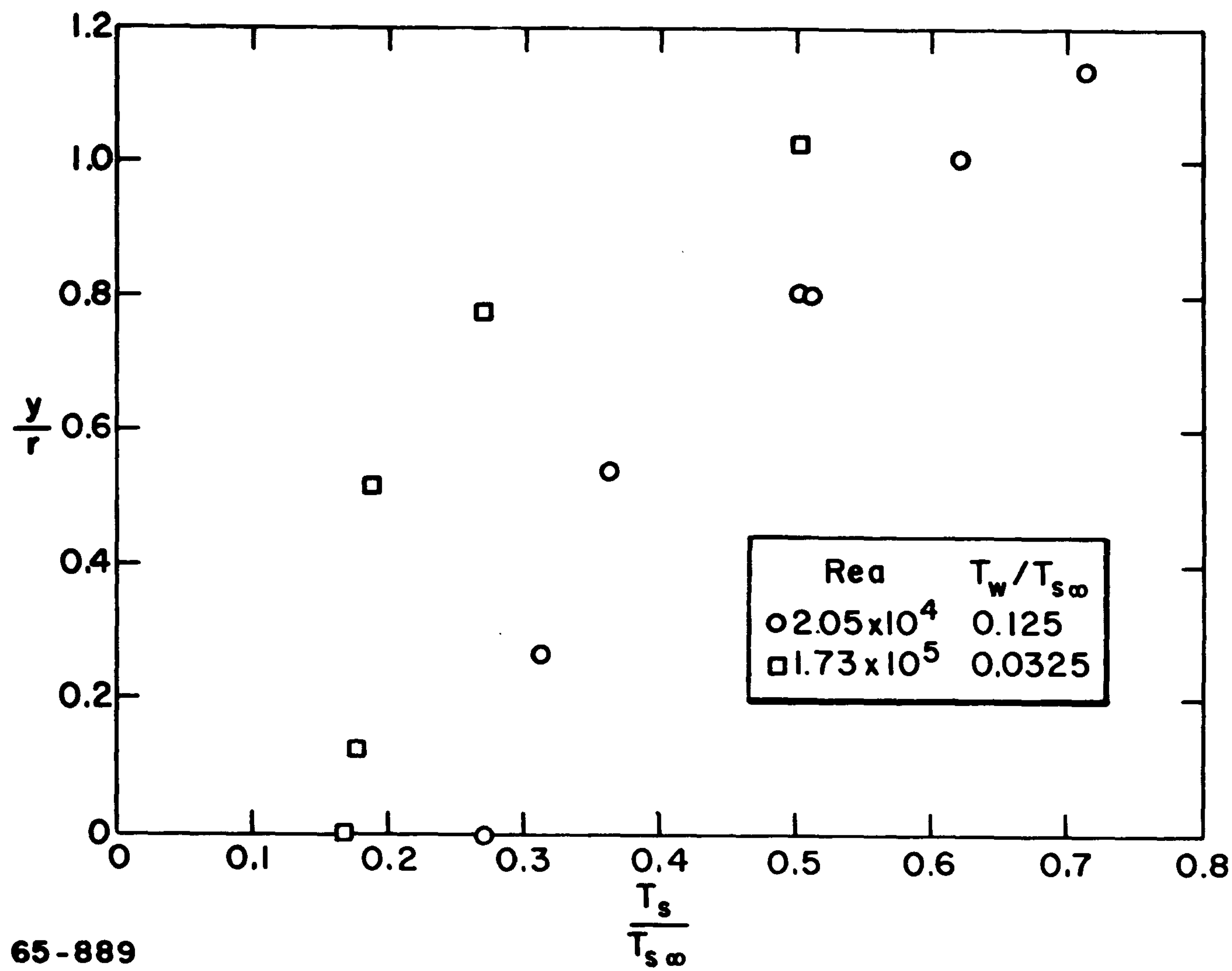

Figure 18 TRANSVERSE TEMPERATURE PROFILE IN THE WAKE OF A 10-DEGREE HALF-ANGLE WEDGE AT x D = 0.645

