63-1-2

ARL 62-375

A PRELIMINARY STUDY OF THE HYPERSONIC FLOW OF HELIUM-AIR MIXTURES

S. L. PETRIE

THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION
COLUMBUS, OHIO

JULY 1962

AERONAUTICAL RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE

NOTICES

. . . .

. . . .

. . . .

AF-WP-L-APR 62 100

UNCLASSIFIED

Aeronautical Research Laboratories, Wright-Patterson Air Force Base, Ohio. A PRELIMINARY STUDY OF THE HYPERSONIC FLOW OF HELIUM-AIR MIXTURES by S. L. Petrie. July 1962. 27 p. incl 10 illus. (Project 7065; Task 7065-0) Contract AF 33(616)-5593 (ARL 62-375
Unclassified Report

Theoretical predictions have been developed to describe the effects of the addition of varying amounts of helium to the flow of air in a hypersonic wind tunnel. Much greater over-all flexibility in operational Mach number and Reynolds number has been demonstrated. Preliminary experimental studies have, in part, substantiated the theoretical predictions.

(over)

UNCLASSIFIED

UNCLASSIFIED

Various possibilities for the use of a helium-air mixture as a wind tunnel testing medium have been examined.

UNCLASSIFIED

UNCLASSIFIED

Aeronautical Research Laboratories, Wright-Patterson Air Force Base, Ohio. A PRELIMINARY STUDY OF THE HYPERSONIC FLOW OF HELIUM-AIR MIXTURES by S. L. Petrie. July 1962. 27 p. incl 10 illus. (Project 7065; Task 7065-0) Contract AF 33(616)-5593 (ARL 62-375
Unclassified Report

Theoretical predictions have been developed to describe the effects of the addition of varying amounts of helium to the flow of air in a hypersonic wind tunnel. Much greater over-all flexibility in operational Mach number and Reynolds number has been demonstrated. Preliminary experimental studies have, in part, substantiated the theoretical predictions.

(over)

UNCLASSIFIED

UNCLASSIFIED

Various possibilities for the use of a helium-air mixture as a wind tunnel testing medium have been examined.

AF-WP-B-JUL 61 1M

UNCLASSIFIED

UNCLASSIFIED

Aeronautical Research Laboratories, **Wright-Patterson** Air Force Base, Ohio. A PRELIMINARY STUDY OF THE HYPERSONIC FLOW OF HELIUM-AIR MIXTURES by S. L. Petrie. July 1962. 27 p. incl 10 illus. (Project 7065; Task 7065-0) Contract AF 33(616)-5593 (ARL 62-375
Unclassified Report

Theoretical predictions have been developed to describe the effects of the addition of varying amounts of helium to the flow of air in a hypersonic wind tunnel. Much greater over-all flexibility in operational Mach number and Reynolds number has been demonstrated. Preliminary experimental studies have, in part, substantiated the theoretical predictions.

(over)

UNCLASSIFIED

UNCLASSIFIED

Various possibilities for the use of a helium-air mixture as a wind tunnel testing medium have been examined.

UNCLASSIFIED

AF-WP-B-JUL 61 1M

UNCLASSIFIED

Aeronautical Research Laboratories, **Wright-Patterson** Air Force Base, Ohio. A PRELIMINARY STUDY OF THE HYPERSONIC FLOW OF HELIUM-AIR MIXTURES by S. L. Petrie. July 1962. 27 p. incl 10 illus. (Project 7065; Task 7065-0) Contract AF 33(616)-5593 (ARL 62-375
Unclassified Report

Theoretical predictions have been developed to describe the effects of the addition of varying amounts of helium to the flow of air in a hypersonic wind tunnel. Much greater over-all flexibility in operational Mach number and Reynolds number has been demonstrated. Preliminary experimental studies have, in part, substantiated the theoretical predictions.

(over)

UNCLASSIFIED

UNCLASSIFIED

Various possibilities for the use of a helium-air mixture as a wind tunnel testing medium have been examined.

UNCLASSIFIED

AF-WP-B-JUL 61 1M

ARL 62-375

A PRELIMINARY STUDY OF THE HYPERSONIC FLOW OF HELIUM-AIR MIXTURES

S. L. PETRIE

THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION
COLUMBUS, OHIO

JULY 1962

CONTRACT AF 33(616)-5593
PROJECT 7065
TASK 7065-01

AERONAUTICAL RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

4-88, 300, 9-24-62

FOREWORD

This interim technical report was prepared by the Aerodynamic Laboratory for the Research Foundation of the Ohio State University on Contract AF 33(616)-5593 for the Aeronautical Research Laboratories, Office of Aerospace Research, United States Air Force. The investigations were performed on Task 7065-01 "Fluid Dynamics Facilities Research," of Project 7065 "Aerospace Simulation Techniques Research," with Mr. Emil Walk, Fluid Dynamics Facilities Laboratory, ARL, as task scientist.

ABSTRACT

Theoretical predictions have been developed to describe the effects of the addition of varying amounts of helium to the flow of air in a hypersonic wind tunnel. Much greater over-all flexibility in operational Mach number and Reynolds number has been domonstrated. Preliminary experimental studies have, in part, substantiated the theoretical predictions.

Various possibilities for the use of a helium-air mixture as a wind tunnel testing medium have been examined.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

In recent years, helium has been found useful as a wind tunnel testing medium for attaining test Mach numbers much higher than those possible with air. The extremely low liquefaction temperature of helium is particularly attractive since high Mach numbers can be obtained without the necessity of preheating the helium. Fundamental gasdynamic studies and conventional fluiddynamic investigations have been performed in helium flows(1,4,6,13) and the usefulness of helium as a wind tunnel working fluid has been amply demonstrated. The problem of converting the data obtained from helium tests to equivalent results in air has been investigated in part(11).

Since the changes in the ratio of specific heats in the hypersonic flow of a gas can have marked effects on the results, means of conveniently providing variations in γ have also been proposed(5).

In most present test facilities, a particular wind tunnel nozzle can deliver only one nominal Mach number and the facilities are generally limited to a relatively narrow Mach number range. The addition of various amounts of helium to a hypersonic air flow appears to be quite useful as a means of extending the Mach number and Reynolds number ranges of a test facility. This investigation was initiated to evaluate the possibilities of using helium-air mixtures in this manner.

Theoretical predictions are developed which give the effects of the addition of varying amounts of helium on the Mach number, Reynolds number, and pressure distributions within a hypersonic flow field. Preliminary experimental results substantiate these theoretical predictions. Basic areas to be investigated theoretically and experimentally with helium-air mixtures include (1) the fundamental effects of helium on the Mach number, Reynolds number and pressure distributions within a hypersonic wind tunnel nozzle, (2) laminar and turbulent boundary layer growth rates in a hypersonic wind tunnel nozzle over a wide Mach number, Reynolds number range, and (3) means of relating aerodynamic data obtained in helium and helium-air mixtures to equivalent air data.

The determination of boundary layer growth rates in hypersonic wind tunnel nozzles is of prime importance in order that suitable nozzle contours can be designed for high Mach number test facilities. In low density wind tunnels, the boundary layers grow quite rapidly and these thick layers in high pressure gradient regions cannot be accurately described theoretically. Instead, empirical growth rates obtained from actual measurements have been determined(2,8) and applied with relative success. These growth rates appear to correlate with relationships of the form $\delta^*/x = C\ M^a/{Re_x}^b$. The constants a, b, and c, have been determined for limited ranges of operation(2,8). More complete investigations as to the form of the correlations and the values of the constants are possible using helium-air mixtures.

"Manuscript released (May 1962) by the Aerodynamic Laboratory, The Ohio State University, for publication as an ARL Technical Documentary Report."

Since the advent of the helium wind tunnels, aerodynamicists have been plagued with the difficulty of properly interpreting the data obtained from helium flows for use in the prediction of the characteristics of air flows. To date, no conclusive investigations have substantiated this means of conversion. With helium-air mixtures, this investigation could conveniently be performed. For example, a basic Mach 8 air wind tunnel could be operated with a helium-air mixture to deliver a Mach 12 flow and the pressure distribution over an aerodynamic body investigated. The same aerodynamic body could then be tested in a Mach 12 air flow and the results compared with those obtained from the helium-air mixture. In this manner, reliable means of conversion of helium and helium-air data could be obtained.

An additional area of interest currently gaining in importance is the description of real-gas effects in partially dissociated streams. Since a non-reacting mixture of helium and air is composed of monatomic and diatomic particles, the mixture may be useful in simulating some of the effects present in dissociated streams. At present this is merely conjecture, however, and much theoretical and experimental data are needed before any conclusions can be reached.

