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FREE JET ENGINE TESTING: WIND TUNNEL STARTING

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13. ABSTRACT

Free jet wind tunnels are used extensively for jet engine testing and development. A facility diffuser is employed for altitude simulation. Diffuser size and performance must be matched to the exhauster pumping capacity and engine installation drag or diffuser unstarts will occur.

The diffuser starting theory of Rudolf Herman was reviewed and extended to determine the allowable drag coefficient of ramjet test installations in free jet wind tunnels. Specific drag limits are calculated for the Air Force free jet test stand located at The Marquardt Corporation, Van Nuys, California.

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DR. PAUL J. ORTWERTH

FOREWORD

This work was done for the Ramjet and Laser Aerodynamics Division integral rocket/ramjet test program, Project 3012, Task 301208, Work Unit 30120818. This work was accomplished in the time period 13 February 1973 to 20 February 1973.

This technical report has been reviewed and is approved for publication.

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LIST OF SYMBOLS

(In order of occurrence in text and figures)

f	Diffuser Contraction Ratio $\left(\frac{F_1}{F_2}\right)$
F_1	Nozzle Exit Area
F_2	Diffuser Throat Area
ν	Test Cabin Differential Pressure Ratio $\nu = \frac{P_c - P_1}{P_1}$
P_c	Static Pressure in Test Cabin
P_1	Nozzle Exit Static Pressure
M_1	Nozzle Exit Mach Number
$C_D{}^*$	Drag Coefficient related to Nozzle Exit Area and Static Pressure $$C_D{}^* = \text{DRAG FORCE}/(P_1 F_1)$$
$C_{D\boxdot}$	Drag Coefficient related to Frontal Area of body in flow and Nozzle Exit dynamic pressure $$C_{D\boxdot} = \frac{\text{Drag Force}}{\frac{1}{2}\gamma_1 P_1 M_1{}^2 F_{\boxdot}}$$
γ	Ratio of Specific Heat of Air Nominally $\gamma = 1.4$
T_T	Total Temperature
R	Specific gas constant for air $R \doteq 1680 \frac{ft^2}{sec^2 {}^\circ R}$
P'	Non-Dimensional Pressure P/P_T
Θ	Non-Dimensional Mass Flux $\rho W/\rho^* a^*$
ρ^*	Reference density of flow depending on local total pressure and total pressure $$\rho^* = \frac{P_T}{RT_T} \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma+1}}$$

K	Total Pressure Recovery of the Diffuser
h_1	Nozzle Exit diameter of Axisymmetric Nozzle or Nozzle Exit Height of two dimensional nozzle
h_2	Diffuser throat diameter of diffuser throat height of two dimensional diffuser
ℓ	Free jet length
$F_{\odot}$	Frontal Area of Body in Flow
β	Blockage Factor $\beta = 1 + \nu\ (1 - f) - f\ C_D{}^*{}_{TOT}$
ρ_1	Density of air at Nozzle Exit
W_1	Velocity of air at Nozzle Exit
ρ_2	Density of air in Diffuser Throat
W_2	Velocity of air in Diffuser Throat
P_2	Static Pressure in Diffuser Throat
P_T	Total Pressure
ρ_T	Total
D	Drag Force
M^*	Velocity normalized to the reference speed of sound a^*
a^*	Reference speed of sound for flow of unit Mach number

$$a^* = \sqrt{\frac{2\gamma}{\gamma+1} R\ T_T}$$

1.0 BACKGROUND

1.1 Introduction - Jet engines, particularly ramjets, are tested and developed in facilities on the ground which simulate the altitude and Mach number of flight. Nearly always a diffuser is required to exhaust the test gas to the atmosphere and for very high altitude a diffuser and compressor are used together as an exhauster. For engine testing where thrust is to be measured or other dynamic problems studied, the facility used is of the free jet type shown in Figure 1.

The theory of the efficiency of the diffuser and the flow processes encountered is well worked out in Reference (1-4) for free jet wind tunnels without model blockage. However, a systematic theoretical study of blockage is not available and in practice the allowable drag or blockage of a given test installation is often determined by the facility operating engineer based on his experience with the facility. Because there are mounting struts, instrumentation, fuel and control lines also installed with the engine, the test item will have many times the drag of a well-faired engine. For a complicated test it is difficult to tell when the engine is well-faired or when the blockage is too high. It often happens that a test will not start after many months, perhaps years, of preparation have been spent on the installation. This causes a loss of many thousands of dollars and manhours as well as a delay or slippage in the program. This situation should not occur. It is the purpose of this report to determine a rational approach to the problem of determining the maximum blockage of the test hardware that can be installed in a given facility.

1.2 Theoretical Discussion - Model drag causes a reduction in stream thrust, and sufficient drag will choke the wind tunnel diffuser. Any further increase in model drag will cause the wind tunnel to remain unstarted at any pressure ratio. If a diffuser with a larger throat is available the facility may be operated successfully.

Many times the tunnel will not start due to insufficient pressure ratio available to make up the losses in total pressure caused by the model even though the diffuser is not choked. Thus the theory will be required to determine the pressure recovery of the diffuser and the choking limit of the diffuser.

The flow entering the diffuser is not uniform due to mixing on the jet boundary and the generation of wakes by the engine installation. The diffuser must be long enough for the flow to mix out these non-uniformities without large friction losses on the diffuser walls, usually on the order of 6-10 diffuser diameters are provided for this purpose. The free jet test section length must also be limited to about 2 to 3 nozzle exit diameters to keep the jet mixing losses with the air in the test cabin small. It will be assumed that the tunnel operating characteristics are known for the case in which no engine is present and the test section is entirely free of blockage. The diffuser total pressure recovery can then be used to determine an effective test section drag coefficient to account for the mixing and diffuser losses just discussed. Experience shows that the wind tunnel will start at nearly the same pressure ratio that it operates at in steady flow with there being a small hysteresis in some tunnels during which the diffuser operates with unsteady pulsations. Thus, based on the above considerations, maximum drag coefficients for the tunnel starting will be calculated for the case of steady one-dimensional flow.

