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HEAT CONDUCTION CONTROLLED COMBUSTION FOR SCRAMJET APPLICATIONS

By Antonio Ferri and Anthony Agnone

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Antonio Ferri† and Anthony Agnone††

SUMMARY

The use of heat conduction flame generated in a premixed supersonic stream is discussed. It is shown that the flame is controlled initially by heat conduction and then by chemical reaction. Such a flame is shorter than the diffusion type of flame and therefore it requires a much shorter burner. The mixing is obtained by injecting the hydrogen in the inlet. Then the inlet can be cooled by film cooling.

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1. Introduction

One of the important problems to be solved for the development of hypersonic vehicles flying in the dense atmosphere is related to the aerodynamic heating. The use of advanced scramjet engines taking advantage of three-dimensional design criteria and thermal compression has reduced substantially the heating problems for the scramjet design (Ref. 1,2,3). Present designs are based on diffusion type of flames where the heat release is controlled by the rate of diffusion of hydrogen into air.

Heat conduction type of flames where the heat release is controlled by the rate of heat conduction in a premixed mixture of fuel and oxidizer, have been analyzed in the past and have been recommended for low Mach number low temperature air operation (Ref. 4-5).

Recently (Ref. 6) NYU has investigated the problem of NO_x formation in scramjets and has determined that heat conduction flames, if conveniently utilized can permit to reduce the NO_x formation because of the possibility of reducing the length of the flame, and therefore the residence time of the combined products in the high temperature region (Ref. 6).

In this report the use of heat conduction flames in scramjets is proposed as a means for improving the overall operation of the engine. It will be shown here that the use of a premixed mixture ignited locally by the temperature rise due to heat conduction from the combusted region presents the following advantages, a) it permits us to reduce substantially the flame length and therefore the size of the combustor, b) it permits easily to control the region where heat is released by controlling the region where high static temperature is reached. Such control permits avoiding thermal choking at low Mach numbers, and permits using tangential injection in all flights required. Presently this control is obtained by using a combination of normal injection at high Mach numbers and tangential injection at low Mach numbers which penalizes the engine performances, c) it permits us to utilize the hydrogen injection for external cooling of the inlet structure, d) it permits rapid expansion downstream of the combustion region decreasing the residence time and the formation of NO_x. The data supporting these basic points are discussed in this report.

2. Comparison of Diffusion Flames and Heat Conduction Flames

In a supersonic flame controlled by diffusion, the rate of heat release is controlled by two different processes: the diffusion of the fuel in the oxidizer and the rate of the chemical process. For scramjet applications the chemical processes are very rapid because of the local high temperature; therefore, the parameters controlling the length of the combustion process is the diffusion process. Diffusion depends on the turbulent characteristics of the flow and on the distribution of gradients of concentration of species. Initially near the injection region the concentration gradients are changing very rapidly because the concentration of fuel goes from 100% to zero in a very short distance, therefore diffusion is very rapid, however the gradients tend to decrease downstream because the fuel concentration at the axis of the injector decreases and the mixing region increases in size. For this reason the length required to reach fairly uniform conditions is many times the size of the initial dimension of the fuel stream. A typical temperature distribution in a diffusion flame is shown in Fig. 1. Here the flame is two-dimensional and the combustion is assumed to occur at constant pressure. The flame occurs in a channel shaped to produce constant pressure (the analysis neglects normal pressure gradients) and the initial conditions are such that the average fuel to air ratio complete mixing corresponds to a fuel-air ratio of 0.7 stoichiometric value. The initial dimension of the channel is assumed to be 1". Mixing and combustion takes place gradually. At a distance of 12 feet downstream of the injection station the flow properties are far from uniform and the combustion is not yet completed. The distribution of $\dot{m}_{H_2O} / (\dot{m}_{H_2})_j$ as a function of distance is shown in Fig. 2. The $(\dot{m}_{H_2})_j$ is the mass of hydrogen injected originally. Therefore the quantity indicates the amount of fuel burned at each station as a percentage of the total fuel injected. The ratio is approximately equal to one for complete combustion. Figure 1 gives also some indication of the thermal compression effect that could be obtained from the combustion. The area variation is from 1 to 2 at the end of the combustion. The flame presented in Fig. 1 corresponds to a free stream Mach number of 7.6, and the length of the diffusion flame does not change drastically when the free stream Mach number changes. However if the static temperature is very low the reaction time becomes also important. Figure 2 gives some indication of the length required for several Mach numbers. The shape of the wall gives some indication of the progress of the combustion along the length. The mixing and combustion is initially rapid; however, the mixing (and as a consequence the heat release) decreases rapidly moving downstream for the injection station corresponding to a more gradual variation of cross sectional area.

Consider now a flame initiated in a completely premixed stream. The mixing takes place in the inlet and is moving from a region of low to higher static temperature and pressure. The flame is initiated locally by a pilot. The temperature of the mixture reached at the point where the flame is initiated is lower than the temperature of detonation so that the mixture will not react chemically for a long time unless the combustion is initiated locally. Such conditions are typical of flow in a scramjet for flight Mach numbers below 10. The approximate range of the detonation limits and the relation between length available before combustion in a high temperature region are shown in Fig. 3.

In the figure the ignition delay has been assumed to correspond to $\tau_{I.D.}p = 8 \times 10^{-3}\ e^{9600/T}$ (milliseconds). Three families of curves are presented in this figure. For these family of curves it is assumed that the flight dynamic pressure is constant and equal to 1000 psf. The first family of curves (family a) gives the pressure temperature relation in the burner for three flight Mach numbers in practical engines. The second family of curves (family b) gives the temperature and pressure in the burner for a fixed burner Mach number for different flight Mach numbers. The conditions at different flight Mach numbers are given by the crossing points of family a and b. The third family (family c) gives the delay time available before auto-ignition takes place. Typical lengths corresponding to the time before auto-ignition are shown in the figure. In addition a line called auto-ignition line corresponding to a length of approximately 3 feet is also shown in the figure. Points on the right of this line are useful for combustion processes controlled by heat conduction.

The conduction controlled type of flame is initiated by a pilot. Several types of pilots are available. The flame can be initiated by creating a localized region of the flow having auto-ignition temperature, or creating a region of low velocity and long residence time, (flame holders), or by initiating the combustion by a pilot flame of subsonic type. Such localized flames because of heat conduction from the burnt mixture in the adjacent unburnt mixture increase locally and gradually the temperature in the unburnt mixture of the streamline near the flame; therefore the combustion process propagates. The main advantage of a premixed flame is that the diffusion process controls the region where the flame is located, and therefore the region where heat release occurs, however it does not control the rate of the heat release process because as soon as the temperature increases locally to a value corresponding to rapid reaction, then the reaction proceeds independently from the heat conduction process and therefore is very rapid, while when the flame is diffusion controlled the diffusion process controls completely the rate of heat release and therefore near the end requires a long time to complete combustion.

The isotherms of two heat conduction flames are shown in Figs. 4 and 5. Both flames have been analyzed by means of a mixing program which neglects normal pressure gradients and with the assumption that the pressure is constant however any pressure gradients produced by the combustion process can be cancelled by starting initially with a nonuniform flow field. The analysis assumes that the initial conditions are reached along the initial line by means of a weak shock produced by the flame holder. The two sets of isotherms show that the initial temperature has a strong influence on the position of the zone where heat release occurs, however in both cases the combustion process is very rapid. The difference between a diffusion controlled and heat conduction controlled flame can be better explained by analyzing the time history of the temperature along a streamline as a function of the initial temperature.

Consider a premixed stream having initially different temperatures varying from 800° to 1100°K. Then if the process is adiabatic, the variation of temperature is as shown in Fig. 6. A small variation of local temperature changes substantially the time for heat release. At a temperature of 800°K no reaction takes place within a time of 5.20×10^{-4} seconds. The time corresponds to a travel of 3.0 ft. However between 800° and 900°K the time changes substantially. Then if the process is adiabatic, and heat transfer takes place, the temperature rises and combustion takes place in short distances.

In an actual case combustion tends to produce pressure variations that propagate through waves; however, such waves interact with waves produced by the boundar! ,. Therefore in the/absent regions which are of combustion, the temperature variation along each streamline is controlled both by the combustion waves and by the waves generated at the boundary. Therefore the region where a flame can start and how the flame propagates depends on the wall design. By controlling the temperature distribution and pressure distribution, the flame shape and length can be controlled. Then the length of the combustion can be controlled and in addition the location and shape of the flame can be selected by selecting the appropriate aerodynamic design. For example in Fig. 7, a variation of static pressure and temperature before combustion has been assumed to exist along the axis. Then the flame becomes different than for the case of constant pressure.

All these results are based on constant pressure mixing and can be somewhat misleading because any static pressure rise tends to increase locally the temperature and (decrease the local flow speed). Therefore it could accelerate the flame propagation. The problem where pressure waves produced by combustion are considered is more complex to analyze. However the conditions do not change. The heat release in a streamtube tends to produce compression waves followed downstream by expansion waves. Therefore the heat release in each stream tube is equivalent from the point of view of formation of waves to the introduction of a solid cusp of finite thickness. Then if the equivalent "cusp" distribution is placed along lines more inclined than the Mach waves, the focusing cannot take place because the compression produced by the second "cusp" is cancelled by the expansion produced by the first cusp (Fig. 8), and the heat conduction process is such that the propagation of heat is much slower than the wave propagation.

An analysis of the flame with the method of viscous characteristics is shown in Fig. 9. Fig. 9a1 corresponds to the case when the local pressure increases due to the combustion process. The compression waves formed ahead of the flame front tend to coalesce and form a detonation shock. For the present conditions a shock with a turning angle of approximately 30° is formed.

Fig. 9b1 shows the case of an expanding wall. The expansion waves produced at the wall cancel the compressions produced by the combustion so as to maintain the pressure nominally constant. The temperature profiles at different stations are shown in Figs. 9a2 and 9b2 for the two cases considered. The flame front is the locus of the inflection point in the temperature profiles. The flame front moves slower in the case of the curved wall than the case with the straight wall. The static pressure profiles are shown in Figs. 9a3 and 9b3 for the two cases. The flame front coincides with the pressure peak in the profiles. In the first case (straight wall), the reflected waves and combustion induced compression waves increase the local static temperature and pressure. The flame front accelerates in these regions to form the detonation wave.

This analysis confirms the description given above. The combustion process depends on the initial conditions (temperature and pressure) on the degree of mixing and on the maximum temperature reached after combustion, because such temperature controls the amount of heat transmitted to the unburnt mixture and therefore the time required to reach the combustion temperature.

Figure 10 gives some indication of the sensitivity of the initial conditions. In the figure several curves indicating the amount of heat released in percentage of the total as a function of initial conditions. The heat released is measured in terms of the percentage of hydrogen burnt (given approximately by the mass of H_2O (divided by 9) with respect to the total hydrogen present). The initial conditions used in the figure for the different Mach numbers are typical of a good scramjet design. In addition, for $M_\omega = 7.6$ the conditions corresponding to three initial temperatures are shown. Small variation of initial temperature produces changes in the flame length.

In the analysis of Fig. 11 it is assumed that the fuel-air mixture is not unidorm and that the α varies from a value of 1.5 at the y = 0 to a value 0.5 @ y - 0.125 ft. Then the heat release is more gradual, than for the fully premixed flame shown in Fig. 12, therefore the required increase of stream tube (thermal compression) occurs also more gradually. The effect of α is shown in Figs. 13a, 13b, and 13c. There the flight Mach Number considered is 4.

3. Use of the Premixed Flames

The analysis shown in the previous examples indicate that very short flames can be produced, however, in order to avoid detonation some control of the initial temperature is required. The analyses show also that by a careful selection of the initial conditions the location of the heat released in the burner can be modified. The reduction in flame length is significant as can be seen from Fig. 14 where the diffusion and heat conduction flame are compared.

The use of a premixed flame presents several other advantages beside reducing the burner length. Hydrogen can be used as coolant for the inlet surface. A possible injection scheme is shown schematically in Figs. 15 and 16. Fuel is injected along the walls of the inlet, and at a few selected stations before combustion. In addition, at low Mach numbers fuel can be added at the pilots. At low Mach numbers pilot B is used to initiate the flame, while at high Mach number pilot A is used. In addition the fuel distribution in the flow can be controlled. Then by changing the distribution between the different injectors, the choking can be eliminated and efficient combustion obtained in all ranges of Mach numbers. It must be noted that the fuel stream produces an aerodynamic contraction that helps starting the inlet at low Mach numbers. An additional possibility is made available by the necessity of a pilot for starting the combustion.

When the flight Mach number decreases, the free stream stagnation temperature decreases. When this temperature is low the ignition delay becomes very large and local ignition is required. The necessity of a pilot permits combustion to be started at different points in the burner. An example of this possibility is shown in Fig. 16. Here we can initiate combustion on one side of the inlet and then we can locate a second pilot downstream on the opposite surface. Then combustion can be produced in both sides efficiently. It must be noted that the premixed flame shape and location depends mainly on the location of the pilot and on the inviscid flow field where the flame is generated. The transport properties change the flame propagation only slightly, however the changes are small. Then the difficulty related to the necessity of an accurate knowledge of transport properties to design a burner decreases substantially with respect to the diffusion flame.

5. Concluding Remarks

The premixed flame characteristics appear to be attractive for some jet applications. Before such flames can be utilized, a detailed analysis of the waves generated by combustion is required and experimental data on such type of flames are required to check the analysis.

