

GE TIS 72SD2061

N72-31943

INVESTIGATION OF THE IGNITION AND
BURNING OF MATERIALS IN SPACE
CABIN ATMOSPHERES

PART II: IGNITION OF A COMBUSTIBLE
MIXTURE BY A HOT BODY WITH
THE EFFECTS OF GRAVITY

H. G. LEW

CASE FILE
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FINAL REPORT - MARCH 1972

NASA CONTRACT NO. NASW-1874

ENVIRONMENTAL

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Re-entry & Environmental
Systems Division



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Part II: Ignition of a Combustible Mixture
By A Hot Body With The Effects Of
Gravity

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SUMMARY

The ignition temperature for a hot horizontal cylinder immersed in a combustible gas mixture in a free convection flow has been studied. The effects of gravity on this flow with chemical reactions and diffusion of the species have been determined. Extensive numerical results are given for a Teflon monomer gas-oxygen mixture. Results of ignition temperature show its increase with increasing gravity and/or inert diluent.

I. INTRODUCTION

Combustible gases over a hot surface often ignite and burn. These gases may have been the result of the pyrolysis of a plastic material covering a heat source. For example, heated wires or a pipe with hot flowing fluid are typical heat sources. Heated wires may be plastic coated which will emit a combustible vapor when they are inadvertently overheated.

It is the purpose of this part of the study (Part II) to consider the ignition of a combustible gas mixture by a hot cylinder under the effect of a gravity field for steady state conditions. For this purpose a horizontal cylinder is considered with gravity as a parameter together with a finite chemical reacting flow generated by free convection with the additional effect of diffusion. Both mass transfer and zero mass transfer cases are considered. By defining an ignition criterion the surface temperature and species are obtained from the analysis as a function of the gravity field. It is supposed that at the point of ignition the heat evolved in the gas is sufficiently high to attain a sustained combustion without any energy from the hot cylinder. As seen in Part I of this report ignition can be defined in several ways. The time-dependent analysis indicates that the first occurrence of sustained burning is the most precise one although it is the most difficult one to calculate due to the complexity of multi-dimensional effects. One definition for ignition is that for zero heat transfer or zero temperature gradient for a non-catalytic body at the body surface. However, it is not assured that this definition will always lead to sustained burning with increasing time as the results of Part I of this study have shown. But the surface temperatures obtained both ways varies with the external environmental parameters in a similar way and the latter definition

is more convenient for steady state considerations. Hence this criterion is utilized in this Part II for steady flow. This criterion has been considered by Zeldovich (1939) and Chambre (1956). Chambre (1956) had studied planar forced convection stagnation flows by an analytical method for a first order Arrhenius rate law for a very thin reaction zone close to the wall. Sharma and Sirignano (1969) had obtained numerical solutions for a mixture of propane and air utilizing a second order Arrhenius rate law and showed that Chambre's results for the ignition wall temperature is 25% lower than their numerical results.

In this study a steady free convection flow about the stagnation region is considered where the flow time and reaction time are comparable. The study has been set up for an arbitrary chemical system; results have been obtained for a typical system of four species consisting of Teflon monomer gas, oxygen, inert gas, and products for a second order chemical kinetic rate. Diffusion of species is considered with their corresponding transport properties including viscosity and conductivity and thermodynamic properties as functions of species concentration and temperature. Thus the Prandtl number takes on the proper value at each point of the field; the Lewis number has been assumed constant.

In the next two chapters the governing equations for the principal situations are set forth with discussions of the dimensionless number pertinent to the problems. The method of solution is then discussed and results are given for the effect of gravity on the solid temperature with the effect of mass transfer. Results are also given for zero mass transfer case.

II. FREE CONVECTION OVER HORIZONTAL CYLINDER IN A REACTING GAS MIXTURE

A steady free convection flow of a compressible gas over a horizontal cylinder with gravity normal to the axis of the cylinder is considered in this part of the study. The configuration is shown on Figure 1. A surface coordinate system is utilized with the y coordinate measured normal from the surface and with the x coordinate along the surface. The gravity vector is aligned along the vertical direction and its intersection with the lower half of the cylinder denotes the stagnation point of the flow. The axis of the horizontal cylinder is normal to the paper and to the gravity vector; thus the flow is two-dimensional with streamlines enveloping the cylinder as they proceed around the equator and to the opposite pole. The flow is a free convection one generated by the buoyancy of the fluid. Thus the buoyancy term is of the same order as the inertia and viscous terms. Similar flows with small temperature differences over horizontal cylinder have been analyzed by Hermann (1954) by considering a boundary layer flow. Experimental measurements have shown that this flow is of the boundary layer type when the Grashof number is greater than 10^4 (Ostrach - 1964). The conditions considered in this report are that the pressure varies from one atmosphere to a tenth of an atmosphere at room temperature of 21°C with a large range of acceleration to gravity. The Grashof numbers are then in the range of 10^5 to 10^9 . Thus the flow can be considered to be of the boundary layer type so that the thickness of the fluid layer is small compared to that of the radius of the body.

The flow generated by the buoyancy force is governed by two momentum equations and an energy equation for the temperature. Consider first the situ-

ation when there is no convective flow. In this case, the fluid is in hydrostatic equilibrium and the pressure gradient balances the gravity force. Then for any ensuing motion any additional pressure can be considered as the excess over this value. Let the velocity components along the x and y coordinates be u and v and let ρ be the variable mass density of the gas then momentum conservation of the boundary layer flow leads to the equations:

$$\rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = - (\rho - \rho_{\infty}) g \sin\left(\frac{x}{R}\right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y} \right) \quad (1)$$

$$- \rho \frac{u^2}{R} = - \frac{\partial p_{ex}}{\partial y} + (\rho - \rho_{\infty}) g \cos\left(\frac{x}{R}\right) \quad (2)$$

It is remembered that the Grashof number is large and the boundary layer is thin compared with the radius of the cylinder R and that the pressure (p_{ex}) is the excess value. The magnitude of the gravity vector is indicated as usual by g. In these equations the transport property of viscosity is considered as a function of the temperature and the species concentration. The subscript ∞ denotes ambient values at the edge of the layer. This set of equations is coupled to the temperature by:

$$\rho c_p \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) - u \frac{\partial p}{\partial x} = \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \mu \left(\frac{\partial u}{\partial y} \right)^2 + \frac{\mu}{Pr} Le \frac{\partial T}{\partial y} \sum c_{p_i} \frac{\partial c_i}{\partial y} - \sum w_i h_i \quad (3)$$

where T is the temperature, c_i is the mass fraction species concentration, c_p the mixture specific heat at constant pressure, Pr the Prandtl number, Le the

Lewis number, h_i the species enthalpy, and w_i the mass rate of production of the i^{th} species as a result of chemical reactions. The energy addition due to chemical reactions is contained in the last term. Moreover, as will be seen, the third and fifth terms are not present in this study. The conservation of mass for a two-dimensional flow is

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (4)$$

and the equation of state is

$$p = \rho \frac{R}{\bar{M}} T \quad (5)$$

where \bar{M} is the mixture molecular weight defined by $\frac{1}{\bar{M}} = \sum \frac{c_i}{M_i}$ with the summation over all the species.

