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ANALYTICAL STUDY OF AERODYNAMIC MEANS OF CONTROLLING SUPERSONIC INLET FLOW

Part Two

TECHNICAL REPORT NO. 496B

by

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ABSTRACT

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A method for achieving variable geometry inlets, by aerodynamic means, for high supersonic Mach numbers is presented. The scheme discussed makes use of fixed passages in the inlet walls to inject air at some angle to the main inlet flow in order to achieve the desired compressions. The injected air is then trapped and recirculated. A typical inlet has been designed for operation at Mach numbers 2, 2.5, and 3.0 taking into account both the inviscid interaction of the jets and main stream and the viscous mixing between the two. Calculations are also performed to estimate the costs in terms of drag and propulsion efficiency of this design. These drawbacks are seen to be small and the overall simplicity of this system when compared to standard variable geometry inlets suggests further investigation, on a laboratory scale, of this inlet design.

AUTHOR

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PART TWO

I. INTRODUCTION*

The purpose of this investigation is to demonstrate a technique whereby variable inlet geometry is accomplished by aerodynamic means; i.e., to minimize the mechanical complexity of an inlet capable of efficient operation up to high supersonic Mach numbers. In Part I of this investigation (Reference 1), a technique was presented where variable geometry could be achieved by tangential slot injection of subsonic air along the inlet wall. A detailed analysis of turbulent mixing in the presence of an axial pressure gradient was performed and a numerical computer program was developed in order to analyze this technique in detail. Although this technique was found to work from a conceptual point of view, the actual inlet design was extremely sensitive to small variations of the injection parameters. It did, however, suggest an alternate possibility, which overcame the practical difficulties, whereby jets of air inclined at an angle to the main stream could be used to achieve the variable compression ratios required for efficient operation of a supersonic engine. The present report is concerned with the detailed analysis of an inlet design using this vectored injection method.

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* The authors wish to acknowledge the guidance provided by Dr. Antonio Ferri.

The proposed solution is based on the concept shown schematically in Figure 1. A two-dimensional fixed geometry inlet with two fixed geometry air passages is depicted. For high Mach number operation, say M=3, air with a stagnation pressure smaller than that of the main stream is injected through these slots in order to compress the main stream and achieve the desired throat area for efficient operation. The injected air is captured by the moveable scoop shown in the throat region of the inlet, and recirculated through the slots. This recirculation is made possible by energizing of the jet flow through viscous mixing with the main stream along regions A,B,C, i.e., high stagnation pressure flow from the main stream mixes with the jet flow so that the stagnation pressure of the captured flow is sufficiently high to facilitate its recirculation. As the flight Mach number decreases, the required inlet compression decreases and hence less air is injected through the slots into the main air stream.

In a conventional variable geometry inlet the jet streamline A,B,C, would have to be replaced by a mechanical moveable ramp. This ramp would have to be displaced up and down in the relatively large forward area of the inlet. In addition the conventional inlet requires some form of boundary layer control along the lower moveable wall, a feature not necessary in the suggested design since the control jets can be used to provide this. Both a conventional inlet and the design proposed herein require a moveable mechanism called the scoop in this investigation. As a result, this aerodynamically controlled inlet replaces the large forward portion of the moveable ramp, and the necessary boundary layer controls with a simple recirculation mechanism discussed in the body of the report.

The discussion of this investigation is organized as follows: first, there is considered the actual design for an inlet operating at Mach numbers 2, 2.5 and 3.0. Purely inviscid considerations are applied with respect to these calculations. The turbulent mixing analysis developed in Reference 1 is then applied; information as to mass flows, recirculation problems etc., is obtained. Detailed profiles of Mach number, mass flow and stagnation pressure of the jets entering the recirculation region are presented. The drag forces produced by the capture and recirculation scheme are estimated. Finally, attention is focused on the mechanical aspects of the moveable capture scoop. One example of a scoop which will traverse the desired trajectory is presented; in this context attention is given the problem of continuous operation and stability of the system, under perturbations of flight conditions.

II. INVISCID INLET DESIGN

The analysis of the inlet scheme depicted schematically in Figure 1 may be conveniently divided into inviscid and viscous sections. In the inviscid situation the jets of air may be deflected only by pressure waves (compressions or expansions) and remain distinct from the main flow, i.e., there exists a dividing streamline, on one side of which is the jet flow and on the other the main stream flow. The actual situation is the viscous one in which there exists no distinct boundary between the jet and main flow due to mixing between the two flows. Since the mixing lengths involved are small, the inlet will be analyzed first on the basis of inviscid flow, and then the departures due to viscous mixing will be calculated using the mixing analysis of Ref. 1. It will be shown that the departure from a segregated stream has little effect on the inviscid wave pattern, but is important in calculating the stagnation pressure of the recaptured air when consideration is given to the means of recirculating this air.

Consider first the inviscid analysis, and in particular what happens to the flow field in the vicinity of the jets. Assume a uniform flow of $M=2.5$, $P=300$ lb/ft^2 approaching a jet of $M=1.5$ inclined at an angle of 10° with respect to the uniform stream (see Figure 2). If the pressure in the jet and the first recirculation region is the same as that in the main flow behind a 10° deflection, then the jet streamline AB will remain straight and a straight shock AC will stand in the flow. Thus, by adjustment of the pressures in the jet (if the jet Mach number is assumed fixed this is equivalent to adjusting the jet mass flow) and the recirculation region, the main stream is deflected through an angle of 10°.

Suppose now it were desired to deflect this stream an additional 10°; then a second jet, with the same Mach number and pressure as the first one, but inclined at an angle of 30° is introduced. Since the pressure is constant along the streamline DE this remains a straight streamline. If the pressure in recirculation region number II is maintained at a value equal to that in the region where the jets merge (Region BFHG), then the steamline FH also remains straight. The shocks BE and EF turn the two jets until they are both inclined at an angle of 20° and the shock BJ deflects the main stream an additional 10°. It should be noticed that the pressure in the main stream behind the shock wave will be slightly higher than that behind the streamline BG. There will exist in the jet flow a series of very weak compressions ($\Delta P = 1.05$) and expansions such that the average Mach number is 1.11 and the average static pressure equal to that in the main flow. The turning up and turning down of the jet streamlines due to these compressions and expansions is less than one half of a degree and can be neglected; the jet streamline is thus drawn straight. Hence, by simply controlling the pressure in the two jets and the recirculation region, there has been effected a 20° turning of the mainstream by purely aerodynamic means.

A set of inviscid calculations concerning the actual design of a typical inlet were performed for three different Mach numbers; Mach numbers 3.0, 2.5, and 2.0. They are shown respectively in Figures 3, 4, and 5. The Mach number of the injected mass flow is fixed by the nozzle geometry in the recirculation hardware; here this is taken to be $M=1.5$. Therefore, the two parameters which control the compression of the main stream are the jet stagnation pressures and the pressures in the recirculation regions behind each jet. These pressures, in turn, are controlled by the amount of mass re-injected through the jets and amount bled into the recirculation regions.

In the Mach number 3 configuration shown in Figure 3, both jets have been turned on and the pressures in the recirculation regions behind each have been adjusted so that the jets come out straight in the inviscid configuration. For Mach number 2.5 (Figure 4), only the first jet is turned on, again with the pressure adjusted so that it comes out straight. It is seen here that by reducing the mass flow to the recirculation region behind the first jet it deflects downward in order to provide the required compression.

In all of these configurations (Figures 3,4, and 5) the first reflected wave from the upper wall is captured by the moveable scoop, i.e., no reflected wave is allowed to enter the merged jet region. The motivation for this is simply one of computational convenience, for if a shock should enter the jet region it might very well drive the low Mach number jet flow subsonic. While this presents no problems from a performance point of view it makes the numerical computations virtually impossible due to the mixed supersonic-subsonic nature of the flow field. In the case of a shock actually entering the jet flow due to a disturbance, it would simply reflect off the bottom jet streamline as an expansion since the recirculation region is maintained at a constant pressure. This expansion would be caught by the lower surfaces of the scoop. There is no indication that this perturbation would effect the pressure maintained in the recirculation region. It should also be noticed in Figures 3,4,5 that the scoop has been designed to capture slightly more mass flow than has been injected through the jets. This was designed after consideration of the viscous mixing effects discussed below.

Essentially it was found that since the mixing of the jet and main stream flows energized the jet flow it therefore left a small part of the main stream with stagnation pressure deemed too low for efficient engine performance. By scooping this low stagnation pressure flow two objectives are met: mass flow with low stagnation pressure is not permitted to enter the engine and mass with stagnation pressures greater than the jet flow, enters the recirculation duct to overcome the losses in the recirculation system.

III. EFFECTS OF VISCOUS MIXING

The aforementioned inviscid calculations, however, give no indication as to the minimum required jet mass flow and stagnation pressure recovery of the recirculation system; hence a set of viscous mixing calculations was performed. For this purpose the analysis of turbulent jet mixing presented in Reference 1 was utilized with compression waves replaced by isentropic compressions. Of the three configurations studied the Mach 3.0 represents the most critical from a design and analysis point of view, i.e., recirculation problems and losses will be maximum at the highest design Mach number. The viscous calculations are discussed, therefore, with particular reference to the Mach 3.0 design configuration, although they are also presented for M = 2.5 and 2.0.

Each jet was assumed to have a height of .2", which based on an inlet capture height of 3 ft. yields a jet mass flow approximately equal to 13% of the captured mass flow in the Mach 3.0 case. In Figure 6 is shown the effect of viscosity on the inviscid flow field of the two interacting jets discussed in Figure 2. Although this flow field does not conform exactly with the details of the present design, the effects of the mixing process on the flow will be very similar. The solid lines represent the jet boundaries predicted by the inviscid analysis. The dotted lines represent the actual streamline deflection due to viscous mixing of the jet and main flows. It is apparent that this deflection is small and would have very little effect on the inlet wave pattern. This is interpreted as meaning that the jet mass flow is at least sufficient to maintain the jet identity which is necessary for obtaining the desired compression.

The viscous mixing program also yields the stagnation pressure profile at the streamline station where the recirculation scoop is located. This serves two purposes: it yields the average stagnation pressure of the recaptured air; and it gives the stagnation pressure profile that will enter the engine. Figure 7 shows the stagnation pressure profile between the upper and lower jet streamline for the M=3 configuration. The Y coordinate of the profile has its origin at the leading edge of the scoop and is measured perpendicular to the axis of the inviscid jet. The profile represents the stagnation pressure of the flow captured for recirculation purposes. The figure shows the variation over the cross-section of the ratio of the total pressure to that in the jet at the point of injection. In Figure 8 is shown the Mach number variation across the same area. Now, since both the average Mach number and hence, stagnation pressure between the jet boundaries has increased there must be a resulting decrease in stagnation pressure flux in the main stream which enters the engine. The flux profile between the upper boundary of the jets and the upper wall of the inlet is shown in Figure 9. There is shown for this section the ratio ρUP_T to that which would exist without mixing; i.e., if the jet were not energized. The cross-hatched area represents the loss due to mixing. Consider now, for the sake of illustration, that the mass flow with a ρUP_T ratio <.70 is not allowed to enter the engine as indicated in Figure 9. Then for the net mass flow which passes through the engine the integrated loss is of the order of 2%, i.e.,

$$\frac{\int \rho UP_T \; dy}{\int (\rho UP_T) \text{ no mixing} \; dy} < .02$$

Although the mass flow for which $\rho UP_T/(\rho UP_T)$ no mixing $<.70$ has too low an energy for efficient engine operation, it does however, have a higher energy level than the mass flow required for recirculation. It is proposed therefore, to use this mass in the recirculation systems. This however, will yield an excess of mass flow into the recirculation system as illustrated by Figure 10. This figure shows the actual mass flow across the region entering the recirculation scoop. The two lower horizontal lines are, respectively, the lower jet boundary and the upper jet boundary, while the third (upper) line represents that additional scooped mass of Figure 9 for which $\rho UP_T/(\rho UP_T)$ no mixing $<.70$.

The vertical line represents the actual mass flow required for the recirculation jets. It is proposed to dump the excess mass flow with lower energy near the lower jet boundary, and use the higher energy flow above the upper jet boundary for recirculation purposes. Referring now back to Figure 7, the average stagnation pressure across the mass flow to be recirculated is seen to be 60% greater than that required for the jets. The vertical line in Figure 7 represents this average stagnation pressure ratio across the mass flow to be recirculated.