II. THEORETICAL RESULTS

RATIO OF SPECIFIC HEATS

The ratio of specific heats, γ, for a mixture of helium and air may be calculated from a basic kinetic theory standpoint$^{(9)}$. The ratio may also be obtained by considering the enthalpy and internal energy of the mixture to be the sum of the separate contributions due to the helium and air. The mixture is thus considered as a two-component perfect gas.

If α denotes the mass fraction of helium in a unit mass of mixture, then $(1 - \alpha)$ gives the mass fraction of air. Further, if h_1 and h_2 are the enthalpies per unit mass of the helium and air, respectively, then for the mixture

$$h = \alpha\, h_1 + (1 - \alpha)\, h_2 \tag{1}$$

$$= h_2 + \alpha\,(h_1 - h_2) \tag{2}$$

Similarly,

$$e = e_2 + \alpha\,(e_1 - e_2) \tag{3}$$

The specific heats for the mixture may now be obtained from Eqs (2) and (3) since

$$C_p = \left(\frac{\partial h}{\partial T}\right)_p$$

$$C_v = \left(\frac{\partial e}{\partial T}\right)_v$$

If it is assumed that both the helium and air behave as perfect gases and that there are no chemical reactions, then the mass fraction of helium may be considered constant throughout the flow field. Thus,

$$C_p = \frac{dh}{dt} = C_{p_2} + \alpha\,(C_{p_1} - C_{p_2})$$

$$C_v = \frac{de}{dt} = C_{v_2} + \alpha\,(C_{v_1} - C_{v_2})$$

and

$$\gamma = \frac{C_p}{C_v} = \frac{C_{p_2} + \alpha\,(C_{p_1} - C_{p_2})}{C_{v_2} + \alpha\,(C_{v_1} - C_{v_2})} \qquad (4)$$

Assuming values of C_p and C_v of 6006 ft^2/sec^2 ^{O}R and 4290 ft^2/sec^2 ^{O}R for air and 31,089 ft^2/sec^2 ^{O}R and 18,651 ft^2/sec^2 ^{O}R for helium and substituting these values into Eq (4) gives

$$\gamma = \frac{6006 + 25083\,\alpha}{4290 + 14361\,\alpha} \qquad (5)$$

Equation (5) is plotted in Figure 1 where it is seen that the effect on the ratio of specific heats is largest for the smaller mass fractions of helium.

The method for calculating α for a particular helium-air mixture is given in the Appendix.

HIGH MACH NUMBER SIMULATION

In any wind tunnel test of an aerodynamic body, the test is useful only if dynamical similarity between the test body and the free-flight vehicle can be obtained. Generally it is assumed that duplication of flight Mach number and Reynolds number is sufficient to reproduce reliably the pressure field about a scaled model of the free-flight body. If, however, a gas different from air is used in the wind tunnel tests, an additional similarity parameter, γ, must be considered in order to obtain dynamical similarity. Some considerations of the difficulties in transferring aerodynamic data from helium flows to air flows is discussed in Ref. 2. If the helium test data can be reliably transferred to equivalent air results, the high Mach numbers obtained in helium wind tunnels coupled with the absence of a heater as is required in a hypersonic air wind tunnel make it particularly attractive as a wind tunnel working gas.

When operated with either air or helium, a specific wind tunnel nozzle delivers only one nominal Mach number. Mach number changes can be accomplished only by changing nozzles. When helium is added to a basic air flow in varying amounts, a wide range of Mach number and Reynolds number is readily obtained from a given wind tunnel nozzle.

Since the helium-air mixture is considered to be a perfect gas with constant specific heats, the relationship between Mach number and area ratio given below applies directly. That is

$$A/A^* = \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma + 1}{2(\gamma - 1)}} M \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma + 1}{2(\gamma - 1)}} \qquad (6)$$

Since Eq (5) gives γ as an explicit function of the mass fraction of helium in the mixture, combination of (5) and (6) gives the Mach number for a given area ratio as a function of the mass fraction of helium. Equation (6) may also be represented as

$$\frac{1}{M}\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma + 1}{2(\gamma - 1)}} = \frac{125}{216}\left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma + 1}{2(\gamma - 1)}} \frac{1}{M_o}\left(1 + \frac{M_o^2}{5}\right)^3 \qquad (7)$$

where M_o is the Mach number for the flow of "pure" air.

Equation (7) is shown graphically in Figure 2. The extremely large range in Mach number for a given area ratio (and thus for a given nozzle) obtainable with various helium-air mixtures is apparent from this figure. For example, for a nozzle delivering a Mach 12 flow with air, the Mach number may be varied from 12 to 28 by simply changing the amount of helium in the flow.

The Reynolds number at any point in the flow through a wind tunnel nozzle is related in a rather complicated manner to the mass fraction of helium present in the mixture. The Reynolds number may be written as

$$Re = M\left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}} \sqrt{\frac{\mathcal{M}\gamma}{\mathcal{R}}}\ \frac{L}{\mu}\ \frac{p_o}{\sqrt{T_o}} \qquad (8)$$

where $\mathcal{M}$ is the molecular weight of the mixture (see Appendix), $\mathcal{R}$ is the universal gas constant, μ is the viscosity of the mixture and L is the reference length.

A convenient Reynolds number parameter may be defined from Eq (8) as

$$\frac{Re\ \ \mu\ \sqrt{T_o}}{L\ p_o} = M\left(1 + \frac{\gamma - 1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}} \sqrt{\frac{\gamma\mathcal{M}}{\mathcal{R}}} \qquad (9)$$

Combination of Eqs (9), (7) and (5) give the Re parameter at a given A/A^* as a function of the helium mass fraction. A form of Eq (9) very useful in the study of boundary layer growth rates in hypersonic nozzles is obtained by writing Eq (9) for the nozzle throat. That is,

$$\frac{Re^*\ \ \mu^*\ \sqrt{T_o}}{L^*\ p_o} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \sqrt{\frac{\gamma\mathcal{M}}{\mathcal{R}}} \qquad (10)$$

The variation of the Reynolds number parameters given in Eqs (9) and (10) with helium mass fraction are shown in Figure 3 for various "air-alone" Mach numbers. The general decrease in the Reynolds number for given stagnation condition with increasing amounts of helium addition is apparent from the figure.

The effect of helium addition is thus to extend greatly both the Mach number and Reynolds number range of a hypersonic test facility. An increase in the Mach number is accompanied by a decrease in the free-stream Reynolds number allowing simulation of higher altitude-Mach number flight conditions.

BOUNDARY LAYER GROWTH RATES

Of particular interest in hypersonic wind tunnels is the rate of growth of the nozzle boundary layer. The low density flows in high Mach number facilities usually generate very thick boundary layers so that a relatively large portion of the nozzle may be filled with a viscous flow. Theoretical descriptions of nozzle boundary layer growth rates are not currently reliable; however, some specification of the boundary layer thickness is required so that a desired Mach number may be achieved at the nozzle exit. Empirical rules have thus been developed for description of these boundary layer thicknesses. It has been suggested that the displacement thickness of the boundary layer can be represented by an equation of the form (8)

$$\frac{\delta^*}{x} = C \frac{M^a}{{Re_x}^b} \qquad (11)$$

where for turbulent boundary layers in a Mach number range from 6 to 12,

$C = .0064$

$a = 1.25$

$b = .14$

Further work(5) has substantiated the general form of Eq (11).

Of prime importance in the boundary layer growth rate is whether the nozzle boundary layer is laminar or turbulent. Experimental studies at the Aerodynamic Laboratory have indicated that the type of boundary layer in the supersonic portion of the nozzle is determined by conditions existing at the nozzle throat. That is, if the boundary layer is laminar at the throat, it remains laminar throughout the nozzle. Data obtained from a 12-inch diameter hypersonic wind tunnel operating with Mach numbers between 6 and 12 indicate that the nozzle boundary layer can be expected to be laminar if the Reynolds number at the throat based on throat diameter is less than 0.120×10^6 and turbulent if it is greater than 0.17×10^6.

Through the use of helium-air mixtures, a wide range of tunnel Mach numbers and Reynolds numbers may be used to obtain further verification of Eq (11) for the boundary layer growth rate. Further, a facility which normally operaties with a turbulent nozzle boundary layer may be used to investigate laminar layers.

The effect of helium addition on the type of boundary layer is given directly by Eq (10). The Reynolds number at the throat may be varied through an appreciable range. This effect is displayed in Figure 4 where the throat Reynolds number for a basic Mach 11 facility operating at 600 psia stagnation pressure. It is seen that, while operating on air the nozzle should consistently deliver a turbulent boundary layer, operation with various amounts of helium addition will allow both laminar and turbulent layers to be investigated.