The theoretical development follows that of Herman, References (1-4) and the same notation is used for ease of reference to that work. Conservation of mass, momentum and energy in the control volume shown in Figure 1 is the subject of the following analysis.

2.0 DIFFUSER AND TEST PARAMETERS

2.1 Diffuser Characteristics - Let us introduce the following notation after Herman

$$f = \frac{F_1}{F_2} < 1 \qquad \text{(Diffuser Contraction Ratio)} \qquad (1)$$

for the area ratio and

$$\nu = \frac{P_c - P_1}{P_1} \qquad \text{(Test Cabin Differential Pressure Ratio)} \qquad (2)$$

for the chamber pressure. The lower limit for ν is -1, corresponding to vacuum in the test chamber. The upper limit for ν can be determined from a recent correlation by Holden, Reference (7), for the pressure necessary to cause incipient separation of hypersonic boundary layers. At supersonic speeds Moore, Reference (8), shows that the pressure to induce boundary layer separation from the nozzle wall can be computed from the formula

$$\nu_{max} = .357M_1^2 - .06M_1^3; \; (1.0 < M_1 < 4.0) \qquad (3)$$

For a test Mach number of 3.05, this results in a value of

$$\nu_{max} = 1.6$$

This is quite a strong shock wave corresponding to a flow deflection of 15° and may be unacceptable. Test cabin differential pressure ratio of zero is generally desired, but not always obtainable.

2.2 Test Installation Blockage - Three components of drag must be considered for the present analysis. These are the drag experienced by the air through the engine called the internal drag, the drag experienced by the air flow around the engine and installation hardware called the external drag, and finally the drag experienced by the air flow on the free jet boundary as it flows through the test cabin called test cabin drag.

Formally we write

$$C^*_{D_{tot}} = C^*_{D_{int}} + C^*_{D_{ext}} + C^*_{D_{test\ cabin}} \tag{4}$$

where

$$C^*_D = \frac{\text{(any component of drag force)}}{p_1 F_1} \tag{5}$$

and in terms of the drag coefficient as usually found in the literature

$$C^*_D = C_{D_{\boxdot}} \frac{\gamma}{2} M_1^{\,2} \left(\frac{F_{\boxdot}}{F_1}\right) \tag{6}$$

This formulation is more convenient for the present analysis since then formally the solution follows Herman. The drag components for internal flow in the engine can be evaluated by standard practice in propulsion analysis such as presented in Reference (5). The external drag analysis can be accomplished by utilizing the data and procedure in Hoerner, Reference (6). The only modification would be evaluating the base drag of ventilated struts which communicate to the test cabin. In this case it is possible to equate base pressure to test chamber pressure. The effective test cabin drag coefficient can be evaluated from the data previously mentioned and the results of this analysis.

2.3 Blockage Reduction Methods - The wind tunnel characteristics including blockage can be conveniently summarized by introducing a new blockage factor. Define:

$$\beta = 1 + \nu\,(1-f) - f\, C^*_{D_{tot}} \tag{7}$$

This factor (β) should be maximized to insure diffuser operation. The blockage factor can be increased by five methods.

a. Reduce the size of the test parts relative to the nozzle size reducing the factor $\left(\frac{F_{\boxdot}}{F_1}\right)$

b. Streamline the external parts and struts with fairings reducing $C_{D_{ext}}$

c. Reduce the free jet length, thus reducing $C_{D_{test\ cabin}}$

d. Increase the diffuser throat area reducing $\int$

e. Allow an increase in the cabin pressure thereby increasing ν

3.0 ANALYSIS

3.1 Conservation Equations

Continuity - It will be assumed that there are no leaks or mass addition during the starting process.

$$F_1\rho_1W_1 = F_2\rho_2W_2 \tag{8}$$

Momentum - The application of the Momentum Integral yields

$$F_2\rho_2W_2^2 - F_1W_1^2\rho_1 = P_1F_1 + (F_2-F_1)\ P_c - P_2F_2 - \frac{D}{P_1F_1}\ P_1F_1 \tag{9}$$

The second term on the right-hand side represents force on the jet applied by the pressure in the test chamber P_c which in the general case is different from the nozzle exit pressure P_1.

The last term is the momentum loss due to internal and external flow drag forces or the engine installation and momentum losses to the jet boundaries and diffuser.

Energy - For the assumption of adiabatic flow the energy integral is

$$\frac{W_1 2}{2} + \frac{\gamma}{\gamma-1}\frac{P_1}{P_1} = \frac{W_2 2}{2} + \frac{\gamma}{\gamma-1}\frac{P_2}{P_2} = \frac{\gamma}{\gamma-1}\frac{P_T}{\rho_T} \tag{10}$$

3.2 Solution - By setting W equal to a*, the sonic reference velocity, the following useful isentropic relations can be obtained

$$\frac{T}{T_T} = 1 - \frac{\gamma-1}{\gamma+1} M^{*2} \tag{11}$$

$$\frac{P}{P_T} = (1 - \frac{\gamma-1}{\gamma+1} M^{*2})^{\gamma/\gamma-1} \tag{12}$$

$$\frac{\rho}{\rho_T} = (1 - \frac{\gamma-1}{\gamma+1} M^{*2})^{1/\gamma-1} \tag{13}$$

Let us introduce the notation

$$\underline{P}' \equiv \frac{P}{P_T} \qquad \text{(non-dimensional pressure)}$$

$$M^* = \frac{W}{a^*} \qquad \text{(Reduced Velocity)}$$

Note that M^* has a maximum $0 \leq M_1^* \leq \sqrt{\frac{\gamma+1}{\gamma-1}}$ even though $M > \infty$.

$$\Theta = \frac{\rho W}{\rho^* a^*} \qquad \text{Reduced Mass Flux}$$

$$K = \frac{P_{T_2}}{P_{T_1}} \qquad \text{Diffuser Total Pressure Ratio}$$

From equation (12) letting $M^* = 1.0$ we can find the useful relation

$$\frac{\rho^* a^{*2}}{P_T} = \gamma \left(\frac{2}{\gamma+1}\right)^{\gamma/\gamma-1} \tag{14}$$

