AEDC-TR-67-249

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November 1967

ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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FOREWORD

The work reported herein was sponsored by Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 6144501F, Project 8951, Task 895106.

A program of research is in progress at Cornell Aeronautical Laboratory, Inc., Buffalo, New York 14221 to develop a catalytic probe as a diagnostic device for use in high temperature test facilities. This is an interim technical report describing the application of a catalytic probe as a diagnostic tool in a nonequilibrium flow produced in a shock tunnel. The research was conducted from July 1966 to June 1967, under Contract AF 40(600)-1093 and the technical cognizance of Captain C. O. Forsythe. The CAL Report No. is AF-1905-A-3.

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The author gratefully acknowledges the invaluable advice of R. J. Vidal during the course of this research.

This technical report has been reviewed and is approved.

Conrad O. Forsythe Captain, USAF Research Division Directorate of Plans and Technology	Edward R. Feicht Colonel, USAF Director of Plans and Technology

ABSTRACT

Heat transfer data are presented which were obtained with a sharp flat plate having surfaces both catalytic and noncatalytic to oxygen atom recombination. The plate was inclined at a compressive angle to the flow to provide a constant-pressure flow field in which the measurements could be readily interpreted. The experiments were made in a shock tunnel using oxygen-argon mixtures as the test gas. Test conditions were chosen such that the flow was in thermochemical nonequilibrium. The intent of the experiment was to illustrate the application of this probe configuration as a diagnostic tool in a high temperature test facility.

The shock tunnel conditions necessary to produce a meaningful experiment are reviewed. In addition, the procedures for conditioning the catalytic surface and reducing data are discussed. Typical data traces are presented to show that the catalytic probe can be used to determine the end of the period of useful test flow. The data obtained with the catalytic and noncatalytic surfaces compare favorably with boundary-layer theory which accounts for Prandtl number effects and variations of the $\rho\mu$-product in the boundary layer. The ratio of catalytic-to-noncatalytic heat transfer rate is interpreted with the theory to infer the ambient stream atom mass fractions. The inferred mass fractions are in fair agreement with values computed for relevant oxygen dissociation-recombination rates.

LIST OF SYMBOLS

C	Chapman-Rubesin constant
C_f	skin friction coefficient
C_H	Stanton number, Equations (4) and (5)
c_p	specific heat at constant pressure
E	equation (2)
h	$c_p T$
h_D	heat of dissociation
H	total enthalpy, $c_p T + \frac{1}{2} u^2 + \alpha h_D$
K_w	$\gamma_c \sqrt{\frac{R T_w}{2 \pi \mathfrak{m}_A}}$
L	chordwise reference length
Le	Lewis number, $\frac{Pr}{Sc}$
M	Mach number
$\mathfrak{m}_A$	atomic weight of reacting species
p	pressure
Pr	Prandtl number
q	heat transfer rate per unit area
R	universal gas constant
Re	Reynolds number
Sc	Schmidt number
T	temperature
u	velocity in the chordwise direction
x	chordwise coordinate

LIST OF SYMBOLS (Cont.)

α	species mass fraction
γ_c	catalytic efficiency
μ	coefficient of viscosity
ρ	density
$\bar{\chi}_L = M^3\sqrt{\frac{C}{Re_L}}$	viscous interaction parameter, equation (3)

SUBSCRIPTS

CAT	catalytic
NC	noncatalytic
e	conditions at the edge of the boundary layer
∞	conditions in the ambient stream
w	conditions at the surface
R	conditions in the reservoir
L	chordwise reference length

I. INTRODUCTION

A program of research has been in progress at CAL to develop a surface catalytic probe for measurement of dissociated freestream atom mass fractions. The ultimate purpose of this probe development is to infer species mass fractions in dissociated air, produced in high temperature test-flow facilities. The present research centers on experiments in a gas with a single reactant, oxygen. The probe configuration chosen was a sharp flat plate.[1] This plate may be pitched at compression or expansion angles, allowing considerable control over flow field reactions. An alternative approach is a blunt body configuration for the catalytic probe.[2] The blunt probe configuration was not investigated experimentally in this program. In the first phase of the program, the applicability of this probe as a diagnostic tool was demonstrated in controlled, equilibrium shock tube experiments.[1] The present phase is concerned with the application of the probe to nonequilibrium nozzle expansions.

The purpose of the present experiments was to illustrate the application of the catalytic flat plate as a diagnostic tool in a nonequilibrium flow produced in a shock tunnel. In the spirit of the shock tube experiments, every attempt was made to minimize spurious effects that could complicate data interpretation. The experimental conditions and model scale were chosen such that the probe laminar boundary layer was thin, transport effects at the shock wave were negligible, and chemical reactions were suppressed in the probe flow field. This allowed confident interpretation of the data.

The succeeding section will describe the experimental apparatus and procedures and is followed by a discussion of the experimental results.

II. APPARATUS AND PROCEDURES

In the design of the experiment, the procedures of Reference 1 were followed as closely as possible to minimize spurious effects that could complicate data interpretation. The test gas used was oxygen with an inert (argon) diluent. This choice serves as an approximate model for air, but restricts consideration to a single dissociation-recombination reaction. Silver was chosen as the catalyst for oxygen atom recombination because of its high catalytic efficiency and because considerable research has been accomplished on the procedures required to produce a silver surface catalytic to oxygen atom recombination.[3,4]

MODEL

The model used in these experiments, Figure 1, was a stainless-steel flat plate. The plate, which was six inches wide and eight and one-half inches long, had two chordwise rows of six heat transfer gauges. These gauges were thin film resistance thermometers about 0.1 μ thick. These were deposited on removable glass buttons (Pyrex brand 7740) using conventional techniques.[5] The gauges were nominally spaced at 2, 2.75, 3.5, 4.25, 5, and 5.75 inches from the model leading edge. An inorganic insulating film about 0.2 μ thick composed of a baked mixture of paints was deposited on the heat transfer buttons in the manner described in Reference 1. This film served as an electrical insulator between the silver and the catalytic gauges. In addition, the film acted as a noncatalytic surface on the noncatalytic gauges. Electrical shorts between the silver and the catalytic gauges were eliminated by capacitor discharge, as described in Reference 1. Prior to depositing the silver surface, the instrumented surface of the model (excluding the heat-transfer buttons) was sprayed with an organic coating* about 0.2 μ thick. This coating served as an electrical insulator between the silver and the model surface. In addition, the coating on the steel surface insured that the surface would be noncatalytic.

SHOCK TUNNEL CONDITIONS AND INSTRUMENTATION

The experiments were made in the CAL Six-Foot Shock Tunnel.[6] With regard to the present research, the important features of the shock tunnel are the mode of operation and the supersonic nozzle arrangement.

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*3M Company FX-703 Fluorochemical Lacquer.

The mode of operation in the present experiments was to use hydrogen driver gas heated to 675°K to drive shock waves, at a shock Mach number of 8 to 10, into oxygen-argon mixtures. This condition resulted in over-tailored shock tube operation, with a test time of approximately 500 μsec.

