CONDITIONS FOR CHOKING IN A CYLINDRICAL COMBUSTION CHAMBER WITH EDDYING PRESSURE LOSSES

Thesis by

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SUMMARY AND ACKNOWLEDGEMENTS

Choking occurs in a cylindrical combustion chamber when the gas reaches sonic velocity at the outlet, and no more fuel can be burned without causing unstable combustion and possibly "blowout" of the flame. In this analysis, the conditions for choking and the maximum possible fuel-air ratio for given inlet conditions are determined by a trial and error method, which proves to give accuracy within about 1/2 percent. Entering Fig. 13, 14, or 15 with the given inlet conditions, the fuel-air ratio for choking (μ_2) is determined. From Fig. 16, 17, or 18, the temperature of the gas at the outlet is determined. Then γ_2 can be found from Fig. 1, 2, or 3, and the pressure and density of the gas at the outlet from equations (12) and (13).

If γ is assumed to remain constant over the temperature range involved, and constant with respect to change in the gas composition due to combustion, then it is possible to solve algebraicly for the conditions for choking. This approximation is reasonably valid for small fuel-air ratios, but may cause errors of over ten percent when the inlet temperature is low and the fuel-air ratio is high.

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SYMBOLS

$( )_1$	Subscript referring to inlet conditions in tail pipe (before combustion)
$( )_2$	Subscript referring to exit conditions in tail pipe (after combustion)
A	Cross-sectional area in tail pipe (sq. ft.)
p	Pressure (lb/sq. in)
ρ	Density (lb/cu.ft.)
T	Absolute temperature (^{o}R)
μ_1	Weight ratio of fuel to air in initial mixture
μ_2	Weight ratio of fuel to gas mixture entering tail pipe
v	Velocity (ft/sec.)
C_p	Specific heat at constant pressure BTU/(lb.mol) (^{o}R)
C_v	Specific heat at constant volume BTU/(lb.mol) (^{o}R)
γ	C_p/C_v (instantaneous ratio of specific heats at a given temperature)
g	Force of gravity (ft/sec.^{2})
h	Lower heating value of fuel (BTU/lb.)
Q	Heat added in the combustion chamber (BTU)
m	Mass of the gas
K	Friction constant
J	Conversion factor = 778 ft.lbs/BTU
Mav.	Average molecular weight of gas
R	Gas constant = R universal/Mav.

SYMBOLS
Cont'd

H	Enthalpy (BTU)
a	Velocity of sound (ft/sec.)
M	Mach number
C_h	Heating ratio - $\frac{\text{Heat added per unit mass}}{\text{Total energy per unit mass}}$
$\mathcal{E}$	Total energy in mixture (BTU)

INTRODUCTION

When gas enters a cylindrical combustion chamber at subsonic velocity, its speed may be increased by the addition of heat until sonic velocity is reached at the exit, and "choking" is said to occur. Mathematical analysis has shown (cf. Ref 1, page 431) that for a further increase in velocity, heat must actually be removed from the gas. In practice, the combustion is known to become unstable at about this point, and actual "blowout" of the flame may occur. For practical purposes, then, the maximum amount of fuel that can be burned in such a chamber is determined by the point at which choking occurs in the chamber. This condition is therefore of considerable interest as an upper limit in designs such as tail pipe injection of fuel for a turbo-jet engine.

The following investigation is intended to determine the conditions producing choking in such a tailpipe, and the maximum amount of fuel which can be burned, considering as parameters the composition of the entering gas, which depends on the fuel-air ratio in the turbojet ahead of the tailpipe (μ_1), and a range of inlet temperatures (T_1) from 1200 degrees to 4000 degrees Rankine.

PROCEDURE

In this analysis the following assumptions are made:

1. That gasoline is used as a fuel, with C_8H_{18} as the average chemical composition;
2. That complete mixing is obtained, giving even heat distribution across any section and completed checmical reactions in the combustion chamber;
3. That pressure losses due to turbulence are directly proportional to the dynamic pressure of the gas at the inlet to the combustion chamber;
4. That no heat is lost through the walls of the combustion chamber;

*5. That chemical dissociation of the products of cumbustion is negligible.

The first assumption is believed to be valid for most grades of gasoline, and this average composition is quite generally used. Complete mixing is assumed in order to simplify the problems, and is considered quite justifiable because of the turbulent flow. The third assumption seems intuitively to be reasonable, and good agreement has been found with experimental data. The amount of heat lost through the walls of the combustion chamber can safely be neglected because of the comparatively short interval of time required for any particle of gas to pass through the chamber. Chemical dissociation does not reach

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*This assumption is strictly justified only for temperatures up to 3500°R. Above 3500°R, dissociation causes significant errors in the gas compositions tabulated, but relatively less error in the enthalpy per pound of mixture.

magnitudes of any importance in the temperature range to be considered here.

From the condition of continuity of flow we can write:

$$\rho_1 v_1 A_1 (1 + \mu_2) = \rho_2 v_2 A_2$$

since $A_1 = A_2$

$$\rho_1 v_1 (1 + \mu_2) = \rho_2 v_2 \tag{1}$$

Since the rate of change of momentum of the gas is equal to the forces acting on the gas, we can write:

$$m_2 v_2 - m_1 v_1 = p_1 A_1 - p_2 A_2 - K/2 \, \rho_1 v_1^2 A_1$$

$$\frac{\rho_2 v_2 A_2 \cdot v_2}{g} - \frac{\rho_1 v_1 A_1 \cdot v_1}{g} = p_1 A_1 - p_2 A_2 - \frac{K}{2} \frac{\rho_1 v_1 A_1 \cdot v_1}{g}$$

$$\frac{\rho_2 v_2^2}{g} - \frac{\rho_1 v_1^2}{g}\left(1 - \frac{K}{2}\right) = p_1 - p_2 \tag{2}$$

Also, since it is assumed that no heat is lost through the walls, the total energy of the gas entering, plus the heat added in the combustion chamber, must equal the total energy of the gas leaving the chamber.

$$H_1 + \frac{v_1^2}{2g} + Q = (1 + \mu_2)\left(H_2 + \frac{v_2^2}{2g}\right) \tag{3}$$

or, since: $$v_2^2 = a_2^2 = \gamma_2 g R_2 T_2 \tag{4}$$

$$H_1 + \frac{v_1^2}{2g} + Q = (1 + \mu_2)\left(H_2 + \frac{\gamma_2 R_2 T_2}{2}\right) \tag{5}$$

From the equation of state,

$$\frac{p}{\rho} = RT \tag{6}$$

Equations 1, 2, 5, and 6, involving respectively continuity, momentum, energy, and the equation of state, provide the basis for this analysis. Since R is a function of the chemical composition and γ is a function of both the temperature and the composition of the gas, these four basic equations can be solved simultaneously for the four unknowns - velocity, pressure, density, and temperature.

If γ is assumed to remain constant over the temperature range involved, and also constant during the change in composition of the gas due to combustion, the solution is greatly simplified, and the four equations can be solved directly, as will be shown later. This assumption of constant γ is not true, however, and the relative magnitude of the errors resulting from such an assumption will be determined. Since the actual γ cannot conveniently be expressed directly as a mathematical function of temperature and composition, a somewhat more laborious "cut and try" solution must be used.

Suppose the problem of determining the maximum amount of fuel which can be burned with given inlet conditions is approached directly. Then V_1, p_1, ρ_1, T_1, and μ_1 are specified, and we are to determine the amount of heat to be added which will produce sonic velocity at some unknown temperature T_2 at the outlet. Using the "cut and try" method is unnecessarily complex, since for every new guess as to the heat required, a different amount of fuel must be burned, giving varying chemical compositions of the gas at the outlet, and consequently varying R_2 and γ_2. Then, since γ_2 also varies with the outlet temperature T_2, the problem becomes quite involved.

Instead, consider a less direct approach to the problem. Suppose we specify μ_2, the fuel-air ratio in the tail pipe, as well as μ_1, the fuel-air ratio in the gas turbine ahead of the tail pipe. With the chamical composition of the gas at the inlet and at the outlet thus considered stabilized, one of the most difficult variables has been removed, and the only problem now is to determine the inlet velocity V_1 which will satisfy the other specified conditions. If this is done for a range of fuel-air ratios in both the tail pipe and the gas turbine, the original problem is completely solved. This is the method which will be used in the following analysis.

As an example, suppose $\mu_1 = 0.02$ and $\mu_2 = 0.04$. The chemical reaction in the gas turbine can be represented by:

$$C_8H_{18} + 41.5\ O_2 + 156.1\ N_2 \rightarrow 8\ CO_2 + 9\ H_2O + 29\ O_2 + 156.1\ N_2$$

Then for the chemical reaction in the tail pipe, the equation is:

$$8\ CO_2 + 9\ H_2O + 29\ O_2 + 156.1\ N_2 + 2.04\ C_8H_{18} \rightarrow$$
$$24.32\ CO_2 + 27.36\ H_2O + 3.5\ O_2 + 156.1\ N_2$$

The weight ratios of the constituents of the mixture at the entrance and at the exit of the tail pipe are then computed to be:

Gas	Weight Fractions	
	Entrance	Exit
CO_2	0.0605	0.1770
H_2O	0.0279	0.0815
O_2	0.1596	0.0185
N_2	0.7519	0.7230
	0.9999	1.0000

The mol fractions of each constituent in the mixture at the exit are found to be:

Gas	Mol Fractions
CO_2	0.1151
H_2O	0.1295
O_2	0.0166
N_2	0.7388
	1.0000

The average molecular weight of the gas, M_{av} , is equal to the total molecular weight divided by the number of mols, so that,

$$M_{1\,av.} = \frac{5824.4}{202.5} = 28.75$$

$$M_{2\,av} = \frac{6045.36}{211.28} = 28.6$$

$$R = \frac{Runiv}{M_{av}}$$

$$R_1 = \frac{1545}{28.75} = 53.72$$

$$R_2 = \frac{1545}{28.6} = 54.0$$

Similar computations with μ_1 equal to .02, .03, and .04, and with μ_2 varying from zero to stoichiometric mixture ratios, yield the values of weight fractions, mol fractions, and R's listed in Tables I, II, and III, respectively.

In Table IV are listed values of H and C_p for CO_2, H_2O, O_2, and N_2, at temperatures ranging from 600 degrees to 5400 degrees Rankine. These values were obtained from Ref. 2, "Empirical Data on Thermal Properities of Gases", published by Georgia School of Technology and Mechanical Engineering. Continuing the example of $\mu_1 = .02$ and $\mu_2 = .04$, consider the case when $T_2 = 1500^\circ R$. Then γ_2 is found to be 1.311 BTU's per mol per degree Rankine, as follows:

Gas	Mol Fractions	C_p (per mol)	C_p (per Mol Fraction)
CO_2	0.1151	12.445	1.4324
H_2O	0.1295	9.299	1.2042
O_2	0.0166	8.119	0.1348
N_2	0.7388	7.571	5.5935
			8.3649 = C_p

$$\gamma_2 = \frac{C_p}{C_v} = \frac{C_p}{C_p - R} = \frac{8.3649}{8.3649 - 1.985} = 1.311$$

Similar computations, with μ_1 equal to .02, .03, and .04, and with μ_2 varying from zero to stoichiometric mixture ratios, yield the values of γ_2 listed in Table V. These values of γ_2 are shown plotted against T_2 in Figs. 1, 2, and 3.

Similarly, the enthalpy of the mixture at the outlet, H_2, is found to be 262.2 BTU's per lb. as follows:

Gas	Wt. Fraction	BTU/lb. Mol	BTU's
CO_2	0.1770	10,538	42.4
H_2O	0.0815	8,236	37.3
O_2	0.0185	7,279	4.2
N_2	0.7230	6,905	178.3

H_2 = 262.2 BTU's per lb.

Values of H_1 and H_2 for other fuel-air ratios and temperatures are listed in Table VI.

With the data thus far obtained, it is now possible to evaluate the right side of equation (5), which represents the total energy in the mixture leaving the combustion chamber per pound of entering gas. Denoting this total energy by $\mathcal{E}_2$, then when

$$\mu_1 = .02$$

$$\mu_2 = .04$$

$$T_2 = 1500^\circ R$$

$$\mathcal{E}_2 = (1+\mu_2)\left(H_2 + \frac{\gamma_2 R_2 T_2}{2J}\right)$$

$$\mathcal{E}_2 = (1.04)\left[262.2 + \frac{(1.311)\ (54.0)\ (1500)}{(2)\ (778)}\right] = 343.6 \text{ BTU's}$$

Similar computations yield the values of $\mathcal{E}_2$ listed in Table VII, and are plotted against T_2 in Figs. 4, 5, and 6 for μ_1 = .02, .03, and .04, respectively.

Referring now to the left side of equation (5), the value of H_1 at any temperature is known (Table VI). The only unknown appearing in the equation is V_1, which must now be expressed in terms of known quantities. From equations (4) and (6)

$$V_2^2 = \frac{\gamma_2 g p_2}{\rho_2}$$

$$\gamma_2 p_2 = \frac{\rho_2 V_2^2}{g} = \rho_2 V_2 \left(\frac{V_2}{g}\right) \tag{7}$$

Substituting this into equation (2):

$$\gamma_2 p_2 + p_2 = p_1 + \frac{\rho_1 V_1^2}{g}\left(1 - \frac{K}{2}\right)$$

$$p_2 = \frac{g p_1 + \rho_1 V_1^2 \left(1 - \frac{K}{2}\right)}{g(1 + \gamma_2)} \tag{8}$$

Also, by substituting equation (1) into (7),

$$p_2 = \frac{\rho_1 V_1 (1 + \mu_2) V_2}{g \gamma_2} \tag{9}$$

Then by equating (8) and (9), collecting terms, and replacing V_2 by its value in (4),

$$V_1^2 - \frac{(1+\mu_2)(1+\gamma_2)(g R_2 T_2)^{1/2}}{(1 - K/2)(\gamma_2)^{1/2}} V_1 + \frac{g R_1 T_1}{1 - K/2} = 0 \tag{10}$$

For selected values of μ_1, μ_2, and T_1, (which determine H_1, Q, R_1 and R) a value of V_1 is assumed, and $\mathcal{E}_1$ is computed. This represents the left side of equation (4). Since $\mathcal{E}_2$ equals $\mathcal{E}_1$, T_2 is determined from Fig. 4, 5, or 6. Then γ_2 is found from Fig. 1, 2, or 3. Equation (10) can then be solved for V_1. If this value does not agree with the assumed value, a second calculation is necessary, using the new V_1 to find $\mathcal{E}_1$. However, since the kinetic energy represents a small part of $\mathcal{E}_1$, more than two calculations are seldom necessary, especially after a few points on the velocity curve have been determined.

In this analysis the eddying pressure loss has been assumed to equal $\frac{1}{4}\rho_1 V_1^2$, so that K equals 0.5. Using the lower heating value of gasoline as 19,450 BTU's per pound, and assuming a combustion efficiency of 90 per cent,

$$Q = \mu_2(19{,}450)\,(.90) = 17{,}500\,\mu_2.$$

As an example, consider the case when:

$$\mu_1 = .02$$
$$\mu_2 = .04$$
$$T_1 = 2000^\circ R$$

$$H_1 = 390.5 \text{ BTU's} \quad \text{(Table VI)}$$

$$Q = (.04)\,(17{,}500) = 700 \text{ BTU's}$$

$$R_1 = 53.72 \qquad R_2 = 54.0 \quad \text{(Table III)}$$

Equation (10) reduces to:

$$V_1^2 - \frac{57.75\,(1+\gamma_2)(T_2)^{1/2}}{(\gamma_2)^{1/2}}\,V_1 + 2308\,T_1 = 0 \tag{11}$$

As a first approximation, assume v_1 = 650 ft/sec.