Stagnation Region

This study is primarily concerned with the stagnation region near $x = 0$. The set of equations for this region may be obtained as follows. For a thin gas layer the state of the flow is dependent only on its initial conditions and the two edge conditions. That is, the large Grashof number implies a boundary layer flow which is described by parabolic equations. For this case, the stagnation region flow is then dependent only on local conditions. By utilizing an expansion in the x distance and by considering the region near $x = 0$ the equations (1) to (5) as set forth above reduces to the form given below. The momentum Equation (1) becomes

$$\frac{d}{d\eta} \left(\frac{df'}{d\eta} \right) = v \frac{df'}{d\eta} + f'^2 - \frac{gR}{U_r^2} \left(\frac{\rho_\infty}{\rho} \right) - 1 \quad (6)$$

where f' is the ratio of u to a velocity characteristic of the stagnation region, U_r is a reference velocity taken to be equal to $\sqrt{R g \frac{1}{T_\infty} (T_w - T_\infty)}$. One sees from U_r that $(T_w - T_\infty)$ is the driving potential and the coefficient of expansion of the gas can be recognized as $1/T_\infty$. The symbols ρ denote the usual ratio of the product of density and viscosity with respect to a reference value; the coordinate η contains the density function such that for constant values of x the increment $d\eta$ is given in terms of dy by

$$d\eta = \sqrt{\frac{U_r}{R(\rho\mu)_r}} \rho dy \quad (7)$$

The V function is obtained through the equation (4) satisfying conservation of mass. At the stagnation region one has

$$\frac{dV}{d\eta} = -f' \quad (8)$$

where by definition the velocity function V is related to the mass flux by

$$V = \sqrt{\frac{R}{(\rho\mu)_r}} U_r \rho u \quad (9)$$

These equations (6) to (9) are valid for the flow over two-dimensional cylinders. It is seen that the buoyancy force appears in the momentum Equation (6) and has been considered to be of the same order of magnitude as the inertia and viscous term. The dimensionless parameter, the Grashof number, can be conveniently

given in terms of U_r in the form

$$\text{Grashof No.} = \left(\frac{R U_r}{\nu} \right)^2 \quad (10)$$

where the radius of the cylinder has been used in its definition. As pointed out above, the Grashof number is of the order 10^6 - 10^9 in this study. The lower limit places the flow in the boundary layer regime and the second value is the upper limit for a laminar boundary layer (prior to turbulent flow) at the equator of the cylinder (Ostrach - 1964).

The pressure variation across the layer is a second order quantity since its thickness is small. This can be seen from Equation (2) where the excess pressure over hydrostatic is of the order of the thickness of the boundary layer. That is, the pressure can be considered as that for hydrostatic equilibrium at the stagnation region. For small distances from the stagnation point $x = 0$ the pressure drops parabolically and this variation can be obtained from Equation (2) for the stagnation region. Thus Equation (2) gives

$$\frac{dP_2}{d\eta} = \frac{-2\sqrt{(\rho\mu)_r}}{R \rho_\infty \sqrt{U_r R}} \left(f^{12} + \frac{gR}{2U_r^2} \right) \quad (11)$$

This function P_2 is defined in such a way that the pressure in the neighborhood of the stagnation region is given by

$$P = \left(1 - \frac{x^2}{R^2} \right) \rho_\infty U_r^2 P_0 - \frac{x^2}{2} \left(\frac{\rho_\infty U_r^2}{R} \right) P_2 \quad (12)$$

and the excess value is obtained by subtracting p_∞ . The value of P_2 is, of

course, zero at the edge of the boundary layer. This is the boundary condition for the determination of the entire function over y .

For a free convection flow over the cylinder the values of the velocities at both boundaries of the layer are zero. That is, at the surface and at the edge of the boundary layer respectively

$$\eta = 0 \text{ and } \eta = \eta_{\max}: f' = 0 \quad (13)$$

For an impervious body the normal component of the velocity is also zero at the surface which means that

$$\text{at } \eta = 0: v = 0 \quad (14)$$

For mass transfer from the body the value of the mass flux (ρv) at the surface is prescribed in Part II only. This case is considered in this study.

The consideration of chemically reacting gases implies the presence of more than one gas species. Thus the diffusion of the species and chemical reactions producing the species are important and have to be included. This is done in the next section.

An additional equation required for the temperature distribution is the energy Equation (3). A convenient variable is the temperature ratio $\theta = (T/T_{\infty})$ which can vary from its wall value θ_w to the ambient value of 1.

It is sufficient for the problem herein to consider binary diffusion. At the stagnation region, Equation (3) becomes for two-dimensional flow

$$v \frac{d\theta}{d\eta} = \frac{1}{c_p} \frac{d}{d\eta} \left(\frac{l}{P_r} c_p \frac{d\theta}{d\eta} \right) + \frac{l L_e}{P_r c_p} \sum c_{pi} \frac{\partial c_i}{\partial \eta} \frac{\partial \theta}{\partial \eta} - \frac{R}{c_p T_e U_r} \sum h_i \frac{w_i}{\rho} \quad (15)$$

Both summations are over the total number of species. Two boundary conditions are necessary for this equation. One is prescribed at the edge of the boundary layer such that

$$\text{at } \eta = \eta_{\max}: \theta = 1 \quad (16A)$$

A second condition is prescribed at the surface of the cylinder. This condition is taken as

$$\text{at } \eta = 0: \frac{\partial \theta}{\partial \eta} = 0 \quad (16B)$$

This condition defines then a surface temperature which is considered indicative of the ignition phenomena in the gas mixture. One notes that the total heat transfer is exactly zero for this condition as it is for an ideal gas even with the effect of diffusion flux at the surface of the cylinder for a non-catalytic body. These equations are equal in number to the number of unknowns which include the velocity components, density, and temperature, and are insufficient for their unique determinations since they implicitly are functions of the concentration of the reacting species. The method of determination of the species concentration is given in the next section.

III. SPECIES CONCENTRATION AND CHEMICAL REACTIONS

For a fuel-oxidizer mixture there are at least three species to be considered. The general case of N species can be treated by this study. These have different thermodynamic and transport characteristics. The concentrations of the different gas species are not only changed by the free convection flow but can also diffuse with respect to each other. The diffusion equation for the i^{th} species is

$$\rho \left(u \frac{\partial c_i}{\partial x} + v \frac{\partial c_i}{\partial y} \right) = + \frac{\partial}{\partial y} \left(\frac{\mu}{Pr} - Le \frac{\partial c_i}{\partial y} \right) + w_i \quad (17)$$

In this conservation equation the convective effect on the left hand side is balanced by diffusion and chemical production of the gas on the right side. There are two boundary conditions for this equation and these may be applied at the edge of the boundary layer and at the surface of the cylinder. Thus, the respective boundary conditions are:

$$\text{at } \eta = \eta_{\text{max}}: c_i = c_{i\infty} \quad (18)$$

and

$$\begin{aligned} \text{at } \eta = 0: c_i &= c_{i_w} \\ &\text{or} \\ \frac{\partial c_i}{\partial y} &= 0 \end{aligned}$$

Mass transfer of fuel from the surface of the body is accomplished by prescribing the mass flux there as indicated above. In this case the mass flux of any element not contained in the cylinder material vanishes. This implies that for

all species

$$\text{at } \eta = 0: \quad \frac{\partial c_i}{\partial y} = \frac{-\dot{m} Pr}{\mu L_e} \left[(1 - \delta_{ij}) - c_i \right] \quad (19)$$

where j is the injected species and δ_{ij} is Kronecker's delta and is one when $i = j$ and zero when $i \neq j$.

At the stagnation region the diffusion Equation (17) becomes

$$v \frac{dc_i}{d\eta} = \frac{d}{d\eta} \left(\frac{Le}{Pr} \frac{dc_i}{d\eta} \right) + \frac{w_i R}{\rho U_r} \quad (20)$$

for the cylinder. The transformation from the y coordinate by means of Equation (7) to the η coordinate has been utilized. Correspondingly, the boundary conditions (18) and (19) can be rewritten in terms of the η coordinate.

The chemical production of reaction products from the fuel and oxidizer mixture has been designated by w_i which is the net mass rate of production of species i per unit volume. This relation has to be formulated. In general, the stoichiometric equation for a chemical reaction of N chemical species can be written in the form



where the summations (and products below) are taken over the number of species and catalytic bodies. There is usually an equation of this form for each reaction. Then the production w_i for each reaction is of the form

$$w_i = M_i (b_i - a_i) \left(k_f \prod \left(\frac{\rho c_j}{M_j} \right)^{a_j} - k_b \prod \left(\frac{\rho c_j}{M_j} \right)^{b_j} \right) \quad (22)$$

where k_f and k_b are the forward and backward rate constants which are functions of temperature, and M_i is the molecular weight of the i^{th} species. These rate constants are prescribed for this study.

