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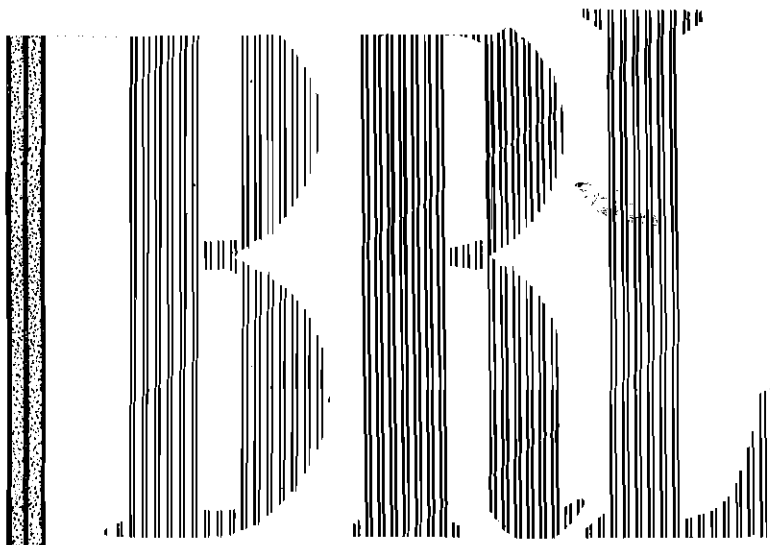

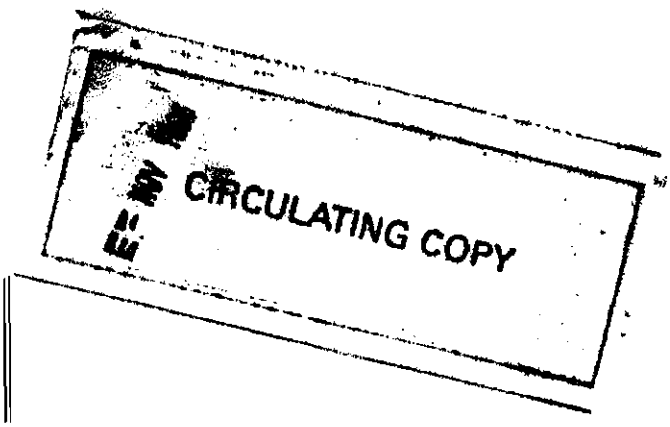

REPORT NO. 729
JULY 1950

TABLES OF SUPERSONIC FLOWS ABOUT CONE CYLINDERS

PART I Surface Data

TECHNICAL REPORTS SECTION
STINFO BRANCH
BLDG. 305

R. F. Clippinger
J. H. Giese
W. C. Carter

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

B A L L I S T I C R E S E A R C H L A B O R A T O R I E S

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Project No. TB3-0108H of the Research and Development Division, Ordnance Department

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A B E R D E E N P R O V I N G G R O U N D, M A R Y L A N D

CONTENTS

	Page
Abstract	3
Introduction	5
Fundamental Equations	7
Description of Calculations	12
Discussion of Results	17
Bibliography	20
Index of Symbols	21
Table I: Extent of Flow Field	23
Table II: p/p_{1_0} ρ/ρ_{1_0} T/T_{1_0} M on Cone Cylinder	25
Table III: Taylor-Maccoll Flow Data (q_{c_0} θ_{w_0} p_0/p_{1_0} ρ_0/ρ_1)	59
Table IV: Free Stream Data	61
Figs. 5 to 14: Characteristic Nets in Physical and Hodograph Planes	68-72
Figs. 15 to 18: Accuracy of Computation	73-76
Figs. 19, 20: Accuracy of Interpolation	77-78
Figs. 21 : Comparison with Lighthill's Method	79
Figs. 22-28: Experimental Checks	80-86
Figs. 29 to 38: Pressure Ratios	87-96

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Clippinger/Giese/Carter/mem
Aberdeen Proving Ground, Md.
July 1950

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PART I: SURFACE DATA

ABSTRACT

A family of inviscid steady axisymmetric supersonic flows about cone cylinders has been calculated by the method of characteristics on the ENIAC. The cones have semi-vertex angles of the form $5k^0$ $(1 \leq k \leq 10)$, while the Mach numbers, contained in the set $1.3, 1.5, 1.7, 2, 3, 4, 5, 7$, are such that the shock wave is attached to and conical near the vertex. Pressure, density, temperature, and local Mach number distributions on the cylinder have been tabulated, and the pressure data have also been presented graphically. The ENIAC results have been compared with computations from other sources and with experimental data.

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INTRODUCTION

It is extremely tedious to construct solutions of the non-linearized equations for compressible inviscid flows about a given object. In the case of supersonic flow, the shape that has been treated with the most conspicuous success is the right circular cone. Axisymmetric flows about cones can be calculated by standard numerical procedures without too much labor because the equations degenerate into a system of ordinary differential equations. More general steady axisymmetric supersonic flows must be calculated by the method of characteristics. The vast amounts of time and labor required by this method tend to discourage manual computations. Consequently such calculations have been performed only for a scattered set of cases. In recent years, however, the appearance of high speed computing machines has completely altered this situation. It is now possible to undertake computations for which considerations of computing time and labor were formerly prohibitive.* In particular, the development and construction of the ENIAC for the Ballistic Research Laboratories spurred the senior author of this report to make an effort to calculate steady axisymmetric supersonic flows on this machine.

At present no accurate and efficient procedure is known for calculating axisymmetric supersonic flows about pointed bodies with attached shockwaves that are doubly curved all the way down to the point of attachment. However, it is possible to determine precisely the conical shock wave in the flow over a right circular cone. This suggests restricting calculations to bodies of revolution with conical tips. The simplest body of this type is a cone cylinder. It seemed desirable to compute a family of flows about this class of objects for the following reasons. Firstly, the results would supplement the Taylor-Maccoll flow data recorded in [12].** Secondly, since these flows contain readily computed shocks and expansion fans, cone cylinders are ideal models for fundamental investigations in wind tunnels and free flight. Thirdly, the results provide a basis for estimating the sizes of numbers to be encountered in the course of calculations of flows about bodies of revolution with curved profiles. The significance of the last remark is brought out at the end of Section 3.

All computations were confined to the domain of determination by the conical (Taylor-Maccoll) part of the shock wave (cf. Fig. 1 infra), and by the body where the flows are irrotational***. All computations were

---

* In this connection it should be remarked that under ideal conditions, neglecting the calculation of Taylor-Maccoll and Prandtl-Meyer input data and the extrapolation to zero grid size, the time required to calculate a single case (one M_1, one θ_s) on the ENIAC twice at two grid sizes was of the order of forty minutes. Naturally this average was not maintained during the entire calculation. The same case would require about six weeks to be completed by manual calculation by one person, with fewer significant figures and more errors.

** Numbers in brackets designate references listed in the bibliography.

*** For $\theta_s = 5^0$ and the lower values of M_1 the computations covered only a part of this region.

performed on two characteristic grids, one twice as fine as the other. At the common points the results were extrapolated to zero grid size, assuming that the computed approximations to any function at finite grid size, $1/h$, varied as even quadratic polynomials in $1/h$. The computational procedures and their accuracy are discussed briefly in Sections 2, 3, 4. They are treated at length in [5]. Table I shows the scope of the calculations. $\gamma = 1.4$ throughout. M_1 denotes free stream Mach number, and θ_s the semi-vertex angle of the cone. The entries in the table are the downstream extents of the calculated region of flow in calibers, measured along the surface of the cylinder from the vertex of the cone. Other flow data are recorded in Tables II, III, and IV, and Figs. 5 to 14 and 29 to 38.

Most readers will be interested primarily in velocity, pressure, density, and temperature distributions on the surface of the cone cylinder. Accordingly these are the only data presented here. For those who wish flow data for use as the basis of perturbation calculations, etc., there has been prepared a companion set of tables of x, y, u, v at points of a characteristic net. The title of Part II is Tables of Supersonic Flows about Cone Cylinders, BRL Report No. 730.

In the near future it is planned to calculate flows with rotation about bodies of revolution (with conical tips) with profiles composed of several circular arcs, and with various boattail configurations. At the same time the cone cylinder calculations for the larger values of θ_s will be continued to greater distances downstream.

The following historical note may be of interest to others planning similar computations. Even at the present time these cone cylinder calculations are among the most complex that have been performed on the ENIAC. When the first steps toward coding the computation were taken in mid 1946, no simple, universal coding procedure had been developed for the ENIAC. Notwithstanding the cumbersome coding procedure then in use, in the course of about nine months the programming was completed. Soon thereafter Prof. J. von Neumann proposed basic improvements in ENIAC operation. His ideas were exploited by many persons associated with the ENIAC, including the senior author, and gradually evolved into the coding and operating procedure now in use, described in [1, 3, 4]. For comparison, it should be remarked that with the new, logical coding procedure it should have required not more than three months to program the calculation of flows about cone cylinders. The contrast becomes clearer when it is pointed out that most of the nine months' period was devoted merely to forcing the computing routine onto the ENIAC. Most of the three months' time would now be spent on the subtler problem of estimating the sizes of numbers that will be encountered during the calculation.

A great many people have made valuable contributions at various stages of this computing project. Unfortunately, the number is so large that space will not permit the authors to make individual acknowledgements

to everyone who has assisted them. However, they particularly wish to express their gratitude to A. Galbraith, B. Bartig, B. Snyder, K. Mauchly, A. Gehring, H. McAllister, and H. Spence.

Wind Tunnel data for cone cylinders were obtained from Dr. L. L. Cronvich and Mr. K. D. Bird of the Applied Physics Laboratory.

FUNDAMENTAL EQUATIONS

In the absence of viscosity, heat conduction, and body forces, the equations for steady axisymmetric flow can be written in the form

$$(2.1)\quad u\,\partial u/\partial x + v\,\partial u/\partial y = -\rho^{-1}\,\partial p/\partial x$$

$$u\,\partial v/\partial x + v\,\partial v/\partial y = -\rho^{-1}\,\partial p/\partial y$$

$$(2.2)\quad \partial(\rho y u)/\partial x + \partial(\rho y v)/\partial y = 0$$

Here x and y are rectangular coordinates in any plane through the axis of symmetry, taken to be the x-axis; u and v denote components of velocity parallel to the x- and y-axes, respectively; and p and ρ are the pressure and density, respectively. The flow is isentropic if

$$(2.3)\quad p/p_0 = (\rho/\rho_0)^{\gamma}$$

where p_0 and ρ_0 are certain constant reference values of the pressure and density, and γ, assumed constant, is the ratio of the specific heat at constant pressure to that at constant volume. The flow is irrotational if

$$(2.4)\quad \partial u/\partial y - \partial v/\partial x = 0$$

For isentropic, irrotational flow Euler's equations (2.1) imply Bernoulli's equation

$$\tfrac{1}{2}\,q^2 + \gamma p/\left[(\gamma-1)\rho\right] = \tfrac{1}{2}\,c^2$$

where

$$(2.5)\quad q^2 = u^2 + v^2$$

and c is a constant with the dimensions of velocity. Now make the following transformation to non-dimensional variables:

$$u^* = u/c,\quad v^* = v/c,\quad q^* = q/c,\quad p^* = p/(\rho_0 c^2),\quad \rho^* = \rho/\rho_0$$

$$x^* = x/\ell,\quad y^* = y/\ell,\quad c^* = 1$$

where ℓ is some convenient reference length. The transformed forms of (2.1) to (2.5) and of Bernoulli's equation can be obtained by replacing

all variables by the corresponding symbols with asterisks. For simplicity, hereafter we shall omit the asterisks in equations (2.1) to (2.5) and

$$(2.6) \qquad \tfrac{1}{2} q^2 + \gamma p/\left[(\gamma-1)\rho\right] = \tfrac{1}{2}$$

and assume that all variables are dimensionless. Let the reference pressure p_0 and density ρ_0 be the stagnation values corresponding to $q = 0$ in (2.6). Then by (2.3) and (2.6)

$$(2.7) \qquad \rho/\rho_0 = (1-q^2)^{1/(\gamma-1)}$$

$$(2.8) \qquad p/p_0 = (1-q^2)^{\gamma/(\gamma-1)}$$

If we eliminate ρ from the equation of continuity (2.2) by means of (2.7), we obtain

$$(2.9) \qquad H\,\partial u/\partial x + K\,(\partial u/\partial y + \partial v/\partial x) + L\,\partial v/\partial y + a^2 v/y = 0$$

where

$$(2.10) \qquad H = a^2 - u^2, \quad K = -uv, \quad L = a^2 - v^2$$

and where a is the velocity of sound defined by

$$a^2 = dp/d\rho = \gamma p/\rho$$

By Bernoulli's equation (2.6)

$$(2.11) \qquad a^2 = \tfrac{1}{2}(\gamma-1)(1-q^2)$$

It suffices to determine u and v as solutions of (2.4) and (2.9), since p/p_0 and ρ/ρ_0 can always be found from (2.7) and (2.8) after u and v are known. The selection of the solution of this system appropriate for the flow around a non-yawing cone cylinder is accomplished by imposing the following boundary and shock conditions. Along the surface of the cone (Fig. 1)

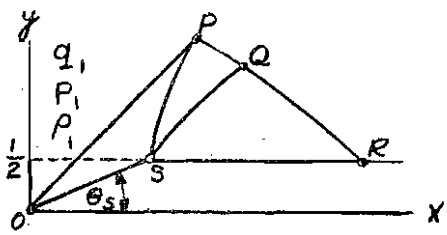

Fig. 1. Physical Plane

$$(2.12) \qquad v/u = \tan\theta_{sp}, \quad y/x = \tan\theta_{sp}, \quad 0 \leqq x \leqq \tfrac{1}{2}\cot\theta_{sp}, \quad 0 \leqq y \leqq \tfrac{1}{2}$$

where the vertex of the cone has been placed at the origin, θ_s is the semi-vertex angle, and the unit of distance in the x y-plane is the caliber of

the cylinder. On the cylinder

$$(2.13) \quad v = 0, \quad y = \frac{1}{2} x \geq \frac{1}{2} \cot \theta_s$$

It will be assumed that the velocity of the free stream, q_1, is great enough and θ_s small enough that there will be a shock wave attached to the vertex of the cone. Assuming that this is also axisymmetric about the x-axis it will suffice hereafter to consider only the curve in which the x y-plane cuts the shock wave. On this curve, the determination of which is part of the problem, the velocities, pressure, density and entropy on the front and rear of the shock wave satisfy the following conditions. The slope of the shock wave is

$$(2.14) \quad dy/dx = (q_1 - u)/v$$

where q_1 is the velocity of the undisturbed flow parallel to the x-axis ahead of the shock wave, and (u, v) is the velocity immediately after the shock. Furthermore, u, v, and q_1 satisfy the equation of the sheck polar

$$(2.15) \quad v^2 (b - u) = (q_1 - u)^2 (u - d), \quad \frac{\gamma-1}{\gamma+1} \frac{1}{q_1} \leq u \leq q_1$$

where

$$b = \frac{\gamma-1}{\gamma+1} \frac{1}{q_1} + \frac{2}{\gamma+1} q_1, \quad d = \frac{\gamma-1}{\gamma+1} \frac{1}{q_1}$$

The ratio of the density ρ behind the shock to that ρ_1 of the undisturbed stream is

$$(2.16) \quad \rho/\rho_1 = 1 + 2 q_1 (q_1 - u) / [(\gamma-1) (1 - q_1 u)]$$

while the corresponding pressure ratio is

$$(2.17) \quad p/p_1 = (\rho/\rho_1) (1 - q^2) / (1 - q_1^2)$$

The nature of the system (2.4) and (2.9) depends on the roots of the characteristic equation

$$(2.18) \quad H \lambda^2 - 2 K \lambda + L = 0$$

It is of hyperbolic, parabolic, or elliptic type accordingly as the discriminant

$$(2.19) \quad R^2 = K^2 - HL = q^2 (q^2 - a^2)$$

is positive, zero, or negative, i.e. as the flow is supersonic, sonic, or subsonic. The flows to be considered here are assumed to be supersonic throughout the fluid. Accordingly the system (2.4) and (2.9) will be hyperbolic everywhere, and (2.18) will have two real roots

$$(2.20) \quad \lambda_1 = (K + R)/H = L/(K - R), \quad \lambda_2 = (K - R)/H$$

The one parameter families of curves defined by $dy/dx = \lambda_1$ or $dy/dx = \lambda_2$ are the characteristic curves. If the first mentioned family is represented by $\beta(x, y) = \text{constant}$ and the second by $\alpha(x, y) = \text{constant}$, and if characteristic curvilinear coordinates (α, β) are introduced, then (2.4), (2.9) and (2.20) will be transformed into the canonical form

$$(2.21) \quad (K - R)\, y_\alpha - L x_\alpha = 0$$

$$(2.22) \quad H y_\beta - (K - R)\, x_\beta = 0$$

$$(2.23) \quad H u_\alpha + (K - R)\, v_\alpha + a^2 v\, x_\alpha / y = 0$$

$$(2.24) \quad (K - R)\, u_\beta + L\, v_\beta + a^2 v\, y_\beta / y = 0$$

The choice of parameters α, β involves considerable arbitrariness. From the preceding discussion it is clear that a transformation $\bar{\alpha} = \bar{\alpha}(\alpha)$, $\bar{\beta} = \bar{\beta}(\beta)$ will leave the form of (2.21) to (2.24) unaltered. This freedom can be used to prescribe the shape of the curve onto which the surface of the cone cylinder maps. However, before this map can be described it is necessary to discuss the general nature of the solution of the system (2.21) to (2.24).

The spirit of the discussion will be heuristic, but the references quoted contain rigorous formulations and proofs of the following propositions. The classical initial value problem for hyperbolic systems of first order partial differential equations is Cauchy's problem [6].

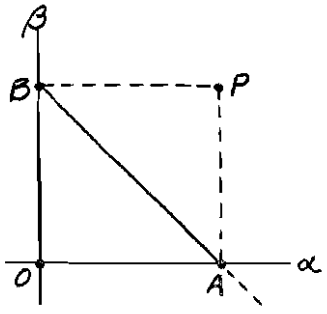

Fig. 2. Characteristic Plane

If the lines $\alpha = \text{const.}$, $\beta = \text{const.}$ are characteristics, and if initial values of x, y, u, v satisfying certain differentiability conditions known as strip conditions are given along the non-characteristic line segment AB, then a solution having the differentiability and continuity properties of the initial data is determined uniquely up to the characteristics BP, AP. The solution defined in APB is independent of the choice of initial values outside the segment AB. In particular, this implies that discontinuities in the derivatives of the initial data will be propagated along characteristics. Another standard initial value problem is the characteristic initial value problem [6]. If values of u, v, x, y consistent with (2.21) to (2.24) are given along the characteristics $0\,A$, $0\,B$, then a solution is uniquely determined in the rectangle OAPB. These considerations suggest that solutions of hyperbolic partial differential equations can be constructed by patching together solutions defined on various adjacent characteristic triangles and rectangles.

A mixed initial value and boundary value problem which occurs for the

present computations involves initial values for u, v, x, y given along the characteristic AP and boundary conditions, $f(x, y) = 0$, $g(u, v, x, y) = 0$ along the non-characteristic line segment AB. A unique continuous solution is determined in the triangle ABP [10].

Calculation of flows about cone cylinders involve the second and third types of problems discussed above. The flow about an infinite right circular cone of sufficiently small semi-apex angle moving at sufficiently high supersonic speed with attached shockwave has been constructed by Busemann and by Taylor and Maccoll [14]. For a finite cone, such as OS in Fig. 1, the region of Taylor-Maccoll flow will terminate at the characteristic SP emanating from the shoulder along which values for u, v, x, y can be computed.

Now consider the behavior of the velocity at the shoulder, S, of the cone-cylinder. At this point $x = y = \text{const.}$, but the velocity changes continuously from the direction OS to SR. The variation of velocity is that which occurs in the well known Prandtl-Meyer expansion around a corner. Thus from the corner S many characteristics of one family, say α = const., will emanate. Accordingly, S will be mapped onto a segment of a characteristic β = const. in the characteristic plane.

Now a procedure for solving the characteristic initial value problem may be applied, and the solution for the canonical system of equations determined in the expansion fan SRQ, where SQ is a segment of the last characteristic emanating from the shoulder, and RQ is a segment of a characteristic of the other family. In particular the values of u, v, x, y are then determined along SQ.

The boundary conditions along the surface of the cylinder are given by (2.13). If a procedure for solving the mixed initial and boundary value problem is applied, values for u, v, x, y may be found in the region SQR. Since Taylor-Maccoll flow is irrotational, the flow about the cone cylinder will be irrotational below the streamline that passes through P. Hence the flow in the whole region SRQR is irrotational.

Advantage was taken of the permissible arbitrariness in the choice of characteristic parameters α & β to standardize the maps of the region SRQR onto the characteristic plane. Such standardization greatly simplifies the routine of machine computing, of course. In particular SP (Fig. 1) was mapped onto $S_1'P'$ in Fig. (3); the shoulder S mapped onto the segment $S_1'S_2'$; and the cylinder SR mapped onto $S_2'R'$.

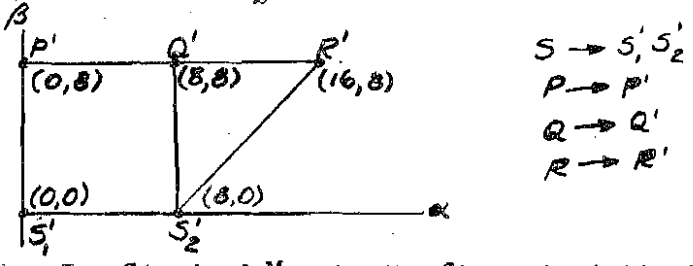

Fig. 3. Standard Map in the Characteristic Plane

DESCRIPTION OF CALCULATIONS

The essential features of our calculations of which a more extensive account is given in [5], will be summarized in this section. The functions x, y, u, v will be determined approximately by a step-by-step process at the lattice points (k, ℓ), where $k \geq 0$, $\ell \geq 0$ are integers, in the trapezoidal region $0 \leq \beta \leq \delta$, $0 \leq \alpha \leq \beta + \delta$ (Fig. 3) of the characteristic $\alpha\beta$-plane. In general, the computational procedure can be described as follows. Consider any lattice point (k, ℓ) for which the values of x, y, u, v are known at some of the adjacent lattice points. In the differential equations and boundary or initial conditions relevant to (k, ℓ) evaluate the coefficients at adjacent lattice points and approximate the derivatives by difference quotients based on values at (k, ℓ) and adjacent points. Observe that the fundamental partial differential equations for x, y, u, v are quasi-linear. If the boundary or initial conditions are not linear in finite form, they can be reformulated in a quasilinear differential form also. Accordingly all of the difference equations just constructed will be linear. Their solutions are first approximations to x, y, u, v at (k, ℓ). Higher order approximations can be obtained by setting up an iterative procedure that uses earlier approximations to improve the values of the coefficients used in the difference equations. An account of the individual computational procedures will now be presented.

Taylor-Maccoll Flow

The initial values x, y, u, v on $\alpha = 0$ are obtained from the downstream characteristic through $x = \frac{1}{2} \cot \Theta_s$, $y = \frac{1}{2}$ in a Taylor-Maccoll flow with free stream velocity q_{1s} about a cone of semi-vertex angle Θ_s with its vertex at the origin. In such a flow the velocity

$$u = u(t) \quad v = v(t)$$

is assigned to the line

$$(3.1) \quad x u'(t) + y v'(t) = 0$$

where accents denote differentiation with respect to the parameter t. Since u and v, and hence t will vary on $\alpha = 0$, introduce t as the parameter on this curve. Then by (2.22) and (2.24)

$$(3.2) \quad H y' - (K - R) x' = 0$$

$$(K - R) u' + L v' + a^2 v y'/y = 0$$

Now choose

$$(3.3) \quad t = v/u$$

eliminate v from (3.1) and (3.2) and solve for u', x', y' to obtain

$$u' = -uy/(x + yt)$$

$$(3.4)\quad x^{\bullet} = -H(y - Lx/K - R)\, u^{\bullet}/a^2\gamma$$

$$y^{\bullet} = -(K - R)\,(y - Lx/K - R)u^{\bullet}/a^2\gamma$$

For future reference it should be remarked that the stream function

$$(3.5)\quad z = (1 - q^2)^{1/\gamma - 1}\, y(yu - xv)$$

Boundary values for the system (3.4) are

$$(3.6)\quad x = 1/2 \cot \Theta_s,\ y = 1/2 \text{ when } t = \tan \Theta_s$$

$$q_1 = q_{1g} \text{ and } \phi\,(t) = 0 \text{ when } t = t_w$$

where $0 < t_w < \tan \Theta_s$ and

$$(3.7)\quad q_1\,(t) = u\,(t) + v\,(t)\, y\,(t)/x(t)$$

$$(3.8)\quad \phi(t) = (v + ux/y)\,(u - vx/y)\,(\gamma + 1)/(\gamma - 1)$$

$$- (x/y)\left[x^2/y^2 + 1 - (v + ux/y)^2\right]$$

In actual computation the boundary value problem is replaced by an initial value problem. To the conditions at $t = \tan \Theta_s$ we add $q = u \sec \Theta_s = q_c$ where q_c is an arbitrary constant. Then the final value $t = t_w$ is defined by $\phi(t_w) = 0$. If $q_1\,(t_w)$ fails to approximate q_{1g} to within some preassigned tolerance ϵ, the original initial value q_c is replaced by the new initial value

$$(3.9)\quad q_c + q_{1g} - q_1\,(t_w)$$

This process of modifying the initial value q_c and solving the initial value problem is repeated until $q_1\,(t_w)$ approximates q_{1g} to the prescribed precision.

The numerical solution of the system (3.4) was obtained by Heun integration. Schematically, the computational procedure is the following. Consider the differential equation,

$x^{\bullet} = f(x, t)$ with initial condition $x\,(t_o) = x_o$. Assume $x(t)$ is known. An approximation to $x(t + \Delta t)$ is desired. Let

$$x_1 = x(t_o) + f(x_o, t_o)\ \Delta t$$

and then define the desired approximation as

$$(3.10)\quad x\,(t_o + \Delta t) = x\,(t_o) + \left[\tfrac{1}{2} f(x_o, t_o) + \tfrac{1}{2} f(x_1, t_o + \Delta t)\right]\ \Delta t$$

When final values of q_s and t_w were determined Δt was chosen to be $(t_s - t_w)/n$ where $n > 0$ is an integer. In practice n was commonly chosen

to be 32, and only every fourth Taylor-Maccoll point computed by the ENIAC was recorded. In certain cases, where the cone angle was small and the shock weak, so the characteristic SP (Fig. 1) extends very far downstream, it was necessary to decrease the increment Δt by taking n to be as large as 256.

Prandtl-Meyer Flow

The initial values of x, y, u, v on $\beta = 0$ for the flow around the shoulder S are obtained from a Prandtl-Meyer type of calculation. Since equations (2.21) to (2.24) are valid near S it is reasonable to assume that they will still apply in the limit at S. But at S, x, y and β are constant, while u, v, and α vary. Hence (2.21) is trivial, but (2.23) implies

$$(3.11) \quad H\,du + (K - R)\,dv = 0$$

Since H, K, and R are known functions of u, v, (3.11) has a unique family of integral curves in the u, v plane, the Prandtl-Busemann epicycloids. These can be described explicitly in parametric form in terms of trigonometric functions. For machine computation, however, it is simpler to integrate the equations numerically than to attempt to use the tabulated functions required to construct the explicit solution. If we introduce

$$(3.12) \quad t = v/u$$

then (3.11) reduces to

$$(3.13) \quad du/dt = -u/\left[t + H/(K - R)\right]$$

where in H, K and R one must set $v = ut$. For $t = \tan \Theta_s$ the initial value of u is $u = q_c \cos \Theta_s = q_c/(1 + t^2)^{\frac{1}{2}}$, where q_c and Θ_s have been defined in the discussion of Taylor-Maccoll flow. The final value $t = 0$ corresponds to $v = 0$ along the cone. The known interval $0 \leqq t \leqq \tan \Theta_s$ can easily be divided into a set of equal intervals $\Delta t = \tan \Theta_s/n$ and then $u(t)$ can be determined by Heun integration. In practice n was commonly taken to be 32, but only every fourth Prandtl-Meyer point computed by the ENIAC was recorded.

General Process

The method chosen to solve (2.21) to (2.24) numerically is an iterated second order process [5]. Consider the rectangle from the coordinate lattice in the α, β plane, shown in Fig. 4.

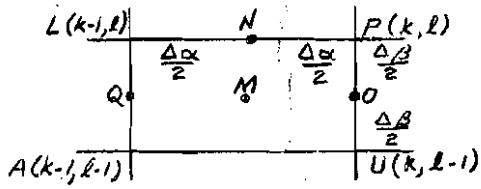

Fig. 4. Typical Configuration in the Characteristic Plane.

N, O are the midpoints of LP, PU, respectively and M is the centroid of the rectangle. Assume the values of x, y, u, v are known at the points L and U, so a characteristic initial value problem is to be solved. To a first order approximation, the values of x, y, u, v at M are the means of the respective values at L and U, while the partial derivatives may be replaced by the following difference quotients, $u_\alpha \sim [u(P)-u(L)]/2\Delta\alpha$, $u_\beta \sim [u(P) - u(U)]/2\Delta\beta$, etc. Since (2.21) to (2.24) are quasi-linear, they yield a set of 4 linear algebraic equations in 4 unknowns, independent of grid size. This set of equations may be solved for first approximations for x, y, u, v at P. Once approximations for x, y, u, v are known at P, the values of x, y, u, v may be evaluated at N and O and the partial derivatives may be replaced by the same difference quotients. However, evaluating the coefficients at N or O as necessary gives a second order approximation [5] to the differential equations, and the numerical values of x, y, u, v now found are called second order approximations to the values at P.

Contour Process

If the points A, P in Fig. 4 lie on the surface of the cylinder, and if the values of x, y, u, v are known at L and A, the following process can be used to obtain the values of the variables at P. Equations (2.21), (2.23) and the boundary conditions (2.13) $v = 0$, $y = 1/2$ must be satisfied. For a first approximation the values of the coefficients at M are approximated by the mean of the values at L and A, partial derivatives with respect to α are approximated as before, and first approximations for u, x are found at P. Then the coefficients are evaluated at N, and a second order approximation for u, x is found at P.