Then $\frac{v_1^2}{2gJ}$ = 8.4 BTU's

and $\mathcal{E}_1$ = 390.5 + 700 + 8.4 = 398.9 BTU's

From Fig. 4, T_2 = 3500°R

From Fig. 1, γ_2 = 1.257

Substituting these values in equation (11) and solving for the lower root (cf. Ref. 1), we find,

$$v_1 = 750 \text{ ft/sec.}$$

Then $\frac{v_1^2}{2gJ}$ = 11.2 BTU's

and $\mathcal{E}_1$ = 390.5 + 700 + 11.2 = 1101.7 BTU's

So T_2 = 3505°R

γ_2 = 1.257 as before.

It should be noted that although the first trial value of v_1 was considerably in error, the results obtained are sufficiently accurate so that a second computation is not necessary, since the only change in the second computation would be $(3505)^{\frac{1}{2}}$ instead of $(3500)^{\frac{1}{2}}$.

Tables VIII and IX list the results obtained for a series of similar solutions for v_1 and T_2, with μ_1 equal to .02, .03, and .04, and with μ_2 varying from zero to a stoichiometric mixture ratio. Figs. 7, 8, and 9 show curves of v_1 vs. T_1, and in Figs. 10, 11, and 12 are curves of T_2 vs. T_1 similarly plotted. For greater facility in use, Figs. 13, 14, and 15 show curves of μ_2 vs. v_1, and Figs. 16, 17, and 18 show curves of T_2 vs μ_2.

With the results now obtained it is possible to evaluate the pressure ratio, p_2/p_1, for any given inlet conditions. From equation (7),

$$(1 + \gamma_2)p_2 - p_1 = \frac{\rho_1 v_1^2}{g} (1 - K/2)$$

$$(1 + \gamma_2)\frac{p_2}{p_1} - 1 = \frac{\rho_1 v_1^2 (1 - K/2)}{p_1 g}$$

$$p_2/p_1 = \frac{1 + \frac{v_1(1 - K/2)}{gR_1T_1}}{(1 + \gamma_2)} = \frac{gR_1T_1 + v_1(1 - K/2)}{gR_1T_1(1 + \gamma_2)} \qquad (12)$$

Using a value of K equal to 0.5 as before, Fig. 19 shows curves of p_2/p_1 vs. μ_2, when $\mu_1 = .02$.

The only remaining unknown, ρ_2, can be determined from equation (1):

$$\rho_2 = \frac{\rho_1 v_1(1 + \mu_2)}{v_2} \qquad (13)$$

RESULTS AND DISCUSSION

The original problem of determining the conditions for choking in a cylindrical combustion chamber has now been completely solved for the case where the eddying pressure loss is equal to $\frac{1}{4}\rho_1 v_1^2$, which is an average value encountered in practice. For given inlet conditions, the value of μ_2 is obtained from Fig. 13, 14, or 15. This is dependent only on v_1, T_1, and μ_1. T_2 is obtained from Fig. 16, 17, or 18, and p_2 and ρ_2 from equations (12) and (13) respectively.

Before proceeding further with any discussion, it is of interest to check the accuracy of the results obtained by this method. Assume, for example,

$$\mu_1 = .02$$
$$\mu_2 = .04$$
$$T_1 = 2000^\circ R$$
$$p_1 = 14.7 \text{ psi}$$

Then

$$v_1 = 750 \text{ ft/sec.}$$
$$T_2 = 3505^\circ R$$
$$\gamma_1 = 1.312$$
$$\gamma_2 = 1.257$$
$$R_1 = 53.72$$
$$R_2 = 54.0$$
$$K = 0.5$$
$$p_2/p_1 = 0.496$$

$$v_2 = (\gamma_2 g R_2 T_2)^{\frac{1}{2}} = 2767.8 \text{ ft/sec.}$$

$$\rho_1 = \frac{p_1}{R_1 T_1} = 0.01971 \text{ lb/ft.}^3$$

$$\rho_2 = \frac{\rho_1 v_1 (1 + \mu_2)}{v_2} = 0.00554 \text{ lb/ft.}^3$$

$$p_2 = 0.496\, p_1 = 1049.9 \text{ lb/ft.}^2$$

As was shown previously, the energy equation was satisfied in the trial and error solution, so that,

$$H_1 + Q + \frac{v_1^2}{2g} = \mathcal{E}_2(T_2)$$

$$390.5 + 700 + 11.2 \approx 1102 \text{ BTU's} \quad \text{(Fig. 4)}$$

The continuity equation is satisfied by the solution for ρ_2 above. Then using these derived values, we should get an equality in the momentum equation:

$$\frac{\rho_2 v_2^2}{g} - \frac{(1 - K/2)(\rho_1 v_1^2)}{g} = p_1 - p_2$$

$$\frac{(.005554)(2767.8)^2}{32.2} - \frac{(.75)(.01971)(750)^2}{32.2} = 2116.8 - 1049.9$$

$$1321 - 258 = 1067$$

$$1063 \approx 1067$$

This seems to indicate acceptable accuracy in the method of solution employed.

Since γ_2 does not vary greatly with small changes in temperature, or with the change in composition of gas due to combustion, it is of interest to compare the results obtained in this analysis with those which would be obtained if γ were assumed to remain constant. From equation (2),

$$g(p_1 - p_2) = \rho_2 v_2^2 - \rho_1 v_1^2 (1 - K/2)$$

a nd substituting from (1),

$$gp_2\left(\frac{p_1}{p_2} - 1\right) = \rho_2 v_2^2 - \frac{\rho_2 v_2 v_1 (1 - K/2)}{(1 + \mu_2)}$$

$$\frac{p_1}{p_2} - 1 = \frac{\gamma \rho_2 v_2^2}{\gamma g p_2} \left[1 - \frac{(1 - K/2)}{(1 + \mu_2)} \frac{v_1}{v_2}\right]$$

$$\frac{p_1}{p_2} = 1 + \gamma M_2^2 \left[1 - \frac{(1 - K/2)}{(1 + \mu_2)} \frac{v_1}{v_2}\right]$$

But $M_2 = 1$

$$\therefore \frac{p_1}{p_2} = (1 + \gamma) - \frac{\gamma (1 - K/2)}{(1 + \mu_2)} \left(\frac{v_1}{v_2}\right) \qquad (14)$$

From equation (4),

$$H_1 + \frac{v_1^2}{2g} + Q = (1 + \mu_2) \left(H_2 + \frac{v_2^2}{2g} \right)$$

But $H = C_pT = \frac{C_pRT}{R} = \frac{C_p}{R}\frac{p}{\rho} = \left(\frac{\gamma}{\gamma-1}\right)\frac{p}{\rho} = \left(\frac{1}{\gamma-1}\right)\frac{a^2}{g}$ (15)

So: $$(1+\mu_2)\left[\left(\frac{1}{\gamma-1}\right)\frac{a_2^2}{g} + \frac{v_2^2}{2g}\right] - \left[\left(\frac{\gamma}{\gamma-1}\right)\frac{p_1}{\rho_1} + \frac{v_1^2}{2g}\right] = Q$$

Define: $$C_h = \frac{Q}{H_1 + \frac{v_1^2}{2g}}$$

Then:

$$(1+\mu_2)\left[\left(\frac{1}{\gamma-1}\right)\frac{a_2^2}{g} + \frac{v_2^2}{2g}\right] - \left[\left(\frac{\gamma}{\gamma-1}\right)\frac{p_1}{\rho_1} + \frac{v_1^2}{2g}\right](1+C_h) = 0$$

Dividing by equation (15):

$$(1+\mu_2)\left[1 + \frac{\gamma-1}{2}M_2^2\right] - \left[\frac{p_1}{p_2}\frac{\rho_2}{\rho_1} + \frac{\gamma-1}{2}M_2^2\left(\frac{v_1}{v_2}\right)^2\right](1+C_h) = 0$$

But $M_2 = 1$, and $\frac{\rho_2}{\rho_1} = \frac{v_1}{v_2}(1+\mu_2)$; so

$$(1+\mu_2)\left(\frac{\gamma+1}{2}\right) - \left[(1+\mu_2)\left(\frac{p_1}{p_2}\right)\left(\frac{v_1}{v_2}\right) + \left(\frac{\gamma-1}{2}\right)\left(\frac{v_1}{v_2}\right)^2\right](1+C_h) = 0$$

Substituting for p_1/p_2 by equation (14) and collecting terms, we get:

$$\left[\left(\frac{\gamma-1}{2}\right) - \gamma(1 - K/2)\right]\left(\frac{v_1}{v_2}\right)^2 + \left[(1+\gamma)(1+\mu_2)\right]\left(\frac{v_1}{v_2}\right) - \frac{(1+\mu_2)(\gamma+1)}{2(1+C_h)} = 0$$

Solving for $\frac{v_1}{v_2}$ and using the lower root (cf. Ref. 1),

$$\frac{v_1}{v_2} = \left[\frac{(\gamma + 1)(1 + \mu_2)}{(\gamma - \gamma K - 1)}\right]\left[1 - \sqrt{1 - \frac{(\gamma - \gamma K + 1)}{(\gamma + 1)(1 + \mu_2)(1 + C_h)}}\right] \quad (16)$$

To compare the results of this simplified method with the actual solutions previously obtained, suppose that γ is computed for inlet conditions, and assumed to remain constant. Then for the case when,

$$\mu_1 = .02$$
$$T_1 = 2000^\circ R$$
$$K = 0.5$$
$$\mu_2 = 0 \quad (C_h = 0)$$
$$\gamma = 1.312 \quad \text{(Fig. 1)}$$

From equation (16)

$$\frac{v_1}{v_2} = \left[\frac{(2.312)}{1.312 - (.5)(1.312) + 1}\right]\left[1 - \sqrt{1 - \frac{1.312 - (.5)(1.312) + 1}{(2.312)}}\right]$$

$$\frac{v_1}{v_2} = 0.652$$

$$\left(\frac{v_1}{v_2}\right) \text{exact} = \frac{1378}{\left[(1.319)(32.2)(53.72)(1830)\right]^{\frac{1}{2}}} = 0.674$$

From equation (14):

$$p_1/p_2 = 2.312 - (1.312)(.75)(.652) = 1.67$$

$$p_2/p_1 = 0.599$$

$$\left(p_2/p_1\right)_{exact} = 0.599 \qquad \text{(Fig. 19)}$$

The error in the velocity ratio computed by the simplified method is -3.3 percent, and there is no error in the pressure ratio.

With the same inlet conditions, but with $\mu_2 = 0.04$,

$$C_h = \frac{Q}{H_1 + \frac{v_1^2}{2g}}$$

$$Q = (.04)(17{,}500) = 700 \text{ BTU's}$$

$$H_1 = \left(\frac{1}{\gamma - 1}\right)\left(\frac{a_1^2}{g}\right) = \frac{\gamma R_1 T_1}{(\gamma - 1)} = 582 \text{ BTU's}$$

$$\frac{v_1^2}{2gJ} = \frac{(750)^2}{(64.4)(778)} = 11.2 \text{ BTU's}$$

$$C_h = \frac{700}{593.2} = 1.18$$

Then from equation (16), $\frac{v_1}{v_2} = 0.251$

and from equation (17), $\frac{p_2}{p_1} = 0.483$

The exact solution gave,

$$\frac{v_1}{v_2} = 0.271$$

$$p_2/p_1 = 0.496$$

The error in the velocity ratio with a high heat input has increased to -7.4 percent and the error in pressure ratio is -2.6 percent. It should be emphasized that H_1 as defined above must be used in computing C_h in the simplified solution. The actual H_1 from Table VI differs greatly from this defined value and use of the actual H_1 will give an error of nearly thirty percent.

Similar comparisons at other inlet conditions show that the errors resulting from assuming γ to be constant increase with reduced inlet temperatures and with high fuel-air ratios in the combustion chamber. When $T_1 = 1200^{o}R$ and $\mu_2 = .04$, the error in the velocity ratio is -10.2 percent and in the pressure ratio is -4.0 percent. This trend might be expected, since from Fig. 1 it can be seen that γ changes most rapidly at low temperatures, and also changes increasingly with increased fuel-air ratios. It is also of interest to note that if γ is evaluated at the inlet and assumed to remain constant, the errors in $^{v}1/v_2$ and $^{p}2/p_1$ are always negative.

CONCLUSIONS AND RECOMMENDATIONS

For given conditions of temperature, velocity, and gas composition at the inlet of a cylindrical combustion chamber, with eddying pressure losses equal to $\frac{1}{4}\rho_1 v_1^2$, the fuel-air ratio required to produce sonic velocity at the outlet can be determined from Figs. 13, 14, or 15. This fuel-air ratio is independent of the inlet pressure and density. The gas temperature at the outlet can be determined from Figs. 16, 17, or 18, and the pressure and density from equations (12) and (13).

For an approximate solution to the problem, γ may be evaluated at the inlet to the combustion chamber and assumed to remain constant. Errors in the results thus obtained are generally quite small, but may amount to over 10 percent under conditions of low inlet temperatures and high fuel-air ratios.

The results of the present investigation indicate that to burn any appreciable quantity of fuel in the tail pipe of a turbojet to obtain additional thrust for very high speed flight, the inlet velocity to the burner in the tail pipe must be lower than approximately 800 ft. per sec. On the other hand, the velocity in the tail pipe of a conventional turbojet unit is generally higher than 1500 ft. per sec. because of the difficulty in stressing the turbine blades at the high operating temperatures. Therefore, for the current design of a projected airplane of very high speed, the exhaust gas from the turbine must be slowed down by the use of a diffuser. This is essential for obtaining large thrust-boost.

REFERENCES

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2. Empirical Data on Thermal Properties of Gases - Bulletin No. 2, January 1941, Georgia School of Technology and Mechanical Engineering.

Composition of Gases - Weight Fractions

$\mu_1 = .02$

Gas \ μ_2	.0	.01	.02	.03	.04	.0445
CO_2	.0605	.0905	.1186	.1488	.1770	.1923
H_2O	.0279	.0417	.0546	.0685	.0815	.0885
O_2	.1596	.1233	.0896	.0528	.0185	.0000
N_2	.7519	.7445	.7374	.7300	.7230	.7192
	0.9999	1.0000	1.0002	1.0001	1.0000	1.0000

$\mu_1 = .03$

Gas \ μ_2	0	.01	.02	.03	.0346
CO_2	.0926	.1224	.1522	.1820	.1925
H_2O	.0426	.0563	.0701	.0841	.0888
O_2	.1213	.0850	.0486	.0123	.0000
N_2	.7435	.7363	.7291	.7216	.7187
	1.0000	1.0000	1.0000	1.0000	1.0000

$\mu_1 = .04$

Gas \ μ_2	0	.01	.02	.0237
CO_2	.1235	.1514	.1830	.1919
H_2O	.0568	.0700	.0841	.0871
O_2	.0831	.0489	.0110	.0000
N_2	.7366	.7297	.7219	.7210
	1.0000	1.0000	1.0000	1.0000

TABLE I

Composition of Gases - Mol Fractions

$\mu_1 = .02$

Gas \ μ_2	0	.01	.02	.03	.04	.0445
CO_2	.0396	.0584	.0773	.0968	.1151	.1250
H_2O	.0445	.0658	.0870	.1090	.1295	.1406
O_2	.1435	.1138	.0802	.0473	.0166	.0000
N_2	.7724	.7620	.7555	.7569	.7388	.7344
	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

$\mu_1 = .03$

Gas \ μ_2	0	.01	.02	.03	.0346
CO_2	.0605	.0798	.0993	.1183	.1251
H_2O	.0680	.0897	.1115	.1137	.1411
O_2	.1089	.0762	.0435	.0110	.0000
N_2	.7626	.7543	.7457	.7370	.7338
	1.0000	1.0000	1.0000	1.0000	1.0000

$\mu_1 = .04$

Gas \ μ_2	0	.01	.02	.0237
CO_2	.0805	.0985	.1190	.1248
H_2O	.0905	.1114	.1137	.1386
O_2	.0744	.0438	.0098	.0000
N_2	.7545	.7463	.7375	.7367
	.9999	1.0000	1.0000	1.0001

TABLE II

Values of R2 and Mav.