One more point is in order here. The low supersonic Mach number jet flow must be turned by the recirculation scoop. At first sight the high turning angle required would seem to indicate that a normal shock would emanate from the lower scoop surface.

However, due to the mixing of the jet and main streams and the fact that the scoop has been raised slightly above the inviscid streamline as discussed above, the actual jet Mach number is higher near the scoop surface than the inviscid calculation shows. Using the Mach number distribution of Figure 8 the shock wave was constructed and is presented in Figure 20. It is seen that the shock is attached and oblique for some distance below the lower scoop surface. As discussed later in this investigation a subsonic diffuser will be attached at the back end of the scoop to provide efficient operation. With the attached shock and a well designed diffuser there should be no difficulty in swallowing the normal part of the shock.

Thus, the viscous calculation has led to the following results. First, the mass flow of the recirculation jets is sufficient for the jets to retain their identity in order to compress the main stream. This by no means implies that the mass flow used in this sample numerical calculation is optimum; in fact, it would appear that a smaller mass flow would indeed be sufficient to compress the main stream. However, this is a parameter that should be determined by laboratory means, it being our purpose here to show that with a reasonable amount of mass flow (13% of the capture mass flow) efficient compression of the main stream is possible. Secondly, the viscous calculation has supplied detailed information as to profiles of mass flow, Mach number, stagnation pressure and stagnation pressure flux across the region entering the recirculation scoop area. Based on these considerations it has been possible to conclude how much and from what regions mass must be scooped in order to effect efficient engine operation and to provide the necessary energy to recirculate this flow; e.g. in the scheme illustrated herein, the mass flow to be recirculated has a stagnation pressure increase of the order of 60%, due generally to mixing. Part of this air comes from the main inlet air stream, which has a higher total pressure than most of the injected air.

Viscous mixing calculations were also performed for the Mach 2.5 and Mach 2.0 design configurations. In the Mach 2.5 case the calculations are identical to those previously discussed for Mach 3.0 and the results are shown in Figures 11 -14. There are no conceptual differences in these two calculations.

In the case of the Mach 2.0 configuration the first jet is turned on simply to provide some boundary layer control i.e., the inner region of the flow downstream of the first jet being assumed to act as if adjacent to a solid surface in this case. Using an approximate turbulent boundary layer analysis, calculations were performed to determine velocity, Mach number and stagnation pressure profiles at the axial location corresponding to the position of the recirculation scoop. These calculations and the associated mass flow and stagnation pressure flux profiles are shown in Figures 15 - 19.

IV. DETAILS OF SCOOP MECHANISM AND RECIRCULATION PROCESS

The only moveable part in the aerodynamically controlled inlet discussed thus far is the recirculation scoop and valves whose function it is to recapture the mass flow injected through the fixed jets. The scoop and its associated nozzles and valves must perform the following two functions: the stagnation pressure of the two jets must be controlled; the pressure in the recirculation region behind each jet must be controlled. Both of these pressure criteria may be controlled by regulating the amount of mass flow recirculated.

In Figure 21 there is a schematic diagram of the capture and recirculation mechanism drawn to the scale of the inviscid calculations Figures 3, 4, and 5. It should be emphasized that this represents only one possible mechanical design of the mechanism. Shown in Figure 21 are the two fixed geometry nozzles located in the fixed jet passageways, the two recirculation regions RI and RII, and the scoop itself in the three design configurations. Points on the scoop are labeled S A_M, B_M, with the subscript M denoting the operating Mach numbers, i.e. S $A_{2.5}$, $B_{2.5}$ represents points S, A and B on the scoop in the Mach number 2.5 configuration shown in Figure 4. Proper movement of the scoop may be implemented by means of circular slots cut into the side walls of the inlet (See Figure 22) in which the points A_M and B_M ride. The upper wall of a subsonic diffuser B_MC may be formed by a standard sliding member mechanism; the lower wall being formed by the inlet wall. At the end of this diffuser is a fixed channel divided into three regions. These regions separate the captured air in order to recirculate it to the rear jet, forward jet and the third small region is used for both overboard dumping of excess mass and pressure control of recirculation region RI. Two small flaps in this fixed channel are used to control the mass flows.

As mentioned previously, actual operation requires control of the jet and recirculation pressures. The air jets are formed by fixed channels in the base of the inlet with fixed geometry nozzles, resulting in a given Mach number of the injected air. The stagnation pressure of the jets may then be controlled, simply by controlling the mass flow entering the nozzles. This is implemented by means of the two flaps shown at the rear of the diffuser. Hence, lowering the mass flow to the jets will lower their static pressure and therefore, decrease the amount of main stream compressions.

Finally it is necessary to control the pressures in recirculation regions RI and RII. In region RII pressure control is easily obtained by adjusting the amount of mass dumped overboard. If the dump flaps are shut, the pressure in RII will rise, and vice versa. Similarly, since a portion of dump flow is shunted to RI, control of this mass flow will provide means of controlling the pressure in RI.

It is to be emphasized that Figure 21 represents only a schematic of a possible mechanical design of recirculation system. The dynamics of the recirculation regions are extremely complex and are not amenable to detailed analysis. It is therefore impossible to discuss these regions in other than a qualitative manner; exact details of the manner in which recirculation is established can be determined only experimentally. Further, the geometry of the passage for diffusing the jet flow to subsonic velocity, and the losses for such diffusion must also be determined experimentally.

V. OPERATING LOSSES

Inherent in the recirculation system outlined above are the following losses: losses in the subsonic diffuser; losses due to mass dumping; losses encountered in bringing the flow from the diffuser exit back to the recirculation jets. Estimates of the losses in the subsonic diffuser may be made based on Ref. (2). It is suggested in Ref. (2) that a subsonic diffuser of the type considered herein may be designed with an operating efficiency, i.e., a stagnation pressure recovery of .9. Consider next, the low energy flow that must be scooped and dumped overboard and which will therefore, contribute a drag force. This force may be calculated as

$$D = \dot{m}_d \, (U_e - U_d) + (p_e - p_d) \, A_d$$

where $\dot{m}_d$ is the mass flow to be dumped at the velocity $U = U_d$ and at the pressure p_d through the area A_d. Consider first the Mach 3 operating conditions where the mass flow to be dumped is a maximum and assume it is expanded to free stream pressure before dumping. From Figure 8 the average Mach number of the air to be dumped is 1.18. Expanding this to free stream pressure ($M_d = 2.22$) there is obtained

$$C_D = \frac{D}{q_e \ A \text{ inlet}} = \frac{2 \ \dot{m}_d}{\dot{m}_e} \left(1 - \frac{U_d}{U_e}\right) = 0.0224$$

With 10% loss in stagnation pressure in the ducting to the exit of the dump, the drag coefficient would be increased to 0.0252.

In the case of the Mach 2.5 design the average Mach number of the air to be dumped is 1.4. Expanding this to free stream pressure ($M_d = 2.07$) the corresponding drag coefficient would be 0.00767. With 10% loss in stagnation pressure in the ducting to the exit of the dump, the drag coefficient would be increased to 0.00806.

Finally, the losses and drag due to the recirculation duct must be calculated. A calculation of this nature requires estimates of losses encountered in pipes and turns; as the subsonic recirculation flow is required to turn through approximately 270°. Data of this sort is highly empirical and at best requires a detailed knowledge of the flow in the recirculation regions. However, the following conditions for the critical Mach 3.0 design condition are noteworthy; a 60% rise in stagnation pressure of the flow to be recirculated has been achieved, with an additional 10% loss in the diffuser. Should the remaining excess stagnation pressure be insufficient to drive the necessary mass flow through the ducts the possibility of raising the scoop slightly remains. Here it should be remembered that the stagnation pressure of any mass flow trapped by raising the scoop is of the order of 100% larger than the jet stagnation pressure. Hence, capturing a small additional mass should provide any necessary energy for recirculation, if necessary at all.

VI. CONTINUOUS OPERATION AND STABILITY

In order for the inlet considered herein to be of practical importance it must be adaptable to continuous operation. In addition it must react stably to any disturbance. Consider first the continuous operation mode. As the system has been depicted here both jets are on maximum power in the Mach number 3 configuration, one jet is on maximum power in the Mach number 2.5 configuration, and in the Mach 2.0 configuration the first jet is turned on slightly, essentially to provide some boundary layer control. Hence, for simplicity, there has been depicted a system wherein between 2.5 and 2.0 the first jet is almost completely shut down. The continuous operation sequence is then a straightforward one. As the flight Mach number decreases the mass flow to the engine decreases. This may be sensed by the scoop S A_M B_M Figure 21, and with this the scoop is lowered; concurrently the mass flow to the second jet is decreased by the flap at the rear of the diffuser and the pressure in RII is decreased by the overboard valve. As the pressure in the second jet and the recirculation region RII drops, the amount of compression of the main stream will also drop. This is consistent with the lowering of the scoop.

The same type of procedure prevails during a perturbation of the free stream Mach number. Consider a sudden drop in free stream Mach number. Two immediate consequences are: decreased mass flow to the engine; the inviscid shock pattern in the inlet moves forward and intercepts the jet flow. Both of these occurrences will tend to decrease the amount of mass flow recirculated and hence, the amount of compression of the main stream. Concurrently the scoop sensing an engine mass flow decrease will travel downward which is consistent both with the lower Mach number and the decreased compression. The opposite situation i.e., an increase in flight Mach number, is also stable. Such a situation increases the engine mass flow and thus the amount captured by the scoop is increased, resulting in a larger mass flow recirculated and greater compression by the jets. Sensing the engine mass flow increase the scoop travels upward in a consistent manner.

VII. CONCLUSIONS

There has been considered herein a method of obtaining variable geometry inlets for high supersonic Mach numbers by aerodynamic means. The use of supersonic air jets injected at some angle to the main stream in order to produce the necessary stream compression eliminates the need of forward moveable ramps in a standard variable geometry nozzle. In addition these jets provide a means of boundary layer control which is required for a standard inlet design. Against these advantageous features there must be weighed the cost of operating the recirculation mechanism discussed herein. Losses involved in this system are those incurred in the subsonic diffuser and the recirculation mechanism.

There has been designed in detail here a variable geometry nozzle operating at Mach numbers 2, 2.5 and 3.0. Analysis of the viscous and inviscid phenomena governing the behavior of such a system has been performed implying that physical implementation can be carried out. The inherent losses in the designed inlet have been estimated in a reasonable fashion. It is concluded that the system merits further consideration, on a laboratory scale, in order to determine its ultimate practicability.

