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Design of Nozzle Contours for the PWT 16-Ft Transonic Wind Tunnel

William Everett Milam
University of Tennessee, Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by William Everett Milam entitled "Design of Nozzle Contours for the PWT 16-Ft Transonic Wind Tunnel." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

R. A. Crawford, Major Professor

We have read this thesis and recommend its acceptance:

Roy J. Shcultz, Ahmad D. Vakili

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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DESIGN OF NOZZLE CONTOURS FOR THE PWT 16-FT TRANSONIC WIND TUNNEL

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

William Everett Milam

August, 1992

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ABSTRACT

The nozzle contours of the Tunnel 16T nozzle were designed in the early 1950's and, for the most part, were calculated by hand. In addition, corrections have been made to the contours through the use of an influence coefficient correction technique in an attempt to remove small flow irregularities. This correction technique is not based on aerodynamic theory, and, as a result the corrected contours are not necessarily aerodynamically correct. A second problem stems from the fact that the application of the nozzle corrections results in nozzle contours that do not change in a monotonic manner. There are some jacks that reverse in direction of travel while increasing in Mach number contour. This is not desirable from a control algorithm standpoint.

New nozzle contours have been designed from Mach 1.1 to Mach 1.6 in increments of Mach 0.1. The contours were determined using the method of characteristics design code developed at AEDC by J. C. Sivells. The nozzle contours form a monotonic family of contours, in that, there are no nozzle wall reversals while traveling from the lowest Mach number to the highest. The new contours were optimized to the maximum extent possible in the location of the nozzle throat and inflection point with respect to jack attachment points.

Comparisons between the ideal contours and the jack supported contours show that there is very little difference in the contour shapes. This fact leads to the conclusion that the resulting flow quality of the new contours should be quite good.

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LIST OF SYMBOLS

C_f - Skin friction coefficient

H - Ratio of δ^*/θ

K - Parameter defined as $2(\theta_A - \theta_{1P})$

M - Mach number

r_w - Radius of viscid contour

u - X component of velocity

v - Y component of velocity

V - Absolute velocity

γ - Specific heat ratio

δ - Boundary layer thickness

δ^* - Boundary layer displacement thickness

θ - Momentum thickness in boundary layer

θ_A - Inflection point wall angle

θ_{1P} - Arbitrary flow angle in radial flow region

ν_C - Prandtl-Meyer angle at nozzle exit

ρ - Density within boundary layer

ρ_e - Density at edge of boundary layer

σ - Zero for planar nozzle, 1 for axisymetric nozzle

τ - Boundary layer shear stress

ϕ_w - Flow angle of viscid flow

CHAPTER 1

INTRODUCTION

The nozzle of the PWT 16 ft Transonic Tunnel is a two-dimensional, or planar nozzle with two flexible plate sidewalls. The flexible nozzle walls are supported by actuator jacks at 15 axial locations. Because of the finite number of support locations, there is a limited amount of control over the shape of the nozzle contour. Current design techniques try to match the support locations to key locations of the contour shape. For instance, the nozzle throat should have a support jack at the point of minimum area and the nozzle inflection point should, likewise, have a support jack. The iterations required on the nozzle contour calculations to place these critical locations at support points can become quite extensive.

The original contour shapes for this nozzle were designed over 40 years ago. Because computing power, at that time, was much less than it is today, the ability to iterate on an aerodynamic contour was severely limited. Instead, the practice was to calculate the desired nozzle contour and fit the actuator positions to coincide with it. Any irregularities in the resulting flow were corrected using an influence coefficient type calculation.

The influence coefficient correction consists of measuring the influence each nozzle actuator jack has on the nozzle centerline pressure distribution. By perturbing each pair by a small amount and measuring the centerline disturbance, a set of corrections can be determined which will result in the optimum flow quality for a given combination of nozzle contour and support locations. This technique is fully developed in Reference 1.

A drawback of the correction method is the fact that the contours are not necessarily aerodynamically correct, nor are they of the same family of contours. The term "family" implies that the contours are all of a similar shape with the entire nozzle plate moving monotonically with increasing nozzle Mach number. What frequently happens when the influence coefficient correction method is applied is that the computed contour corrections require that the actuator jacks reverse direction of travel while progressing to either higher or lower Mach number contours. In the past this jack reversal was not a serious problem because the nozzle control system controlled each discrete Mach number contour individually with no provision for intermediate aerodynamic contours. It has been proposed that a new control system be installed in the 16T nozzle, which will speed up operations. One of the requirements of the new control systems is the monotonic movement of jacks with Mach number. Consequently, the previous corrected contours are not acceptable.

An approach to meeting the control system requirements of monotonic actuator jack travel that satisfies the Mach number uniformity requirements of the tunnel is to redesign the contours using modern nozzle design tools. The objective is to design the nozzle contour shape in harmony with the previously prescribed support geometry. Obviously, a preferable situation is to design the contours and then place the support structure at the optimum control points, but this luxury is not available in this instance. For this reason, some compromises have to be made in selecting the best nozzle contour for each Mach number. As would be expected, the highest Mach number, Mach 1.60, presents the greatest design obstacles for this effort. The higher Mach number contours require more axial length than the lower Mach number contours. The available nozzle length severely limits the design options for the Mach 1.60 contour.

In Chapter 2, description of the 16T facility and components are presented. In Chapter 3, a description of the proposed nozzle design method and pertinent design parameters are presented. Also described is the calculation of the jack supported nozzle plate as well as the stress determination. Chapter 4 presents the results of this design effort. In Chapter 5, conclusions and recommendations are given.