$\mu_1 = .02$

μ_2	Mav.	R_2
.0	28.75	53.72
.01	28.72	53.79
.02	28.70	53.80
.03	28.65	53.90
.04	28.60	54.00
.0445	28.56	54.10

$\mu_1 = .03$

μ_2	Mav.	R_2
.0	29.0	53.8
.01	28.7	53.9
.02	28.63	53.95
.03	28.60	54.00
.0346	28.57	54.05

$\mu_1 = .04$

μ_2	Mav.	R_2
.0	28.68	53.85
.01	28.64	53.9
.02	28.6	54.0
.0237	28.58	54.02

TABLE III

Carbon Dioxide and Water

CO_2 (M = 44.00)

T	C_p	H
600	9.283	547
700	9.788	1499
800	10.251	2502
900	10.670	3550
1000	11.049	4637
1100	11.392	5759
1200	11.695	6913
1300	11.970	8096
1400	12.218	9305
1500	12.445	10538
1600	12.650	11794
1700	12.832	13069
1800	13.005	14362
1900	13.159	15671
2000	13.298	16994
2100	13.425	18330
2200	13.541	19678
2300	13.648	21037
2400	13.747	22406
2500	13.839	23785
2600	13.923	25174
2700	14.002	26570
2800	14.075	27974
2900	14.142	29385
3000	14.205	30803
3100	14.264	32227
3200	14.317	33656
3300	14.369	35091
3400	14.417	36531
3500	14.460	37975
3600	14.501	39243
3700	14.539	40875
3800	14.575	42331
3900	14.610	43790
4000	14.644	45253
4100	14.677	46720
4200	14.708	48190
4300	14.739	49662
4400	14.768	51136
4500	14.797	52614
4600	14.824	54094
4700	14.850	55577
4800	14.875	57063
4900	14.899	58553
5000	14.922	60645
5100	14.944	61539
5200	14.965	63035
5300	14.984	64532
5400	15.003	66030

H_2O (M = 18.016)

C_p	H	T
8.044	481	600
8.136	1291	700
8.249	2110	800
8.379	2940	900
8.523	3784	1000
8.669	4643	1100
8.821	5518	1200
8.977	6408	1300
9.136	7314	1400
9.299	8236	1500
9.464	9174	1600
9.631	10128	1700
9.799	11099	1800
9.964	12087	1900
10.127	13092	2000
10.287	14114	2100
10.443	15152	2200
10.595	16205	2300
10.742	17272	2400
10.883	18353	2500
11.019	19447	2600
11.151	20555	2700
11.274	21675	2800
11.392	22807	2900
11.505	23951	3000
11.613	25106	3100
11.717	26272	3200
11.815	27449	3300
11.910	28636	3400
12.000	29833	3500
12.086	31039	3600
12.167	32253	3700
12.244	33475	3800
12.318	34704	3900
12.388	35940	4000
12.455	37182	4100
12.519	38430	4200
12.580	39684	4300
12.639	40944	4400
12.695	42210	4500
12.748	43482	4600
12.798	44760	4700
12.846	46043	4800
12.892	47331	4900
12.935	48623	5000
12.976	49919	5100
13.015	51219	5200
13.052	52522	5300
13.088	53828	5400

Enthalpy Values - BTU/lb. Mol above 540°R

TABLE IV

Nitrogen and Oxygen

N_2 (M = 28.016)

T	C_p	H
600	6.968	418
700	6.986	1116
800	7.019	1816
900	7.071	2520
1000	7.140	3231
1100	7.216	3950
1200	7.300	4676
1300	7.389	5411
1400	7.482	6154
1500	7.571	6905
1600	7.657	7665
1700	7.740	8435
1800	7.821	9214
1900	7.899	10001
2000	7.971	10795
2100	8.036	11596
2200	8.094	12402
2300	8.148	13214
2400	8.199	14031
2500	8.247	14853
2600	8.292	15680
2700	8.334	16511
2800	8.373	17346
2900	8.410	18185
3000	8.444	19028
3100	8.475	19874
3200	8.504	20723
3300	8.531	21575
3400	8.557	22430
3500	8.581	23287
3600	8.604	24146
3700	8.625	25007
3800	8.646	25871
3900	8.665	26737
4000	8.684	27605
4100	8.701	28474
4200	8.717	29345
4300	8.733	30218
4400	8.747	31092
4500	8.761	31967
4600	8.774	32843
4700	8.786	33721
4800	8.798	34601
4900	8.809	35482
5000	8.820	36364
5100	8.831	37246
5200	8.841	38129
5300	8.851	39013
5400	8.860	39898

O_2 (M = 32.00)

C_p	H	T
7.075	423	600
7.174	1136	700
7.297	1860	800
7.434	2596	900
7.570	3345	1000
7.700	4109	1100
7.822	4885	1200
7.931	5672	1300
8.030	6471	1400
8.119	7279	1500
8.201	8095	1600
8.275	8918	1700
8.341	9749	1800
8.399	10587	1900
8.452	11431	2000
8.501	12279	2100
8.548	13131	2200
8.591	13987	2300
8.631	14848	2400
8.669	15712	2500
8.705	16580	2600
8.740	17453	2700
8.774	18329	2800
8.807	19208	2900
8.840	20091	3000
8.872	20977	3100
8.903	21866	3200
8.935	22759	3300
8.966	23654	3400
8.998	24552	3500
9.029	25454	3600
9.059	26360	3700
9.098	27268	3800
9.118	28179	3900
9.148	29092	4000
9.177	30008	4100
9.206	30928	4200
9.234	31850	4300
9.262	32774	4400
9.290	33701	4500
9.317	34631	4600
9.344	35565	4700
9.371	36501	4800
9.397	37440	4900
9.423	38382	5000
9.449	39325	5100
9.474	40270	5200
9.498	41218	5300
9.522	42168	5400

Enthalpy Values - BTU/lb. Mol above 540°R

TABLE IV

Values of γ_2

$\mu_1 = .02$

μ_2 \ T_2	1500	2000	2500	3000	3500	4000	4500	5000
0	1.334	1.312	1.298	1.289	1.282	1.277	1.273	1.270
.01	1.328	1.306	1.291	1.282	1.275	1.270	1.266	1.263
.02	1.322	1.2995	1.285	1.276	1.269	1.264	1.260	1.257
.03	1.317	1.294	1.279	1.270	1.263	1.258	1.254	1.251
.04	1.311	1.288	1.273	1.264	1.257	1.252	1.249	1.246
.0445	1.309	1.285	1.271	1.261	1.254	1.250	1.246	1.243

$\mu_1 = .03$

μ_2 \ T_2	1500	2000	2500	3000	3500	4000	4500	5000
0	1.3275	1.3051	1.2909	1.2810	1.2744	1.2694	1.2657	1.2626
.01	1.3218	1.2995	1.2846	1.2747	1.2681	1.2632	1.2595	1.2565
.02	1.3161	1.2930	1.2768	1.2676	1.2617	1.2571	1.2534	1.2506
.03	1.3102	1.2874	1.2726	1.2628	1.2560	1.2512	1.2474	1.2446
.0346	1.3082	1.2853	1.2707	1.2608	1.2540	1.2491	1.2455	1.2426

$\mu_1 = .04$

μ_2 \ T_2	1500	2000	2500	3000	3500	4000	4500	5000
0	1.3215	1.2987	1.2843	1.2746	1.2679	1.2630	1.2593	1.2564
.01	1.3159	1.2931	1.2786	1.2688	1.2621	1.2572	1.2534	1.2506
.02	1.3100	1.2871	1.2725	1.2626	1.2559	1.2509	1.2474	1.2443

TABLE V

Values of H - BTU's

Values of H_1 - (Inlet)

T_1 °R	1200	1600	2000	2400	2800	3200	3600	4000
For μ_1 = .02 H_1	168	278.4	390.6	509.0	629.0	752.0	878.1	1004.0
For μ_1 = .03 H_1	170.3	280.7	396.7	516.9	640.1	766.0	893.5	1023.3
For μ_1 = .04 H_1	172.5	284.8	402.7	525.0	650.8	779.3	909.4	1042.2

Values of H_2

μ_1 = .02

μ_2 \ T_2 °R	1500	2000	2500	3000	3500	4000	4500	5000
0	245.9	390.5	535.7	691.3	860.1	1004	1164.0	1325.1
.01	251.8	396.4	546.9	702.1	861.0	1022.2	1185.9	1350.9
.02	256.0	401.5	554.8	712.9	876.2	1039.5	1205.6	1376.1
.03	259.1	406.7	564.4	725.4	890.3	1058.2	1224.7	1402.7
.04	262.2	412.7	571.4	735.1	903.2	1074.2	1247.8	1422.8
.0445	264.0	418.6	575.8	741.0	911.0	1084.6	1257.3	1436.2

μ_1 = .03

μ_2 \ T_2 °R	1500	2000	2500	3000	3500	4000	4500	5000
0	250.0	390.0	545.8	702.3	861.8	1032.4	1189.1	1362.0
.01	254.1	394.1	555.7	713.4	876.7	1041.7	1211.3	1377.1
.02	259.4	398.2	564.3	725.8	891.1	1059.4	1229.9	1402.2
.03	263.7	414.1	573.0	737.5	906.1	1077.8	1251.8	1427.6
.0346	264.0	416.0	575.9	741.4	911.1	1088.1	1259.1	1436.1

μ_1 = .04

μ_2 \ T_2 °R	1500	2000	2500	3000	3500	4000	4500	5000
0	256.9	402.7	555.1	715.6	877.8	1042.2	1209.3	1380.0
.01	259.4	408.2	564.3	725.8	891.3	1059.4	1229.8	1402.1
.02	262.8	414.5	573.1	737.6	906.3	1078.0	1251.9	1427.8

TABLE VI

Values of $\mathcal{E}_2$ - Total Energy in Outlet - BTU

$\mu_1 = .02$

μ_2 \ T_2 °R	1500	2000	2500	3000	3500	4000	4500	5000
0	321.0	481.1	650.0	823.0	1001.0	1180.1	1361.9	1544.6
.01	324.9	491.6	665.1	843.5	1025.5	1209.8	1396.6	1584.9
.02	331.5	501.0	680.0	863.0	1050.0	1239.0	1430.0	1623.0
.03	337.5	511.5	695.0	882.5	1074.0	1268.5	1465.0	1664.0
.04	343.6	522.3	709.1	901.7	1097.8	1297.9	1500.5	1704.9
.0445	346.3	526.3	715.6	910.4	1108.5	1311.0	1516.1	1723.1

$\mu_1 = .03$

μ_2 \ T_2 °R	1500	2000	2500	3000	3500	4000	4500	5000
0	319.1	480.2	657.4	835.2	1016.0	1198.6	1386.0	1580.3
.01	323.5	487.6	668.3	847.2	1029.2	1218.5	1408.7	1596.9
.02	329.2	499.7	679.6	860.2	1048.3	1237.1	1429.8	1623.2
.03	334.0	508.9	690.2	872.9	1061.1	1256.7	1450.0	1650.0
.0346	334.5	510.1	693.0	877.3	1067.0	1265.8	1458.9	1659.4

$\mu_1 = .04$

μ_2 \ T_2 °R	1500	2000	2500	3000	3500	4000	4500	5000
0	325.5	492.6	666.3	848.0	1031.4	1217.1	1405.5	1597.5
.01	328.7	498.7	677.2	859.0	1045.0	1235.4	1427.7	1620.9
.02	332.4	505.6	686.4	871.7	1061.3	1255.1	1451.0	1648.0

TABLE VII

Values of v_1 (ft/sec.) for $M_2 = 1.0$

$\mu_1 = .02$

μ_2 \ T_1 °R	1200	1600	2000	2400	2800	3200	3600	4000
0	1048	1205	1340	1460	1578	1684	1784	1879
.01	735	909	1068	1208	1335	1453	1565	1672
.02	607	768	920	1060	1183	1310	1423	1530
.03	529	680	823	954	1080	1198	1307	1415
.04	475	617	750	880	995	1117	1220	1327
.0445	457	595	725	848	967	1080	1186	1290

$\mu_1 = .03$

μ_2 \ T_1 °R	1200	1600	2000	2400	2800	3200	3600	4000
0	1050	1200	1330	1439	1537	1628	1718	1814
.01	758	922	1059	1178	1289	1390	1498	1599
.02	619	779	913	1032	1142	1249	1352	1458
.0346	497	654	788	909	1022	1130	1235	1339

$\mu_1 = .04$

μ_2 \ T_1 °R	1200	1600	2000	2400	2800	3200	3600	4000
0	1050	1193	1312	1422	1520	1618	1713	1811
.01	829	974	1092	1199	1296	1390	1480	1619
.02	663	820	946	1050	1148	1239	1328	1411

TABLE VIII

Values of T_2 (°R) at $M_2 = 1.0$

$\mu_1 = .02$

μ_2 \ T_1, °R	1200	1600	2000	2400	2800	3200	3600	4000
0	1085	1455	1830	2210	2580	2955	3330	3705
.01	1585	1930	2275	2635	2990	3350	3710	4065
.02	2065	2390	2715	3050	3380	3725	4075	4420
.03	2505	2810	3120	3445	3765	4090	4430	4760
.04	2925	3215	3505	3815	4125	4440	4770	5075
.0445	3100	3385	3675	3980	4280	4585	4905	5220

$\mu_1 = .03$

μ_2 \ T_1, °R	1200	1600	2000	2400	2800	3200	3600	4000
0	1195	1465	1800	2140	2495	2870	3245	3630
.01	1560	1905	2270	2600	2970	3330	3685	4080
.02	2070	2400	2705	3030	3400	3765	4120	4485
.0346	2600	2940	3270	3605	3960	4325	4635	4985

$\mu_1 = .04$

μ_2 \ T_1, °R	1200	1600	2000	2400	2800	3200	3600	4000
0	1190	1495	1845	2220	2610	3000	3380	3750
.01	1650	1940	2310	2640	3030	3420	3780	4150
.02	2110	2400	2745	3055	3440	3810	4140	4510