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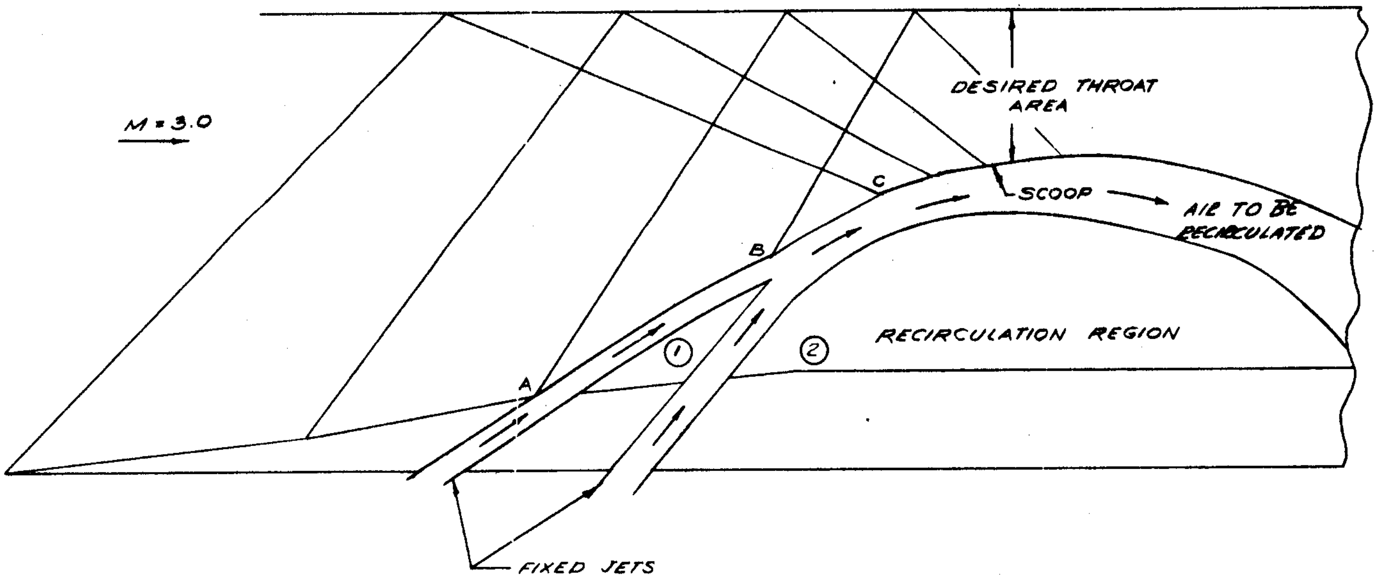


FIG. 1 INLET SCHEMATIC

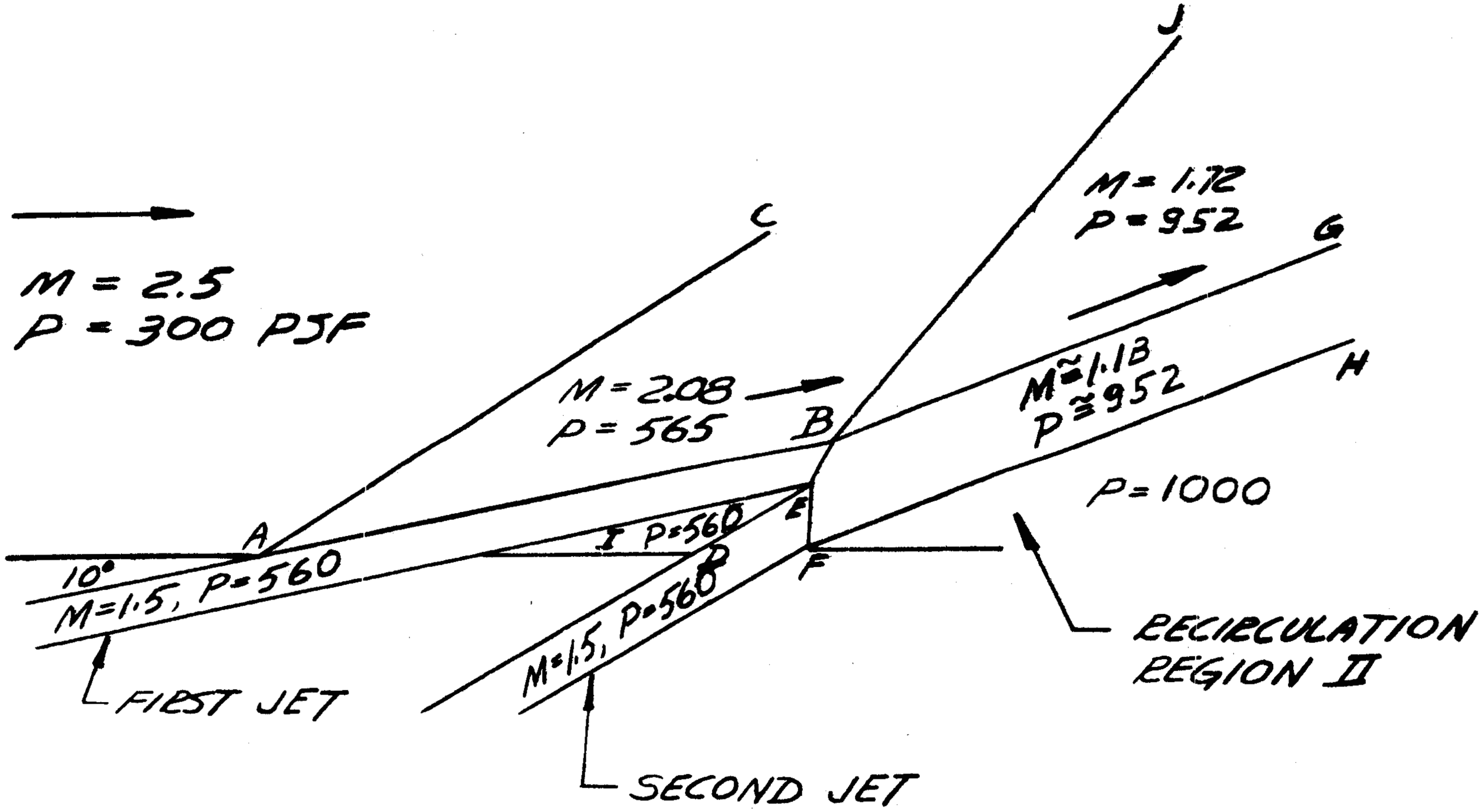


FIG 2 INVISCID JET INTERACTION

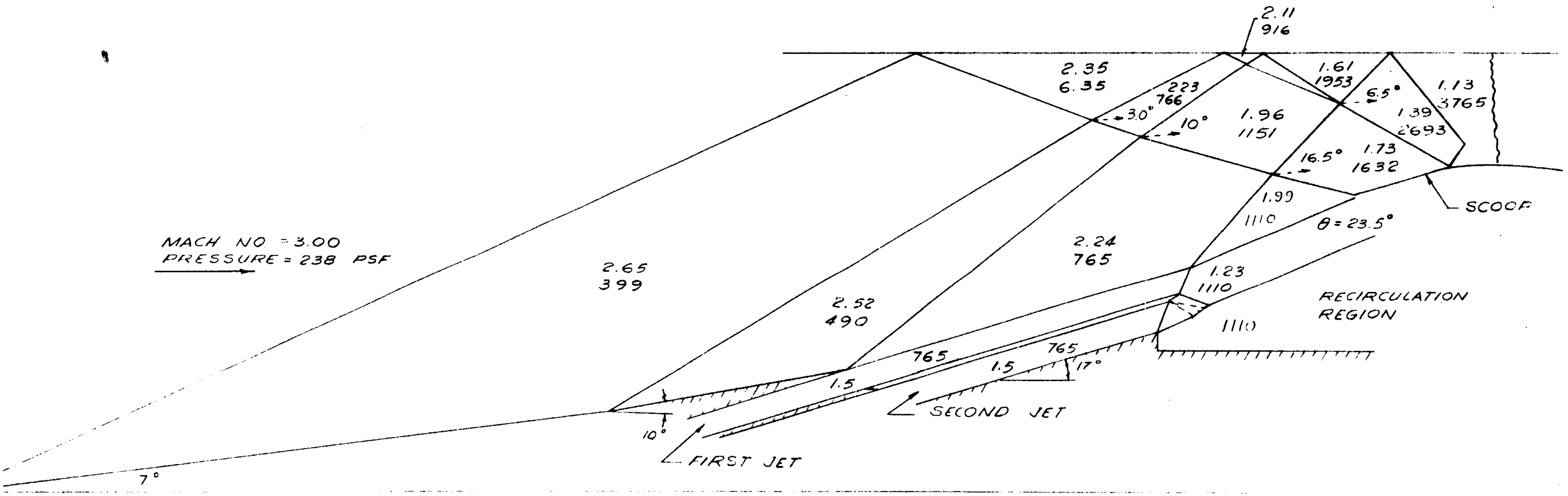


FIG. 3 INLET DESI
FOR MACH 3.0

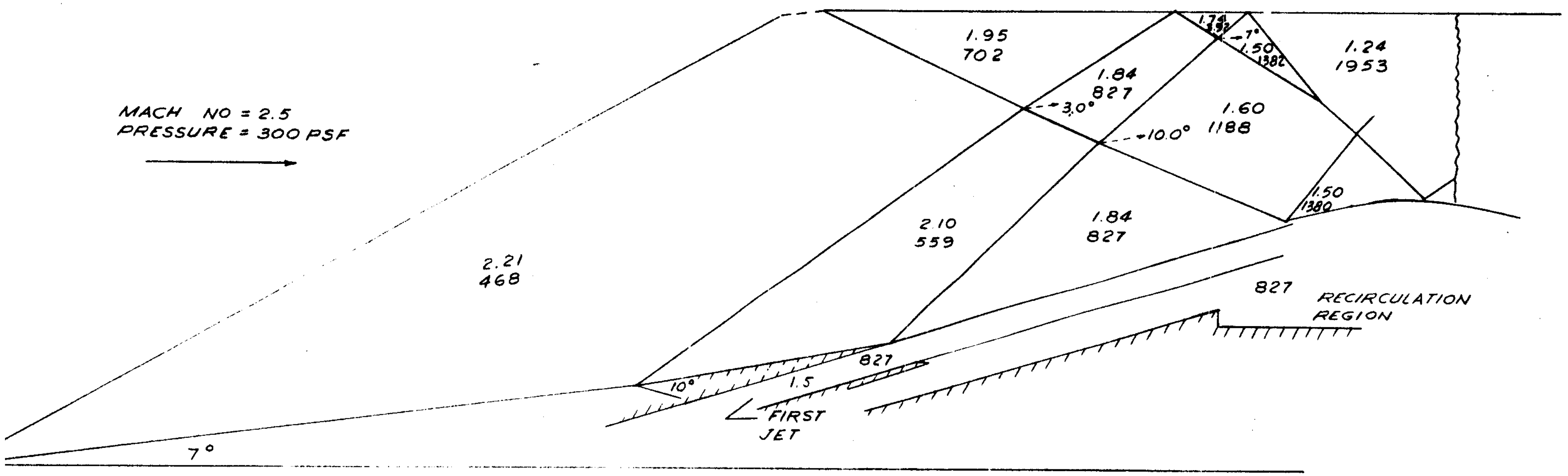


FIG. 4 INLET DESIGN FOR MACH 2.5

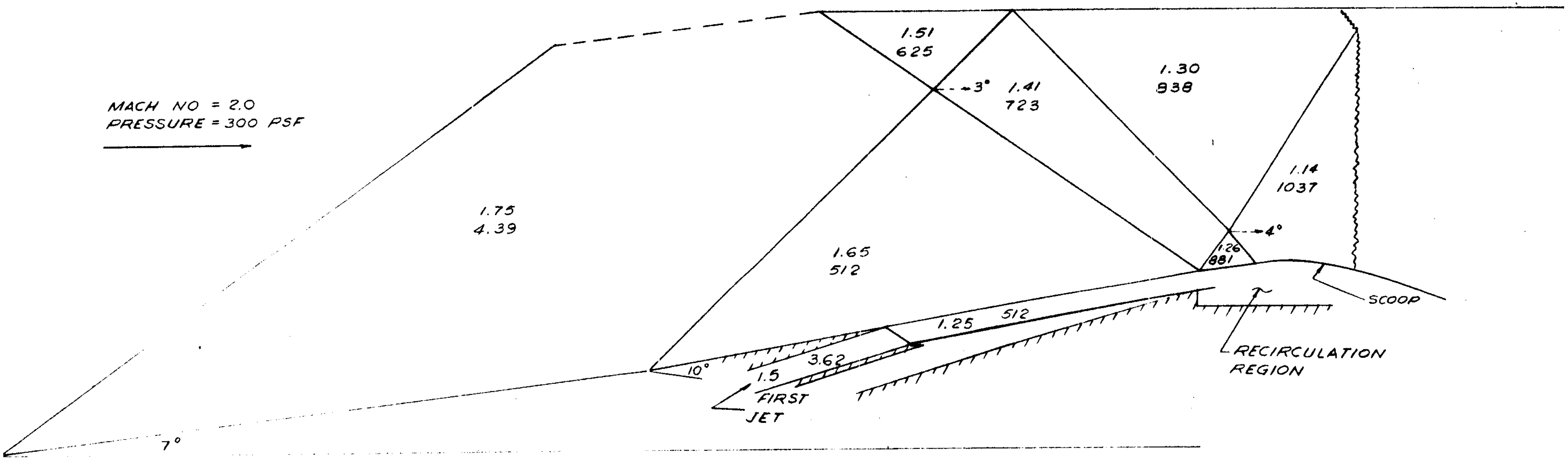


FIG. 5 INLET DESIGN FOR
MACH 2.0
)