III. PRELIMINARY EXPERIMENTAL STUDIES

TEST FACILITY

The preliminary experimental investigations were performed in one of the Laboratory's small hypersonic wind tunnels. The facility is a continuous, free-jet tunnel that exhausts into a two-stage vacuum pumping station utilizing six Allis-Chalmers 27D vacuum pumps. Stored, high pressure air (or a helium-air mixture) is heated by a 24-kilowatt electrical resistance heater to temperatures over 2500°R. A three-inch diameter conical nozzle was used to obtain a nominal air-alone Mach number of 11. The nozzle was equipped with nine static pressure taps along its length. The nozzle details and the locations of the static pressure orifices are shown in Figure 5.

An impact pressure survey probe was mounted in the tunnel test cabin on a sliding mount and was inserted in the flow 1.10 inches upstream of the nozzle exit, opposite the second nozzle static pressure tap. The full width of the nozzle could be surveyed with the probe.

INSTRUMENTATION

Tunnel stagnation pressures were measured with Laboratory Test gages having an accuracy of 0.25 per cent of the full-scale gage readings. Stagnation temperatures were measured with a type S (platinum-platinum-rhodium) thermocouple. The thermocouple outputs were recorded on Brown self-balancing potentiometers.

Pressure distributions along the length of the nozzle were measured with tiltable silicone manometers. The manometers were inclined at an angle of 45 degrees to the horizontal in order to obtain greater sensitivity in the pressure readings obtained from the high Mach number portion of the flow. A small vacuum pump was used to maintain a low reference pressure for the manometers. The reference pressure was measured with a Consolidated Vacuum Corporation thermocouple gage. The typical reference pressure was 0.010 mm Hg.

Pressures obtained from the impact pressure probe were measured with a Wallace and Tiernan Absolute Pressure Indicator with an accuracy of 0.33% of the gage full-scale reading.

TEST RESULTS

Preliminary tests were performed to determine the change in flow Mach number with varying amounts of helium addition. Tests were performed at stagnation pressures of 214 psia and 354 psia with stagnation temperatures of 1710°R and 1470°R, respectively. The nozzle calibrations for the lower stagnation pressure runs are shown in Figure 6.

The ratio of total pressure across a normal shock wave may be used to obtain Mach number from the standard impact pressure ratio formula. Since the helium-air mixture is considered a perfect gas with constant specific heats, we may write

$$\frac{p_{t_2}}{p_{t_1}} = \left[\frac{(\gamma + 1) M_1^2}{(\gamma - 1) M_1^2 + 2}\right]^{\gamma/(\gamma-1)} \left[\frac{\gamma + 1}{2 \gamma M_1^2 - (\gamma - 1)}\right]^{1/(\gamma-1)} \qquad (12)$$

Since γ is given as an explicit function of α by Eq (5), Eq (12) gives the Mach number for a given impact pressure ratio as a function of the helium mass fraction. For reducing the calibration data, Eq (12) does not give a convenient result for M_1 for a given α. Instead, p_{t_2}/p_{t_1} must be plotted as a function of M_1 for various α's so that a measured value of the impact pressure ratio can be converted to a Mach number. This plot is shown in Figure 7. Figure 7 was used to obtain the various Mach numbers shown in Figure 6.

Nozzle static pressure distributions with no helium addition were taken at both operating conditions and are displayed in Figure 8.

The checks between the theoretical predictions and the experimental results are shown in Figure 9. The Mach number on the tunnel centerline obtained from the air-alone calibration was used as M_0 in Eq (7). This equation was then used to predict the centerline Mach number as a function of α.

The experimentally determined Mach numbers as obtained from the impact pressure ratios are shown in Figure 9. It is to be noted that the higher stagnation pressure condition agrees with the theoretical prediction. However, the results from the lower stagnation pressure condition fall far below the predictions.

The disagreement between the theoretical and experimental results at the low stagnation pressure operating condition is attributed to a separation of the nozzle boundary layer caused by the decrease in static pressure with increased amounts of helium addition.

The effect of helium addition on nozzle static pressure can be obtained from the following expression:

$$\frac{p}{p_0} = \left(1 + \frac{\gamma-1}{2} M_1^2\right)^{\gamma/\gamma-1} \qquad (13)$$

When this is combined with Eq (7), the change in wall static pressure at a particular area ratio and stagnation pressure can be obtained uniquely as a function of α and M_0. The effect of helium addition on the wall static pressure distribution is displayed in Figure 10 for several values of M_0. It can be seen that the addition of helium to the flow results in a decrease in the static pressure.

Nozzle static pressures were recorded during the operation of the facility with air. They were not recorded during the preliminary operations with helium-air mixtures. The data of Figure 8 indicate that the nozzle boundary layer was not separated when the facility was operated on air. However, because of the decrease in static pressure accompanying the addition of helium, the nozzle boundary layer may have been separated at the lower stagnation pressure. At the higher stagnation pressure, the separation was apparently eliminated and the theoretical and experimental results show very close agreement.

IV. CONCLUSION

Theoretical predictions of the effect of helium addition on air flows through hypersonic wind tunnels have been obtained. Large increases in the Mach number and Reynolds number ranges of a particular facility are possible with helium addition. The preliminary experimental results initially demonstrate the applicability of the theory.

Various experimental programs may be performed to substantiate further the theory and to investigate phenomenon of interest conveniently over large Mach number-Reynolds number ranges. Of particular interest are the boundary layer growth rate phenomenon in hypersonic wind tunnel nozzles and the comparisons between aerodynamic data obtained from tests in air flows and those obtained from tests in helium-air mixtures.

When a mixture of helium and air is examined on a microscopic scale, one finds a collection of both monatomic and diatomic particles. This suggests that the mixture might possibly be useful in simulating the real-gas properties of a dissociated air stream. Since the effects of changes in specific heats can have rather marked effect in hypersonic flows, the helium-air mixture concept could also prove quite valuable in experimentally investigating these phenomenon. Certainly a great deal of experimental and theoretical research is needed before either the basic γ change effects or the real-gas effects can be accurately simulated by an accelerated helium-air mixture.

V. REFERENCES

1. S. M. Bogdonoff, and A. G. Hammet, The Princeton Helium Hypersonic Tunnel and Preliminary Results above M = 11, WADC Tech Rept 54-124, July 1954.
2. A. Burke, Cornell Aeronautical Laboratory, Private Communication, February 1961.
3. E. R. G. Eckert, W. E. Ibele, and T. F. Irvine, Jr., Prandtl Number, Thermal Conductivity, and Viscosity of Air-Helium Mixtures, NASA Tech Note D-533.
4. Wayne D. Erickson, Study of Pressure Distributions on Simple Sharp-Nosed Models at Mach Numbers from 16 to 18 in Helium Flow, NACA Tech Note 4113, October 1957.
5. Albert R. George, Exploratory Studies of a Low γ, High Mach Number Wind Tunnel Using "Freon 14' as the Working Fluid, Princeton University Report No. 591, (AFOSR 1876), December 1961.
6. Arthur Henderson, Jr., Investigation of the Flow Over Simple Bodies at Mach Number of the Order of 20, NASA Tech Note D-449, August 1960.
7. Arthur Henderson, Jr., and Frank E. Swalley, Effects of Air Contamination in a Helium Tunnel, NASA Tech Note D-406, June 1960.
8. J. D. Lee, Axisymmetric Nozzles for Hypersonic Flows, Report No. TN(ALOSU)459-1, The Ohio State University Research Foundation, June 1959.
9. J. D. Lee, The Molecular Flow of Diatomic Gases and Gas Mixtures, The Ohio State University Research Foundation (to be published).
10. James N. Mueller, Equations, Tables and Figures for Use in the Analysis of Helium Flow at Supersonic and Hypersonic Speeds, NACA Tech Note 4063, September 1957.
11. James N. Mueller, Conversion of Inviscid Normal-Force Coefficients in Air for Simple Shapes at Hypersonic Speeds, NACA Tech Note 3087, October 1956.
12. K. Pearce, S. Samet and R. J. Whalen, Similarity Studies for Dissociating Gases in Hypersonic, Low Density Flow, WADD Tech Rept 60-341, September
13. I. E. Vas and S. M. Bogdonoff, An Exploratory Study at M = 14 of the Flow About a Hemisphere Cylinder at Angle of Attack, Princeton University Rept No. 438, (WADC TN-58-331, ASTIA AD 205-461), September 1958.