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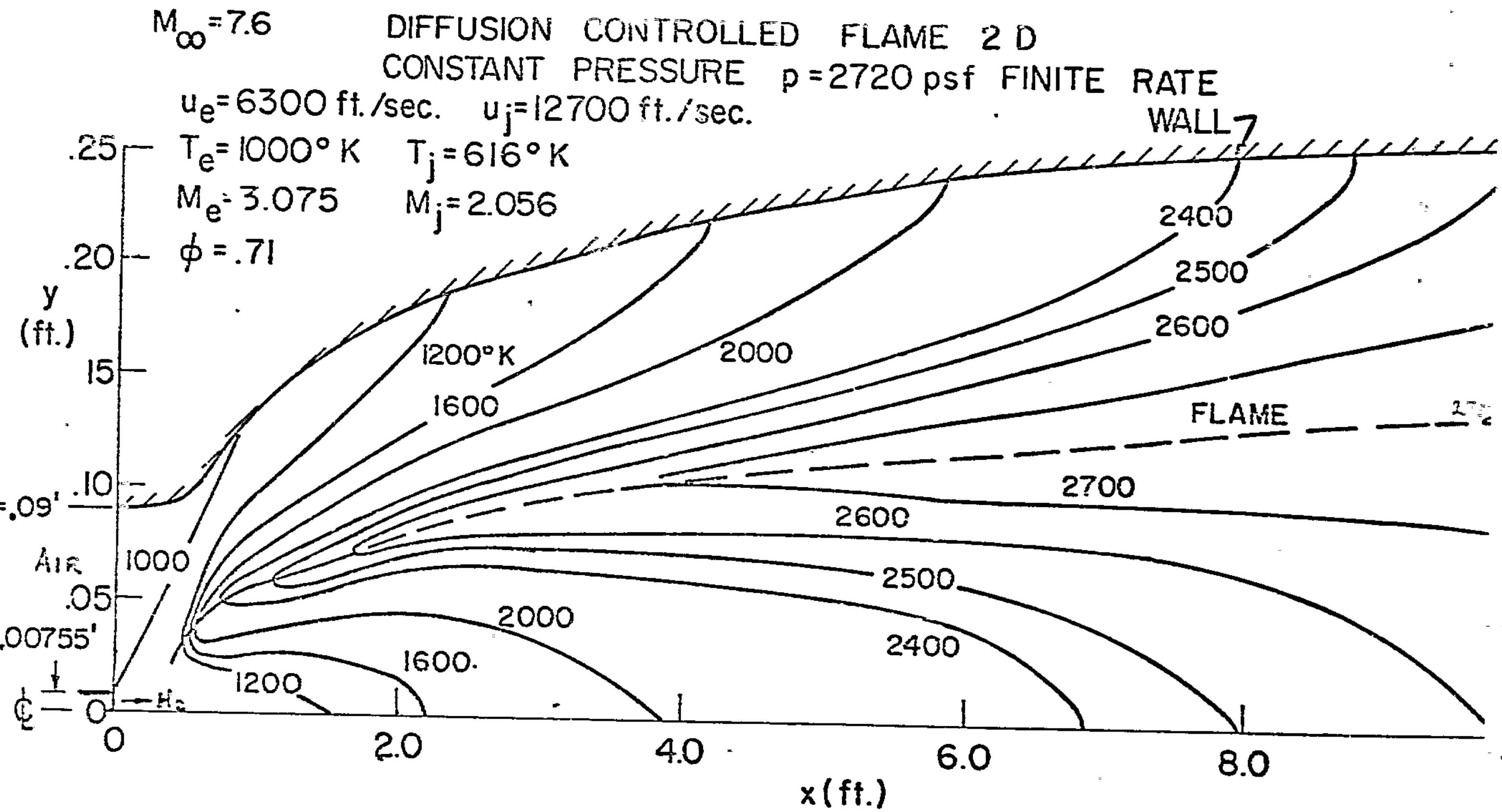