INVISCID SOLUTION - - - -
VISCOUS SOLUTION ———
TOTAL JET MASS FLOW = 13.3 lb/ft.-sec.
JET MASS FLOW/CAPTURE MASS FLOW = 13%

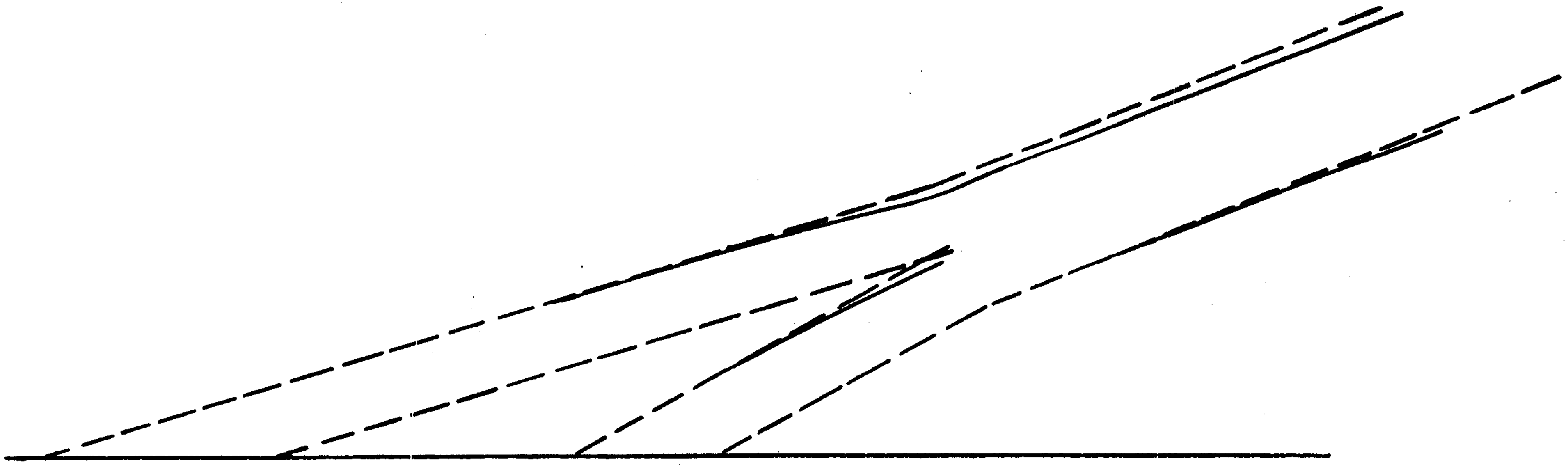


FIG 6 EFFECT OF VISCOUS MIXING ON JET ORIENTATION

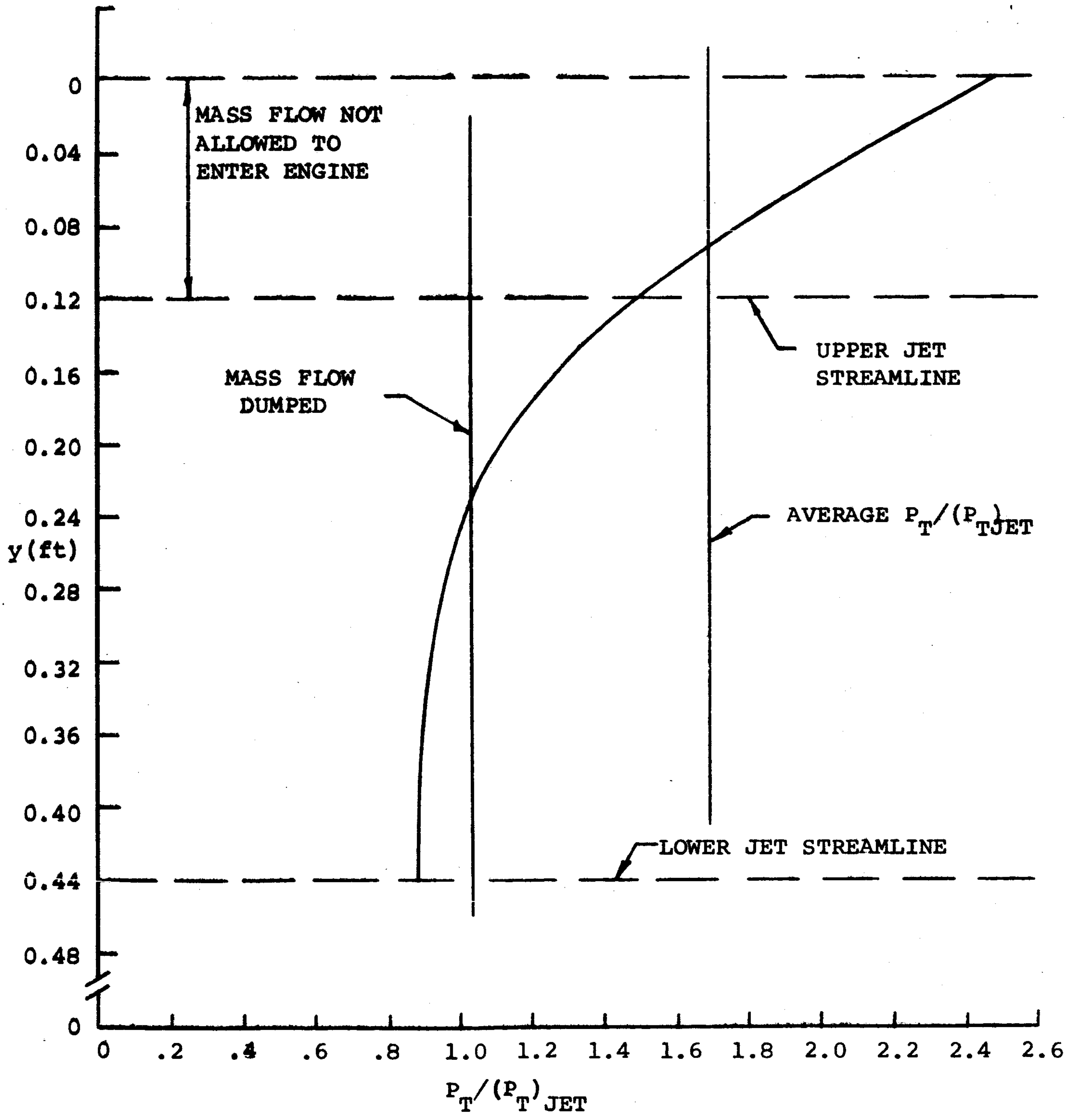


FIGURE 7 - ENERGIZING OF JET STREAM DUE TO VISCOUS MIXING

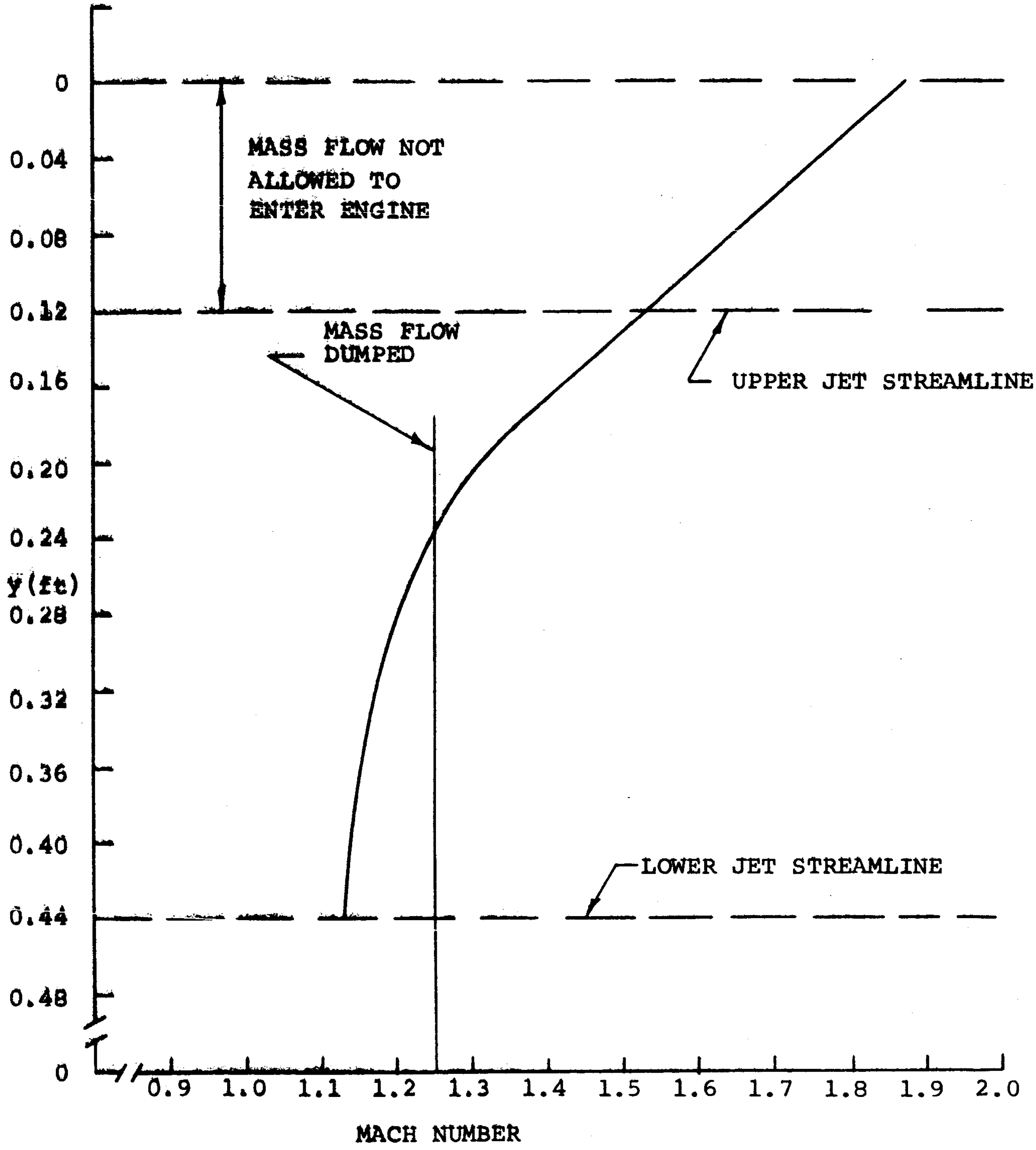


FIGURE 8 - MACH NUMBER DISTRIBUTION ($M_e = 3.0$)