This iterated second order method was used because it is simple to program for a machine such as the ENIAC which has rather limited storage space. In addition, for fairly large grid sizes second order processes converge much more rapidly than first order processes. Clippinger and Gerber [5] have shown empirically that this particular method converges fairly rapidly and smoothly. As suggested by their work, these calculations were performed at two grid sizes, one using eight input points each from the Taylor-Maccoll and Prandtl-Meyer initial data, the second using double grid size or four points each from the Taylor-Maccoll and Prandtl-Meyer data. Then the assumption was made that the error made in a given calculation varies as the square of the grid size. If $f(1/4)$ denotes the value of any of the functions x, y, u, v, z computed in the coarser 1/4 x 1/4 lattice, while $f(1/8)$ denotes the value computed at the same point in the finer 1/8 x 1/8 grid, and $f(0)$ denotes the limiting value for zero grid size, this leads to the extrapolation formula

$$(3.14) \quad f(0) = f(1/8) + [f(1/8) - f(1/4)]/3$$

Such an extrapolation was performed at all lattice points $(2h, 2k)$, $h \geq 1$, $k \geq 1$. On the basis of Clippinger's and Gerber's empirical results u, v should have truncation errors of less than 3×10^{-5}, $x < 3 \times 10^{-4}$ and

$y < 2 \times 10^{-4}$. Since ten figures are carried throughout the calculations the round-off errors should be small in comparison to the truncation errors.

When the semi-apex angle of the cone was 5° and the free stream Mach number was close to one, only six or seven significant figures could be carried in the calculations because of the large range of size of x and y. The results for large α, β are thus affected by round-off error as well as truncation error. Even for these cases, however, the computations were also carried out to $\beta = 4$ or 6, with more significant figures and thus with negligible round-off error.

Pressure Distributions, etc.

Along the surface of the cylinder the local Mach number and the ratios of the local pressure, density and temperature to the free stream pressure, density and temperature respectively were calculated using equations derived from the Rankine-Hugoniot equations (2.) and the equation of state. In the following equations θ_w is the semi-apex angle of the conical shockwave, M_1 is the free stream Mach number, q_2 is the magnitude of the velocity immediately behind the shockwave and q is the magnitude of the velocity at the point on the surface of the body:

$$M = \left[5\, q^2 / (1-q^2)\right]^{\frac{1}{2}}$$

$$(3.15)\quad p/p_1 = \left[(7\, M_1^2 \sin^2 \theta_w - 1)/21(1-q_2^2)\right](1-q^2)^{7/2}$$

$$\rho/\rho_1 = \left[12\, M_1^2 \sin^2 \theta_w/(5\, M_1^2 \sin^2 \theta_w + 2)(1-q_2^2)\right](1-q^2)^{5/2}$$

$$T/T_1 = (p/p_1)/(\rho/\rho_1)$$

Comments on Machine Computation

The length of time required to code a complicated problem for computation by a high speed computing machine may very well considerably exceed that necessary to carry out the computation several times manually. To derive real benefit from use of the machine it is necessary to apply it to a repetitive computation with a great number of similar cases. For such mass production the utmost standardization is desirable. Not only is a standard computing routine necessary but it is even convenient to transform variables so that in all cases the domain of the independent variables is always the same, as we have done in our choice of characteristic map.

A consequence of following a set routine is the fact that the numbers at a given stage of the calculation are always handled in the same way in all cases considered. However, a machine is designed to deal with numbers containing only a fixed number of digits. To avoid losing the most significant digits, a number must not be held in the machine too far to the left, while to maintain a high level of accuracy it must not be shifted too far to the right. This means that pains must be taken to estimate the expected

ranges of sizes of numbers as precisely as possible.

In our cone cylinder calculations ranges of values were estimated when possible by straightforward manipulation of the expressions encountered or by reference to well known tabulations of Taylor-Maccoll and Prandtl-Meyer flows, [2, 12]. In other cases estimates had to be based on guesses, which were then modified as the computation progressed.

Another important aspect of machine calculation is the detection of errors. To test for errors produced by incorrect coding or by mis-set switches, the results obtained step-by-step by the ENIAC were compared with a hand-computed test run. A guard against intermittent errors in ENIAC operation is to perform all computations in duplicate, and to retain only the results obtained in those cases in which both sets of data agree. Errors that arise from improperly shifting or handling numbers may become evident in recorded functions, especially at the carry-over to the next higher power of ten. To test for these and other errors, the tabulated data (on characteristics β = const.) were first scanned visually to make sure that differences followed a reasonable trend, and then the characteristic curves were plotted in both the physical (xy) and hodograph (uv) planes to check for smoothness.

DISCUSSION OF RESULTS

The calculated family of flows about cone cylinders is characterized by the values of free stream Mach number M_1 and cone semi-vertex angle θ_s listed in Table I. Table II lists values of pressure, density, and temperature ratios, and local Mach numbers at points of the cylinder. Table III contains Taylor-Maccoll data, Table IV free stream data. Figs. 5 to 8 and 10 to 13 depict the characteristic nets in the physical (xy) and hodograph (uv) planes for a number of cases. Figs. 9 and 14 present selected density ratio data in graphical form. Figs. 29 to 38 summarize graphically the pressure ratio data for the entire family of flows.

Judgments of the accuracy of these calculations can be formed on the following bases. The present Taylor-Maccoll flow calculations for $\gamma = 1.4$ have been compared with those of Kopal [12] for $\gamma = 1.405$. Fig. 15 shows the speed q_c at the surface of the cone as a function of the free stream Mach number M_1 and the cone semi-angle θ_s for both sets of Taylor-Maccoll flows. In Fig. 16 the shockwave angle θ_w has been plotted in terms of the same variables. In general the agreement is very good, to within 0.5% in q_c and 1.5% in θ_w. The present Prandtl-Meyer flows have been checked as follows. It is well known that the hodographs of the flows around the shoulder of the cone cylinder are Prandtl-Busemann epicycloids. By suitable rotations about the origin all of these epicycloids can be brought into coincidence with the one which passes through $u = \left[(\gamma-1)/(\gamma+1)\right]^{\frac{1}{2}}$, $v = 0$ and lies below the u-axis. Now let ω_c be the direction of the velocity at the point of this standard epicycloid where $q = q_c$. Then for any cone cylinder make the rotation

$$u' = u \cos(\theta_c + \omega_c) + v \sin(\theta_c + \omega_c)$$

$$v' = -u \sin(\theta_c + \omega_c) + v \cos(\theta_c + \omega_c)$$

for $0 \leq \alpha \leq \gamma$, $\beta = 0$. By virtue of the definition of ω_c, (u', v') for $\alpha = \beta = 0$ will be on the standard epicycloid. Generally speaking, for any particular case the fit of (u', v') taken from $\beta = 0$ will deteriorate with increasing α. Accordingly, it should suffice to plot u', v' for $\alpha = 8$, $\beta = 0$ only. This has been done in Fig. 17, the solid curves being the standard epicycloid (obtained, e.g., from [2]). It is seen that values of u check to within 0.75% while the values of v are somewhat better.

The accuracy of the computations at points in the fluid away from the cone cylinder has been the subject of an empirical study reported in [5]. As indicated by the hodograph plots of Figs. 8, 12, and 13, the greatest variation of velocity occurs in the expansion fan SRQ of Fig. 1. This suggests that the computation of x, y, u, v, z at Q will be critical in an investigation of accuracy. Accordingly, for a 20° cone cylinder at M = 2.13 the flow in the expansion fan was computed, with not only the usual 1/4 x 1/4 and 1/8 x 1/8 grids, but also for 1/h x 1/h grids where h = 3, 4, 5, 6, 8, 10, 12, 15, 16, 24, 30, 32. As indicated in Fig. 18, this makes it possible to determine empirically the limiting values of x, y, u, v at Q for $h = \infty$. In this particular case the value of any function f (f = x, y, u, or v) at Q for grid size h was approximated in the form

$$f(1/h) = A(f) + B(f)\, h^{-2}$$

where the coefficients A(f) and B(f) were chosen, to fit the known values of f(1/h) for h = 4 and 8. From fits of the type observed in Fig. 18 it was concluded that by operating at the two fairly coarse grid sizes with h = 4, h = 8 and extrapolating to $h = \infty$ in the formula above, values f(0) are obtained which are comparable to those obtained with a grid seven times as fine as the larger (h = 28) and are accurate to three or four significant figures.

Table II presents results of flow calculations at the 1/8 x 1/8 grid and those extrapolated to zero grid. This information can be used in two ways. Firstly, the values of x, u, etc. at points (α, β) of the 1/8 x 1/8 grid not contained in the zero grid can be reduced approximately to zero grid by basing estimates of the required corrections on those observed at the common points of the two sets of data. As indicated by Fig. 18, these corrections will generally be on the order of a few tenths of a per cent, so the 1/8 x 1/8 data will probably be accurate enough for most purposes. Secondly, if the results for the 1/4 x 1/4 grid are desired, they can easily be obtained from

$$f(1/4) = 4f(1/8) - 3f(0)$$

In applying the information compiled in these tables of flows over cone cylinders it will often be necessary to interpolate between the tabulated θ_s and M_1. Some indication of the confidence with which this can be done is given by two special examples. Fig. 19 compares the "exact" pressure distribution computed by the ENIAC by the method of characteristics for $\theta_s = 15^\circ$, $M_1 = 2.3$ with that obtained by Lagrange's three point interpolation from the flows for $\theta_s = 15^\circ$, $M_1 = 1.7$, 2.0, and 3.0. Likewise, Fig. 20 compares the "exact" pressure distribution for $\theta_s = 12.5^\circ$, $M_1 = 1.7$ with the results of interpolation based on $M_1 = 1.7$, $\theta_s = 10^\circ$, 15° and 20°. In these cases the pressure distributions obtained by both methods agree to within 0.2%. Such close agreement is not unexpected. It is true that the interpolated value of x (α) may be inaccurate. Fortunately, the hodograph plots in Figs. 8, 12, and 13 show comparatively slight velocity variation outside the expansion fan. Accordingly, the superposition of errors in the interpolated value of x (α) and u (α) is not disastrous.

A double interpolation on θ_s and M_1 has been performed to make a very rough comparison with the results of Kai [11] for $\theta_s = 21^\circ$, $M_1 = 1.86$. In general, the values of p/p_1 on the cylinder check to within 2%.

Fig. 21 compares pressure distributions computed by the method of characteristics with some obtained with a method devised by Lighthill [13] for thin bodies. Near the expansion at the shoulder the agreement is good, and for $\theta_s = 5^\circ$ the two sets of results differ by only 2.5% at a point four calibers from the shoulder. For the thicker body with $\theta_s = 10^\circ$ the agreement deteriorates rapidly with increasing x.

Two types of experimental checks of the calculations have been made. The general nature of the flow field as a whole can be investigated with the aid of interferograms, such as that in Fig. 22. If there were actually a region of Taylor-Maccoll flow near the cone, then for measurements in this vicinity a plot of $\delta(x, y)/x$ vs. y/x should be a curve, where $\delta(x, y)$ is the fringe shift measured at x, y [9]. Fig. 23 tends to confirm this prediction. Furthermore, the data from traces 6 and 7, and also visual examination of the interferogram itself, Fig. 24, suggest that the region of approximate Taylor-Maccoll flow has the general shape indicated in Figs. 5, 6, 7, 10, and 11. A check on the nature of the rest of the flow field is given by Figs. 24 and 25. The former contains theoretical isopycnals, while the latter shows isopycnals calculated from fringe shifts measured on an interferogram of a cone cylinder with $\theta_s = 30^\circ$ in free flight at $M_1 \sim 2.7$. There seems to be fair qualitative agreement between the two families of curves. In particular this shows the presence of the expansion region, though, as one would expect, this has spilled around the shoulder somewhat.

Figs. 26 to 28 show comparisons of computed pressure distributions on a cone cylinder with $\theta_s = 10^\circ$ at $M_1 = 1.65$, 1.72, and 2.0 with Daingerfield wind tunnel results for the same body at small angles of attack not exceeding 0.3° [7]. In general, the agreement is quite satisfactory. On the other hand, pressure coefficients measured at Guidonia [8] at $M_1 = 2.06$ disagree violently with those calculated from ENIAC results for $M_1 = 2.00$.

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PARTIAL INDEX OF SYMBOLS

α, β characteristic variables

γ = c_p/c_v = 1.400

θ_s = semi-vertex angle of cone

θ_w = shock wave angle in Taylor-Maccoll flow

x = distance from vertex, parallel to axis of symmetry

y = distance normal to axis of symmetry, unit of length = caliber

u = x component of velocity

v = y component of velocity

q = $(u^2 + v^2)^{\frac{1}{2}}$ = speed of flow

q_c = speed at surface of cone

a = speed of sound

unit of speed = speed of efflux into vacuum

M = q/a = Mach number

p = P = static pressure

ρ = density

T = absolute temperature

Subscripts 0 denote stagnation values.

Subscripts 1 denote free stream values.

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TABLE I

EXTENT OF FLOW FIELD IN CALIBERS FROM VERTEX

θ_s \ M_1	1.3	1.5	1.7	1.72*	2.0	2.13*	2.3*	2.7*	3.0	3.8*	4.0	5.0	7.0
5°	19.7	19.0	**		18.05				18.3	8.0	85.6	66.5	36.7
*9°30'	87.9	86.4	71.7		52.5				24.6				
10°	68.9	67.9	57.6	55.1	43.2				21.4		14.8	12.1	8.3
*12°30'			24.6										
15°	4.9	4.2	6.7		11.8	11.1	10.4	9.0	8.3		6.9	6.3	5.9
20°		5.7	6.0		5.8	5.7			4.9		4.5	4.3	4.3
25°		2.7	3.4		3.6	3.6			3.2		3.3	3.3	3.3
30°			2.0		2.5	2.5	2.6		2.6		2.6	2.6	2.7
35°					1.6	1.8			2.0		2.1	2.2	2.2
40°									1.6		1.7	1.7	1.8
45°									1.1		1.3	1.4	1.5
50°											0.8	1.0	1.1

* Results for this θ_s or M_1 have not been included in this report.

** Results for this case will be distributed when the calculations have been completed.

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TABLE II

P/P_1, ρ/ρ_1, T/T_1, M on Cone Cylinder

$\theta_s = 5^\circ \quad M_1 = 1.3$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
5.71502	1.05260	1.03730	1.01470	1.26260	.49168
5.71502	.81371	.86307	.94280	1.44050	.54156
5.97261	.85713	.89573	.95690	1.40383	.53171
6.45490	.90858	.93381	.97297	1.36220	.52025
7.73636	.96092	.97193	.98867	1.32165	.50882
19.73157	.99043	.99315	.99725	1.29950	.50246

8 x 8 grid

5.71502	1.05260	1.03730	1.01470	1.26260	.49168
5.71502	.81371	.86307	.94280	1.44050	.54156
5.82715	.83459	.87884	.94964	1.42268	.53680
5.97256	.85738	.89591	.95698	1.40363	.53163
6.16981	.88229	.91443	.96485	1.38324	.52608
6.45473	.90899	.93412	.97310	1.36188	.52016
6.90605	.93640	.95415	.98140	1.34044	.51415
7.73538	.96202	.97272	.98899	1.32082	.50858
9.75142	.97788	.98415	.99362	1.30887	.50516
19.71782	.99246	.99461	.99784	1.29800	.50203

$\theta_s = 5^\circ \quad M_1 = 1.5$

zero grid

5.71502	1.06250	1.04420	1.01750	1.45790	.54617
5.71502	.82913	.87473	.94787	1.62735	.58843
6.04589	.87348	.90790	.96209	1.59225	.58004
6.66349	.92381	.94497	.97761	1.55474	.57074
8.25205	.97246	.98025	.99205	1.51910	.56194
19.05837	.99822	.99873	.99949	1.50109	.55633

8 x 8 grid

5.71502	1.06250	1.04420	1.01750	1.45790	.54617
5.71502	.82913	.87473	.94787	1.62735	.58843
5.85899	.85062	.89086	.95482	1.61015	.58434
6.04584	.87369	.90805	.96215	1.59209	.58000
6.29910	.89837	.92630	.96984	1.57322	.57541
6.66333	.92416	.94522	.97771	1.55396	.57067
7.23350	.94992	.96397	.98542	1.53519	.56600
8.25122	.97337	.98090	.99231	1.51846	.56178
10.53663	.99112	.99365	.99745	1.50602	.55862
19.04959	1.00017	1.00012	1.00005	1.49974	.55702

$\theta_s = 5^\circ \quad M_1 = 2.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
5.71502	1.11720	1.08240	1.03220	1.92860	.65313
5.71502	.82327	.87031	.94595	2.12468	.68882
6.34054	.88174	.91402	.96468	2.08075	.68122
7.74196	.94487	.96030	.98392	2.03643	.67333
10.82445	.98300	.98783	.99511	2.01102	.66870
18.05042	.99556	.99683	.99873	2.00286	.66719

8 x 8 grid

5.71502	1.11720	1.08240	1.03220	1.92860	.65313
5.71502	.82327	.87031	.94595	2.12468	.68882
5.97750	.85170	.89167	.95517	2.10295	.68509
6.34045	.88203	.91424	.96477	2.08054	.68118
6.87536	.91385	.93768	.97459	2.05783	.67717
7.74154	.94552	.96077	.98412	2.03599	.67325
9.36290	.97369	.98113	.99241	2.01714	.66982
10.82325	.98400	.98854	.99540	2.01037	.66858
13.27928	.99205	.99431	.99772	2.00513	.66761
18.05093	.99504	.99645	.99858	2.00320	.66725

2 2

$\theta_s = 5^\circ \quad M_1 = 3.0$

zero grid

5.71502	1.17770	1.12400	1.04780	2.89160	.79106
5.71502	.79667	.85012	.93711	3.15274	.81567
6.41653	.85017	.89053	.95468	3.10883	.81181
7.64007	.90721	.93281	.97256	3.06517	.80787
10.24553	.95985	.97115	.98836	3.02740	.80437
18.27849	.99070	.99334	.99733	3.00628	.80238

8 x 8 grid

5.71502	1.17770	1.12400	1.04780	2.89160	.79106
5.71502	.79667	.85012	.93711	3.15274	.81567
6.02347	.82302	.87012	.94587	3.13073	.81375
6.41642	.85043	.89072	.95476	3.10863	.81180
6.93297	.87886	.91189	.96377	3.08650	.80981
7.63991	.90759	.93308	.97267	3.06489	.80785
8.66122	.93543	.95344	.98111	3.04464	.80598
10.24450	.96057	.97167	.98857	3.02690	.80433
12.94779	.98062	.98612	.99442	3.01310	.80302
18.27714	.99021	.99299	.99719	3.00661	.80241

$\theta_s = 5^\circ \quad M_1 = 4.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
5.71502	1.27250	1.18780	1.07130	3.82020	.86284
5.71502	.77278	.83183	.92901	4.19578	.88250
7.05586	.85389	.89329	.95588	4.11936	.87886
10.03471	.94171	.95800	.98300	4.04510	.87518
20.06613	.98746	.99101	.99641	4.00943	.87336
85.52439	.99999	.99998	1.00001	3.99996	.87287

8 x 8 grid

5.71502	1.27250	1.18780	1.07130	3.82020	.86284
5.71502	.77278	.83183	.92901	4.19578	.88250
6.27629	.81278	.86236	.94250	4.15705	.88067
7.05545	.85446	.89372	.95606	4.11885	.87884
8.20365	.89683	.92515	.96937	4.08207	.87703
10.03509	.93692	.95451	.98156	4.04899	.87538
13.29302	.96334	.97366	.98939	4.02803	.87431
20.05855	.98773	.99121	.99649	4.00923	.87334
38.06433	.99906	.99932	.99974	4.00067	.87290
85.56063	1.00057	1.00039	1.00017	3.99954	.87284

$\theta_s = 5^\circ \quad M_1 = 5.0$

zero grid

5.71502	1.40270	1.27330	1.10160	4.71520	.90355
5.71502	.75451	.81768	.92275	5.24512	.91989
7.26621	.83921	.88223	.95123	5.15150	.91731
10.49788	.92905	.94872	.97928	5.06304	.91475
19.68239	.98120	.98645	.99468	5.01601	.91335
66.49753	.99878	.99904	.99974	5.00078	.91289

8 x 8 grid

5.71502	1.40270	1.27330	1.10160	4.71520	.90355
5.71502	.75451	.81768	.92275	5.24512	.91989
6.37186	.79655	.84996	.93715	5.19727	.91858
7.26572	.83989	.88274	.95145	5.15079	.91729
8.54558	.88370	.91539	.96537	5.10646	.91602
10.49771	.92530	.94597	.97814	5.06657	.91486
13.72939	.95471	.96735	.98693	5.03956	.91406
19.67516	.98171	.98681	.99482	5.01557	.91334
32.38353	.99633	.99729	.99903	5.00288	.91295
66.47418	.99965	.99966	.99998	5.00003	.91287

$\theta_s = 5^\circ \quad M_1 = 7.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
5.71502	1.70500	1.46220	1.16610	6.42760	.94448
5.71502	.73027	.79802	.91511	7.34908	.95669
7.48123	.81301	.86160	.94360	7.22682	.95531
10.68789	.89942	.92606	.97123	7.11329	.95397
17.62780	.95952	.96984	.98935	7.04138	.95309
36.75874	.98518	.99374	.99141	7.00995	.95270

8 x 8 grid

5.71502	1.70500	1.46220	1.16610	6.42760	.94448
5.71502	.73027	.79802	.91511	7.34908	.95669
6.48350	.77181	.83018	.92969	7.28585	.95599
7.48059	.81385	.86224	.94388	7.22565	.95530
8.81889	.85626	.89409	.95768	7.16839	.95463
10.68727	.89708	.92434	.97051	7.11621	.95401
13.41843	.92918	.94784	.98031	7.07703	.95353
17.62262	.96011	.97027	.98952	7.04071	.95308
24.52044	.98215	.98613	.99595	7.01560	.95277
36.74370	.98611	.99112	.99797	7.00781	.95267

$\theta_s = 10^\circ \quad M_1 = 1.3$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
2.83564	1.16410	1.11470	1.04430	1.18600	.46857
2.83564	.70775	.78122	.90596	1.54449	.56832
3.09772	.77932	.83686	.93124	1.47816	.55145
3.62615	.87298	.90753	.96193	1.39847	.53025
5.39645	.97092	.97915	.99161	1.32194	.50891
68.85244	1.00112	1.00080	1.00032	1.29953	.50247

8 x 8 grid

2.83564	1.16410	1.11470	1.04430	1.18600	.46857
2.83564	.70775	.78122	.90596	1.54449	.56832
2.94850	.74173	.80783	.91818	1.51233	.56023
3.09759	.78019	.83753	.93153	1.47739	.55125
3.30658	.82445	.87120	.94634	1.43886	.54112
3.62560	.87444	.90861	.96239	1.39728	.52992
4.18087	.92746	.94763	.97871	1.35516	.51829
5.39274	.97470	.98186	.99270	1.31913	.50810
9.60077	1.00128	1.00091	1.00036	1.29941	.50244
68.86340	1.00179	1.00128	1.00051	1.29904	.50233

$\theta_s = 10^\circ \quad M_1 = 1.5$

zero grid

2.83564	1.19430	1.13520	1.05210	1.37540	.52391
2.83564	.72599	.79554	.91257	1.71604	.60881
3.19572	.80408	.85577	.93960	1.64810	.59330
3.95022	.89775	.92584	.96965	1.57388	.57558
6.56989	.97988	.98559	.99421	1.51406	.56067
67.88333	1.00048	1.00034	1.00014	1.49973	.55701

8 x 8 grid

2.83564	1.19430	1.13520	1.05210	1.37540	.52391
2.83564	.72599	.79554	.91257	1.71604	.60881
2.98929	.76346	.82466	.92578	1.68267	.60128
3.19556	.80482	.85633	.93984	1.64749	.59316
3.49020	.85049	.89077	.95478	1.61044	.58441
3.94960	.89906	.92681	.97005	1.57289	.57533
4.76626	.94620	.96126	.98432	1.53807	.56672
6.56589	.98315	.98793	.99515	1.51178	.56009
12.50655	1.00076	1.00054	1.00022	1.49953	.55696
67.87691	1.00089	1.00063	1.00025	1.49945	.55694

$\theta_s = 10^\circ \quad M_1 = 1.7$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
2.83564	1.23030	1.15950	1.06110	1.56090	.57239
2.83564	.73195	.80020	.91470	1.90413	.64833
3.27870	.81349	.86291	.94273	1.83556	.63449
4.22001	.9[illegible]683	.93253	.97245	1.76452	.61947
7.44481	.98228	.98731	.99491	1.71183	.60787
57.57253	.99963	.99973	.99990	1.70023	.60527

8 x 8 grid

2.83564	1.23030	1.15950	1.06110	1.56090	.57239
2.83564	.73195	.80020	.91470	1.90413	.64833
3.02388	.77136	.83075	.92851	1.87014	.64155
3.27850	.81421	.86345	.94297	1.83499	.63437
3.64488	.86046	.89821	.95797	1.79893	.62683
4.21933	.90812	.93347	.97284	1.76359	.61927
5.23949	.95244	.96579	.98617	1.73222	.61241
7.44070	.98530	.98948	.99578	1.70980	.60742
14.12141	1.00020	1.00014	1.00006	1.69986	.60518
57.55589	1.00048	1.00034	1.00014	1.69968	.60514

$\theta_s = 10^\circ \quad M_1 = 2.0$

zero grid

2.83564	1.29190	1.20070	1.07600	1.83430	.63424
2.83564	.73249	.80061	.91491	2.19932	.70122
3.38331	.81726	.86575	.94399	2.12931	.68960
4.54145	.91046	.93518	.97357	2.06017	.67758
8.27049	.98209	.98716	.99486	2.01157	.66880
43.20236	1.00028	1.00018	1.00009	1.99978	.66662

8 x 8 grid

2.83564	1.29190	1.20070	1.07600	1.83430	.63424
2.83564	.73249	.80061	.91491	2.19932	.70122
3.06807	.77379	.83260	.92936	2.16426	.69547
3.38308	.81801	.86631	.94423	2.12873	.68951
3.83597	.86478	.90141	.95935	2.09315	.68339
4.54067	.91177	.93613	.97397	2.05925	.67742
5.76520	.95417	.96703	.98670	2.03010	.67218
8.26645	.98487	.98915	.99567	2.00976	.66846
14.88464	.99317	.99510	.99806	2.00437	.66747
43.18983	1.00127	1.00089	1.00038	1.99914	.66650

$\theta_s = 10^\circ \quad M_1 = 3.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
2.83564	1.55080	1.36750	1.13400	2.71030	.77136
2.83564	.71943	.79008	.91056	3.22102	.82146
3.59951	.80565	.85662	.94049	3.14415	.81492
5.05757	.89560	.92390	.96937	3.07282	.80857
8.60364	.97448	.98132	.99304	3.01628	.80333
21.38745	.99572	.99654	.99917	3.00192	.80196

8 x 8 grid

2.83564	1.55080	1.36750	1.13400	2.71030	.77136
2.83564	.71943	.79008	.91056	3.22102	.82146
3.16539	.76216	.82333	.92570	3.18176	.81816
3.59919	.80652	.85728	.94078	3.14342	.81486
4.19490	.85213	.89163	.95569	3.10629	.81159
5.05666	.89694	.92488	.96978	3.07182	.80848
6.38534	.93765	.95467	.98216	3.04207	.80574
8.60370	.96984	.97797	.99168	3.01949	.80363
12.70590	.98463	.98860	.99598	3.00939	.80267
21.37743	.99652	.99712	.99940	3.00138	.80191

$\theta_s = 10^\circ \quad M_1 = 4.0$

zero grid

2.83564	1.88900	1.57110	1.20230	3.53060	.84482
2.83564	.70846	.77977	.90854	4.25602	.88525
3.69253	.78891	.84204	.93690	4.17303	.88143
5.15164	.87131	.90397	.96387	4.09718	.87778
8. 2346	.94446	.95755	.98633	4.03619	.87473
14.84802	.98260	.98501	.99755	4.00642	.87320

8 x 8 grid

2.83564	1.88900	1.57110	1.20230	3.53060	.84482
2.83564	.70846	.77977	.90854	4.25602	.88525
3.21404	.74881	.81125	.92304	4.21316	.88330
3.69217	.78986	.84277	.93722	4.17211	.88139
4.31420	.83158	.87432	.95110	4.13273	.87951
5.15077	.87264	.90495	.96429	4.09603	.87772
6.31909	.91111	.93327	.97625	4.06333	.87610
8.02183	.94445	.95754	.98633	4.03620	.87473
10.62685	.97010	.97604	.99391	4.01604	.87370
14.84313	.98329	.98550	.99775	4.00589	.87317

$\theta_s = 10^\circ \quad M_1 = 5.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
2.83564	2.30800	1.80210	1.28070	4.29230	.88687
2.83564	.70232	.77037	.91167	5.28264	.92089
3.73538	.77509	.82657	.93771	5.19541	.91853
5.13781	.84876	.88196	.96236	5.11596	.91629
7.54086	.91691	.93198	.98383	5.04903	.91434
12.13727	.96097	.96375	.99711	5.00865	.91313

8 x 8 grid

2.83564	2.30800	1.80210	1.28070	4.29230	.88687
2.83564	.70232	.77037	.91167	5.28264	.92089
3.24060	.73914	.79900	.92507	5.23731	.91968
3.73503	.77608	.82733	.93805	5.19429	.91850
4.35130	.81336	.85552	.95071	5.15313	.91735
5.13703	.85007	.88293	.96278	5.11462	.91626
6.16334	.88515	.90881	.97397	5.07951	.91524
7.53951	.91703	.93207	.98386	5.04892	.91434
94.36896	.94427	.95176	.99213	5.02371	.91358
12.13374	.96165	.96424	.99731	5.00804	.91311

$\theta_s = 10^\circ \quad M_1 = 7.0$

zero grid

2.83564	3.39660	2.30940	1.47080	5.63170	.92942
2.83564	.69992	.74732	.93656	7.25651	.95565
3.77904	.75844	.79144	.95830	7.16584	.95460
5.09315	.81640	.83419	.97868	7.08349	.95361
7.01940	.87035	.87320	.99674	7.01258	.95273
9.99535	.91654	.90605	1.01157	6.95570	.95201

8 x 8 grid

2.83564	3.39660	2.30940	1.47080	5.63170	.92942
2.83564	.69992	.74732	.93656	7.25651	.95565
3.27119	.72985	.77001	.94784	7.20911	.95511
3.77881	.75926	.79205	.95859	7.16463	.95458
4.37758	.78850	.81372	.96900	7.12228	.95408
5.09265	.81748	.83497	.97904	7.08204	.95359
5.95782	.84539	.85523	.98848	7.04477	.95313
7.01831	.87175	.87420	.99719	7.01081	.95271
8.33535	.89608	.89156	1.00507	6.98049	.95233
9.99341	.91749	.90672	1.01187	6.95457	.95200

$\theta_s = 15^\circ \quad M_1 = 1.3$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.86602	1.32380	1.22180	1.08350	1.08390	.43620
1.86602	.61437	.70610	.86999	1.63988	.59138
2.05464	.68245	.76114	.89653	1.56898	.57438
2.40196	.78142	.83845	.93196	1.47597	.55088
3.35881	.91854	.94109	.97604	1.36177	.52014