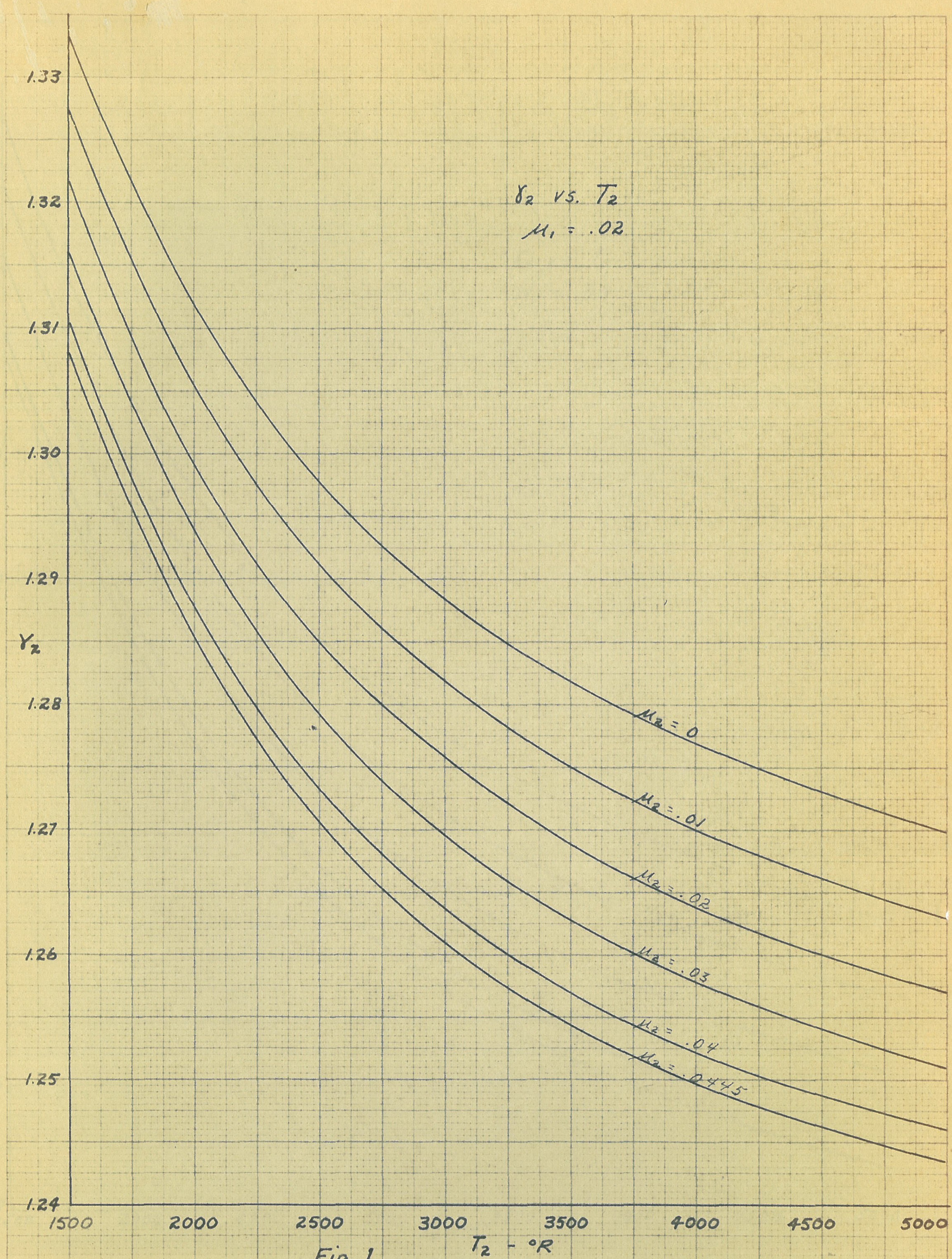
TABLE IX

Values of p_2/p_1 for $M_2 = 1.0$

$\mu_1 = .02$

μ_2 \ T_1 °R	1200	2000	3000	4000
0	.593	.599	.604	.605
.01	.514	.543	.562	.575
.02	.493	.519	.540	.553
.03	.483	.506	.526	.540
.04	.477	.497	.516	.530
.0445	.476	.494	.513	

TABLE X



γ_2 vs. T_2
$\mu_1 = .02$
γ_2
1.33
1.32
1.31
1.30
1.29
1.28
1.27
1.26
1.25
1.24
$\mu_2 = 0$
$\mu_2 = .01$
$\mu_2 = .02$
$\mu_2 = .03$
$\mu_2 = .04$
$\mu_2 = .0445$
1500
2000
2500
3000
3500
4000
4500
5000
T_2 - °R

Fig. 1

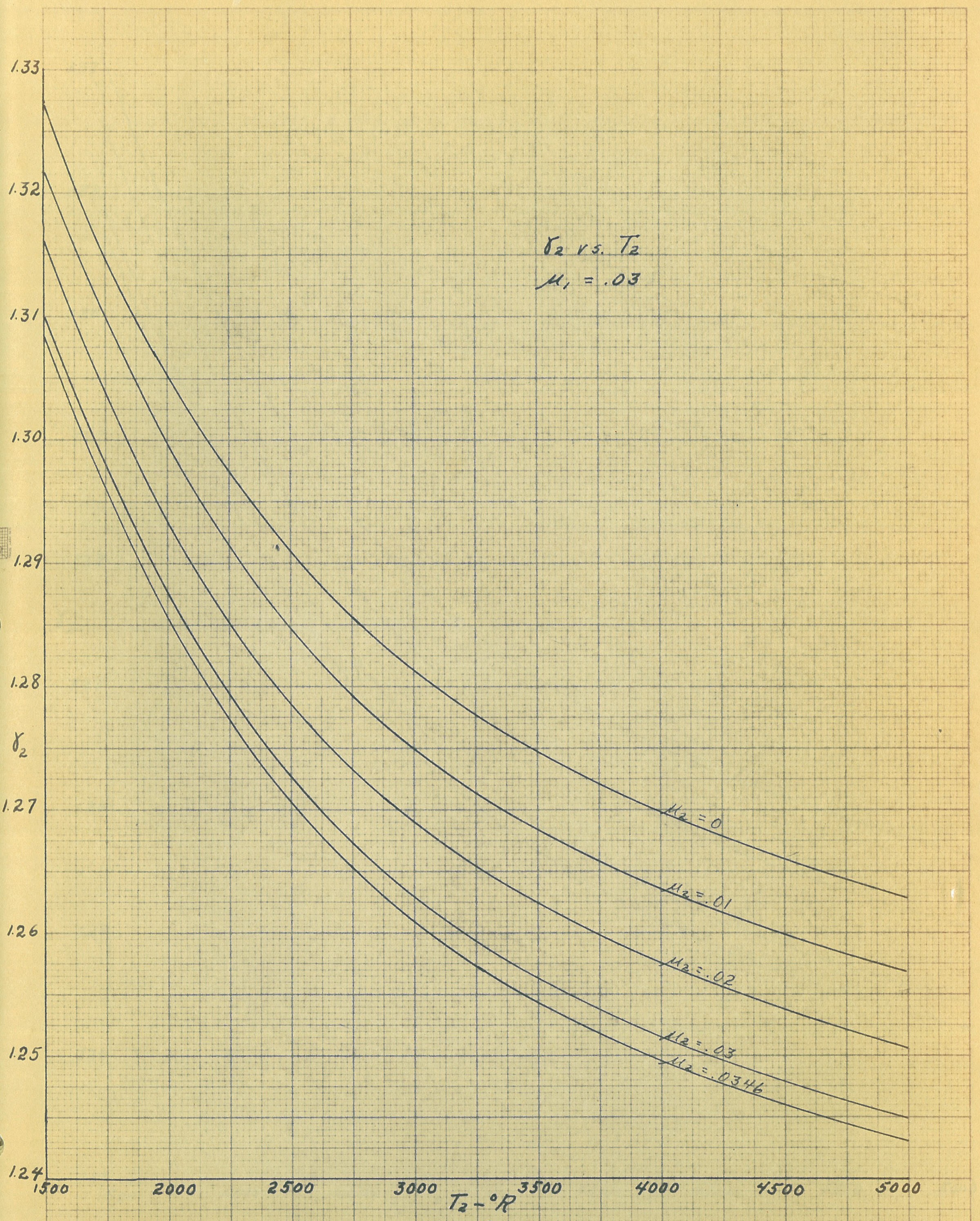
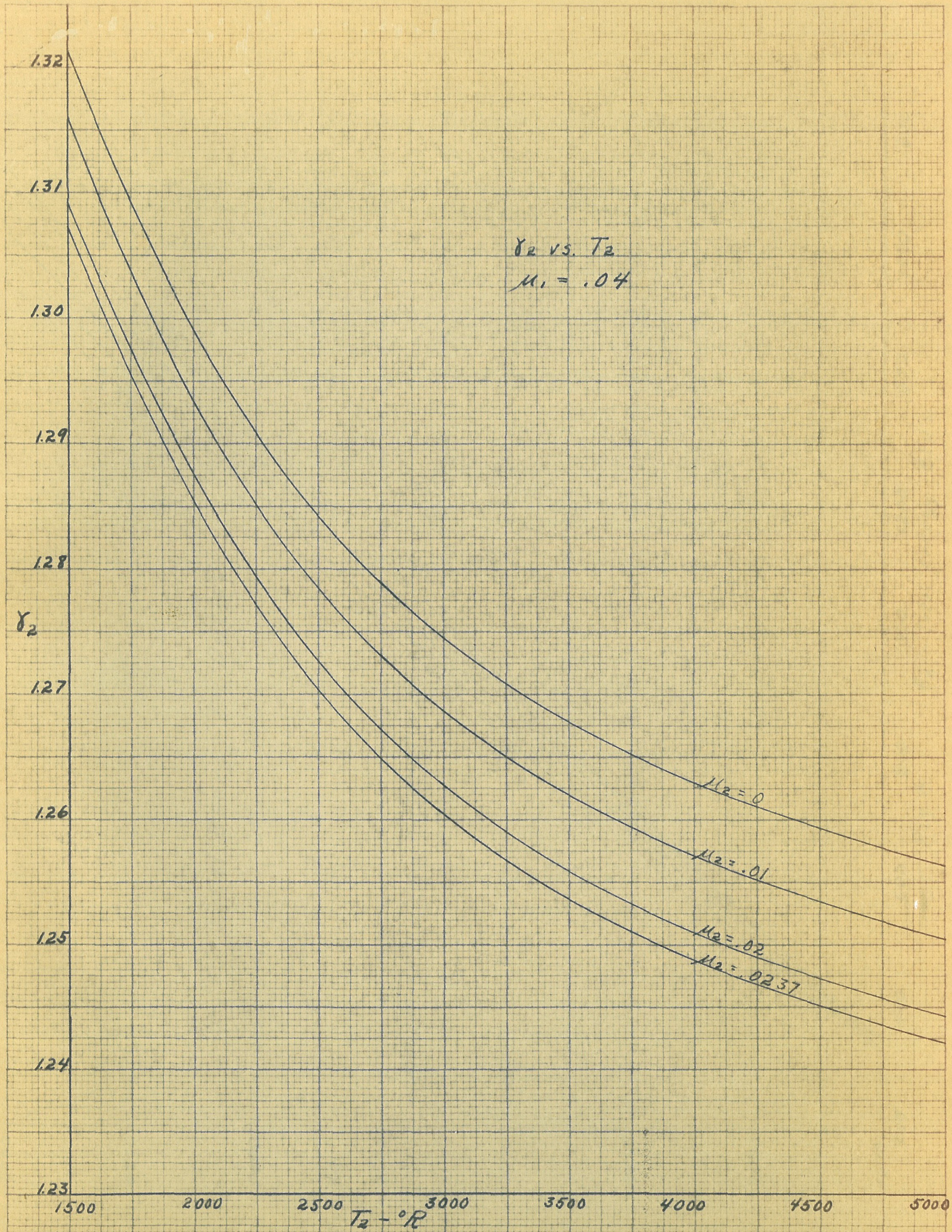

γ_2 vs. T_2
$\mu_1 = .03$
$\mu_2 = 0$
$\mu_2 = .01$
$\mu_2 = .02$
$\mu_2 = .03$
$\mu_2 = .0346$
1.33
1.32
1.31
1.30
1.29
1.28
γ_2
1.27
1.26
1.25
1.24
1500
2000
2500
3000
3500
4000
4500
5000
T_2 - °R

Fig 2



γ_2 vs. T_2
$\mu_1 = .04$
$\mu_2 = 0$
$\mu_2 = .01$
$\mu_2 = .02$
$\mu_2 = .0237$
γ_2
1.32
1.31
1.30
1.29
1.28
1.27
1.26
1.25
1.24
1.23
1500
2000
2500
3000
3500
4000
4500
5000
T_2 - °R

Fig. 3

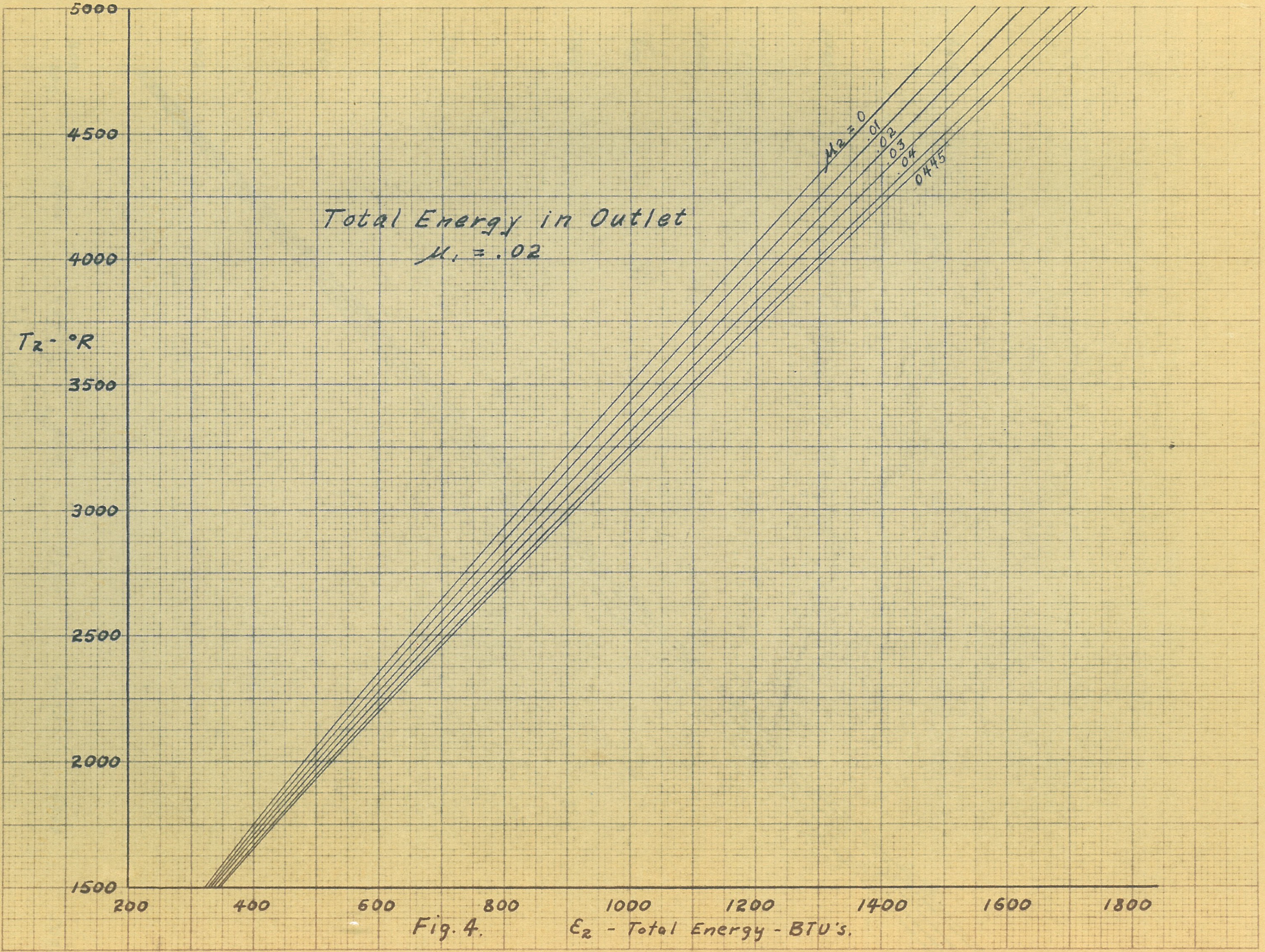

Total Energy in Outlet
$\mu_1 = .02$
$\mu_2 = 0$
.01
.02
.03
.04
.0445
T_2 - °R
5000
4500
4000
3500
3000
2500
2000
1500
200
400
600
800
1000
1200
1400
1600
1800
$\mathcal{E}_2$ - Total Energy - BTU's.

Fig. 4.