With some algebraic reduction using the above relations in the conservation equations the continuity equation becomes

$$K = f \frac{\Theta 1}{\Theta 2} \tag{15}$$

momentum $$K \underline{P}_2' - \beta \underline{P}_1' = \gamma \left(\frac{2}{\gamma+1}\right)^{\gamma/\gamma-1} f \, \Theta_1 \, (M_1^* - M_2^*) \tag{16}$$

now the continuity equation (15) can be used to reduce the momentum equation (16) to a relation relating M_2^* and M_1^*

$$\frac{\underline{P}_2'}{\Theta_2} - \frac{\beta}{f} \frac{\underline{P}_1'}{\Theta_1} = \gamma \left(\frac{2}{\gamma+1}\right)^{\gamma/\gamma-1} (M_1^* - M_2^*) \tag{17}$$

since it can be verified by equations (12) and (13) that locally

$$\frac{\underline{P}'}{\Theta} = \left(\frac{2}{\gamma+1}\right)^{1/\gamma-1} \frac{\left(1 - \frac{\gamma-1}{\gamma+1} M^{*2}\right)}{M^*} \tag{18}$$

Then equation (17) can be reduced to a simple quadratic form

$$M_2^{*2} - \left[\frac{\frac{\beta}{f} + \left(\frac{2\gamma}{\gamma+1} - \frac{\beta}{f}\frac{\gamma-1}{\gamma+1}\right) M_1^{*2}}{M_1^*}\right] M_2^* + 1 = 0 \tag{19}$$

Solution of equation (20) by the quadratic formula yields

$$M_2^* = \frac{\frac{\beta}{f} + \left(\frac{2\gamma}{\gamma+1} - \frac{\beta}{f}\frac{\gamma-1}{\gamma+1}\right) M_1^{*2}}{2\,M_1^*} \pm \left[\left(\frac{\frac{\beta}{f} + \left(\frac{2\gamma}{\gamma+1} - \frac{\beta}{f}\frac{\gamma-1}{\gamma+1}\right) M_1^{*2}}{2\,M_1^*}\right)^2 - 1\right]^{\frac{1}{2}} \tag{20}$$

The solution if completed by the formula for total pressure loss.

$$K = \frac{f\,M_2^*\left(1 - \frac{\gamma-1}{\gamma+1} M_1^{*2}\right)^{1/\gamma-1}}{M_2^*\left(1 - \frac{\gamma-1}{\gamma+1} M_2^{*2}\right)^{1/\gamma-1}} \tag{21}$$

There are two solutions, one supersonic and the other subsonic. For reasons which are well known, Reference (1-4), the subsonic solution is usually observed and more desirable since it yields the greatest range of test chamber pressure. For a thorough examination of the design implication of this equation and the verification of its validity, one should consult References (1-4). We will be primarily interested in the blockage limitations set by this equation. We note the identity

$$M^*_{2_+}\,M^*_{2_-} \equiv 1.0 \tag{22}$$

which has important implications for us.

First we observe, for either subsonic or supersonic solutions, that as drag increases, β decreases and the square root in equation (21) will go to zero, at this point $M_2^* = 1.0$. Once the model drag exceeds this critical amount steady normal diffuser operation is impossible as implied by the imaginary solutions obtained from equation (21) for M_2^*. Once this happens the diffuser will be called choked. It is important to note that the maximum amount of drag to choke the diffuser is the same for a subsonic or supersonic diffuser. In the next section we will examine the conditions necessary to choke the diffuser.

4.0 RESULTS

All results are presented graphically using ordinary mach number for ease of application.

4.1 Minimum Blockage Factor - The minimum blockage factor can be determined at choking of the diffuser. This factor can be made universal by dividing by area ratio. Thus:

$$\left(\frac{\beta}{f}\right)_{min} = \frac{2\,M_1^* - \frac{2\gamma}{\gamma+1} M_1^{*2}}{1 - \frac{\gamma-1}{\gamma+1} M_1^{*2}} \tag{23}$$

The universal function $(\beta/f)_{min}$ determined for $\gamma = 1.4$ in equation (23) depicted graphically in Figure 2 can be used to determine the maximum drag coefficient for which a given diffuser operation is possible. Alternately if the installation drag coefficient has been estimated, the diffuser throat can be sized if more than one diffuser is available. As will be shown, it is advantageous to use the smallest possible diffuser throat.

Generally, the test chamber pressure is desired to be equal to the nozzle exit pressure. However, this pressure generally changes as the tunnel starts from ν greater than zero to some final value less than zero as the operating pressure ratio increases. When the diffuser chokes, ν can be solved from equation (7) if C_D and f are specified. This feature essentially explains how control of the chamber pressure is achieved by varying the diffuser minimum area or test section drag. This point is discussed by Herman, References (1-4).

It is also possible to determine the test section drag coefficient of a given nozzle diffuser combination by measuring ν and the operating pressure ratio with no blockage in the test section. In principle, the test installation drag or thrust due to engine operations can be determined from test section pressure and operating pressure ratio.

4.2 Diffuser Area Ratio and Maximum Aerodynamics Drag Coefficient - The combined effects of Mach number and diffuser area ratio on maximum blockage can be seen in Figure 3. We see that large diffusers can be used to great advantage at low Mach numbers, but that the area ratio effects become less important at high Mach numbers. Also, if the diffuser area were about twice the nozzle exit area, $f \sim 0.5$, a constant blockage model could tested over a wide range of Mach number without changing the diffusers.