VI. APPENDIX

Calculation of Helium Mass Fraction, α

The mass fraction of helium, α, is defined as the mass of helium in a unit mass of mixture. Thus

$$\alpha = \frac{\mathcal{M}_h N_h}{\mathcal{M}_h N_h + \mathcal{M}_a N_a} \tag{A1}$$

where $\mathcal{M}_h$ = molecular weight of helium

$\mathcal{M}_a$ = molecular weight of air

N_h = number density of helium

N_a = number of density of air

For a perfect gas, $N = \frac{p N_o}{\mathcal{R} T}$ where N_o is Avogadro's and $\mathcal{R}$ is the universal gas constant. Thus,

$$\alpha = \frac{p_h}{p_h + \frac{\mathcal{M}_a}{\mathcal{M}_h} p_a}$$

or

$$\alpha = \frac{p_h}{p_h + 7.248\, p_a} \; ; \; p = p_h + p_a \tag{A2}$$

The desired mixtures were prepared in mixing tanks prior to a wind tunnel test and stored at high pressure. Commercially pure helium was used. The air used in the mixtures was supplied by the Laboratory's high pressure air storage system. The system stores approximately 1500 ft^3 of air at a pressure of 2400 psig with a dew point of -160°F.

Before the initial mixture was prepared, the mixing tanks were flushed and filled with a desired amount of air to an absolute pressure of p_{a_1}. Helium was then added to give a pressure p_{m_1} and thus a helium partial pressure of $p_{h_1} = p_{m_1} - p_{a_1}$. Once these partial pressures are known, the mass fraction may be calculated from equation (2). Thus,

$$\alpha_1 = \frac{p_{h_1}}{p_{h_1} + 7.248\, p_{a_1}} \tag{A3}$$

For the pressure and temperature ranges of this study the mixture is assumed to be a perfect gas with no chemical reactions. The mass fraction thus remains constant throughout the heating and expansion process.

A test is performed with this α_1 during which the pressure in the mixing tanks is reduced to p_{m_1}'. Since $\alpha_1' = \alpha_1$, the partial pressure of helium is given by

$$p_{h_1}' = \frac{7.248\, p_{m_1}'}{6.248 + \frac{1}{\alpha_1}} \tag{A4}$$

More air is then added to give a final pressure of p_{m_2} and the new mass fraction may be calculated from

$$\alpha_2 = \frac{p_{h_1}'}{p_{h_1}' + 7.248\, p_{a_2}} \tag{A5}$$

Since $p_{a_2} = p_{m_2} - p_{h_1}$, substitution of (A4) into (A5) gives

$$\alpha_2 = \frac{p_{m_1}'}{6.248\,(p_{m_2} - p_{m_1}') + \frac{p_{m_2}}{\alpha_1}} \tag{A6}$$

A wind tunnel test is then performed with this new α, more air is added and the above calculation procedure is repeated.

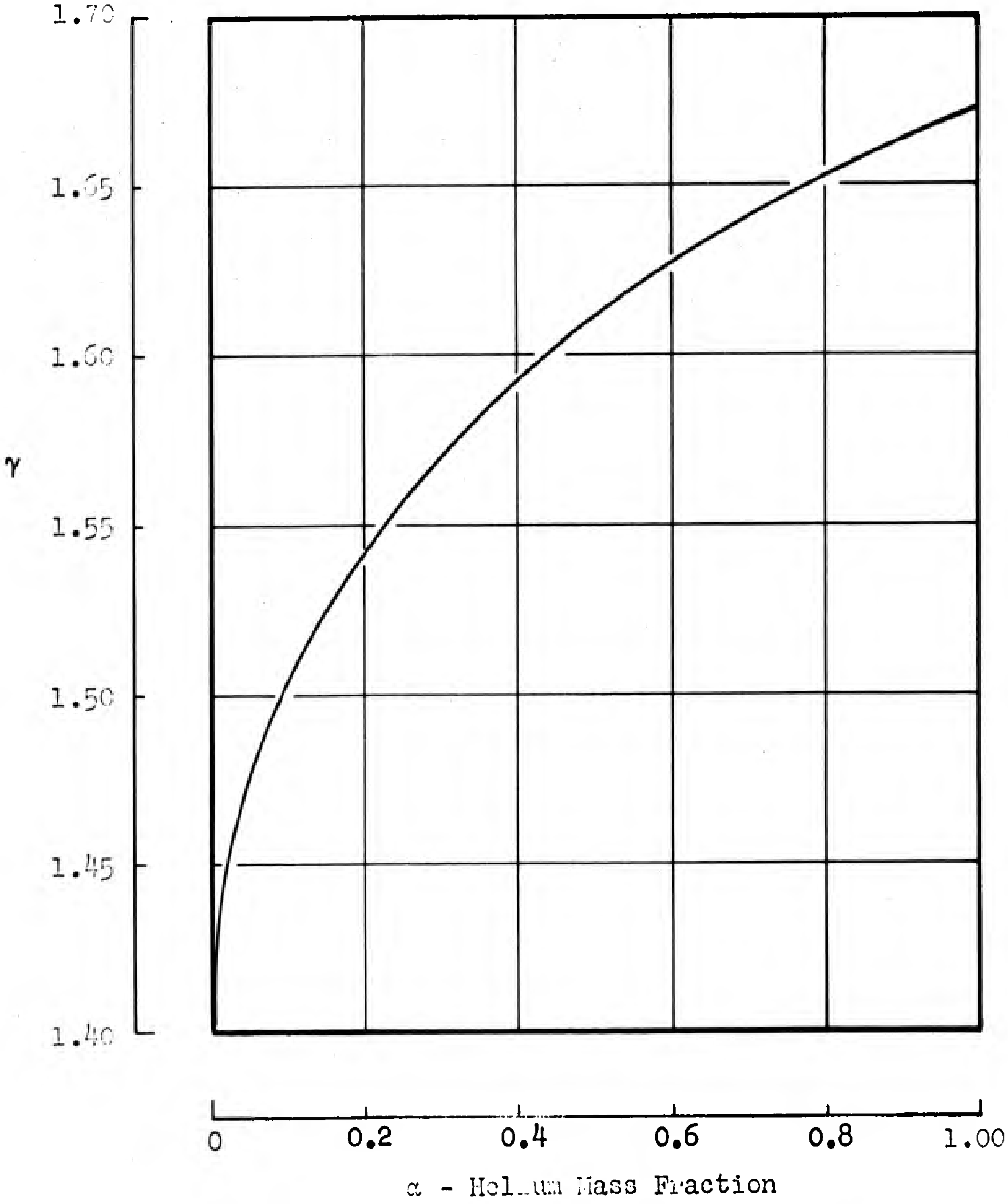


Figure 1: Ratio of Specific Heats for Helium - Air Mixtures:

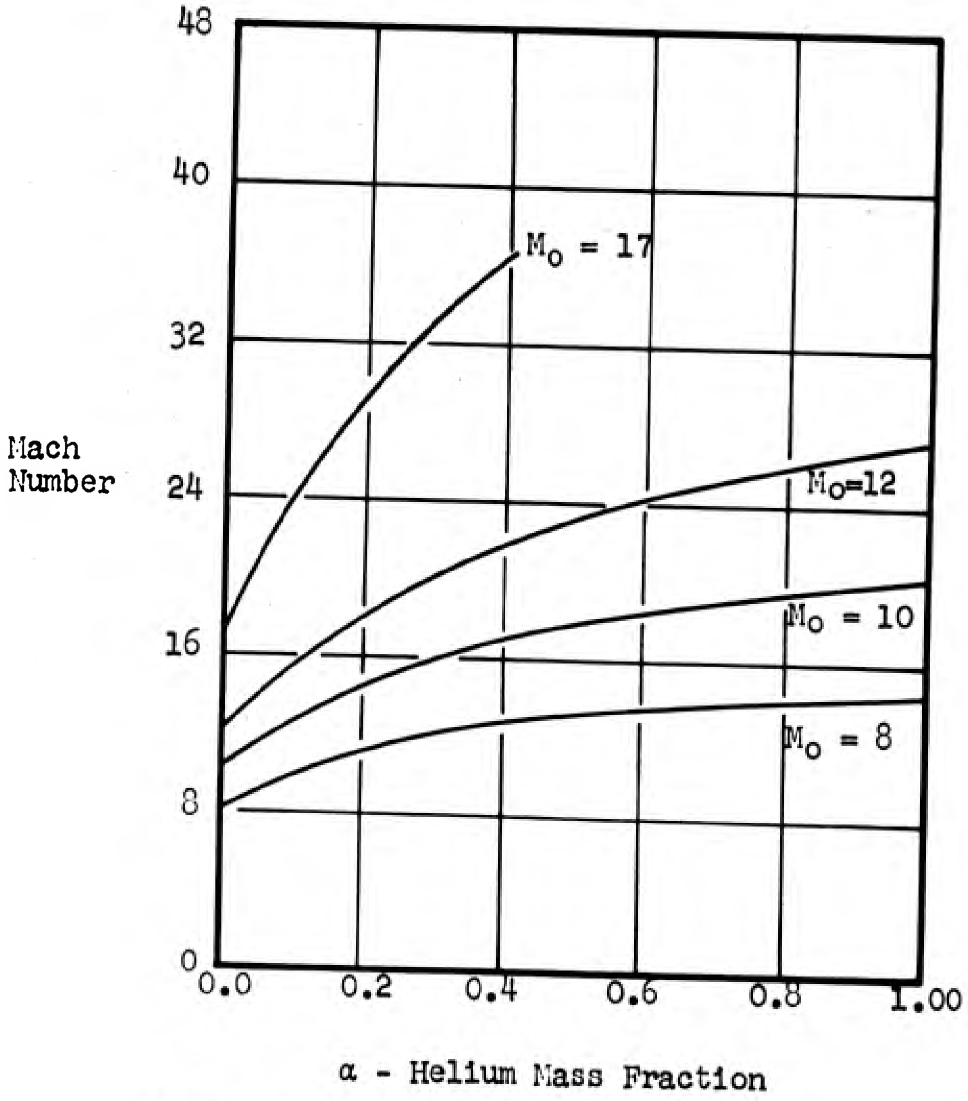


Figure 2: Mach Number for Helium-Air Mixtures

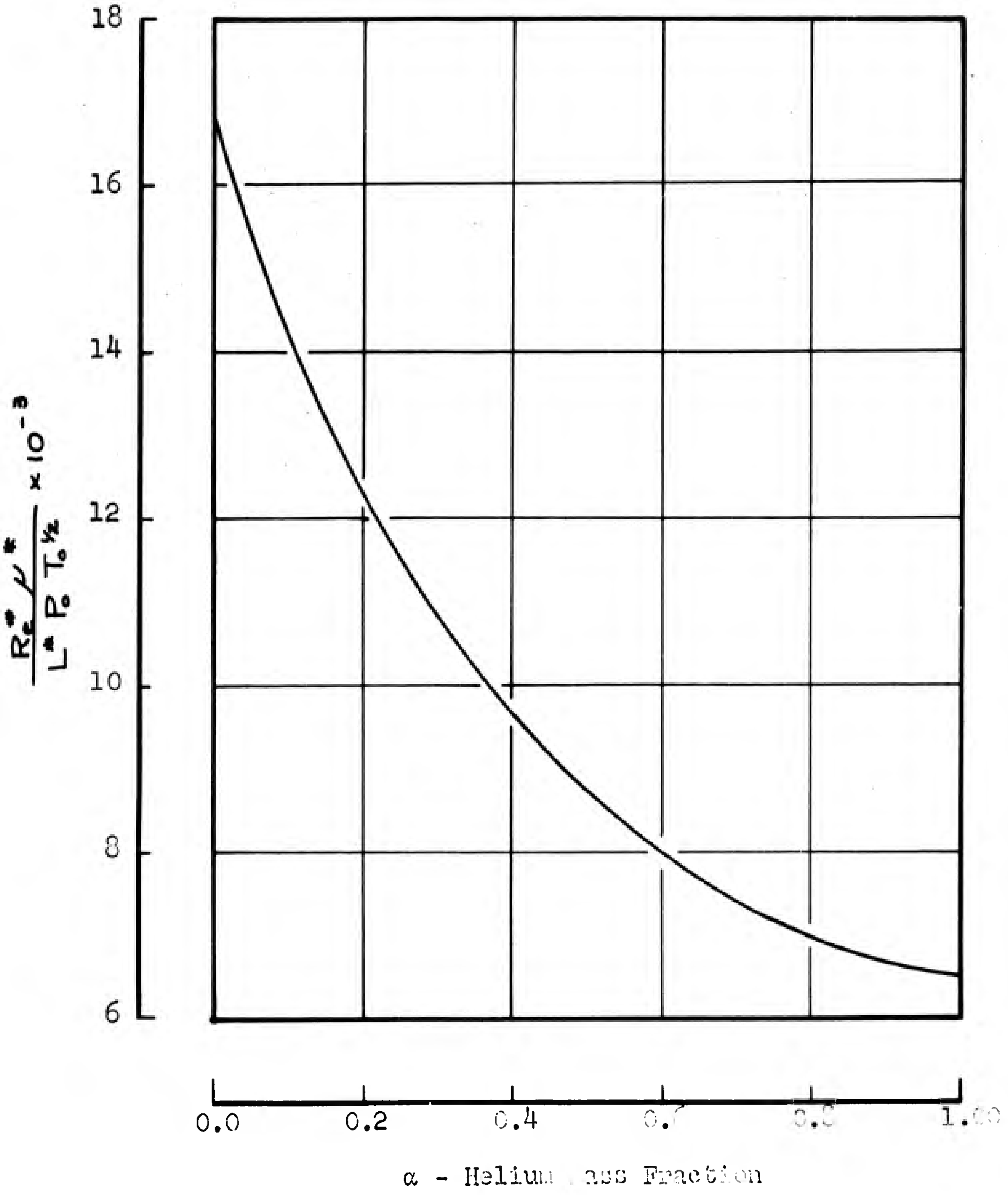


Figure 3 Reynolds Number Parameter

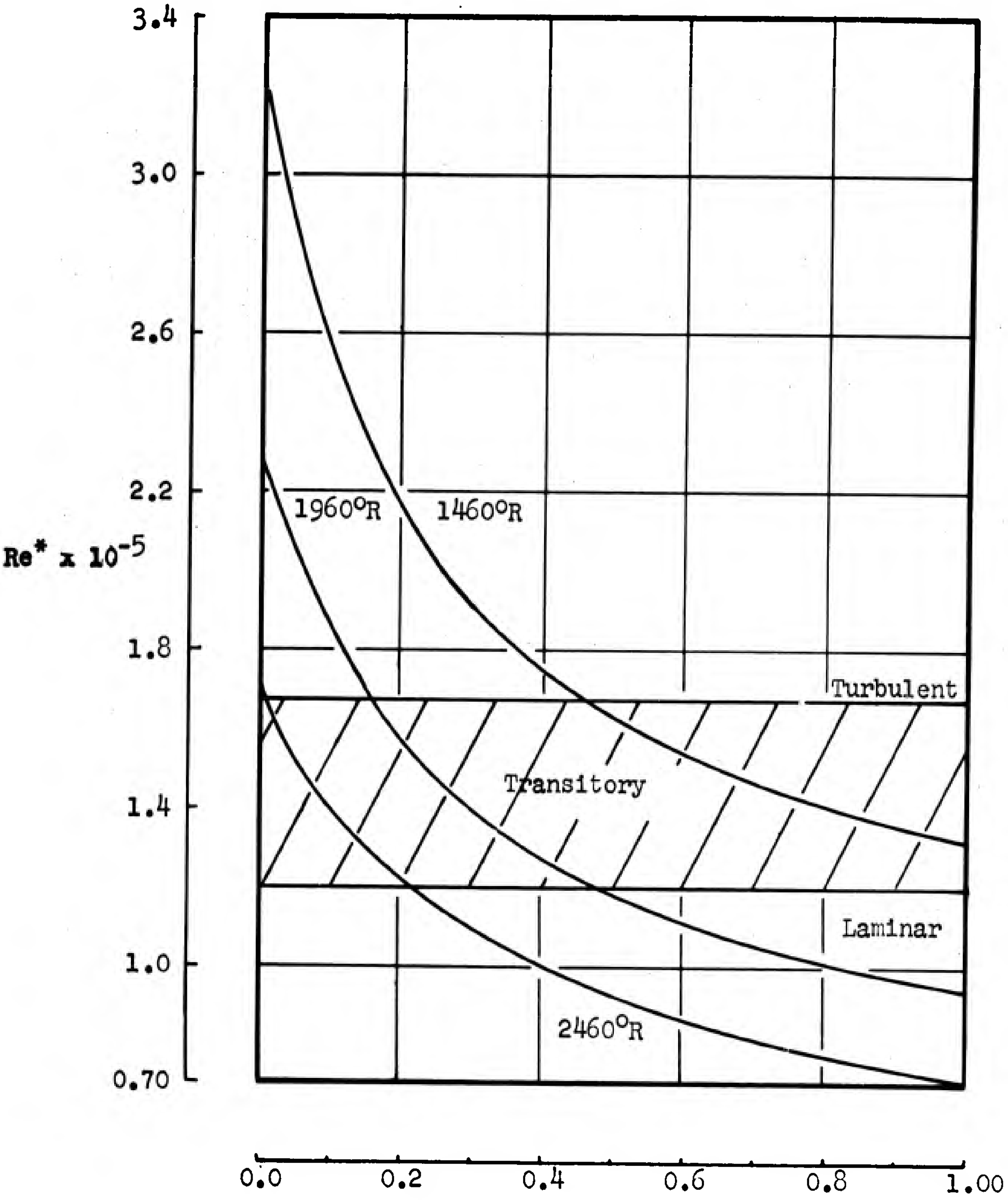