CHAPTER 2

APPARATUS

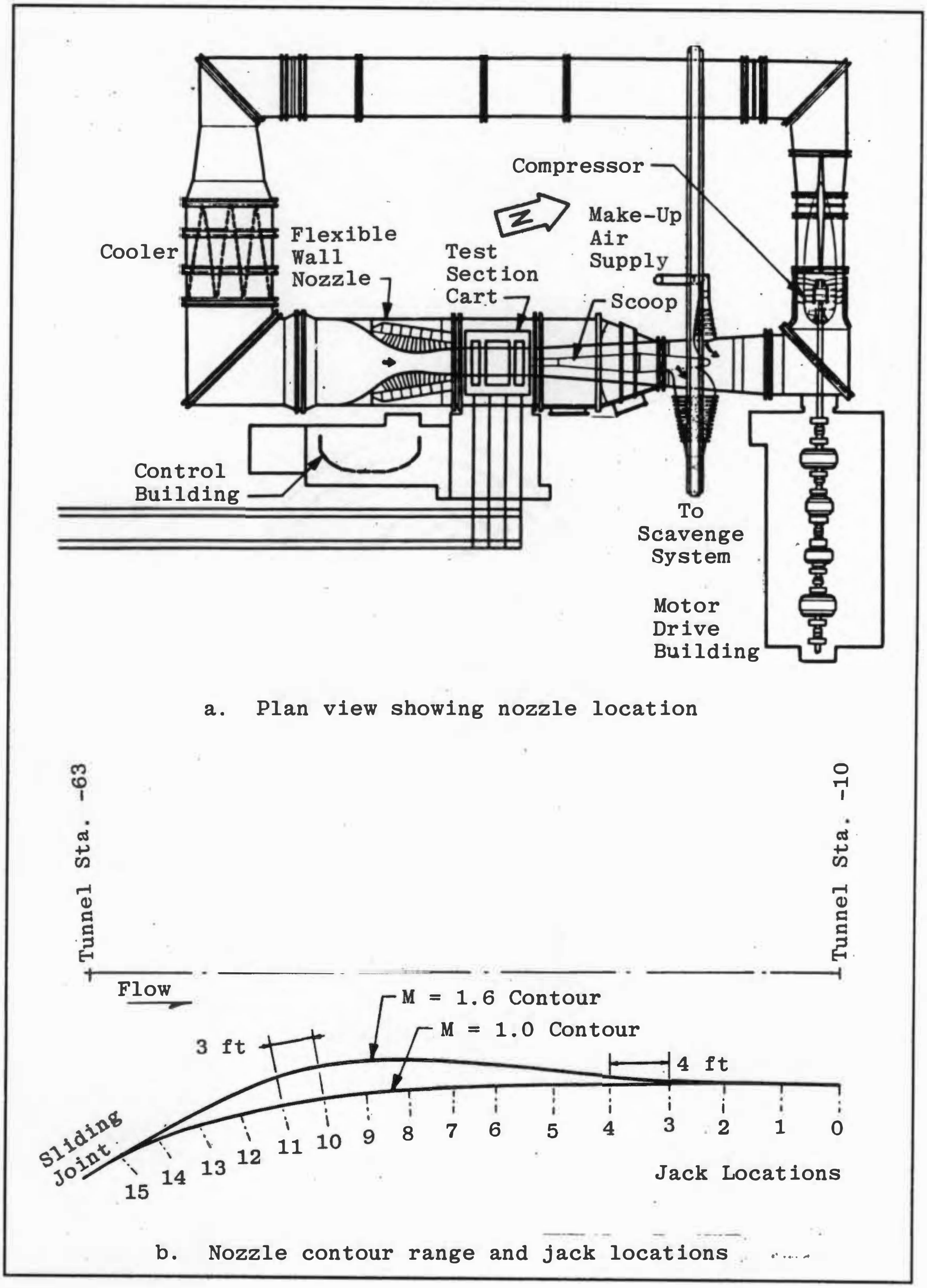
Tunnel 16T

The PWT 16 ft Transonic Tunnel (Propulsion Wind Tunnel, Transonic (16T)) is a continuous flow, closed circuit tunnel capable of operation within a Mach number range of 0.06 to 1.60. The tunnel compressor is a three stage axial machine powered by four electric motors, (two induction and two synchronous), which produce a shaft power of 271,000 hp. The tunnel can be operated within a stagnation pressure range of 120 to 4000 psfa depending on the Mach number. The stagnation temperature can varied from an average minimum of about 80 °F to a maximum of 150 °F depending on the temperature and availability of cooling water. Additional information on the Tunnel 16T Facility can be found in Reference 2.

Tunnel 16T Nozzle

The 16T nozzle is a flexible wall, continuous curvature, Laval type nozzle. The nozzle is approximately 54 feet long, extending from a 16 x 32 ft entrance to a 16 x 16 ft exit. The sidewalls are made of flexible steel plates which are 0.85 in. thick. Sidewall positioning is accomplished by means of 16 electric motor driven actuators or jacks. A mechanical type control system guides the nozzle automatically to any selected programmed contour resulting in Mach numbers ranging from subsonic to Mach 1.60. Figure 1 shows the nozzle contour range and the location of the nozzle control jacks.

Starting at the downstream end of the nozzle, the control jacks are numbered sequentially from jack 0 at the nozzle exit to Jack 15 near the nozzle entrance. Jacks 0 through 6 are equally spaced four feet apart along the nozzle wall. Jacks 6 through 15 are spaced 3 feet apart along the nozzle wall. The upstream end of the nozzle terminates in a slip joint which maintains a constant nozzle slope and allows for different wall lengths associated with the different nozzle contours. The downstream end of the nozzle plate terminates in a slope control jack, (Jack 0), which allows variable nozzle exit slope for wave cancellation. Figure 2 shows the nozzle looking upstream from the nozzle exit. Note the marks on the nozzle ceiling which indicate the range of travel between the sonic contour and the Mach 1.6 contour. Figure 3 shows a view of the nozzle control jacks looking in the upstream direction.



a. Plan view showing nozzle location

b. Nozzle contour range and jack locations

Figure 1. Flexible nozzle for Tunnel 16T

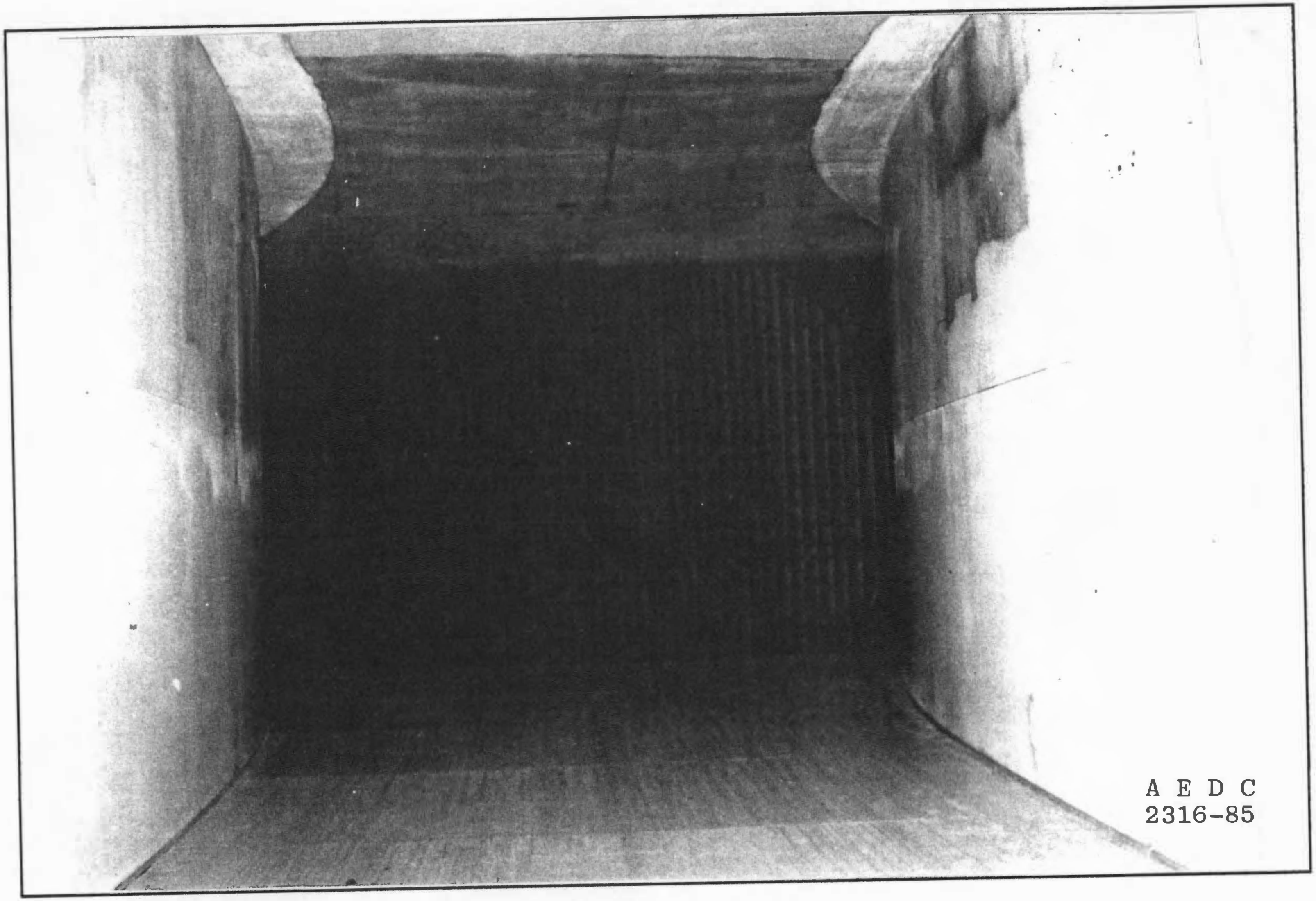


Figure 2. Interior view of Tunnel 16T nozzle.