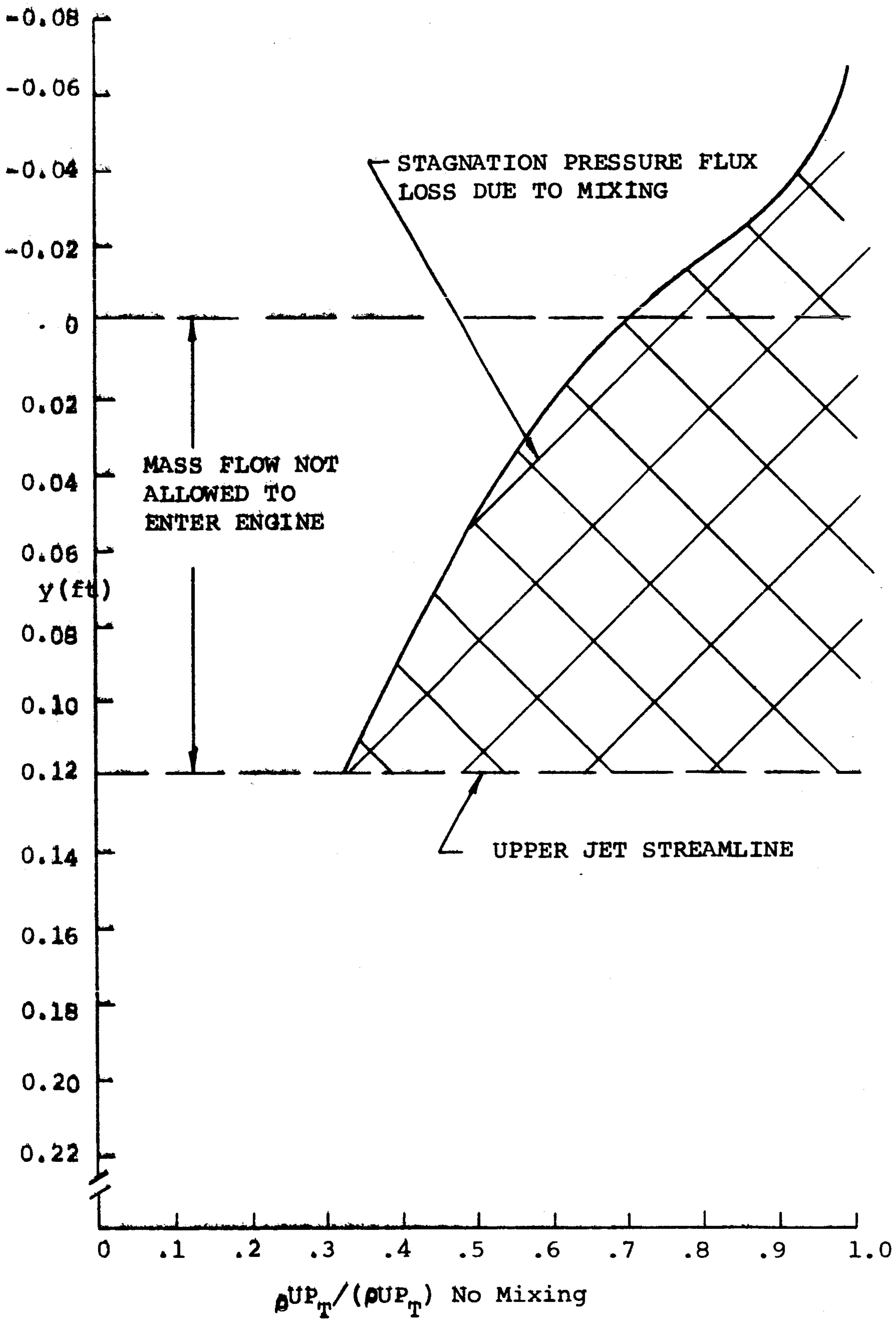
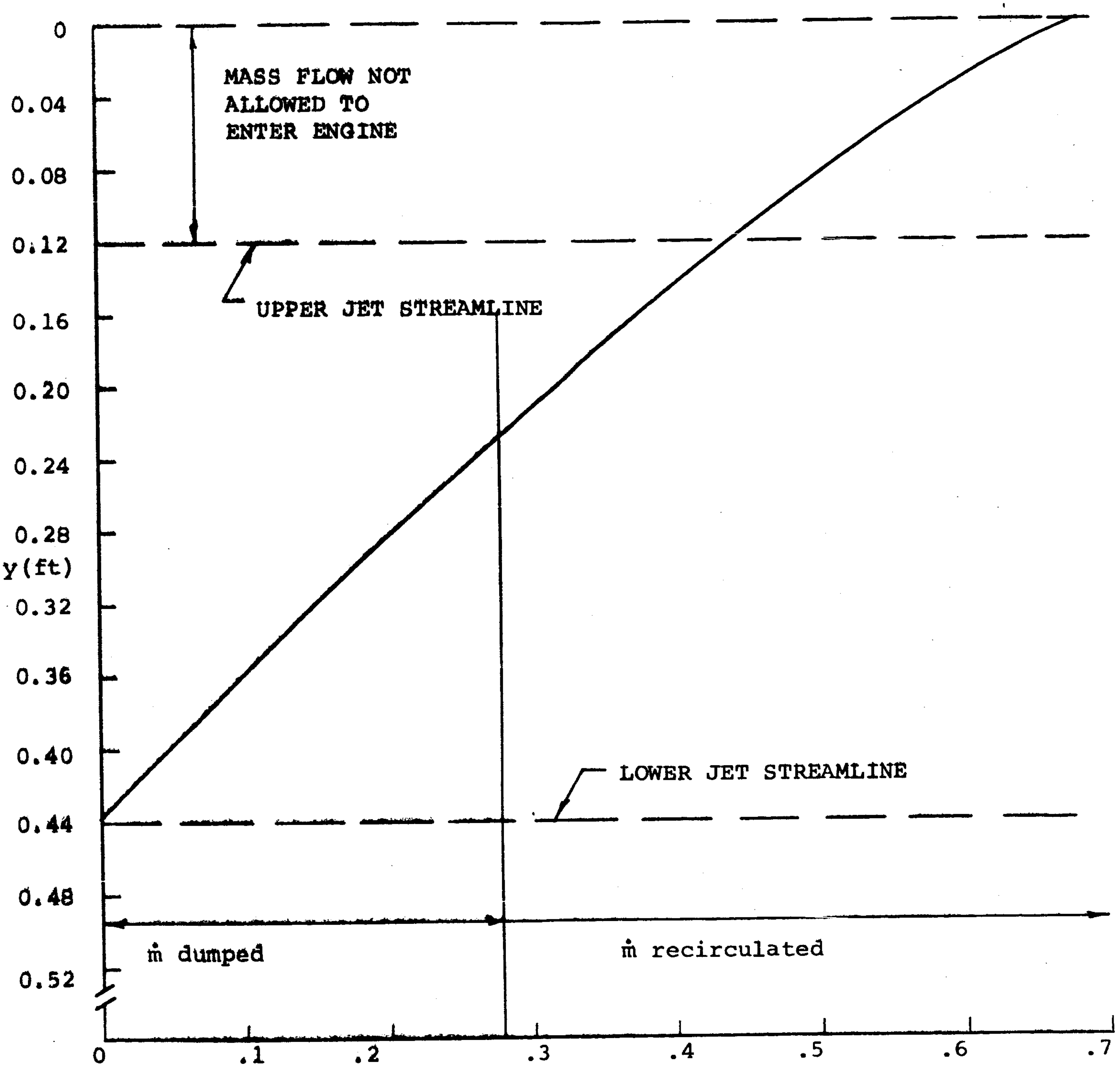


FIGURE 9 - STAGNATION PRESSURE FLUX LOSS DUE TO ENERGIZING OF JET STREAM (M_e=3.0)



$$\dot{m} = \int_{y}^{y\,\text{lower jet}} \rho u \, dy \text{ , lb(mass)/sec per unit width}$$

FIGURE 10 - MASS FLOW DISTRIBUTION ($M_e = 3.0$)

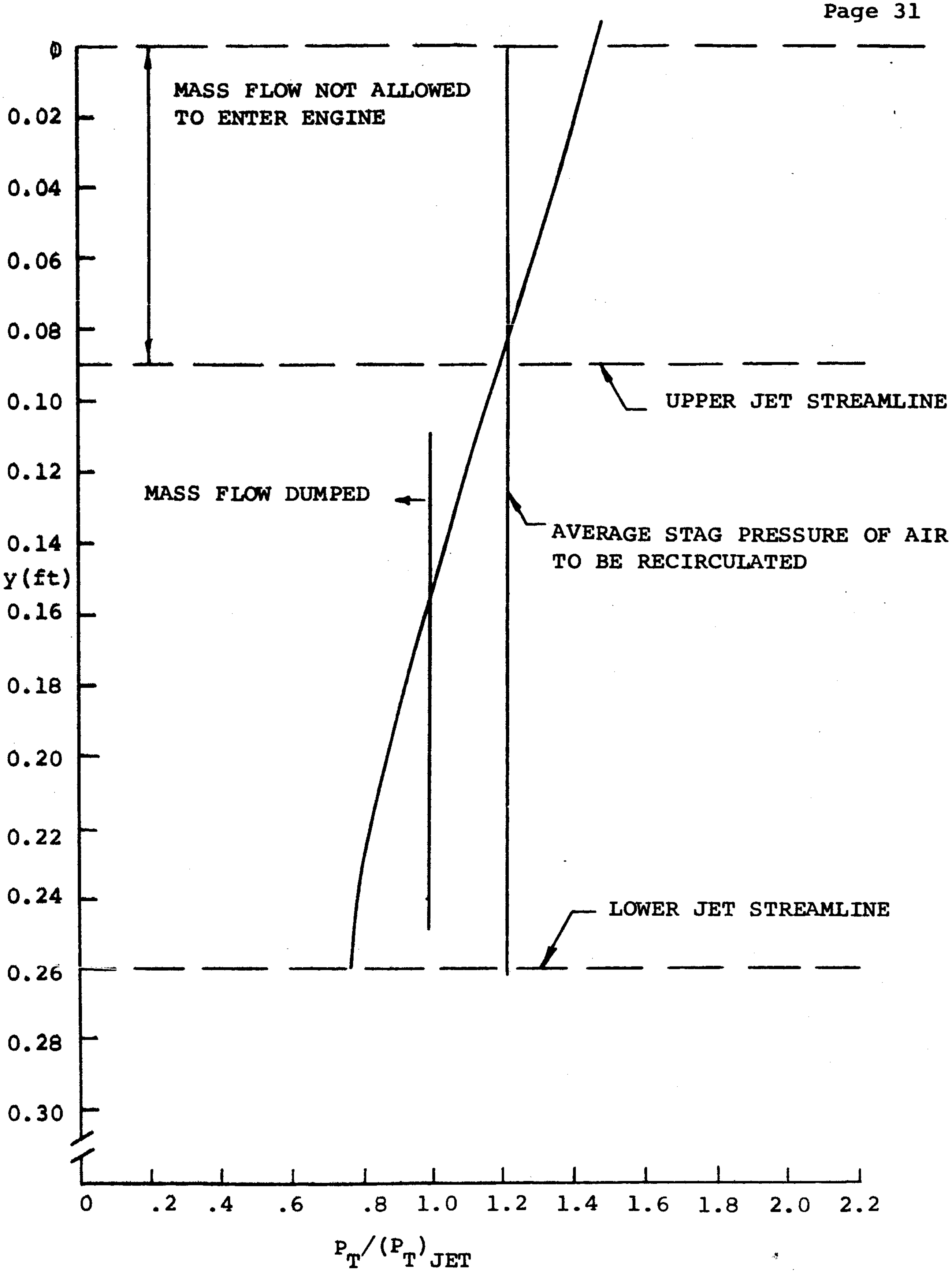


FIGURE 11 - ENERGIZING OF JET STREAM DUE TO VISCOUS MIXING

(M_e = 2.5)