Fig. 1a Isotherms of a supersonic diffusion flame - M_∞ = 7.6 conditions

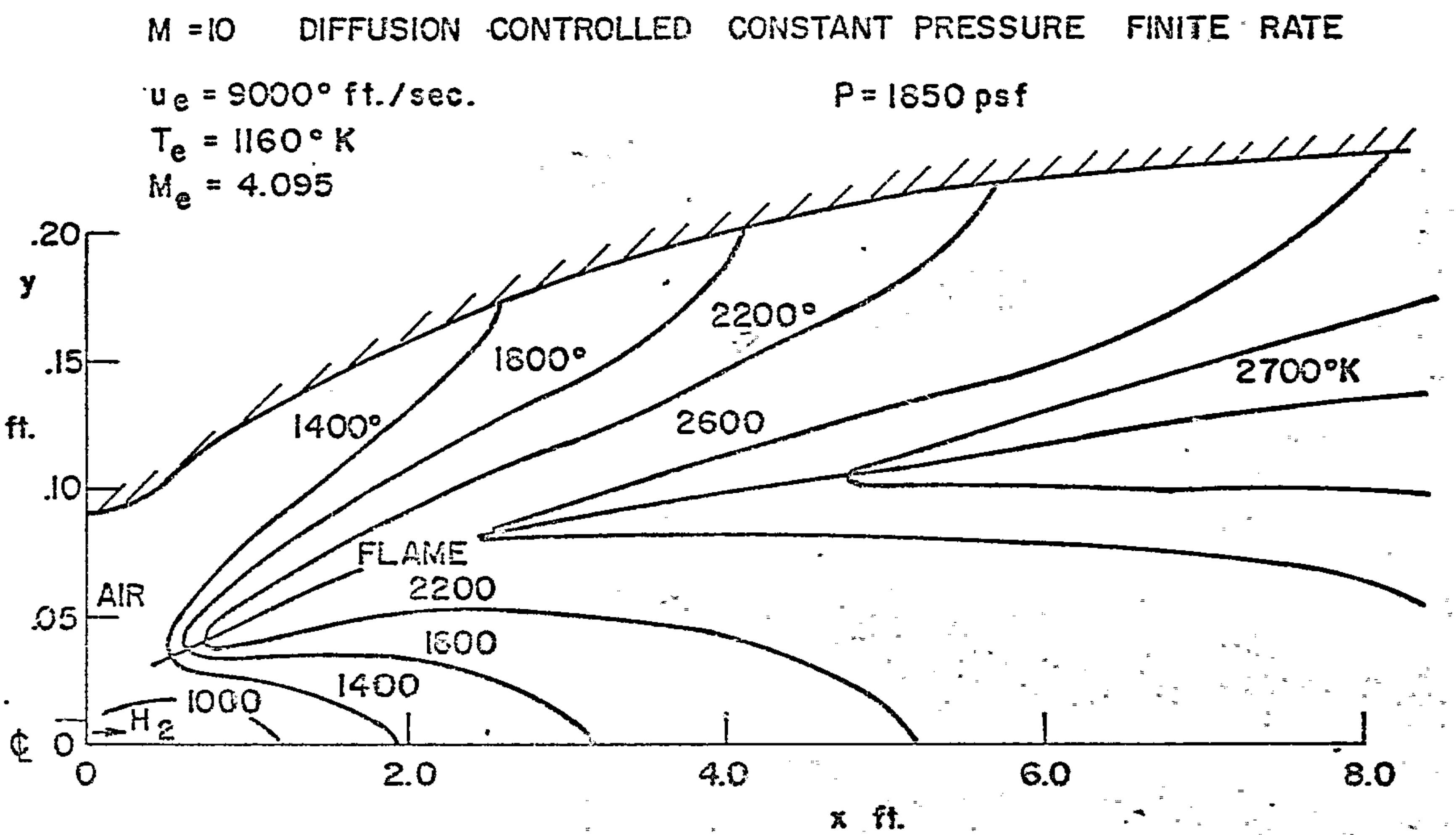


Fig. 1b Isotherms of a supersonic diffusion flame - M_∞ = 10.0 conditions

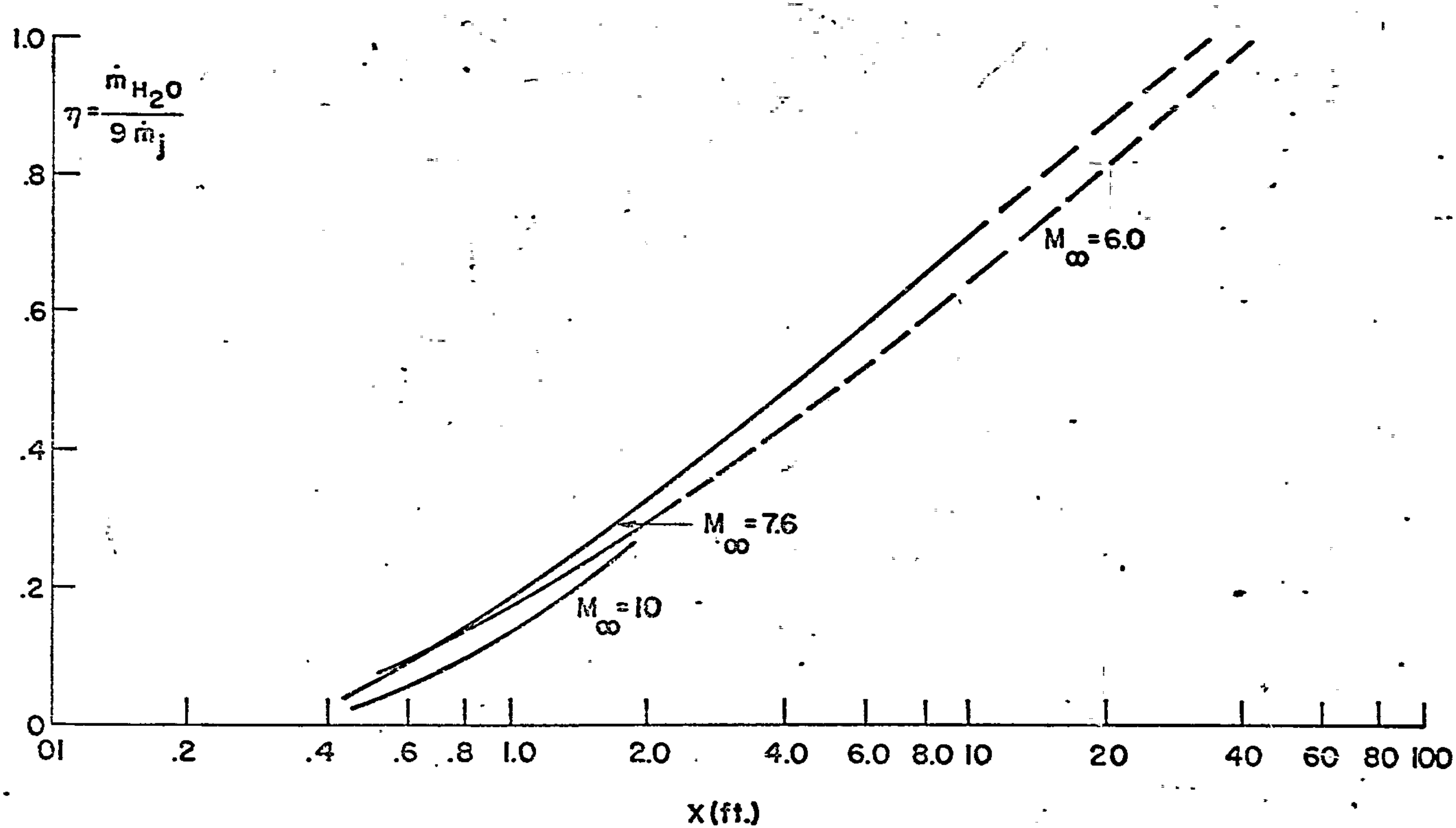


Fig. 2 Combustion efficiency of a diffusion flame

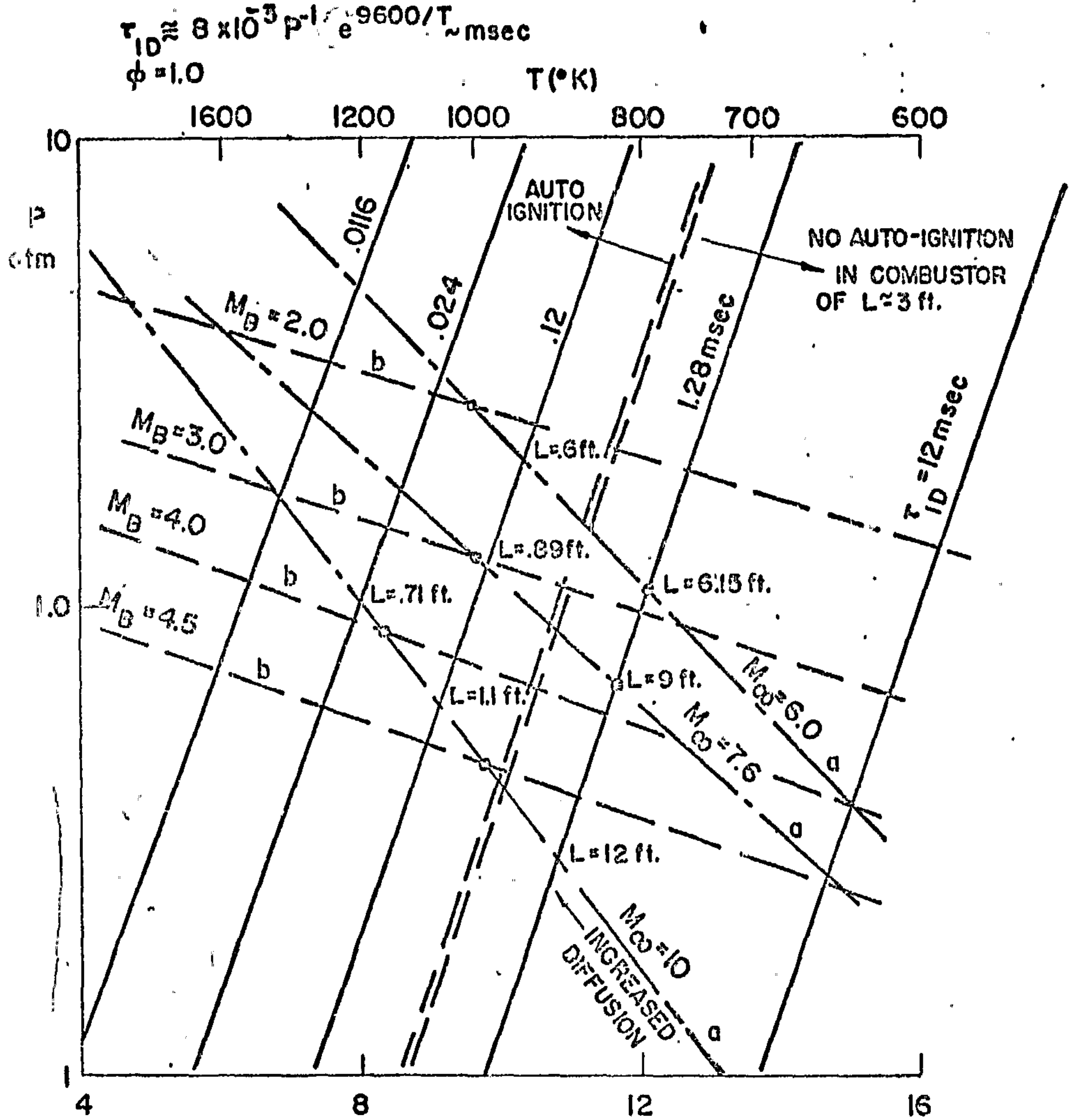


Fig. 3 Auto-ignition limits

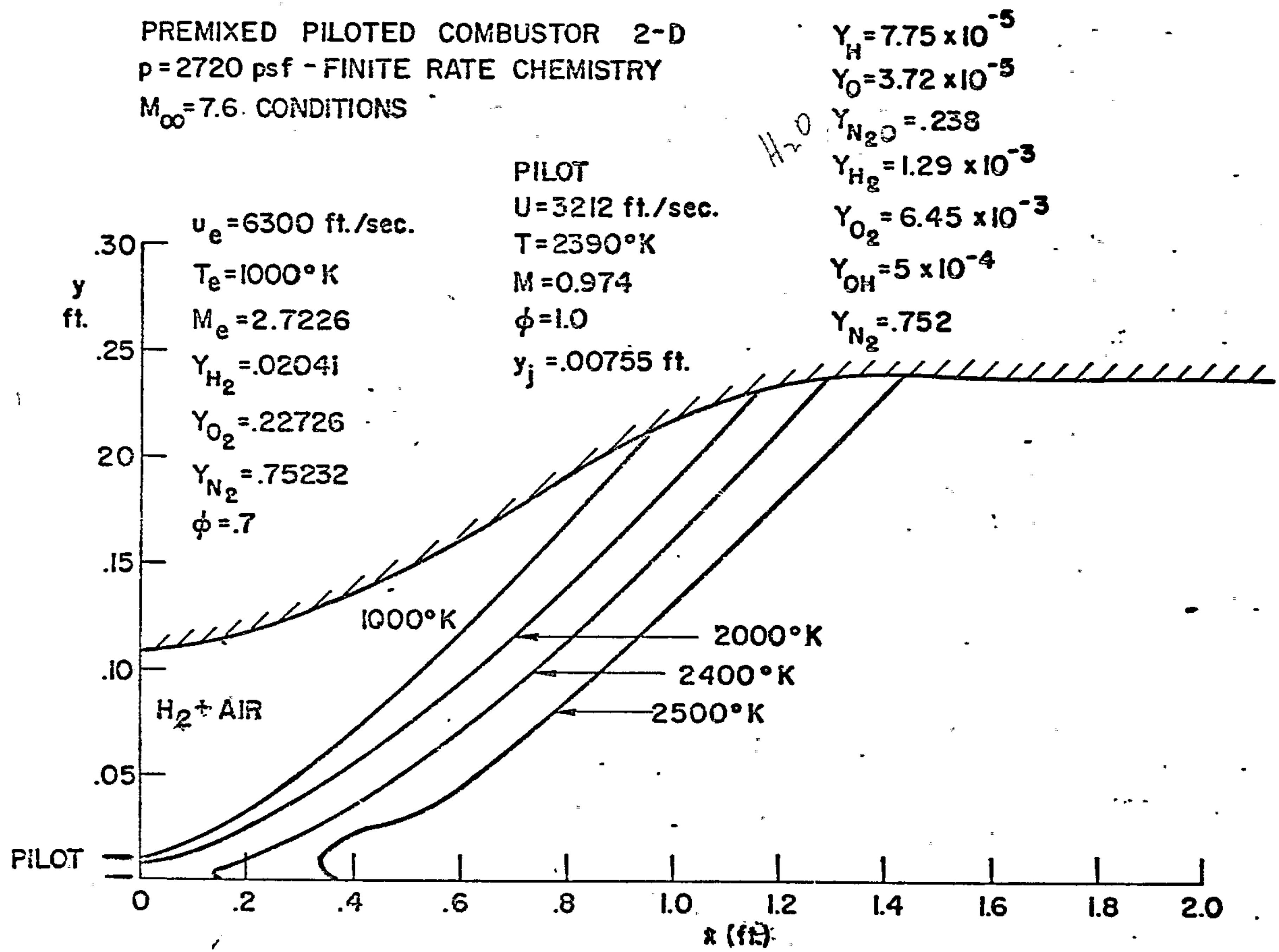


Fig. 4a Isotherms of a supersonic heat conduction flame - $M_\infty = 7.6$, $T_e = 1000^\circ K$ $\varphi = .7$

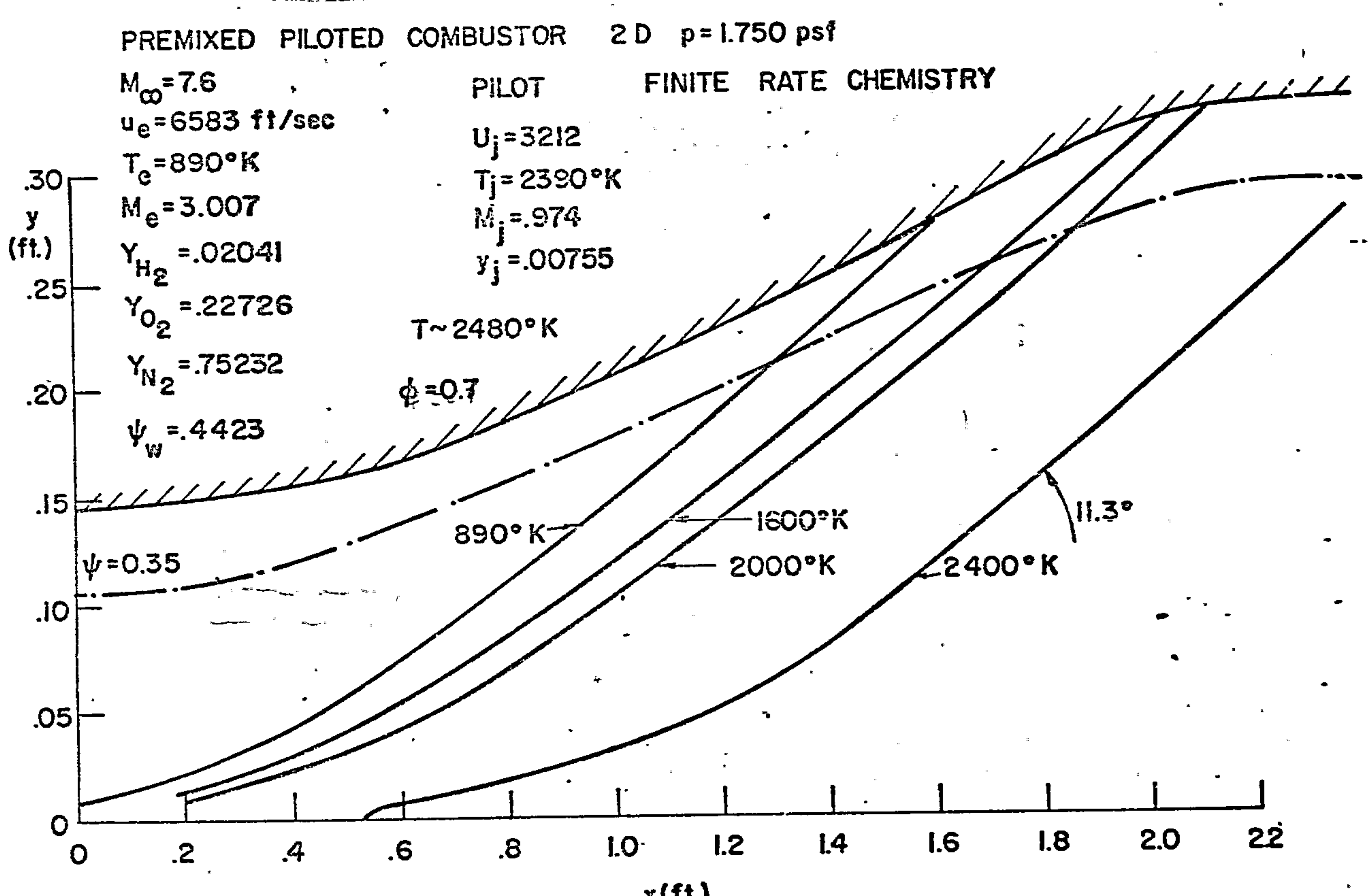


Fig. 4b Isotherms of a supersonic heat conduction flame - $M_\infty = 7.6$, $T_e = 890^\circ K$ $\varphi = .7$

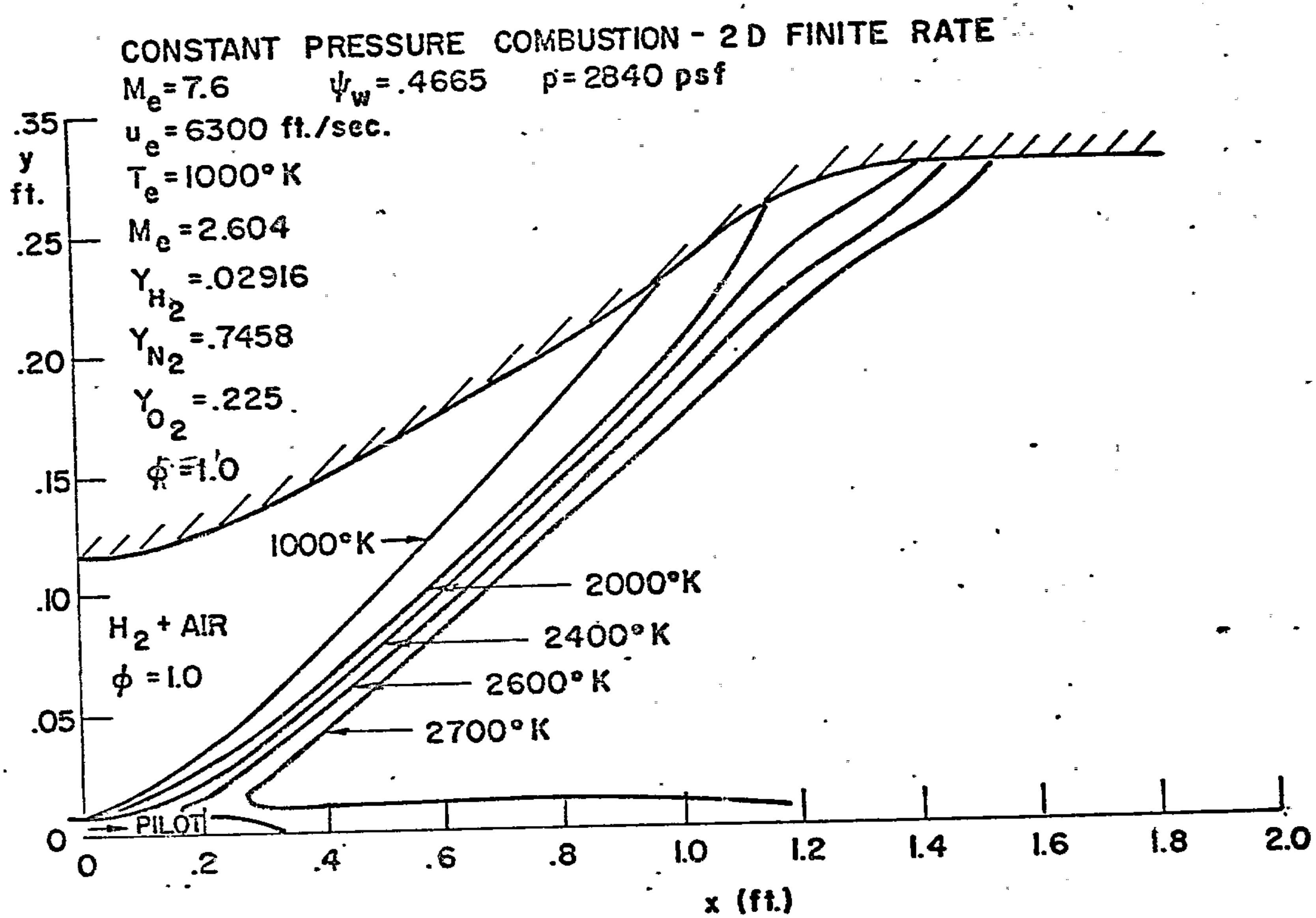


Fig. 4c Isotherms of a supersonic heat conduction flame - $M_\infty = 7.6$, $T_e = 1000°K$ $\varphi = 1.0$

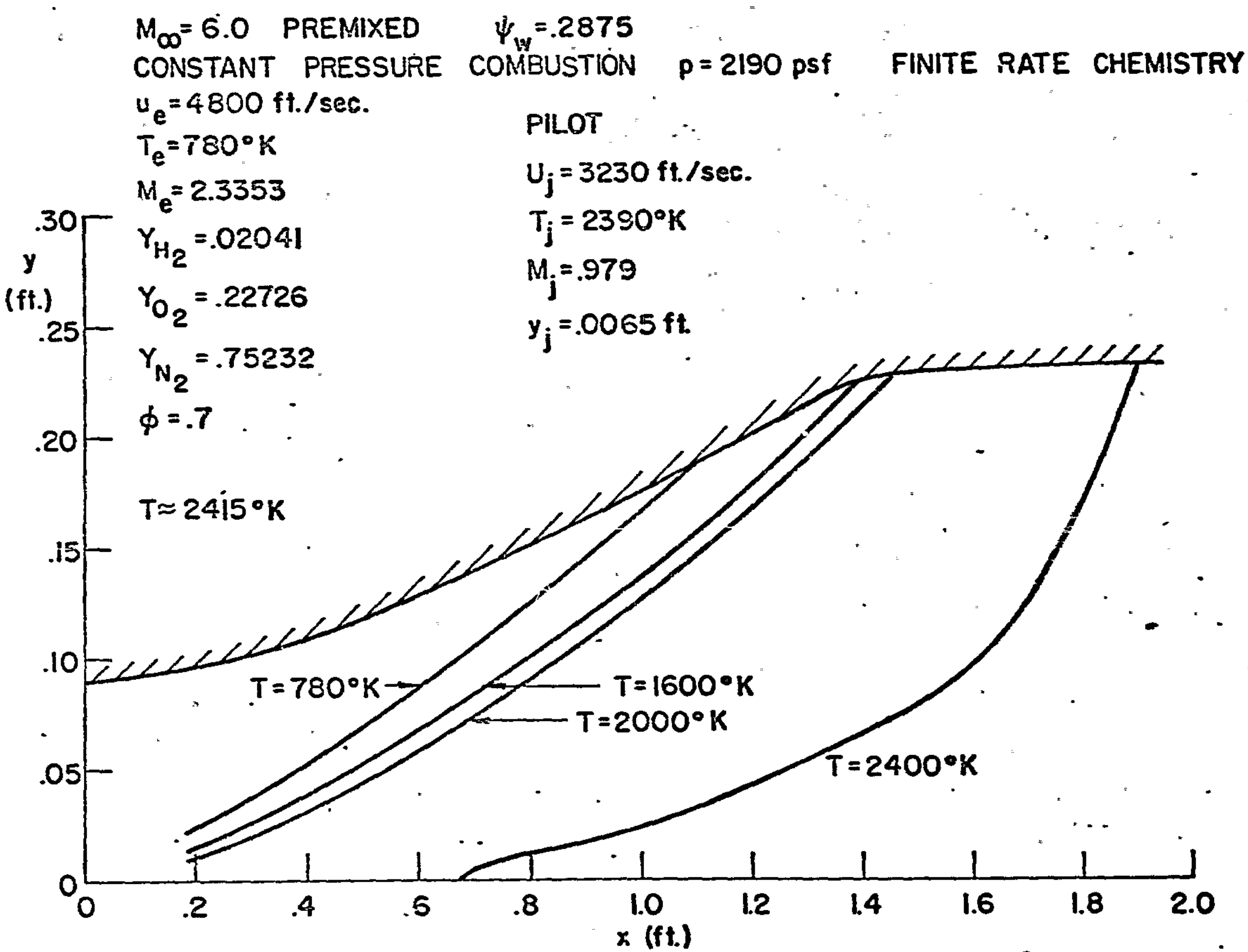


Fig. 5a Isotherms of a supersonic heat conduction flame - $M_\infty = 6.0$, $T_e = 780°K$ $\varphi = .7$