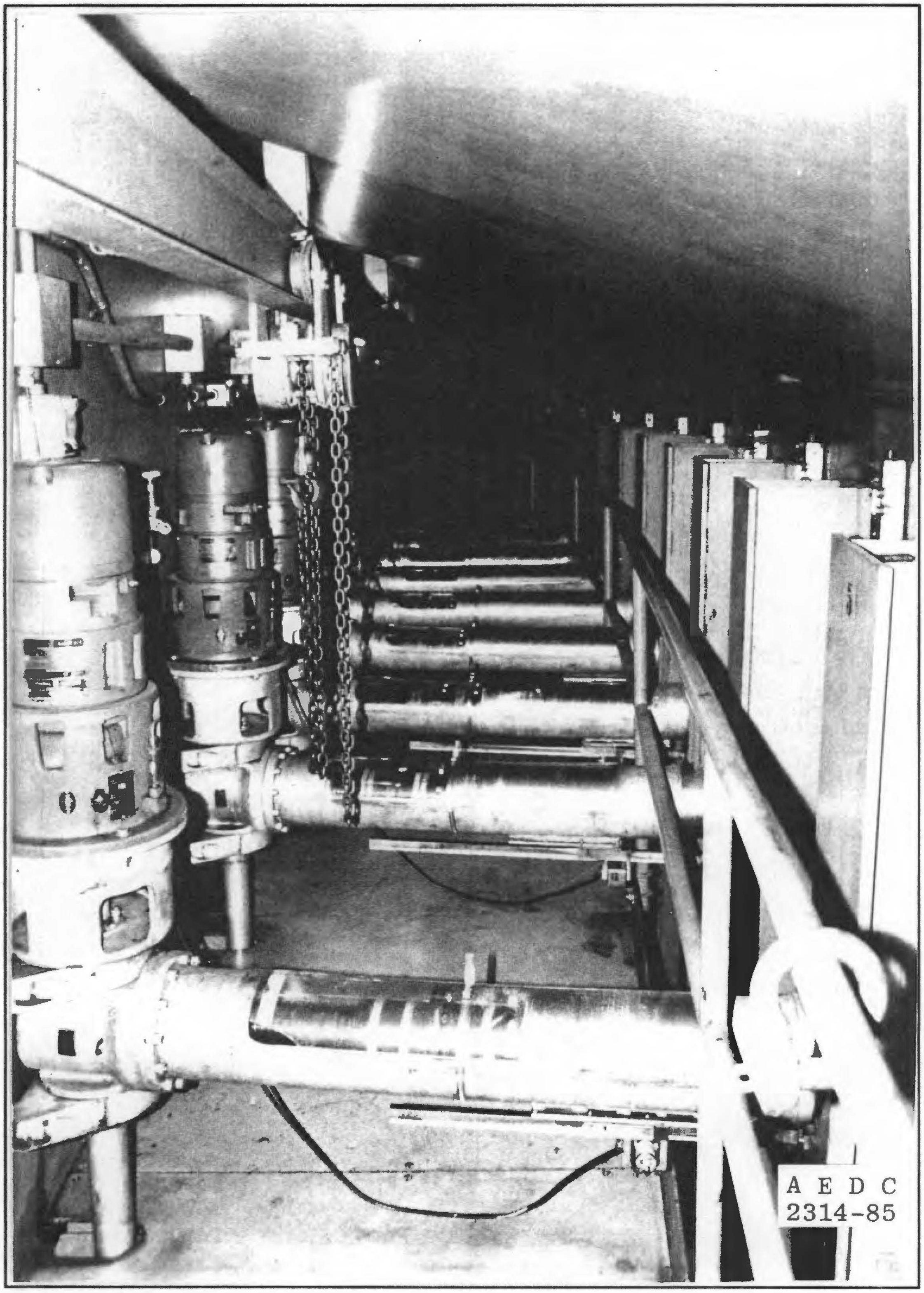


Figure 3. Tunnel 16T nozzle control jacks.

CHAPTER 3

NOZZLE DESIGN METHOD

The purpose of a supersonic wind tunnel nozzle is to provide test section air flow at a desired Mach number that is uniform in temperature, pressure and Mach number, and is parallel to the flow axis. The level of success in achieving these objectives depends largely on the nozzle contour. The contour is governed by both aerodynamic considerations and physical properties of the nozzle and supporting structure. The nozzle designer must weigh these considerations and often choose the best compromise of design parameters. Varner et al give an excellent survey of current nozzle design methods in Reference 3.

The aerodynamic nozzle contours were designed using the method and computer code developed by Sivells as described in Reference 4. The objective was to develop a family of contours which will take an initial, non-uniform, throat-region flow and expand it to uniform supersonic flow at the nozzle exit. In Sivells' approach, an inviscid contour is first designed by means of a method of characteristics calculation and then the boundary layer displacement thickness is added.

The nomenclature conventions used by Sivells will be maintained for consistency. Figure 4 shows a typical supersonic nozzle contour with key areas labeled. Point T is the throat or minimum area of the contour. The sonic line, which is in close proximity to the throat, is also shown. Points G, F, and E bound a region of radial flow. Point A is the inflection point of the nozzle and marks the beginning of the wave cancellation region. Point J marks the beginning of the region where expansion waves striking the nozzle wall are identically cancelled. The span between A and J is the transition region between the point of zero wave cancellation and full wave cancellation. The length of this region will be discussed later. The line C-D is the beginning of the uniform flow region and is a straight line. The slope at D is zero because the flow is uniform and the curvature is zero at D because any curvature at this point would induce expansion or compression waves in the test section.

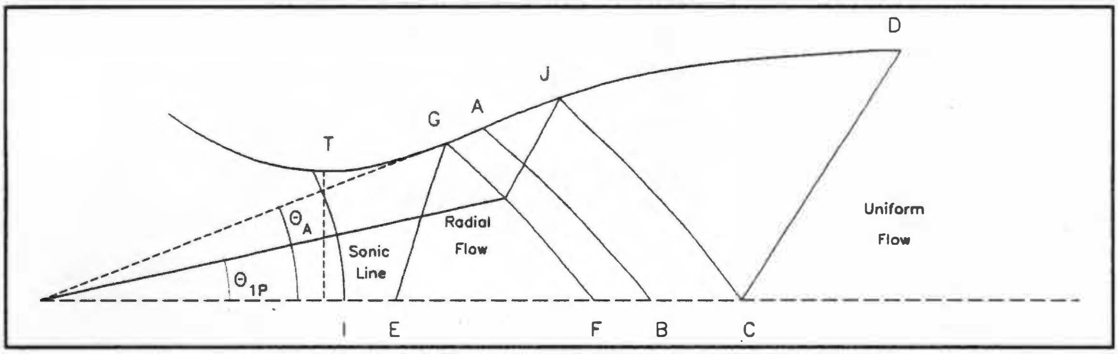


Figure 4. Nozzle contour illustrating different nozzle regions.

A brief description of the method of characteristics technique used by Sivells is presented here. As a starting point the sonic line in the throat region is determined. If the flow in the nozzle had zero acceleration the sonic line would theoretically be straight. However, such a situation results in an excessively long nozzle. In practice, the nozzle throat has a finite radius of curvature and the sonic line is curved. A technique for finding the transonic solution is as follows. The two velocity components are first expanded in a power series. Because of symmetry, the odd powers drop out of the u component expansion while the even powers drop of the v component expansion.

$$u(x,y) = a_0 + \frac{1}{2!}a_2y^2 + \frac{1}{4!}a_4y^4 + \dots \qquad (1)$$

$$v(x,y) = b_1y + \frac{1}{3!}b_3y^3 + \dots \qquad (2)$$

Introducing the requirement of irrotationality:

$$\frac{\partial u}{\partial y} = \frac{\partial v}{\partial x} \qquad (3)$$

Taking derivatives of (1) and (2) results in:

$$a_2y + \frac{1}{3!}a_4y^3 = b_1'y + \frac{1}{3!}b_3'y^3 \qquad (4)$$

Introducing the continuity equation.

$$(c^2 - u^2)\frac{\partial u}{\partial x} - 2uv\frac{\partial u}{\partial y} + (c^2 - v^2)\frac{\partial v}{\partial y} = 0 \tag{5}$$

With the speed of sound defined as:

$$c^2 = \frac{\gamma-1}{2}\left(V_{max}^2 - V^2\right) \tag{6}$$

Substituting into the continuity equation results in:

$$b_1 = -\frac{V_{max}^2 - \frac{\gamma+1}{\gamma-1}a_0^2}{V_{max}^2 - a_0^2}\,a_0' \tag{7}$$

The boundary condition of attached flow at the nozzle wall gives:

$$\frac{v_f}{u_f} = \frac{dy}{dx} = \frac{df}{dx} = f' \tag{8}$$

Substituting (1), (2), and (4) into the boundary conditions results in:

$$b_1 f + \frac{1}{6}b_3 f^3 = f'\left(a_0 + \frac{1}{2}a_2 f^2 + \frac{1}{24}b_3' f^4\right) \tag{9}$$

This results in a set of relations which may be solved if a_0 is known. The procedure is to assume a functional description of a_0 and calculate b_1. The remaining constants may then be determined from the above relations. As a check of the guess of a_0, the following continuity equation is used to determine if the total flow is consistent.

$$\int_0^{f} u\rho dy = constant \tag{10}$$

Further details of this technique can be found in Reference 4.