8 x 8 grid

1.86602	1.32380	1.22180	1.08350	1.08390	.43620
1.86602	.61437	.70610	.86999	1.63988	.59138
1.94898	.64711	.73277	.88308	1.60498	.58311
2.05452	.68437	.76267	.89724	1.56709	.57391
2.19628	.72940	.79818	.91382	1.52357	.56308
2.40148	.78424	.84060	.93290	1.47349	.55024
2.73128	.85015	.89048	.95465	1.41694	.53526
3.35640	.92332	.94458	.97747	1.35807	.51910

$\theta_s = 15^\circ \quad M_1 = 1.5$

zero grid

1.86602	1.37740	1.25690	1.09590	1.27110	.49419
1.86602	.65019	.73523	.88421	1.78835	.62458
2.14942	.73252	.80058	.91498	1.70986	.60743
2.68430	.83745	.88092	.95063	1.62057	.58683
4.15206	.94932	.96346	.98526	1.53553	.56609

8 x 8 grid

1.86602	1.37740	1.25690	1.09590	1.27110	.49419
1.86602	.65019	.73523	.88421	1.78835	.62458
1.98962	.68979	.76695	.89927	1.74953	.61621
2.14918	.73381	.80160	.91541	1.70870	.60717
2.36633	.78377	.84020	.93275	1.66494	.59721
2.68355	.83942	.88240	.95126	1.61901	.58645
3.19512	.89831	.92619	.96988	1.57320	.57541
4.14909	.95306	.96617	.98636	1.53286	.56541

$\theta_s = 15^\circ \quad M_1 = 1.7$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.86602	1.44630	1.30130	1.11140	1.44890	.54379
1.86602	.66586	.74778	.89044	1.96486	.66008
2.01768	.70654	.78014	.90566	1.92660	.65273
2.21407	.75173	.81546	.92185	1.88649	.64483
2.48160	.80140	.85359	.93885	1.84494	.63642
2.87053	.85444	.89358	.95620	1.80314	.62772
3.48739	.90762	.93295	.97284	1.76358	.61926
4.59124	.95409	.96683	.98682	1.73070	.61207
6.94068	.98478	.98895	.99579	1.70977	.60741
13.45909	.99713	.99779	.99934	1.70152	.60555

16 x 16 grid

1.86602	1.44630	1.30130	1.11140	1.44890	.54379
1.86602	.66586	.74778	.89044	1.96486	.66008
1.93734	.68590	.76378	.89802	1.94575	.65643
2.01765	.70680	.78034	.90575	1.92637	.65269
2.10898	.72884	.79765	.91374	1.90652	.64880
2.21402	.75203	.81569	.92195	1.88623	.64478
2.33656	.77637	.83446	.93038	1.86557	.64062
2.48151	.80176	.85387	.93897	1.84465	.63636
2.65603	.82803	.87376	.94766	1.82364	.63202
2.87036	.85490	.89392	.95635	1.80279	.62765
3.13960	.88187	.91397	.96487	1.78247	.62333
3.48706	.90822	.93340	.97302	1.76314	.61917
3.94996	.93297	.95149	.98053	1.74546	.61532
4.59057	.95492	.96743	.98706	1.73013	.61194
5.51834	.97284	.98036	.99232	1.71785	.60922
6.93920	.98586	.98972	.99610	1.70905	.60725
9.27131	.99396	.99552	.99843	1.70363	.60603
13.45605	.99810	.99848	.99961	1.70088	.60541

$\theta_s = 15^\circ \quad M_1 = 2.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.86602	1.56580	1.37690	1.13720	1.70710	.60681
1.86602	.67563	.75538	.89443	2.24994	.70929
2.28589	.76210	.82323	.92574	2.17299	.69692
3.05702	.86016	.89758	.95832	2.09557	.68381
4.89974	.95094	.96426	.98619	2.03126	.67239
11.81888	.99288	.99445	.99842	2.00355	.66732

8 x 8 grid

1.86602	1.56580	1.37690	1.13720	1.70710	.60681
1.86602	.67615	.75579	.08945	0.02249	.70928
2.04932	.72499	.79439	.09125	0.02205	.70219
2.28562	.76657	.82667	.09272	0.02169	.69637
2.60372	.81298	.86213	.09428	0.02132	.69008
3.05628	.85916	.89683	.09579	0.02096	.68401
3.74642	.90267	.92904	.09715	0.02065	.67846
4.89734	.93934	.95584	.09826	0.02039	.67390
7.05662	.98745	.99056	.09968	0.02007	.66805
11.81748	.99674	.99721	.09994	0.02001	.66694

$\theta_s = 15^\circ \quad M_1 = 3.0$

zero grid

1.86602	2.09140	1.68540	1.24090	2.50680	.74625
1.86602	.68304	.75783	.90130	3.24574	.82349
2.40502	.76050	.81827	.92940	3.17256	.81737
3.27328	.84232	.88023	.95686	3.10349	.81134
4.86425	.91869	.93652	.98085	3.04521	.80603
8.29501	.97046	.97393	.99639	3.00856	.80259

8 x 8 grid

1.86602	2.09140	1.68540	1.24090	2.50680	.74625
1.86602	.68304	.75783	3.49437	0.00000	.00032
2.10727	.72186	.78836	.91557	3.20801	.82037
2.40470	.76162	.81913	.92976	3.17157	.81729
2.78133	.80258	.85036	.94371	3.13611	.81422
3.27256	.84385	.88137	.95737	3.10228	.81123
3.93504	.88393	.91108	.97016	3.07108	.80841
4.86263	.92079	.93805	.98150	3.04370	.80589
6.21715	.95183	.96054	.99090	3.02152	.80382
8.29180	.97234	.97528	.99694	3.00729	.80247

$\theta_s = 15^\circ \quad M_1 = 4.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.86602	2.80090	2.04690	1.36840	3.21670	.82110
1.86602	.68613	.74945	.91551	4.23541	.88432
2.45091	.75221	.80032	.93978	4.16459	.88103
3.30423	.81989	.85111	.96321	4.09885	.87786
4.64552	.88410	.89821	.98427	4.04177	.87501
6.93610	.93821	.93715	1.00111	3.99711	.87272

8 x 8 grid

1.86602	2.80090	2.04690	1.36840	3.21670	.82110
1.86602	.68613	.74944	.91548	4.23541	.88432
2.13344	.71965	.77542	.92801	4.19860	.88263
2.45091	.75327	.80112	.94018	4.16353	.88098
2.83336	.78731	.82682	.95220	4.12973	.87936
3.30360	.82128	.85214	.96369	4.09758	.87780
3.89228	.85445	.87659	.97468	4.06756	.87631
4.64427	.88591	.89953	.98484	4.04024	.87493
5.62540	.91444	.92012	.99378	4.01638	.87371
6.93406	.93894	.93766	1.00132	3.99654	.87269

$\theta_s = 15^\circ \quad M_1 = 5.0$

zero grid

1.86602	3.69930	2.43060	1.52200	3.83550	.86391
1.86602	.69228	.73423	.94286	5.17860	.91807
2.47749	.74878	.77655	.96424	5.11005	.91612
3.31382	.80545	.81809	.98455	5.04685	.91428
4.51597	.85928	.85678	1.00291	4.99126	.91260
6.33556	.90613	.88989	1.01824	4.94595	.91120

8 x 8 grid

1.86602	3.69930	2.43060	1.52200	3.83550	.86391
1.86602	.69228	.73423	.94286	5.17860	.91807
2.14962	.72102	.75587	.95388	5.14298	.91707
2.47730	.74942	.77702	.96447	5.10930	.91610
2.86032	.77793	.79803	.97482	5.07690	.91516
3.31347	.80622	.81865	.98482	5.04603	.91425
3.85639	.83385	.83859	.99434	5.01703	.91338
4.51531	.86022	.85745	1.00323	4.99033	.91257
5.32535	.88496	.87499	1.01139	4.96609	.91183
6.33443	.90724	.89067	1.01860	4.94491	.91117

$\theta_B = 15^\circ \quad M_1 = 7.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.86602	6.07110	3.17170	1.91420	4.81770	.90706
1.86602	.71896	.69096	1.04051	6.84812	.95060
2.52015	.76096	.71956	1.05749	6.78686	.94977
3.35215	.80196	.74704	1.07345	6.73064	.94899
4.44161	.84069	.77263	1.08807	6.68044	.94828
5.91008	.87523	.79518	1.10066	6.63781	.94767

8 x 8 grid

1.86602	6.07110	3.17170	1.91420	4.81770	.90706
1.86602	.71895	.69095	1.04045	6.84812	.95060
2.17476	.74000	.70534	1.04913	6.81694	.95018
2.52014	.76113	.71967	1.05756	6.78663	.94977
2.90958	.78200	.73372	1.06580	6.75761	.94937
3.35208	.80234	.74730	1.07359	6.73015	.94899
3.85816	.82226	.76050	1.08113	6.70401	.94862
4.44140	.84130	.77304	1.08830	6.67969	.94827
5.11835	.85929	.78481	1.09478	6.65726	.94795
5.90949	.87612	.79576	1.10096	6.63676	.94765

$\theta_s = 20^\circ \quad M_1 = 1.5$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.37373	1.60900	1.40360	1.14630	1.15090	.45765
1.37373	.58285	.67959	.85757	1.85834	.63915
1.57594	.65857	.74155	.88801	1.77860	.62250
1.91858	.73875	.80496	.91759	1.70290	.60587
2.68469	.86830	.90344	.96105	1.59481	.58066
5.70450	.98208	.98651	.99547	1.51083	.55985

8 x 8 grid

1.37373	1.60900	1.40360	1.14630	1.15090	.45765
1.37373	.58285	.67959	.85757	1.85834	.63915
1.46419	.61800	.70862	.87211	1.82020	.63130
1.57593	.65688	.74018	.88735	1.78031	.62287
1.72071	.69257	.76870	.90087	1.74554	.61534
1.91840	.73859	.80484	.91757	1.70305	.60590
2.21016	.78993	.84442	.93543	1.65835	.59569
2.68342	.87075	.90526	.96182	1.59293	.58021
3.58078	.94264	.95804	.98388	1.53899	.56695
5.71781	.96802	.97639	.99140	1.52078	.56237

$\theta_s = 20^\circ \quad M_1 = 1.7$

zero grid

1.37373	1.71620	1.46890	1.16830	1.32420	.50955
1.37373	.61212	.70341	.87021	2.01659	.66972
1.63504	.69095	.76699	.90087	1.93860	.65506
2.07413	.78898	.84323	.93567	1.85267	.63800
3.01095	.90023	.92654	.97161	1.76649	.61989
6.03070	.97920	.98390	.99523	1.71106	.60770

8 x 8 grid

1.37373	1.71620	1.46890	1.16830	1.32420	.50955
1.37373	.61212	.70341	.87021	2.01659	.66972
1.49028	.65072	.73482	.88556	1.97727	.66242
1.63471	.69260	.76829	.90148	1.93707	.65476
1.82094	.73945	.80506	.91849	1.89476	.64647
2.07329	.79130	.84499	.93645	1.85077	.63761
2.43765	.84715	.88718	.95488	1.80632	.62839
3.00882	.90369	.92908	.97267	1.76398	.61935
4.00689	.95386	.96564	.98780	1.72840	.61156
6.02558	.98239	.98618	.99615	1.70892	.60722

$\theta_s = 20^\circ \quad M_1 = 2.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.37373	1.91250	1.58450	1.20700	1.56780	.57409
1.37373	.63462	.72061	.88064	2.28500	.71471
1.69104	.71361	.78359	.91067	2.21004	.70295
2.20907	.80584	.85466	.94282	2.13234	.69012
3.22489	.90235	.92658	.97382	2.05992	.67754
5.83548	.97808	.98149	.99647	2.00821	.66818

8 x 8 grid

1.37373	1.91250	1.58450	1.20700	1.56780	.57409
1.37373	.63462	.72061	.88064	2.28500	.71471
1.51581	.67378	.75210	.89575	2.24674	.70878
1.69071	.71512	.78478	.91121	2.20869	.70273
1.91331	.76014	.81976	.92722	2.16968	.69637
2.20829	.80786	.85619	.94348	2.13075	.68985
2.61843	.85713	.89318	.95960	2.09287	.68334
3.22304	.90524	.92870	.97469	2.05789	.67718
4.18013	.94764	.95957	.98752	2.02852	.67189
5.83230	.97886	.98204	.99670	2.00771	.66809

$\theta_s = 20^\circ \quad M_1 = 3.0$

zero grid

1.37373	2.79150	2.04240	1.36680	2.28990	.71547
1.37373	.66380	.73210	.90670	3.23136	.82231
1.77687	.73055	.78396	.93189	3.16616	.81683
2.36292	.80144	.83757	.95676	3.10358	.81135
3.29121	.87166	.88937	.98009	3.04717	.80621
4.91454	.93208	.93297	.99903	3.00239	.80201

8 x 8 grid

1.37373	2.79150	2.04240	1.36680	2.28990	.71547
1.37373	.66380	.73210	.90670	3.23136	.82231
1.55835	.69756	.75851	.91956	3.19755	.81949
1.77656	.73180	.78491	.93233	3.16502	.81673
2.03933	.76713	.81180	.94493	3.13312	.81396
2.36226	.80308	.83880	.95732	3.10222	.81122
2.76796	.83899	.86542	.96935	3.07281	.80857
3.28988	.87383	.89094	.98076	3.04553	.80606
3.97883	.90630	.91446	.99107	3.02113	.80378
4.91202	.93482	.93493	.99986	3.00045	.80182

$\theta_s = 20^\circ \quad M_1 = 4.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.37373	4.00770	2.54670	1.57370	2.88890	.79079
1.37373	.68329	.71977	.94919	4.13808	.87977
1.81391	.73787	.76038	.97038	4.07959	.87691
2.40654	.79374	.80107	.99070	4.02448	.87413
3.24611	.84811	.83989	1.00969	3.97479	.87155
4.50241	.89718	.87432	1.02615	3.93286	.86931

8 x 8 grid

1.37373	4.00770	2.54670	1.57370	2.88890	.79079
1.37373	.68329	.71977	.94919	4.13808	.87977
1.57874	.71106	.74054	.96011	4.10772	.87830
1.81365	.73881	.76107	.97073	4.07864	.87686
2.08606	.76690	.78163	.98115	4.05043	.87545
2.40599	.79499	.80198	.99117	4.02331	.87407
2.78647	.82278	.82190	1.00097	3.99751	.87274
3.24507	.84978	.84107	1.01026	3.97334	.87147
3.80528	.87549	.85918	1.018 7	3.95109	.87029
4.50062	.89930	.87580	1.02683	3.93112	.86922

$\theta_s = 20^\circ \quad M_1 = 5.0$

zero grid

1.37373	5.55950	3.03740	1.83030	3.37510	.83364
1.37373	.70714	.69636	1.01542	4.95425	.91146
1.83978	.75251	.72799	1.03356	4.90145	.90979
2.43884	.79796	.75913	1.05104	4.85200	.90819
3.23657	.84156	.78853	1.06728	4.80743	.90671
4.33674	.88113	.81484	1.08125	4.76915	.90542

8 x 8 grid

1.37373	5.55950	3.03740	1.83030	3.37510	.83364
1.37373	.70714	.69636	1.01542	4.95425	.91146
1.59316	.72999	.71236	1.02462	4.92721	.91061
1.83961	.75299	.72832	1.03374	4.90093	.90978
2.11903	.77588	.74407	1.04264	4.87563	.90896
2.43850	.79867	.75962	1.05131	4.85127	.90817
2.80701	.82097	.77471	1.05962	4.82817	.90740
3.23590	.84260	.78923	1.06762	4.80641	.90668
3.73958	.86324	.80299	1.07498	4.78623	.90600
4.33550	.88257	.81580	1.08176	4.76780	.90537

$\theta_s = 20^\circ \quad M_1 = 7.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.37373	9.68230	3.87090	2.50130	4.07310	.87659
1.37373	.78334	.64239	1.21935	6.26775	.94185
1.88102	.81687	.66190	1.23400	6.22555	.94113
2.50224	.84952	.68070	1.24804	6.18629	.94045
3.28025	.88020	.69817	1.26062	6.15092	.93982
4.27498	.90759	.71362	1.27173	6.12049	.93927

8 x 8 grid

1.37373	9.68230	3.87090	2.50130	4.07310	.87659
1.37373	.78334	.64239	1.21935	6.26775	.94185
1.61545	.79904	.65156	1.22628	6.24774	.94151
1.88117	.81597	.66139	1.23361	6.22666	.94115
2.17527	.83262	.67099	1.24085	6.20641	.94080
2.50246	.84880	.68028	1.24772	6.18715	.94046
2.86862	.86447	.68923	1.25415	6.16889	.94014
3.28047	.87966	.69786	1.26042	6.15154	.93983
3.74633	.89390	.70591	1.26630	6.13558	.93954
4.27506	.90736	.71349	1.27163	6.12075	.93928

$\theta_s = 25^\circ \quad M_1 = 1.5$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.07225	1.89740	1.57560	1.20420	1.01020	.41172
1.07225	.49477	.60324	.82018	1.95941	.65904
1.16902	.54382	.64539	.84266	1.89827	.64718
1.33052	.60931	.70002	.87051	1.82433	.63217
1.67408	.72580	.79320	.91512	1.70943	.60735
2.75501	.90709	.93013	.97531	1.55990	.57216

8 x 8 grid

1.07225	1.89740	1.57560	1.20420	1.01020	.41172
1.07225	.49477	.60324	.82018	1.95941	.65904
1.11624	.52427	.62871	.83387	1.92204	.65184
1.16976	.54822	.64910	.84458	1.89313	.64615
1.23838	.57772	.67386	.85732	1.85913	.63932
1.33155	.61607	.70552	.87321	1.81728	.63069
1.46581	.66681	.74655	.89318	1.76547	.61967
1.67410	.73394	.79950	.91800	1.70219	.60571
2.03231	.81977	.86521	.94747	1.62844	.58869
2.75115	.91648	.93696	.97814	1.55301	.57044

$\theta_s = 25^\circ \quad M_1 = 1.7$

zero grid

1.07225	2.04210	1.65790	1.23170	1.18550	.46841
1.07225	.55966	.65768	.85086	2.06680	.67876
1.25989	.62549	.71205	.87835	1.99539	.66581
1.54729	.71095	.78026	.91115	1.91282	.65004
2.08061	.82112	.86483	.94937	1.81925	.63110
3.43473	.93894	.95176	.98651	1.73127	.61220

8 x 8 grid

1.07225	2.04210	1.65790	1.23170	1.18550	.46841
1.07225	.55966	.65768	.85086	2.06680	.67876
1.15764	.59255	.68505	.86490	2.03018	.67219
1.25949	.62786	.71397	.87930	1.99299	.66536
1.38503	.66817	.74642	.89507	1.95292	.65781
1.54632	.71422	.78282	.91234	1.90988	.64946
1.76427	.76689	.82362	.93101	1.86377	.64026
2.07861	.82548	.86809	.95082	1.81584	.63039
2.57113	.88736	.91410	.97068	1.76852	.62033
3.42984	.94505	.95616	.98832	1.72705	.61126

$\theta_s = 25^\circ \quad M_1 = 2.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.07225	2.32700	1.81190	1.28430	1.41740	.53538
1.07225	.59926	.68751	.87155	2.30811	.71822
1.31329	.66879	.74358	.89938	2.23795	.70740
1.67454	.75154	.80820	.92989	2.16341	.69533
2.29933	.84558	.87921	.96169	2.08798	.68249
3.62343	.93613	.94548	.99008	2.02274	.67084

8 x 8 grid

1.07225	2.32700	1.81190	1.28430	1.41740	.53538
1.07225	.59926	.68751	.87155	2.30811	.71822
1.18222	.63401	.71575	.88578	2.27209	.71273
1.31290	.67062	.74504	.90008	2.23622	.70713
1.47247	.71061	.77651	.91512	2.19921	.70120
1.67363	.75402	.81010	.93074	2.16132	.69498
1.93695	.80050	.84547	.94681	2.12307	.68854
2.29751	.84895	.88171	.96278	2.08546	.68205
2.81828	.89701	.91708	.97810	2.05017	.67580
3.61961	.94065	.94873	.99143	2.01969	.67028

$\theta_s = 25^\circ \quad M_1 = 3.0$

zero grid

1.07225	3.64010	2.40750	1.51200	2.06320	.67820
1.07225	.65513	.70721	.92631	3.18003	.81801
1.38823	.71321	.75144	.94896	3.12252	.81303
1.81970	.77535	.79764	.97197	3.06632	.80798
2.44943	.83883	.84377	.99403	3.01364	.80308
3.44124	.89856	.88626	1.01380	2.96783	.79868

8 x 8 grid

1.07225	3.64010	2.40750	1.51200	2.06320	.67820
1.07225	.65513	.70721	.92631	3.18003	.81801
1.21902	.68462	.72980	.93806	3.15019	.81545
1.38789	.71449	.75241	.94948	3.12133	.81292
1.58507	.74538	.77550	.96105	3.09281	.81038
1.81897	.77705	.79890	.97258	3.06486	.80784
2.10120	.80911	.82231	.98393	3.03777	.80534
2.44809	.84108	.84538	.99481	3.01187	.80291
2.88285	.87214	.86756	1.00523	2.98770	.80060
3.43891	.90145	.88830	1.01474	2.96571	.79847

$\theta_s = 25^\circ \quad M_1 = 4.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.07225	4.00760	2.54670	1.57360	2.55990	.75314
1.07225	.69689	.69115	1.00817	3.97855	.87175
1.42301	.74391	.72414	1.02732	3.92987	.86915
1.87475	.79226	.75746	1.04585	3.88321	.86659
2.48067	.83998	.78977	1.06358	3.84012	.86417
3.32922	.88461	.81952	1.07931	3.80219	.86198

8 x 8 grid

1.07225	4.00760	2.54670	1.57360	2.55990	.75314
1.07225	.69689	.69115	1.00817	3.97855	.87175
1.23733	.72061	.70787	1.01798	3.95357	.87042
1.42275	.74460	.72462	1.02757	3.92919	.86911
1.63312	.76889	.74143	1.03691	3.90537	.86781
1.87419	.79327	.75815	1.04623	3.88228	.86654
2.15321	.81751	.77463	1.05534	3.86008	.86530
2.47965	.84141	.79074	1.06406	3.83889	.86410
2.86578	.86456	.80621	1.07230	3.81898	.86295
3.32751	.88656	.82082	1.08001	3.80059	.86189

$\theta_s = 25^\circ \quad M_1 = 5.0$

zero grid

1.07225	7.84430	3.56050	2.20310	2.93510	.79550
1.07225	.74716	.66393	1.12526	4.65393	.90135
1.44750	.78639	.68864	1.14181	4.61216	.89982
1.91453	.82575	.71309	1.15798	4.57253	.89833
2.51330	.86386	.73645	1.17291	4.53609	.89694
3.30282	.89910	.75778	1.18648	4.50396	.89568

8 x 8 grid

1.07225	7.84430	3.56050	2.20310	2.93510	.79550
1.07225	.74716	.66393	1.12526	4.65393	.90135
1.25031	.76629	.67603	1.13338	4.63328	.90060
1.44737	.78628	.68857	1.14178	4.61229	.89982
1.66722	.80618	.70098	1.14996	4.59198	.89907
1.91423	.82592	.71320	1.15802	4.57237	.89833
2.19385	.84540	.72517	1.16579	4.55353	.89761
2.51265	.86437	.73676	1.17310	4.53563	.89692
2.87888	.88267	.74787	1.18015	4.51877	.89626
3.30170	.90003	.75834	1.18680	4.50314	.89565

$\theta_s = 25^\circ \quad M_1 = 7.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
1.07225	14.13660	4.38830	3.22140	3.43000	.83771
1.07225	.89488	.61120	1.46400	5.64671	.92975
1.48343	.92477	.62572	1.47787	5.61608	.92906
1.97804	.95444	.63999	1.49127	5.58679	.92839
2.58493	.98199	.65313	1.50341	5.56048	.92779
3.34521	1.00696	.66495	1.51427	5.53735	.92725

8 x 8 grid

1.07225	14.13660	4.38830	3.22140	3.43000	.83771
1.07225	.89488	.61120	1.46400	5.64671	.92975
1.26905	.90728	.61724	1.46976	5.63387	.92946
1.48360	.92264	.62469	1.47689	5.61825	.92911
1.71891	.93775	.63198	1.48374	5.60316	.92877
1.97828	.95245	.63904	1.49036	5.58874	.92844
2.26551	.96668	.64584	1.49665	5.57502	.92812
2.58517	.98026	.65231	1.50265	5.56213	.92783
2.94278	.99323	.65846	1.50836	5.55001	.92754
3.34536	1.00552	.66428	1.51366	5.53868	.92728

$\theta_s = 30^\circ \quad M_1 = 1.7$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.86602	2.43400	1.86680	1.30380	1.02530	.41681
0.86602	.48529	.59002	.82234	2.14304	.69193
0.96680	.52901	.62753	.84306	2.08775	.68245
1.11598	.58782	.67662	.86879	2.02010	.67037
1.38287	.68200	.75240	.90648	1.92438	.65231
2.00450	.82801	.86422	.95806	1.79835	.62672

8 x 8 grid

0.86602	2.43400	1.86680	1.30380	1.02530	.41681
0.86602	.48529	.59002	.82234	2.14304	.69193
0.91269	.51075	.61197	.83451	2.11033	.68636
0.96703	.53350	.63132	.84505	2.08243	.68152
1.03282	.56070	.65414	.85715	2.05056	.67587
1.11610	.59433	.68194	.87148	2.01318	.66909
1.22673	.63659	.71623	.88868	1.96899	.66086
1.38208	.69004	.75868	.90947	1.91698	.65086
1.61597	.75696	.81054	.93382	1.85698	.63888
2.00149	.83709	.87094	.96103	1.79136	.62522

$\theta_s = 30^\circ \quad M_1 = 2.0$

zero grid

0.86602	2.80950	2.05060	1.37010	1.25330	.48893
0.86602	.56196	.64962	.86496	2.32519	.72078
1.04548	.62057	.69732	.88983	2.26176	.71113
1.29787	.69292	.75447	.91830	2.19129	.69992
1.69996	.78154	.82221	.95050	2.11433	.68705
2.46607	.88246	.89672	.98405	2.03652	.67335

8 x 8 grid

0.86602	2.80950	2.05060	1.37010	1.25330	.48893
0.86602	.56196	.64962	.86496	2.32519	.72078
0.94904	.59181	.67408	.87793	2.29210	.71580
1.04499	.62298	.69925	.89081	2.25931	.71075
1.15857	.65763	.72682	.90476	2.22473	.70530
1.29676	.69618	.75700	.91955	2.18833	.69943
1.47055	.73892	.78991	.93542	2.15025	.69314
1.69791	.78584	.82542	.95200	2.11087	.68645
2.00973	.83625	.86290	.96905	2.07106	.67951
2.46235	.88805	.90076	.98583	2.03252	.67262

$\theta_s = 30^\circ \quad M_1 = 3.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.86602	4.62580	2.75900	1.67660	1.83080	.63350
0.86602	.65569	.68344	.95926	3.09753	.81080
1.12003	.70768	.72173	.98041	3.04628	.80613
1.45345	.76412	.76239	1.00224	2.99503	.80130
1.91727	.82332	.80413	1.02380	2.94542	.79648
2.60785	.88221	.84480	1.04427	2.89968	.79189

8 x 8 grid

0.86602	4.62580	2.75900	1.67660	1.83080	.63350
0.86602	.65569	.68344	.95926	3.09753	.81080
0.98507	.68207	.70297	.97016	3.07102	.80841
1.11964	.70899	.72268	.98093	3.04507	.80602
1.27372	.73699	.74295	.99185	3.01916	.80360
1.45259	.76593	.76367	1.00292	2.99347	.80115
1.66336	.79562	.78471	1.01387	2.96816	.79871
1.91573	.82577	.80583	1.02465	2.94347	.79628
2.22322	.85591	.82673	1.03528	2.91972	.79392
2.60532	.88542	.84699	1.04534	2.89731	.79165

$\theta_s = 30^\circ \quad M_1 = 4.0$

zero grid

0.86602	7.19300	3.42970	2.09730	2.23920	.70760
0.86602	.72705	.66727	1.08951	3.77817	.86057
1.15310	.76984	.69509	1.10750	3.73659	.85808
1.51321	.81441	.72360	1.12538	3.69590	.85559
1.98202	.85906	.75172	1.14275	3.65750	.85318
2.61521	.90195	.77834	1.15882	3.62260	.85094

8 x 8 grid

0.86602	7.19300	3.42970	2.09730	2.23920	.70760
0.86602	.72705	.66727	1.08951	3.77817	.86057
1.00199	.74818	.68106	1.09843	3.75733	.85933
1.15280	.77024	.69535	1.10764	3.73624	.85806
1.32170	.79261	.70971	1.11679	3.71551	.85680
1.51256	.81519	.72409	1.12568	3.69523	.85555
1.73020	.83783	.73840	1.13461	3.67550	.85432
1.98083	.86033	.75251	1.14324	3.65645	.85311
2.27222	.88245	.76628	1.15153	3.63825	.85195
2.61331	.90381	.77949	1.15947	3.62115	.85085

$\theta_s = 30^\circ \quad M_1 = 5.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.86602	10.49900	3.98670	2.63350	2.52850	.74910
0.86602	.81347	.64150	1.26796	4.31977	.88807
1.17512	.85008	.66199	1.28400	4.28539	.88656
1.55294	.88752	.68268	1.30002	4.25190	.88507
2.02770	.92402	.70262	1.31504	4.22071	.88365
2.64253	.95852	.72126	1.32881	4.19247	.88234

8 x 8 grid

0.86602	10.49900	3.98670	2.63350	2.52850	.74910
0.86602	.81347	.64150	1.26796	4.31977	.88807
1.01334	.83047	.65104	1.27549	4.30361	.88736
1.17495	.84936	.66159	1.28372	4.28606	.88659
1.35362	.86829	.67209	1.29179	4.26891	.88583
1.55252	.88712	.68246	1.29985	4.25226	.88508
1.77538	.90578	.69269	1.30751	4.23614	.88435
2.02690	.92404	.70264	1.31504	4.22071	.88365
2.31275	.94189	.71230	1.32219	4.20595	.88297
2.64118	.95907	.72156	1.32906	4.19203	.88232