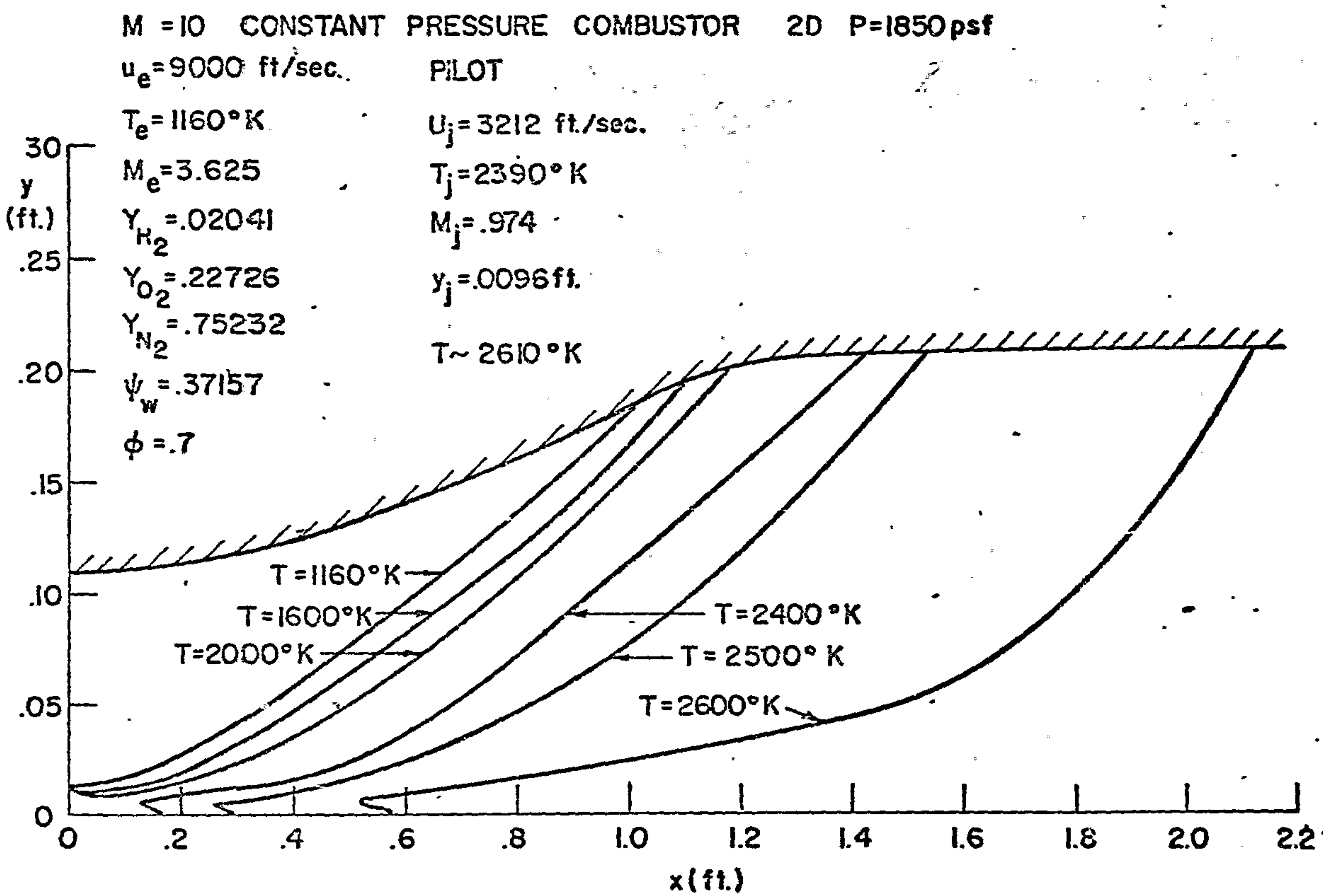


Fig. 5b Isotherms of a supersonic heat conduction flame - M_∞ = 10, T_e = 1160°K φ = 1.0

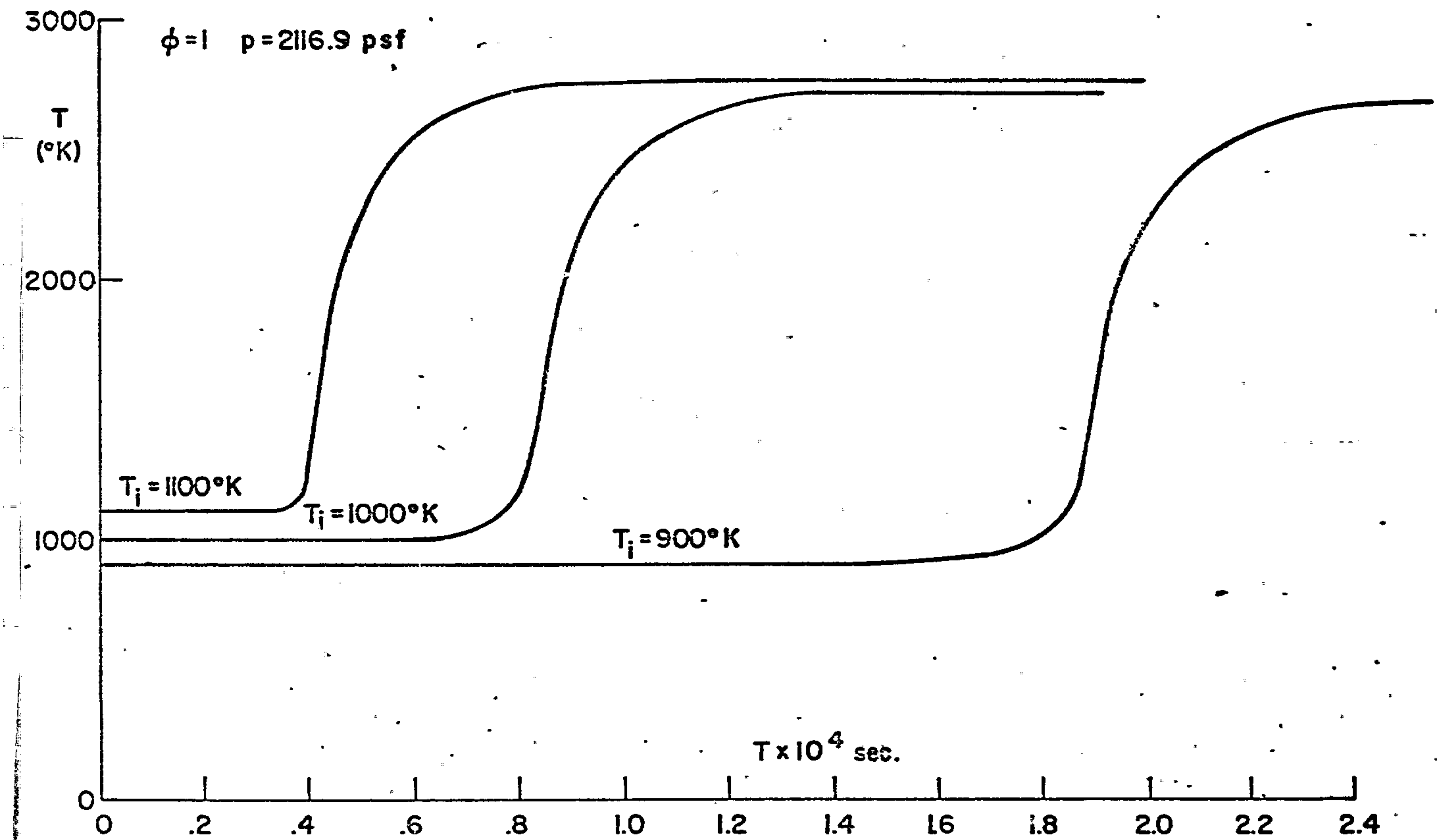
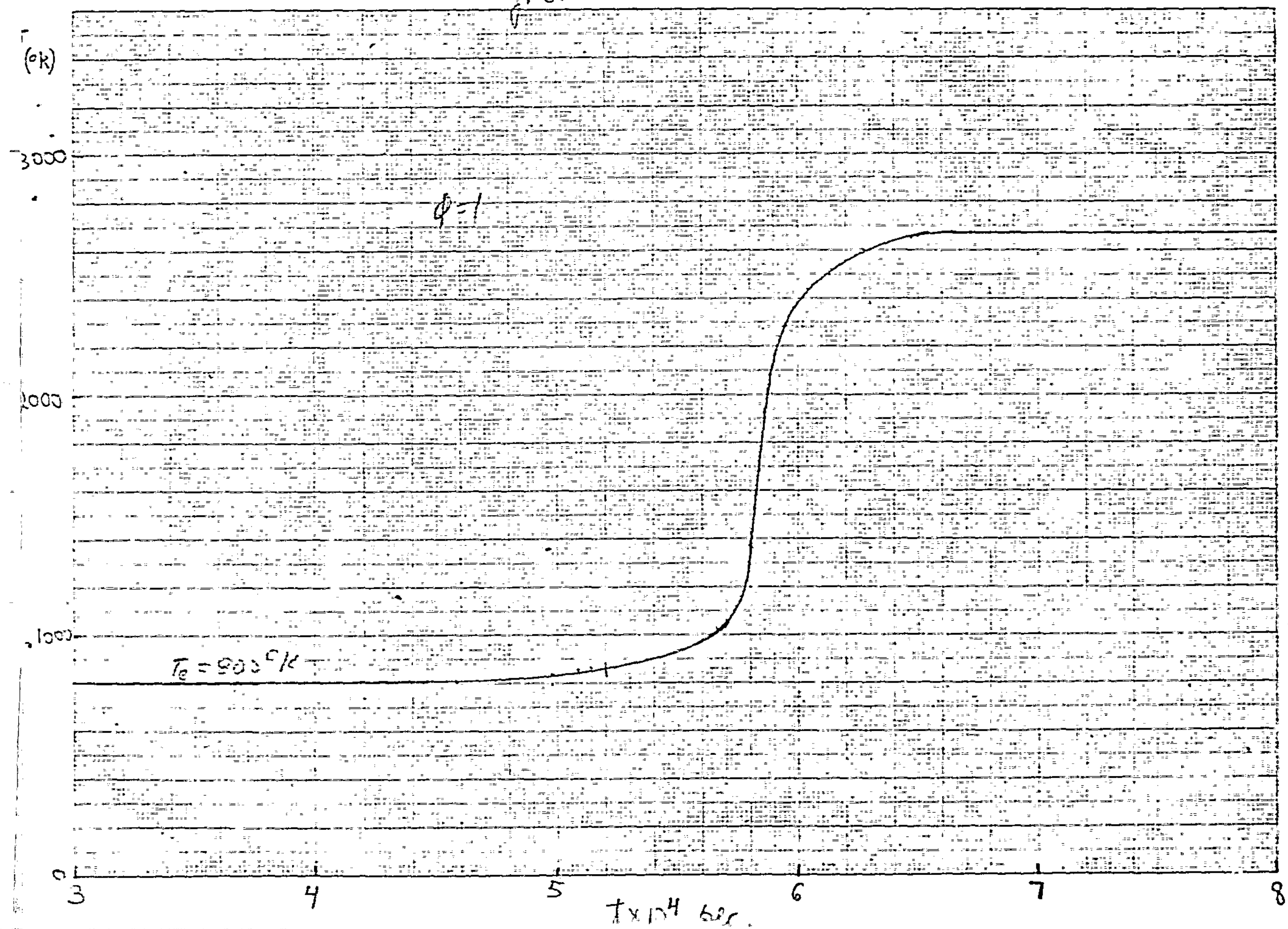


Fig. 6 Temperature histories of the hydrogen air reaction for various initial temperatures - $\varphi = 1$. $p = 1$ atm

Fig. 6.



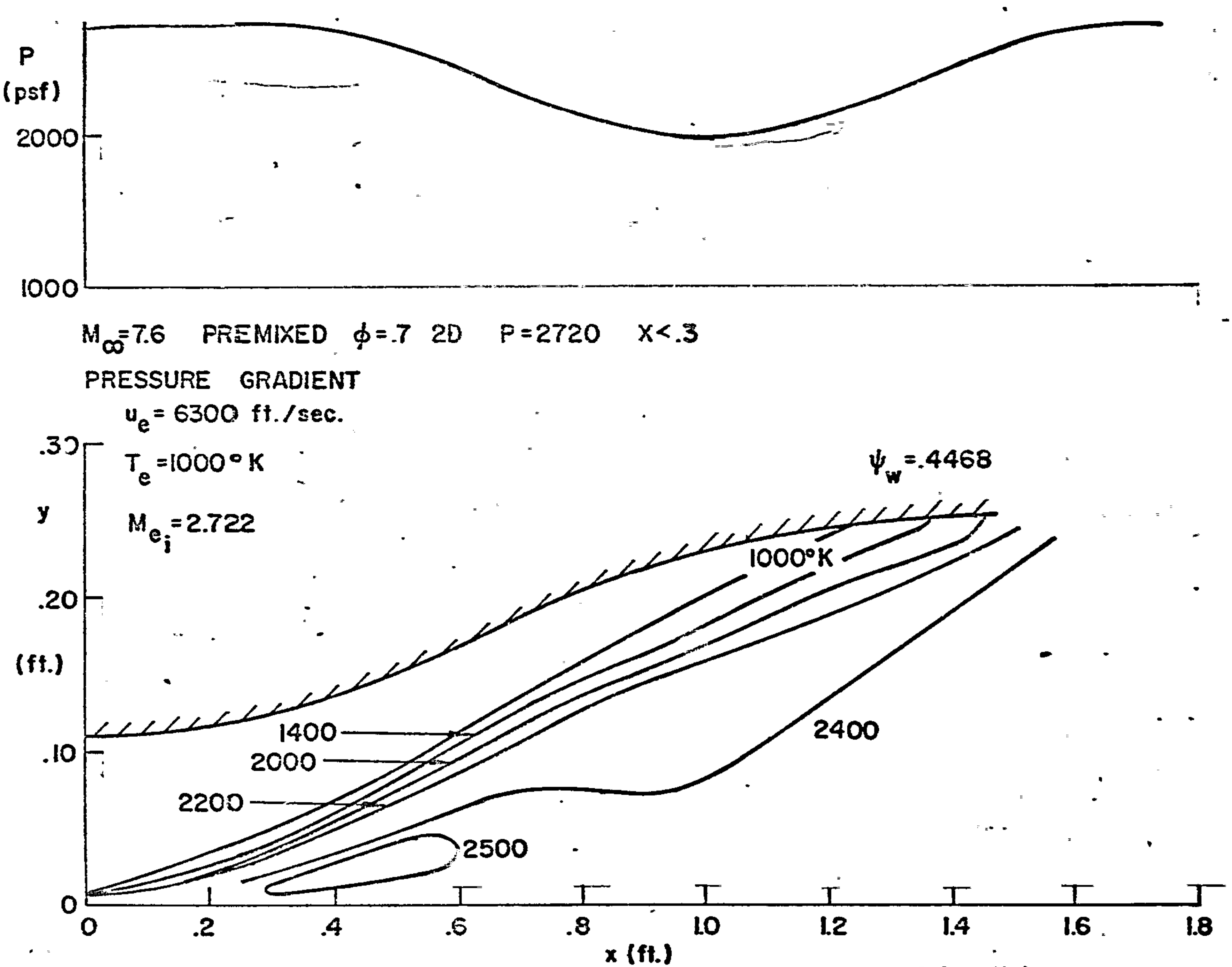


Fig. 7 Effect of a favorable pressure gradient on a heat conduction flame - M_∞ = 7.6 conditions