The thermodynamic and transport properties of the gas mixture are obtained by the appropriate summation rules. The individual species enthalpies are functions of temperature and are considered as such. The enthalpy of the gas mixture is then obtained as

$$h = \sum_{i=1}^N c_i h_i \quad (23)$$

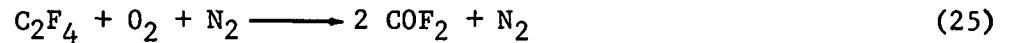
Similarly, the mixture specific heat is

$$c_p = \sum_{i=1}^N c_i c_{p_i} \quad (24)$$

The transport properties such as the mixture viscosity and conductivity is evaluated by Wilkes' rule from the individual values which have been evaluated as functions of the temperature and the appropriate collision integrals. In general, this permits the Prandtl number for the gas mixture and the product ($P\mu$) to be variable throughout the flow. It is appropriate to utilize a constant Lewis number in the study.

Results for a four species gas model will be used to show the effects of gravity on the ignition of a gas system in steady state. The four species can be considered as the two reactants, fuel and oxygen, a product of the chemical reaction, and an inert gas. Numerical results are given in the report for the reduced fluorocarbon gas reaction considered in Part I of the study. This

reaction is given for a Teflon monomer-oxygen mixture by



with the mass rate of production of product of the form

$$W_{\text{COF}_2} = M_{\text{COF}_2} \rho^{3/2} \left(\frac{C_{\text{O}_2}}{M_{\text{O}_2}} \right) \left(\frac{C_{\text{C}_2\text{F}_4}}{M_{\text{C}_2\text{F}_4}} \right)^{1/2} k_f \quad (26)$$

where k_f is the rate constant which is a function of temperature and of the form $A \exp (-E/RT)$. The results to be given in the next section utilizes $A = .91 \times 10^{14}$ and $(E/R) = 25,800^\circ\text{K}$. This choice for this mixture has been discussed in Part I.

IV. EFFECT OF GRAVITY ON IGNITION TEMPERATURE

The system of equations which will lead to the solution of this problem is given by Equations (6), (8), (11), (15), (20) for the unknown velocity ratio f' , temperature, and the species concentration. These equations are nonlinear and each requires two boundary conditions which are usually given at the material surface and in the ambient environment outside of this mixing layer. These conditions are given by Equations (13), (14), (16), and (19). The method of solution chosen was that of finite differences utilizing an accelerated iteration technique to enhance the convergence of the solution of the finite difference representation to the nonlinear equations. A guess is used to start the solution and it is then completed by means of iteration of the entire system of equations. A number of cases with mass transfer and without mass transfer was obtained. These are discussed below.

Consider a typical situation such as a plastic coated hot source which may be a short-circuited electrical wire bundle which then pyrolyzes and transfers pyrolysis gases to the environment. The temperature of the surface material rises with time to some value at which the gradient of the temperature at the non-catalytic material surface is zero. This temperature with a given mass transferred from the surface is the principal result of the study. Results are given for a mass flux of 10^{-5} slugs/ft²sec.

The variation of ignition wall temperature with gravity at the wall is given in Figure 2 for an ambient pressure of 200 lb/ft². It is remembered that the flow is generated by buoyancy only so that the flow velocity is directly

proportional to the gravity. It is seen from Figure 2 that a higher wall temperature is required to satisfy the ignition condition at the higher values of the gravity and hence a higher flow velocity. For the range of conditions considered, the wall temperature follows the relation

$$T_w(^{\circ}\text{K}) \sim \log (g/g_0) \quad (27)$$

The effect of gravity on the wall species of a non-catalytic body with mass transfer at its surface is shown on Figure 3. There is a rise in oxygen concentration at the wall and a corresponding drop in the injected species concentration as the wall temperature increases, that is, as the convection velocity also increases. The reaction product concentration at the wall also increases with wall temperature. These effects are primarily due to the V function (mass flux) variation which is inversely proportional to the characteristic convection velocity U_r . Thus the gradient of the species concentration is inversely proportional to the convection velocity (cf. Equation 20, in particular, the V function and a similar factor in the chemical production term). Then the relationship of $C_{i,w}$ to U_r can be seen readily from Equation (19) and this is indicated by the results of Figure 3. Since the injected species decreases across the layer away from the wall and oxygen increases, the reaction product achieves a maximum slightly off the wall. This can be seen from Figure 4.

The effect of the gravity on the species production can be discussed in terms of the relative magnitudes of the flow time and chemical reaction time. These quantities are contained in the last term of Equation (20). It is seen from that term that the flow time is given by the ratio R/U_r whereas the typical chemical reaction time is the inverse of the term $(k_f \rho^{1/2})_{\text{COF}_2} / M_{\text{O}_2} M_{\text{C}_2\text{F}_4}^{1/2}$.

For the cylinder of radius R equaled to one the characteristic flow time and chemical time are respectively 0.2 sec and 0.3 sec for the results given on Figures 4 and 5. These times are of the same order and points to their equal importance in this problem. Thus Figure 2 shows, in general, that the ignition temperature decreases with increasing characteristic flow time.

Figure 5 contains the velocity and temperature profiles characteristic of this type of flow. The free convection velocity generated by the buoyancy is small. Since the stagnation region is of concern here, the f' ratio is the downstream gradient of the tangential velocity. A maximum value of 0.764 is obtained in the layer leading to a velocity variation of the form $3.82 x$. That is, the velocity increases along the layer linearly at this rate. The temperature profile shown has a maximum at the surface as expected; the exothermic chemical energy for this condition is insufficient to cause a peak within the layer and therefore the surface zero temperature gradient will impose the maximum value there.

Zero Mass Transfer

Additional results have been obtained for the zero mass transfer case. In this case the hot cylinder is immersed in a mixture of fuel, oxygen, and nitrogen. The nitrogen gas is assumed to be inert. The same reaction as before is used. Numerical results are given at atmospheric conditions. The ignition temperatures for different gas mixtures are given on Figure 6 for a wall concentration of fuel of mass fraction equaled to 0.1. The mass fluxes of the various species are small non-zero quantities since the species concentrations have been prescribed. The gradient of temperature at the wall is zero. Thus, the wall is maintained at almost adiabatic conditions.

Figure 6 shows that the variation of ignition temperature due to an increase in gravity is the same as that shown on Figure 2. An increase in flow time due to decreasing the gravity generally favors a decrease in ignition temperature. Generally, also, the effect of an inert diluent is to increase the necessary wall temperature to ignite the gas mixture. An example of a 50% O₂-50% N₂ (by mass fraction) at one gravity shows that the ignition temperature is increased by about 105°K. At 1/2 normal gravity this increase has been reduced to 45°K which is less than one-half that at one gravity. The effect of increasing the concentration of inert diluent is also given for other mixtures as indicated on the figure. The effect of the addition of inert diluent to a mixture of fuel and inert diluent is small as compared to that when it is added to the fuel alone. For a given gravity situation the ignition temperature increases with an increase of the inert diluent. Figure 7 gives an idea of this increase where the free stream oxidizer concentration is shown to drop sharply (corresponding to the increase of diluent) with increasing ignition temperature. Typical velocity and temperature profiles are shown on Figure 8. These have the same shape as before as shown on Figure 5. The corresponding species concentrations are given on Figure 9. The peak of F₂CO species within the layer is evident. Finally, the chemical production of the combustion product is given on Figure 10. Since the temperature is highest at the wall the chemical production of the combustion product is highest there and drops rapidly away from the wall.

The flow dynamics for the cases studies are given on Figure 11 in terms of the square of the reference velocity which is a product of the gravity and temperature difference across the stream. Thus the peak velocity ratio is

almost a constant for the various combinations of temperature difference and gravity and the displacement thickness approaches a constant for large values of this velocity. The effect on these two quantities of the addition of inert diluent is small.

V. CONCLUDING REMARKS

The ignition temperature for a horizontal cylinder immersed in a combustible mixture subjected to a free convection flow generated by buoyancy forces has been obtained for steady state conditions. The nonlinear problems at the stagnation region have been studied in detail for the combustion of a mixture of fuel and oxidizer. Besides the flow convection due to the buoyancy the diffusion of each species has been included.

Results show that gravity increases the ignition time required for a given mixture. The effect of an inert diluent is to also increase this temperature.