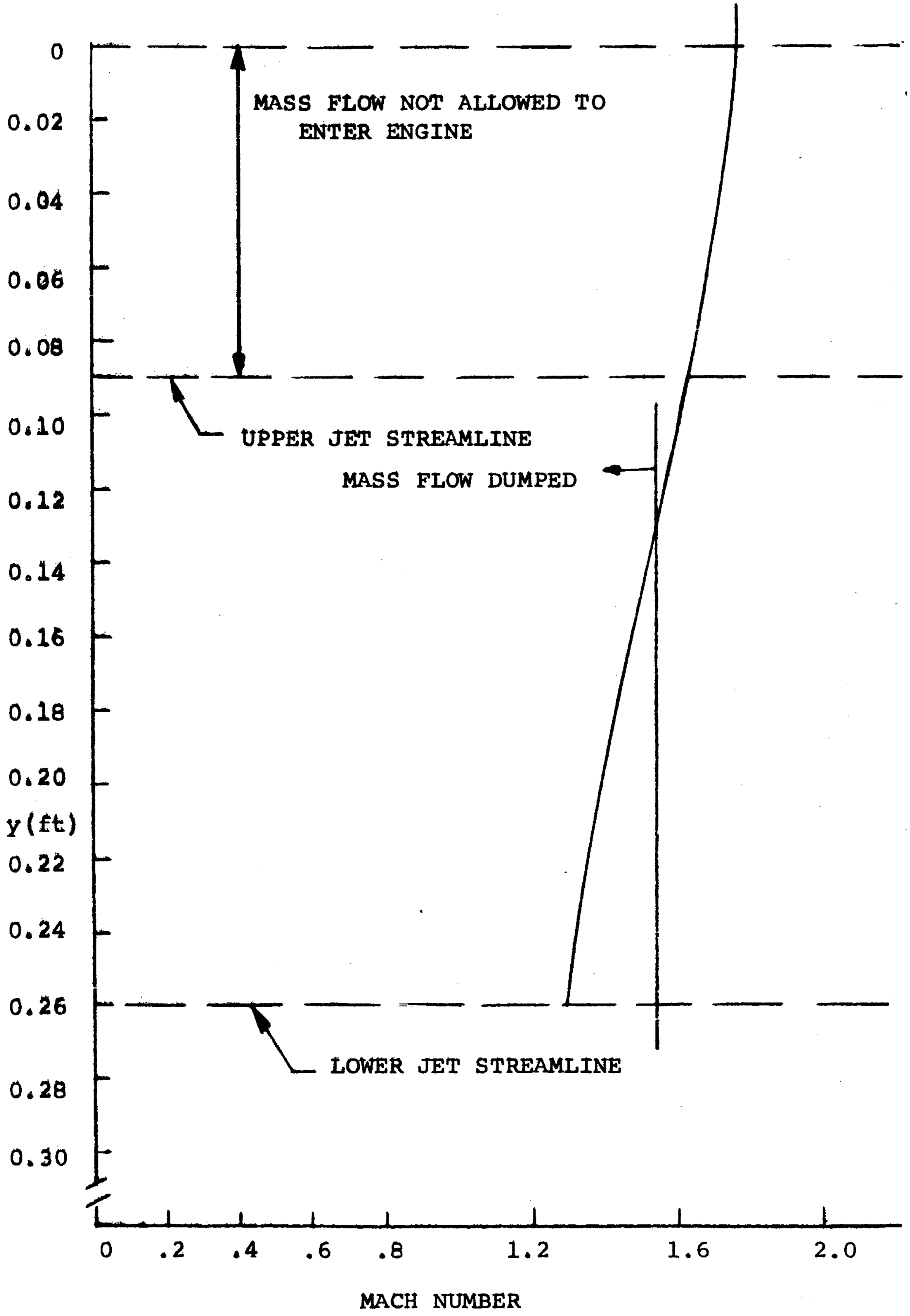


FIGURE 12 - MACH NUMBER DISTRIBUTION ($M_e=2.5$)

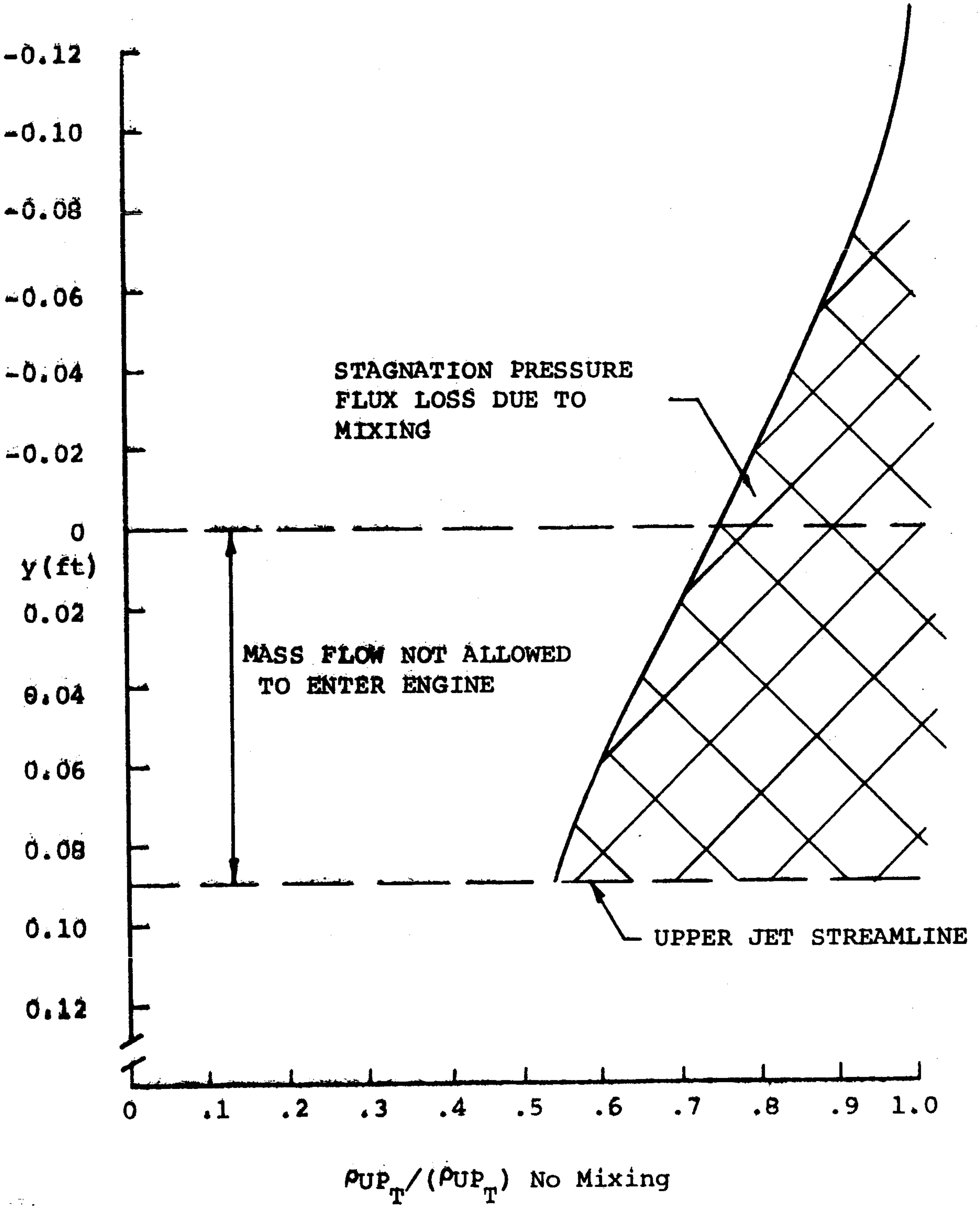
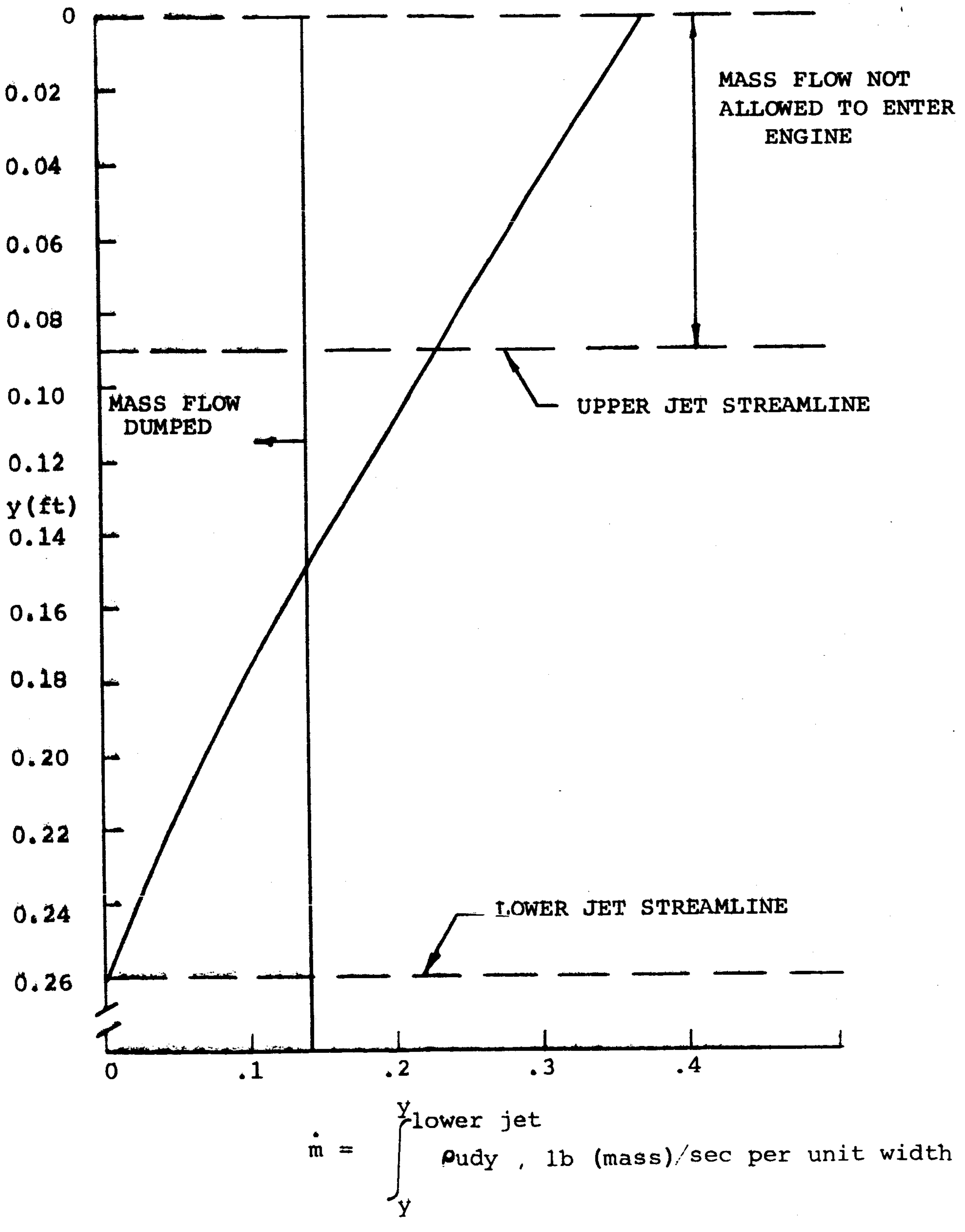


FIGURE 13 - STAGNATION PRESSURE FLUX LOSS DUE TO ENERGIZING OF JET STREAM (M_e=2.5)



$$\dot{m} = \int_{y}^{y_{\text{lower jet}}} \rho u dy \text{ , lb (mass)/sec per unit width}$$

FIGURE 14 - MASS FLOW DISTRIBUTION ($M_e=2.5$)

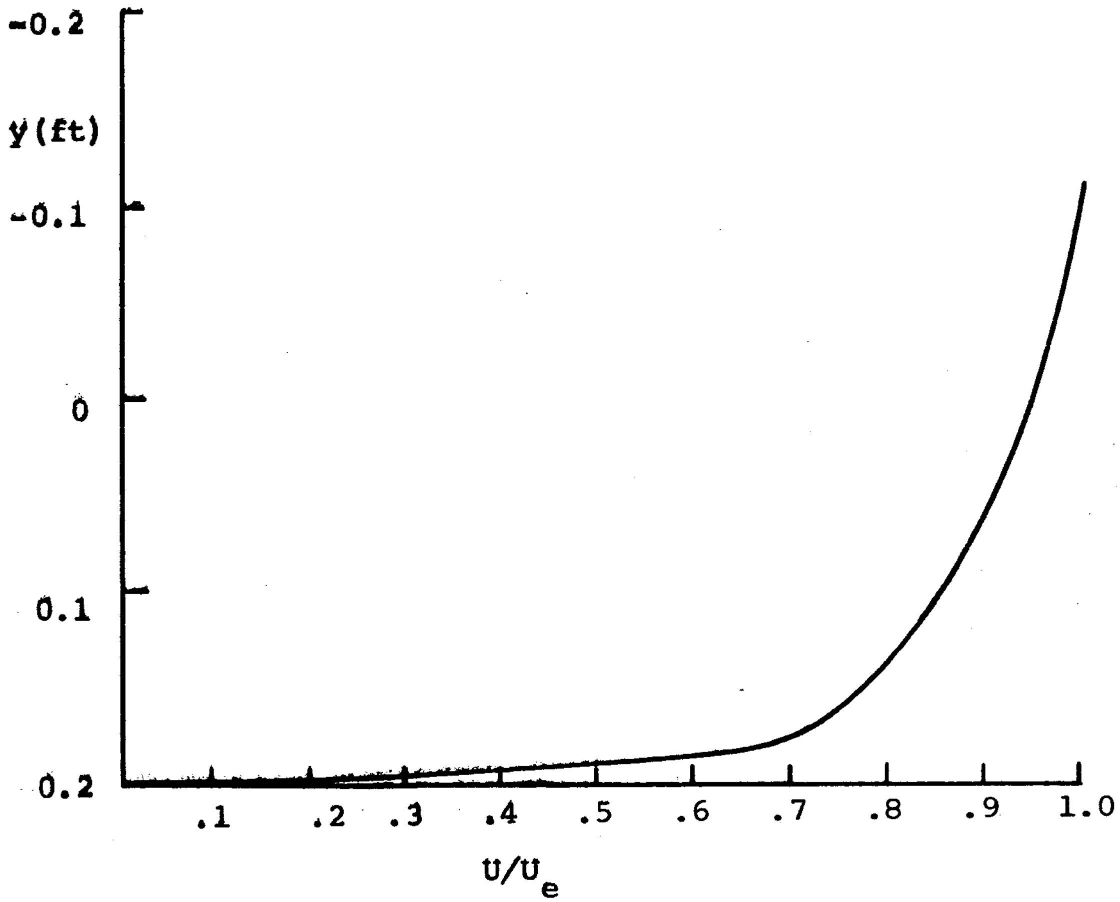


FIGURE 15 - VELOCITY DISTRIBUTION
(M_e = 2.0)