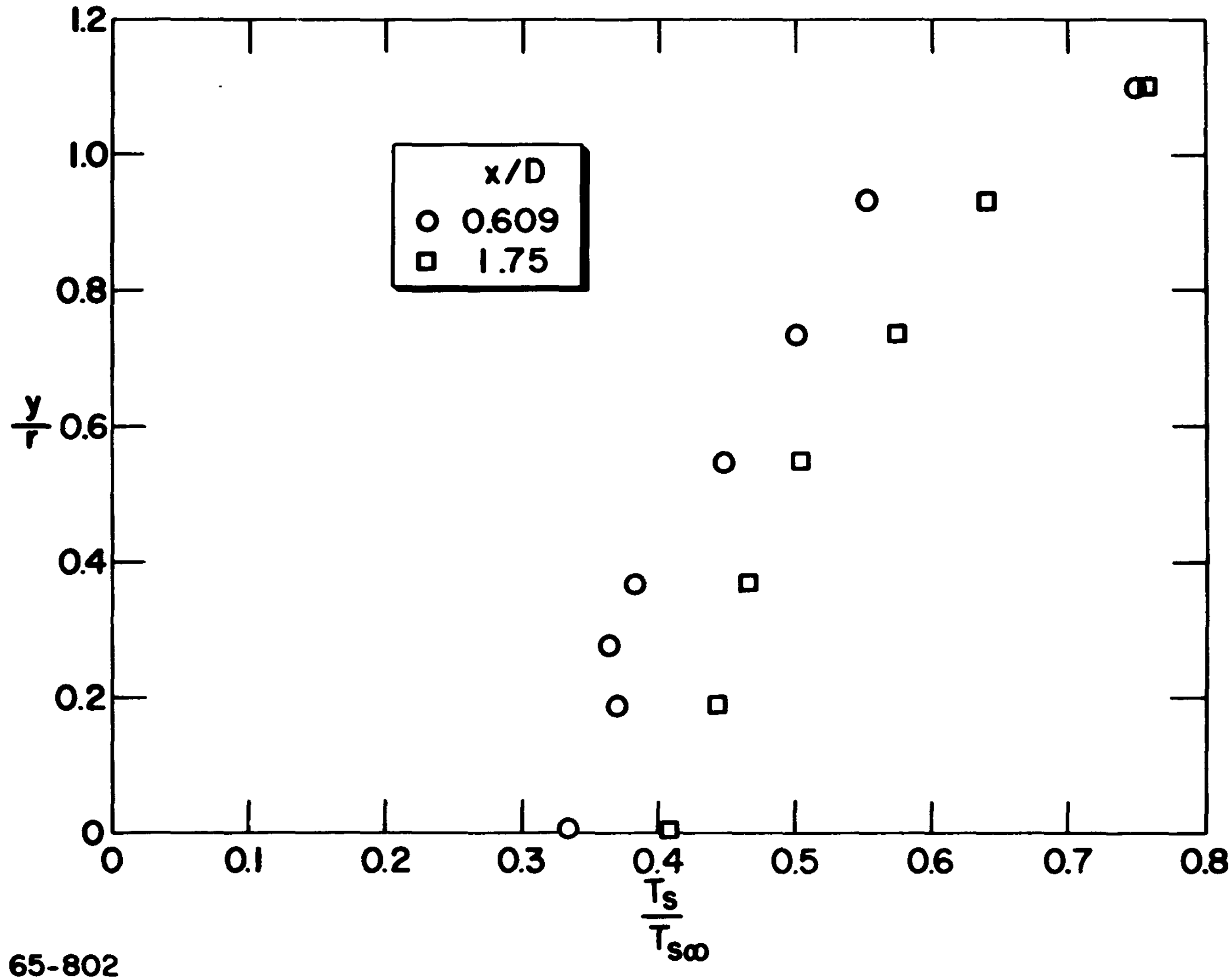

Figure 19 TRANSVERSE TEMPERATURE PROFILE IN THE WAKE OF A 10-DEGREE HALF-ANGLE CONE FOR $Re_d = 4.45 \times 10^4$, $T_w/T_{s\infty} = 0.125$