Referring to Figure 4, the velocity distribution between points I and E is specified with a general fifth degree polynomial. The first and second derivatives of the velocity at point I and E are used to determine the coefficients of the polynomial. The specified centerline velocity distribution determines the curvature of the nozzle between points T and G. The left-running characteristic between points E and G forms the upstream boundary of the radial flow region. The flow angle is the same at points G and A. Both are shown to illustrate a general nozzle design. The flow in the radial flow region is assumed to emanate from a source at some point on the nozzle axis upstream of the throat. Similar to above, the Mach numbers and their first and second derivatives are used to determine a polynomial in Mach number between points B and C. The remainder of the nozzle contour is determined from a specified variation in the centerline Mach number from point B through C.

The method of calculating the boundary layer growth is based on obtaining a solution to the von Kármán momentum integral equation. The basis of the momentum integral technique is as follows. The continuity equation multiplied by (u-U) and subtracted from the momentum equation yields:

$$-\frac{1}{\rho}\frac{\partial\tau}{\partial y} = \frac{\partial}{\partial t}(U - u) + \frac{\partial}{\partial x}(uU - u^2) + (U - u)\frac{\partial U}{\partial x} + \frac{\partial}{\partial y}(vU - vu) \qquad (11)$$

Integrating from the wall to infinity:

$$\frac{\tau_w}{\rho} = \frac{\partial}{\partial t}\int_0^\infty (U - u)\,dy + \frac{\partial}{\partial x}\int_0^\infty u(U - u)\,dy + \frac{\partial U}{\partial x}\int_0^\infty (U - u)\,dy - Uv_w \qquad (12)$$

Using the relations:

$$\delta^* = \int_0^\infty \left(1 - \frac{u}{U}\right)dy \qquad (13)$$

$$\theta = \int_0^\infty \frac{u}{U}\left(1 - \frac{u}{U}\right)dy \qquad (14)$$

Substituting (13) and (14) into (12), the general momentum integral relation is:

$$\frac{\tau_w}{\rho U^2} = \frac{C_f}{2} = \frac{1}{U^2}\frac{\partial}{\partial t}(U\delta^2) + \frac{\partial \theta}{\partial x} + (\theta + 2\delta^*)\frac{1}{U}\frac{\partial U}{\partial x} - \frac{v_w}{U} \qquad (15)$$

The calculations used in the design code use the momentum integral written for axisymetric flow. The relation becomes:

$$\frac{d\theta}{dx} + \theta\left[\frac{2. - M^2 + H}{M\,[1 + (\gamma-1)\,M^2/2]}\frac{dM}{dx} + \frac{1}{r_w}\frac{dr_w}{dx}\right] = \frac{C_f}{2}\sec\phi_w \qquad (16)$$

The last term in the brackets of the above equation effectively becomes one for a planar flow field. The difference between the axisymetric and the planar solutions is small if the boundary layer thickness is small compared to the nozzle cross section, which is generally true. Additional information on the boundary layer relationships used in the calculation and the techniques used to solve the equations are presented in Reference 4.

The correction for a planar nozzle is usually applied to the contoured walls only, but the correction also allows for the growth of the boundary layer of the parallel walls in order to maintain a constant Mach number along the test section centerline. Therefore, the correction applied is greater than the displacement thickness on the contoured walls, and the flow in the test section is diverging in the longitudinal plane normal to the contoured walls. In the longitudinal plane normal to the parallel walls, the flow is converging because of the boundary layer growth. Also, transverse pressure gradients present on the parallel walls cause the boundary layer to be thicker on the wall centerline. Although these physical effects make a true correction impossible for a planar nozzle, the calculations are made as if the cross section were circular.

A feature of Sivells' technique is that it produces a contour with continuously varying curvature which is essential if the contour is to be formed with a flexible plate. Traditionally, fixed Mach number two-dimensional nozzles have been machined from blocks of metal. These nozzles are typically shaped with an abrupt change in wall curvature at the inflection point. Upstream of the inflection point the wall curves away from the nozzle axis causing expansion waves in the flow. At the inflection point, the wall curvature changes sign so as to identically cancel any expansion wave impinging on it. A consequence of this technique is another discontinuity in the wall curvature at the nozzle exit. This type of nozzle terminates with a finite slope with the test section walls having zero slope.

The change in slope at the nozzle exit serves to cancel the final expansion wave hitting the nozzle wall. Conversely, a continuous curvature nozzle transitions from positive to negative curvature continuously by passing through a point of zero curvature. As a result, there is a region where expansion waves impinging on the nozzle wall are only partially cancelled. This region is nozzle wall segment A-J in Figure 4. At point A there is no wave cancellation because the wall has zero curvature. The wave cancellation increases to full wave cancellation at point J. A consequence of this technique is a slightly longer nozzle since these partially cancelled waves continue to propagate in diminished strength and must be cancelled at the exit of the nozzle. The last full strength expansion wave impinges on the nozzle wall upstream of the exit. From this point, to the nozzle exit, the strength of the expansion waves decrease in strength to zero at the exit. A further consequence is the fact that the wall slope at the exit gradually transitions to zero slope at the exit and presents no discontinuities at the intersection with the test section wall.

Because a flexible plate nozzle must have continuous curvature and the spacing of the supporting jacks governs the rate of change of curvature over a given length, it is important that the designed contour does not exceed the capabilities of the plate and jack combination. The region in and about the inflection point is especially important from the standpoint of flow quality. Because wide spacing between jacks is not compatible with abrupt changes of plate curvature, the inflection region must be designed in a manner which can be achieved with the available number and spacing of jacks. Curvature changes are most important in the region between the inflection point and the point where full wave cancellation begins. In designing the nozzle contour, the designer has at his disposal three parameters to work with. These are:

θ_A - inflection point wall angle

θ_{1P} - arbitrary flow angle in radial flow region

ν_C - Prandtl-Meyer angle at nozzle exit

It can be easily shown that

$$\theta_A \leq \frac{\nu_C}{2} \tag{17}$$

However, for a flexible plate nozzle, Riise (Reference 5) recommends

$$\theta_A \leq \frac{\nu_C}{2} - \frac{\theta_A - \theta_{1P}}{4}. \tag{18}$$

θ_{1P} can take on values ranging from $+\theta_A$ for a non-continuous curvature nozzle to $-\theta_A$ for a maximum length nozzle. Defining

$$K = 2(\theta_A - \theta_{1P}), \tag{19}$$

then, K can take on values ranging from zero to $4\theta_A$. Experience has shown that in order to position the nozzle wall plate accurately with a finite number jacks, it is advisable to keep K above $2\theta_A$, (see Reference 6). The value of K is an indicator of the length of the nozzle wall segment A-J. Keeping this value above $2\theta_A$ allows better control of the transition from expansion to complete wave cancellation with the available number of plate positioning jacks. Smaller values of K may result in an inflection region that can not be accurately shaped with the jack spacing of the plate. However, physical constraints sometimes force a lower value of K at the higher Mach number contours in order to fit the contour in the available length.

For a given exit Mach number an infinite number of contours can be designed to produce uniform flow. It is desirable, however, to have all the contours of one family, that is, all the contours have a similar shape and all points on the nozzle wall move monotonically from the lowest to highest Mach number contour. The above parameters can be used to help ensure progressive contours are similar. Since the exit Mach number is pre-defined, the Prandtl-Meyer angle at the exit is also defined. That leaves θ_A and θ_{1P} to work with. In practice, the Mach number at point B on Figure 4 is specified instead of θ_{1P}. The effect is the same, however. The procedure is to vary these two parameters with Mach number in a smooth fashion. Considerable latitude is given to the designer at this point and engineering judgement must be exercised.

The contour calculation described above addresses only the region of the nozzle from the throat to the exit. With a flexible plate nozzle the region from the fixed contraction to the throat must also be determined. Typically, this flexible contraction region is formed with a polynomial of sufficient order to match the appropriate boundary conditions at each end. These boundary conditions include the ordinate, slope and curvature at upstream end of the fixed plate and the ordinate, slope, curvature, and, sometimes, the rate of change of curvature at the throat. If the last condition is included, the required polynomial must be of at least sixth order.