$\theta_s = 30^\circ \quad M_1 = 7.0$

zero grid

0.86602	19.31780	4.76080	4.05770	2.88410	.79030
0.86602	1.05202	.59576	1.76581	5.05796	.91460
1.20466	1.08201	.60784	1.78005	5.03369	.91388
1.60846	1.11236	.61997	1.79418	5.00991	.91317
2.09933	1.14087	.63128	1.80713	4.98822	.91251
2.70749	1.16679	.64149	1.81883	4.96903	.91192

8 x 8 grid

0.86602	19.31780	4.76080	4.05770	2.88410	.79030
0.86602	1.05202	.59576	1.76581	5.05796	.91460
1.02848	1.06268	.60006	1.77082	5.04925	.91435
1.20476	1.07851	.60644	1.77841	5.03651	.91397
1.39726	1.09398	.61263	1.78558	5.02425	.91360
1.60853	1.10913	.61868	1.79268	5.01244	.91324
1.84130	1.12382	.62453	1.79943	5.00114	.91290
2.09929	1.13797	.63013	1.80581	4.99043	.91257
2.38646	1.15157	.63550	1.81195	4.98027	.91226
2.70724	1.16432	.64052	1.81774	4.97086	.91197

$\theta_s = 35^\circ \quad M_1 = 2.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.71407	3.36380	2.29510	1.46560	1.06800	.43099
0.71407	.50277	.59046	.85137	2.35998	.72590
0.82649	.54481	.62534	.87112	2.30854	.71829
0.97803	.59977	.66978	.89536	2.24710	.70885
1.21041	.67720	.73046	.92719	2.16949	.69635
1.63694	.78630	.81271	.96758	2.07392	.68003

8 x 8 grid

0.71407	3.36380	2.29510	1.46560	1.06800	.43099
0.71407	.50277	.59046	.85137	2.35998	.72590
0.76668	.52634	.61010	.86264	2.33068	.72160
0.82615	.54888	.62866	.87296	2.30387	.71758
0.89504	.57490	.64980	.88473	2.27427	.71307
0.97717	.60538	.67423	.89776	2.24127	.70792
1.07851	.64142	.70266	.91281	2.20432	.70203
1.20860	.68430	.73590	.92988	2.16297	.69526
1.38375	.73523	.77462	.94911	2.11706	.68751
1.63349	.79482	.81896	.97049	2.06716	.67882

$\theta_s = 35^\circ \quad M_1 = 3.0$

zero grid

0.71407	5.71850	3.08010	1.85660	1.59390	.58045
0.71407	.66028	.65898	1.00197	2.99541	.80134
0.91807	.70788	.69257	1.02211	2.94911	.79684
1.17858	.76097	.72929	1.04343	2.90122	.79204
1.53025	.81860	.76833	1.06532	2.85308	.78707
2.03739	.87899	.80841	1.08732	2.80633	.78209

8 x 8 grid

0.71407	5.71850	3.08010	1.85660	1.59390	.58045
0.71407	.66028	.65898	1.00197	2.99541	.80134
0.81024	.68437	.67607	1.01228	2.97155	.79904
0.91757	.70930	.69357	1.02268	2.94779	.79671
1.03880	.73553	.71179	1.03335	2.92373	.79432
1.17751	.76303	.73070	1.04424	2.89945	.79186
1.33854	.79172	.75022	1.05531	2.87510	.78936
1.52839	.82146	.77025	1.06649	2.85082	.78683
1.75611	.85197	.79057	1.07766	2.82685	.78429
2.03440	.88281	.81091	1.08867	2.80353	.78178

$\theta_s = 35^\circ \quad M_1 = 4.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.71407	9.09920	3.78050	2.40690	1.93040	.65348
0.71407	.77283	.64955	1.18974	3.55713	.84662
0.94990	.81402	.67409	1.20744	3.52040	.84411
1.24096	.85807	.69995	1.22582	3.48328	.84152
1.61349	.90321	.72606	1.24397	3.44733	.83896
2.11045	.94818	.75170	1.26131	3.41340	.83649

8 x 8 grid

0.71407	9.09920	3.78050	2.40690	1.93040	.65348
0.71407	.77283	.64955	1.18974	3.55713	.84662
0.82614	.79266	.66141	1.19834	3.53919	.84540
0.94951	.81418	.67419	1.20752	3.52026	.84410
1.08653	.83624	.68719	1.21683	3.50142	.84280
1.24011	.85874	.70035	1.22610	3.48275	.84149
1.41379	.88152	.71357	1.23533	3.46436	.84018
1.61200	.90452	.72681	1.24447	3.44633	.83889
1.84062	.92748	.73995	1.25332	3.42881	.83762
2.10807	.95026	.75288	1.26208	3.41189	.83638

$\theta_s = 35^\circ \quad M_1 = 5.0$

zero grid

0.71407	13.44150	4.32290	3.10940	2.15620	.69413
0.71407	.90304	.62822	1.43744	3.98390	.87203
0.96938	.93989	.64642	1.45398	3.95400	.87045
1.27824	.97869	.66537	1.47081	3.92391	.86883
1.66246	1.01726	.68400	1.48709	3.89526	.86726
2.17282	1.05956	.70419	1.50458	3.86518	.86558

8 x 8 grid

0.71407	13.44150	4.32290	3.10940	2.15620	.69413
0.71407	.90304	.62821	1.43741	3.98389	.87203
0.83599	.91922	.63624	1.44473	3.97061	.87133
0.96911	.93860	.64579	1.45341	3.95504	.87050
1.11547	.95818	.65538	1.46190	3.93966	.86968
1.27760	.97785	.66496	1.47046	3.92456	.86886
1.45832	.99751	.67449	1.47889	3.90978	.86806
1.66130	1.01699	.68387	1.48697	3.89546	.86727
1.89087	1.03628	.69311	1.49500	3.88157	.86650
6.60668	1.05874	.70381	1.50424	3.86576	.86562

$\theta_s = 35^\circ \quad M_1 = 7.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.71407	25.14240	5.04290	4.98570	2.41470	.73373
0.71407	1.25412	.59244	2.11686	4.52863	.89665
0.99310	1.28748	.60365	2.13279	4.50750	.89582
1.32420	1.32266	.61539	2.14923	4.48591	.89497
1.72546	1.35639	.62656	2.16486	4.46579	.89417
2.22218	1.38767	.63685	2.17882	4.44763	.89344

8 x 8 grid

0.71407	25.14240	5.04290	4.98570	2.41470	.73373
0.71407	1.25412	.59244	2.11683	4.52863	.89665
0.84805	1.26458	.59596	2.12178	4.52195	.89639
0.99304	1.28263	.60203	2.13045	4.51056	.89594
1.15100	1.30048	.60800	2.13881	4.49948	.89551
1.32395	1.31825	.61392	2.14718	4.48861	.89508
1.51436	1.33554	.61966	2.15521	4.47819	.89466
1.72493	1.35250	.62527	2.16306	4.46811	.89426
1.95920	1.36876	.63063	2.17036	4.45857	.89388
2.22120	1.38449	.63580	2.17741	4.44947	.89351

$\theta_s = 40^\circ \quad M_1 = 3.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.59587	6.91480	3.36930	2.05230	1.34970	.51677
0.59587	.66170	.63040	1.04965	2.88742	.79063
0.75385	.70552	.65994	1.06908	2.84516	.78624
0.95161	.75674	.69382	1.09068	2.79916	.78131
1.21352	.81553	.73191	1.11425	2.75023	.77590
1.58635	.88185	.77395	1.13932	2.69929	.77009

8 x 8 grid

0.59587	6.91480	3.36930	2.05230	1.34970	.51677
0.59587	.66170	.63039	1.04966	2.88742	.79063
0.67066	.68402	.64551	1.05962	2.86555	.78837
0.75323	.70741	.66120	1.06987	2.84342	.78605
0.84561	.73254	.67789	1.08055	2.82050	.78361
0.95023	.75953	.69564	1.09180	2.79677	.78105
1.07054	.78846	.71447	1.10347	2.77232	.77836
1.21117	.81943	.73440	1.11574	2.74716	.77556
1.37871	.85235	.75536	1.12833	2.72148	.77264
1.58266	.88707	.77721	1.14126	2.69551	.76965

$\theta_s = 40^\circ \quad M_1 = 4.0$

zero grid

0.59587	11.14690	4.07020	2.73870	1.63330	.58985
0.59587	.82650	.63466	1.30226	3.33542	.83061
0.78623	.86798	.65725	1.32059	3.30165	.82798
1.01867	.91418	.68205	1.34026	3.26604	.82514
1.31346	.96335	.70805	1.36052	3.23021	.82222
1.70387	1.01461	.73477	1.38073	3.19488	.81927

8 x 8 grid

0.59587	11.14690	4.07020	2.73870	1.63330	.58985
0.59587	.82649	.63465	1.30213	3.33542	.83061
0.68649	.84602	.64533	1.31095	3.31931	.82936
0.78571	.86813	.65733	1.32064	3.30154	.82797
0.89534	.89116	.66974	1.33051	3.28355	.82654
1.01752	.91506	.68252	1.34062	3.26539	.82508
1.15507	.93975	.69562	1.35088	3.24717	.82361
1.31148	.96514	.70900	1.36121	3.22895	.82211
1.49134	.99115	.72259	1.37159	3.21082	.82061
1.70082	1.01748	.73626	1.38184	3.19298	.81911

$\theta_s = 40^\circ \quad M_1 = 5.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.59587	16.61210	4.58720	3.62140	1.81210	.62961
0.59587	1.01301	.62207	1.62843	3.66349	.85356
0.80391	1.05284	.63944	1.64639	3.63582	.85180
1.05424	1.09650	.65827	1.66562	3.60679	.84991
1.36444	1.14153	.67747	1.68489	3.57813	.84802
1.76160	1.18685	.69658	1.70384	3.55051	.84617

8 x 8 grid

0.59587	16.61210	4.58720	3.62140	1.81210	.62961
0.59587	1.01301	.62207	1.62843	3.66349	.85356
0.69532	1.02973	.62939	1.63602	3.65174	.85281
0.80350	1.05118	.63872	1.64563	3.63697	.85187
0.92220	1.07314	.64823	1.65543	3.62218	.85092
1.05328	1.09556	.65787	1.66522	3.60741	.84995
1.19915	1.11839	.66763	1.67502	3.59271	.84899
1.36276	1.14145	.67744	1.68487	3.57819	.84803
1.54777	1.16467	.68725	1.69457	3.56389	.84707
1.75900	1.18781	.69698	1.70420	3.54994	.84613

$\theta_s = 40^\circ \quad M_1 = 7.0$

zero grid

0.59587	31.20690	5.22410	5.97360	2.00970	.66845
0.59587	1.49954	.59753	2.50953	4.06404	.87613
0.82338	1.54032	.60910	2.52873	4.04374	.87511
1.09308	1.58504	.62168	2.54969	4.02219	.87401
1.42012	1.62987	.63418	2.56999	4.00124	.87293
1.82665	1.67332	.64621	2.58937	3.98154	.87190

8 x 8 grid

0.59587	31.20690	5.22410	5.97360	2.00970	.66845
0.59587	1.49953	.59753	2.50949	4.06404	.87613
0.70507	1.51160	.60096	2.51530	4.05799	.87583
0.82313	1.53429	.60739	2.52588	4.04674	.87526
0.95170	1.55702	.61380	2.53665	4.03564	.87470
8.74144	1.66090	.64278	2.58393	3.98713	.87220
1.24731	1.60281	.62664	2.55776	4.01383	.87358
1.41890	1.62563	.63300	2.56808	4.00322	.87303
1.61009	1.64817	.63926	2.57813	3.99289	.87250
1.82470	1.67022	.64536	2.58801	3.98294	.87198

$\theta_s = 45^\circ \quad M_1 = 3.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.50000	8.23210	3.63170	2.26670	1.08450	.43640
0.50000	.62177	.57381	1.08345	2.81422	.78294
0.59961	.65665	.59663	1.10063	2.77840	.77904
0.72239	.70020	.62464	1.12105	2.73643	.77435
0.88462	.75745	.66072	1.14649	2.68524	.76845
1.11989	.83375	.70761	1.17840	2.62298	.76101

8 x 8 grid

0.50000	8.23210	3.63170	2.26670	1.08450	.43640
0.50000	.62177	.57381	1.08345	2.81422	.78294
0.54733	.64193	.58704	1.09345	2.79330	.78067
0.59902	.66080	.59932	1.10258	2.77434	.77859
0.65640	.68201	.61299	1.11257	2.75371	.77629
0.72104	.70610	.62838	1.12368	2.73107	.77374
0.79521	.73362	.64578	1.13599	2.70617	.77088
0.88218	.76520	.66552	1.14977	2.67878	.76769
0.98668	.80160	.68797	1.16516	2.64864	.76411
1.11590	.84351	.71348	1.18223	2.61564	.76010

$\theta_s = 45^\circ \quad M_1 = 4.0$

zero grid

0.50000	13.33040	4.31160	3.09180	1.33870	.51366
0.50000	.87244	.61496	1.41869	3.13080	.81376
0.64499	.91471	.63609	1.43794	3.09889	.81093
0.82058	.96479	.66078	1.46002	3.06306	.80768
1.04234	1.02193	.68850	1.48412	3.02454	.80410
1.33759	1.08640	.71926	1.51035	2.98372	.80022

8 x 8 grid

0.50000	13.33040	4.31160	3.09180	1.33870	.51366
0.50000	.87244	.61495	1.41870	3.13080	.81376
0.56908	.89239	.62497	1.42774	3.11554	.81241
0.64430	.91555	.63651	1.43831	3.09828	.81087
0.72712	.94031	.64876	1.44938	3.08034	.80925
0.81903	.96683	.66178	1.46090	3.06166	.80755
0.92230	.99517	.67558	1.47295	3.04230	.80576
1.03971	1.02539	.69017	1.48557	3.02230	.80389
1.17506	1.05754	.70555	1.49883	3.00170	.80194
1.33358	1.09156	.72170	1.51240	2.98060	.79992

$\theta_s = 45^\circ \quad M_1 = 5.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.50000	19.96100	4.79680	4.16130	1.48630	.55357
0.50000	1.12803	.61604	1.83108	3.37398	.83355
0.66287	1.17282	.63341	1.85156	3.34700	.83150
0.85814	1.22489	.65337	1.87467	3.31702	.82918
1.10007	1.28184	.67493	1.89909	3.28575	.82672
1.41228	1.34299	.69777	1.92460	3.25380	.82415

8 x 8 grid

0.50000	19.96100	4.79680	4.16130	1.48630	.55357
0.50000	1.12803	.61604	1.83104	3.37398	.83355
0.57785	1.14662	.62327	1.83965	3.36265	.83270
0.66226	1.17142	.63287	1.85093	3.34784	.83157
0.75474	1.19743	.64288	1.86255	3.33266	.83040
0.85675	1.22472	.65331	1.87460	3.31712	.82919
0.97025	1.25327	.66415	1.88692	3.30125	.82794
1.09770	1.28308	.67540	1.89961	3.28509	.82666
1.24244	1.31400	.68698	1.91271	3.26876	.82536
1.40865	1.34595	.69887	1.92582	3.25230	.82402

$\theta_s = 45^\circ \quad M_1 = 7.0$

zero grid

0.50000	37.68400	5.37020	7.01720	1.64190	.59185
0.50000	1.77360	.60525	2.93033	3.66440	.85362
0.68013	1.82605	.61798	2.95476	3.64346	.85229
0.89357	1.88726	.63271	2.98276	3.61988	.85077
1.15350	1.95177	.64808	3.01153	3.59591	.84920
1.47982	2.01835	.66380	3.04061	3.57205	.84762

8 x 8 grid

0.50000	37.68400	5.37020	7.01720	1.64190	.59185
0.50000	1.77360	.60525	2.93035	3.66440	.85362
0.58634	1.78967	.60916	2.93781	3.65792	.85321
0.67962	1.81957	.61641	2.95176	3.64604	.85245
0.78116	1.85044	.62386	2.96605	3.63399	.85168
0.89239	1.88233	.63153	2.98053	3.62177	.85089
1.01513	1.91500	.63934	2.99527	3.60948	.85009
1.15147	1.94855	.64732	3.01010	3.59710	.84928
1.30415	1.98270	.65540	3.02517	3.58473	.84846
1.47669	2.01720	.66353	3.04010	3.57247	.84764

$\theta_s = 50^o \quad M_1 = 4.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.41954	12.65300	4.21530	3.00170	1.01860	.41453
0.41954	.64216	.50135	1.28074	3.02472	.80412
0.46762	.67585	.52001	1.29961	2.99052	.80087
0.57123	.70621	.53661	1.31603	2.96120	.79804
0.68247	.74996	.56017	1.33902	2.92125	.79408
0.84317	.81392	.59390	1.37070	2.86714	.78855

8 x 8 grid

0.41954	12.65300	4.21530	3.00170	1.01860	.41453
0.41954	.64216	.50135	1.28074	3.02472	.80412
0.45212	.66679	.51502	1.29451	2.99960	.80174
0.48752	.68085	.52275	1.30234	2.98570	.80041
0.52666	.69616	.53112	1.31062	2.97090	.79898
0.57084	.71406	.54084	1.32016	2.95403	.79733
0.62168	.73519	.55223	1.33114	2.93469	.79541
0.68128	.76041	.56569	1.34419	2.91236	.79317
0.75278	.79066	.58167	1.35918	2.88660	.79055
0.84042	.82703	.60066	1.37681	2.85696	.78748

$\theta_s = 50^o \quad M_1 = 5.0$

zero grid

0.41954	21.97000	4.89530	4.48790	1.15740	.45968
0.41954	1.10238	.57753	1.90864	3.14729	.81520
0.52918	1.14532	.59350	1.92977	3.12147	.81293
0.65985	1.20014	.61366	1.95574	3.08996	.81012
0.82243	1.26752	.63808	1.98636	3.05327	.80678
1.03626	1.35044	.66763	2.02265	3.01087	.80282

8 x 8 grid

0.41954	21.97000	4.89530	4.48790	1.15740	.45968
0.41954	1.10238	.57753	1.90864	3.14729	.81520
0.47188	1.12221	.58493	1.91851	3.13525	.81415
0.52839	1.14680	.59405	1.93047	3.12061	.81286
0.59008	1.17390	.60405	1.94338	3.10486	.81146
0.65807	1.20381	.61500	1.95739	3.08793	.80994
0.73385	1.23696	.62705	1.97257	3.06968	.80828
0.81941	1.27366	.64029	1.98909	3.05007	.80648
0.91745	1.31439	.65485	2.00702	3.02901	.80452
1.03163	1.35946	.67081	2.02650	3.00649	.80240

$\theta_s = 50^\circ \quad M_1 = 7.0$

zero grid

x	P/P_1	ρ/ρ_1	T/T_1	M	q
0.41954	47.28500	5.52300	8.56150	1.29100	.49998
0.41954	2.13739	.60476	3.53412	3.33897	.83089
0.55024	2.20698	.61876	3.56682	3.31685	.82917
0.70497	2.29503	.63629	3.60670	3.28994	.82705
0.89440	2.39698	.65635	3.65189	3.26013	.82466
1.13627	2.51377	.67904	3.70173	3.22760	.82200

8 x 8 grid

0.41954	47.28500	5.52300	8.56150	1.29100	.49998
0.41954	2.13739	.60476	3.53412	3.33897	.83089
0.48205	2.16150	.60962	3.54565	3.33123	.83029
0.54947	2.20240	.61784	3.56467	3.31830	.82928
0.62283	2.24630	.62661	3.58484	3.30470	.82822
0.70324	2.29358	.63601	3.60607	3.29038	.82708
0.79217	2.34442	.64604	3.62887	3.27533	.82588
0.89147	2.39903	.65676	3.65278	3.25955	.82461
1.00363	2.45747	.66814	3.67797	3.24308	.82327
1.13182	2.51999	.68025	3.70437	3.22592	.82186

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TABLE III: Taylor-Maccoll Flow Data

M_1	1.3	1.5	1.7	2.0	3.0	4.0	5.0	7.0
	.49168	.54617		.65313	.79106	.86284	.90355	.94448
θ_s	50.018	41.867		30.091	19.711	14.950	12.291	9.526
	2.7727	3.6710		7.8246	36.736	151.83	528.93	4123.9
5°	2.0719	2.5317		4.3470	13.120	36.150	88.155	381.84
	.46857	.52391	.57239	.63424	.77136	.84482	.88687	.92942
	51.098	42.627	36.966	31.190	21.710	17.713	15.607	13.540
10°	2.7721	3.6714	4.9360	7.8241	36.682	150.48	513.60	364.45
	2.0715	2.5319	3.1280	4.3467	13.101	35.828	85.603	337.45
	.43620	.49419	.54379	.60681	.74625	.82110	.86391	.90706
	53.763	45.083	39.436	33.907	25.260	21.790	20.028	18.365
15°	2.7710	3.6700	4.9332	7.8118	36.110	141.91	450.03	2590.0
	2.0708	2.5311	3.1262	4.3399	12.895	33.787	75.004	239.82
		.45765	.50955	.57409	.71547	.79079	.83364	.87659
		49.017	43.252	37.800	29.617	26.487	24.955	23.530
20°		3.6625	4.9149	7.7515	34.362	124.51	354.64	1619.8
		2.5259	3.1146	4.3056	12.271	29.643	59.104	149.97
		.41172	.46841	.53538	.67820	.75314	.79550	.83771
		54.754	48.233	42.553	34.490	31.567	30.160	28.902
25°		3.6348	4.8595	7.5892	31.451	102.83	261.51	975.80
		2.5068	3.0796	4.2154	11.233	24.480	43.583	90.340
			.41681	.48893	.63350	.70760	.74910	.79030
			54.602	48.102	39.792	36.942	35.611	34.431
30°			4.7468	7.3095	27.861	81.777	187.51	595.80
			3.0081	4.0598	9.9489	19.469	31.249	55.125
				.43099	.58045	.65348	.69413	.73373
				54.746	45.500	42.611	41.277	40.126
35°				6.9052	24.088	63.912	134.20	376.14
				3.8363	8.6028	15.214	22.365	34.829
					.51677	.58985	.62961	.66845
					51.783	48.624	47.229	46.044
40°					20.512	49.785	97.238	247.89
	Entries are				7.3258	11.854	16.207	22.954
	q_c				.43640	.51366	.55357	.59185
	θ_w				59.145	55.219	53.623	52.304
45°	p_c/p_1				17.244	38.946	71.842	170.46
	ρ_c/ρ_1				6.1587	9.2371	11.974	15.783
						.41453	.45968	.49998
						63.210	60.933	59.226
50°						24.479	50.426	129.41
						6.7537	8.8618	11.337

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TABLE IV: Free Stream Data

M_1	q_1	P_1/P_{o1}	ρ_1/ρ_{o1}	T_1/T_{o1}	$2/(\gamma M_1^2)$
1.3	.502609	.360907	.482896	.747380	.846308
1.5	.557086	.272403	.394984	.689655	.634920
1.7	.605216	.202594	.319693	.633714	.494315
2.0	.666667	.127805	.230048	.555557	.357143
3.0	.801784	.0272236	.0762263	.357143	.158730
4.0	.872872	.00658606	.0276615	.238095	.0892856
5.0	.912871	.00189004	.0113402	.0166667	.0571428
7.0	.952579	.000241555	.00260880	.0925925	.0291545

Subscripts o1 denote free stream stagnation values.

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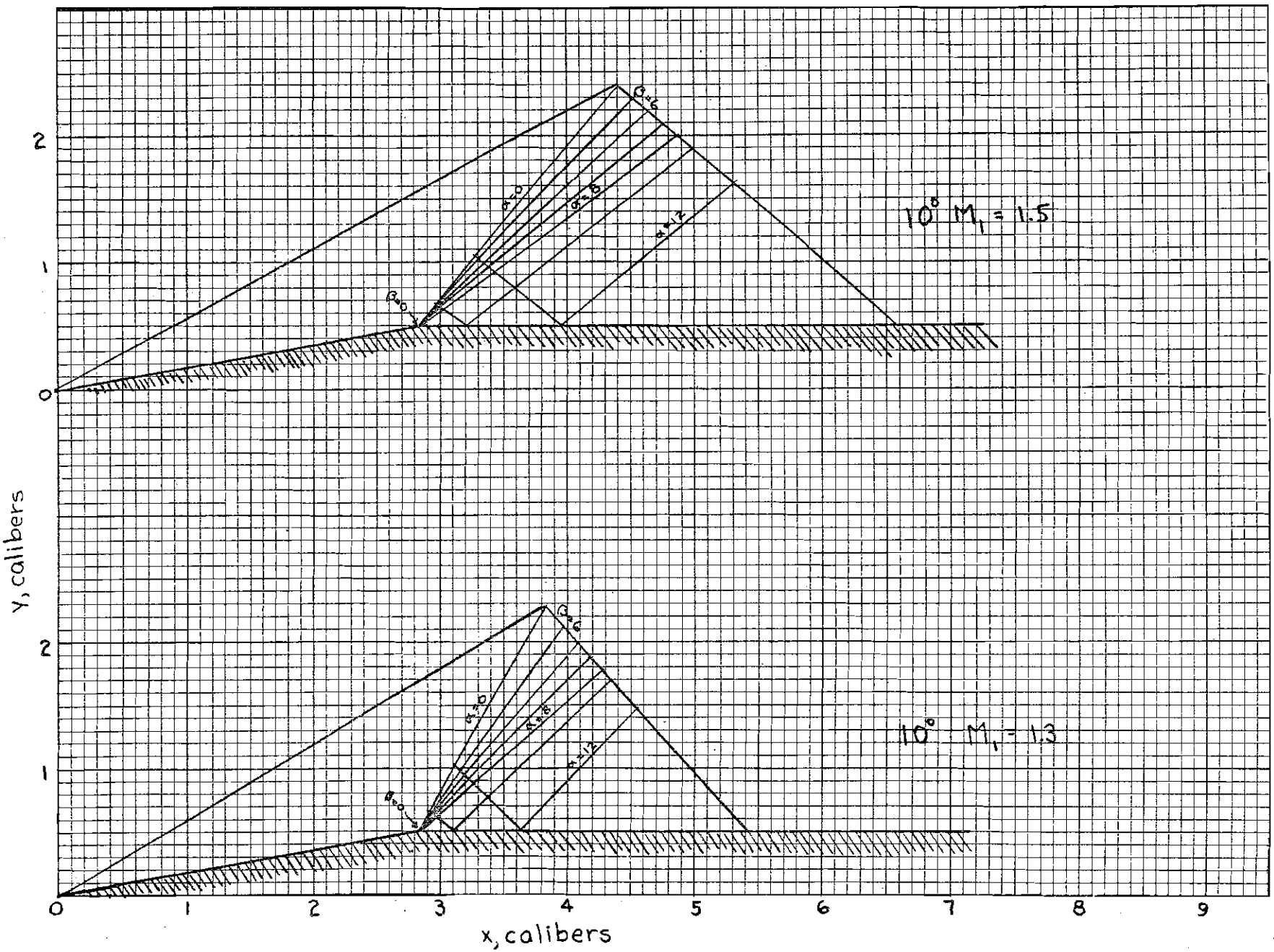