Figure 4: Throat Reynolds Number - P_o = 600 psia

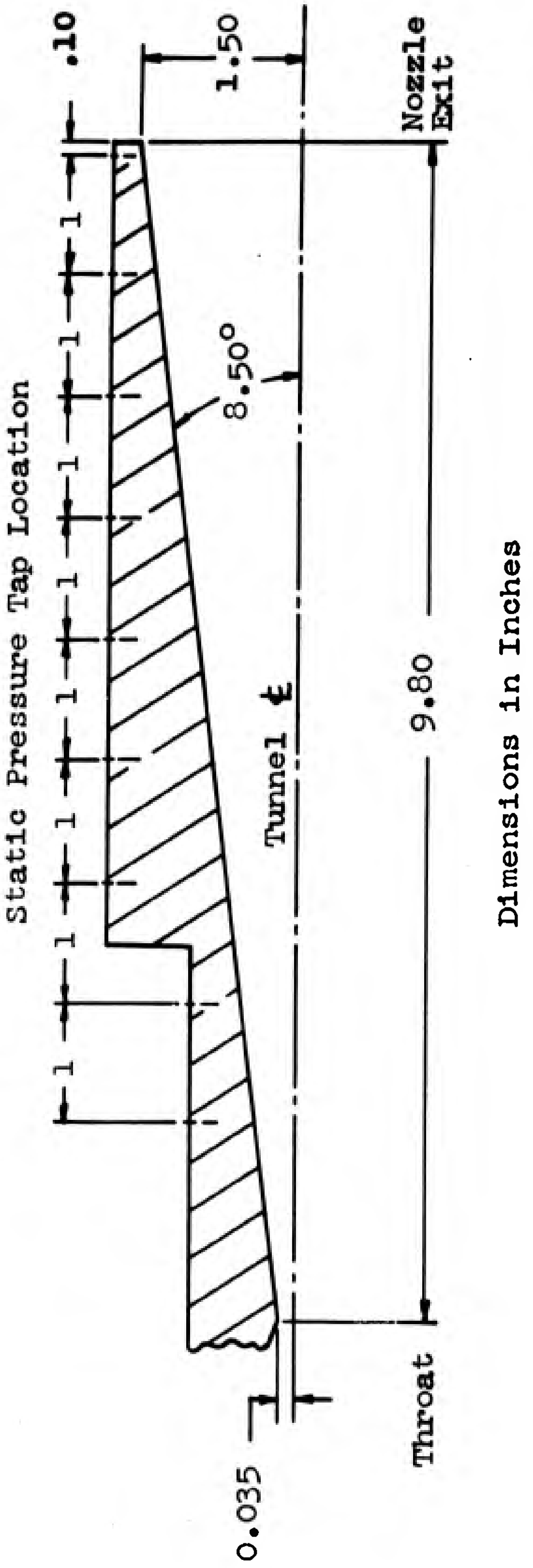


Figure 5: Nozzle Detail

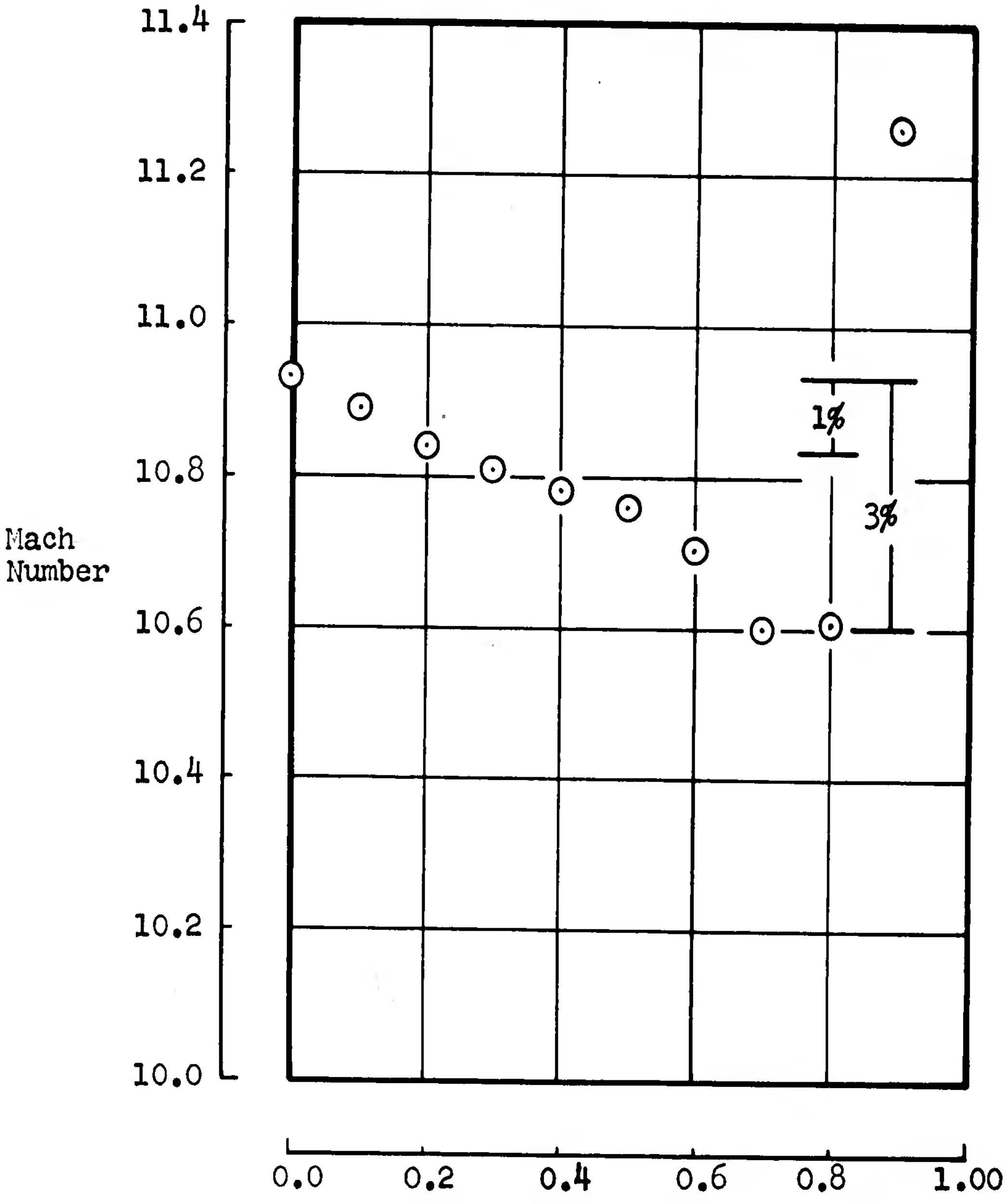


Figure 6: Nozzle Calibration: P_o = 214 psia
T_o = 1695°R