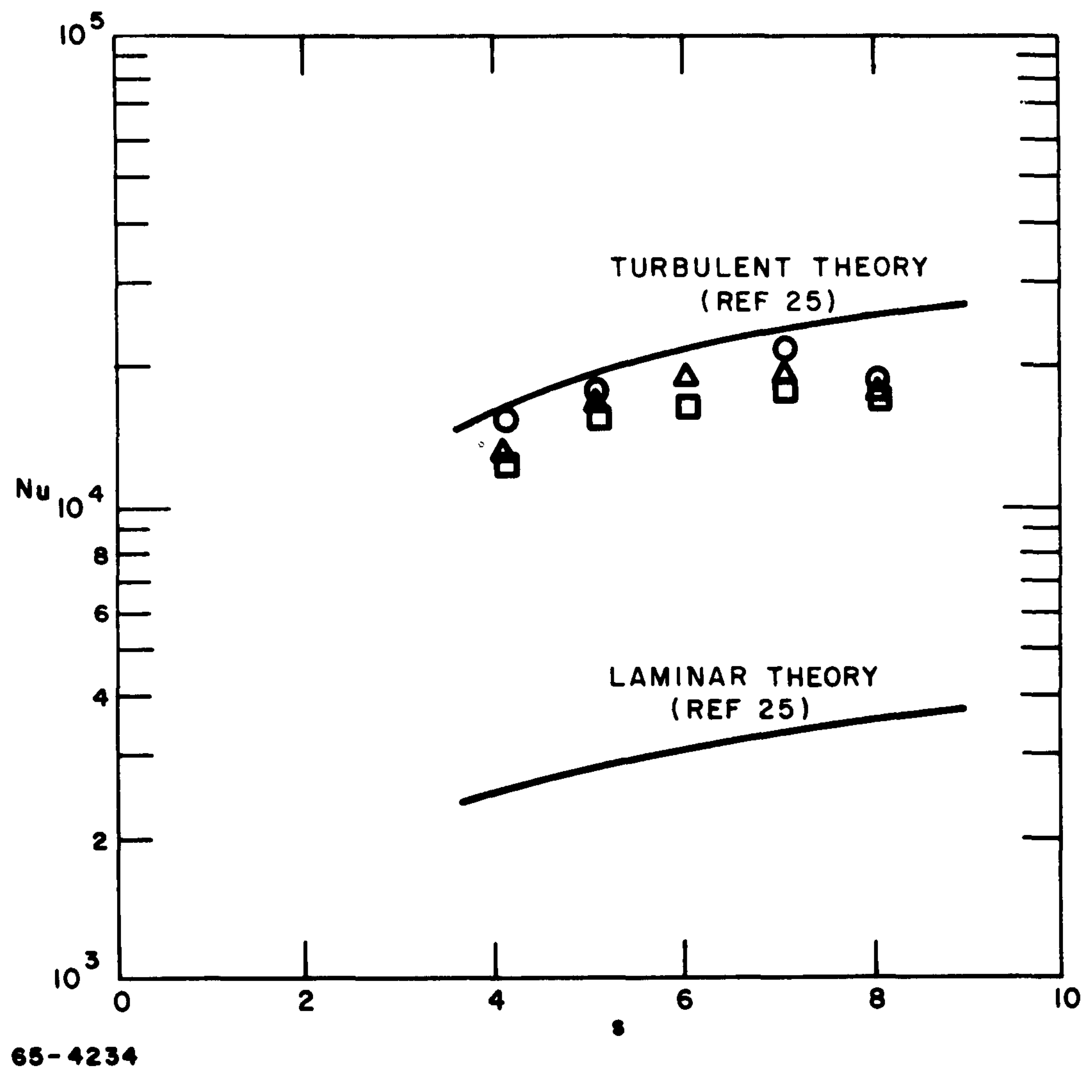

Figure 20 SURFACE HEAT-TRANSFER DISTRIBUTION $M_\infty = 5.5$, $Re_\infty = 8.71 \times 10^6$/FT

The ratio of the wake centerline temperature to the freestream stagnation temperature at several locations from the wedge base is shown in figure 21. One may note that in going from a laminar to a turbulent boundary layer the stagnation temperature has increased substantially. Additional measurements are being made at other Mach numbers, Reynolds numbers, and wall-to-stagnation temperature ratios.