Once the ideal contour is calculated, the real contour, supported by a finite number of jacks, must be determined. The real contour is determined by forcing the jack attachment points to lie on the ideal contour. The shape of the real contour between the jack attachment points can be determined as follows. From elementary strength of materials the following relationships are derived.

$$EIY'' = m = \int shear = \int sdx = sx + C_1 \qquad (20)$$

$$EIY' = \int (sx + C_1)\,dx = \frac{sx^2}{2} + C_1 x + C_2 \qquad (21)$$

$$EIY = \int \left(\frac{sx^2}{2}\ C_1 x + C_2\right) dx = \frac{sx^3}{6} + \frac{C_1 x^2}{2} + C_2 x + C_3 \qquad (22)$$

Since the equation for Y, above, is a cubic polynomial, the shape of the plate between the support jacks can be calculated using cubic splines. The bending stress at the jack points is also calculated from the above equations. The plate stress is at a maximum at the support point so it is only necessary to calculate it at the support point and not in between jacks. The technique used to fit the flexible plate to the ideal contour is to start at the fixed downstream end and calculate the plate distance to the first support jack attachment. The Y dimension is set to agree with the design contour at this axial station. The plate length is then recalculated to make sure the axial location of the jack is correct. Once agreement is reached at the first jack, the calculation is extended to the second jack and so on until the upstream end of the plate is reached.

This technique assures that the flex plate coincides with the design contour, at least at the attachment points. With the jack attachment points located, it is a simple matter to determine the individual jack lengths by calculating the distance from the nozzle plate attachment point, allowing for local plate slope, to the pivot point on the fixed frame.

CHAPTER 4

PRESENTATION AND DISCUSSION OF RESULTS

With any nozzle design there are numerous design constraints the designer must deal with. These include the length available for the nozzle, permissible stress limits of the flexible plate, control system limitations on the mode of jack travel, etc. Because the case being considered here is an existing nozzle and no physical changes are being made to the mechanical structure, the contour design is forced to accommodate all existing constraints.

The 16T nozzle is operated with two stress limits. The first, at 55,000 psi, is a warning limit and the second, at 60,000 psi, is a danger limit. Reaching either limit during operations causes the nozzle control system to stop and interrupts testing until the stress can be cleared. For this reason the throat radius of curvature was chosen so as to result in a plate stress of less than 50,000 psi. The Mach 1.60 contour has the smallest throat radius of curvature and the radius of curvature increases for the lower Mach numbers.

The total length of the nozzle structure is approximately 52 ft. This dimension is from the upstream slip joint to the nozzle exit at the test section entrance. The upstream end of the nozzle forms an interface with the fixed contraction of the stilling chamber. Therefore, the flexible plate must transition from the contraction slope gradually to the nozzle throat. This means that the available length for the supersonic portion of the nozzle is substantially less than the above stated length.

The present nozzle actuator control system is a mechanical design which treats each contour individually. It causes the nozzle to move in discrete increments from one position to another. As such, there is no limitation on the direction of jack travel as long as the magnitude of the travel is within prescribed limits. The drawback of this type of system is that it is slow in moving the nozzle from one contour to the next. It has been proposed to replace it with a more modern control system which will allow variable speed jack travel. The proposed scheme will determine the required jack travel for each of the actuator jacks and then adjust the speed of each so that they all start and stop simultaneously. This mode of operation results in the minimum plate stress levels during nozzle movement. A requirement of the variable speed control system is that the jacks move monotonically from the lowest Mach number contours to the highest. This requirement results from the requirement to set finer increments in Mach number than are designed. Interpolation is used to determine intermediate contours and stress problems can arise if the interpolated contour results in some jacks moving in one direction while others move in the opposite. The existing contour schedule includes situations in which actuator jacks reverse direction in their progression of Mach number contours.

The existing nozzle contours were designed with a finite slope at the nozzle exit. This slope was selected to try to match the slope of the boundary layer growth along the nozzle walls. However, there is no assurance that the test section wall slope will match the nozzle wall slope. The change in wall slope between the nozzle exit and the test section entrance has been noticed to cause Mach number disturbances in the test section induced from sudden expansions or contractions at the wall. It is felt that it is advantageous to avoid these disturbances by setting the nozzle exit slope to zero or to match the test section slope if not zero. For the design effort, the nozzle exit slope is set to zero. In the physical situation, the downstream end of the nozzle wall is clamped to the test section wall and is forced to assume the wall slope of the test section wall. The transition in wall slope is accomplished through a flexible attachment piece. When it is considered that this particular wind tunnel employs a porous wall test section, the boundary layer growth problem is diminished when compared to a solid wall test section.

For the nozzle in question, the Mach 1.60 contour requires the greatest axial length. To fit the contour into the available length requires that the radius of curvature at the throat be as small as stress limitations will allow. The minimum allowable radius of curvature to stay below the 50,000 psi stress limit is on the order of 25 ft. As mentioned in Chapter 3, it is advisable to keep the parameter K at or above $2\theta_A$ for a flexible plate nozzle in order to smoothly transition from positive to negative curvature at the inflection point. However, the available length will not permit this criterion to be met in this case. An alternative approach was taken to adjust the contour so that the throat location coincided with a support jack and the inflection point was as close to a jack station as possible. Figure 5 shows a comparison of the ideal contour and the actual contour for Mach 1.60. The scale of the plot was greatly exaggerated in the transverse dimension to show detail. As can be seen the two contours coincide quite well with only some minor differences in the throat region. The axial location of the throat differs by 1.36 inches. For a nozzle of this size, this is not thought to be a significant difference. For completeness, comparisons of all nozzle contours (actual and ideal) are shown in Figure 6.

At the opposite end of the spectrum, the Mach 1.10 contour presented some problems because it is much shorter