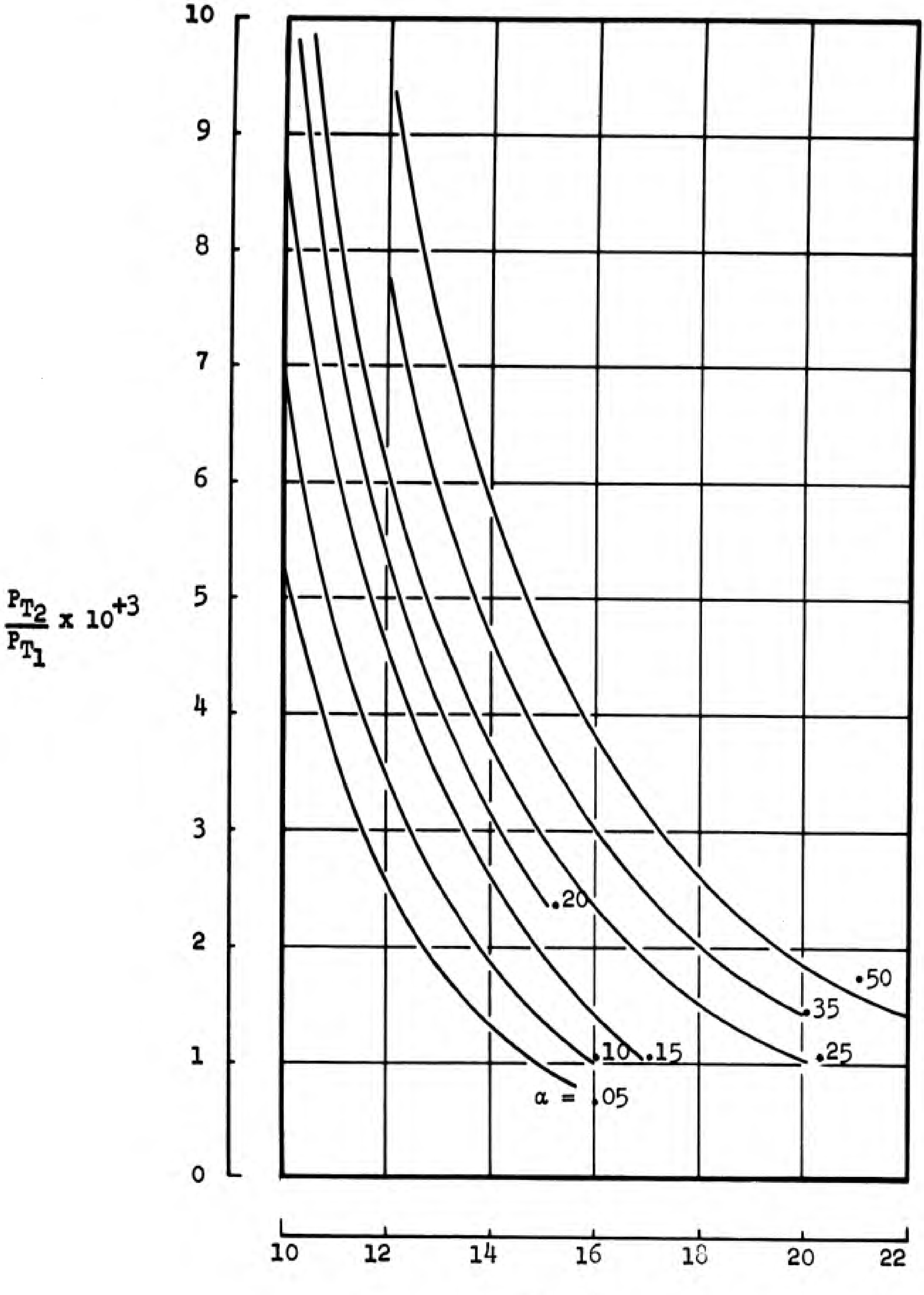
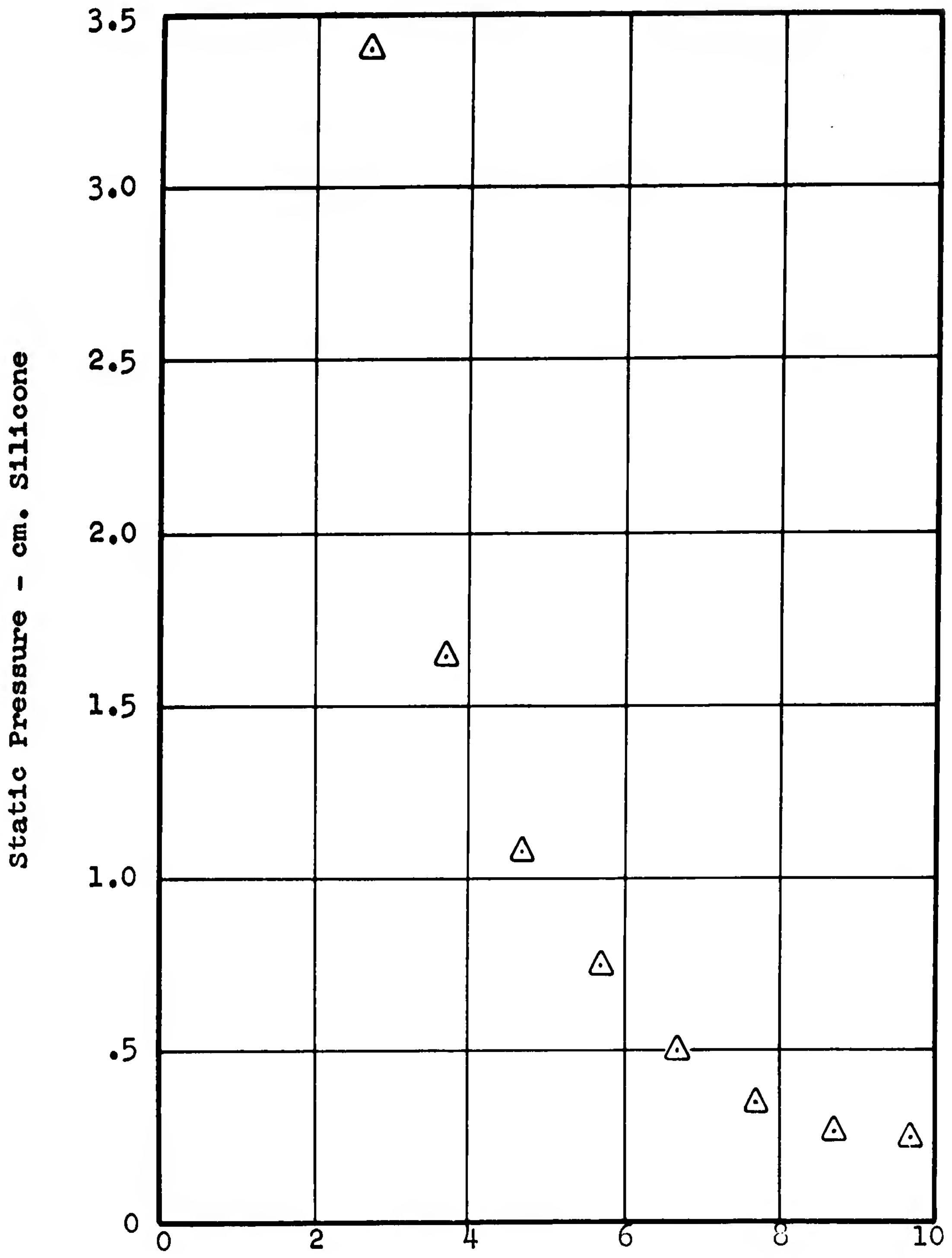


Figure 7: Impact Pressure Ratio



X - Inches From Throat

Figure 8: Nozzle Static Pressures - P_o = 200 psig
T_o = 1660°R, Probe on Center Line