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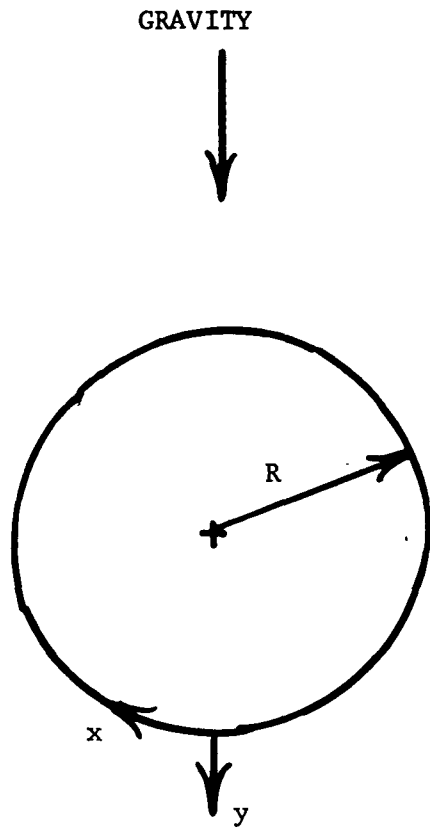


FIGURE 1. COORDINATE SYSTEM FOR HORIZONTAL CYLINDER

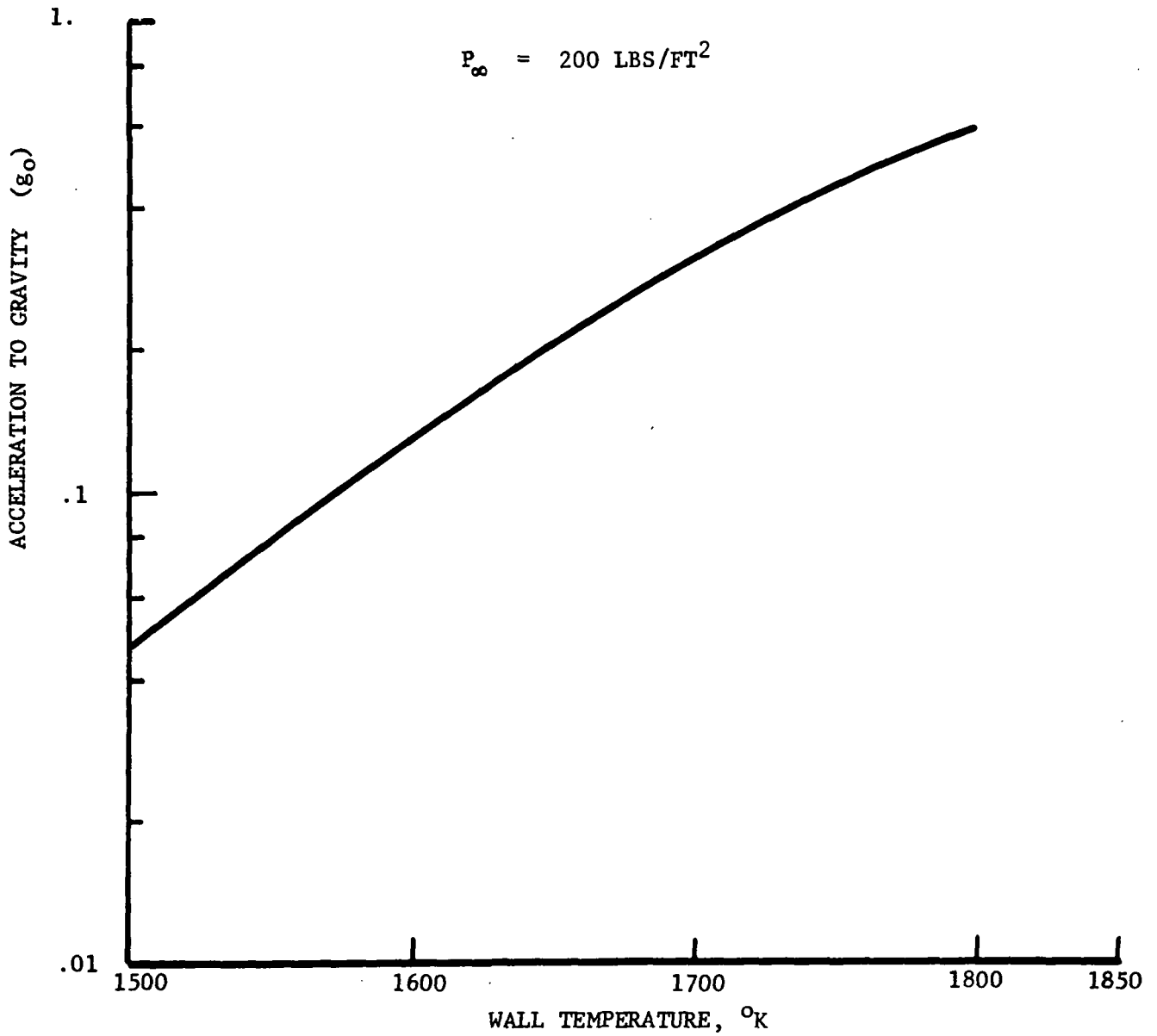


FIGURE 2. IGNITION TEMPERATURE OF GAS MIXTURE WITH MASS ADDITION AT MATERIAL SURFACE