The nozzle system consists of a two-dimensional contoured nozzle which produces a flow Mach number of about 5 at its exit. This is followed by a wedge which turns the flow 11° to centrifuge particles from the flow. The flow is then intercepted by a 10° half angle conical nozzle with an exit diameter of six feet.

To insure acceptable flow uniformity, pitot pressure surveys[+] were made with a horizontal array of ten transducers at the nominal 40-inch diameter nozzle station. Each pressure transducer consists of a diaphragm flush with the pitot probe surface which drives a piezoelectric crystal. The important features of these transducers are the high sensitivity (about 1/2 volt per psi) and a 40 μsec response time. Pitot pressure distributions are shown in Figure 2. It can be seen that the core of the flow is uniform to about ±5% over the model width of six inches.

One requirement in choosing shock tube conditions was than the oxygen be almost fully dissociated in the reservoir with a minimum of recombination in the nozzle expansion. This condition was achieved by selecting a high incident shock velocity and a low initial pressure in the shock tube.

The model was installed at the nominal 40-inch diameter nozzle station of the shock tunnel and was pitched at a compressive angle of 25° with respect to the flow. This angle was chosen because calculations indicated that it would produce flow field conditions closely corresponding to an equilibrium state for the species frozen in the ambient flow. Estimates were made of the flow field reactions using the rates reported by Camac and Vaughan[7] and those based on the data of Byron,[8] which have been used previously at CAL.[9,10,11] The following reactions were considered:

$$O_2 + M \rightleftharpoons 2O + M \; ; \; M = O, \; O_2, \; Ar. \tag{1}$$

Calculated variations in chemical composition in the flow field were found to be acceptably small. At the maximum temperature in the boundary layer, dissociation resulted in a maximum increase in atom mass fraction of 2% over the instrumented length. Recombination near the wall was estimated

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[+] The surveys were made under CAL internal funding.

at the point where the velocity was 1/10 of the velocity at the edge of the boundary layer, and resulted in a maximum decrease of atom mass fraction of 2% over the instrumented length.

An additional requirement in the experiment was to minimize the effect of the catalytic efficiency on the results by insuring that the surface atom mass fraction is diffusion controlled. This condition is satisfied[1] for

$$E = \frac{C_f \sqrt{Re}}{2(Pr)^{2/3}} \left[\frac{\rho_e u_e}{\rho_w K_w} \right] \frac{1}{\sqrt{Re}} << 1 \qquad (2)$$

The reservoir conditions, in combination with the model scale and pitch angle, were chosen such that the parameter E was never larger than 0.19 in the experiments, assuming a catalytic efficiency of 0.15.[12]

The output from the thin-film thermometer gauges on the model was recorded as surface temperature, and additionally, converted to heat transfer rate through analogue networks.[13] The surface temperature data were recorded primarily as a precautionary measure. In Reference 1, noise in the temperature signals produced large fluctuations in the heat transfer rate data obtained through the analogue networks. No such noise was observed in the present experiments, however. These surface temperature data were processed using standard techniques[5] to spot-check the data processed with analogue networks, with good agreement.

The shock tunnel data included time-of-arrival measurements obtained with thin-film thermometers at five positions in the shock tube. The reservoir pressure was recorded with conventional pressure transducers, and pitot pressure was recorded at the model location with a flush diaphragm pressure transducer previously discussed.

The basic test gas was an oxygen-argon mixture with the following mass spectrometer analysis:

O_2 - 0.513 mole fraction
Ar - 0.486 mole fraction
N_2 - 590 ppm
CH_4 - 6.5 ppm
other - < 1 ppm

Mixtures of different compositions were made by diluting the basic gas with either high-purity oxygen or argon.

SURFACE CONDITIONING

It has been shown by Myerson[3,4] at CAL that a virgin silver surface initially is noncatalytic, and exposure to a flux of oxygen atoms produces a surface catalytic to oxygen atom recombination. In the interest of eliminating spurious effects in the conditioning process, the apparatus and procedures reported in Reference 1 were used. The apparatus and procedures were unaltered in the present experiments, except for the following modifications.

The free-jet length, that is, the distance from the end of the drift tube to the model surface, was increased to maintain the same ratio of model length to free-jet length. The purpose of this change was to insure the same flux of atoms to the model surface as in the shock tube experiments. It is noted that the distance from the R-F discharge electrodes to the model surface was unchanged to eliminate recombination path length as a variable.

For convenience, the conditioned model was stored in a nitrogen atmosphere until just prior to the experiment. This differs from the helium atmosphere used in the shock tube experiments. No effect due to the change in storage atmosphere was apparent in the experiments.

The conditioning procedure was used to check that the silver surface was catalytic prior to each experiment. No loss of catalytic efficiency between experiments was detected.

After the conditioning process, the originally bright silver surface was discolored, ranging from an orange-yellow at the model center through purple at the apparent extremities of the jet, and finally a cloudy silver beyond the apparent jet extremities. These observations, in accord with Reference 1, may suggest an early stage in the formation of silver oxide on the surface.

DATA REDUCTION

The flow conditions about the model were computed in the following manner. The shock tube time-of-arrival data were used to determine incident shock wave velocity at the end of the driven tube. Equilibrium properties behind the reflected shock wave were computed using the normal shock machine code developed at CAL, based on initial shock tube conditions and incident shock wave velocity. Compression of the gas from the reflected shock wave pressure to the measured reservoir pressure ranged from 1.05 to 1.56 in the experiments. This process was approximated by assuming an isentropic compression. This approximation should be quite accurate, since the entropy increase is small for the worst case of a single normal shock wave. The equilibrium reservoir conditions were computed using the isentropic assumption and the machine code for reacting gases developed at CAL.[11]

With these reservoir conditions as input data, finite-rate nozzle-flow solutions were generated using the CAL machine code[11] for nonequilibrium expansions of reacting gases. These solutions were run to the nozzle station at which the computed pitot pressure equalled the measured pitot pressure.

The geometric area distribution was used in the machine code without boundary-layer correction. It was found that this correction was small in the contoured portion of the nozzle where the thermochemical reactions are most sensitive to area distribution. In the conical nozzle, where boundary-layer growth may become appreciable, the flow chemistry is essentially frozen. The computed stream quantities then become only weakly dependent upon the boundary-layer correction. The effective area distribution through the Prandtl-Meyer fan was determined from the density distribution along the streamline which becomes the centerline of the conical nozzle.