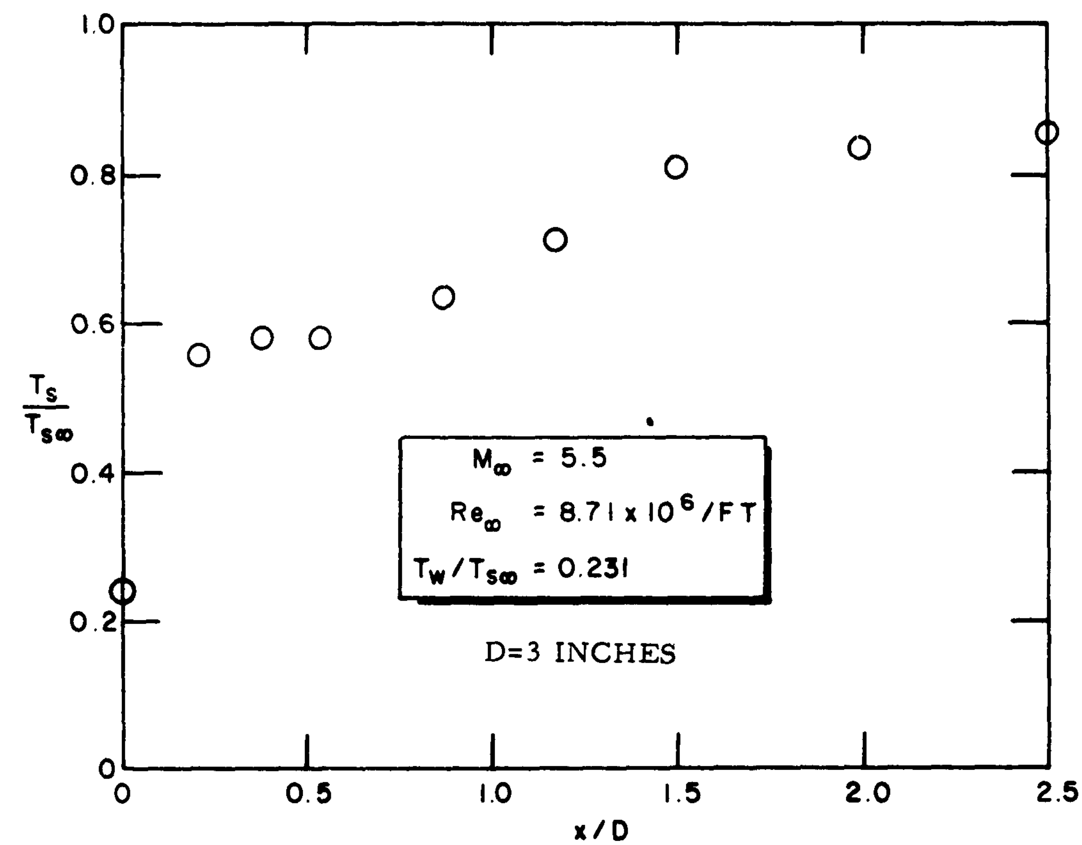

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Figure 21 CENTERLINE TEMPERATURE IN THE WAKE OF A 10-DEGREE HALF-ANGLE WEDGE

V. CONCLUSIONS

Temperature measurements using a constant-temperature hot-wire technique were obtained in the wakes of a 10-degree half-angle wedge and a 10-degree half-angle cone in a hypersonic shock tunnel at a Mach number of 16, stagnation temperature of 2400°K, two Reynolds numbers of 5.7×10^4/ft and 4.8×10^5/ft, and ratios of wall-to-stagnation temperature of 0.0325, 0.125, and 0.155.

This investigation has shown that the stagnation temperature is influenced substantially by the Reynolds number and the wall-to-stagnation temperature ratio. For both bodies, a region of constant temperature exists at 0.3 D to 0.75 D. For the models tested, the stagnation temperature in the near-wake was found to decrease with increasing Reynolds number and to approach a limiting value as the ratio of wall-to-stagnation temperature approaches zero. These limiting values are a function of Reynolds number. Changing the base configuration from an abrupt (flat base) to a more gentle expansion resulted only in a translation of the axial temperature distribution.

Schlieren photographs indicate that the time for wake formation is on the order of 1 millisecond.

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Avco Corporation, Research and Advanced Development Division, Wilmington, Massachusetts.
NEAR-WAKE FLOWFIELD MEASUREMENTS, by A. Todisco and A. Pallone. 5 May 1965. 48 pp., incl. illus. (Technical Memorandum RAD-TM-65-21)
Contract No. AF04(694)-687. Task 2.2. REST Program.
Unclassified report

Measurements of the stagnation temperature field behind a 10-degree half-angle wedge and a 10-degree half-angle cone have been made in the Avco RAD hypersonic shock tunnel at Mach 16 and stagnation temperature of 2400°K, using a constant temperature hot-wire anemometer. The effect of Reynolds number and wall-to-stagnation temperature ratios was investigated. Reynolds numbers 5.7×10^4/ft and 4.8×10^5/ft and ratios of wall-to- stagnation temperature of 0.0325, 0.125 and 0.155 were used.

UNCLASSIFIED

1. Fluid Dynamics
2. Wake-flowfield measurements

I. Todisco, A.
II. Pallone, A.
III. Avco, Research and Advanced Development Division
IV. Contract AF04(694)-687
V. Series
VI. Title

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