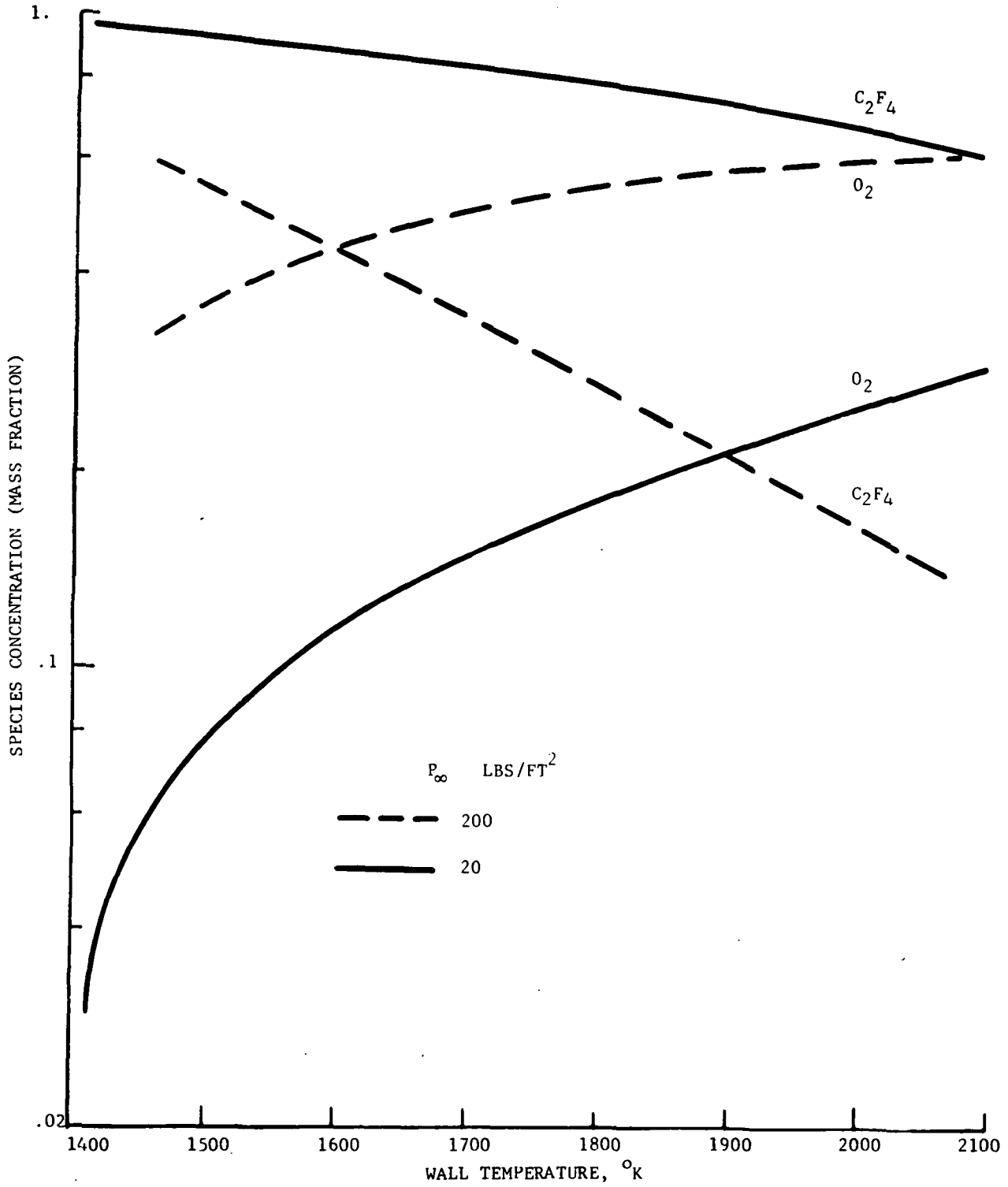


FIGURE 3. CONCENTRATION OF FUEL AND OXYGEN AT THE SURFACE

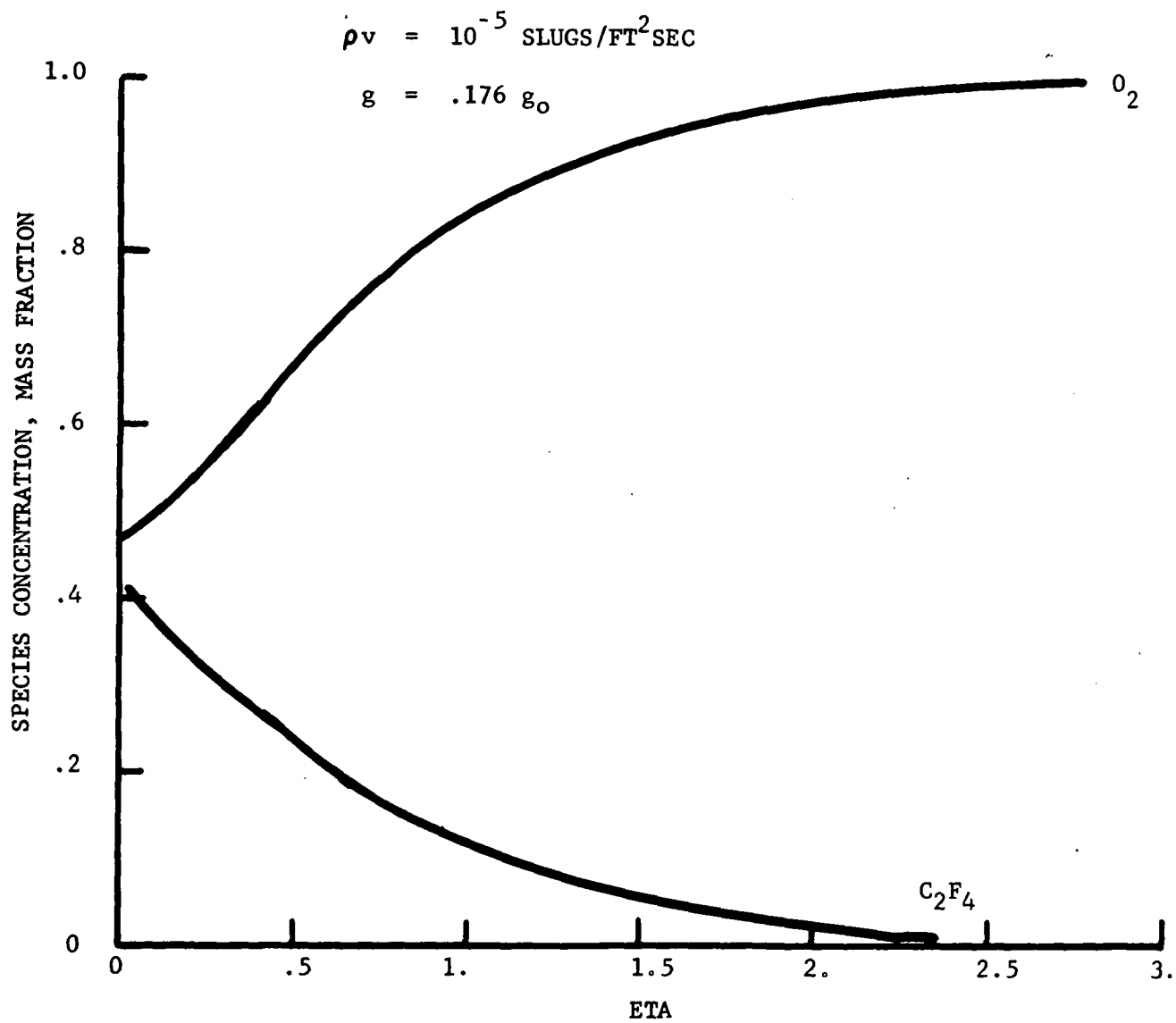


FIGURE 4. SPECIES CONCENTRATION ACROSS THE LAYER

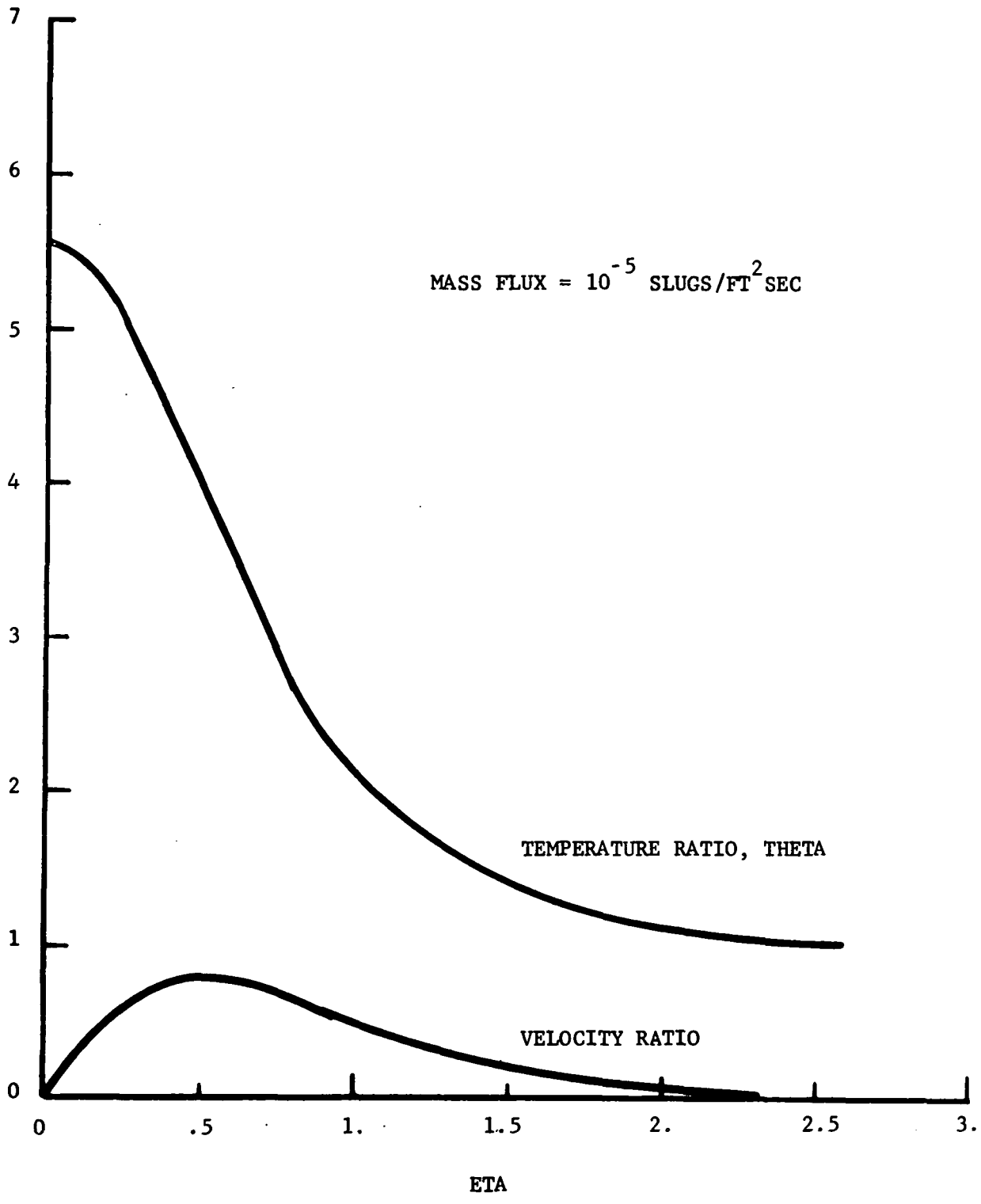


FIGURE 5. TEMPERATURE AND VELOCITY PROFILES