Estimates were made of O_2 vibrational freezing in the nozzle expansion, using the shock tube rates for vibrational relaxation reported by Lutz and Kiefer.[14] Calculations were made with the Stollery and Smith finite - difference approximation[15] for the Landau-Teller relaxation equation. The estimates indicated that vibration would freeze in the Prandtl-Meyer expansion fan and remain frozen downstream of the expansion. Consideration was given to the possibility of a faster vibrational relaxation rate in the expanding flow. For example, the vibrational relaxation rate reported by Hurle, Russo, and Hall[16] for N_2 in an expanding flow is about 1/70 that of the rate determined behind a shock wave. If a faster rate for O_2 is similarly applicable for the expanding flow, then estimates indicate that vibration would freeze in the conical nozzle. In either case, the amount of energy frozen in the vibrational mode would be at most about 1% of the total enthalpy of the flow. For this reason, the contribution of the vibrational mode to properties of the stream should be small. Based on the foregoing, finite-rate chemistry calculations were made with the machine code for two limiting cases. In the first, O_2 vibration was assumed to freeze at the Prandtl-Meyer fan. In the second case, O_2 vibration was assumed to be equilibrated in the expansion. No attempt was made to account for coupling between vibrational and chemical nonequilibrium, because there is no established model for vibrational relaxation in a gas in which thermochemical nonequilibrium processes are occurring. Finite-rate chemistry calculations made for these two cases verified the hypothesis that the O_2 vibrational contribution to the stream properties is small. Although the effect on the free stream static temperature and pressure is about 10%, the ambient atom concentration is affected by only about 1%. In addition, flow properties behind the oblique shock wave on the wedge model are affected less than 2%. All results reported assume vibration freezes at the Prandtl-Meyer expansion fan, since there is no basis for assuming a faster vibrational relaxation rate in O_2.

The finite-rate calculations were made for two sets of oxygen dissociation-recombination rates: those reported by Camac and Vaughan[7] and those based on the data of Byron.[8] These rates are summarized in Table I.

TABLE I
OXYGEN DISSOCIATION - RECOMBINATION RATES

$O_2 + M_i \underset{}{\overset{k_{f_i}}{\rightleftharpoons}} 2O + M_i \qquad k_{f_i} = A_i\, T^{\eta_i}\, e^{-\frac{59380}{T}}\ \frac{CM^3}{MOLE\,SEC}$, WHERE T IS IN °K

SOURCE	M_i	A_i	η_i
CAMAC AND VAUGHAN [7]	O_2	1.07×10^{19}	-1.0
	O	8.91×10^{19}	-1.0
	Ar	3.56×10^{18}	-1.0
REFERENCES 8, 9, 10, 11	O_2	3.6×10^{21}	-1.5
	O	2.1×10^{18}	-0.5
	Ar	1.2×10^{21}	-1.5

A typical nozzle flow solution is presented in Figure 3. From this plot, it can be seen that the chemistry is essentially frozen at the exit of the contoured nozzle. Expansion through the Prandtl-Meyer fan further freezes the chemistry. These calculations support the programmed area distribution previously discussed.

Calculations of properties in the inviscid flow field of the model were made using ideal gas, oblique shock wave relations. The O_2 vibrational mode was assumed frozen throughout the flow field. As previously mentioned, O_2 vibration is energetically small, and therefore may be neglected.

The transport properties were calculated at the edge of the boundary layer (T ≈ 3300°K) and at the model surface (T = 300°K) in the manner indicated in Reference 1.

In these experiments, the model scale is quite large, and the measurements were made at a point relatively far upstream in the conical nozzle. For these reasons, the effects of source flow on the data were considered. The flow was assumed to eminate from the apex of the 10° half angle conical nozzle. The inviscid perturbation analysis of Hall[17] was used to compute a correction to the wedge surface pressure to account for the source-like nature of the flow. A correction to measured heat transfer was then made from the pressure correction, using the similarity relationship between heat transfer and pressure given by Cheng:[18]

$$M^3 C_H \approx 0.332 \; \bar{\chi}_L \; \frac{p}{p_\infty} \left(\int_0^x \frac{p}{p_\infty} \, \frac{dx}{L} \right)^{-1/2} \qquad (3)$$

No attempt was made to account for boundary-layer growth in the nozzle. Boundary-layer growth would tend to turn the flow toward the nozzle centerline and reduce the source flow correction. The data corrected with the inviscid correction,and uncorrected data, should therefore represent limiting conditions.

III. RESULTS

To produce a variation in experimental parameters, the oxygen composition of the test gas was varied from 0.3 to 0.6 mole fraction. Table II presents nominal test conditions obtained in the experiments.

TABLE II

NOMINAL TEST CONDITIONS

INITIAL MOLE FRACTION O_2	INCIDENT SHOCK MACH NUMBER	P_R ATM	T_R °K	MOLE FRACTION O_2 IN RESEVOIR	AMBIENT MOLE FRACTION O	M_∞	$(Re)_\infty$ IN^{-1}	Te °K	u_e FPS	$(Re)_e$ IN^{-1}	$\frac{\alpha_e h_D}{H_R}$
0.30	8.1	125	6320	0.03	0.15	23.1	3750	3150	10200	635	0.13
0.41	9.2	122	6410	0.04	0.22	22.4	2180	3350	11200	450	0.16
0.51	10.2	104	6340	0.05	0.29	21.2	1340	3430	11900	340	0.20
0.60	10.0	104	5900	0.11	0.28	19.6	1210	3240	11900	390	0.20

SOURCE FLOW CORRECTION

The source flow correction ranged from 4% at the 2-inch chordwise station on the model to 11% at the 5.75-inch station, and was the same for both the catalytic and noncatalytic surfaces. This is due to the fact that the prime effect of the source flow is to alter the mass flux to the surface. The ratio of catalytic-to-noncatalytic heat transfer rate is therefore unaltered by the correction in the limit of an infinitely catalytic surface.

In all cases considered, the agreement between theory and experiment was not appreciably affected by the source flow correction.

NONCATALYTIC SURFACE

The heat transfer rate data obtained with the noncatalytic surface (corrected for source flow effects) are compared with thin laminar boundary layer theory in Figure 4. The freestream properties were calculated using the rates reported by Camac and Vaughan[7] and the rates based on the data of Byron.[8] The data are presented in the form of Stanton number

$$C_{H_{NC}} = \frac{q_{NC}}{\rho_e u_e (H_e - \alpha_e h_D - h_w)} \qquad (4)$$

versus Reynolds number at the edge of the boundary layer. This form of the Stanton number, based on the flow enthalpy, is appropriate to the noncatalytic surface.[1] All the data fall in the thin boundary layer regime in which viscous interaction effects[18] and shock wave transport effects[19] are negligible. The data are in reasonably good agreement with the modified Crocco solution of References 1 and 20, which accounts for Prandtl number effects and variations in the $\rho\mu$ -product in the boundary layer. The change in the theoretical solutions due to Prandtl and Schmidt number variations between experiments is indicated in this figure and is comparable to the experimental scatter. The data scatter, about ±8%, is typical for a shock tunnel experiment. The Blasius solution (Pr = 1, $\rho\mu$ = constant) and the theory of Lees[21] (Pr = 1, $\rho\mu$ = constant, $C = C_w$) differ from the modified Crocco theory by about 18% and 20% respectively. This demonstrates the importance of accounting for Prandtl number effects and especially variations in the $\rho\mu$ -product. In the present experiments, the value of $\frac{\rho_w \mu_w}{\rho\mu}$ varied from 1 to more than 2 throughout the boundary layer.