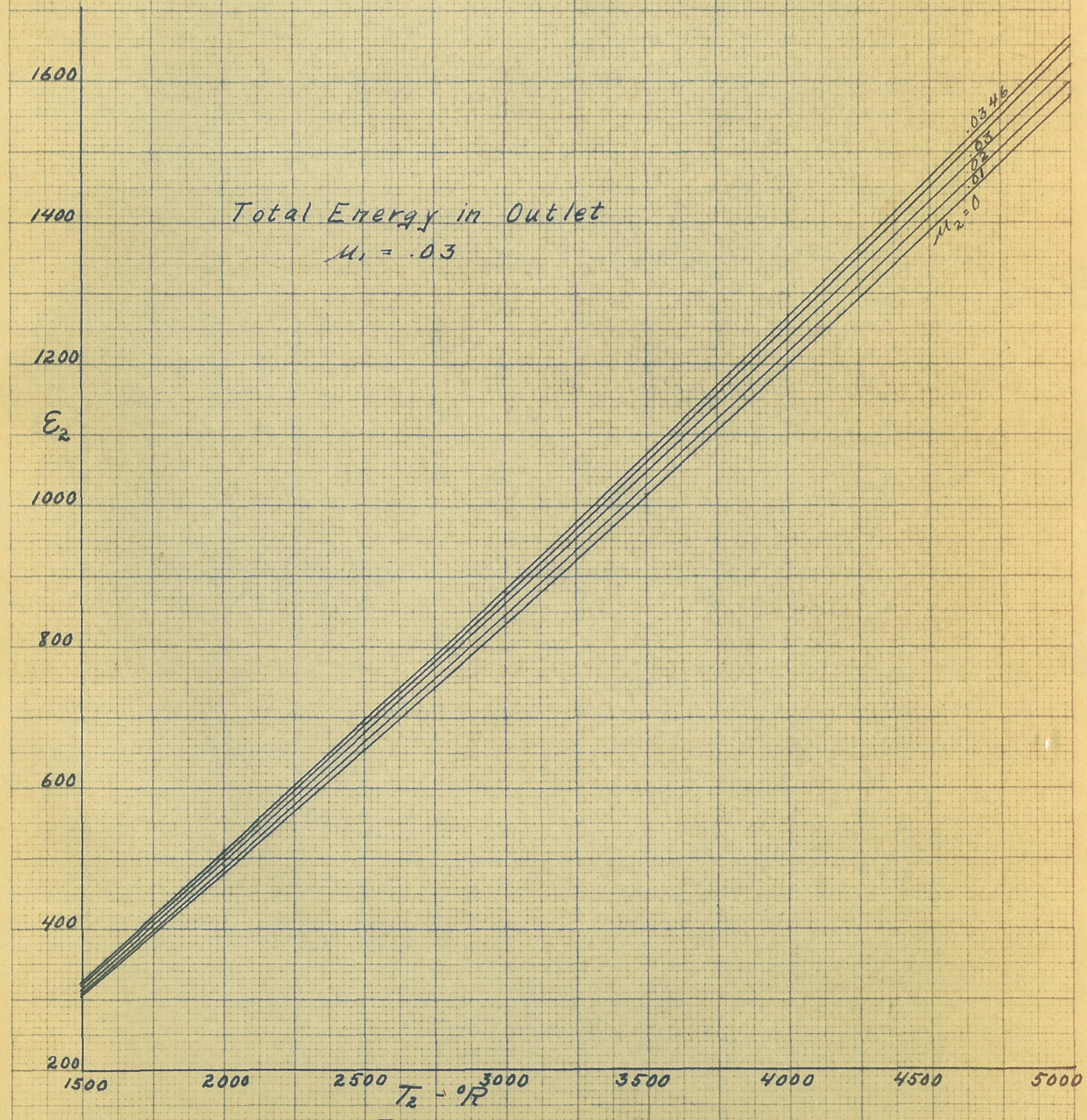
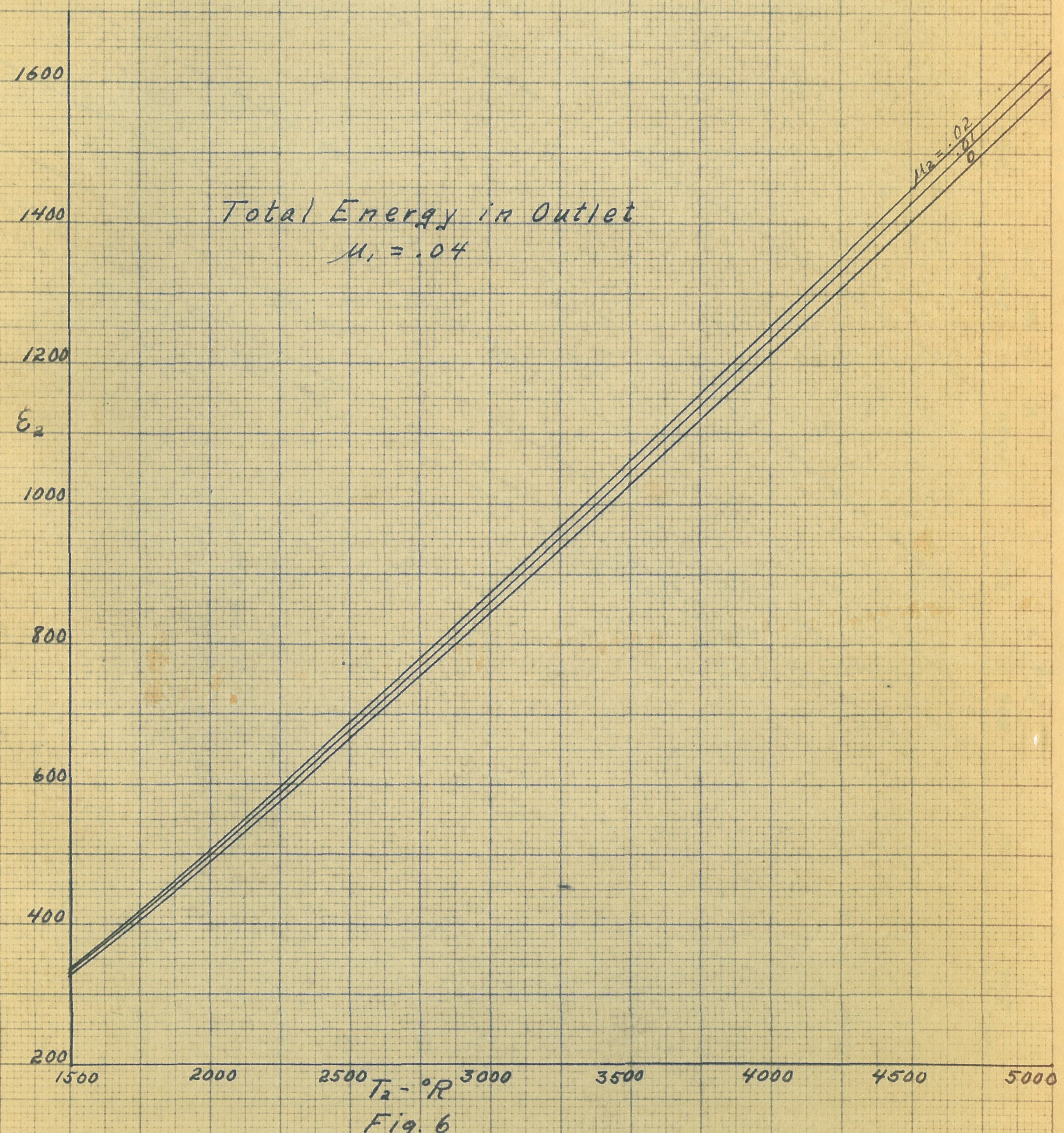

Total Energy in Outlet
μ₁ = .03
1600
1400
1200
1000
800
600
400
200
ℰ₂
1500
2000
2500
3000
3500
4000
4500
5000
T₂ - °R
.0346
.03
.02
.01
μ₂ = 0

Fig. 5



Total Energy in Outlet
μ₁ = .04
μ_2 = .02
.01
0
$\mathcal{E}_2$
1600
1400
1200
1000
800
600
400
200
1500
2000
2500
3000
3500
4000
4500
5000
T_2 - °R

Fig. 6

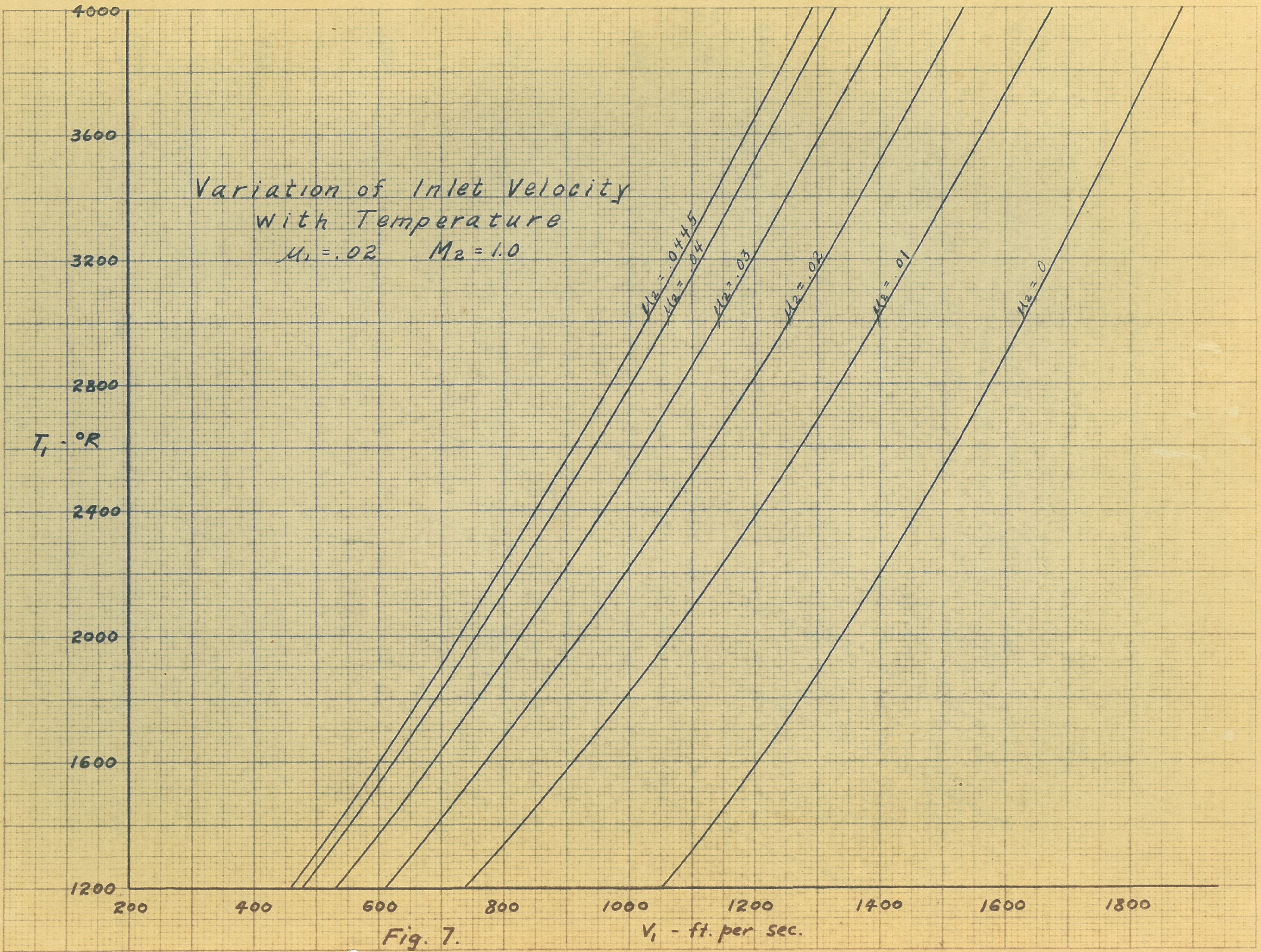
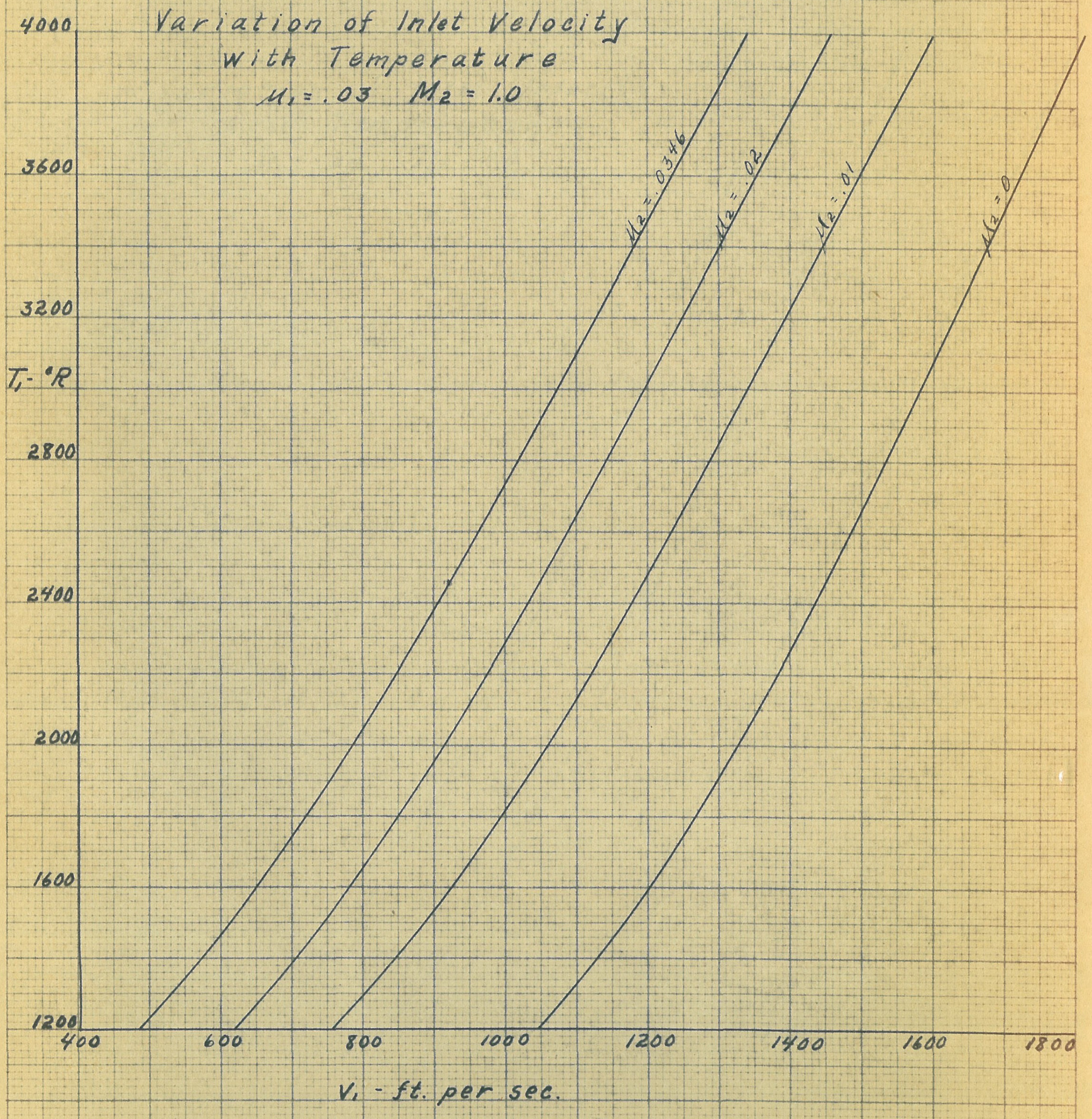

Variation of Inlet Velocity
with Temperature
$\mu_1 = .02$ $M_2 = 1.0$
$\mu_2 = .0445$
$\mu_2 = .04$
$\mu_2 = .03$
$\mu_2 = .02$
$\mu_2 = .01$
$\mu_2 = 0$
T_1 - °R
4000
3600
3200
2800
2400
2000
1600
1200
200
400
600
800
1000
1200
1400
1600
1800
V_1 - ft. per sec.