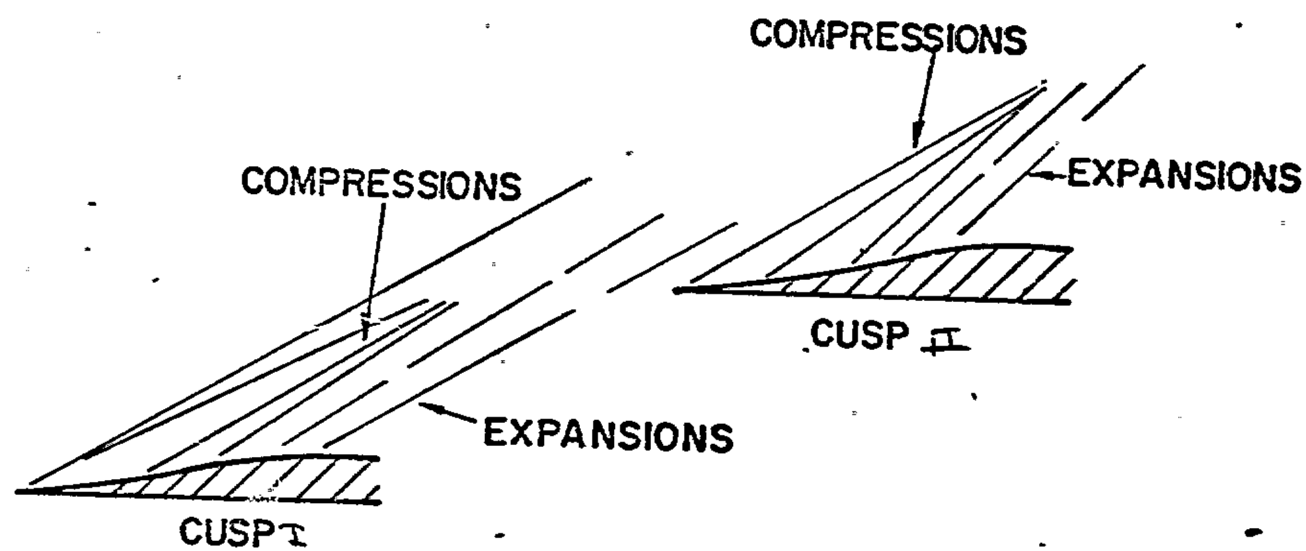


Fig. 8 Scher-‿ic of the interactions of the pressure waves produced by several flames