CATALYTIC SURFACE

The heat transfer rate data obtained with the catalytic surface (corrected for source flow effects) are presented in Figure 5. The data are again presented in the form of Stanton number

$$C_{H_{CAT}} = \frac{q_{CAT}}{\rho_e u_e (H_e - h_w)} \qquad (5)$$

versus Reynolds number. It should be noted that the Stanton number for a catalytic surface is based on the total enthalpy[1] as compared with that for a noncatalytic surface, which is based on the flow enthalpy. The theories plotted correspond to an infinitely catalytic wall. The effect of finite catalysis would alter the theoretical solution no more than 1%, assuming γ_c = 0.15. The reasonably good agreement between the experiments and the modified Crocco solution, and the large differences between the Blasius and Lees solutions and the modified Crocco solution again demonstrate the importance of accounting for Prandtl number effects and variations in the $\rho\mu$ - product.

In summary, it can be seen from Figures 4 and 5 that the choice of kinetic rates for the two sets of rates considered had little effect on agreement between experiment and theory. These figures show reasonably good agreement between the modified Crocco theory and experiment, for both the noncatalytic and catalytic surfaces.

AMBIENT ATOM MASS FRACTION

The catalytic and noncatalytic data were interpreted with the modified Crocco theory to infer ambient atom mass fraction. These inferred values were then compared with the mass fractions computed for the rates considered.

Using the modified Crocco theory[1,20] the noncatalytic-to-catalytic heat transfer ratio may be cast in the form

$$\frac{\alpha_e h_D}{H_e - h_w} = \frac{\left\{1 - \frac{q_{NC}}{q_{CAT}} - \left[1 - \left(\frac{Pr_{CAT}}{Pr_{NC}}\right)^{2/3} \left(\frac{1 + \frac{u_e^2}{2} \frac{\left[\sqrt{Pr_{NC}} - 1\right]}{H_e - h_w}}{1 + \frac{u_e^2}{2} \frac{\left[\sqrt{Pr_{CAT}} - 1\right]}{H_e - h_w}} \right)\right]\right\} \left\{1 + \frac{u_e^2}{2} \frac{\left[\sqrt{Pr_{CAT}} - 1\right]}{H_e - h_w}\right\}}{\left(\frac{Pr_{CAT}}{Pr_{NC}}\right)^{2/3} + \left[\left(\frac{Pr_{CAT}}{Sc_{CAT}}\right)^{2/3} - 1 - \left(\frac{Pr_{CAT}}{Sc_{CAT}}\right)^{2/3} \frac{\alpha_w}{\alpha_e}\right] \frac{q_{NC}}{q_{CAT}}} \tag{6}$$

To minimize the effects of data scatter on data interpretation, both the catalytic and noncatalytic data were faired for each run. This fairing process was done by averaging the quantity $q\sqrt{x}$, which is a constant according to boundary-layer theory. The purpose of averaging was to minimize amplification of experimental error because of the relatively small ratio of q_{CAT}/q_{NC}. The value of α_e was computed from Equation (6) using the value of q_{CAT}/q_{NC} so determined. In this computation, catalytic surface properties were evaluated at the midpoint of the instrumented surface. Chordwise variations in catalytic surface properties, and finite catalysis of the catalytic surface were found to have a negligible effect on the determined value of α_e.

The atom mass fractions inferred from the data are compared with the mass fractions computed for the rates considered in Figure 6. The two are in perfect agreement if the data points fall on the 45° line. A bar representing ±5% variation in the ratio q_{CAT}/q_{NC} is shown to demonstrate the high sensitivity of the inferred value of α_e to the ratio q_{CAT}/q_{NC}. The ±5% variation is representative of the uncertainty in the q_{CAT}/q_{NC} ratio in these experiments. The data points lie within the ±5% uncertainty in this plot. Choice of kinetic rates has a greater effect on the computed atom mass fraction than on the inferred fraction, although in an absolute sense, the effect on the computed fraction is relatively weak. The inferred value of α_e is sensitive to the q_{CAT}/q_{NC} ratio, and therefore is sensitive to the experimental scatter. For this reason, it is not possible to assess the kinetic rates considered with these data.

TEST TIME INDICATED BY THE PROBE

Plots of typical data obtained in a run with a mixture of 0.51 O_2 - 0.49 Ar are presented in Figure 7. These data include reservoir pressure, pitot pressure at the model location, heat transfer rate to the catalytic and noncatalytic surfaces at a given chordwise station, and the computed ratio of catalytic-to-noncatalytic heat transfer rate. This ratio is a direct measure of ambient atom concentration.[1] Consequently, the end of the test period should be indicated by a rapid decline in the atom mass fraction measured by the probe.

The ratio of catalytic-to-noncatalytic heat transfer rate serves as a useful indicator of test time in the present experiment. After a transient nozzle starting process, a period of constant ambient atom mass fraction is indicated. This period correlates in time with plateaus in the heat transfer rate data and pitot pressure. After this steady period, the indicated atom mass fraction shows transient behavior, as opposed to the anticipated decline in indicated mass fraction. This behavior probably stems from the rapid fluctuations occurring in the flow, which prevent correlation of the two heat transfer rates in time.

The reservoir pressure trace shows a small variation with time during the test period. The effect of variations in reservoir quantities on the free stream properties was considered, using the machine code solutions. It was found that a ±5% variation in reservoir pressure from the mean value during the test period, typical for these experiments, would result in only a ±3% variation in ambient atom mass fraction. The variations in other ambient quantities are comparably small. This might have been anticipated. The reservoir total enthalpy and entropy, which completely specify the (equilibrium) reservoir state, are weakly dependent on reservoir pressure variations.[22]

IV. CONCLUDING REMARKS

The purpose of the present experiment was to illustrate the application of the catalytic flat plate as a diagnostic tool in a nonequilibrium nozzle-flow expansion. The flat plate probe was successfully used to determine free stream atom mass fraction in a flow of dissociated oxygen. Comparisons of computed atom mass fractions and values inferred with the probe show fair agreement. It was found that the inferred mass fractions were quite sensitive to the experimental data scatter because of the small ratio q_{CAT}/q_{NC} in these experiments. For this reason, no quantatative assessment of reaction rates was attempted.

In addition to the determination of free stream atom fractions, the probe data provided an indication of the end of useful test flow in these experiments.

Because of the promising results of these experiments, it is anticipated that further work will be undertaken on the methods of increasing the sensitivity of this probe, i.e., on increasing the q_{CAT}/q_{NC} ratio.