Diffuser area ratio is also determined by test section length. The mixing on the boundary of the jet spreads the jet. Practical area ratios that smoothly capture the jet have been plotted by Herman as a function of test section L/h, Figure 4. This area ratio will also be sensitive to test section pressure, model drag, gas temperature and Mach number. A detailed jet mixing analysis is beyond the scope of the present report; however, details can be found in Reference 9. For engineering purposes Figure 4 is sufficient for most supersonic wind tunnel applications. However, longer test section lengths than those of Figure 4 have been recently achieved without large mixing losses by using the jet stretcher technique, Reference 10.

4.3 Total Pressure Recovery - The total pressure recovery of the diffuser at choking conditions called critical pressure recovery is a function of Mach number and area ratio only

$$K_{crit} = \frac{f[M_1^* \left(1-\frac{\gamma-1}{\gamma+1} M_1^{*2}\right)^{\frac{1}{\gamma-1}}]}{.6339} \tag{24}$$

The universal critical pressure recovery function $(K/f)_{crit}$ is plotted in Figure 5. This function decreases rapidly with Mach number in a manner very similar to the normal shock total pressure recovery function which is also plotted for comparison. The critical diffuser recovery is always less than normal shock recovery unless f is greater than one. However, the area ratio f must always be less than one as shown in Figure 4. Thus, presentation of diffuser performance in terms of a normal shock efficiency is most appropriate.

The curves for efficiency showing the Mach number and area ratio effects is found in Figure 6. This figure shows dramatically the compressor power savings that can be obtained by using the smallest possible diffuser area.

4.4 Wind Tunnel Operation Map - A wind tunnel operation map may be computed for a given facility from which users can determine the model blockage allowed. For the Air Force axisymmetric free jet wind tunnel operated by The Marquardt Company in Van Nuys California the following data are given.

$$M_1 = 3.05$$

$$h_1 = 32.86 \text{ in}$$

$$h_2 = 44 \text{ in}$$

Thus

$$f = 0.56$$

and from equation (3) we find

$$\nu_{max} = 1.6$$

The diffuser is ducted into a large receiver conduit which then manifolds into a number of exhausters. There is no subsonic diffuser so that diffuser flow jets into the receiver with loss of dynamic pressure in the jet due to mixing. Thus, diffuser total pressure recovery will be nearly equal to the static pressure P_2.

The map is constructed by solving equations 21, 22, 11 and 18 for various values of β/f. The results of this calculation are presented in Figure 7. The arrows labeled CET on the abscissas correspond to the estimated drag coefficients for a free jet installation of a ramjet missile. The installation did not start in the original configuration. The contractor then proposed a clean installation with a much reduced drag coefficient which should operate satisfactorily.

5.0 CONCLUSIONS

The cause of wind tunnel unstarts has been clarified. Model drag will cause additional total pressure losses through shock waves and turbulence which when added to the diffuser losses can choke the diffuser. When the drag is high enough, the diffuser will choke. If the model has more drag than the critical amount the wind tunnel cannot be started at any pressure ratio without enlarging the diffuser throat.

A simple one dimensional theory quantitatively explains the features of this phenomena. This theory can be used to predict when choking will occur and thus, the test engineer can a priori determine how clean his installation must be to successfully start the wind tunnel.

This should allow the future savings of many lost manhours and dollars usually incurred when test installations do not start.

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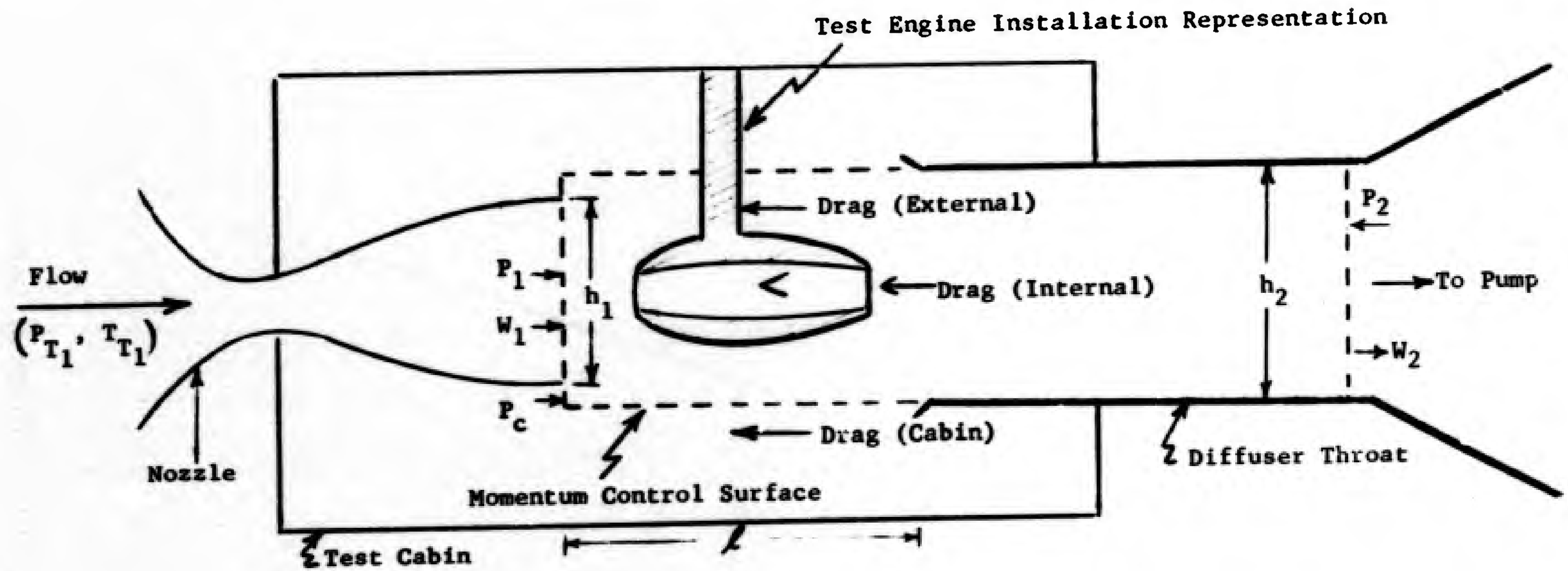