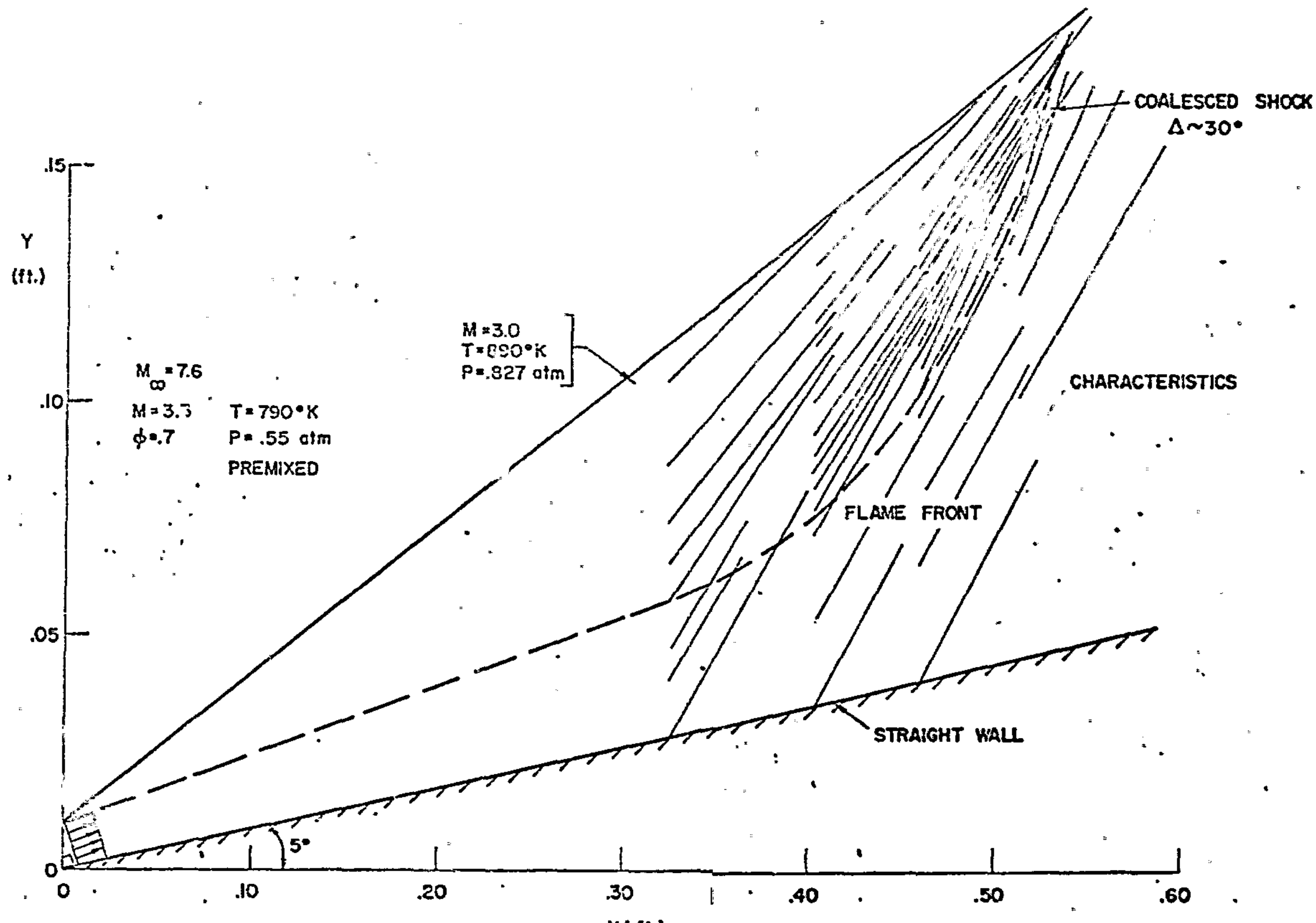


Fig. 9a1 Pre-mixed combustion flow field and flame front-straight wall case

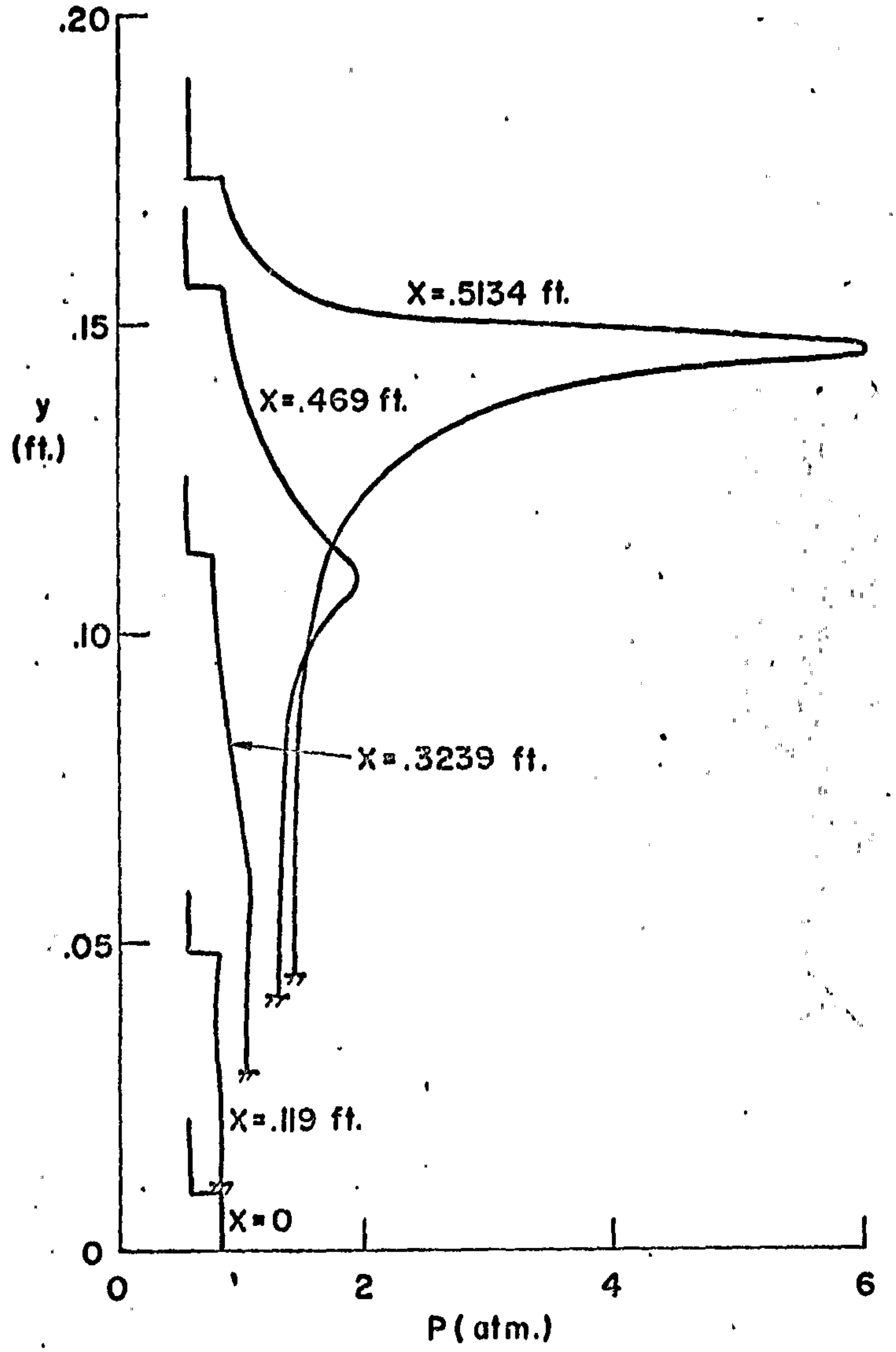


Fig. 9a2 Static Pressure profiles in a Premixed combustion - straight wall

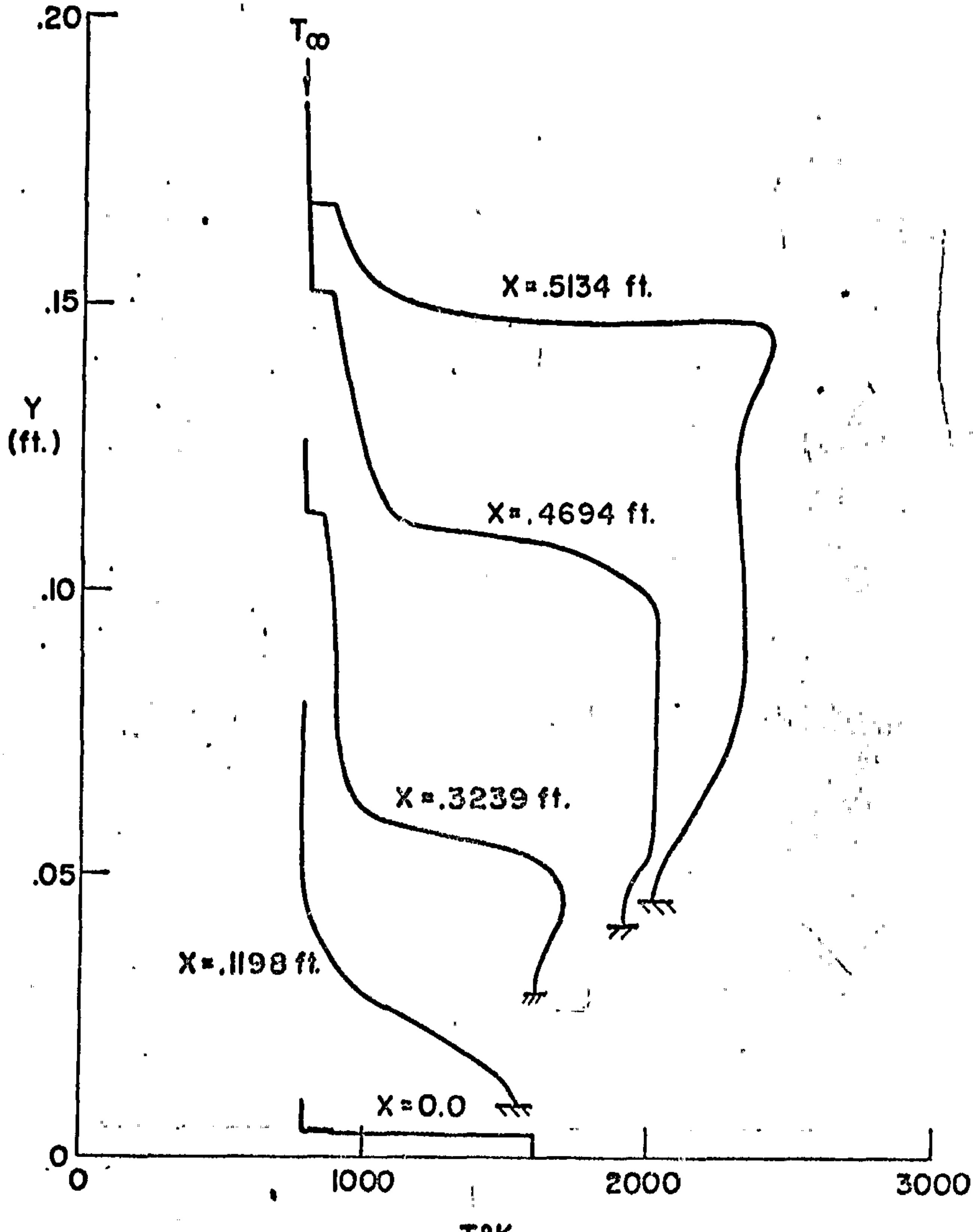


Fig. 9a3 Static Temperature Profiles in a Premixed Combustion - Straight Wall

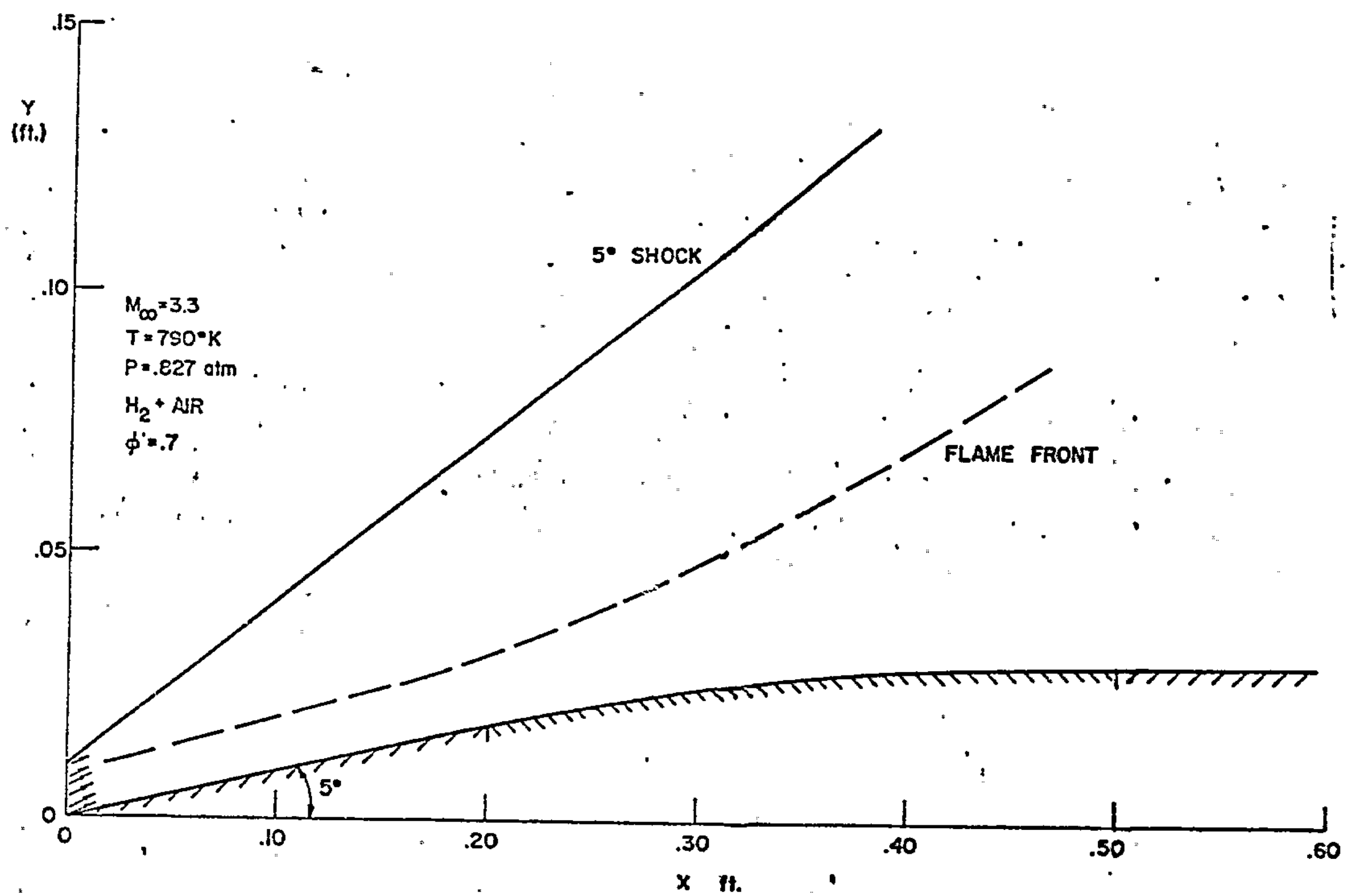


Fig. 9b Curved Wall Geometry and Flame Front Shape in Premixed Combustion

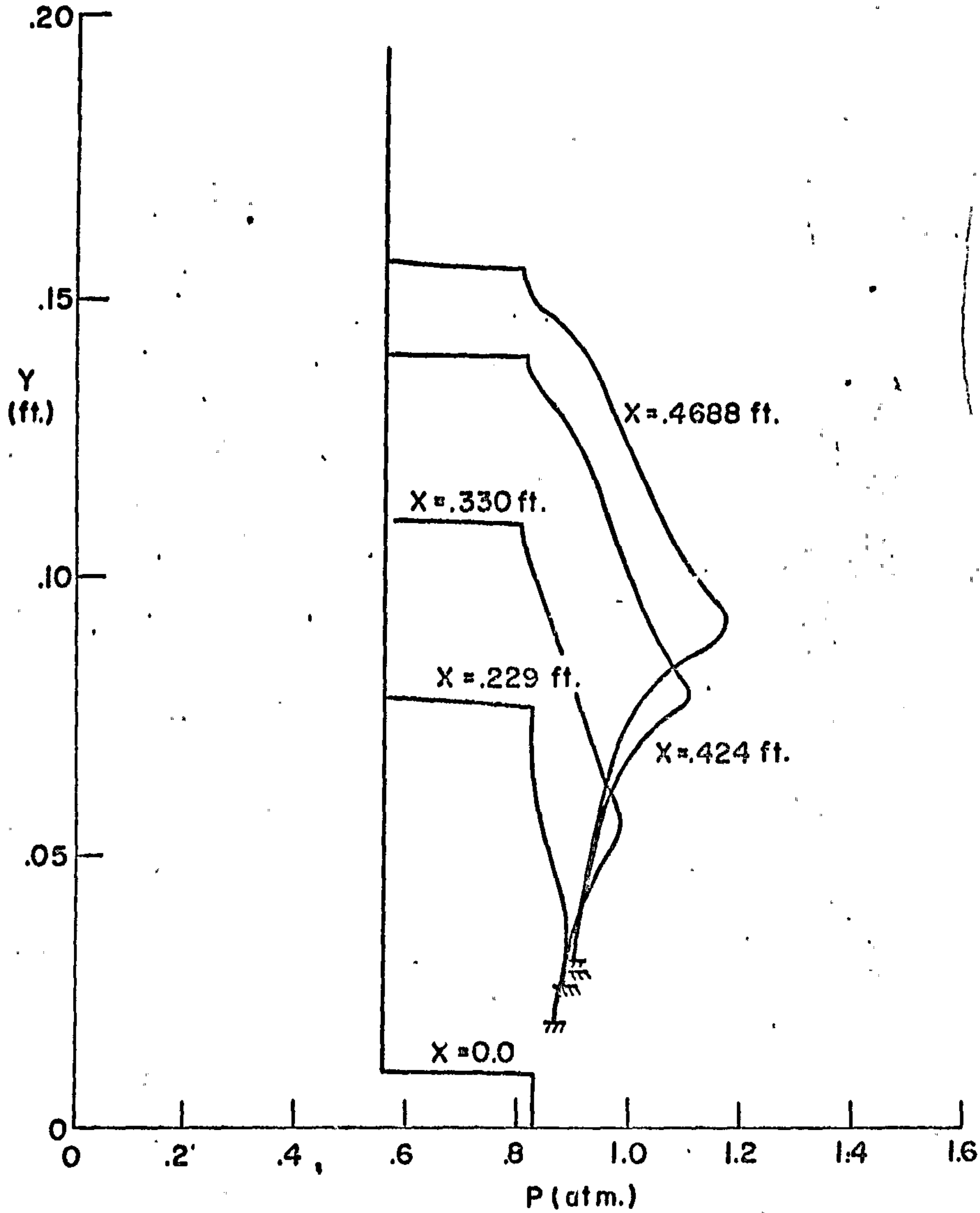


Fig. 9b2 Static Pressure Profiles in a Premixed Combustion - Curved Wall

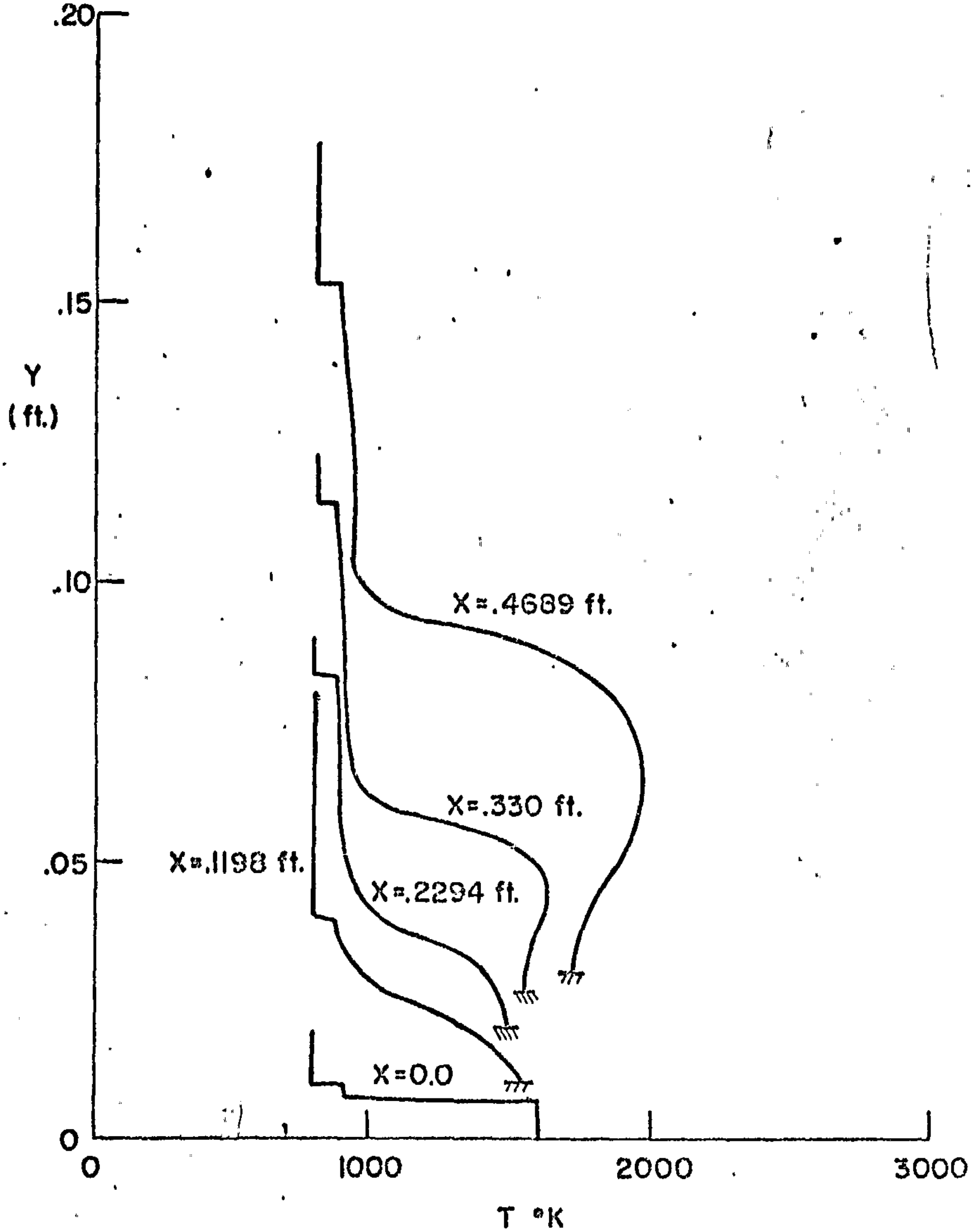