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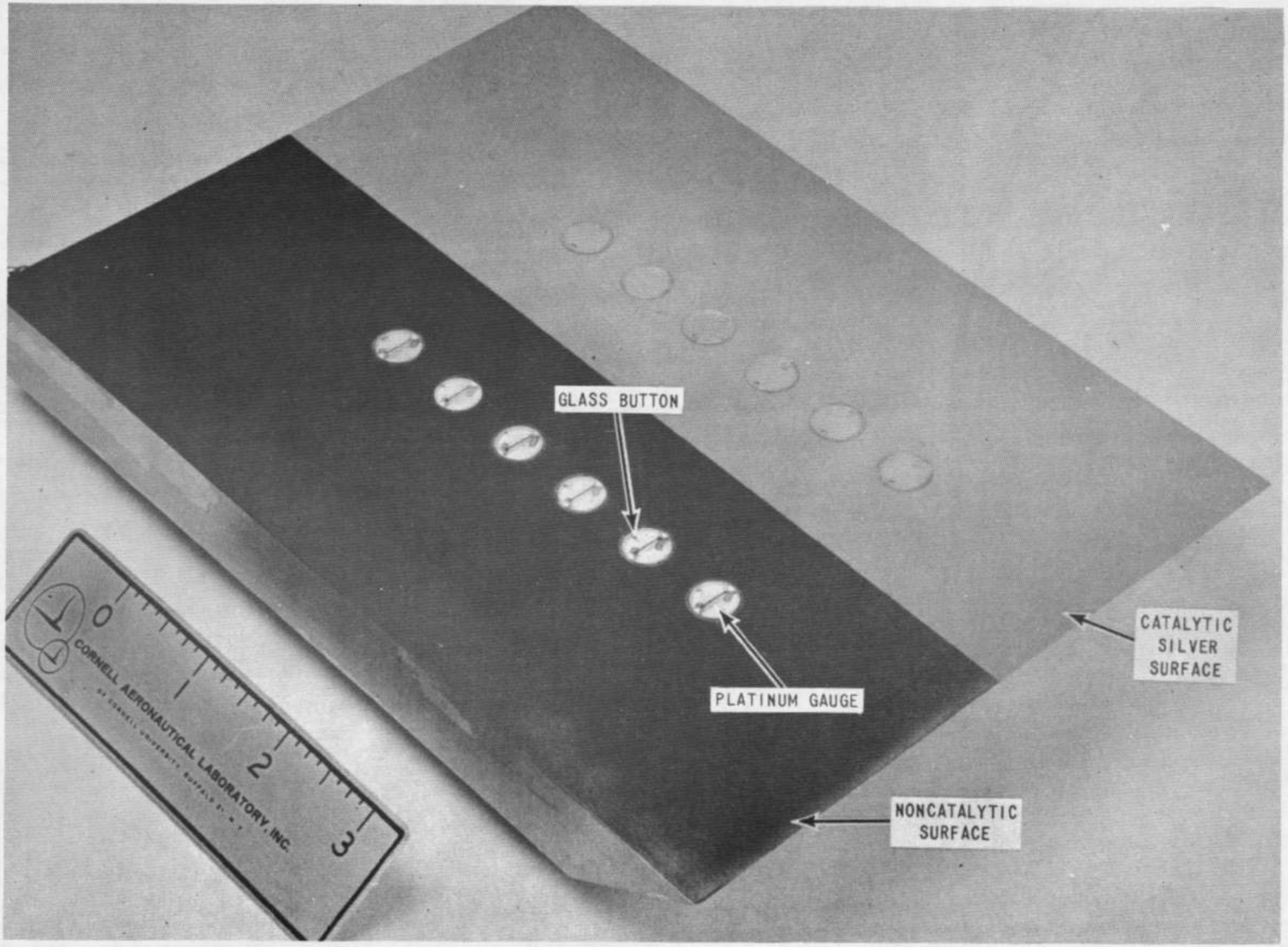