Fig. 7.



Variation of Inlet Velocity
with Temperature
$\mu_1 = .03$ $M_2 = 1.0$
$\mu_2 = .0346$
$\mu_2 = .02$
$\mu_2 = .01$
$\mu_2 = 0$
4000
3600
3200
T_1 - °R
2800
2400
2000
1600
1200
400
600
800
1000
1200
1400
1600
1800
V_1 - ft. per sec.

Fig. 8

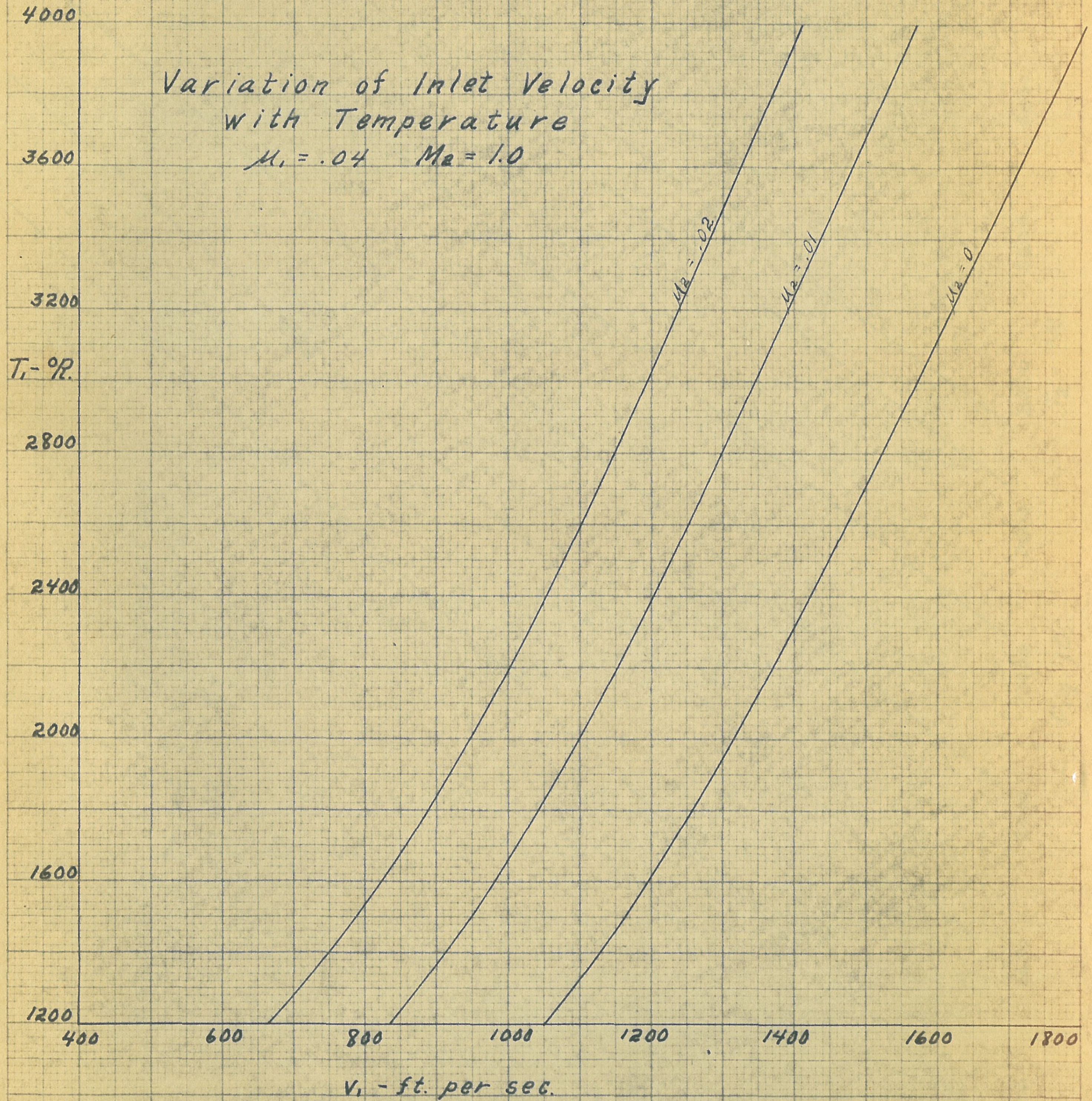

Variation of Inlet Velocity
with Temperature
$\mu_1 = .04$ $M_2 = 1.0$
$\mu_2 = .02$
$\mu_2 = .01$
$\mu_2 = 0$
4000
3600
3200
T_1 - °R.
2800
2400
2000
1600
1200
400
600
800
1000
1200
1400
1600
1800
V_1 - ft. per sec.

Fig. 9

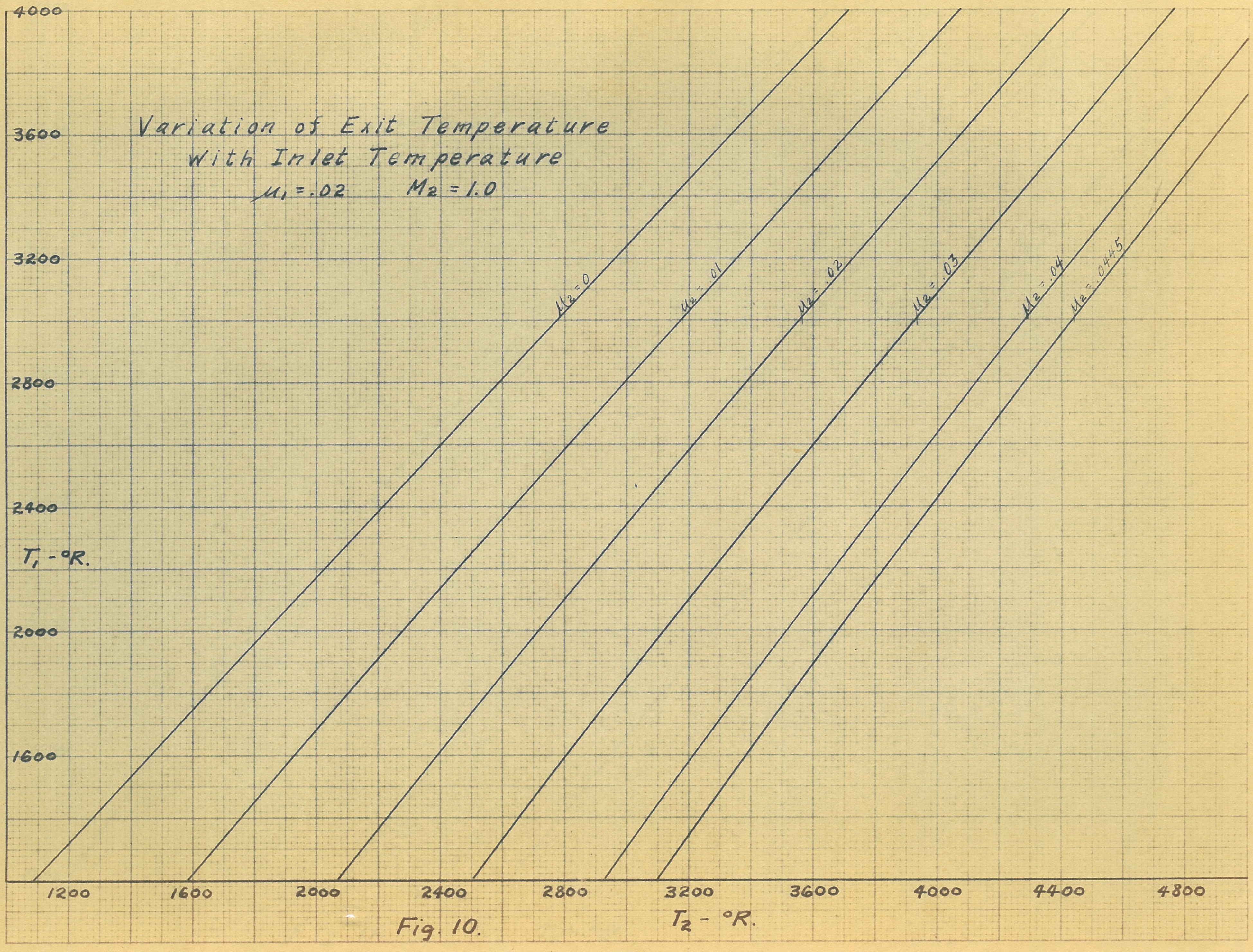

Variation of Exit Temperature
With Inlet Temperature
$\mu_1 = .02$ $M_2 = 1.0$
$\mu_2 = 0$
$\mu_2 = .01$
$\mu_2 = .02$
$\mu_2 = .03$
$\mu_2 = .04$
$\mu_2 = .0445$
4000
3600
3200
2800
2400
2000
1600
T_1 - °R.
1200
1600
2000
2400
2800
3200
3600
4000
4400
4800
T_2 - °R.

Fig. 10.

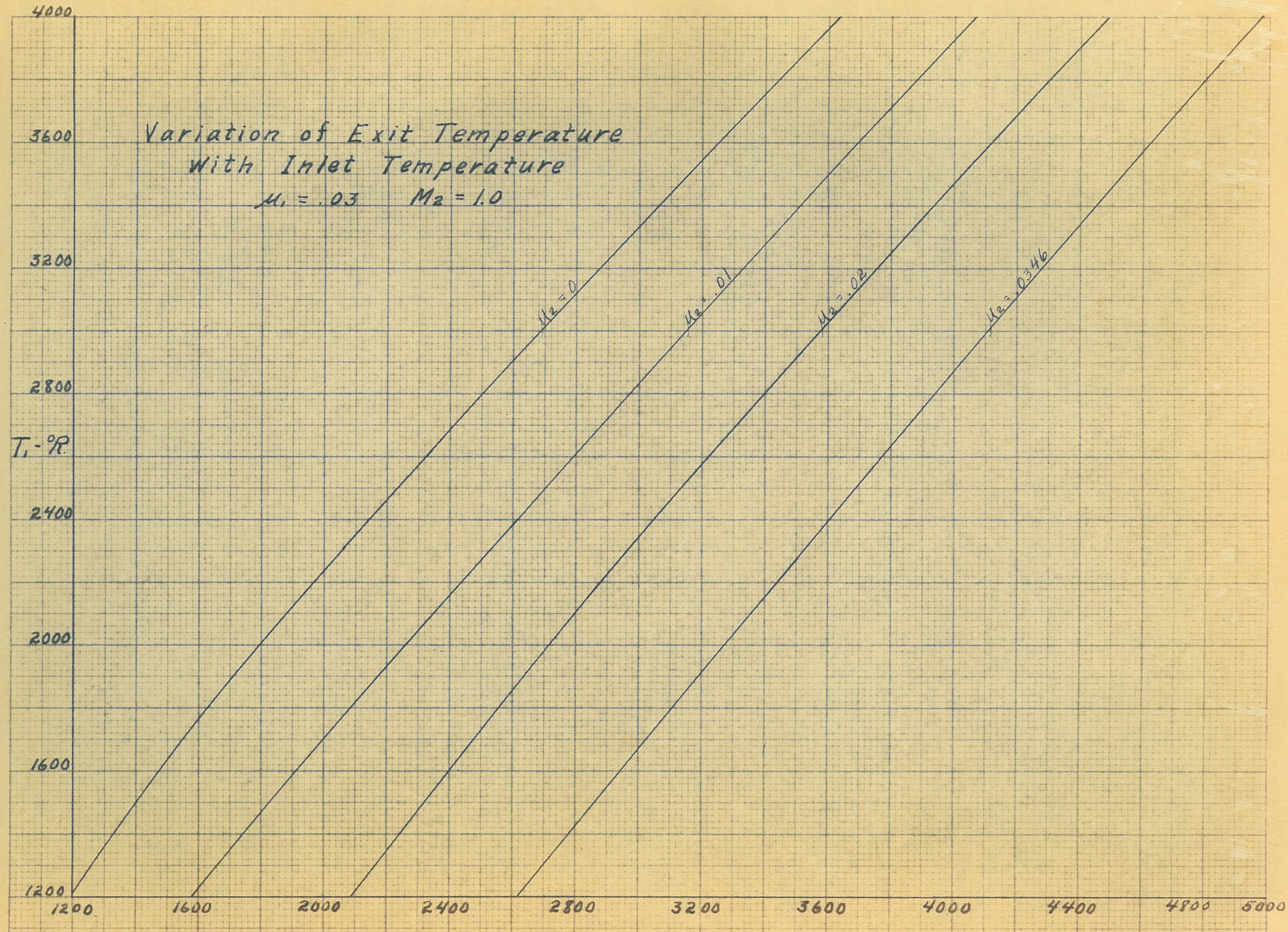
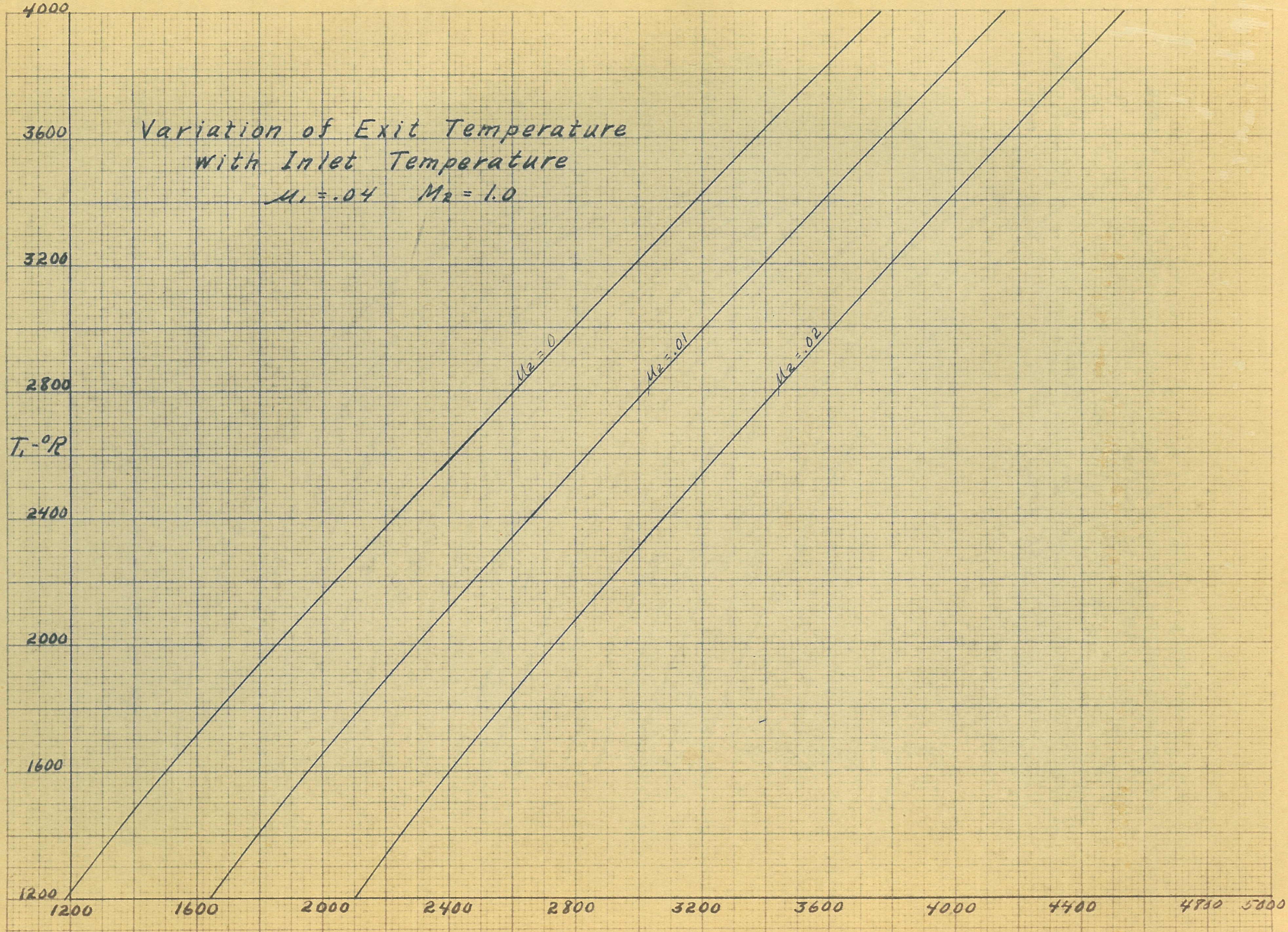