Figure 5. Physical Plane, θ_s=10°

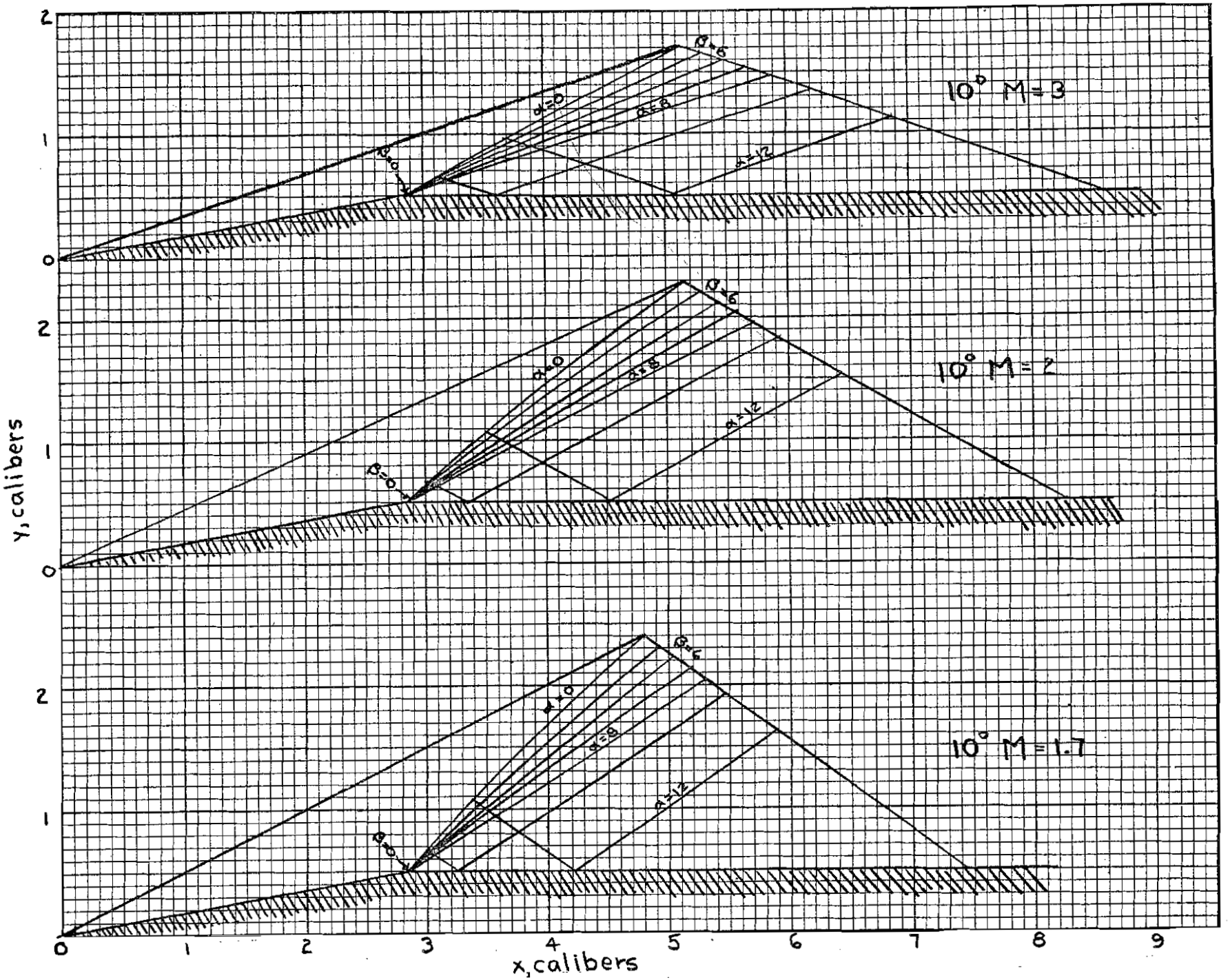


Figure 6. Physical Plane, θ_s=10°

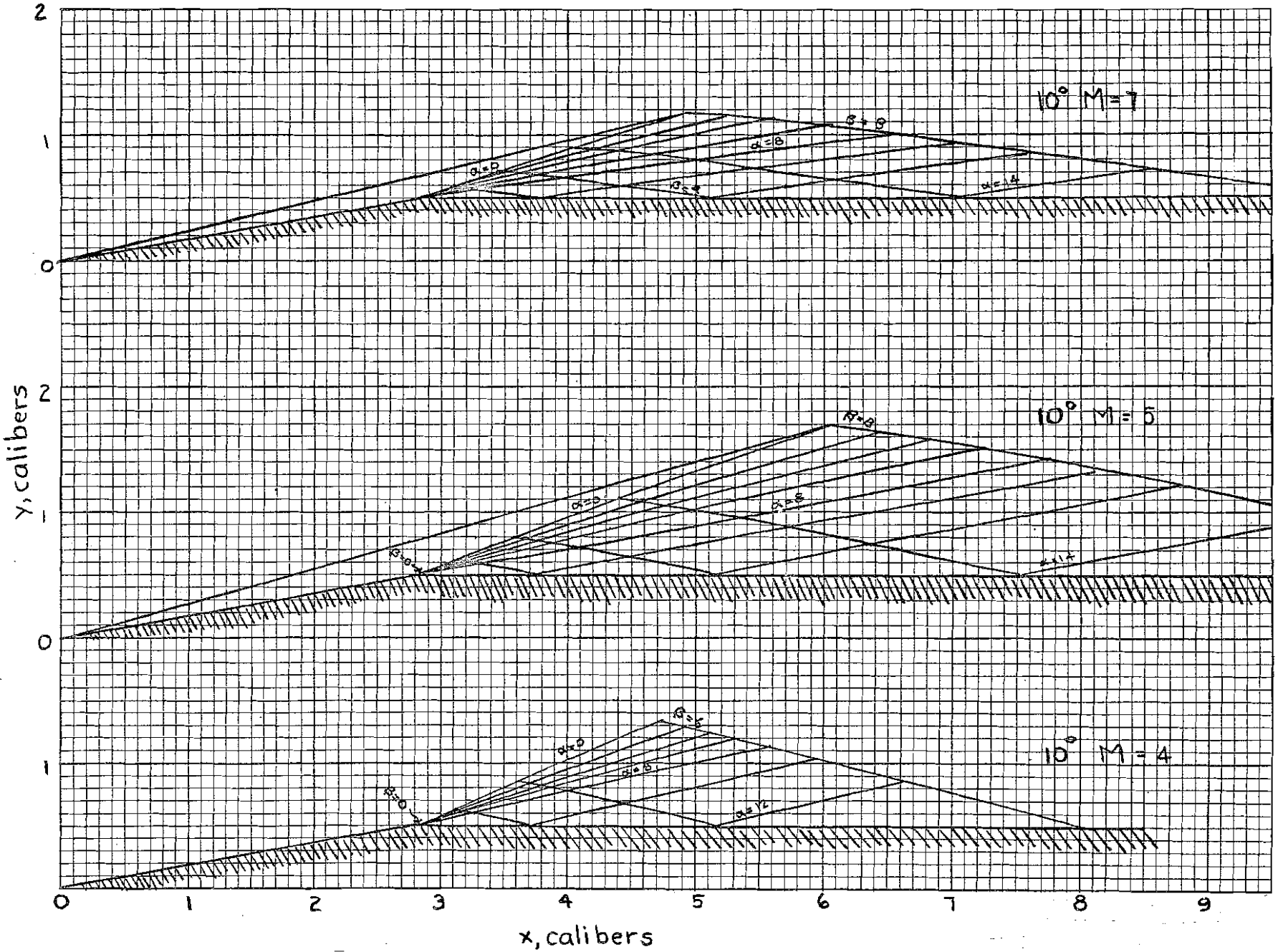


Figure 7. Physical Plane, θ_c=10°

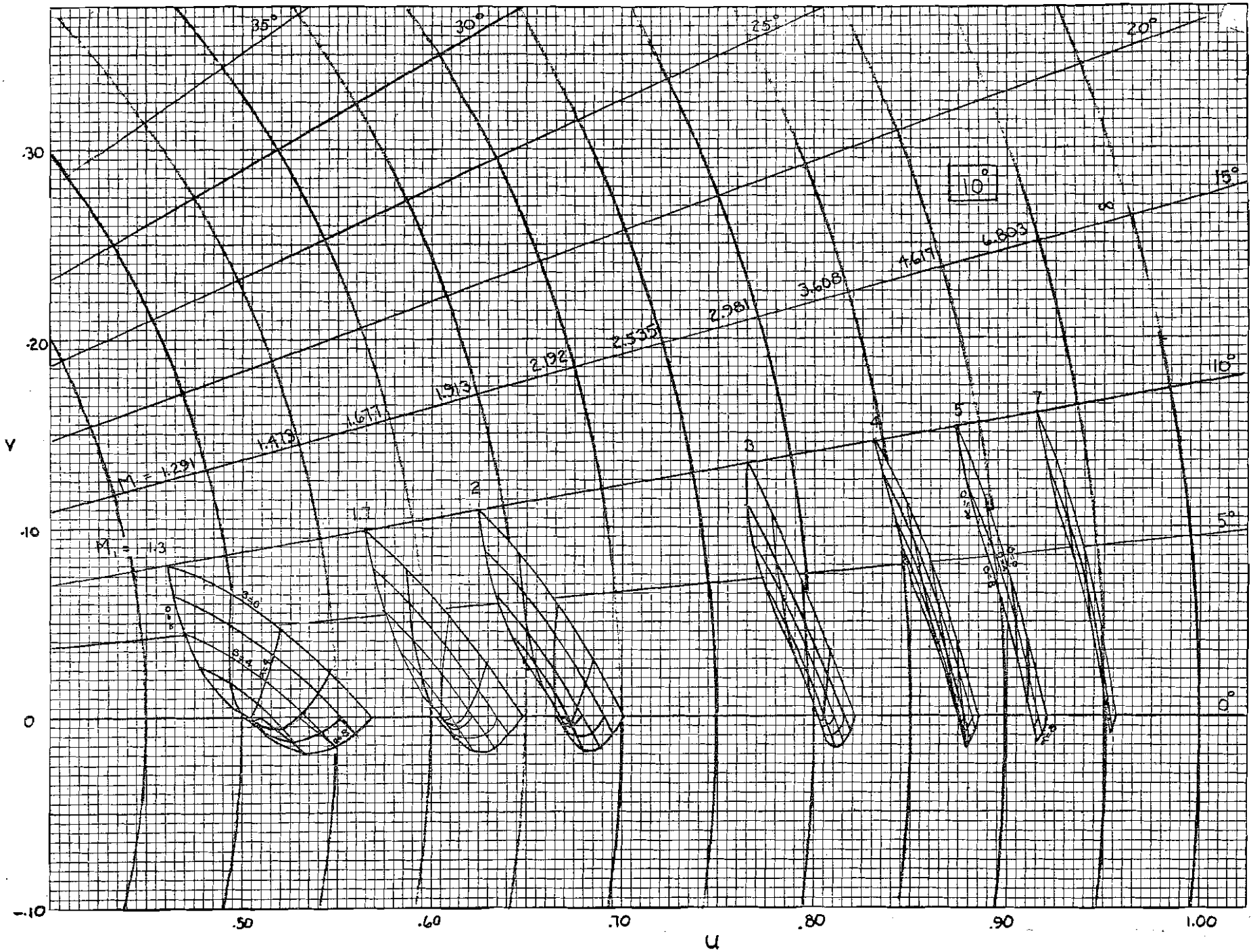


Figure 8. Hodograph Plane, θ_s=10°

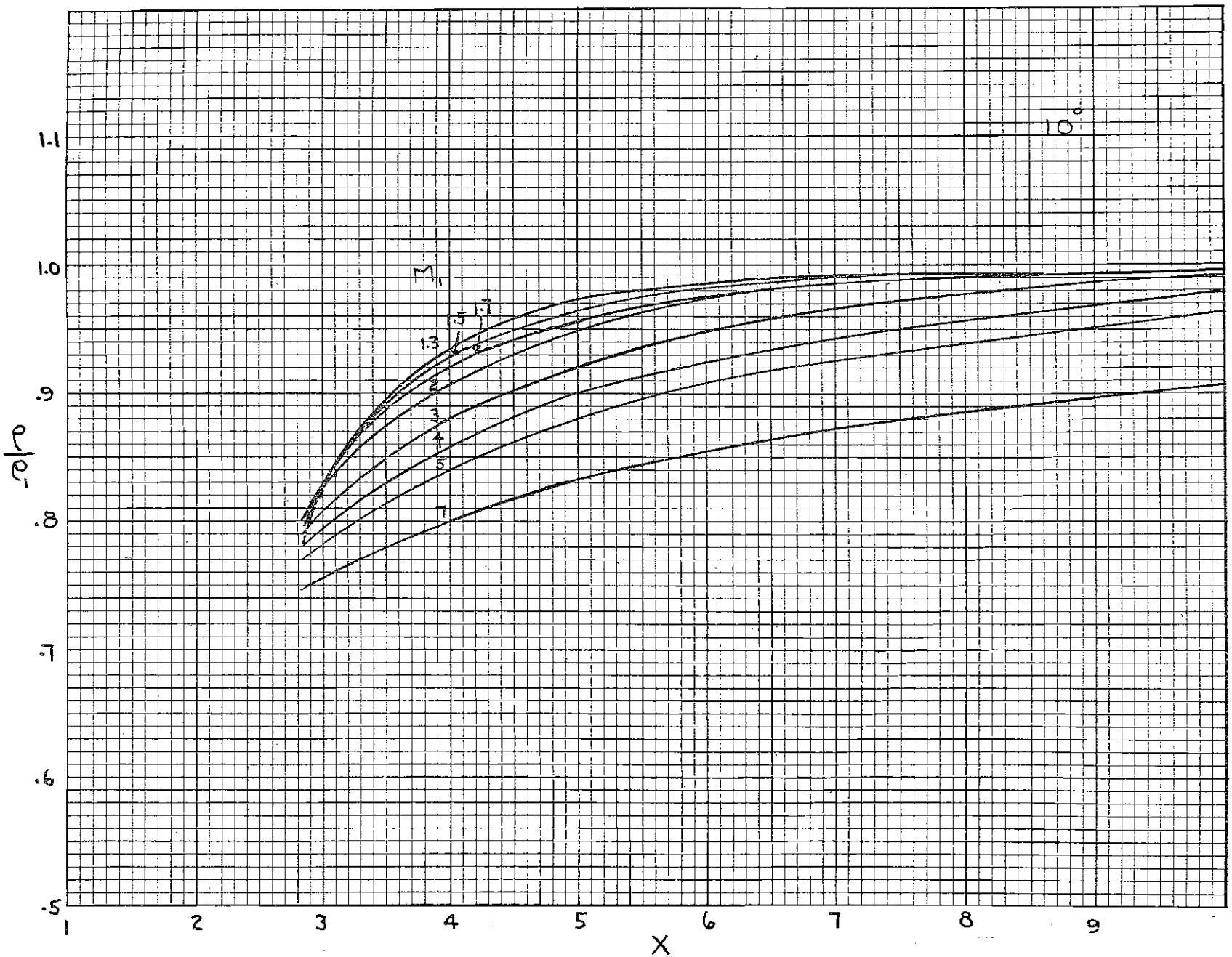


Figure 9. Density Ratio θ_s=10°

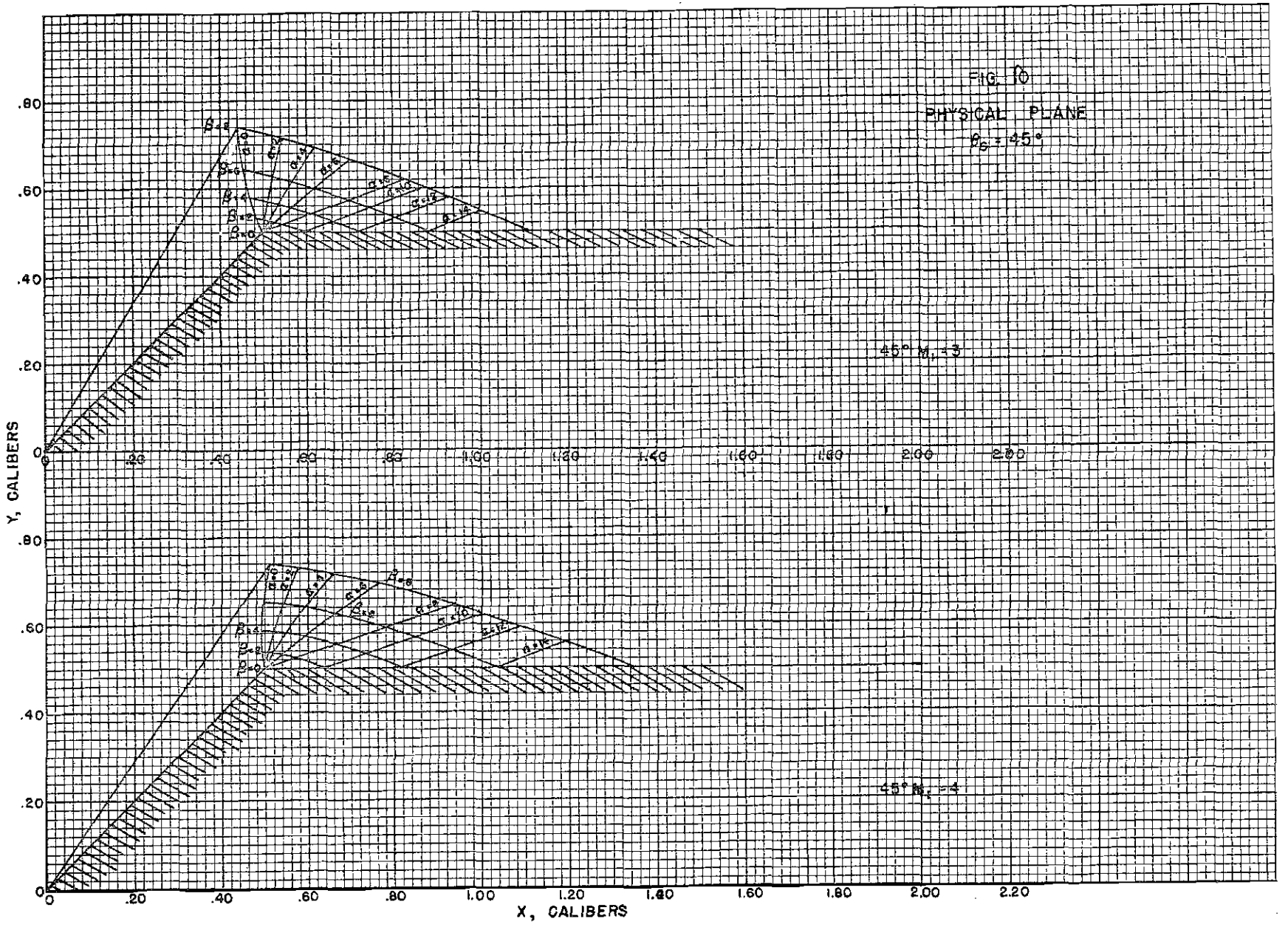


FIG. 10
PHYSICAL PLANE
$\theta_c = 45°$
45° $M_1 = 3$
45° $M_1 = 4$
Y, CALIBERS
X, CALIBERS
0
.20
.40
.60
.80
1.00
1.20
1.40
1.60
1.80
2.00
2.20

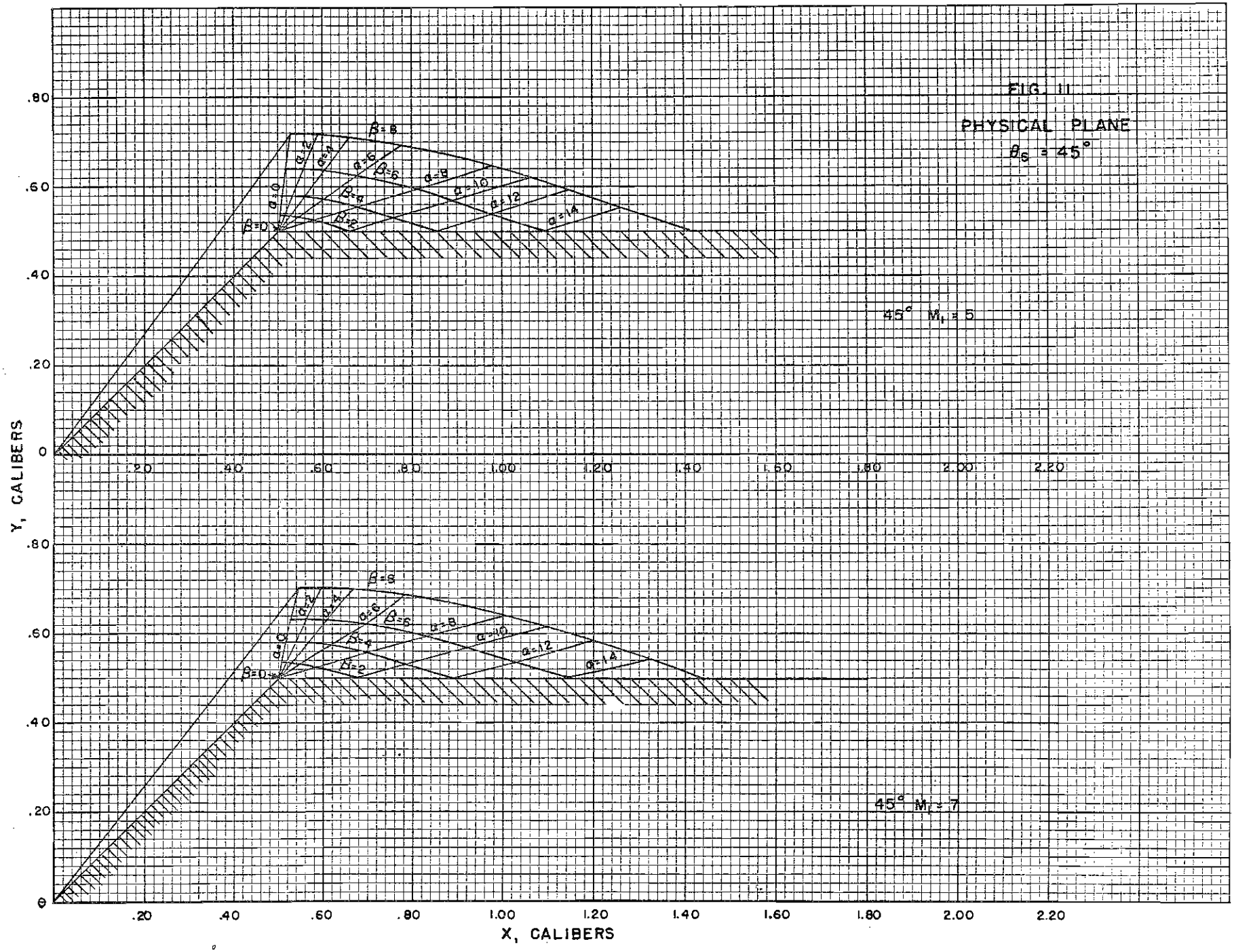


FIG. 11
PHYSICAL PLANE
$\theta_s = 45°$
45° $M_1 = 5$
45° $M_1 = 7$
Y, CALIBERS
X, CALIBERS
.80
.60
.40
.20
0
.20
.40
.60
.80
1.00
1.20
1.40
1.60
1.80
2.00
2.20
$\beta=8$
$\beta=6$
$\beta=4$
$\beta=2$
$\beta=0$
$\alpha=2$
$\alpha=4$
$\alpha=6$
$\alpha=8$
$\alpha=10$
$\alpha=12$
$\alpha=14$

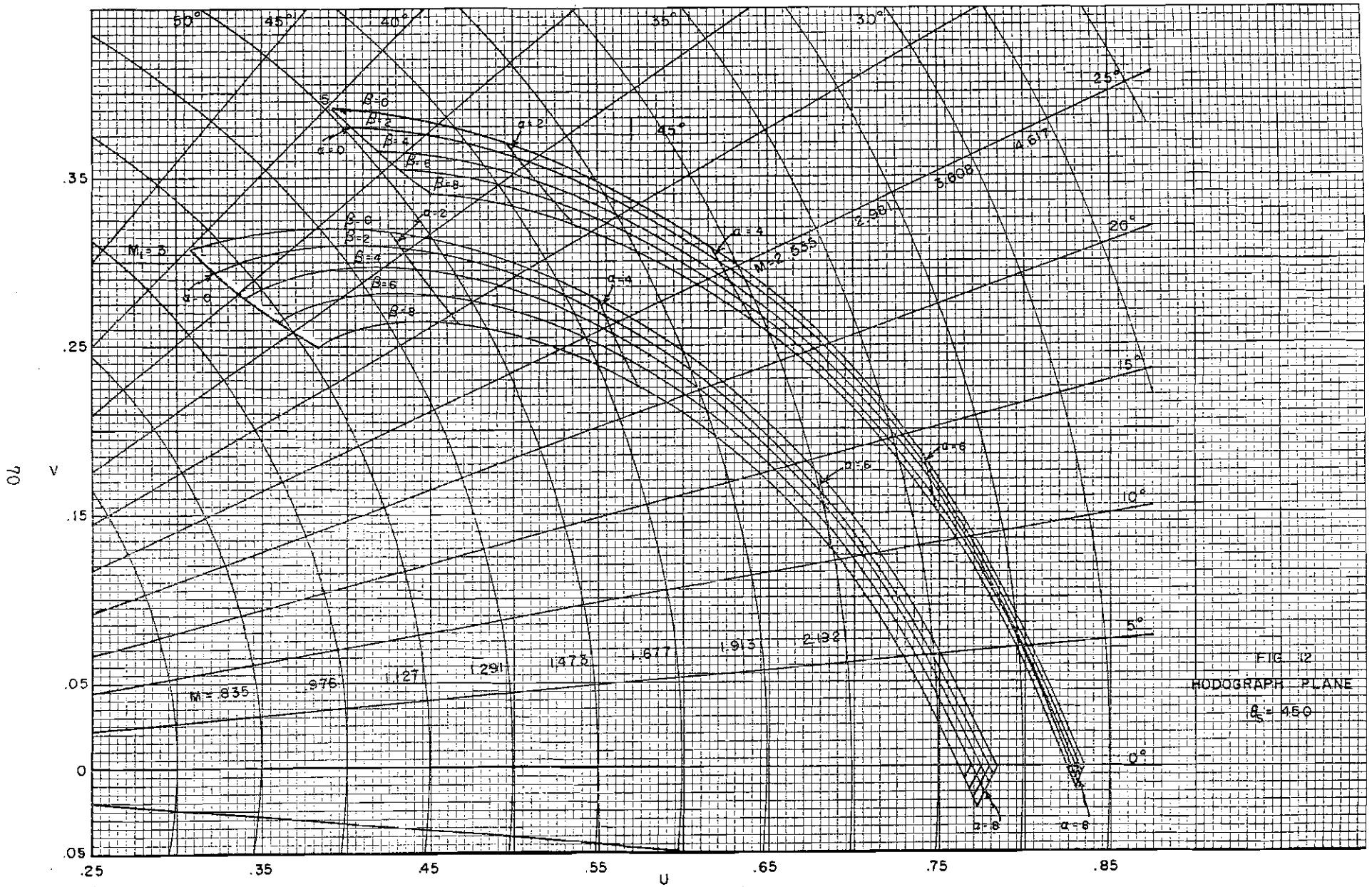


FIG. 12
HODOGRAPH PLANE
$\theta_c = 45°$

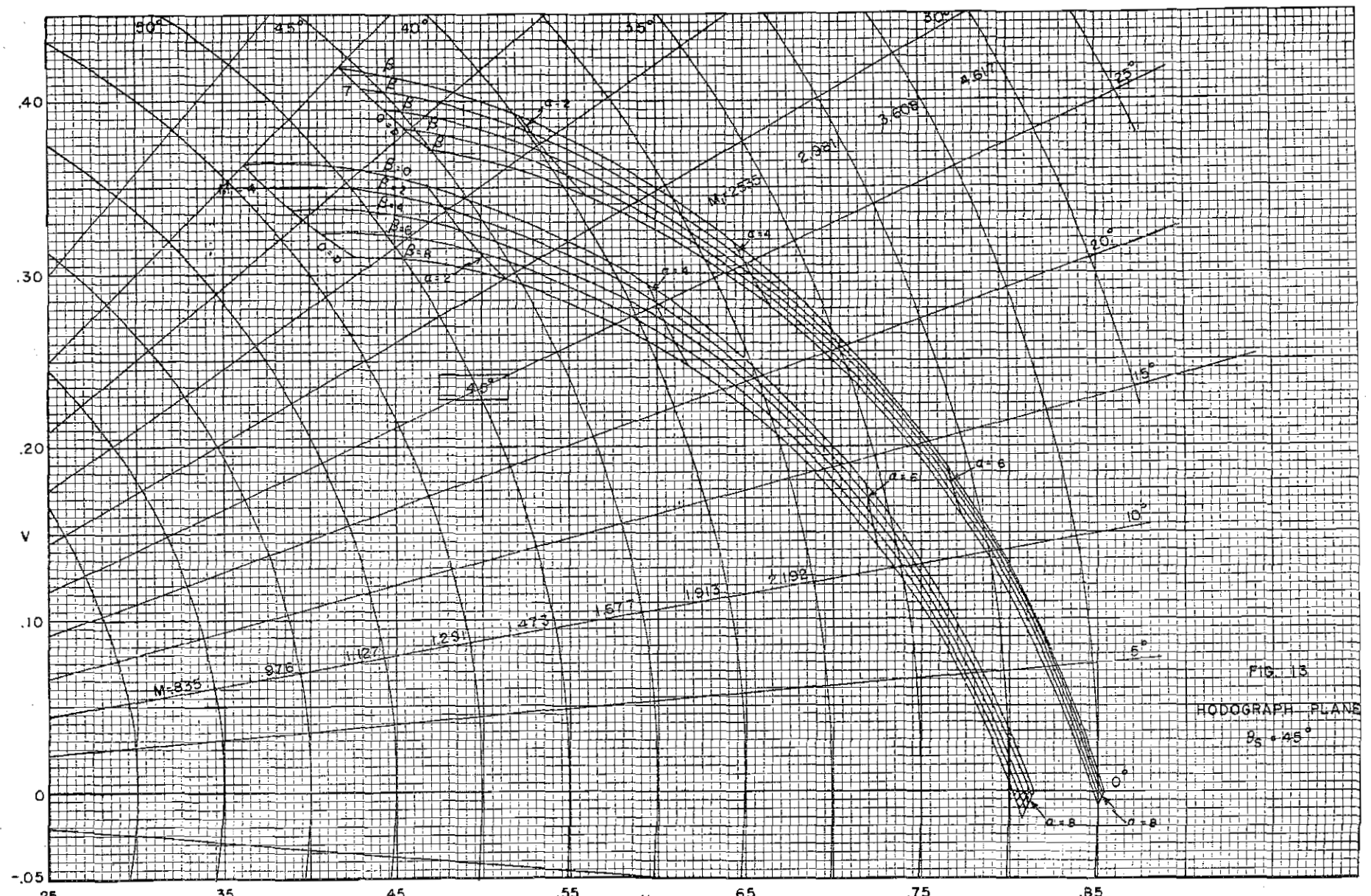


FIG. 13

HODOGRAPH PLANE

$\beta_S = 45°$

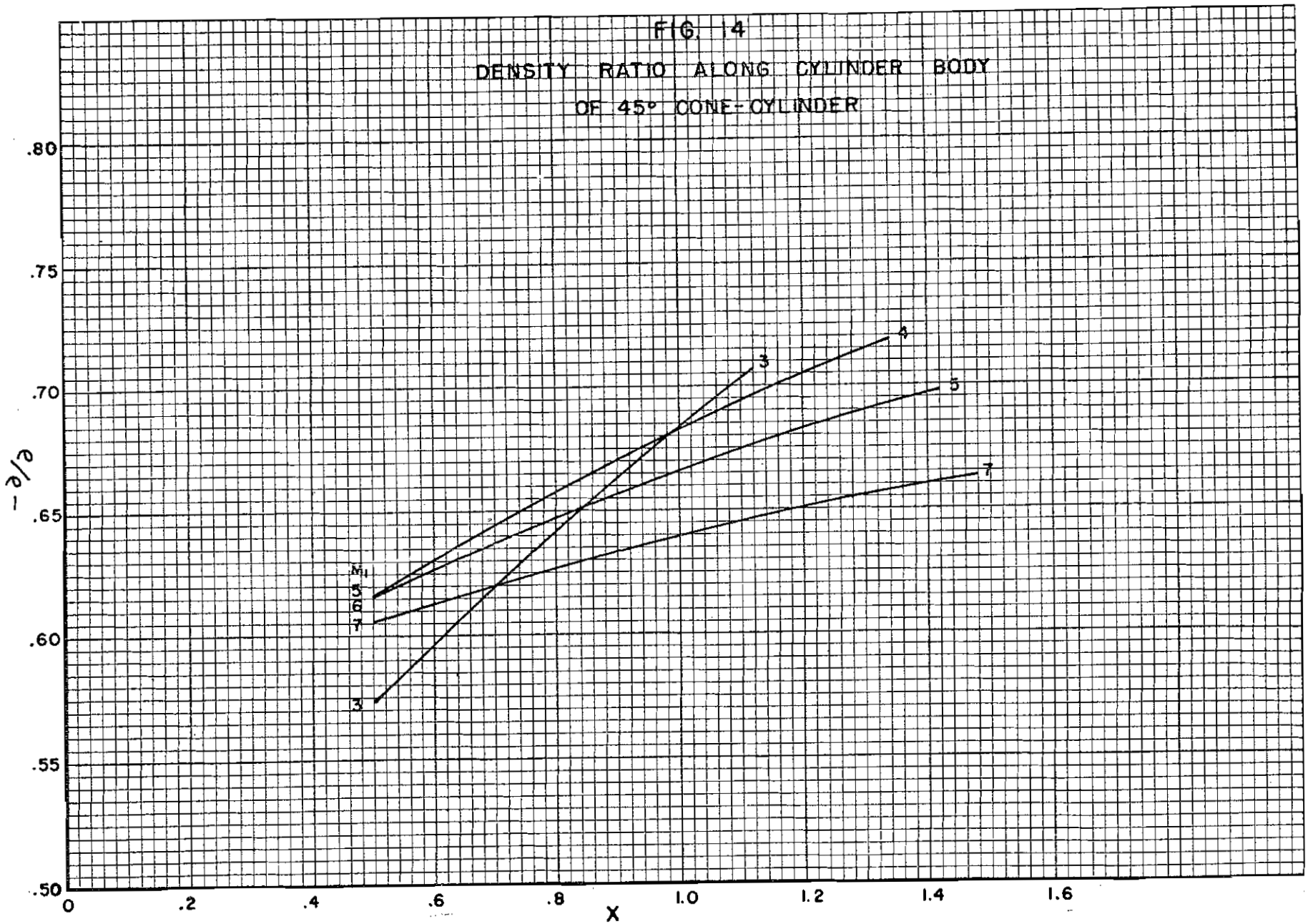


FIG. 14
DENSITY RATIO ALONG CYLINDER BODY
OF 45° CONE-CYLINDER
.80
.75
.70
.65
.60
.55
.50
ρ/ρ∞
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
X
3
4
5
7
M∞
3
5
6
7