Figure 1. Schematic of Free Jet Wind Tunnel Test

Minimum value of test installation blockage factor which causes choking of wind tunnels $\gamma = 1.4$ (normalized by diffuser contraction ratio)

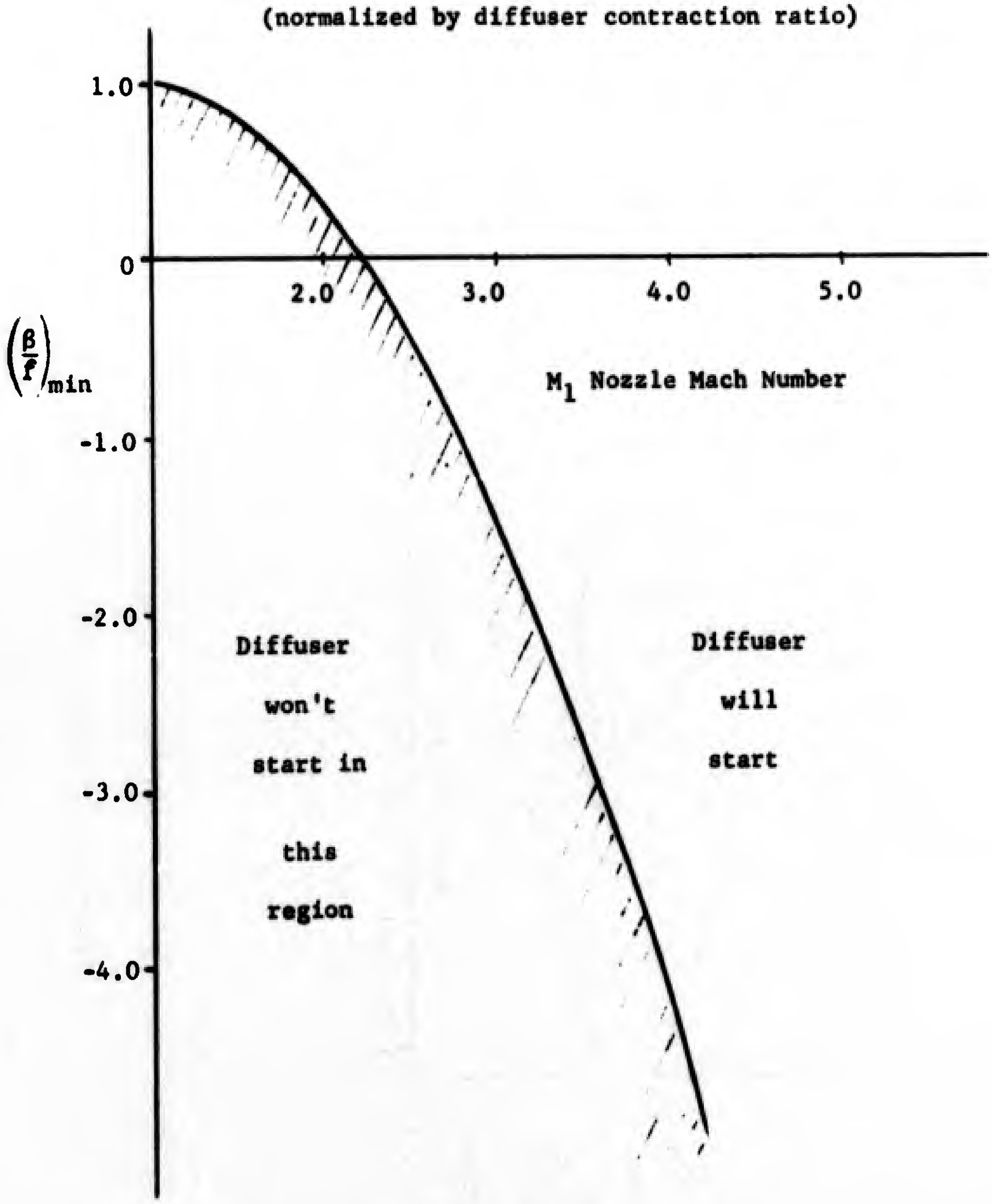


Figure 2. Minimum Blockage Factor

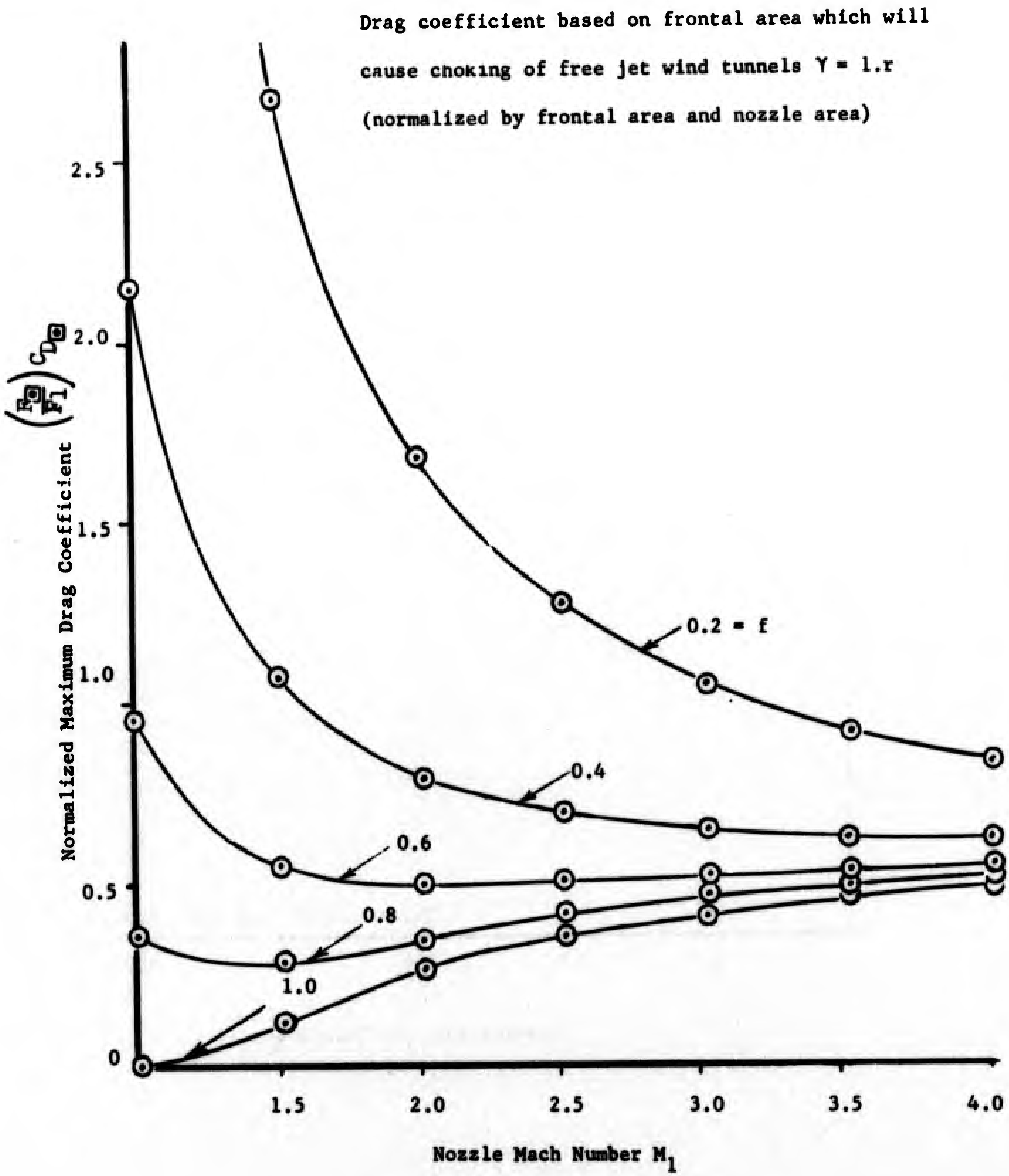