Variation of Exit Temperature
With Inlet Temperature
μ1 = .03   M2 = 1.0
μ2 = 0
μ2 = .01
μ2 = .02
μ2 = .0346
T1 - °R
T2 - °R
4000
3600
3200
2800
2400
2000
1600
1200
1200
1600
2000
2400
2800
3200
3600
4000
4400
4800
5000

Fig. 11



Variation of Exit Temperature
with Inlet Temperature
$\mu_1 = .04$ $M_2 = 1.0$
$\mu_2 = 0$
$\mu_2 = .01$
$\mu_2 = .02$
4000
3600
3200
2800
T_1 - °R
2400
2000
1600
1200
1200
1600
2000
2400
2800
3200
3600
4000
4400
4810
5000
T_2 - °R

Fig. 12

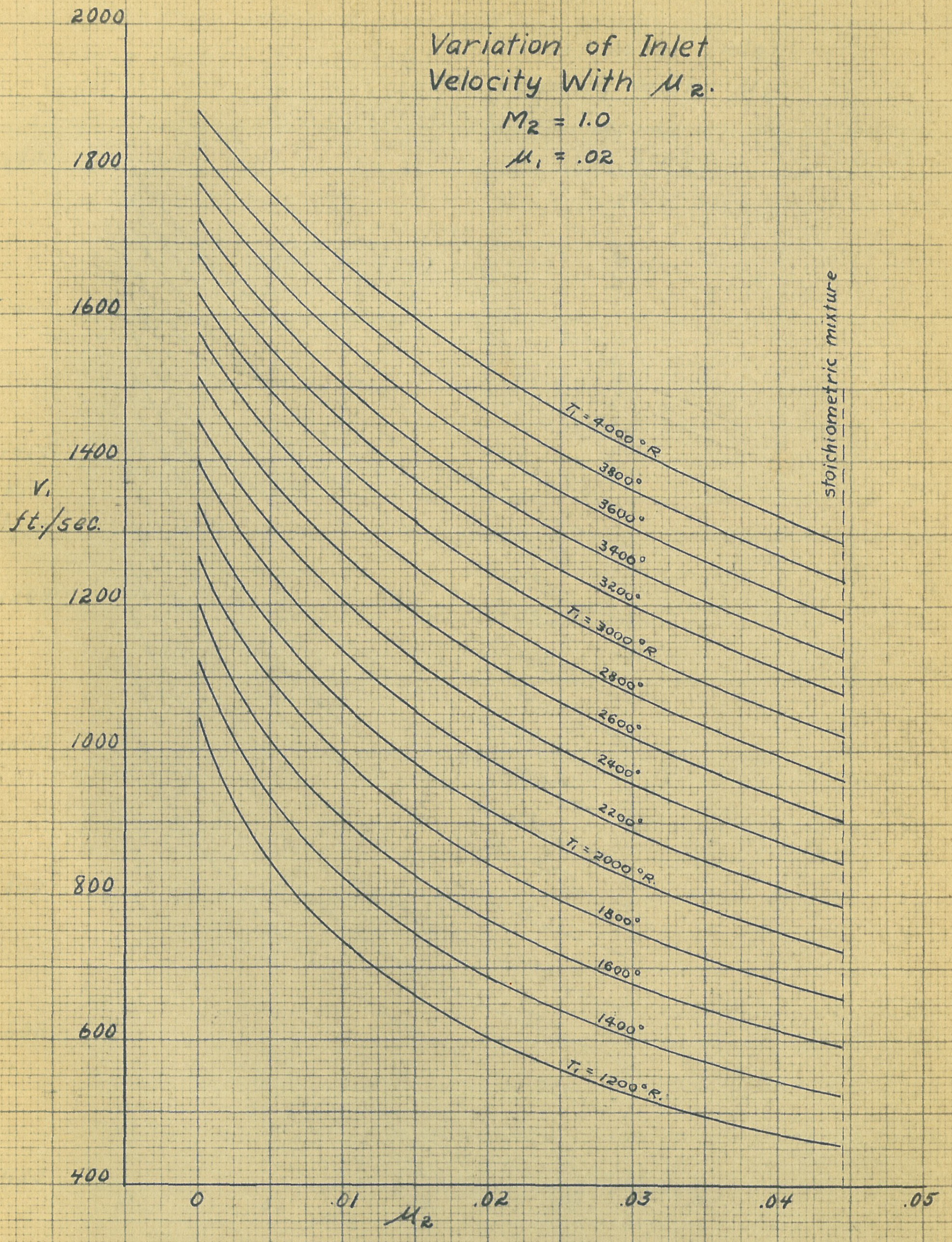
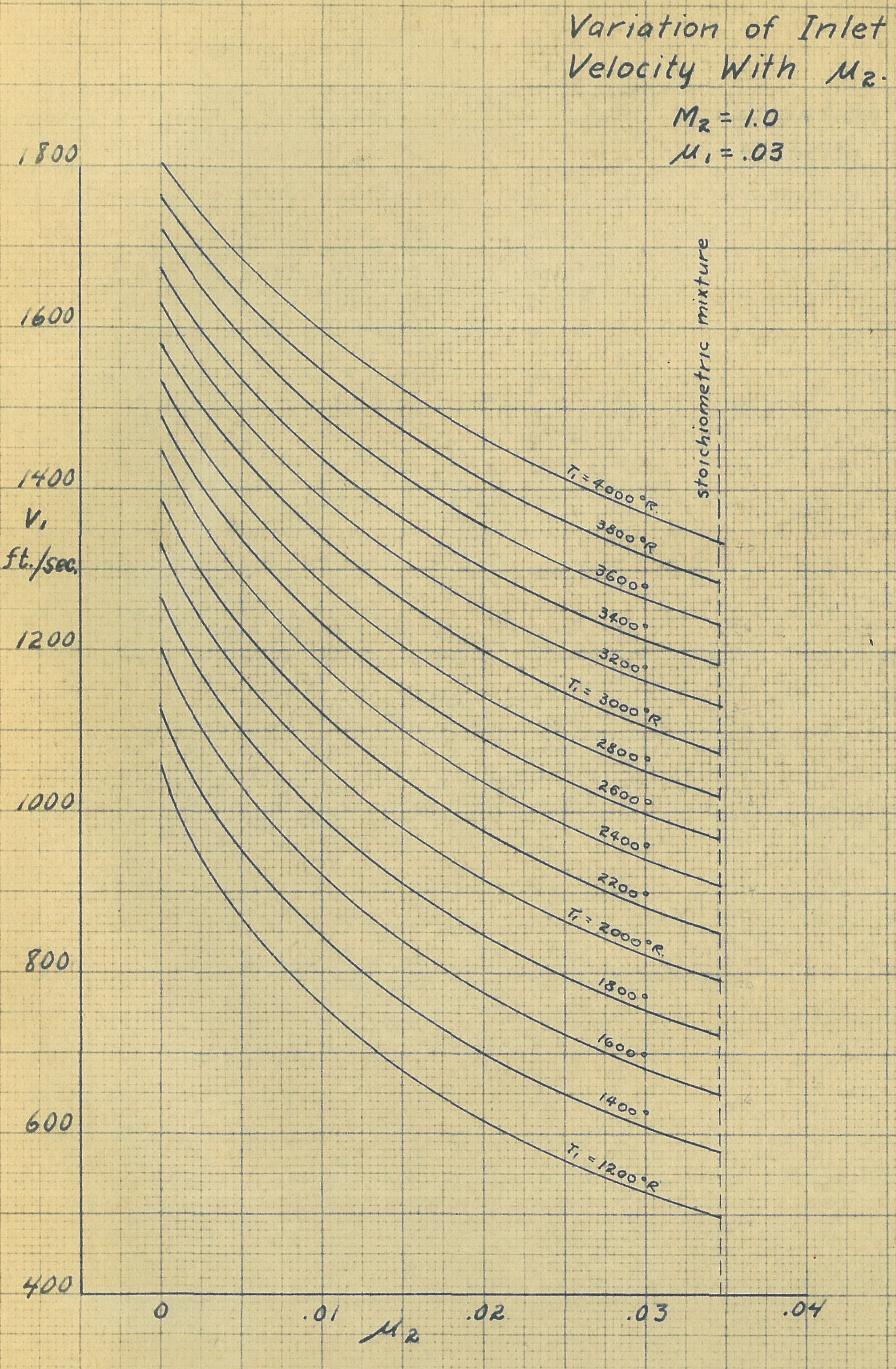

Variation of Inlet
Velocity With μ_2.
$M_2 = 1.0$
$\mu_1 = .02$
2000
1800
1600
1400
1200
1000
800
600
400
V_1
ft./sec.
0
.01
.02
.03
.04
.05
μ_2
T_1 = 4000 °R
3800°
3600°
3400°
3200°
T_1 = 3000 °R
2800°
2600°
2400°
2200°
T_1 = 2000 °R.
1800°
1600°
1400°
T_1 = 1200 °R.
stoichiometric mixture

Fig. 13



Variation of Inlet Velocity With μ_2.
$M_2 = 1.0$
$\mu_1 = .03$
1800
1600
1400
V_1 ft./sec.
1200
1000
800
600
400
0
.01
.02
.03
.04
μ_2
stoichiometric mixture
$T_1 = 4000°R.$
3800°R
3600°
3400°
3200°
$T_1 = 3000°R.$
2800°
2600°
2400°
2200°
$T_1 = 2000°R.$
1800°
1600°
1400°
$T_1 = 1200°R.$

Fig. 14

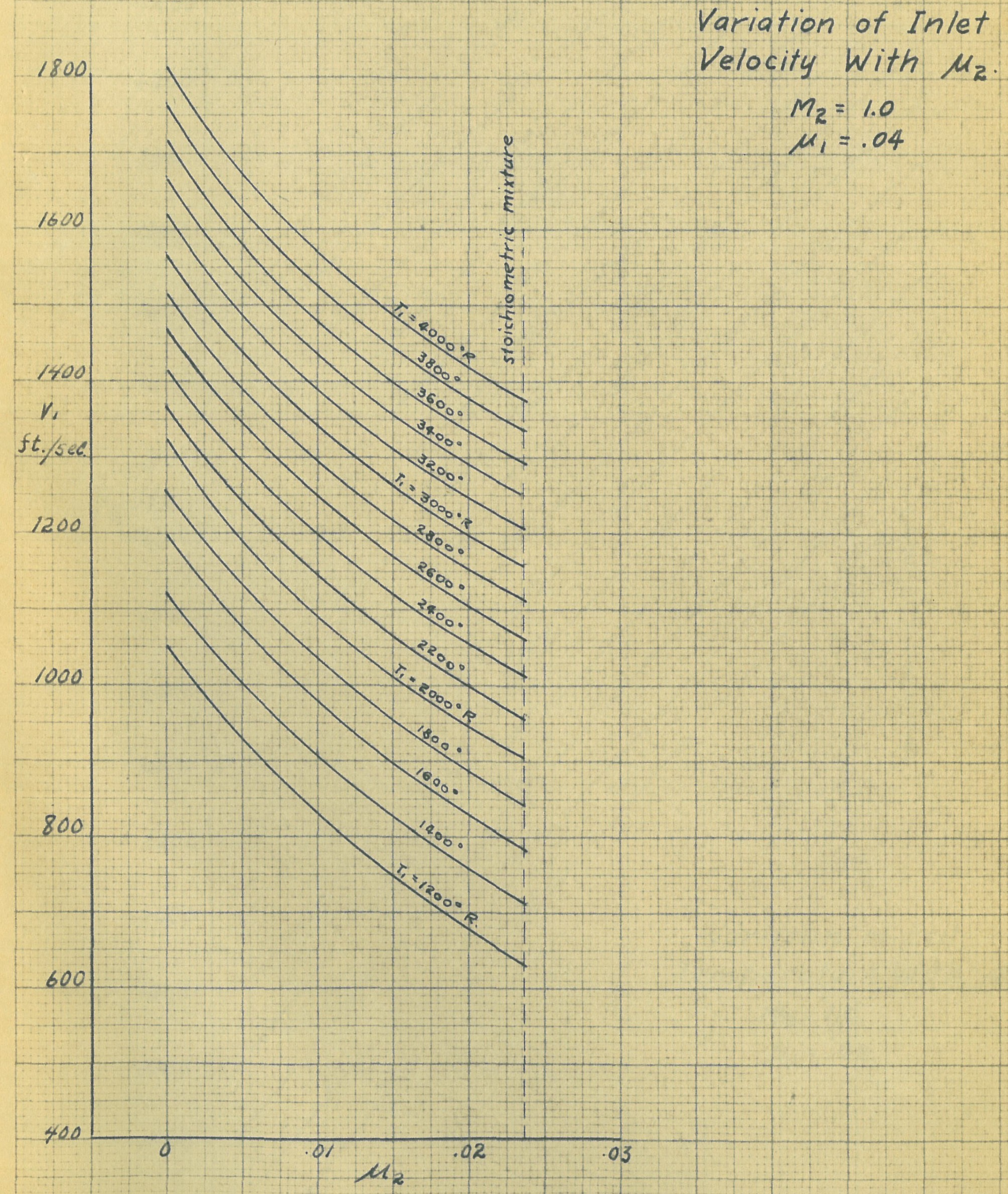
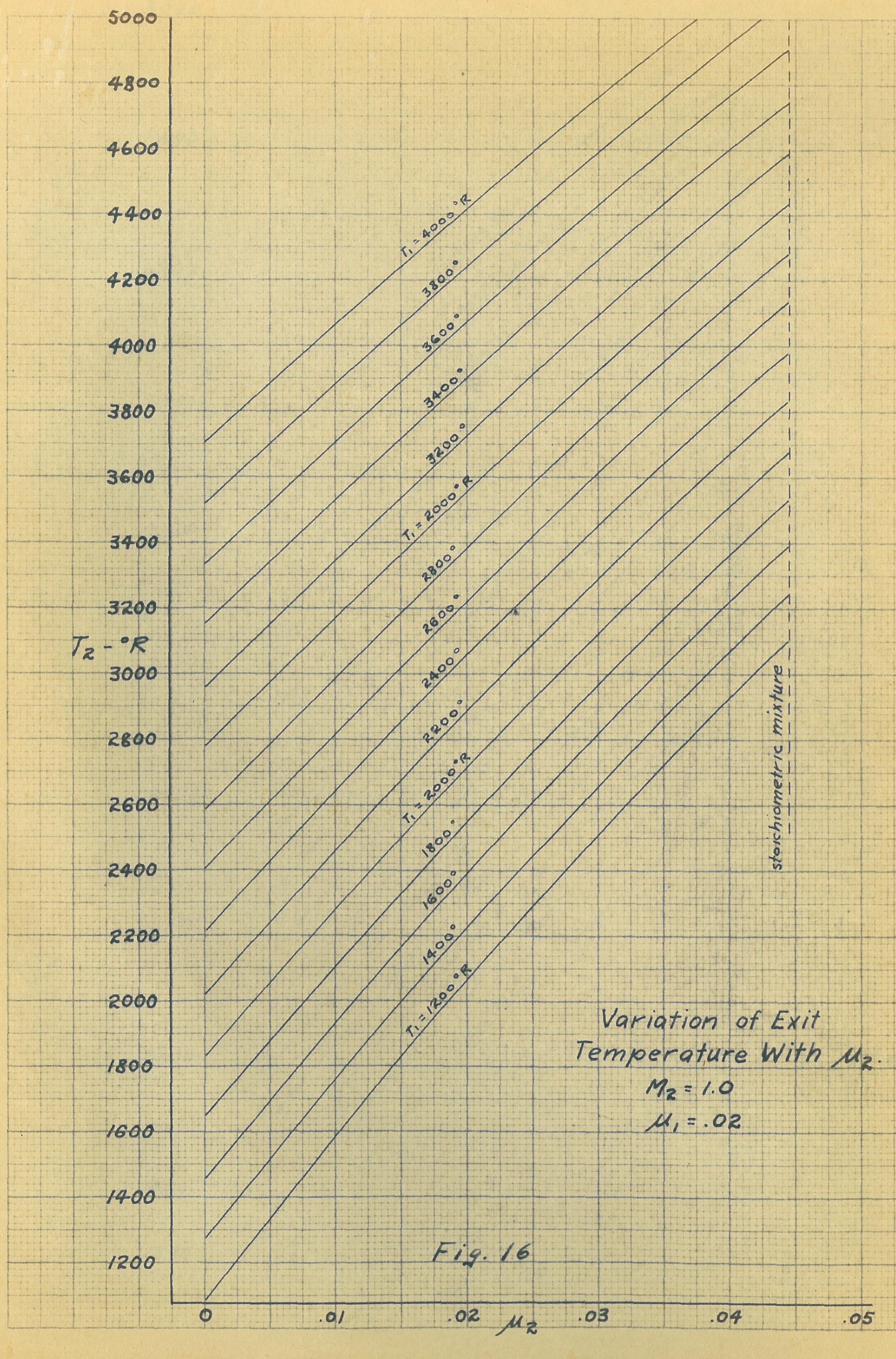