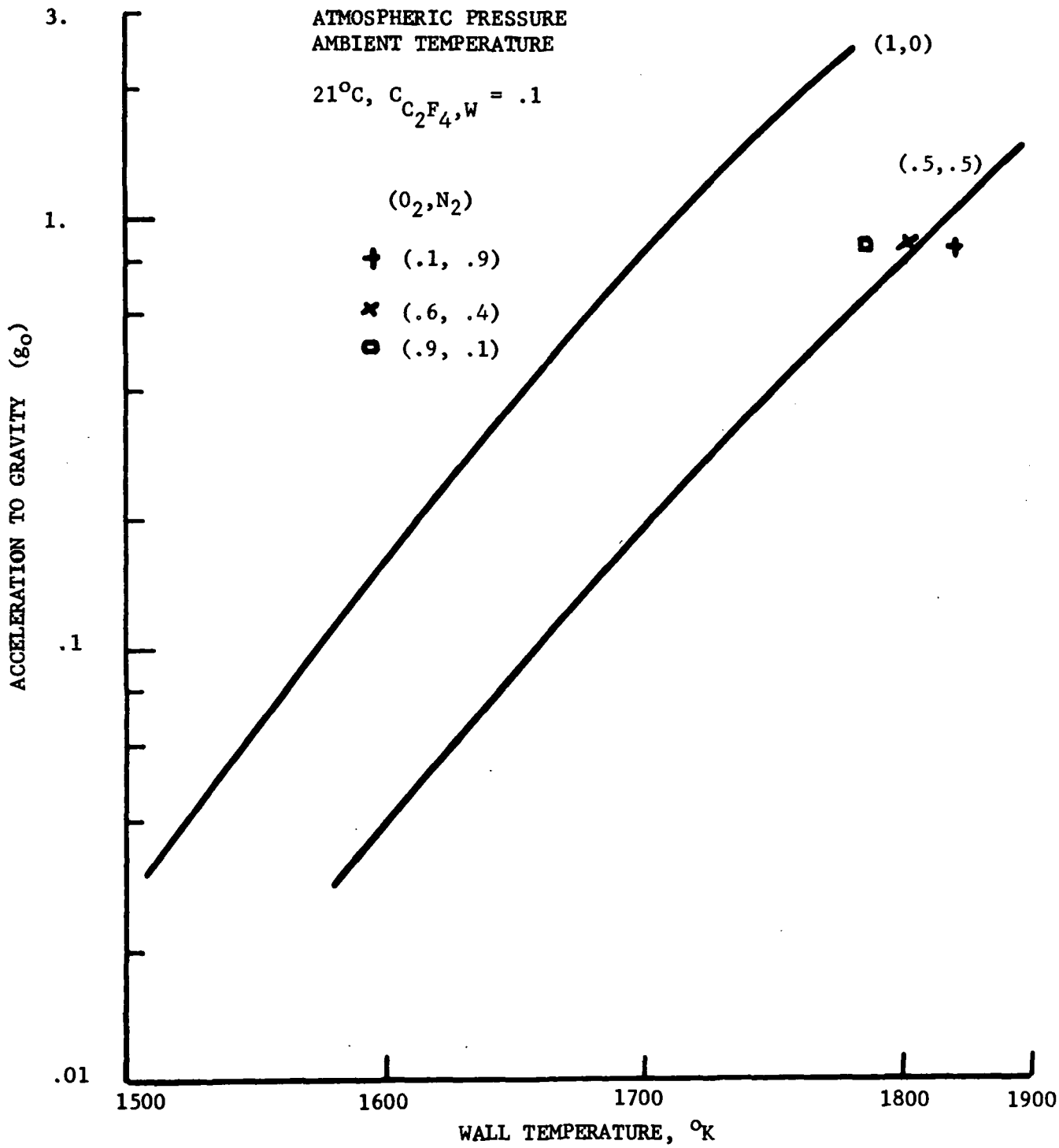


FIGURE 6. IGNITION TEMPERATURE OF ($C_2F_4, O_2 + N_2$) MIXTURE, N_2 INERT

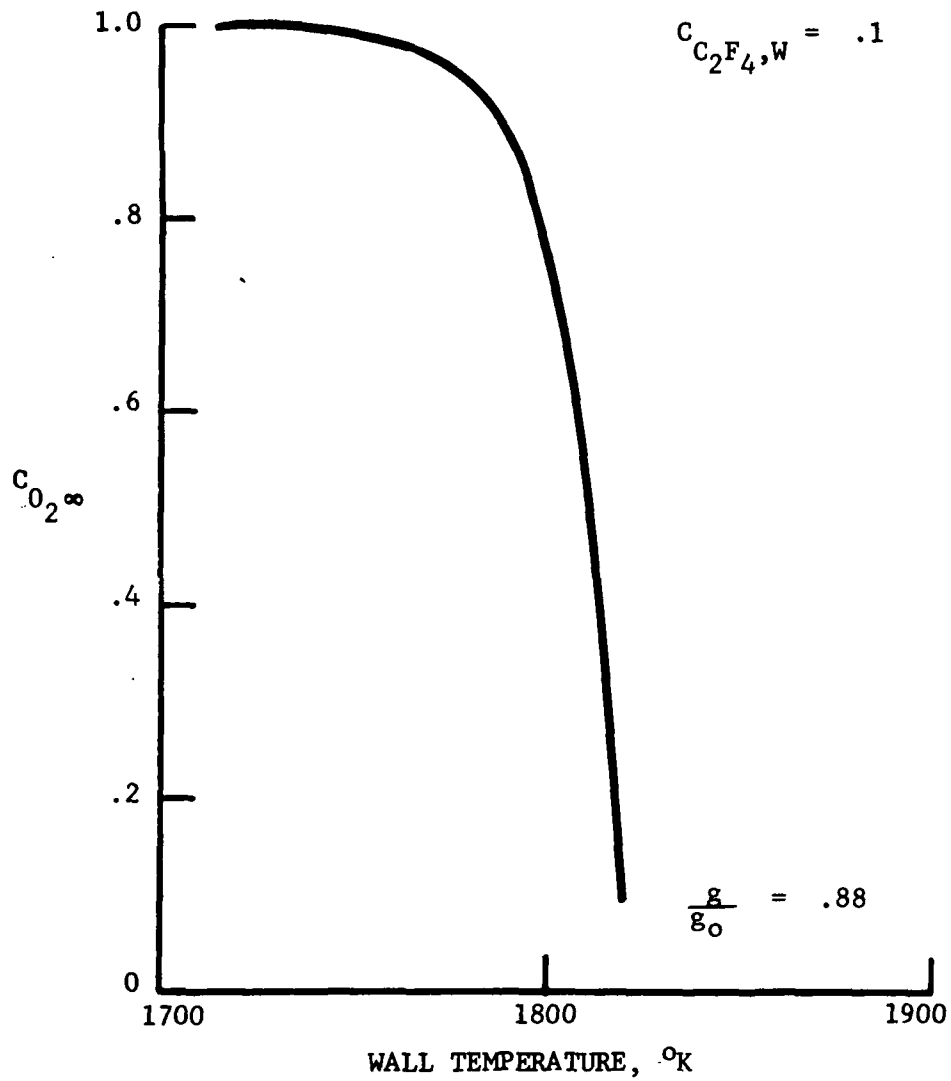


FIGURE 7. EFFECT OF INERT DILUENT ON IGNITION TEMPERATURE

ATMOSPHERIC PRESSURE OXYGEN ATMOSPHERE,

C_2F_4 GAS