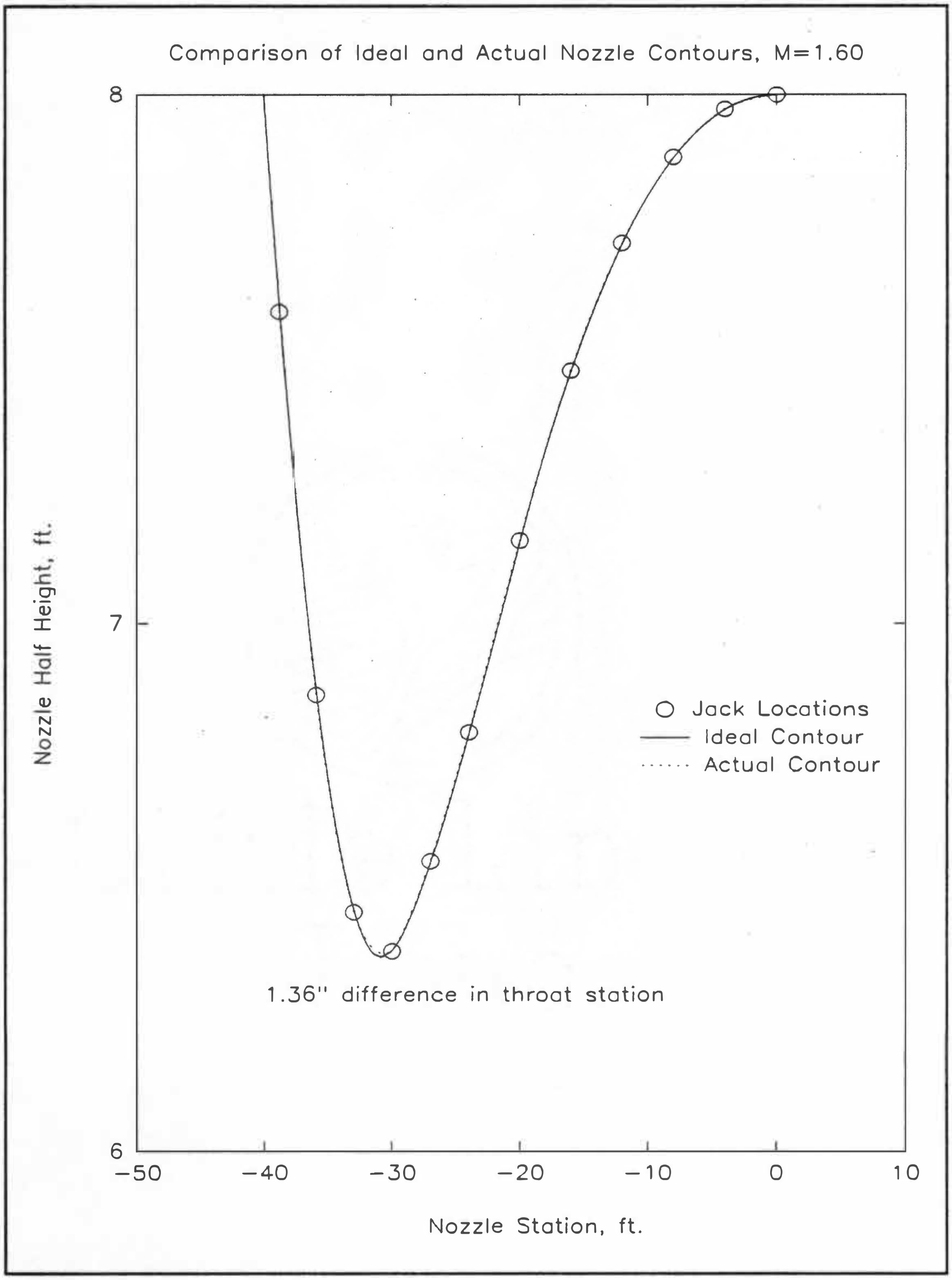
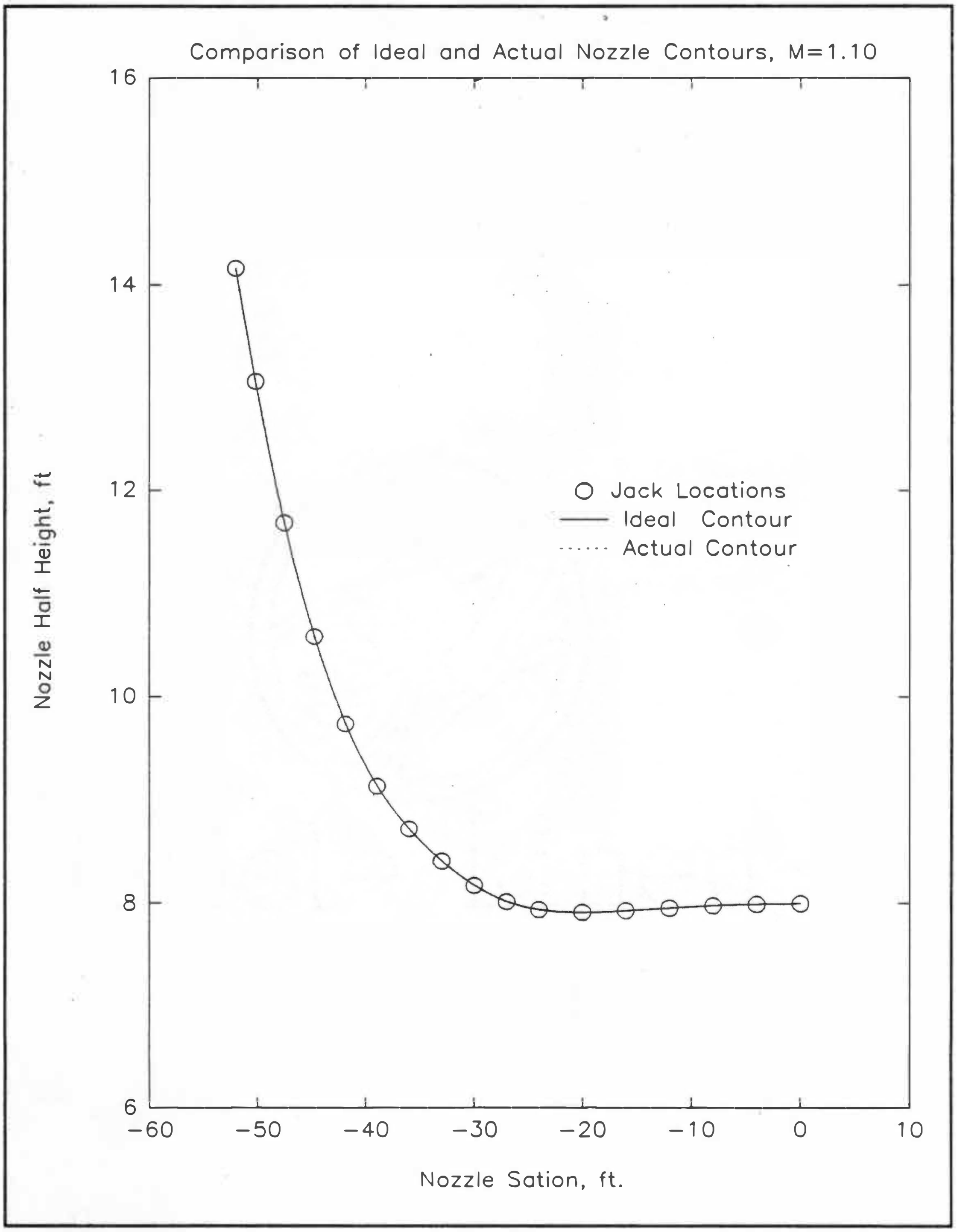
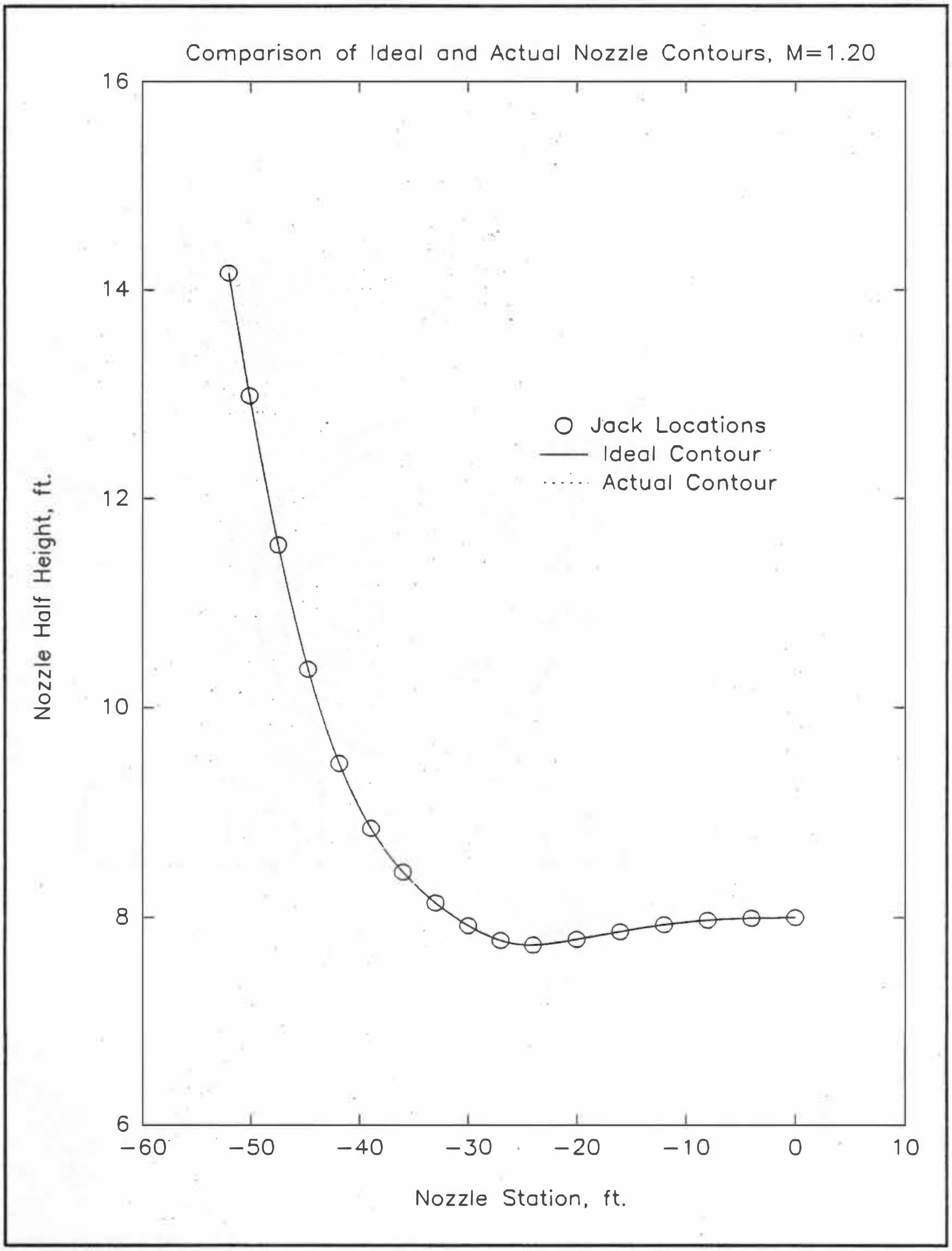


Figure 5. Comparison of ideal and actual plate shapes for Mach number 1.60 contour.