Figure 1 CATALYTIC FLAT-PLATE MODEL

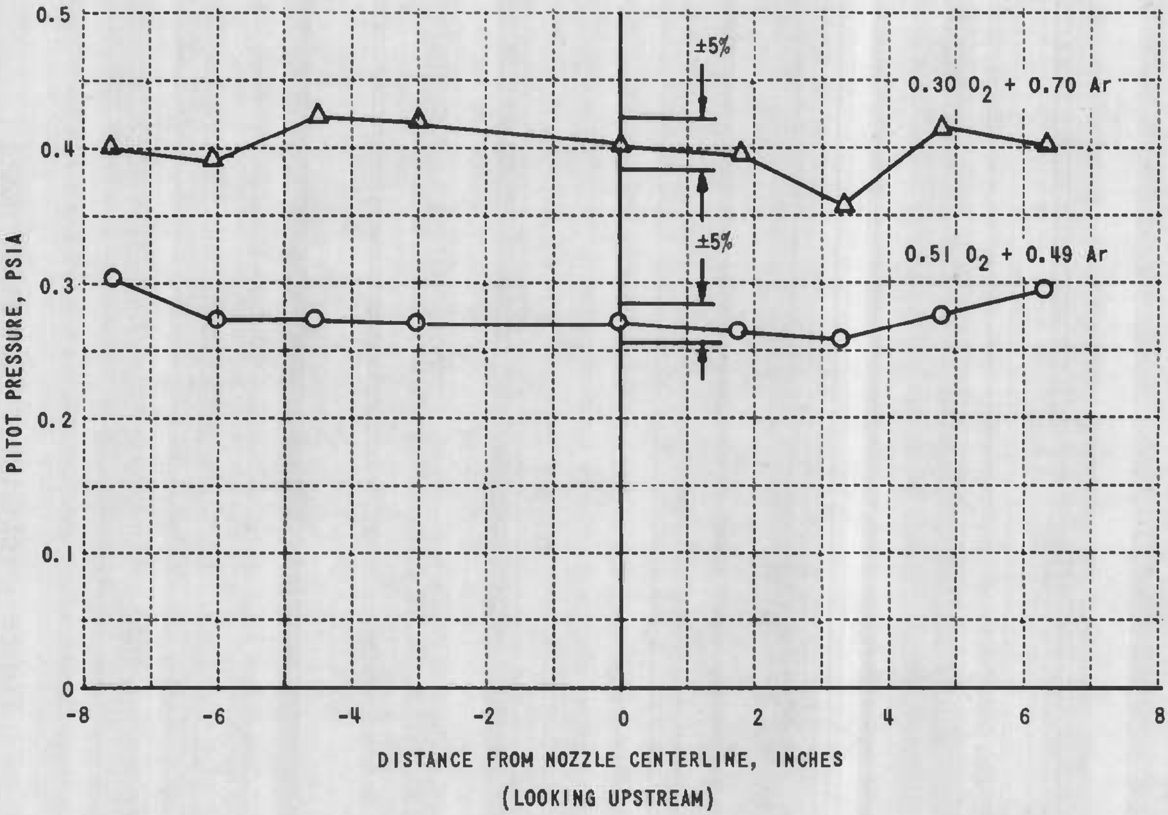


Figure 2 PITOT PRESSURE DISTRIBUTIONS IN THE SHOCK TUNNEL NOZZLE

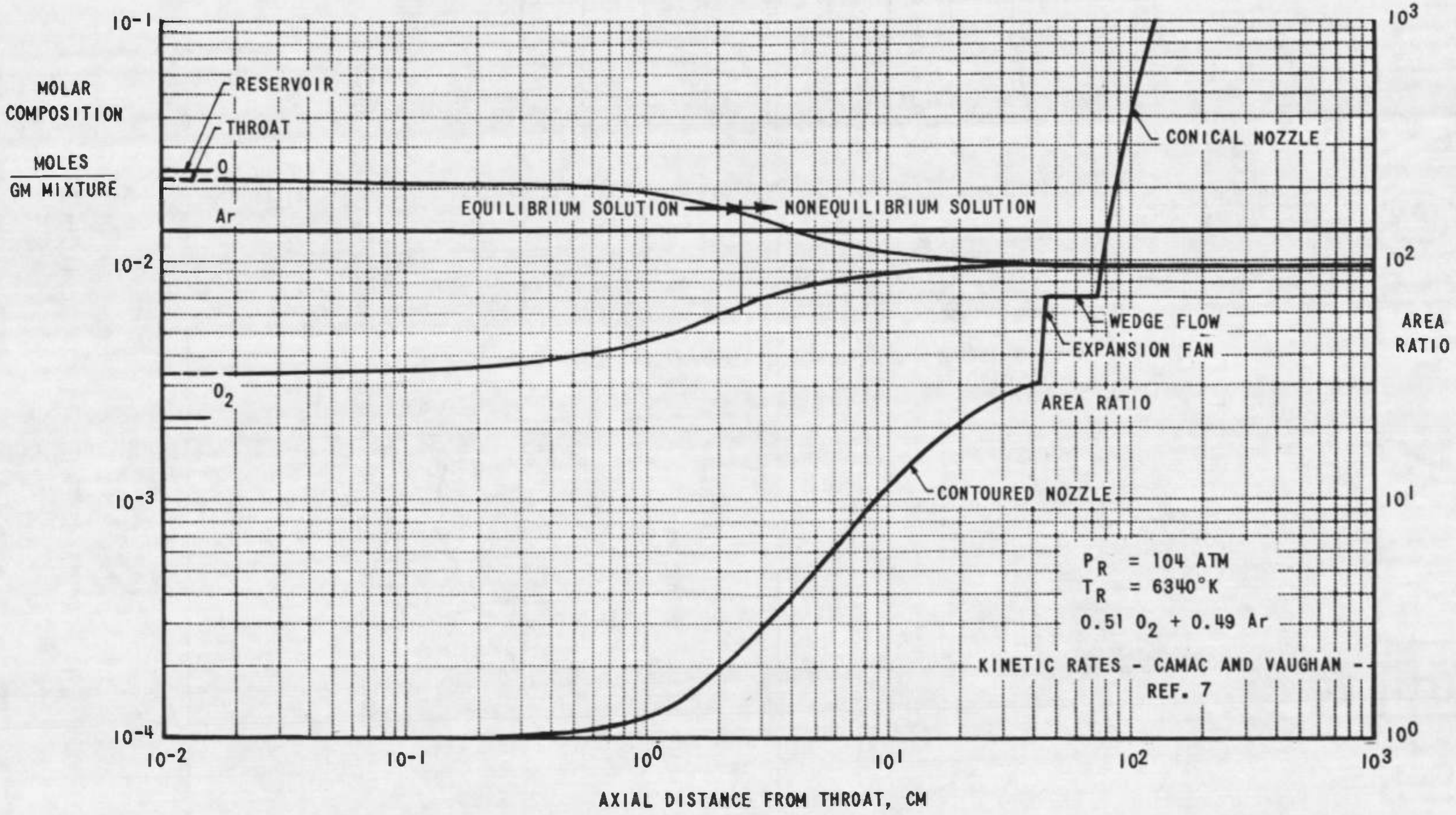
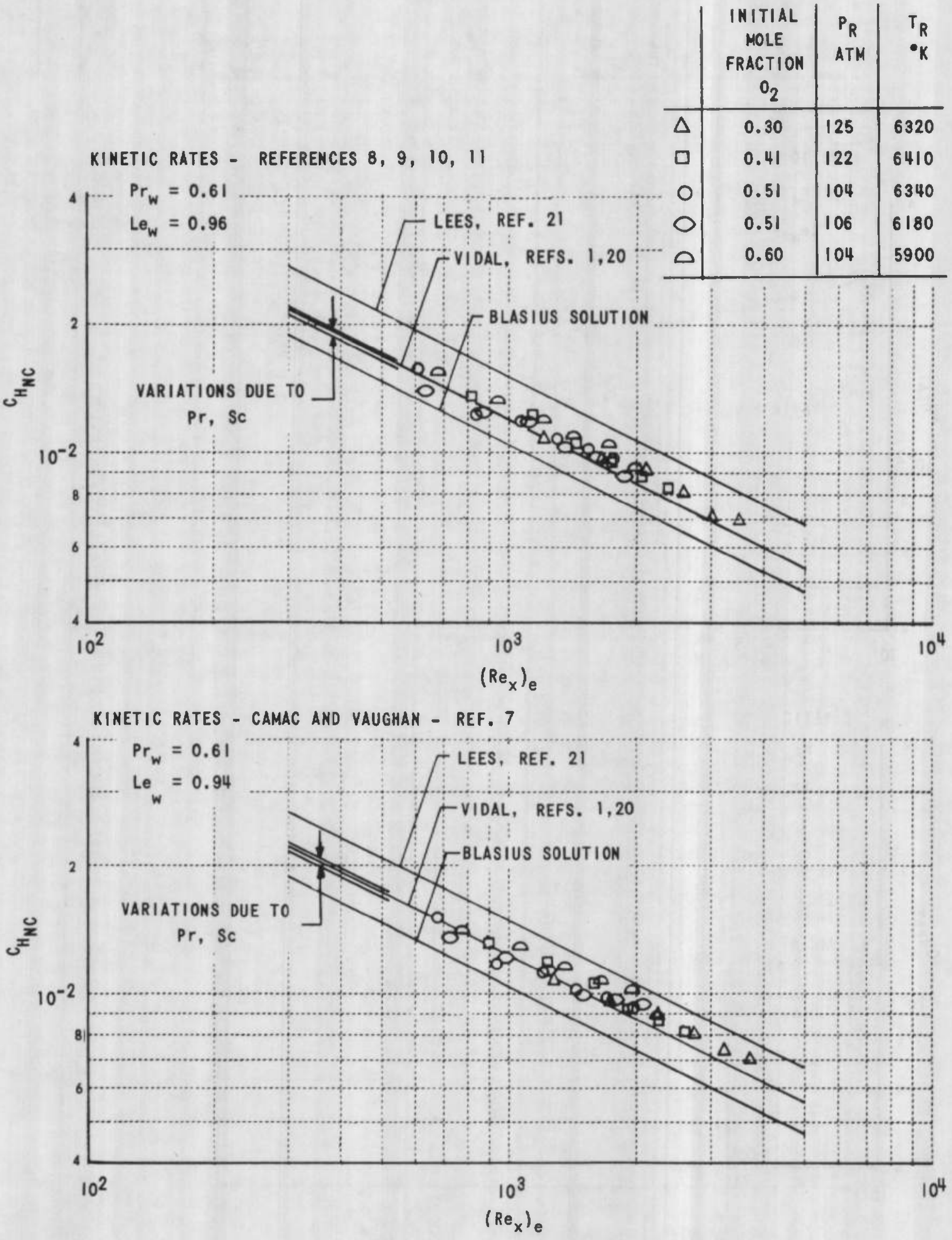