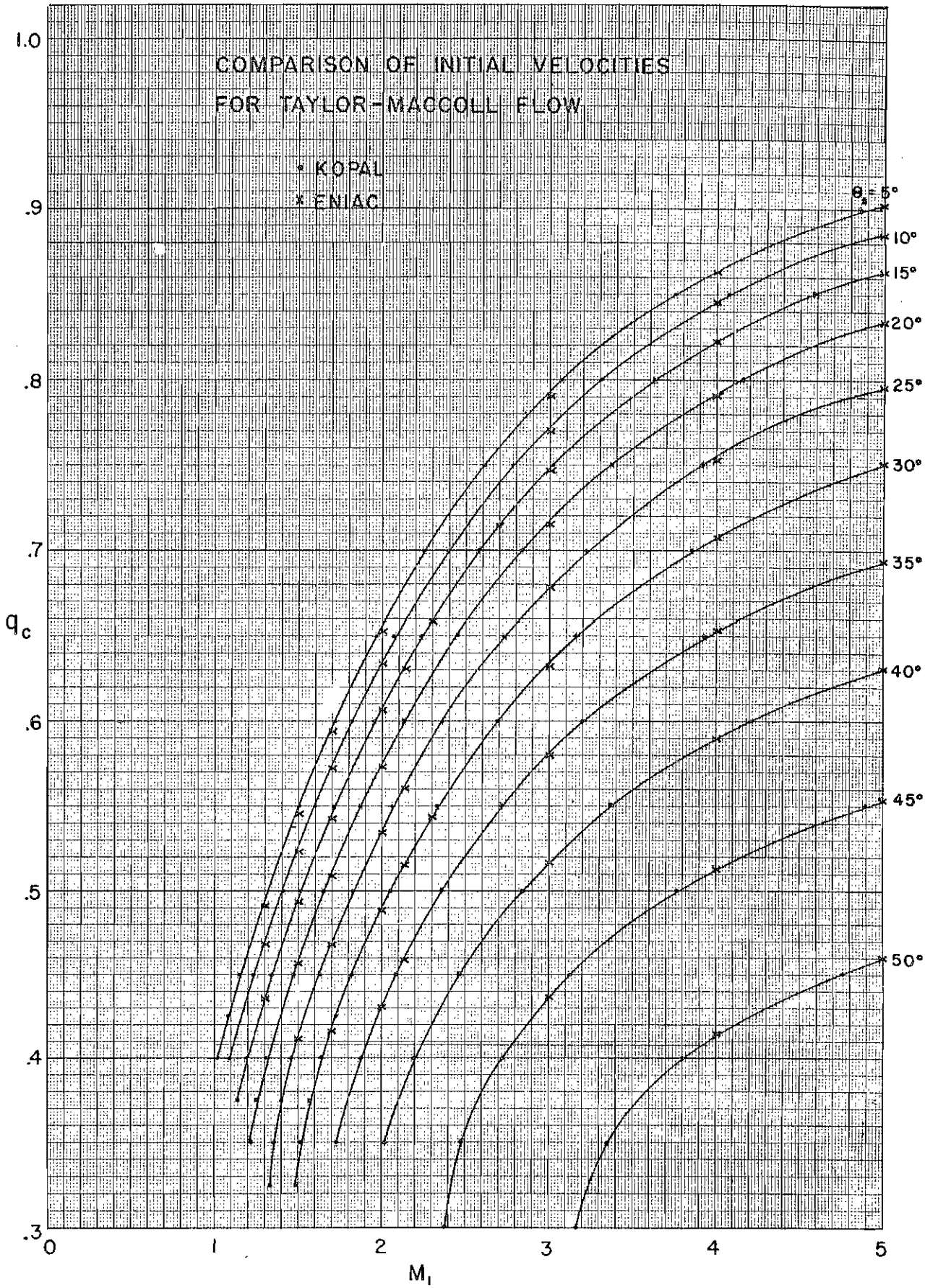

COMPARISON OF INITIAL VELOCITIES
FOR TAYLOR-MACCOLL FLOW
• KOPAL
× ENIAC
θ_s = 5°
10°
15°
20°
25°
30°
35°
40°
45°
50°
q_c
1.0
.9
.8
.7
.6
.5
.4
.3
0
1
2
3
4
5
M_1

Figure 15

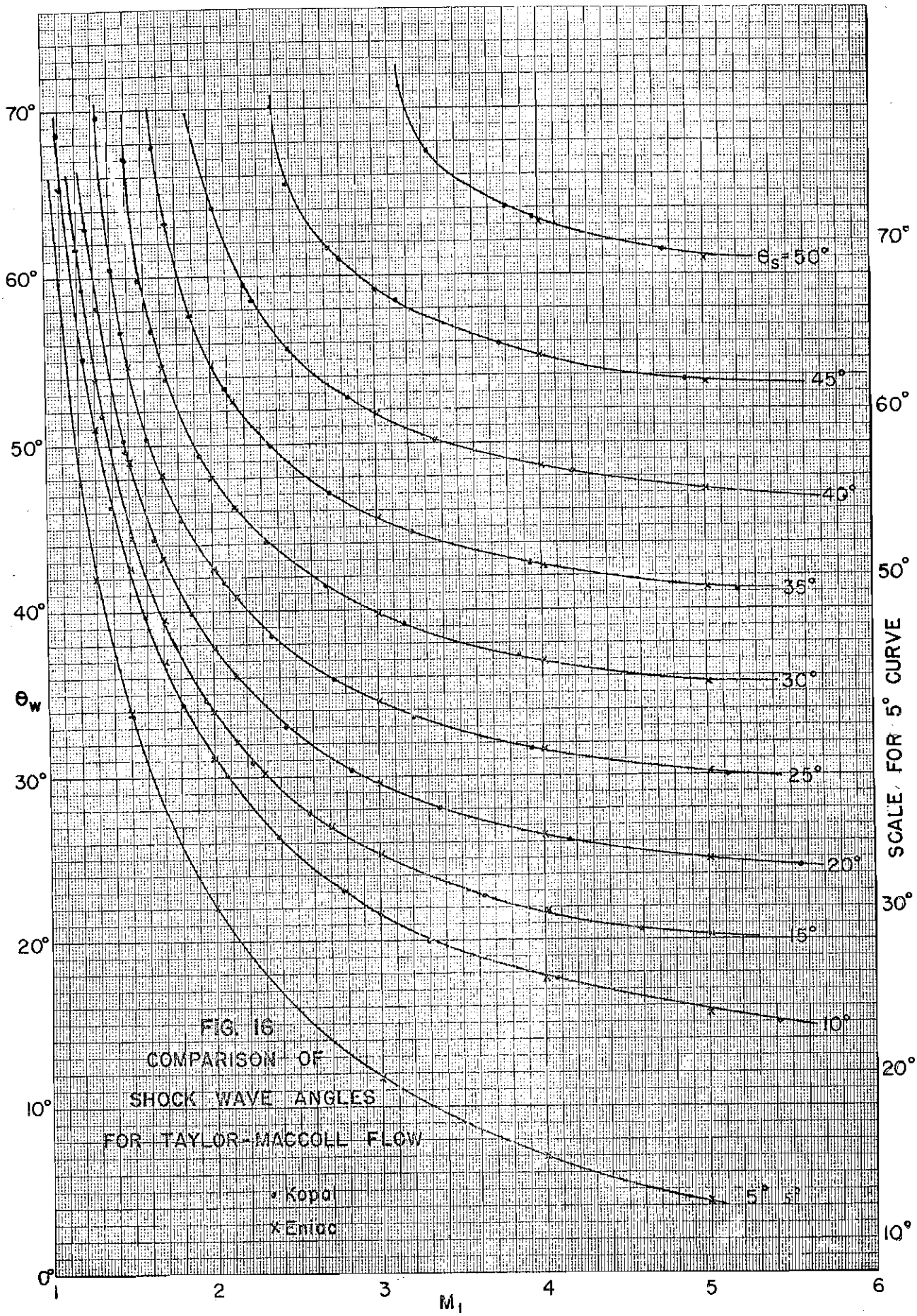


FIG. 16
COMPARISON OF
SHOCK WAVE ANGLES
FOR TAYLOR-MACCOLL FLOW

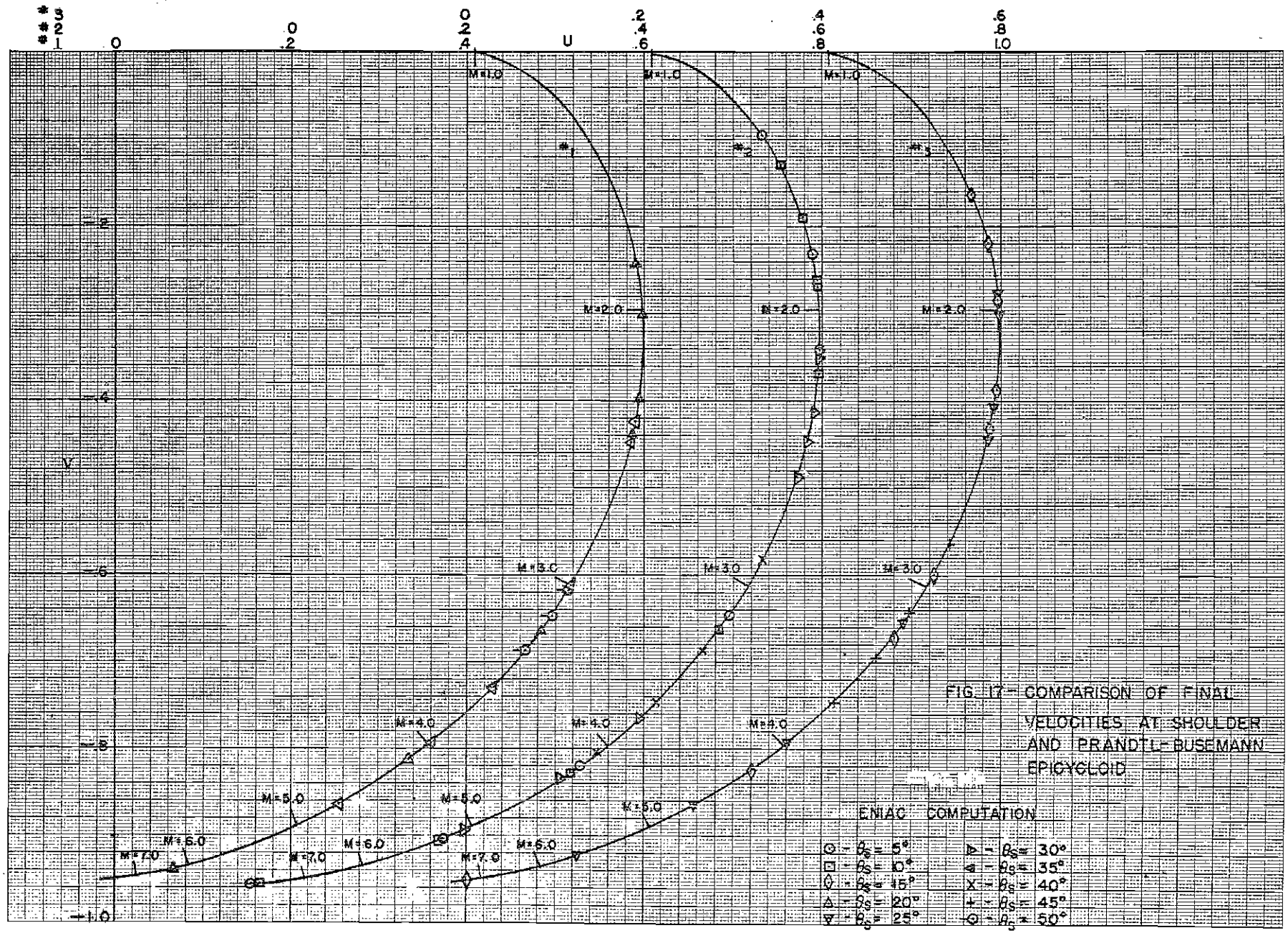


FIG. 17 - COMPARISON OF FINAL VELOCITIES AT SHOULDER AND PRANDTL-BUSEMANN EPICYCLOID

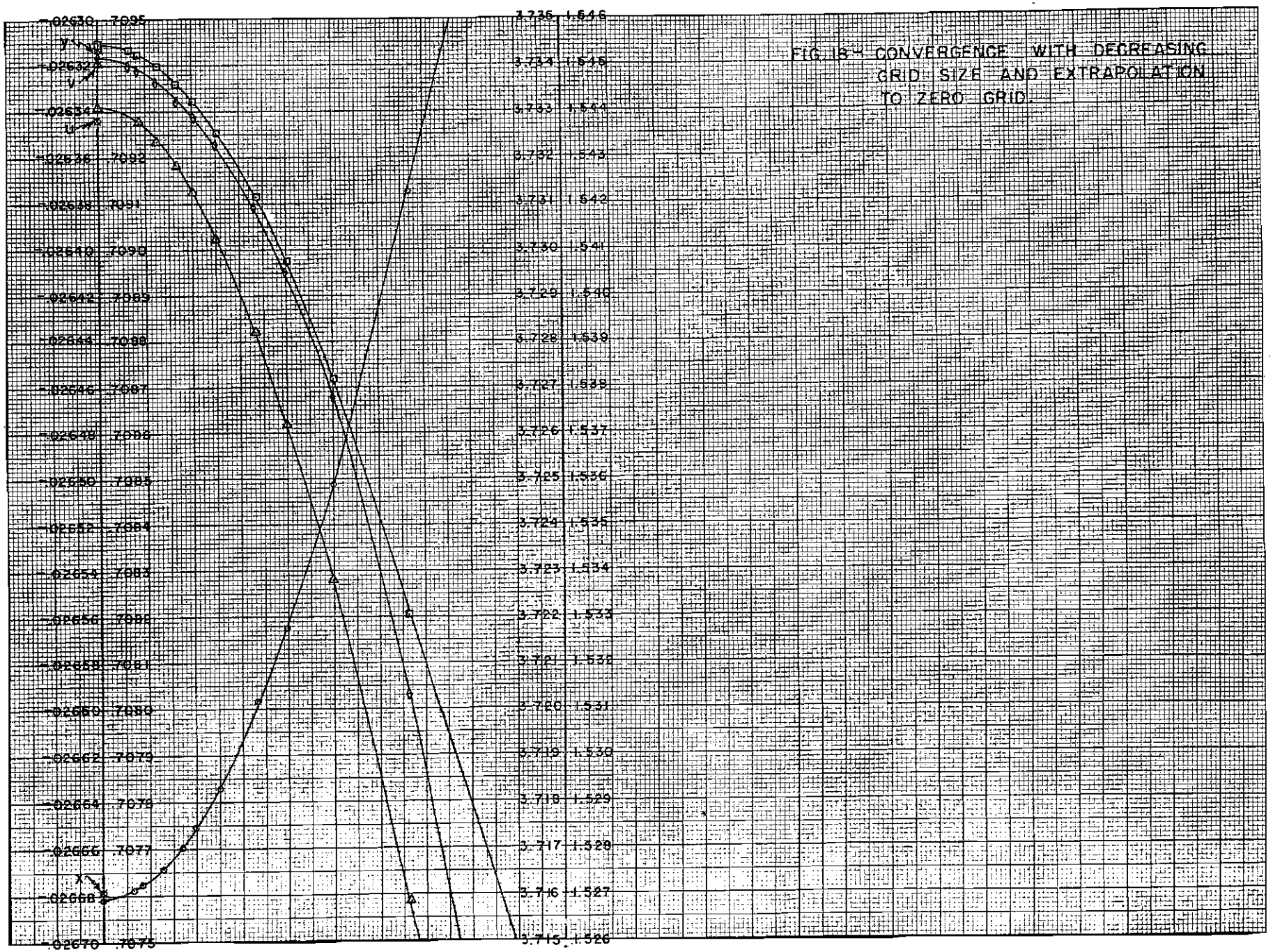
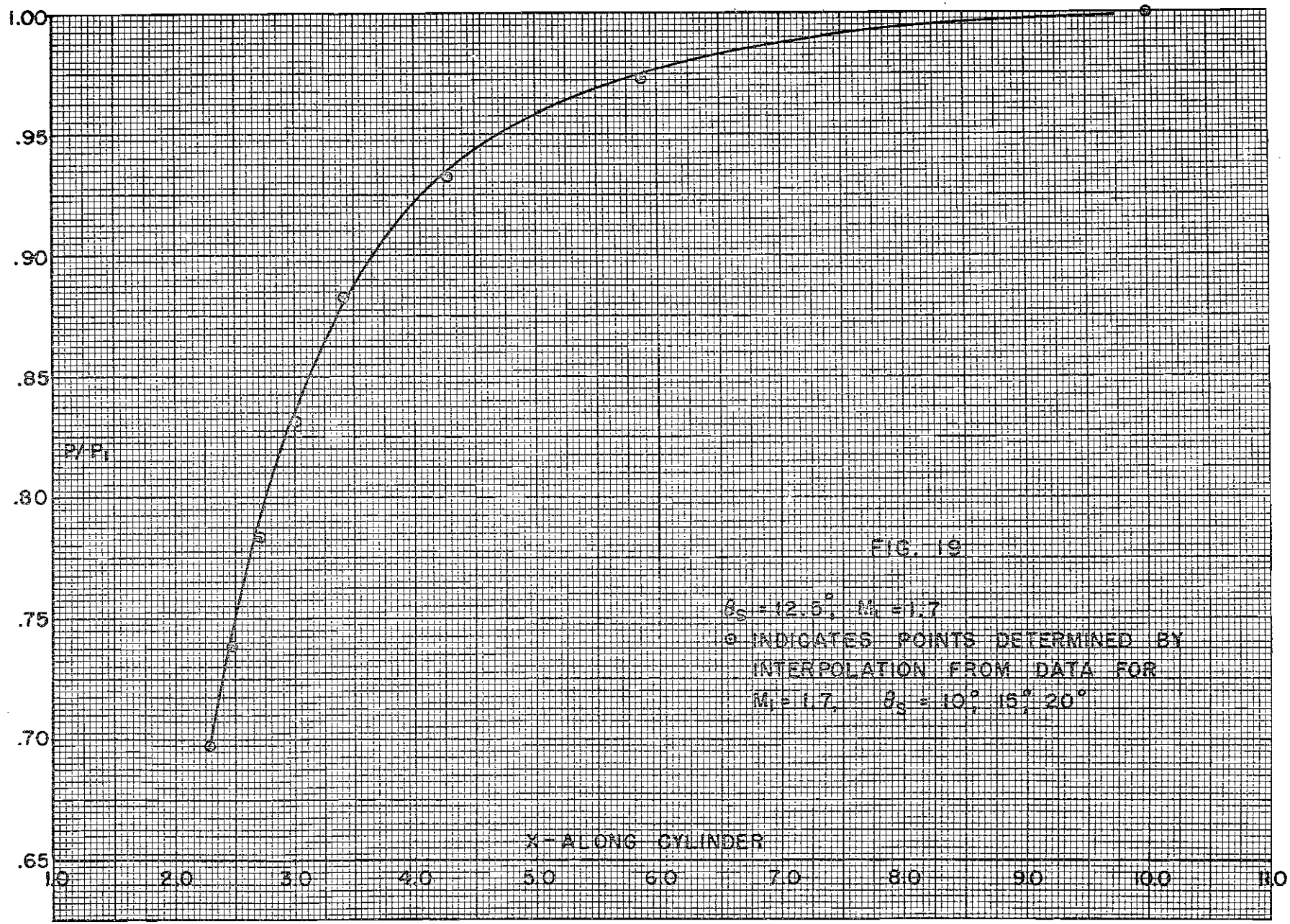
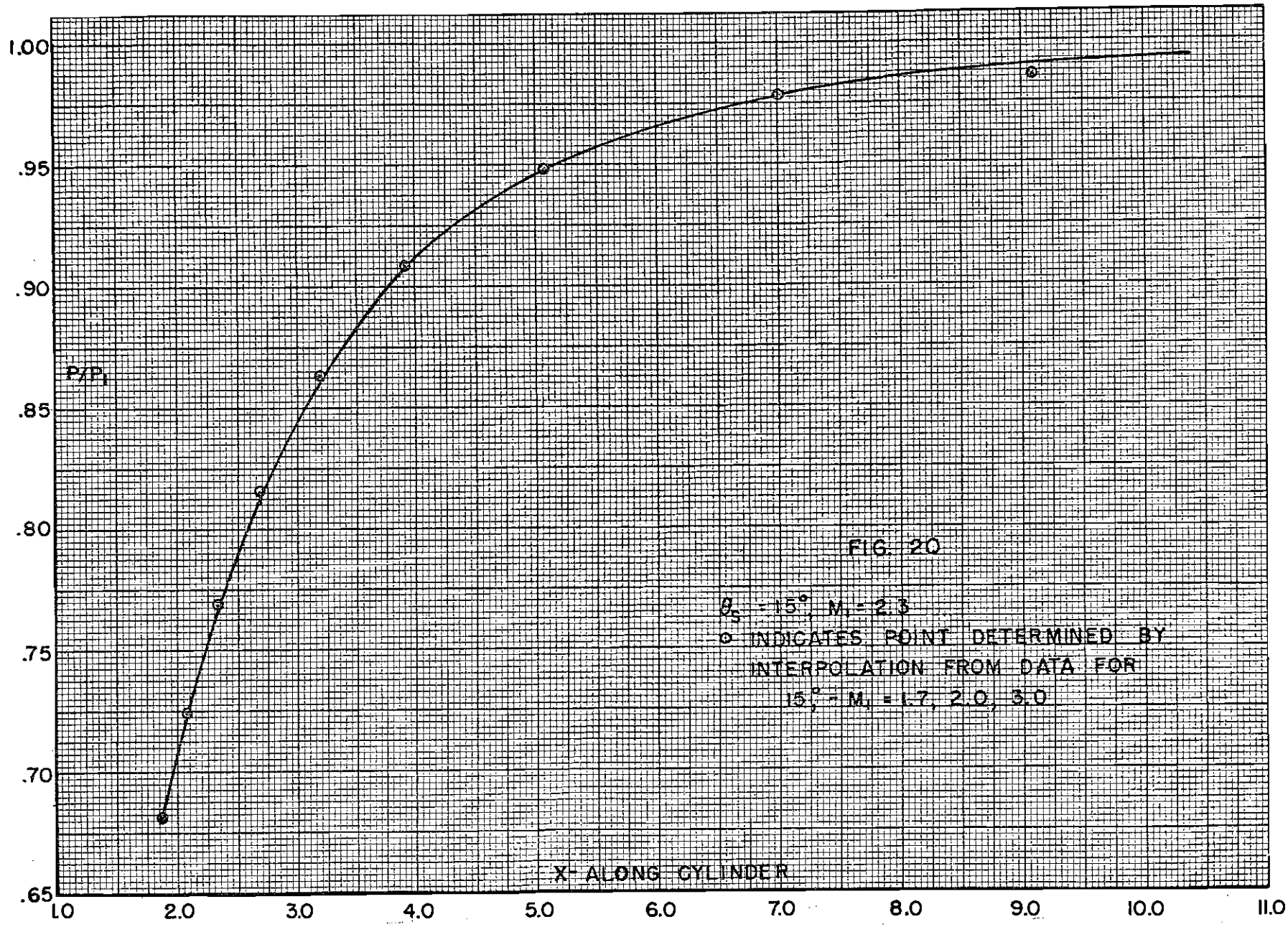


FIG. 18 — CONVERGENCE WITH DECREASING GRID SIZE AND EXTRAPOLATION TO ZERO GRID.


1.00
.95
.90
.85
.80
.75
.70
.65
P/P1
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
X - ALONG CYLINDER
FIG. 19
θs = 12.5°, M1 = 1.7
⊙ INDICATES POINTS DETERMINED BY INTERPOLATION FROM DATA FOR M1 = 1.7, θs = 10°, 15°, 20°


1.00
.95
.90
.85
.80
.75
.70
.65
P/P1
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
X- ALONG CYLINDER
FIG. 20
θs = 15°, M1 = 2.3
⊙ INDICATES POINT DETERMINED BY INTERPOLATION FROM DATA FOR 15°, M1 = 1.7, 2.0, 3.0

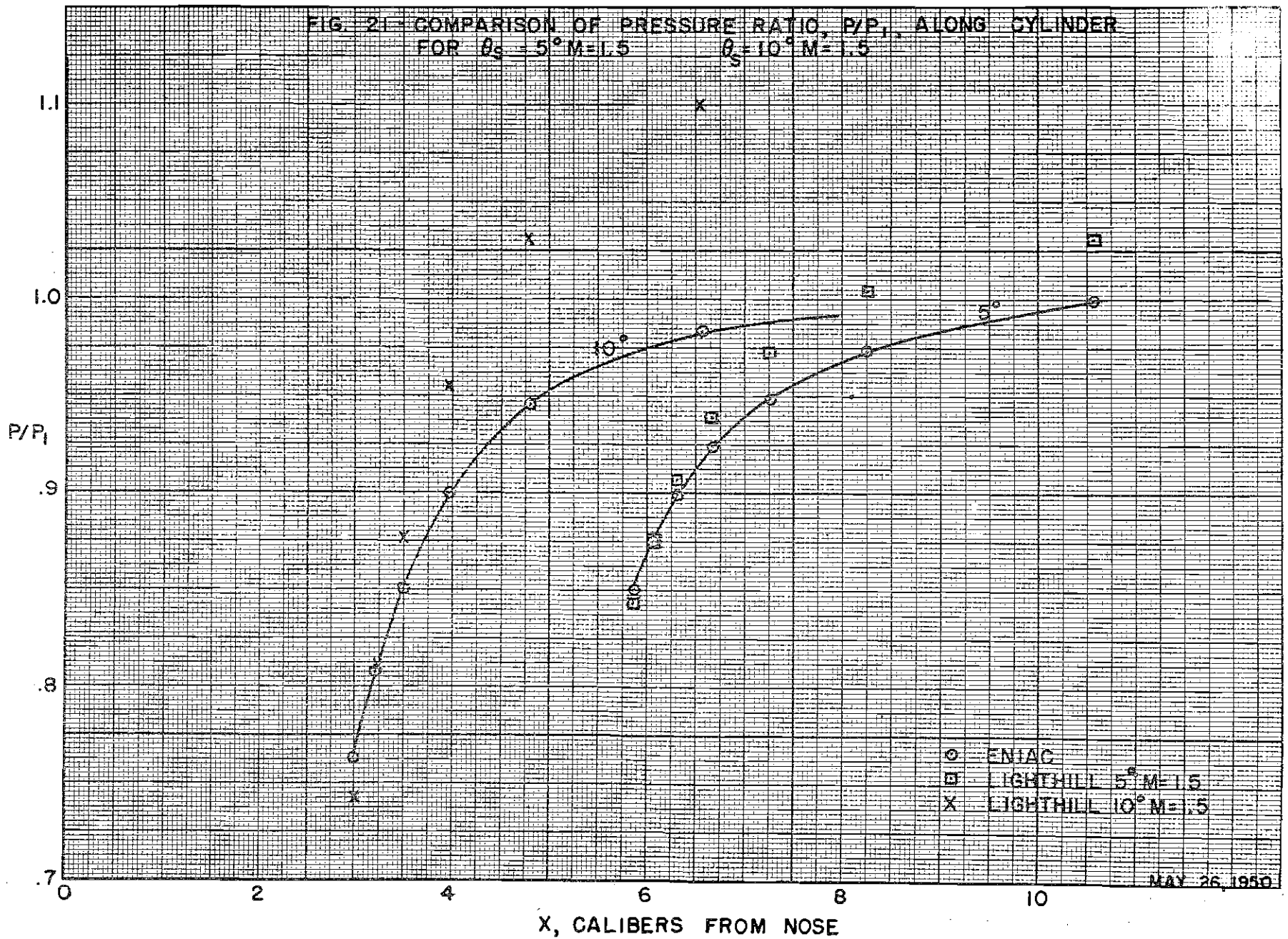


FIG. 21 - COMPARISON OF PRESSURE RATIO, P/P1, ALONG CYLINDER
FOR θS = 5° M=1.5 θS = 10° M=1.5
1.1
1.0
.9
.8
.7
P/P1
0
2
4
6
8
10
X, CALIBERS FROM NOSE
10°
5°
ENIAC
LIGHTHILL 5° M=1.5
LIGHTHILL 10° M=1.5
MAY 26, 1950

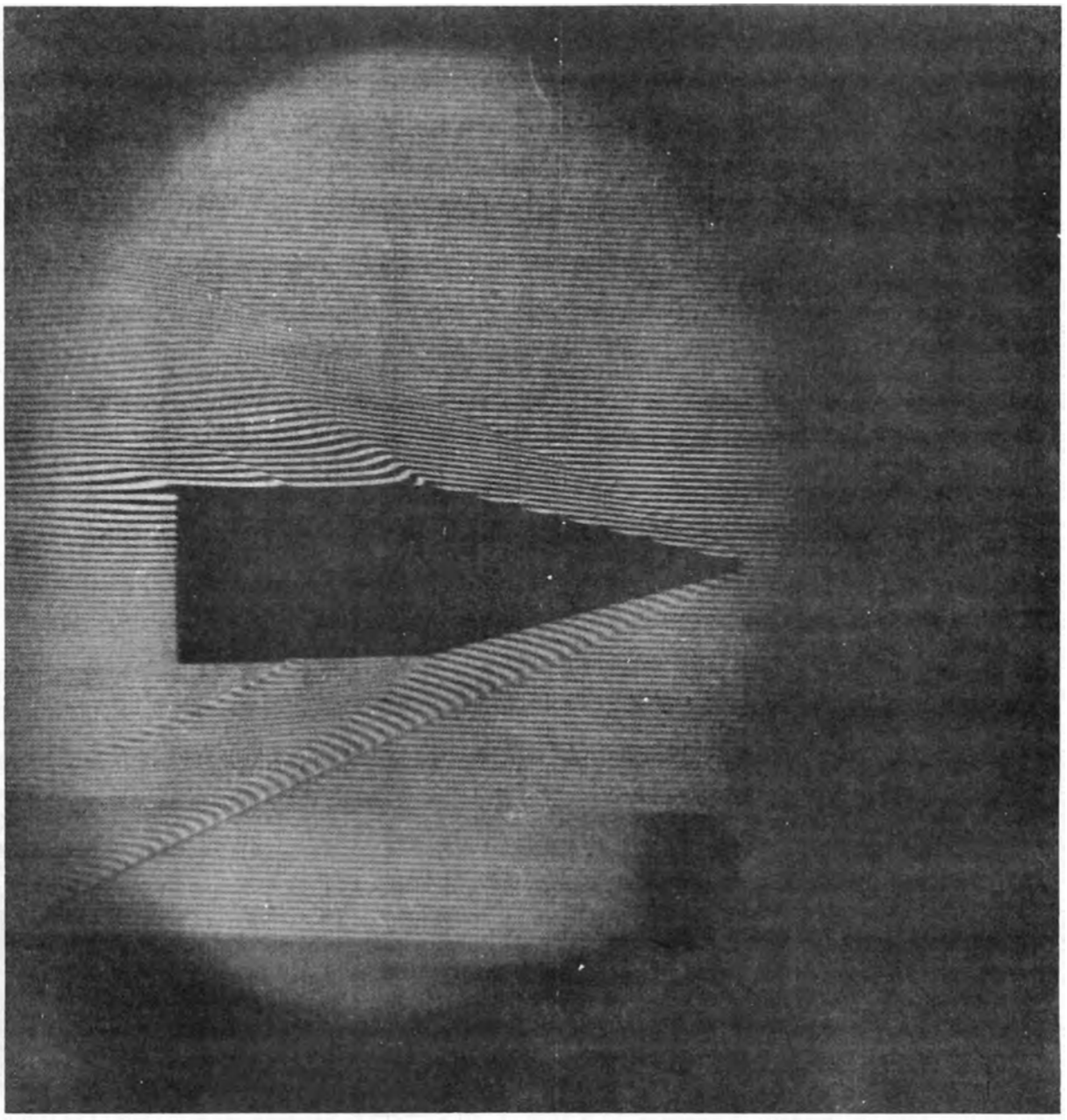


Figure 22. Interferograme $\theta_s = 30°$, u= 3080 f.p.s.