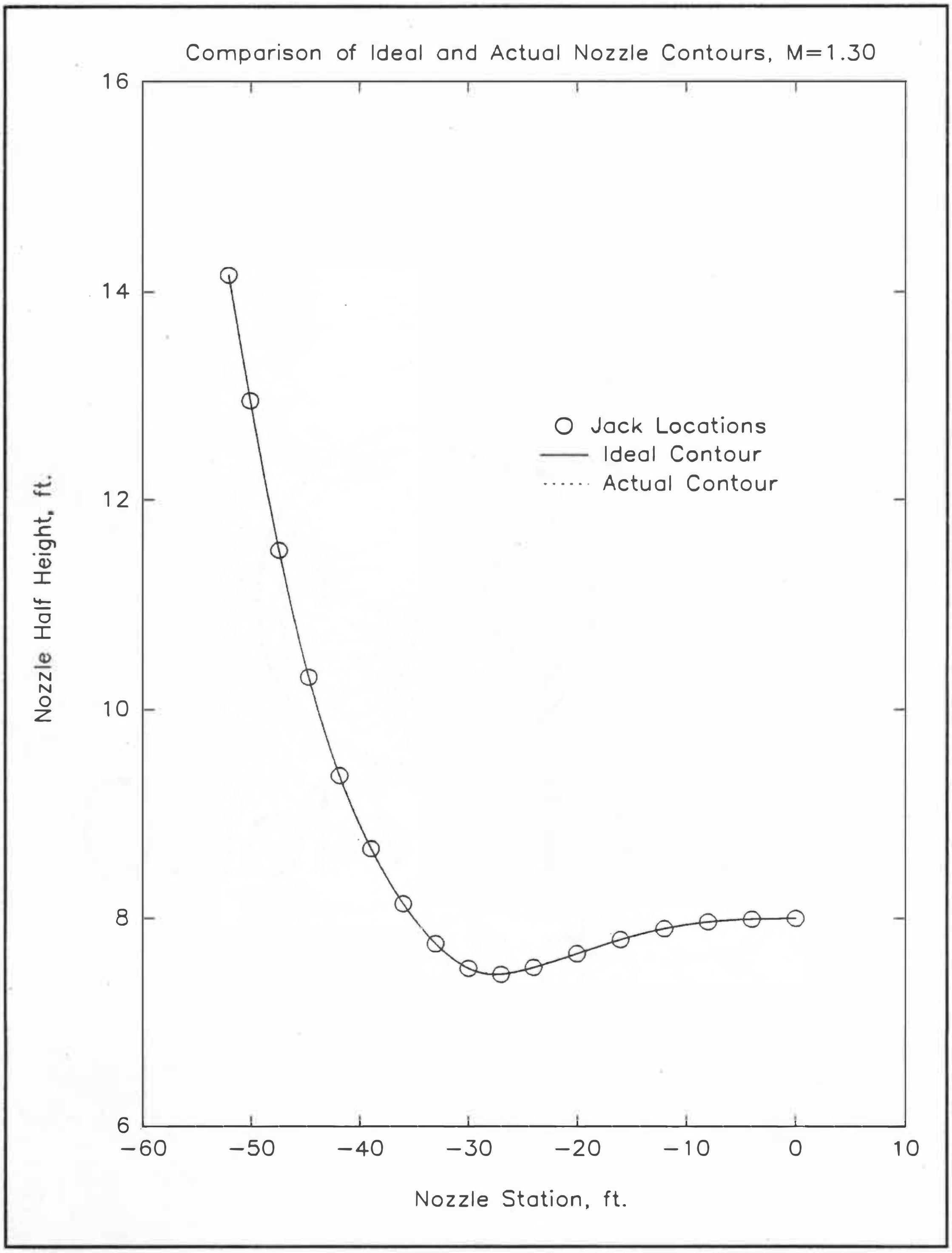
a. M=1.10

Figure 6. Comparison of ideal and actual nozzle plate shapes.



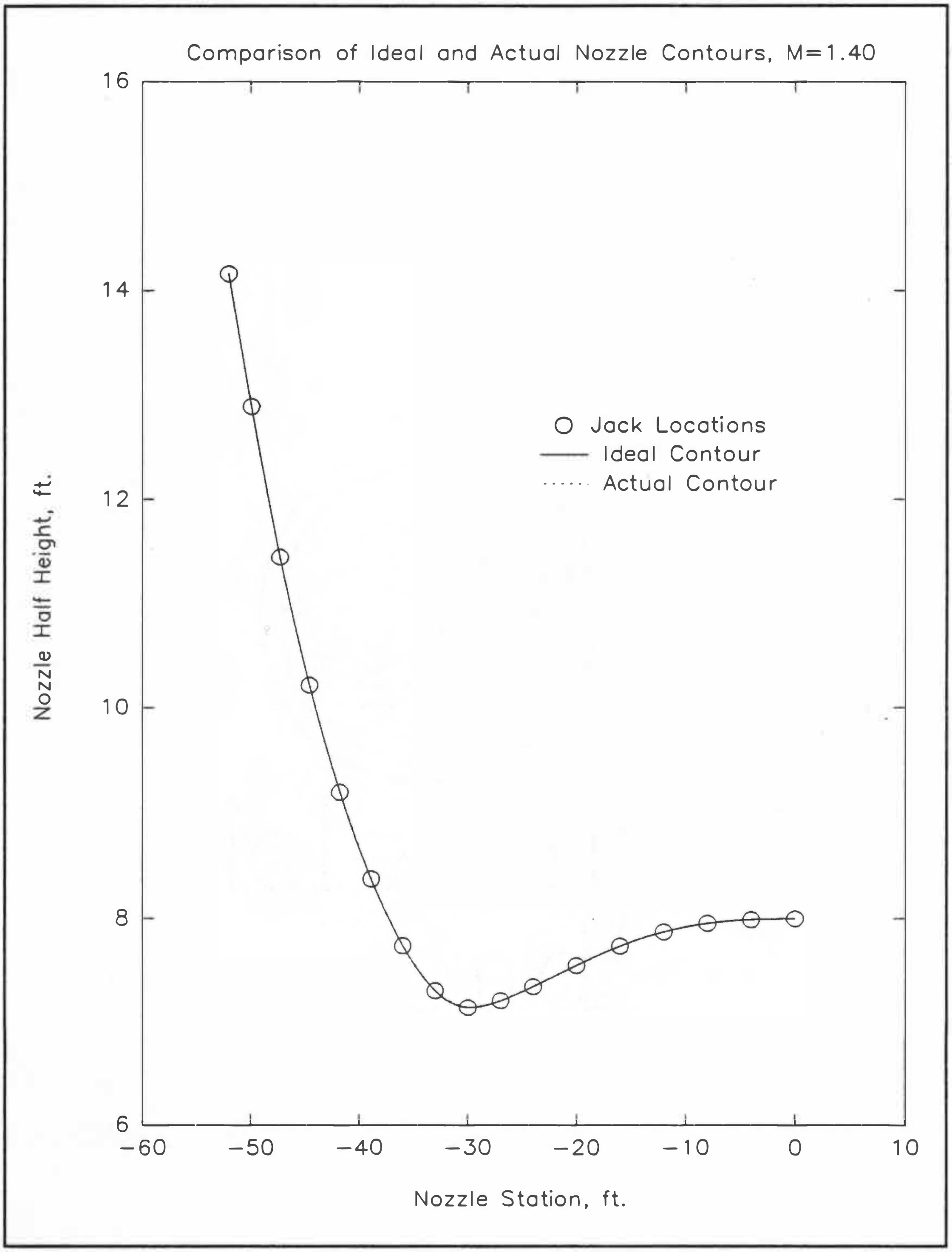
b. M=1.20

Figure 6. Continued.