Figure 3. Maximum Drag Coefficients

Experimental diffuser area ratio for smooth jet capture (supersonic tunnels)

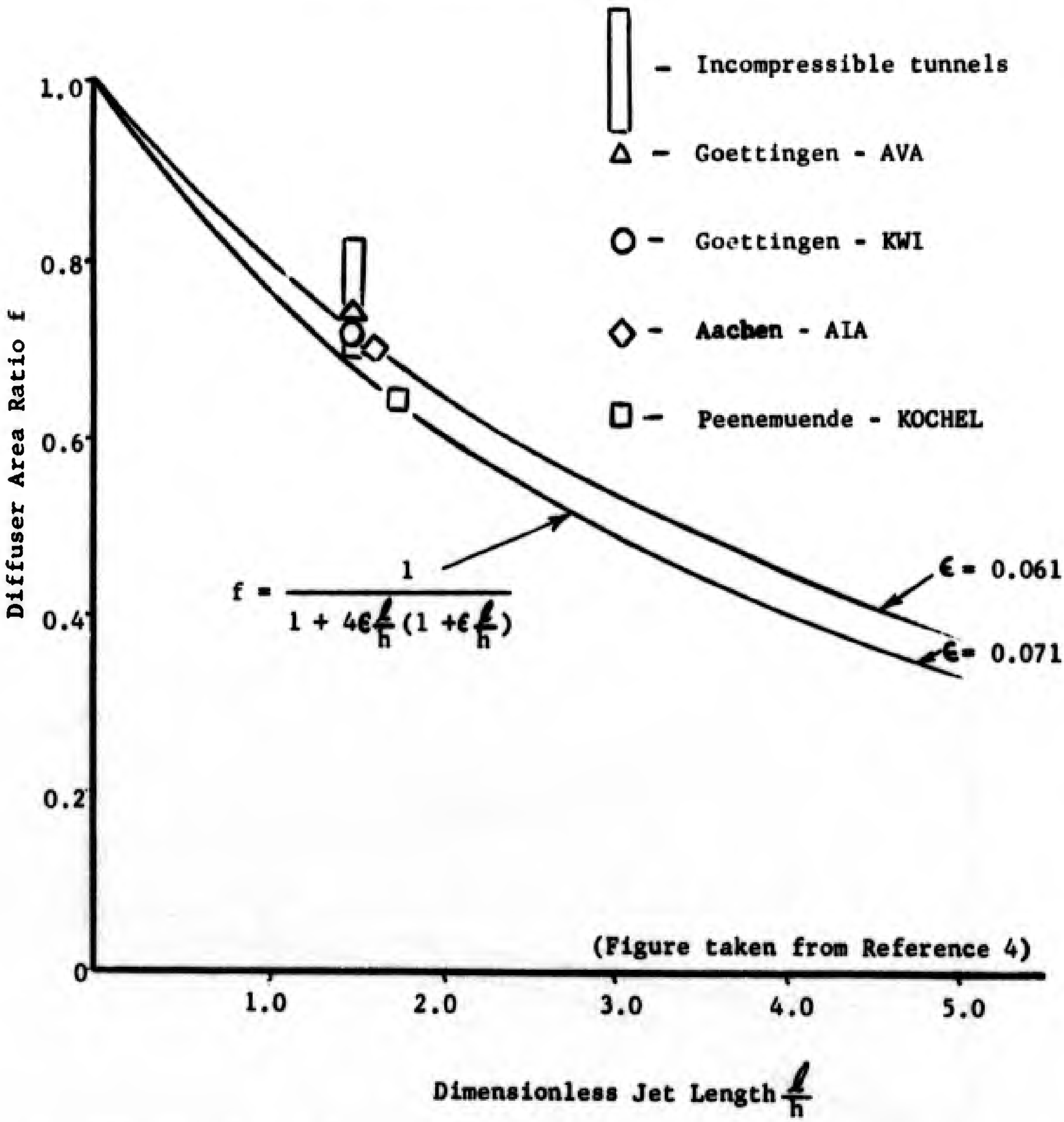


Figure 4. Diffuser Area Ratio

Diffuser total pressure recovery when throat is choked (normalized by diffuser contraction ratio)