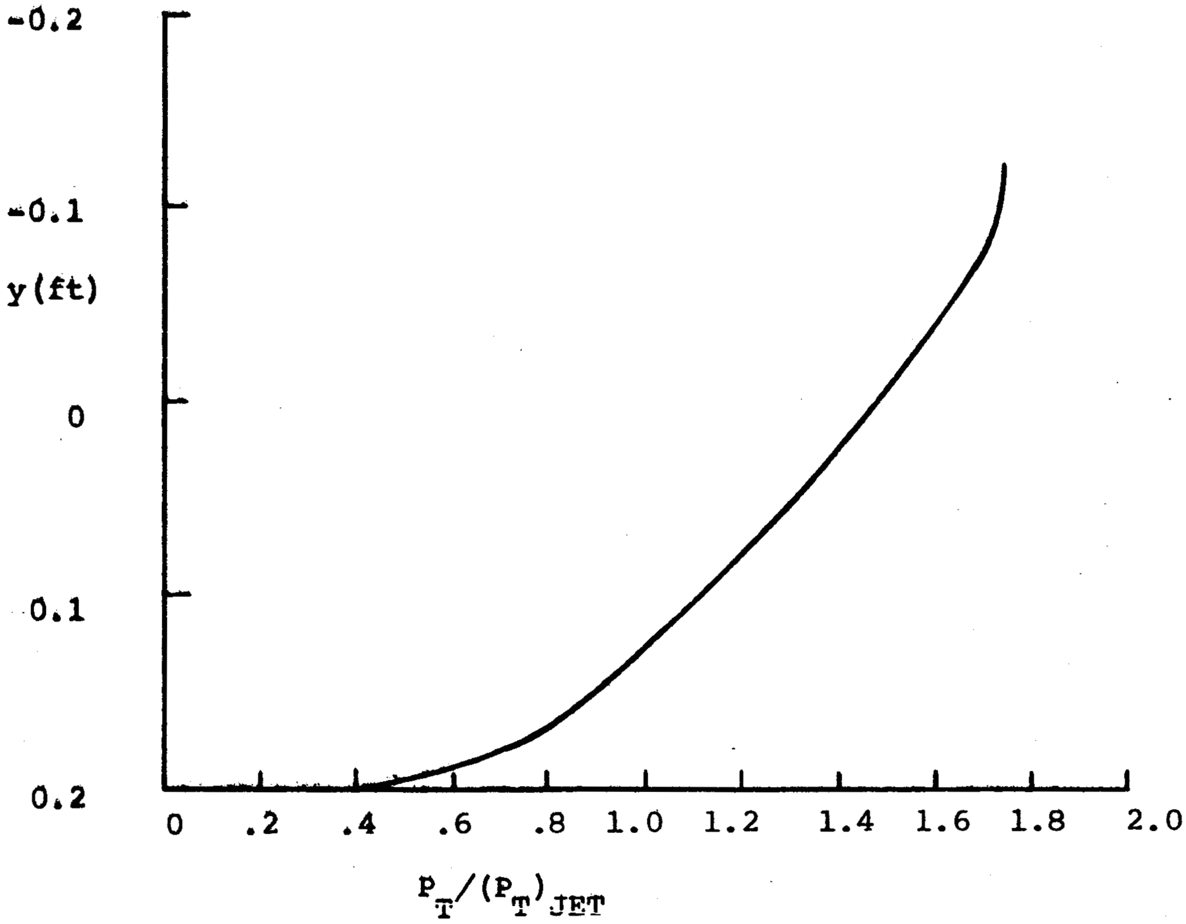


FIGURE 16 - ENERGIZING OF JET STREAM DUE TO VISCOUS MIXING (M_e=2.0)

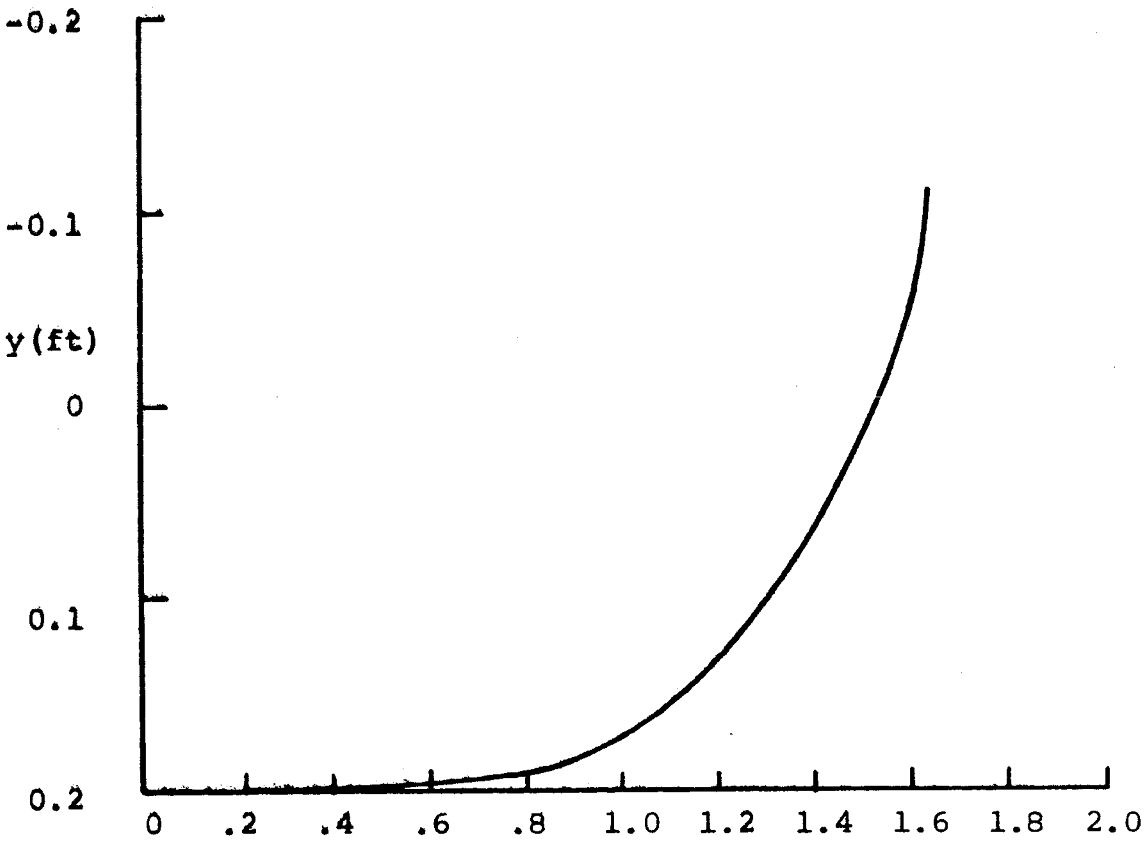


FIGURE 17 - MACH NUMBER DISTRIBUTION
(M_e=2.0)

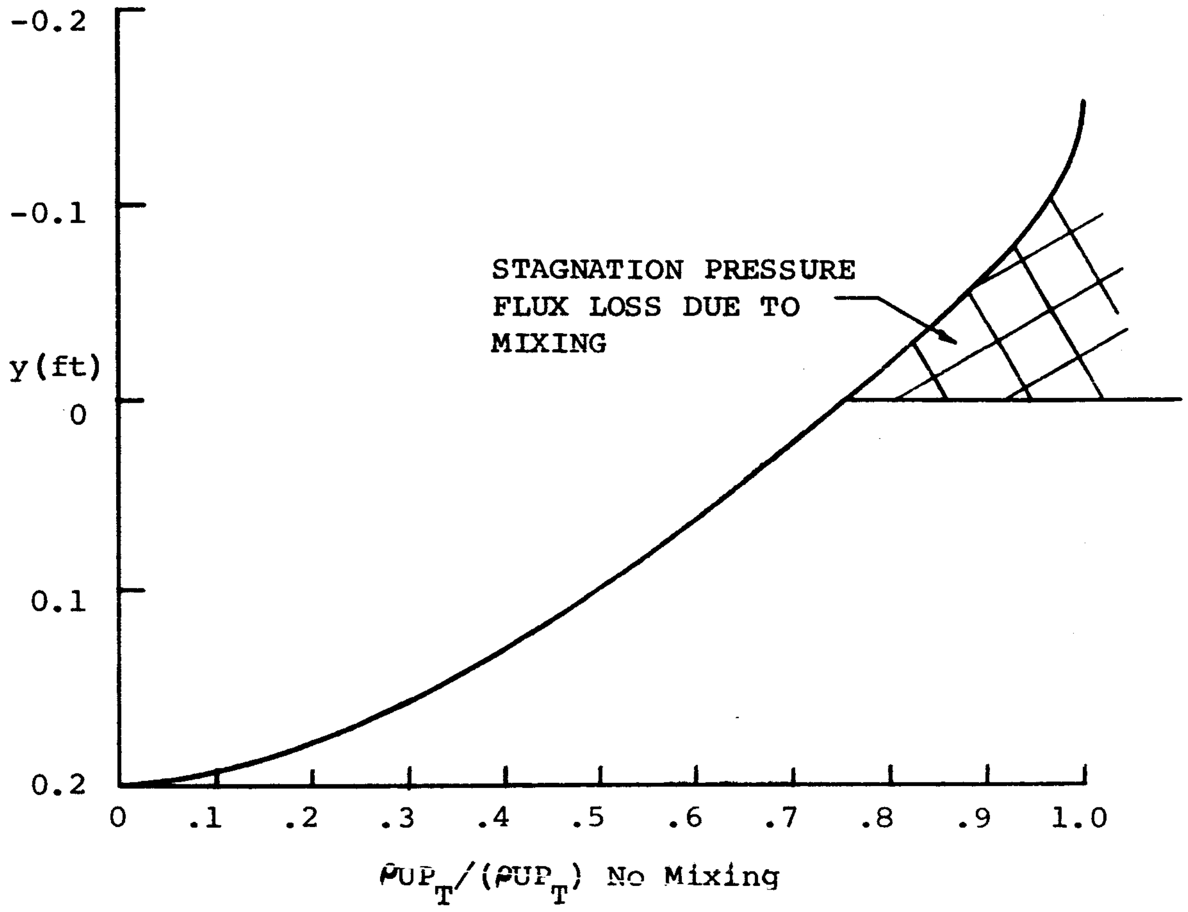
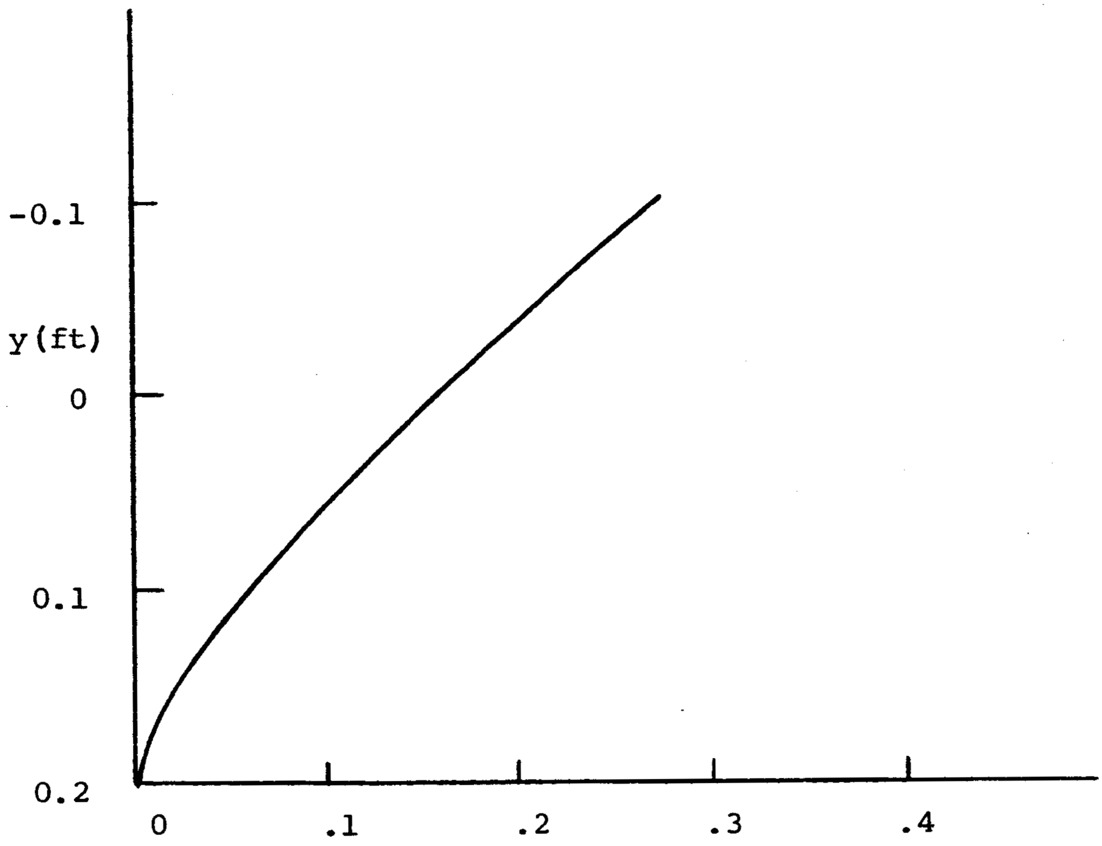