Variation of Inlet Velocity With μ_2.
$M_2 = 1.0$
$\mu_1 = .04$
1800
1600
1400
1200
1000
800
600
400
V_1 ft./sec.
0
.01
.02
.03
μ_2
stoichiometric mixture
$T_1 = 4000°R$
3800°
3600°
3400°
3200°
$T_1 = 3000°R$
2800°
2600°
2400°
2200°
$T_1 = 2000°R$
1800°
1600°
1400°
$T_1 = 1200°R$

Fig. 15



5000
4800
4600
4400
4200
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
T_2 - °R
0
.01
.02
.03
.04
.05
μ_2
T_1 = 4000°R
3800°
3600°
3400°
3200°
T_1 = 2000°R
2800°
2600°
2400°
2200°
T_1 = 2000°R
1800°
1600°
1400°
T_1 = 1200°R
stoichiometric mixture
Variation of Exit
Temperature With μ_2.
M_2 = 1.0
μ_1 = .02

Fig. 16

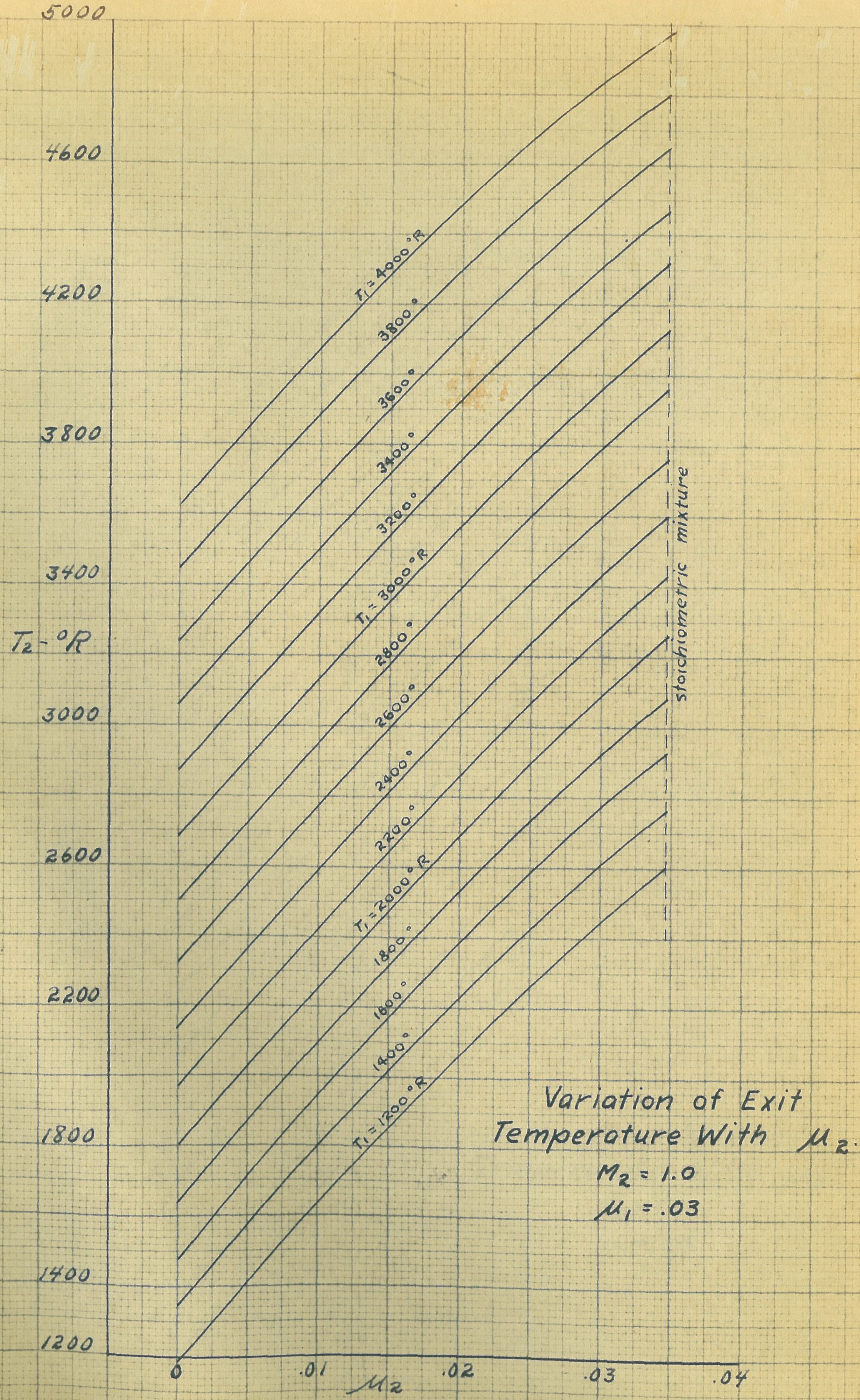
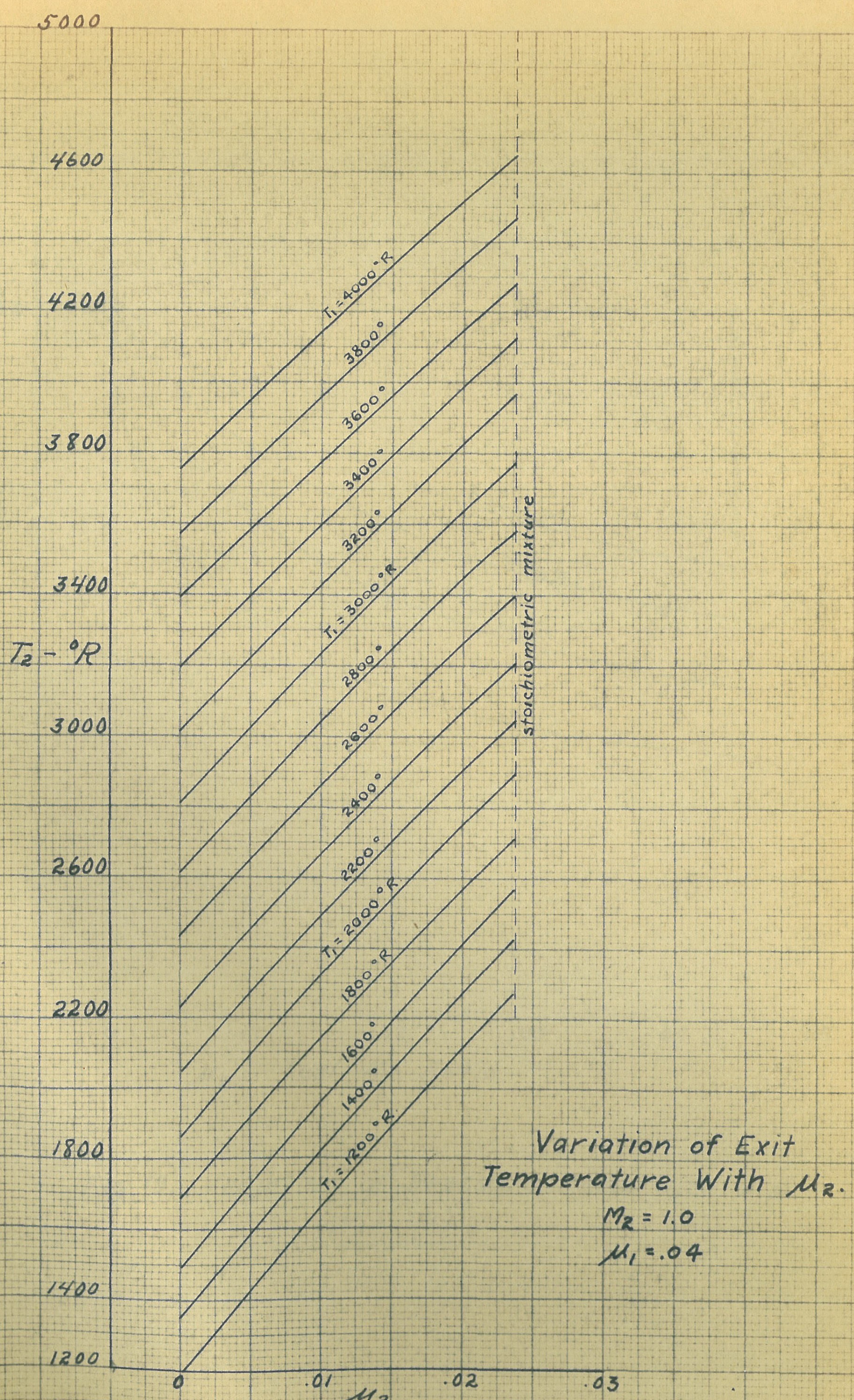

5000
4600
4200
3800
3400
3000
2600
2200
1800
1400
1200
T_2 - °R
0
.01
.02
.03
.04
μ_2
T_1 = 4000 °R
3800°
3600°
3400°
3200°
T_1 = 3000 °R
2800°
2600°
2400°
2200°
T_1 = 2000 °R
1800°
1600°
1400°
T_1 = 1200 °R
stoichiometric mixture
Variation of Exit Temperature With μ_2
M_2 = 1.0
μ_1 = .03

Fig. 17



5000
4600
4200
3800
3400
3000
2600
2200
1800
1400
1200
T_2 - °R
0
.01
.02
.03
μ_2
T_1=4000°R
3800°
3600°
3400°
3200°
T_1=3000°R
2800°
2600°
2400°
2200°
T_1=2000°R
1800°R
1600°
1400°
T_1=1200°R
stoichiometric mixture
Variation of Exit
Temperature With μ_2.
M_2 = 1.0
μ_1 = .04

Fig. 18

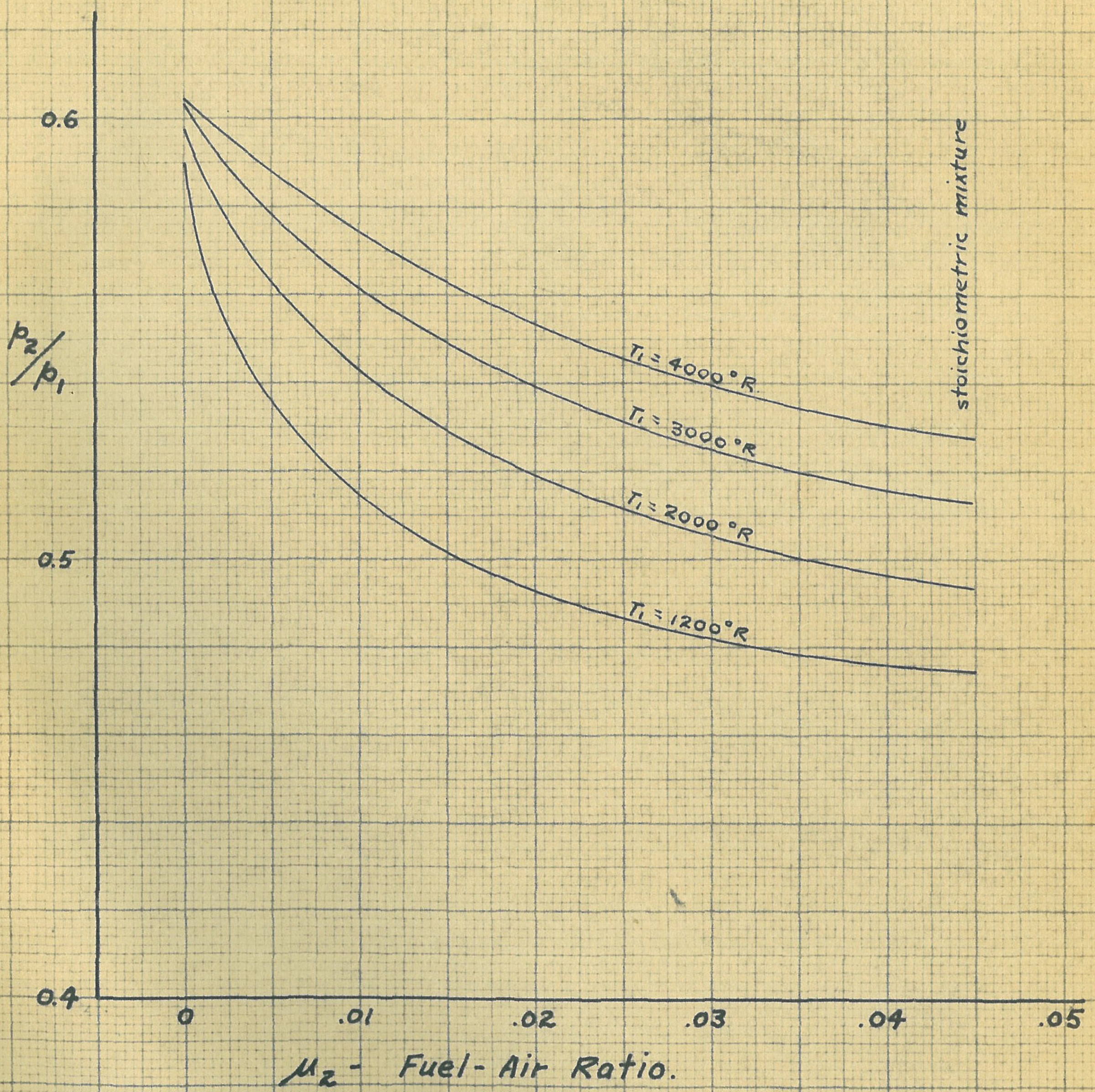


Fig. 19. Variation of Pressure Ratio With μ_2.
($\mu_1 = .02$)