MAXIMUM VELOCITY = 107 CM/SEC

STAGNATION - TWO DIMENSIONAL

$T_\infty = 294^\circ K$

GRAVITY = .191 SEA LEVEL VALUE

$C_{C_2F_4,W} = .1$

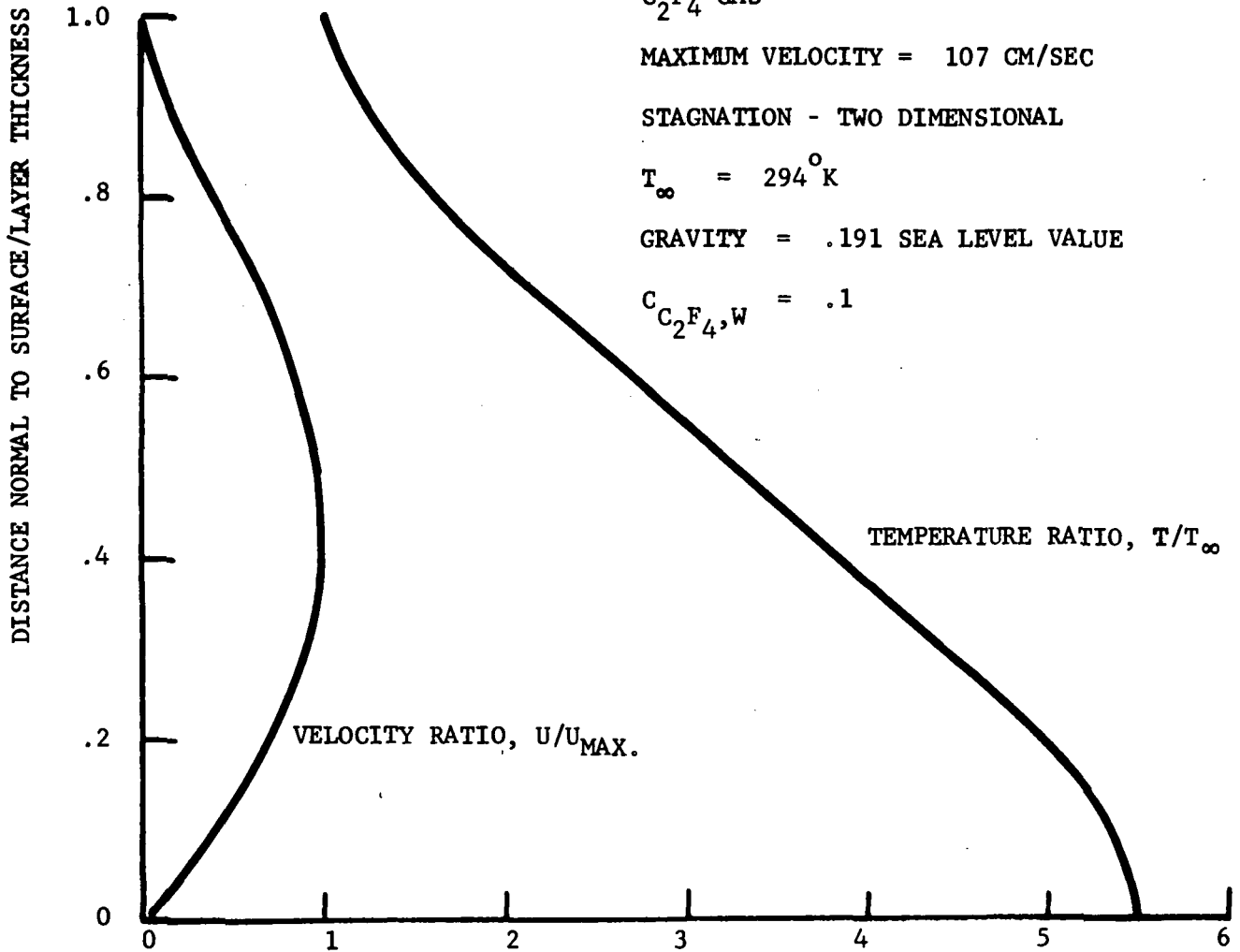


FIGURE 8. VELOCITY AND TEMPERATURE DISTRIBUTIONS

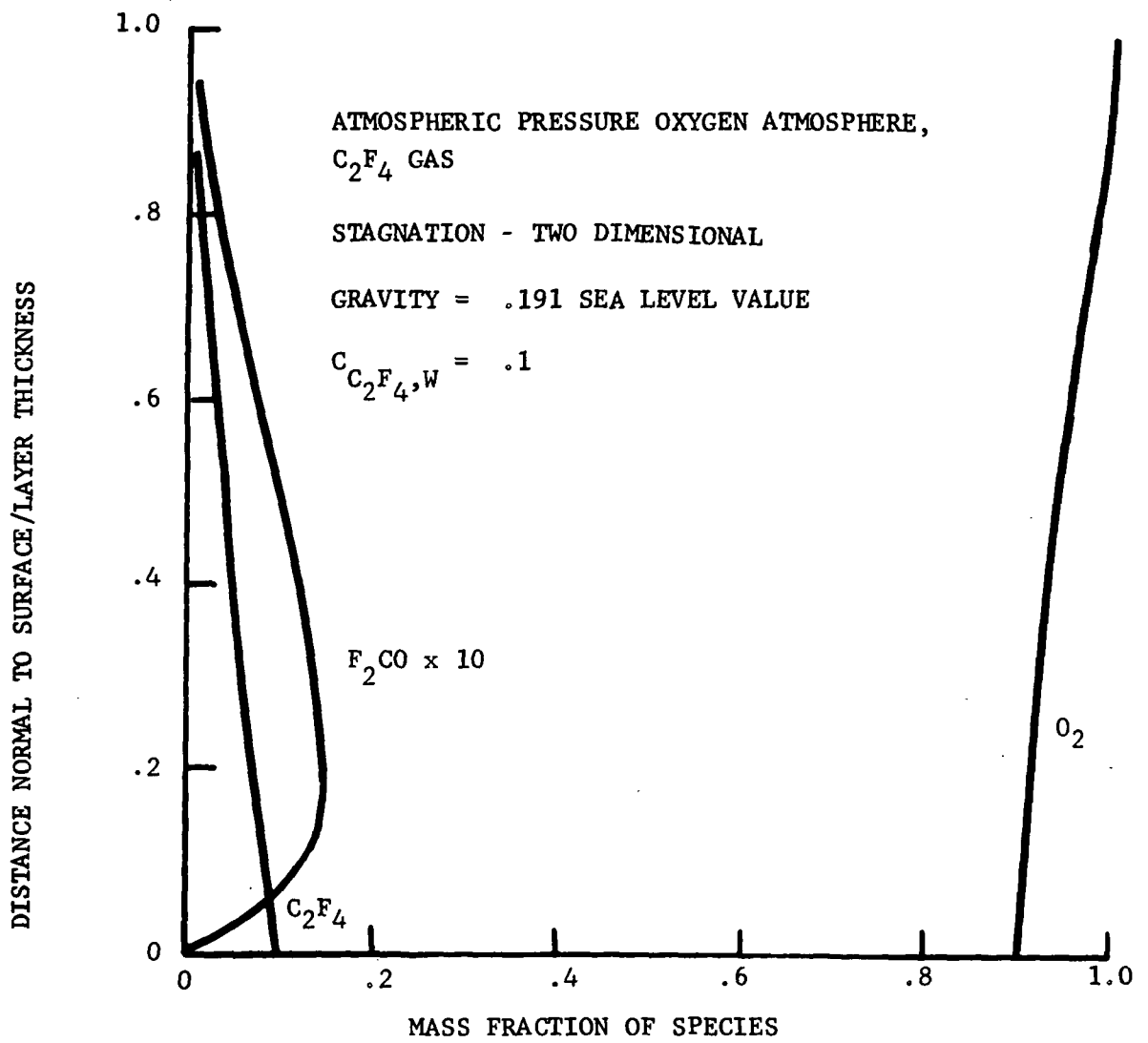