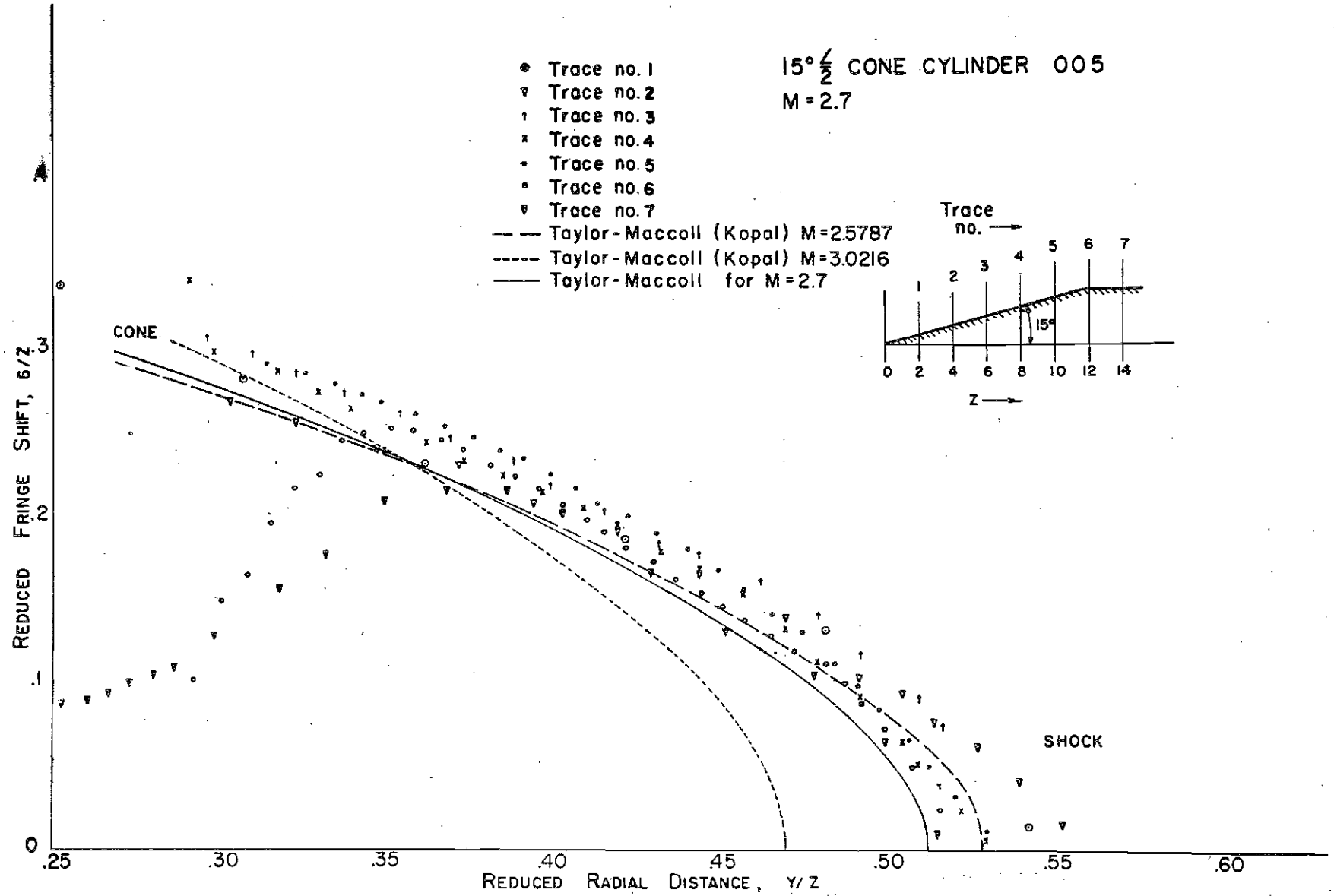


Figure 23. Test for Taylor-Maccoll Flow

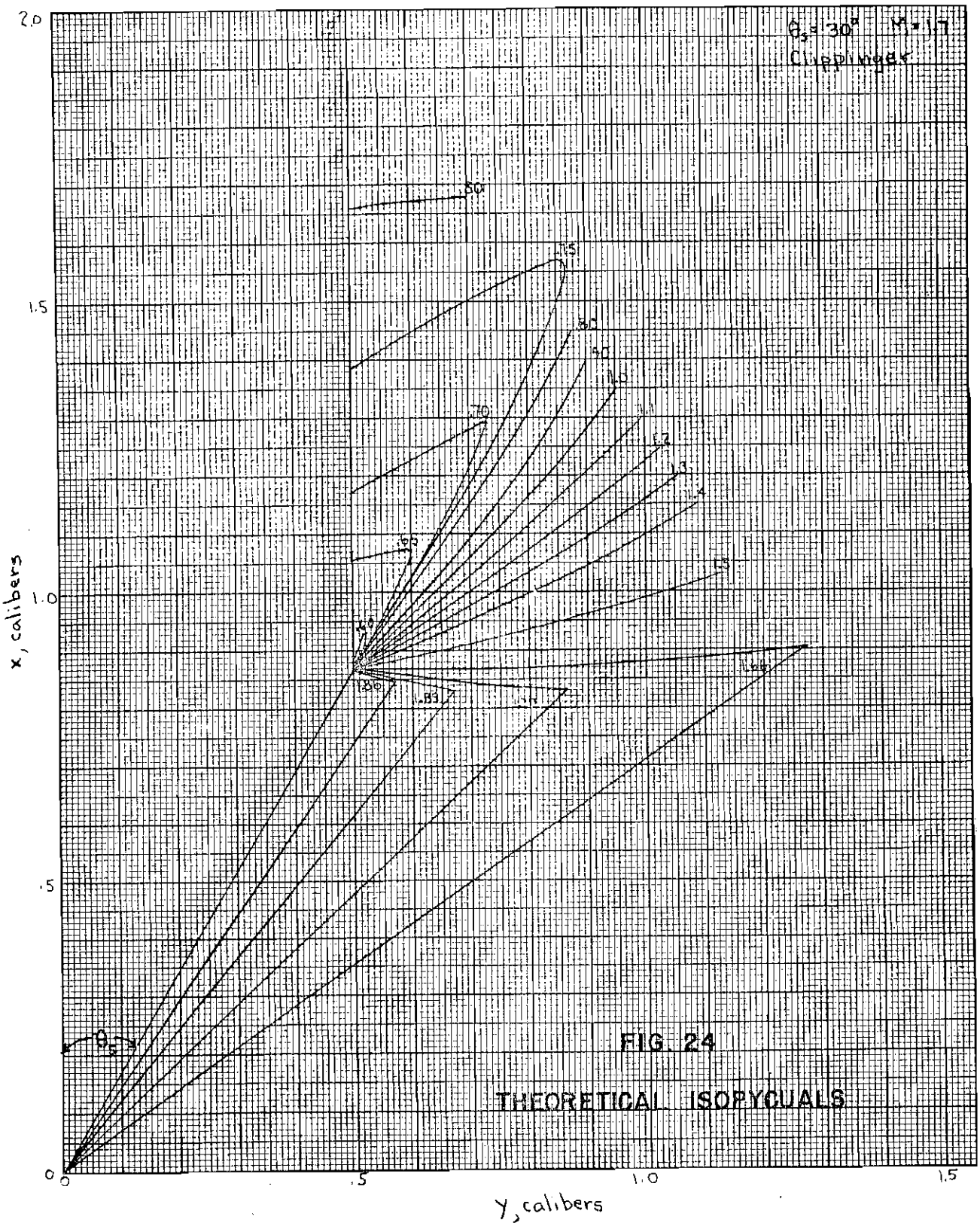


FIG. 24

THEORETICAL ISOPYCUALS

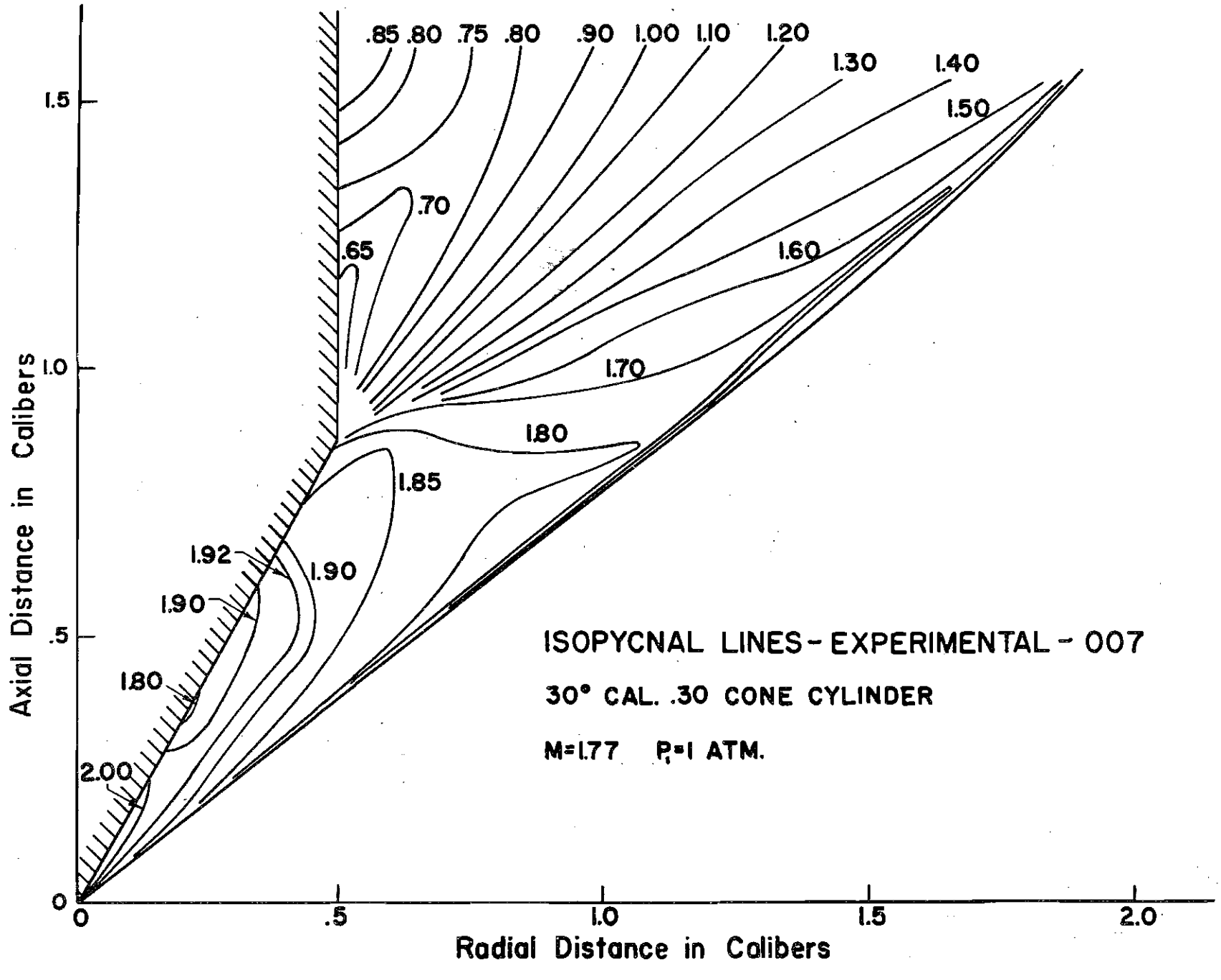


Figure 25. Experimental Isopycnals

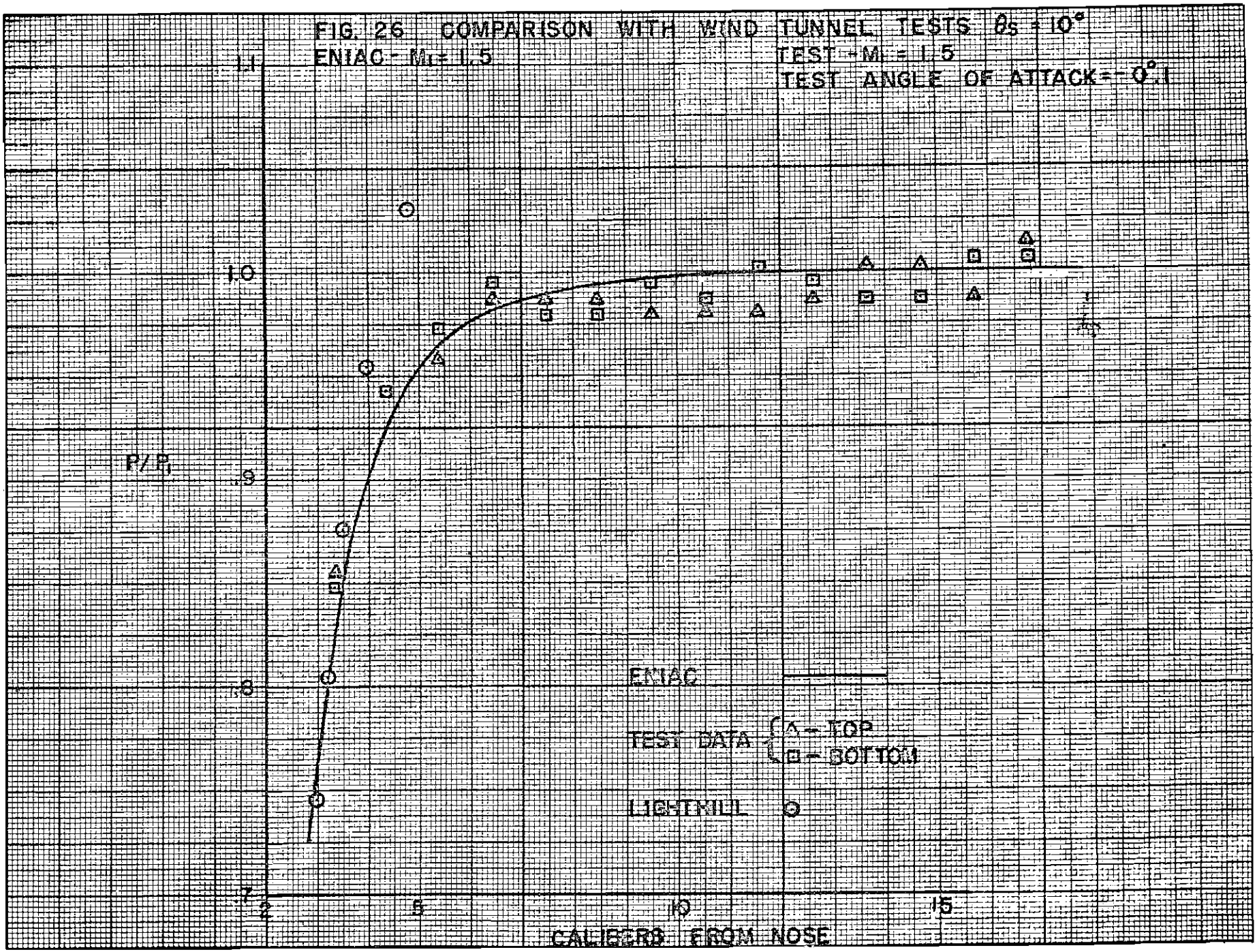


FIG. 26 COMPARISON WITH WIND TUNNEL TESTS $\theta_s = 10°$
ENIAC - $M_1 = 1.5$
TEST - $M_1 = 1.5$
TEST ANGLE OF ATTACK = - 0°.1
1.1
1.0
.9
.8
.7
P/P1
ENIAC
TEST DATA
△ - TOP
□ - BOTTOM
LIGHTHILL
0
5
10
15
CALIBERS FROM NOSE

FIG. 27 COMPARISON WITH WIND TUNNEL TESTS $\delta_f = 10°$
ENAC $M_\infty = 1.72$ TEST $M_\infty = 1.73°$
TEST ANGLE OF ATTACK = 0°
C_{P_1}
1.0
.9
.8
.7
0
5
10
15
CALIBERS FROM NOSE
ENAC
TEST DATA (A TMS
(B BOTTOM

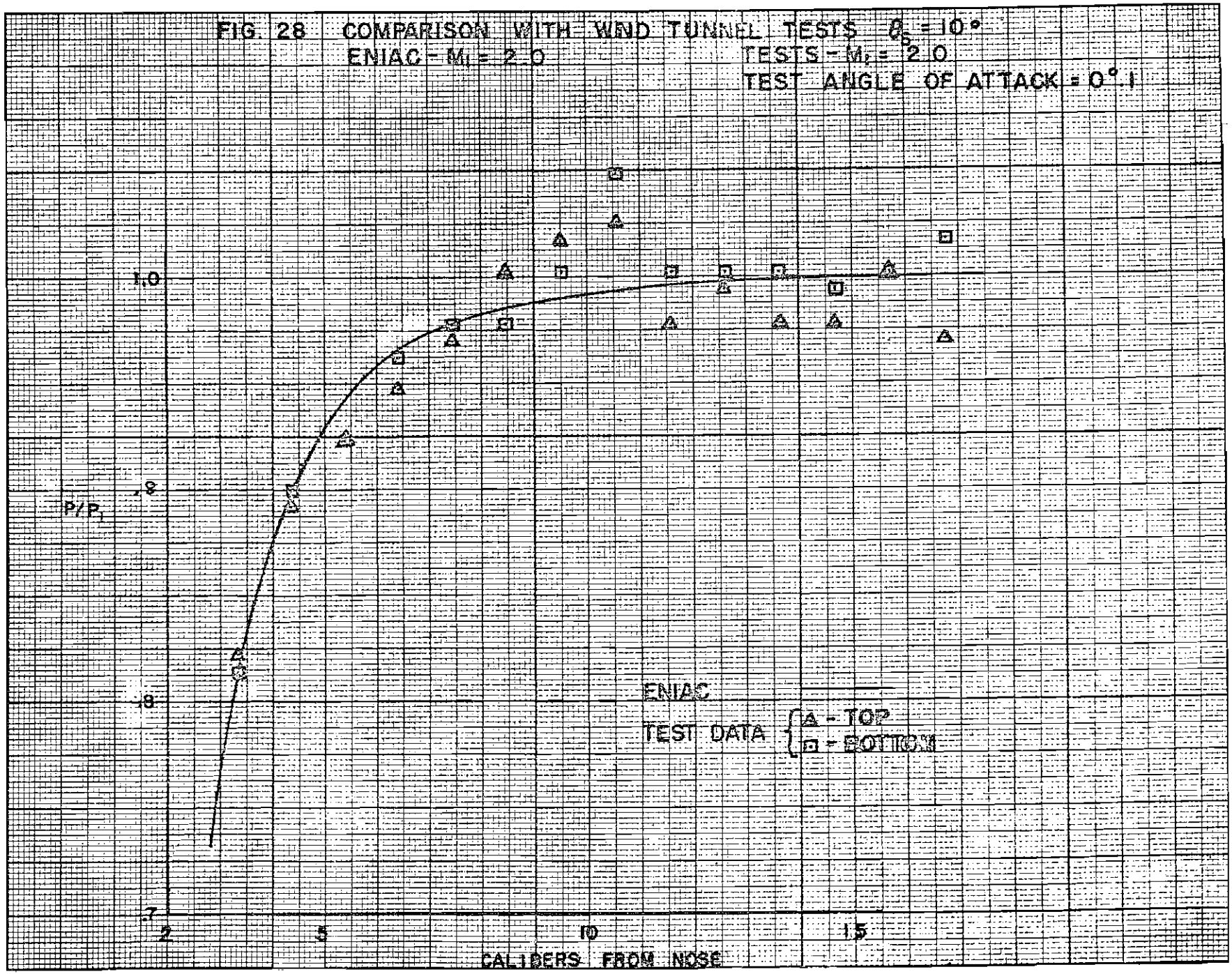


FIG. 28 COMPARISON WITH WIND TUNNEL TESTS $\theta_s = 10°$
ENIAC - $M_1 = 2.0$
TESTS - $M_1 = 2.0$
TEST ANGLE OF ATTACK = 0°.1
1.0
.9
.8
.7
P/P1
2
5
10
15
CALIBERS FROM NOSE
ENIAC
TEST DATA
Δ - TOP
□ - BOTTOM

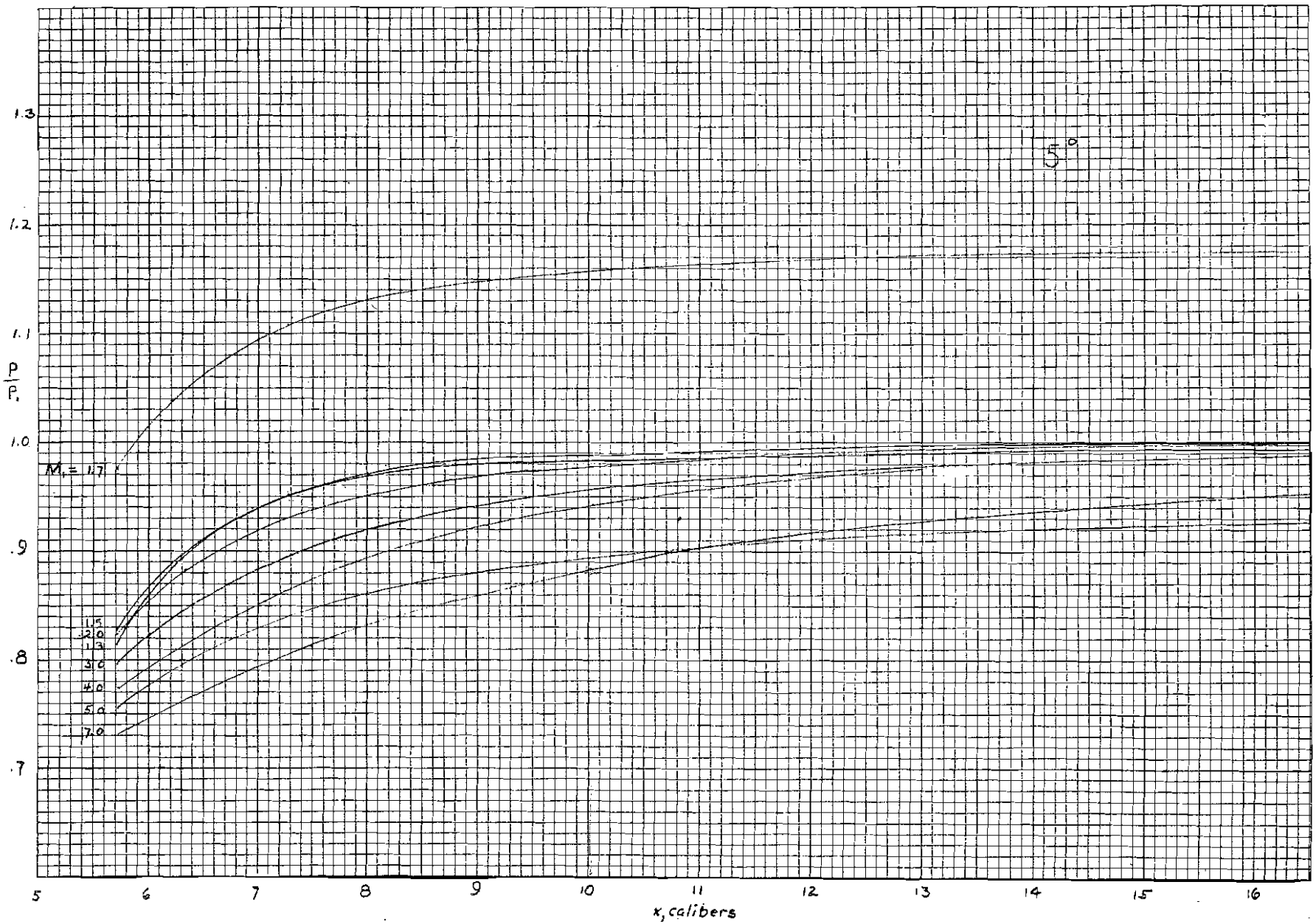

1.3
1.2
1.1
P/P1
1.0
.9
.8
.7
M1 = 1.7
1.5
2.0
1.3
3.0
4.0
5.0
7.0
5°
5
6
7
8
9
10
11
12
13
14
15
16
x, calibers