Figure 3 SPECIES IN THE NOZZLE EXPANSION



	INITIAL MOLE FRACTION O_2	P_R ATM	T_R °K
△	0.30	125	6320
□	0.41	122	6410
○	0.51	104	6340
⬭	0.51	106	6180
⌓	0.60	104	5900

Figure 4 HEAT TRANSFER TO A NONCATALYTIC WEDGE

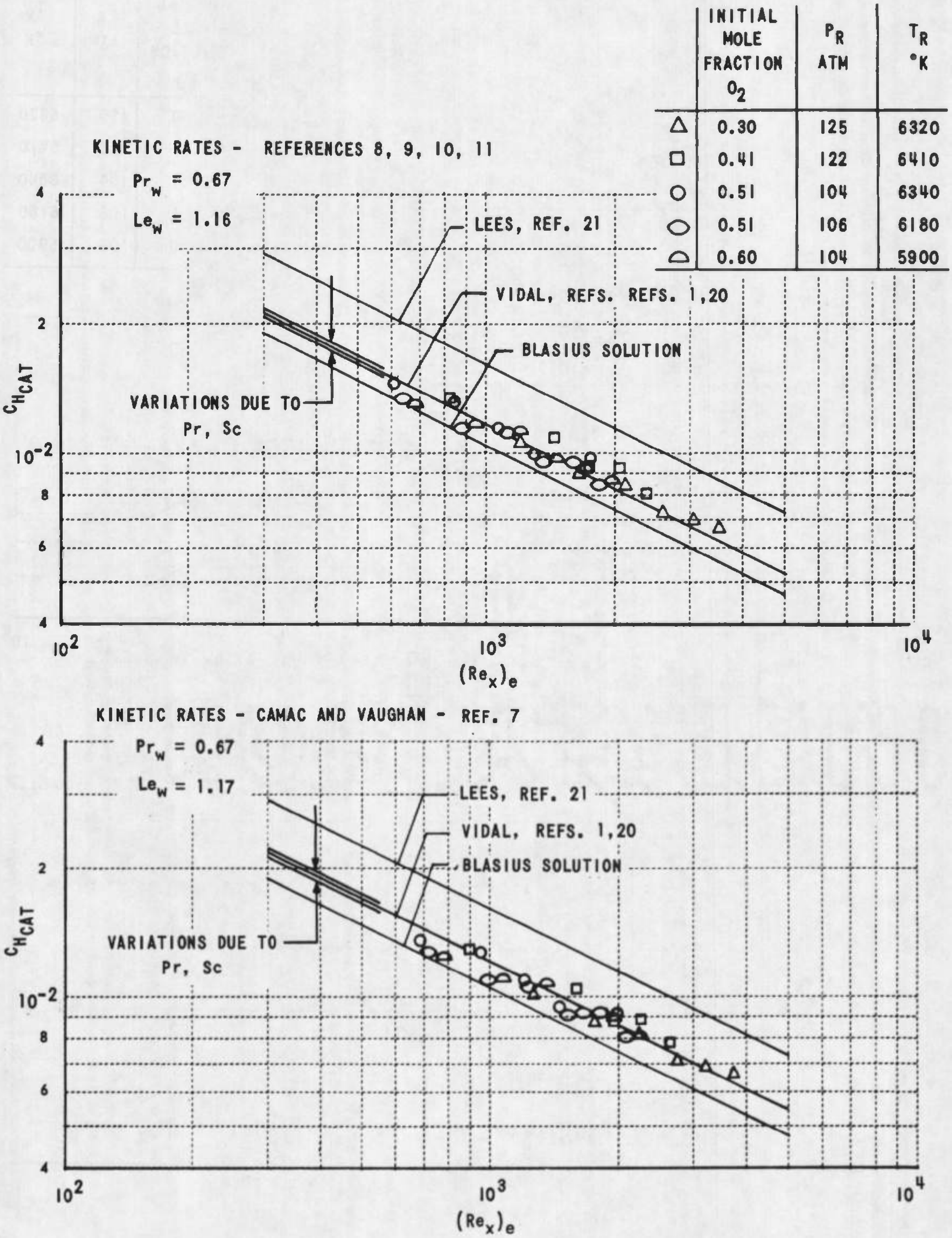


Figure 5 HEAT TRANSFER TO A CATALYTIC WEDGE

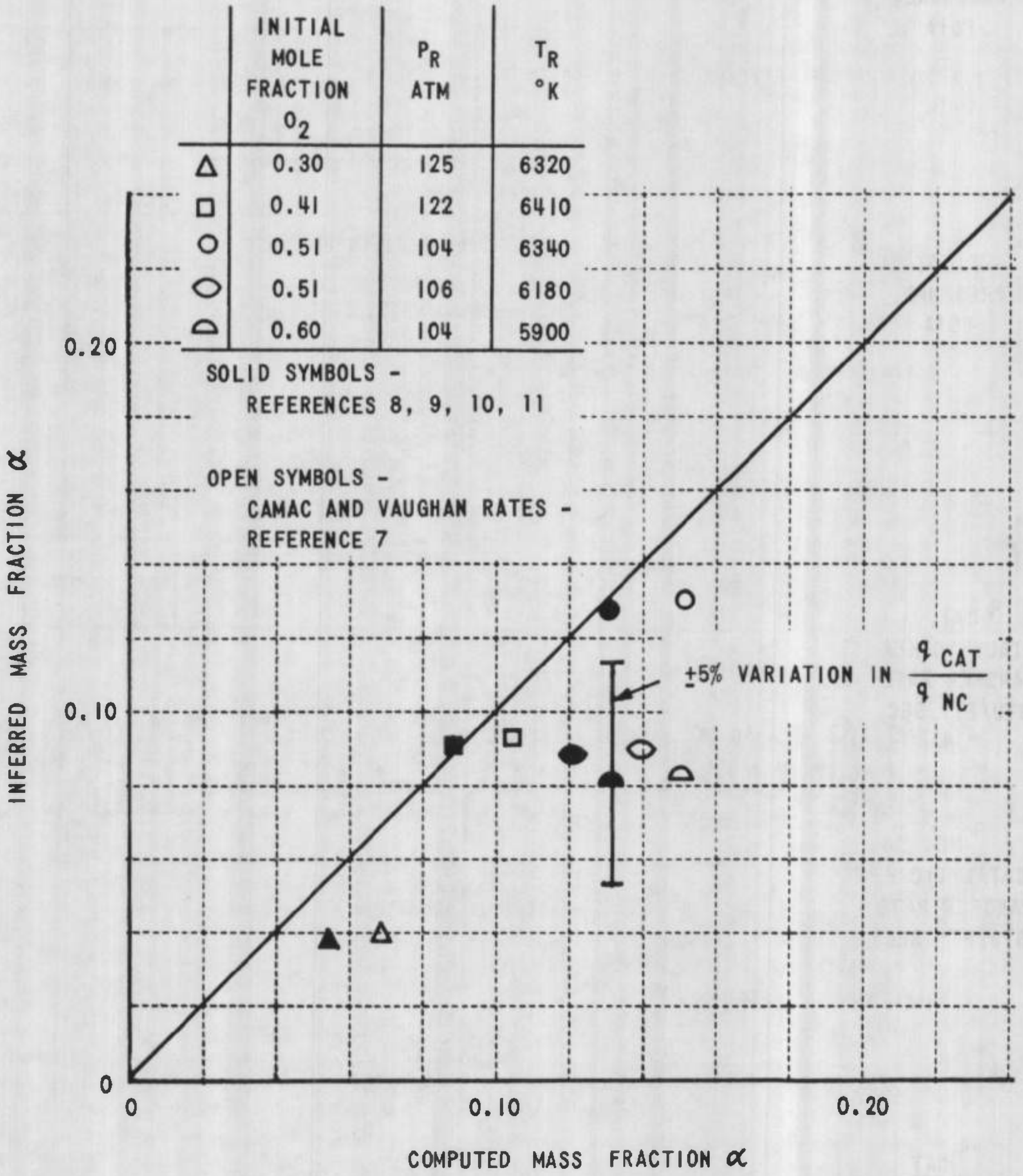


Figure 6 AMBIENT ATOM MASS FRACTIONS

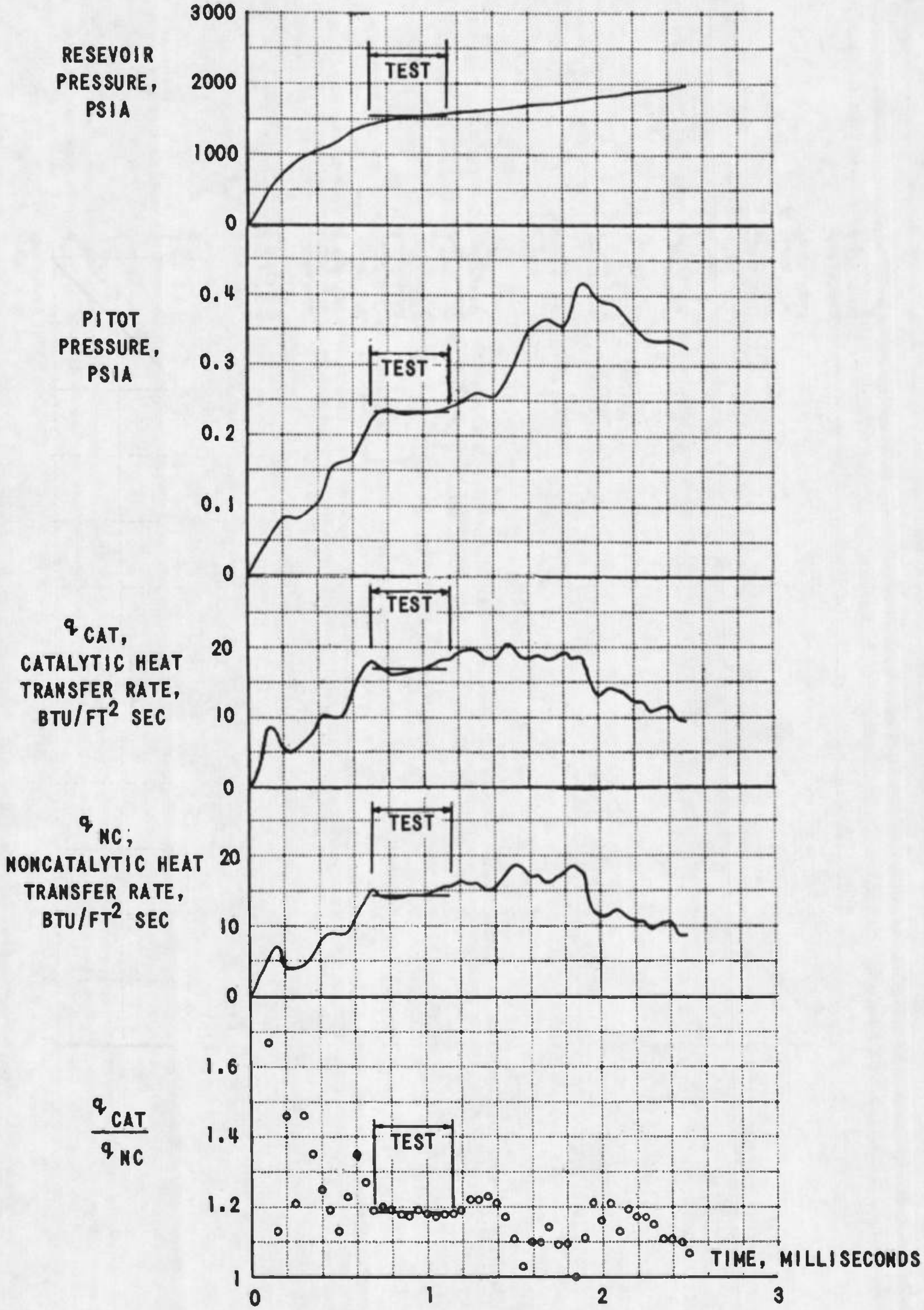


Figure 7 PLOTS OF TYPICAL DATA TRACES p_R = 104 ATM T_R = 6340°K
0.51 O_2 + 0.49 Ar

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Cornell Aeronautical Laboratory, Inc. Buffalo, New York 14221	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3. REPORT TITLE
HEAT TRANSFER MEASUREMENTS WITH A CATALYTIC FLAT PLATE IN A NONEQUILIBRIUM EXPANSION OF OXYGEN

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
July 1966 to June 1967 Interim Report

5. AUTHOR(S) *(First name, middle initial, last name)*
J. A. Bartz

6. REPORT DATE November 1967	7a. TOTAL NO. OF PAGES 25	7b. NO. OF REFS 22

8a. CONTRACT OR GRANT NO. AF 40(600)-1093	9a. ORIGINATOR'S REPORT NUMBER(S) AEDC-TR-67-249
b. PROJECT NO. 8951	
c. Program Element 6144501F	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* AG-1905-A-3
d. Task 895106	

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES Available in DDC	12. SPONSORING MILITARY ACTIVITY Arnold Engineering Development Center Air Force Systems Command Arnold Air Force Station, Tennessee

13. ABSTRACT

Heat transfer data are presented which were obtained with a sharp flat plate having surfaces both catalytic and noncatalytic to oxygen atom recombination. The plate was inclined at a compressive angle to the flow to provide a constant-pressure flow field in which the measurements could be readily interpreted. The experiments were made in a shock tunnel using oxygen-argon mixtures as the test gas. Test conditions were chosen such that the flow was in thermochemical nonequilibrium. The intent of the experiment was to illustrate the application of this probe configuration as a diagnostic tool in a high temperature test facility. The shock tunnel conditions necessary to produce a meaningful experiment are reviewed. In addition, the procedures for conditioning the catalytic surface and reducing data are discussed. Typical data traces are presented to show that the catalytic probe can be used to determine the end of the period of useful test flow. The data obtained with the catalytic and noncatalytic surfaces compare favorably with boundary-layer theory which accounts for Prandtl number effects and variations of the $\rho\mu$-product in the boundary layer. The ratio of catalytic-to-noncatalytic heat transfer rate is interpreted with the theory to infer the ambient stream atom mass fractions. The inferred mass fractions are in fair agreement with values computed for relevant oxygen dissociation-recombination rates.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
test facilities						
heat transfer measurements						
catalytic flat plates						
oxygen						
high temperature simulation						