Fig. 9b3 Static Temperature Profiles in Premixed Combustion - Curved WAll

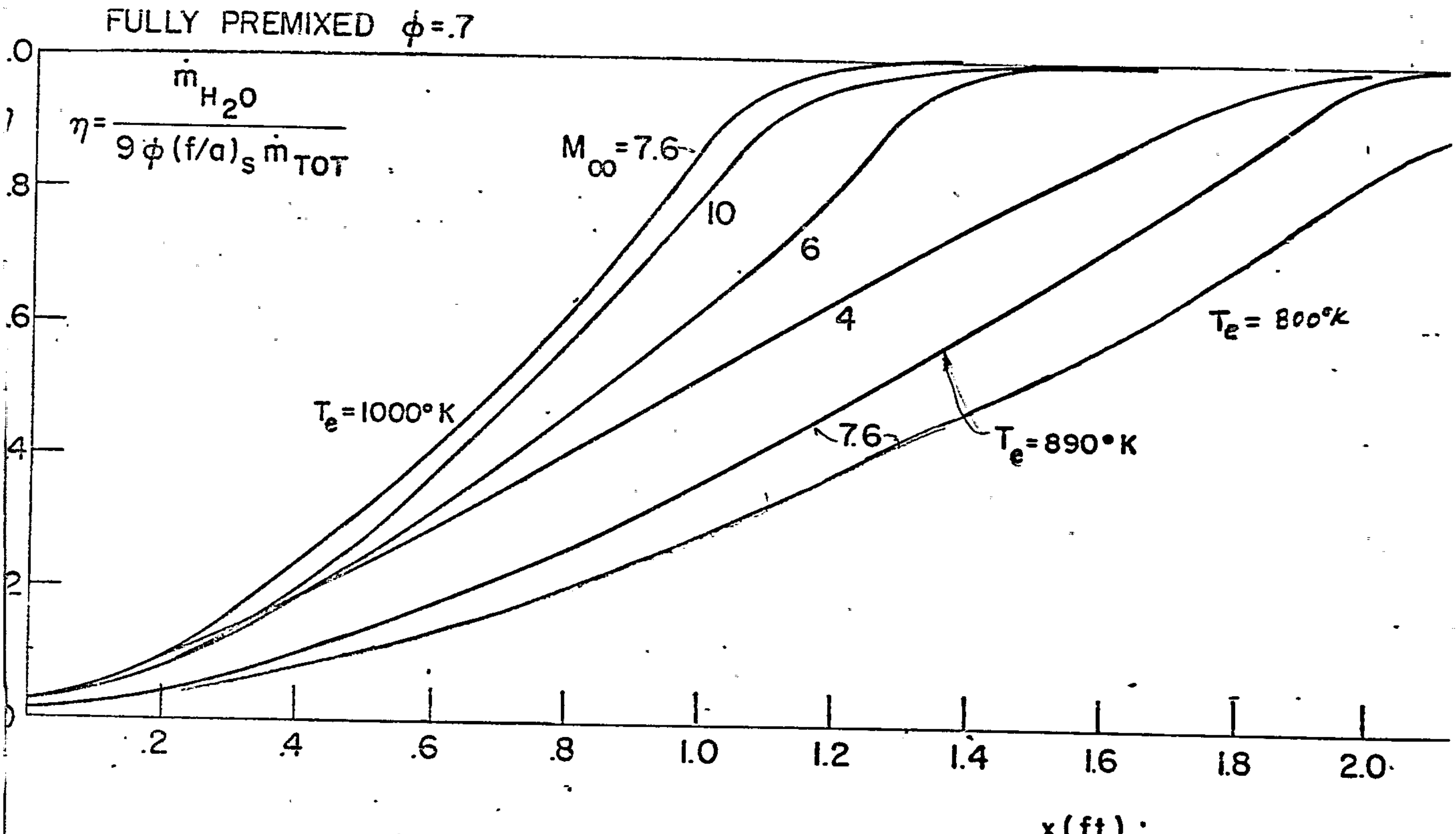


Fig. 10 Combustion efficiency of a heat conduction flame

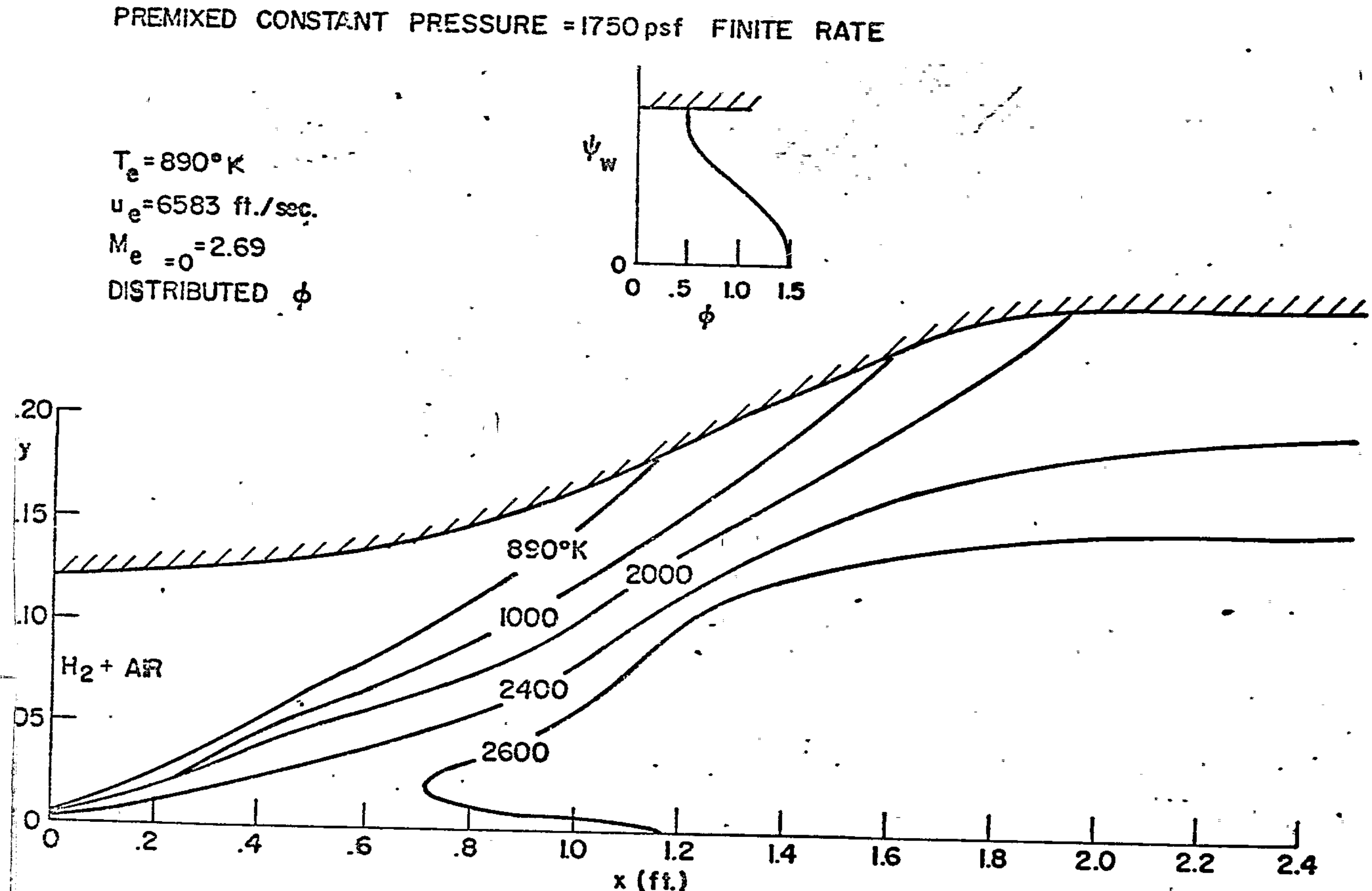


Fig. 11 Isotherms of a supersonic heat conduction flame with a nonuniform fuel distribution .

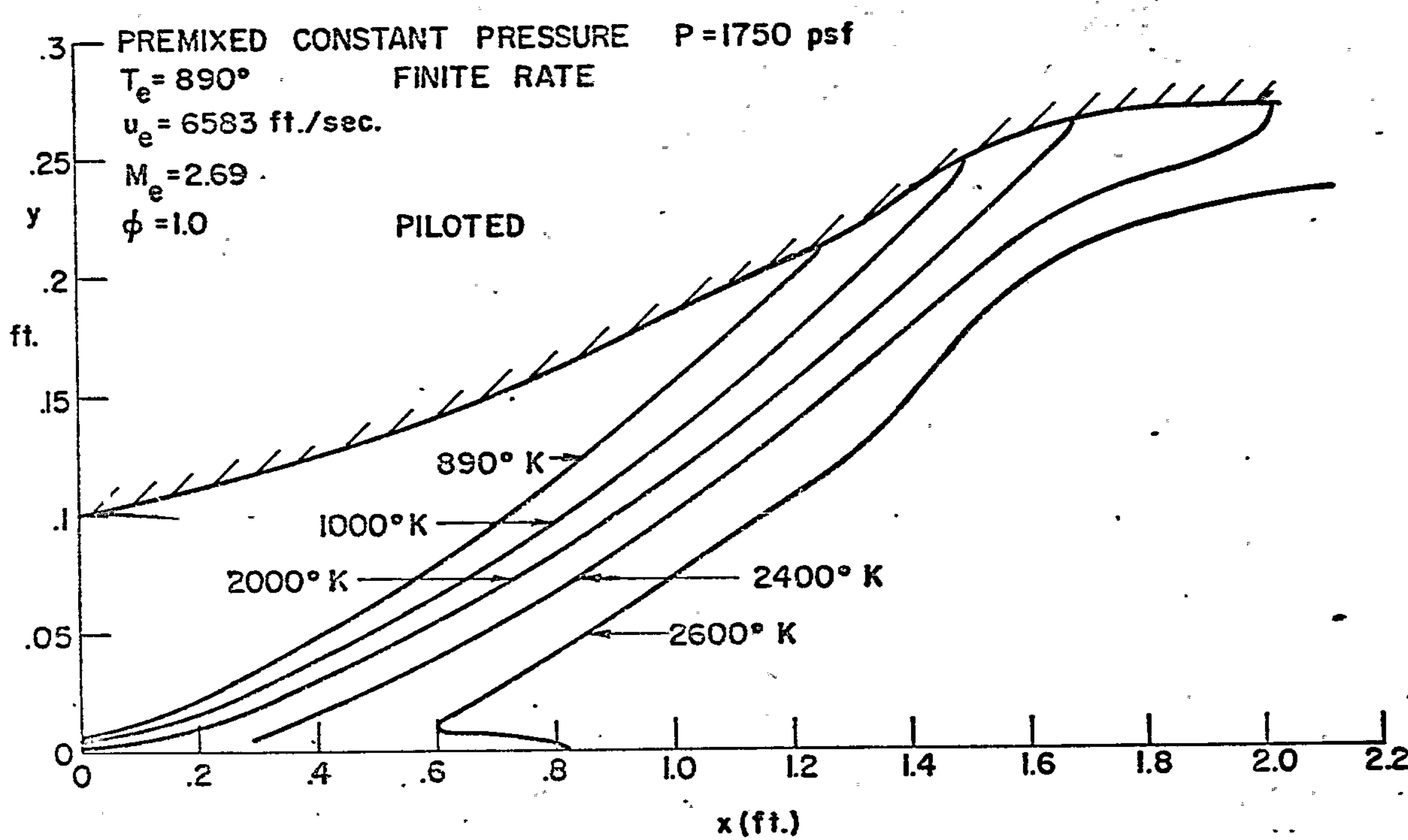


Fig. 12 Isotherms of a supersonic heat conduction flame with uniform fuel distribution $M_\infty = 7.6$ $\varphi = 1$

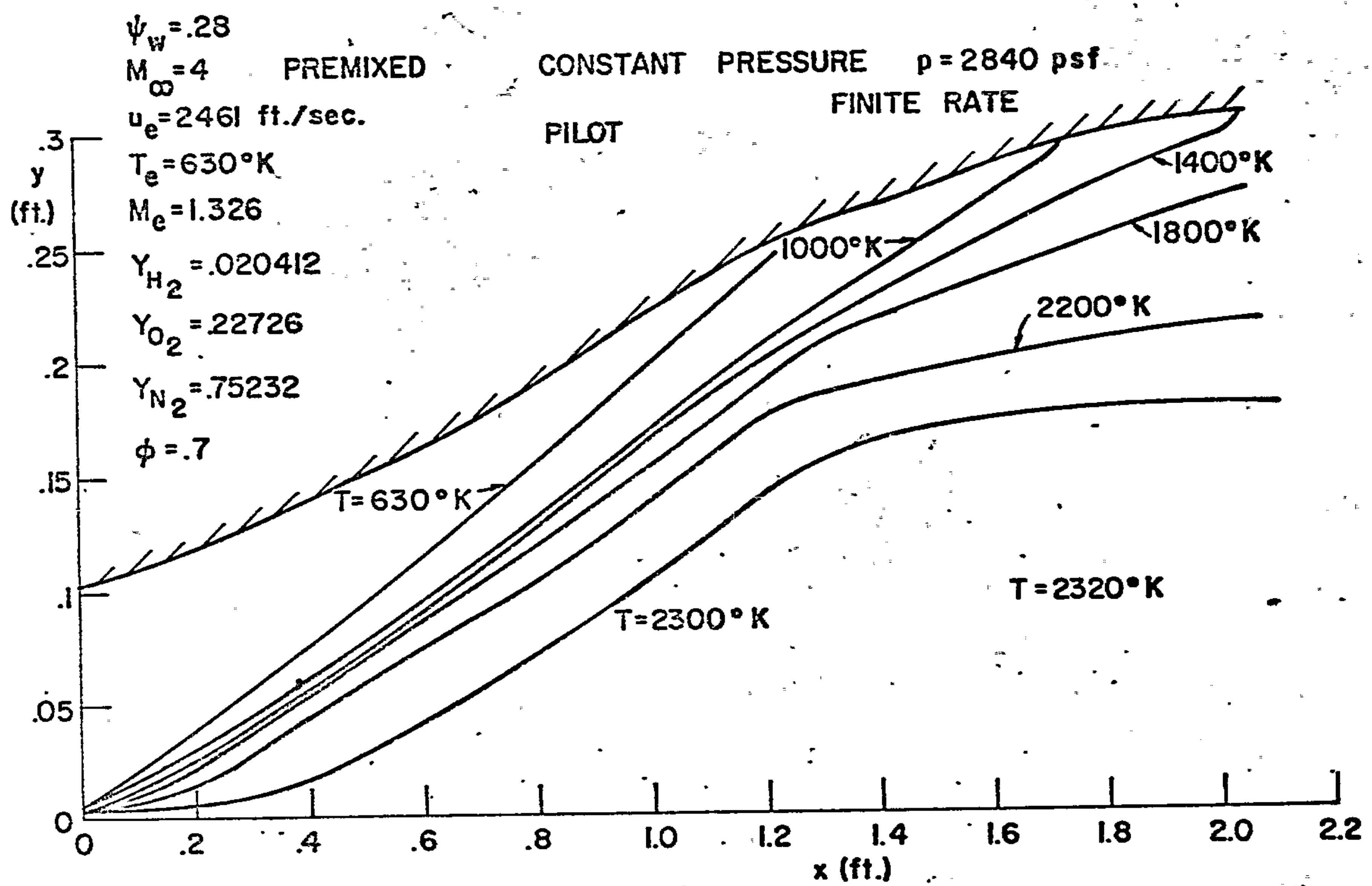


Fig. 13a Isotherms of a supersonic heat conduction flame - M_∞ = 4.0 conditions φ = .7