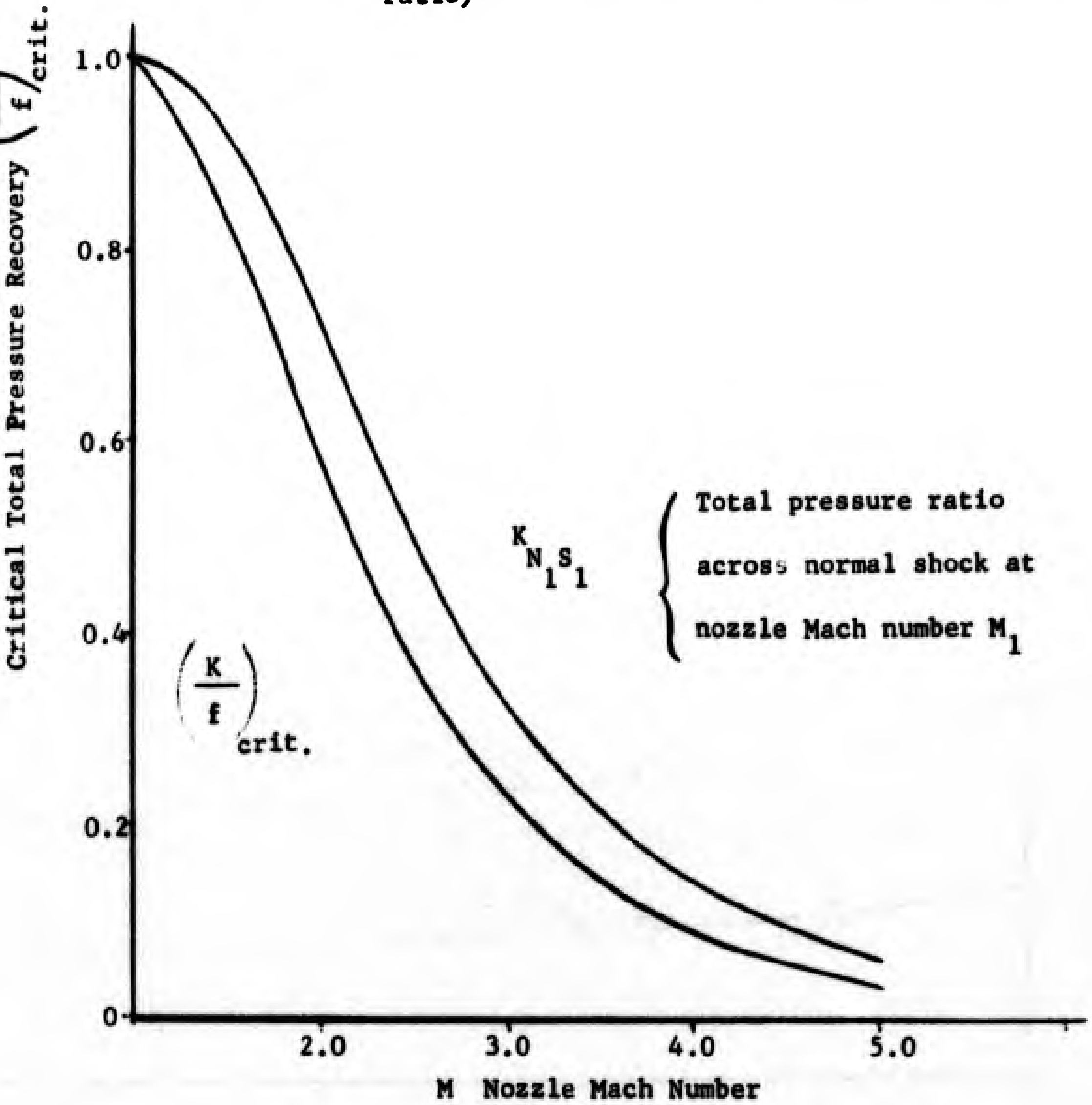


Figure 5. Total Pressure Recovery

Diffuser normal shock efficiency at choked conditions

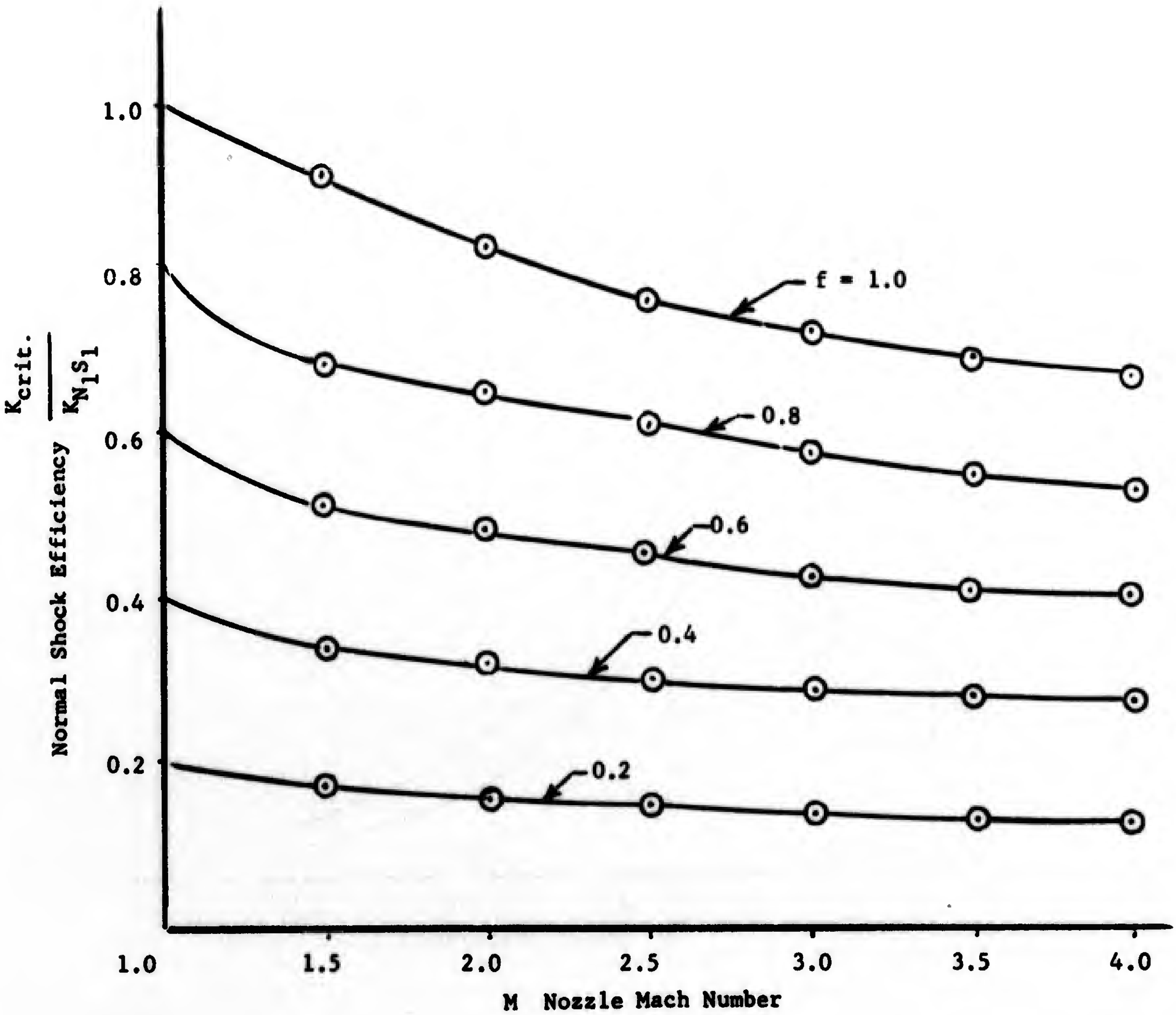
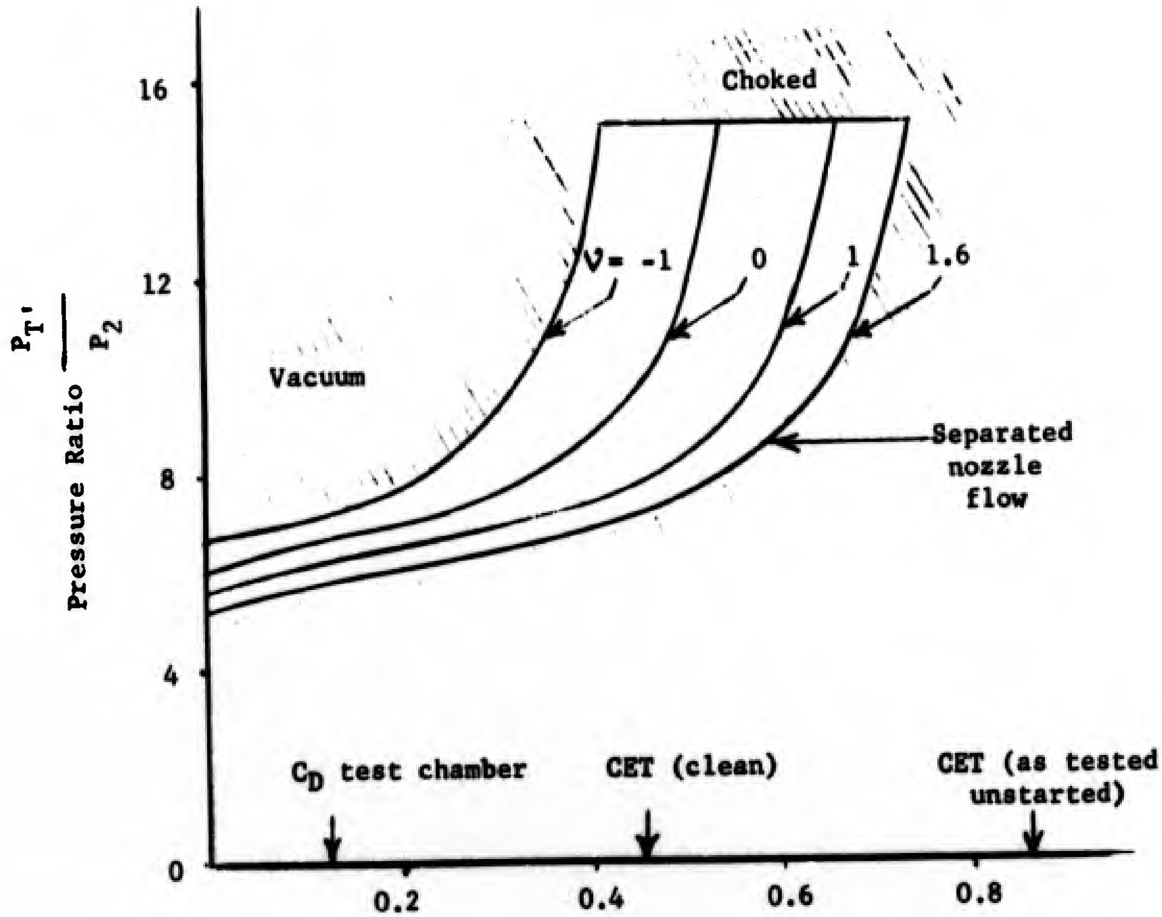


Figure 6. Normal Shock Efficiency

Marquardt Jet Laboratory free jet

facility operating pressure ratio



$$C_{D_{tot}} = \frac{DRAG}{\frac{\gamma}{2} P_1 M_1^2 F_1}$$

(Total Drag Coefficient Based on Nozzle Exit Area)

Figure 7. Marquardt Jet Lab Operating Map