FIGURE 9. SPECIES CONCENTRATION ACROSS THE LAYER

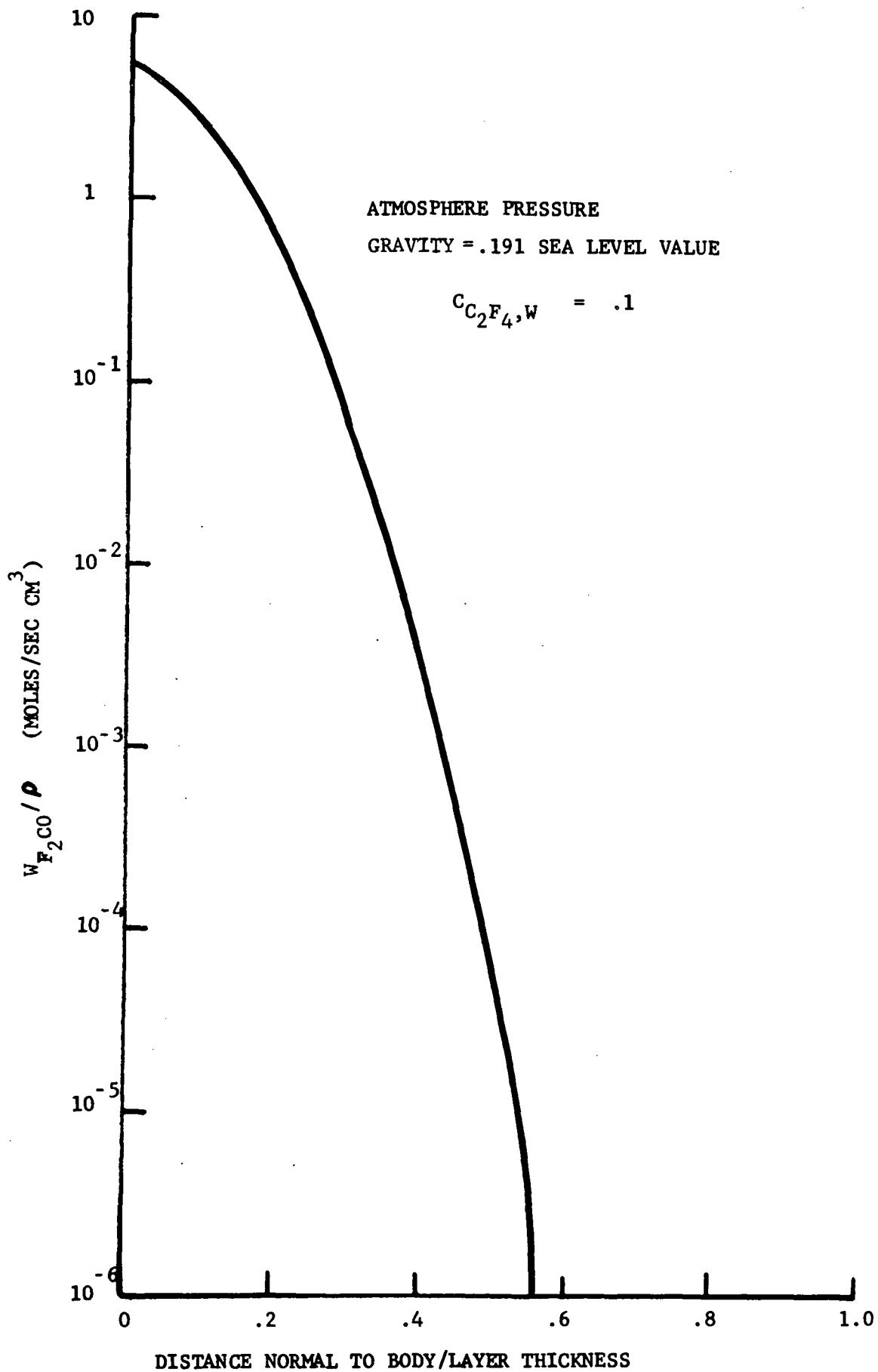


FIGURE 10. CHEMICAL PRODUCTION OF PRODUCT IN C_2F_4 - O_2 MIXTURE

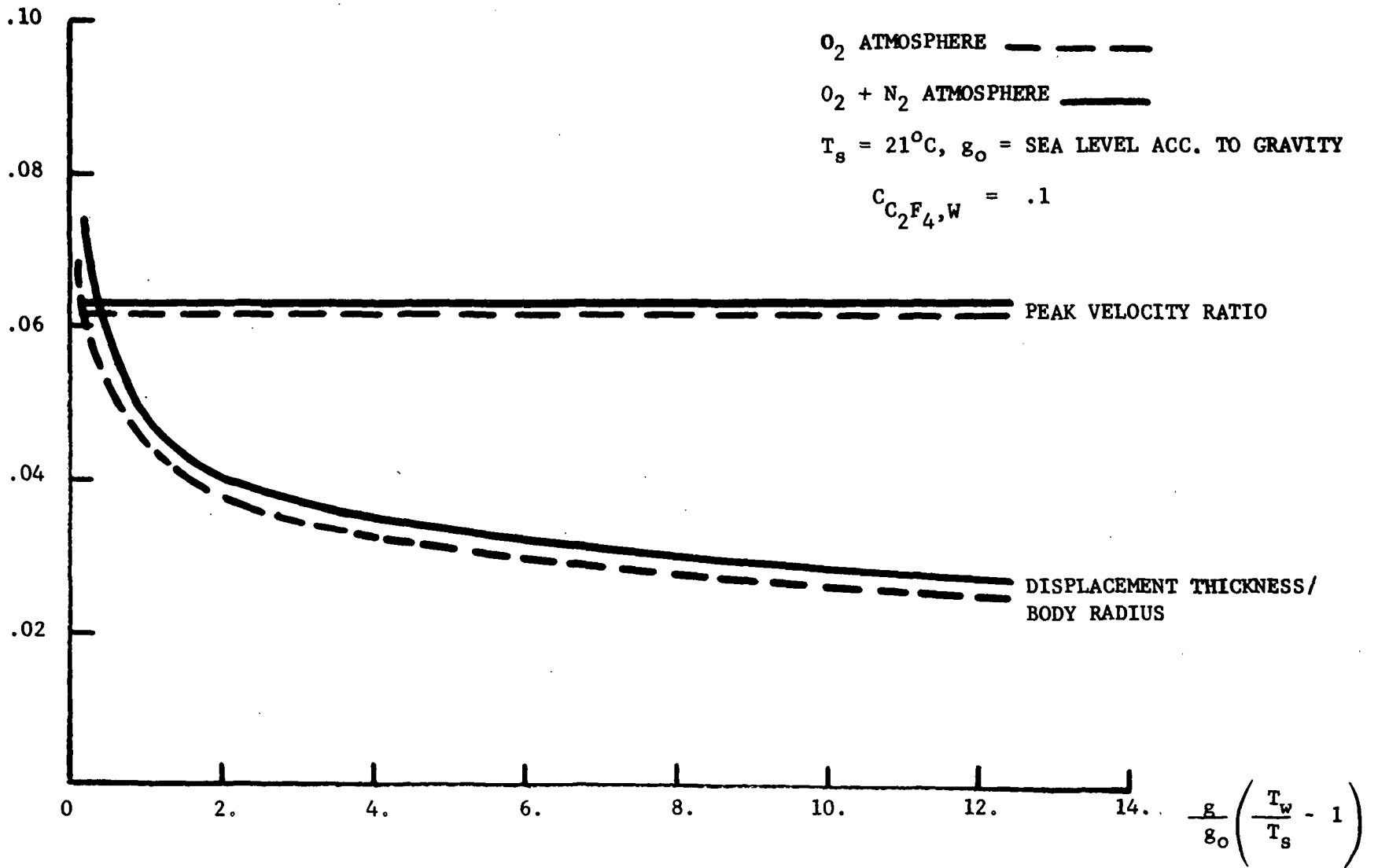


FIGURE 11. CONVECTION LAYER DISPLACEMENT THICKNESS AND PEAK VELOCITY

GENERAL  ELECTRIC