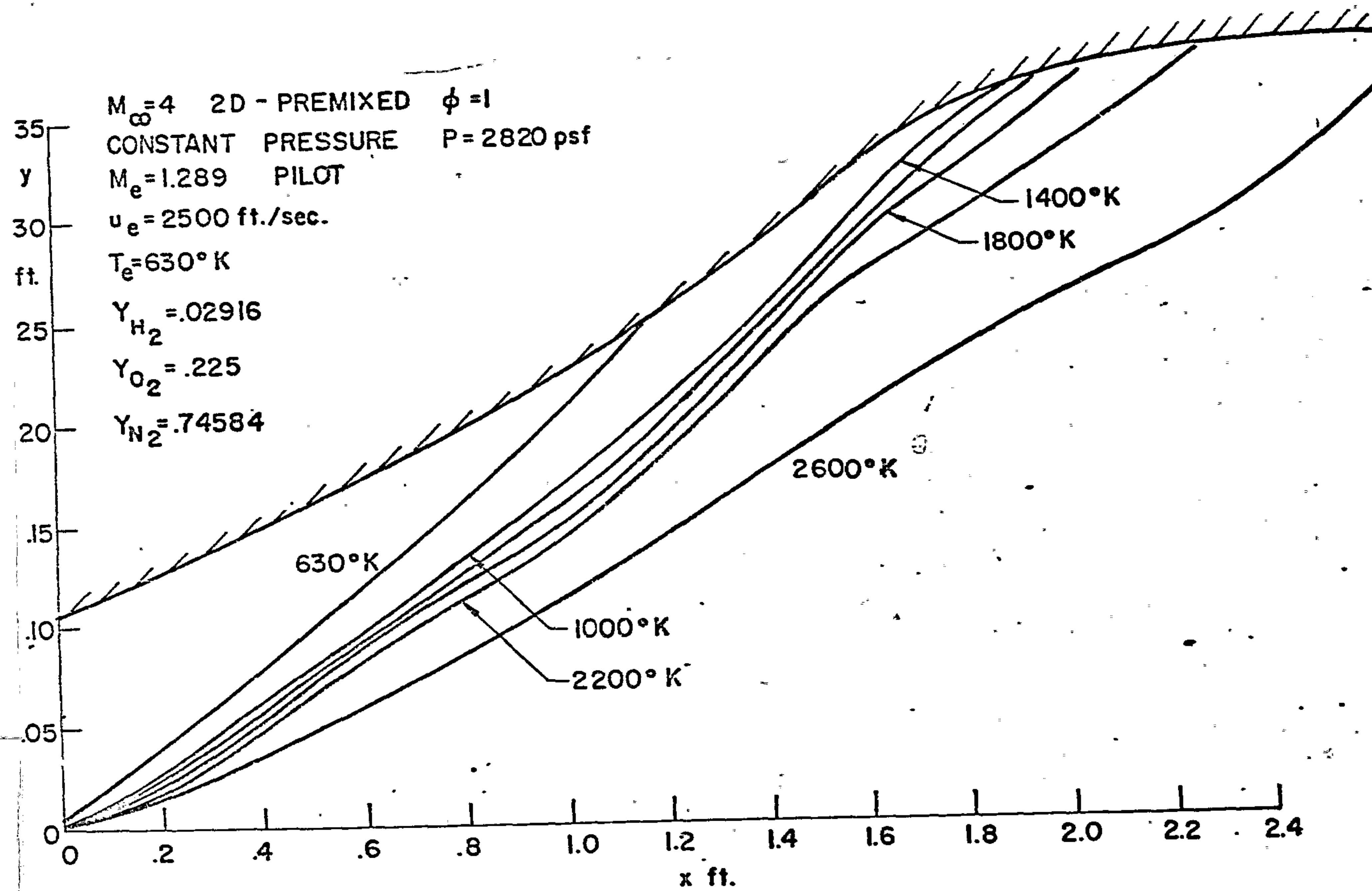


Fig. 13 b Isotherms of a supersonic heat conduction flame - M_∞ = 4.0 conditions φ = 1.0

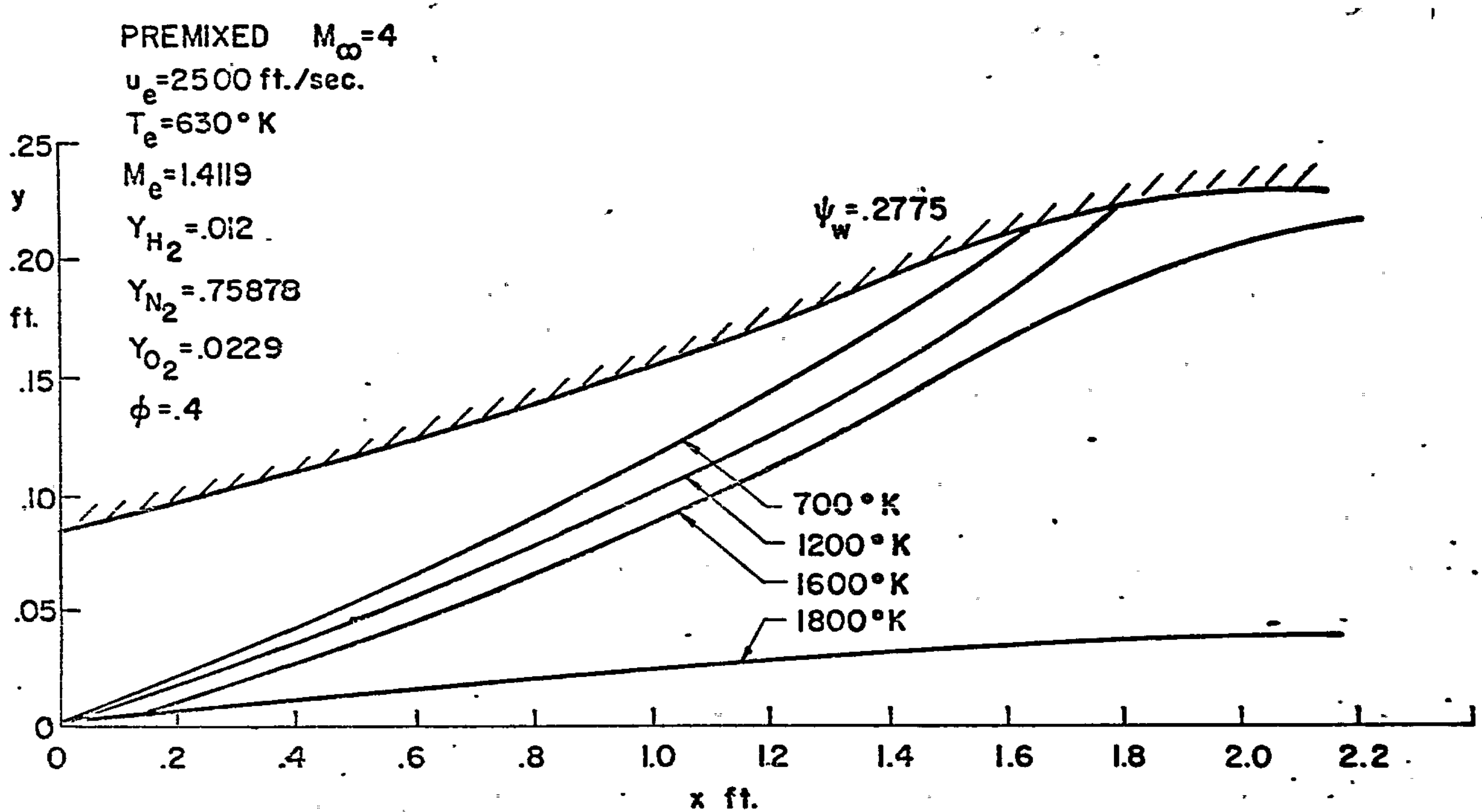


Fig. 13c Isotherms of a supersonic heat conduction flame - $M_\infty = 4.0$ conditions $\varphi = .4$

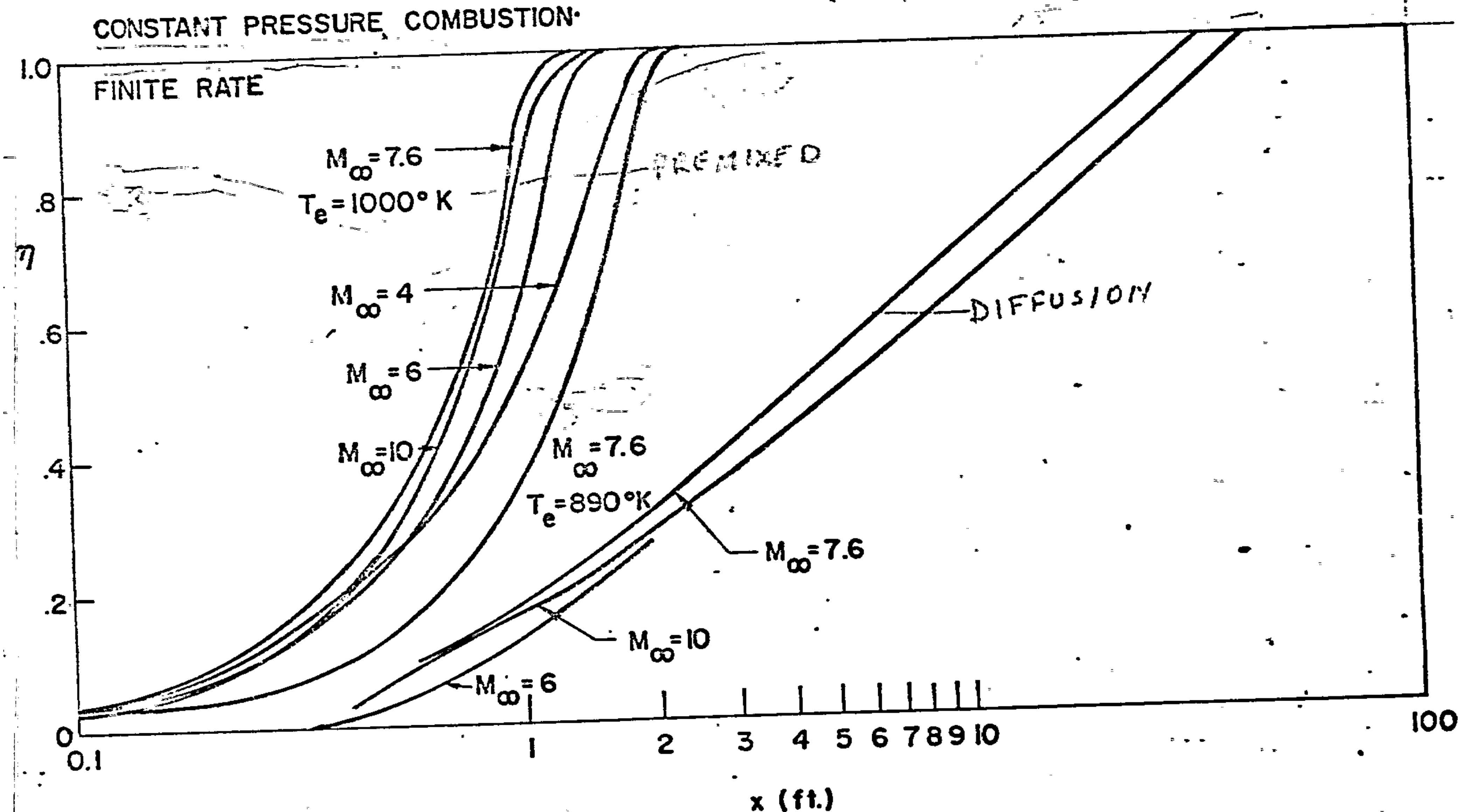
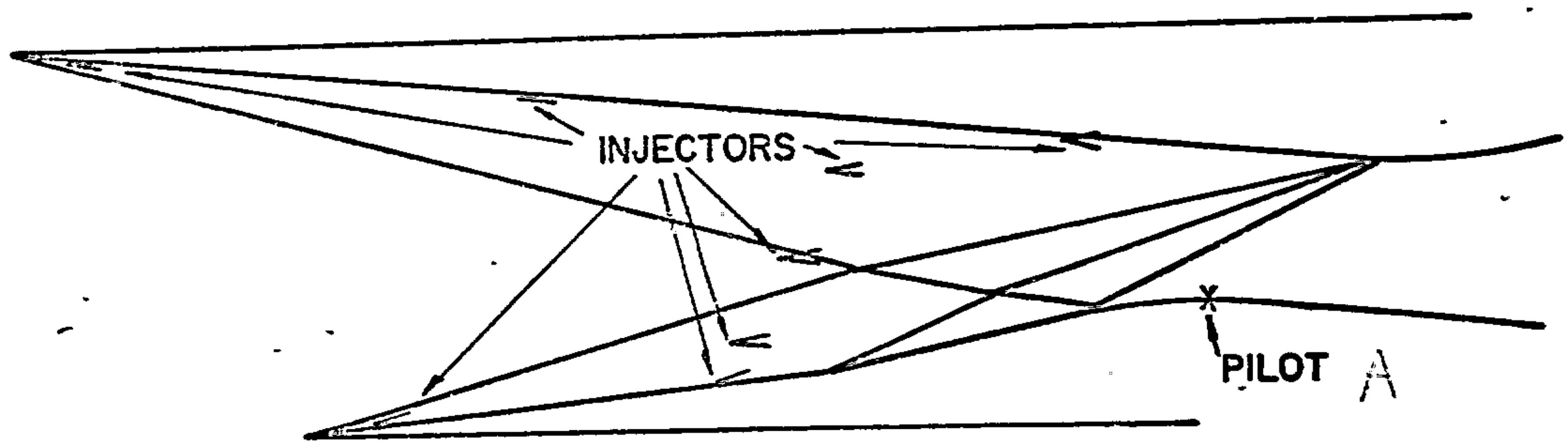
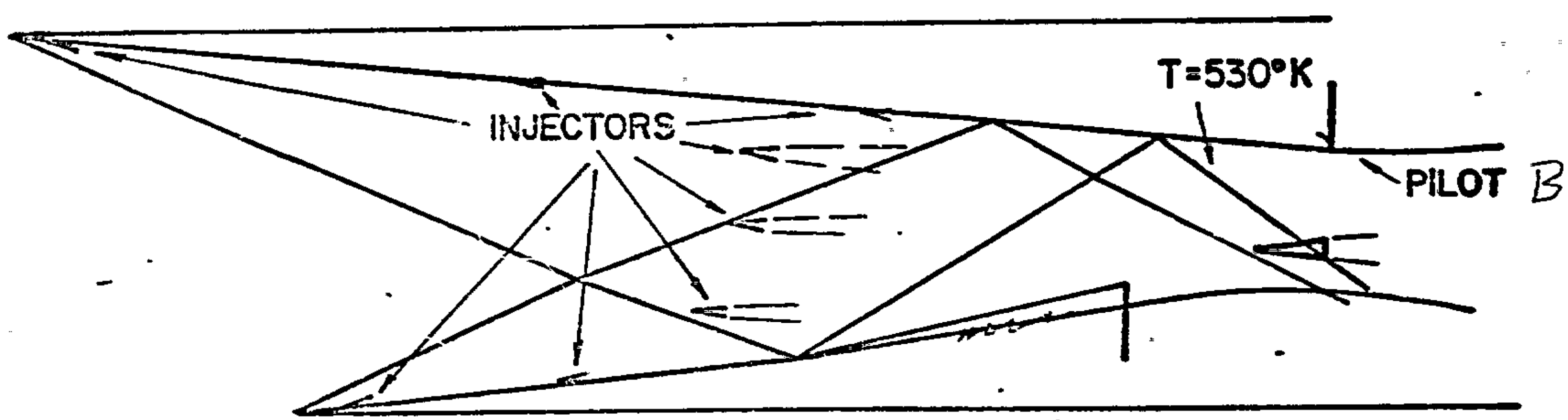


Fig. 14 Comparison of the combustion efficiency of a heat conduction flame with a diffusion flame



FREE STREAM MACH NUMBER = 7.6
MACH NUMBER AHEAD OF INLET = 5.955
SWEEPBACK = 30°

Fig. 15 Fuel injector arrangements - M_∞ = 7.6



FREE STREAM MACH NUMBER = 4.0
SWEEPBACK = 30°

Fig. 16 Fuel injector arrangements - $M_\infty = 4.0$