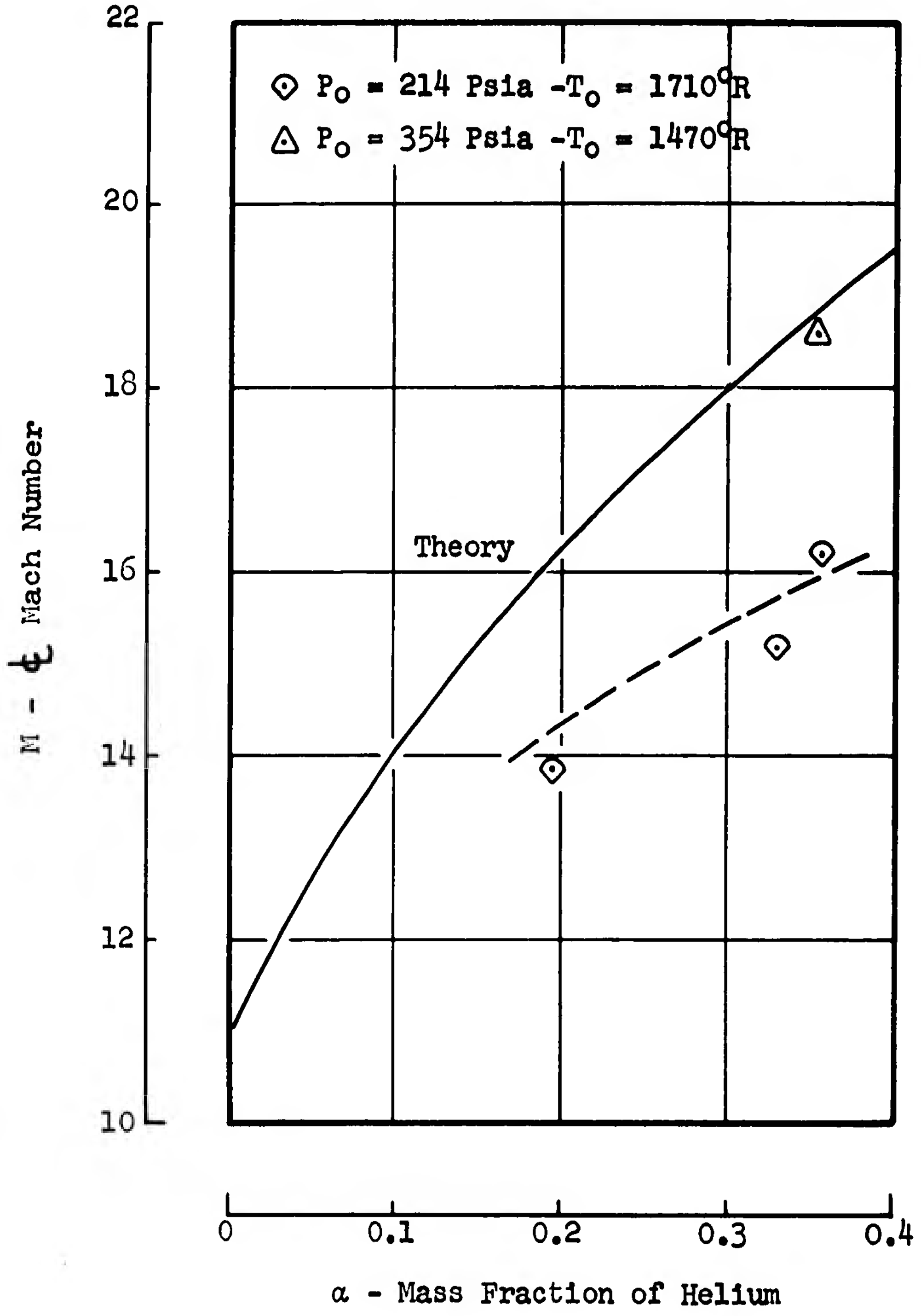


Figure 9: Mach Number Variation Due To Helium Injection

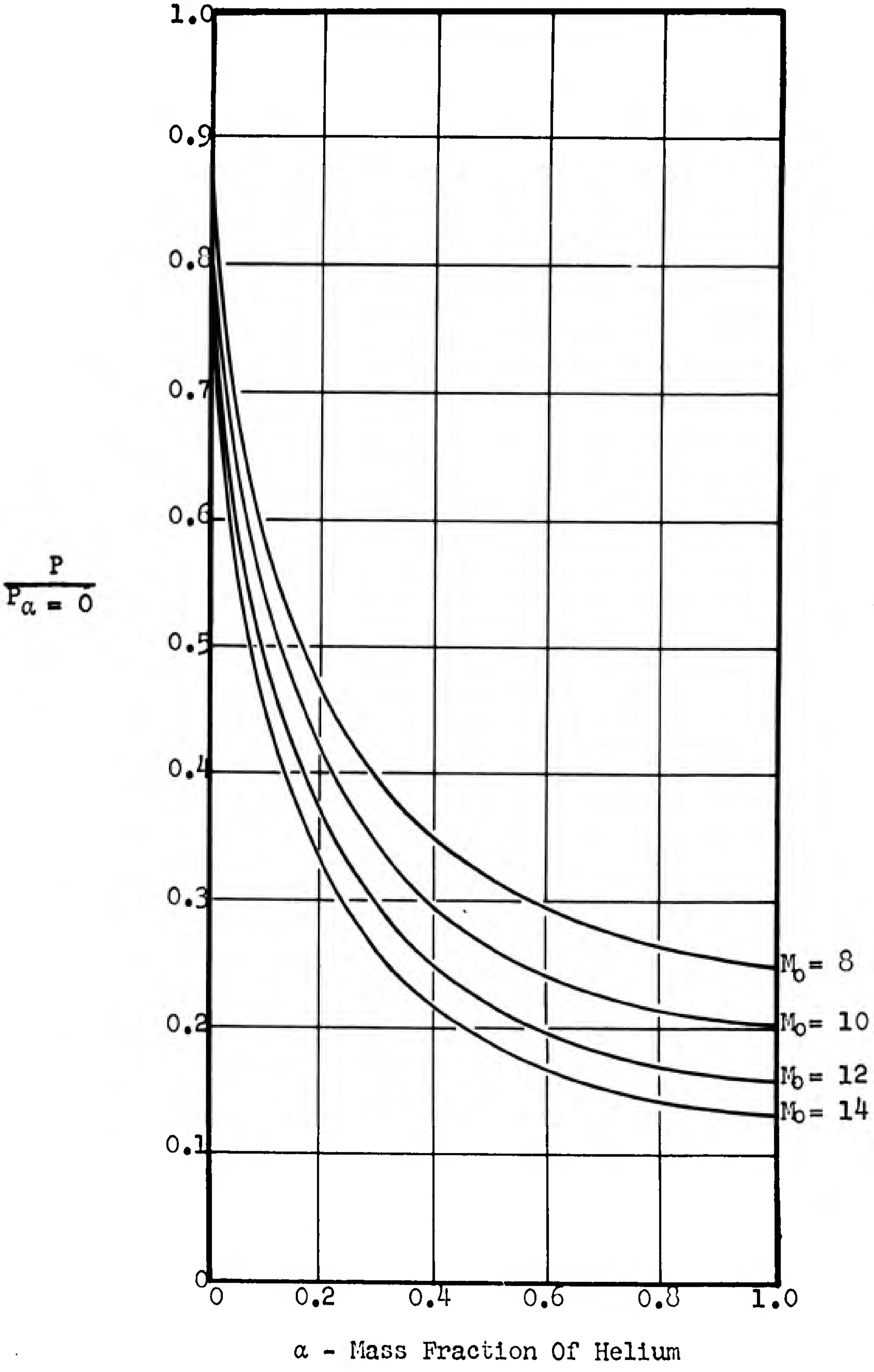


Figure 10: Static Pressure Variation Due to Helium Injection

Aeronautical Research Laboratories, **Wright-Patterson Air Force Base, Ohio.** A PRELIMINARY STUDY OF THE HYPERSONIC FLOW OF HELIUM-AIR MIXTURES by S. L. Petrie. July 1962. 27 p. incl 10 illus. (Project 7065; Task 7065-0) Contract AF 33(616)-5593 (ARL 62-375

Unclassified Report

Theoretical predictions have been developed to describe the effects of the addition of varying amounts of helium to the flow of air in a hypersonic wind tunnel. Much greater over-all flexibility in operational Mach number and Reynolds number has been demonstrated. Preliminary experimental studies have, in part, substantiated the theoretical predictions.

(over)

UNCLASSIFIED

UNCLASSIFIED

Various possibilities for the use of a helium-air mixture as a wind tunnel testing medium have been examined.

UNCLASSIFIED

UNCLASSIFIED

Aeronautical Research Laboratories, **Wright-Patterson Air Force Base, Ohio.** A PRELIMINARY STUDY OF THE HYPERSONIC FLOW OF HELIUM-AIR MIXTURES by S. L. Petrie. July 1962. 27 p. incl 10 illus. (Project 7065; Task 7065-0) Contract AF 33(616)-5593 (ARL 62-375

Unclassified Report

Theoretical predictions have been developed to describe the effects of the addition of varying amounts of helium to the flow of air in a hypersonic wind tunnel. Much greater over-all flexibility in operational Mach number and Reynolds number has been demonstrated. Preliminary experimental studies have, in part, substantiated the theoretical predictions.

(over)

UNCLASSIFIED

UNCLASSIFIED

Various possibilities for the use of a helium-air mixture as a wind tunnel testing medium have been examined.

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

Aeronautical Research Laboratories, Wright-Patterson Air Force Base, Ohio. A PRELIMINARY STUDY OF THE HYPERSONIC FLOW OF HELIUM-AIR MIXTURES by S. L. Petrie. July 1962. 27 p. incl 10 illus. (Project 7065; Task 7065-0) Contract AF 33(616)-5593 (ARL 62-375
Unclassified Report

Theoretical predictions have been developed to describe the effects of the addition of varying amounts of helium to the flow of air in a hypersonic wind tunnel. Much greater over-all flexibility in operational Mach number and Reynolds number has been demonstrated. Preliminary experimental studies have, in part, substantiated the theoretical predictions.

(over)

UNCLASSIFIED

UNCLASSIFIED

Various possibilities for the use of a helium-air mixture as a wind tunnel testing medium have been examined.

AF-WP-B-JUL 61 1M

UNCLASSIFIED

UNCLASSIFIED

Aeronautical Research Laboratories, Wright-Patterson Air Force Base, Ohio. A PRELIMINARY STUDY OF THE HYPERSONIC FLOW OF HELIUM-AIR MIXTURES by S. L. Petrie. July 1962. 27 p. incl 10 illus. (Project 7065; Task 7065-0) Contract AF 33(616)-5593 (ARL 62-375
Unclassified Report

Theoretical predictions have been developed to describe the effects of the addition of varying amounts of helium to the flow of air in a hypersonic wind tunnel. Much greater over-all flexibility in operational Mach number and Reynolds number has been demonstrated. Preliminary experimental studies have, in part, substantiated the theoretical predictions.

(over)

UNCLASSIFIED

UNCLASSIFIED

Various possibilities for the use of a helium-air mixture as a wind tunnel testing medium have been examined.

AF-WP-B-JUL 61 1M

UNCLASSIFIED