FIGURE 18 - STAGNATION PRESSURE FLUX

(M_e=2.0)



$$\dot{m} = \int_{y}^{y_w} \rho u \, dy$$, lb(mass)/sec per unit width

FIGURE 19 - MASS FLOW DISTRIBUTION (M_e=2.0)

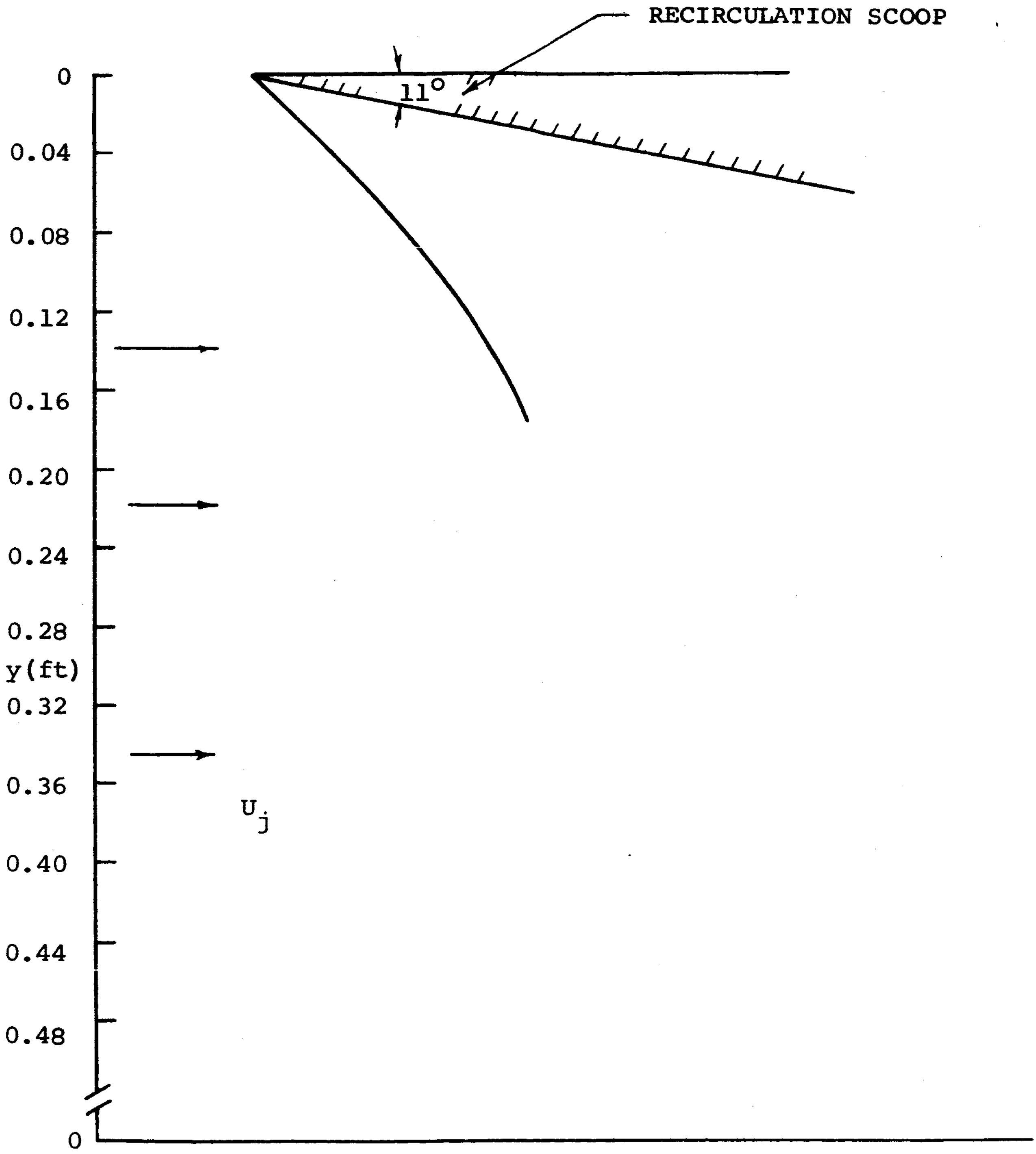


FIGURE 20 - SHOCK PATTERN AT SCOOP LIP (M_e=3.0)

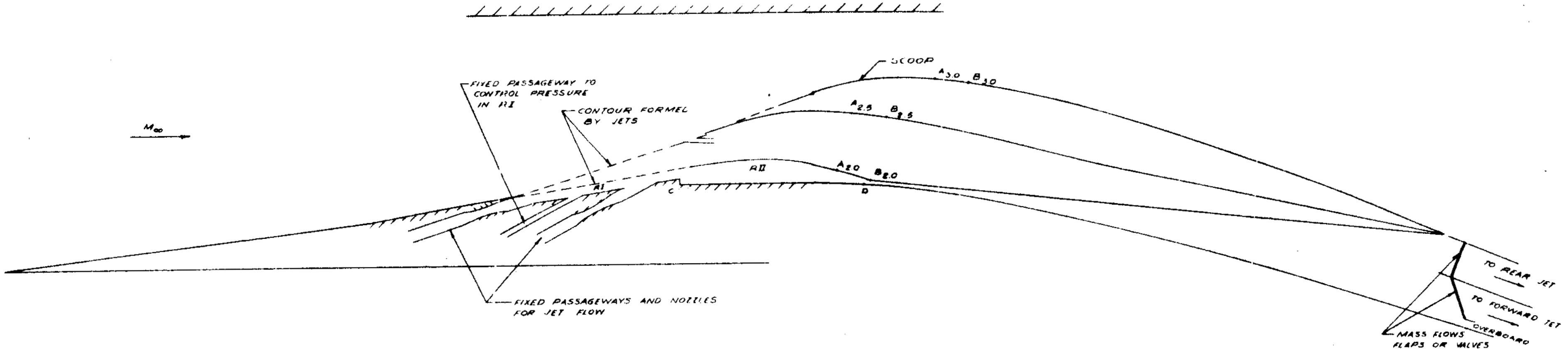


FIG 21 SCHEMATIC RECIRCULATION MECHANISM

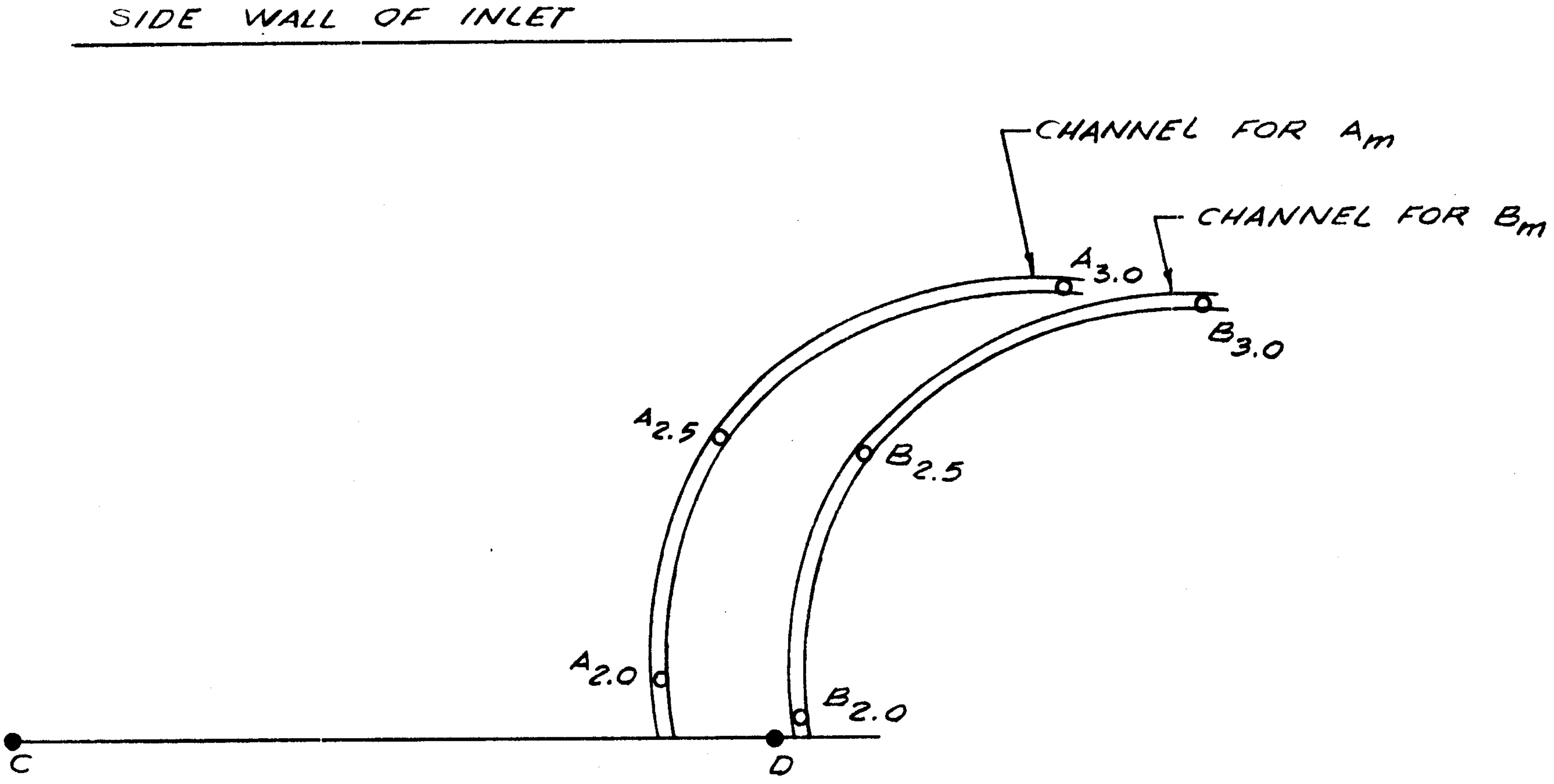


FIG. 22 CUT AWAY OF INLET SIDEWALL