Figure 29

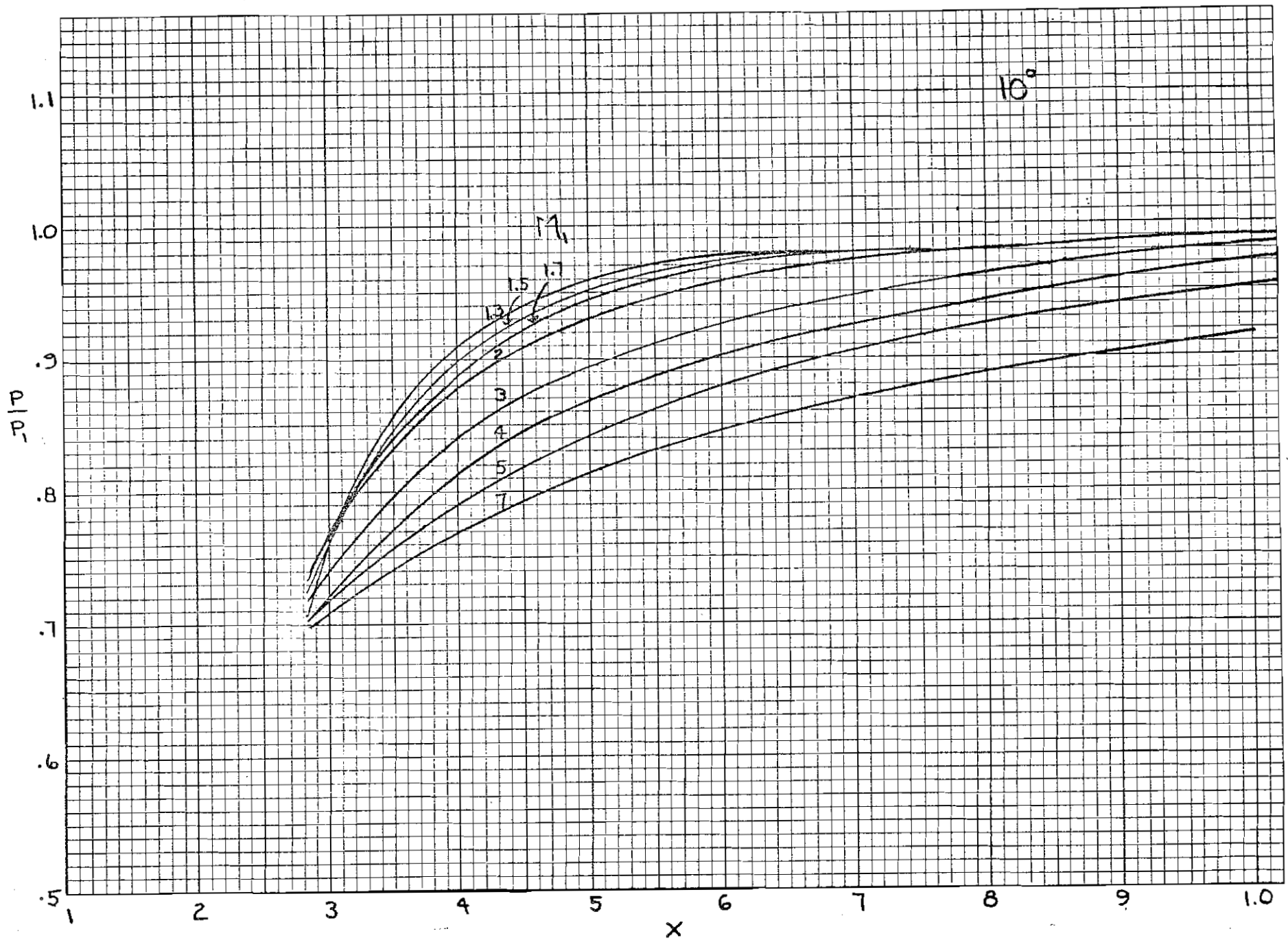


Figure 30

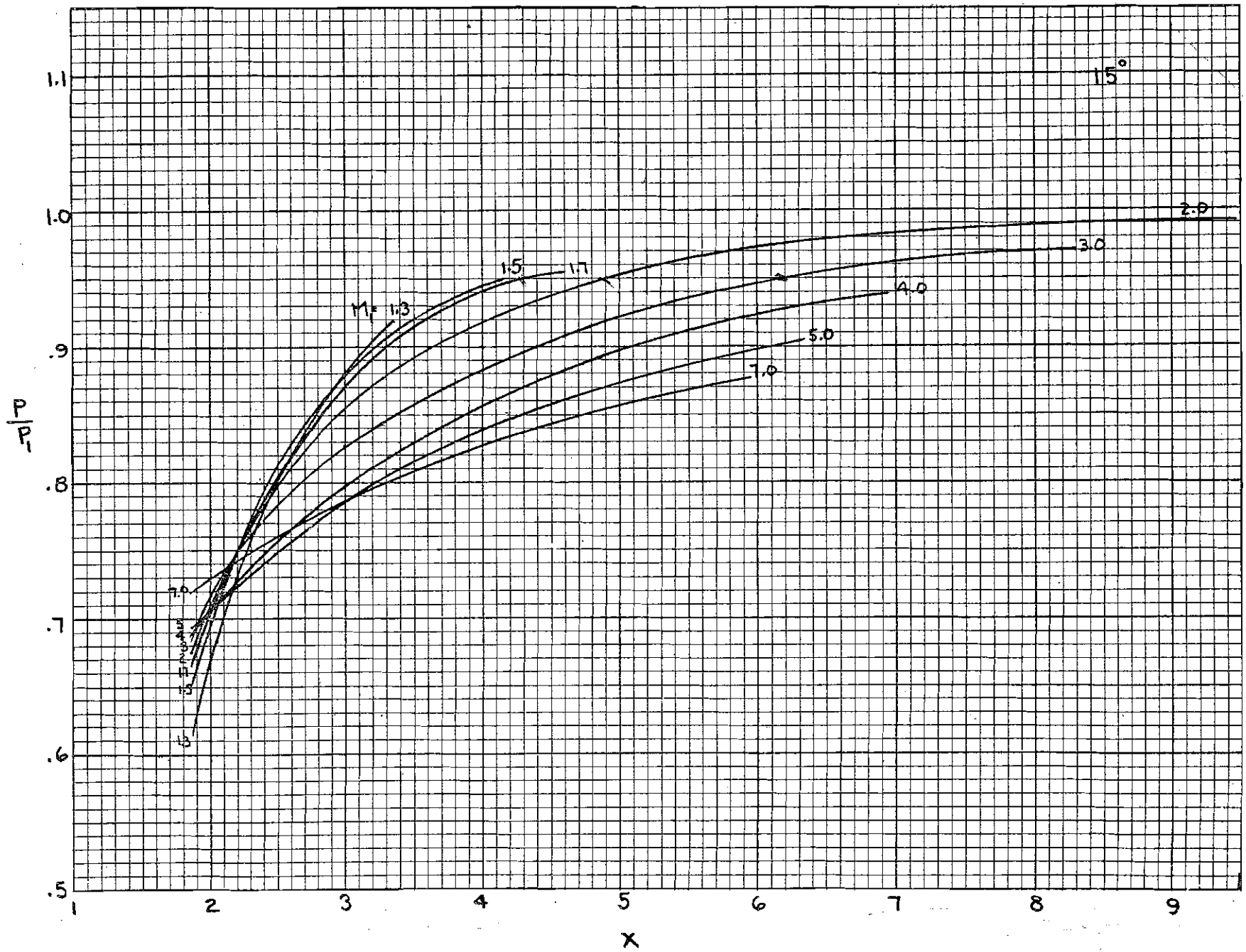


Figure 31

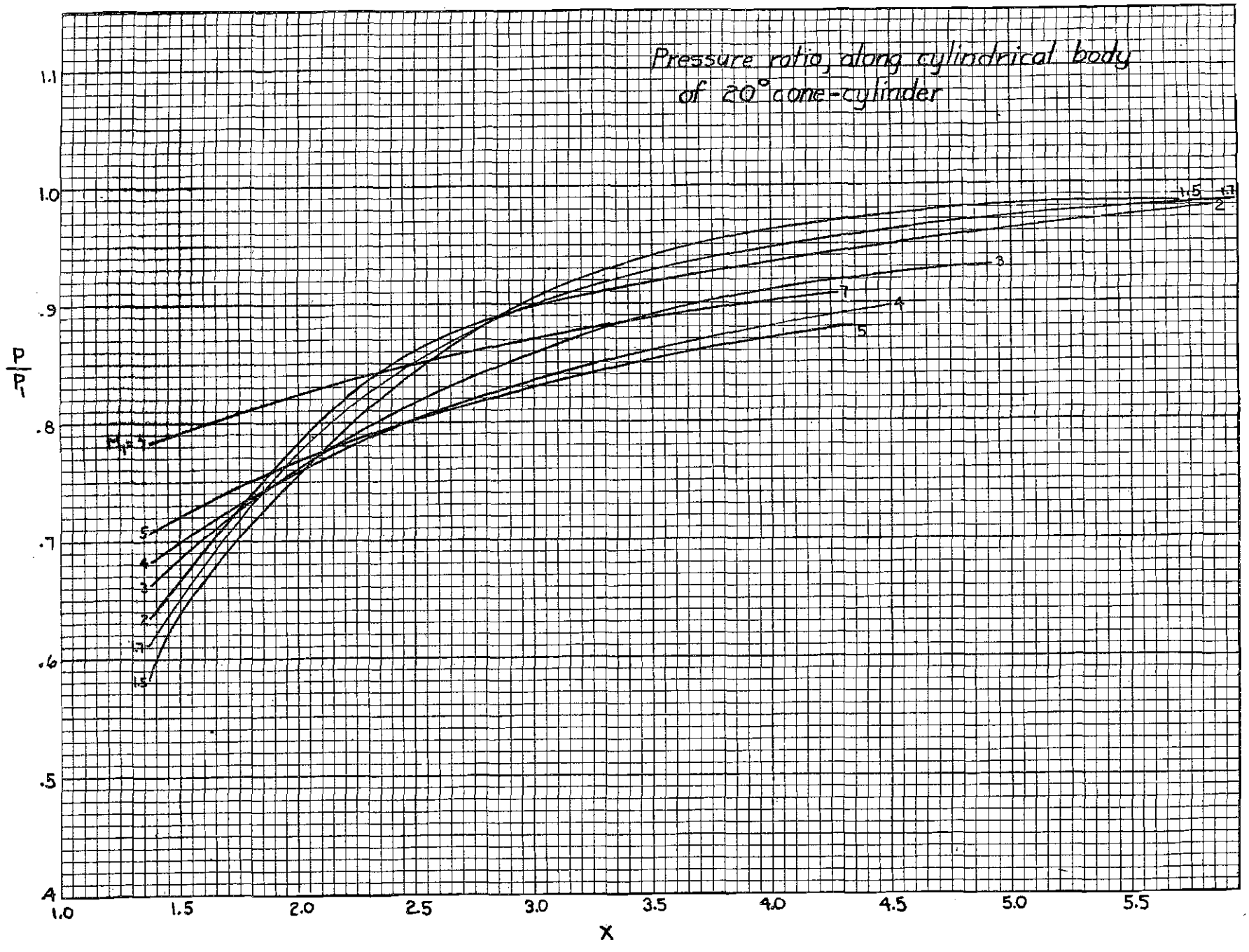

Pressure ratio, along cylindrical body of 20° cone-cylinder
P/P1
X
1.1
1.0
.9
.8
.7
.6
.5
.4
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
M1=5
5
4
3
2
1.7
1.5
1.5
1.7
2
3
4
5

Figure 32

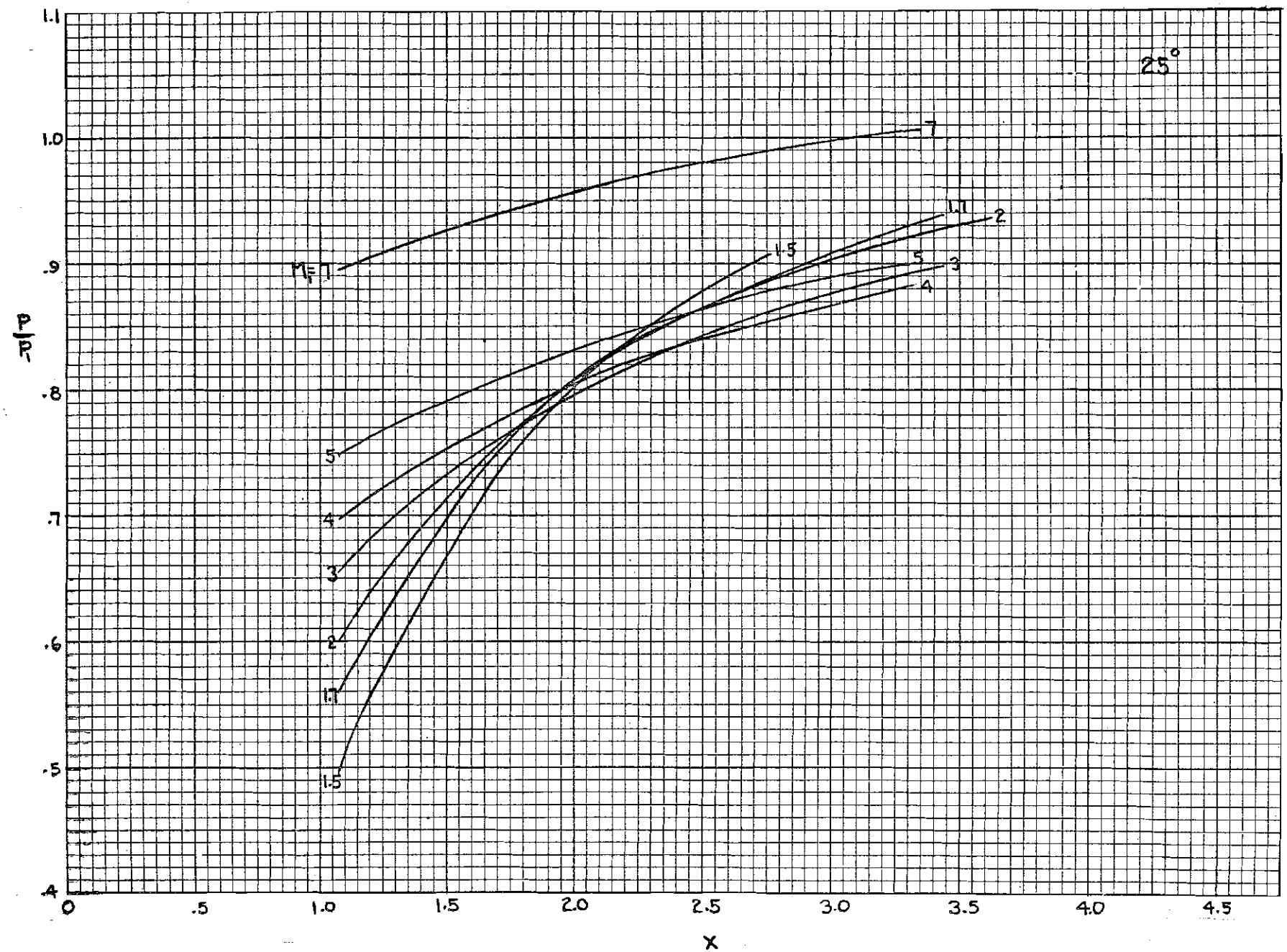

25°
$M_1 = 7$
7
1.1
2
1.5
5
3
4
5
4
3
2
1.1
1.5
$\frac{P}{P_1}$
1.1
1.0
.9
.8
.7
.6
.5
.4
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
X

Figure 33

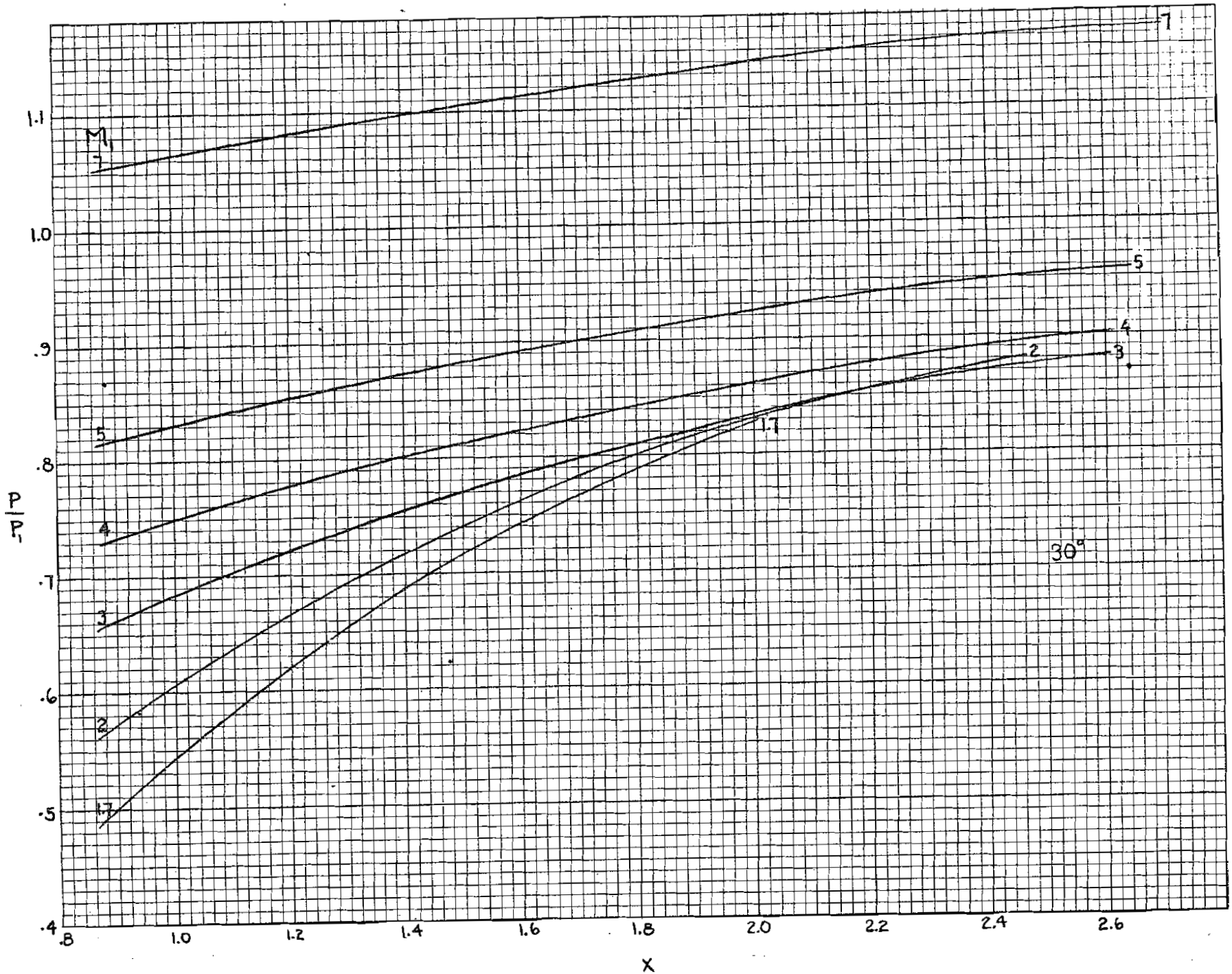


Figure 34

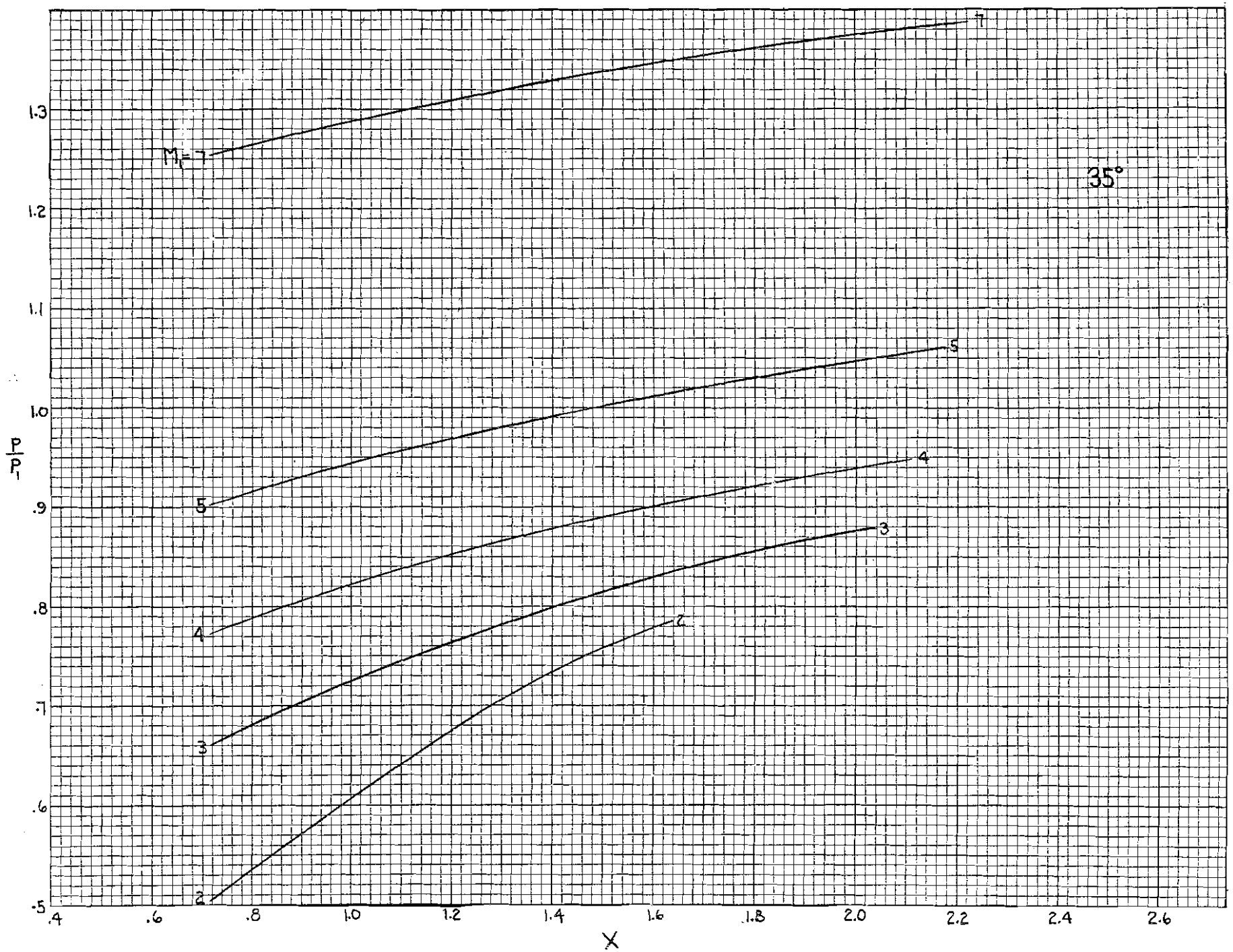

M_1=7
35°
7
5
4
3
2
$\frac{P}{P_1}$
X
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6

Figure 35

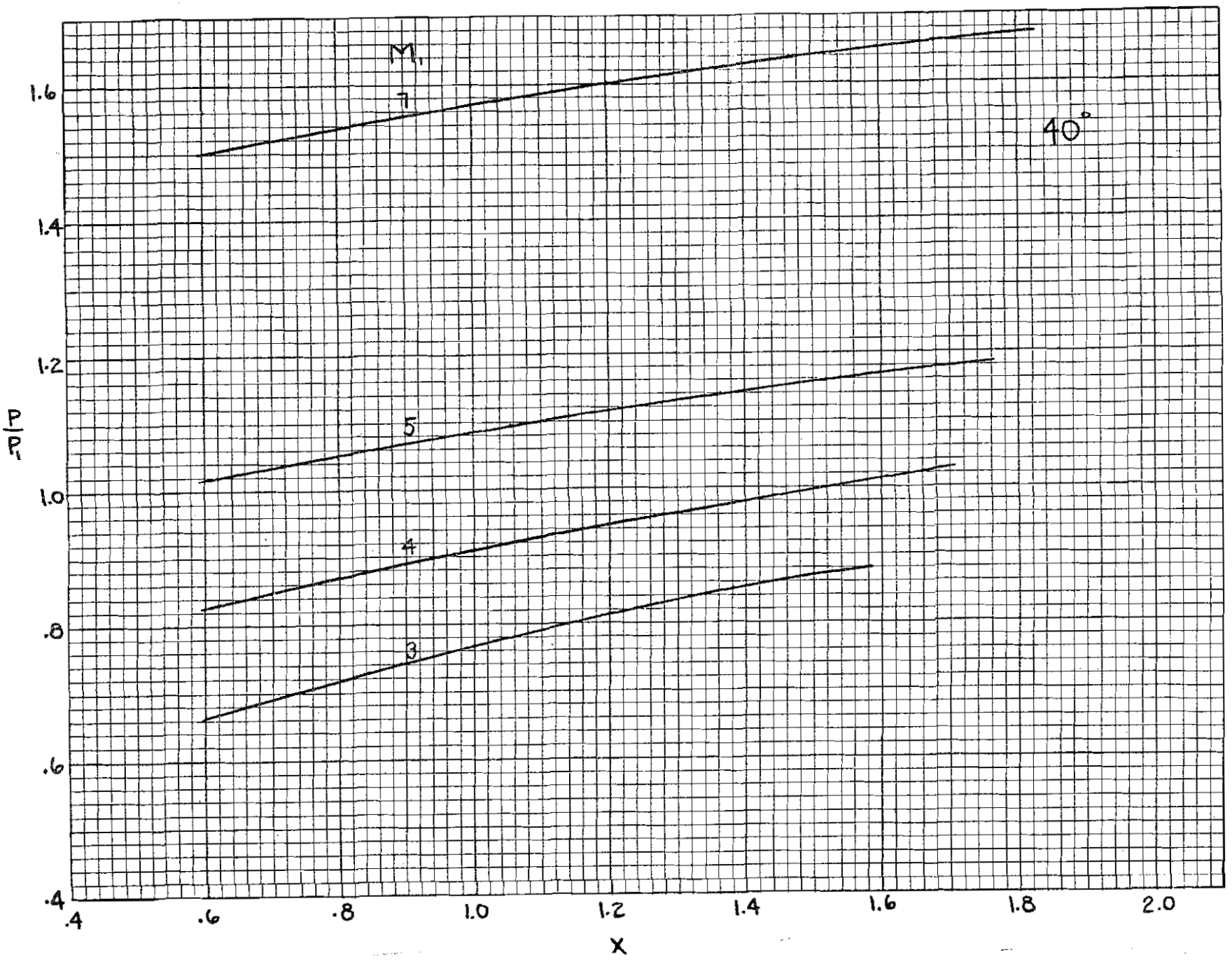


Figure 36

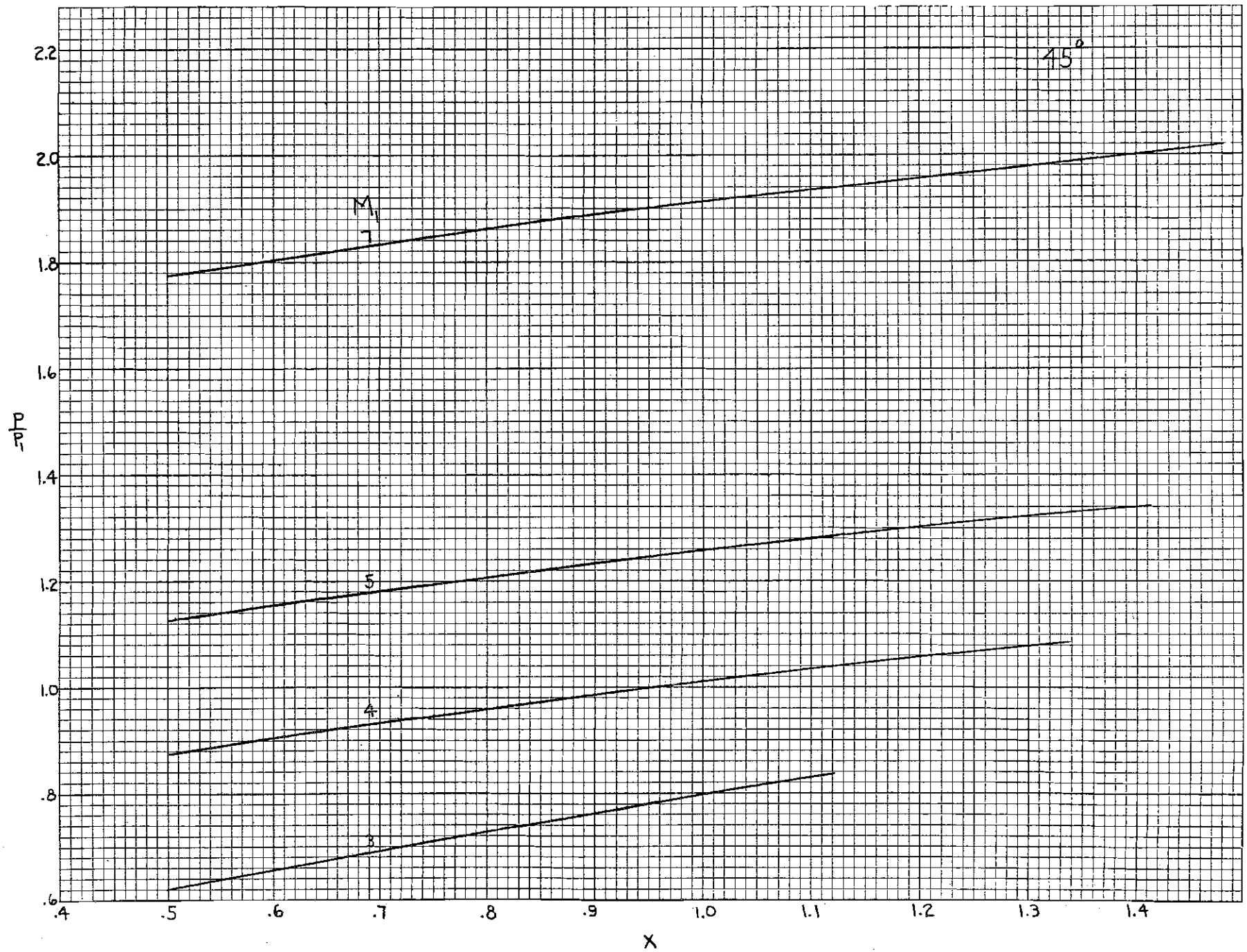


Figure 37

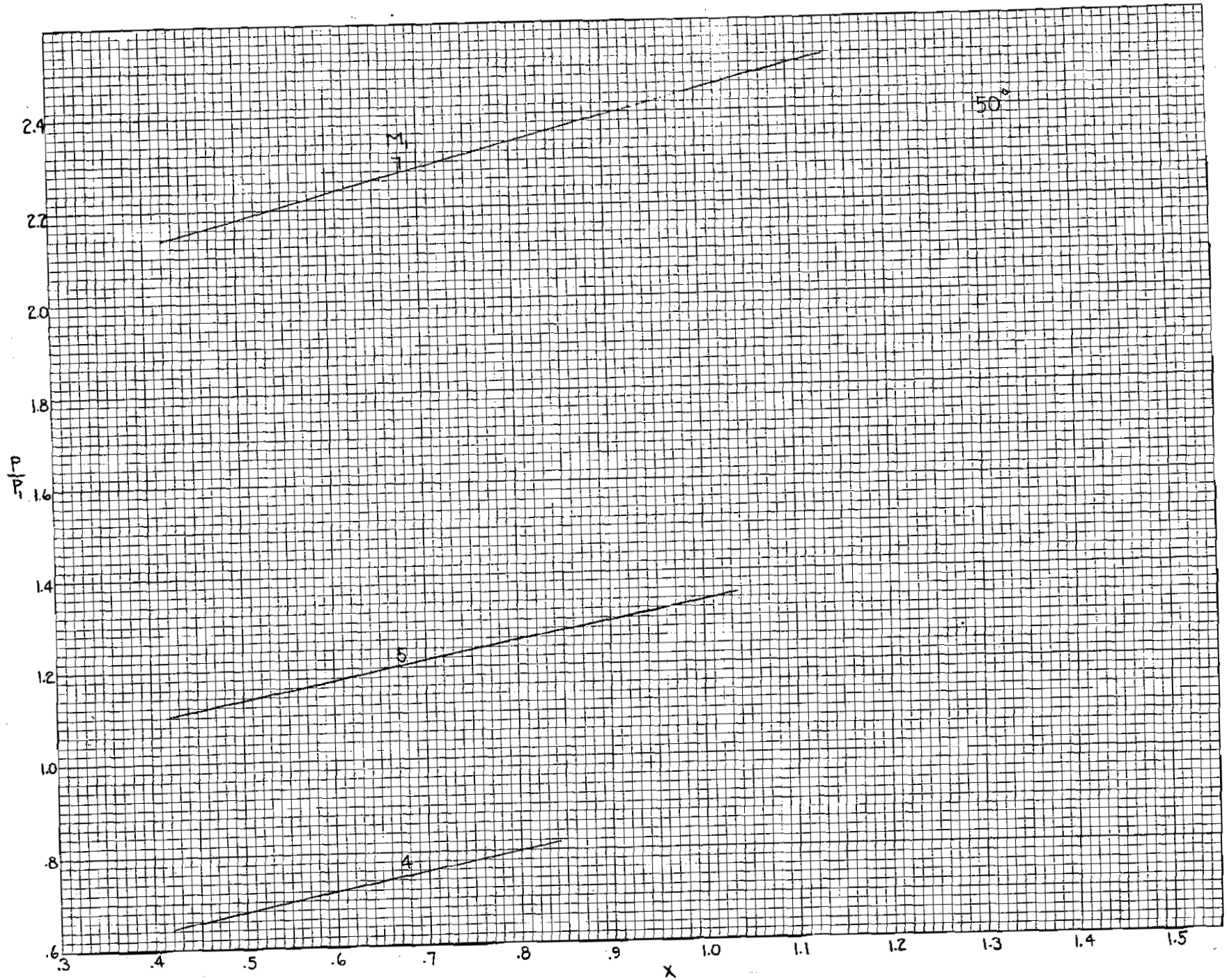

50°
M_1
7
6
4
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
$\frac{P}{P_1}$
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
X

Figure 38

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TITLE: Tables of Supersonic Flows About Cone Cylinders - Part 1; Surface Data (Ballistic Research Laboratories Report)

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ABSTRACT:

A family of inviscid steady axisymmetric supersonic flows about cone cylinders has been calculated by the method of characteristics on the ENIAC mathematical computer. All computations were confined to the domain of determination by the conical (Taylor-Maccoll) part of the shock wave, and by the body where the flows are irrotational. The cones have semi-vertex angles of the form 5k° ($1 \leq k \leq 10$), while the Mach numbers, contained in the set 1.3, 1.5, 1.7, 2, 3, 4, 5, 7, are such that the shock wave is attached to and conical near the vertex. Pressure, density, temperature, and local Mach number distributions on the cylinder have been tabulated, and the pressure data also have been presented graphically. The ENIAC results have been compared with computations from other sources and with experimental results.

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