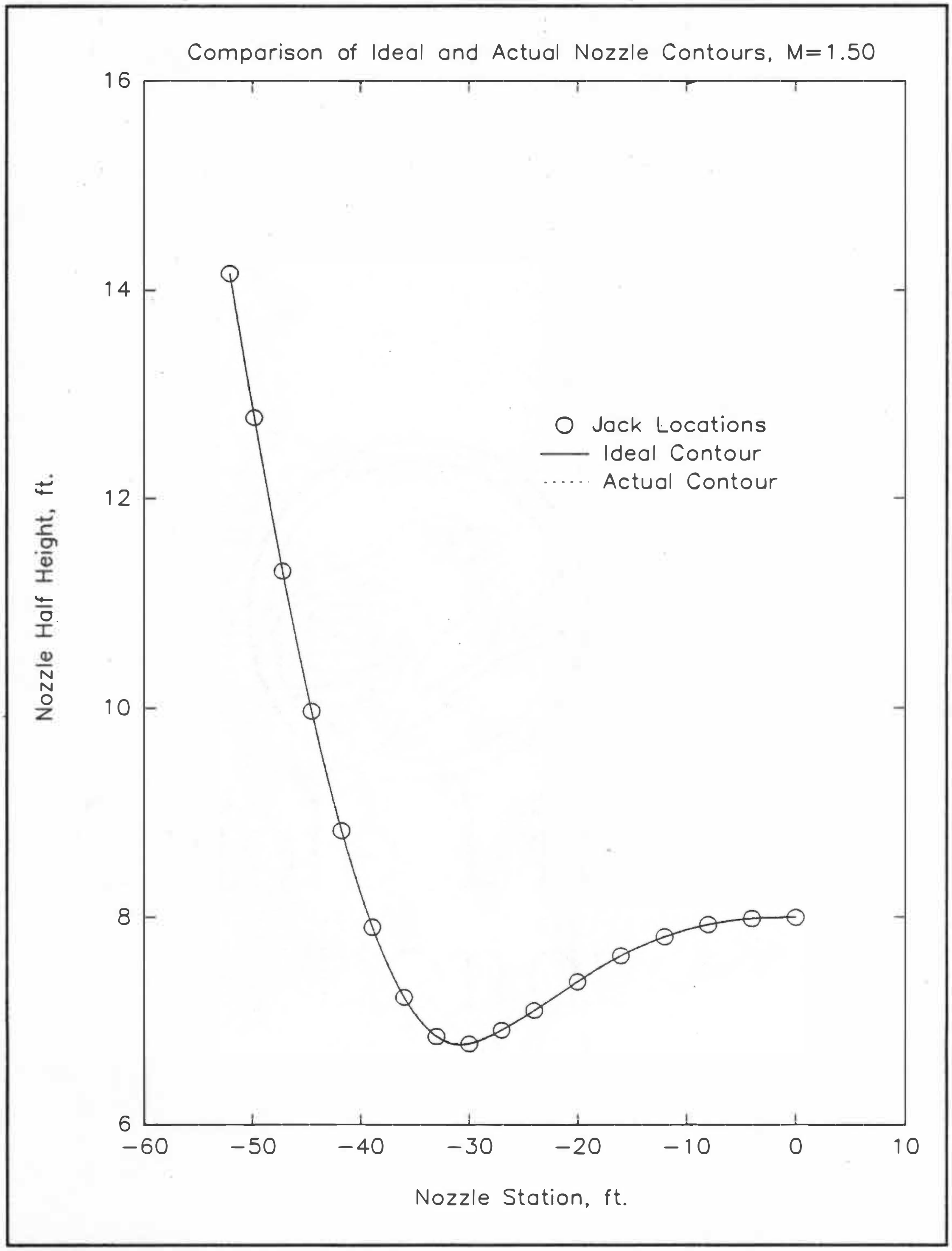
c. M=1.30

Figure 6. Continued.



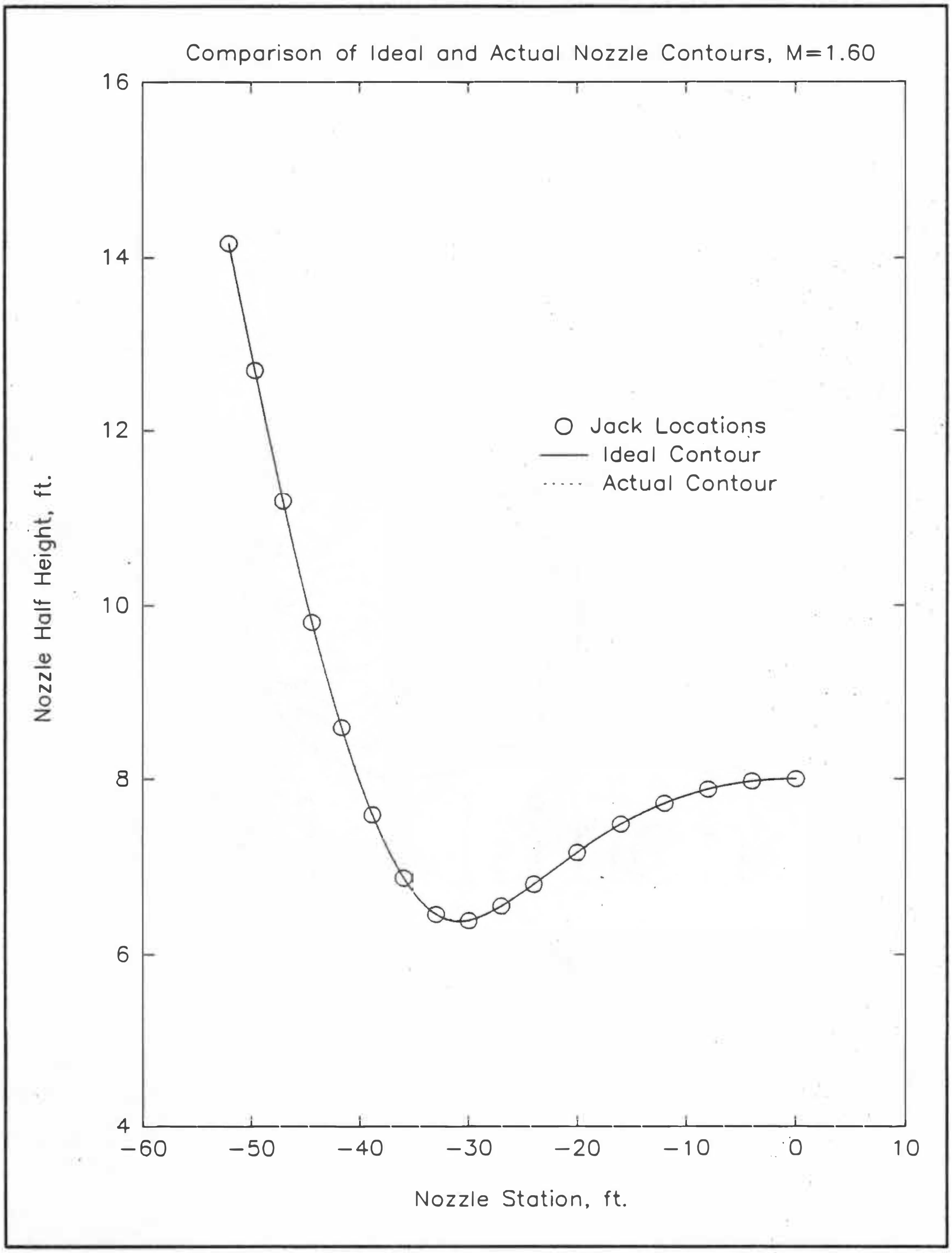
d. M=1.40

Figure 6. Continued.



e. M=1.50

Figure 6. Continued.



f. M=1.60

Figure 6. Continued.

than the available length. Forming the contour from the nozzle throat to the exit was no problem, however, the contraction from the nozzle entrance to the throat presented some challenges. As mentioned in Chapter 3, the contraction region is normally formed with a suitable polynomial to match the boundary conditions at each end. In this case matching the boundary conditions was not enough, primarily because of the long span of the contraction for this contour. Remember that it is required that the nozzle jacks move monotonically with increasing Mach number. Applying a sixth order polynomial to this contraction results in a contour in which the jacks must reverse when travelling from the Mach 1.1 to Mach 1.2 contour. To alleviate this problem, a series of polynomials were patched together with appropriate intermediate "boundary conditions" to insure that the contours satisfied the requirement of monotonic jack travel.

The remaining contours between Mach 1.1 and Mach 1.6 were designed as a family of similar contour shapes. Figure 7 shows a composite of the contours illustrating the monotonic nature of the plate movement. Also note that the throat location makes a gradual transition from the Mach 1.6 contour to the sonic contour. Figure 8 shows each individual contour with its associated stress distribution. Of interest is the location of the point of maximum stress. For the Mach 1.6 contour, the maximum stress occurs at the throat,

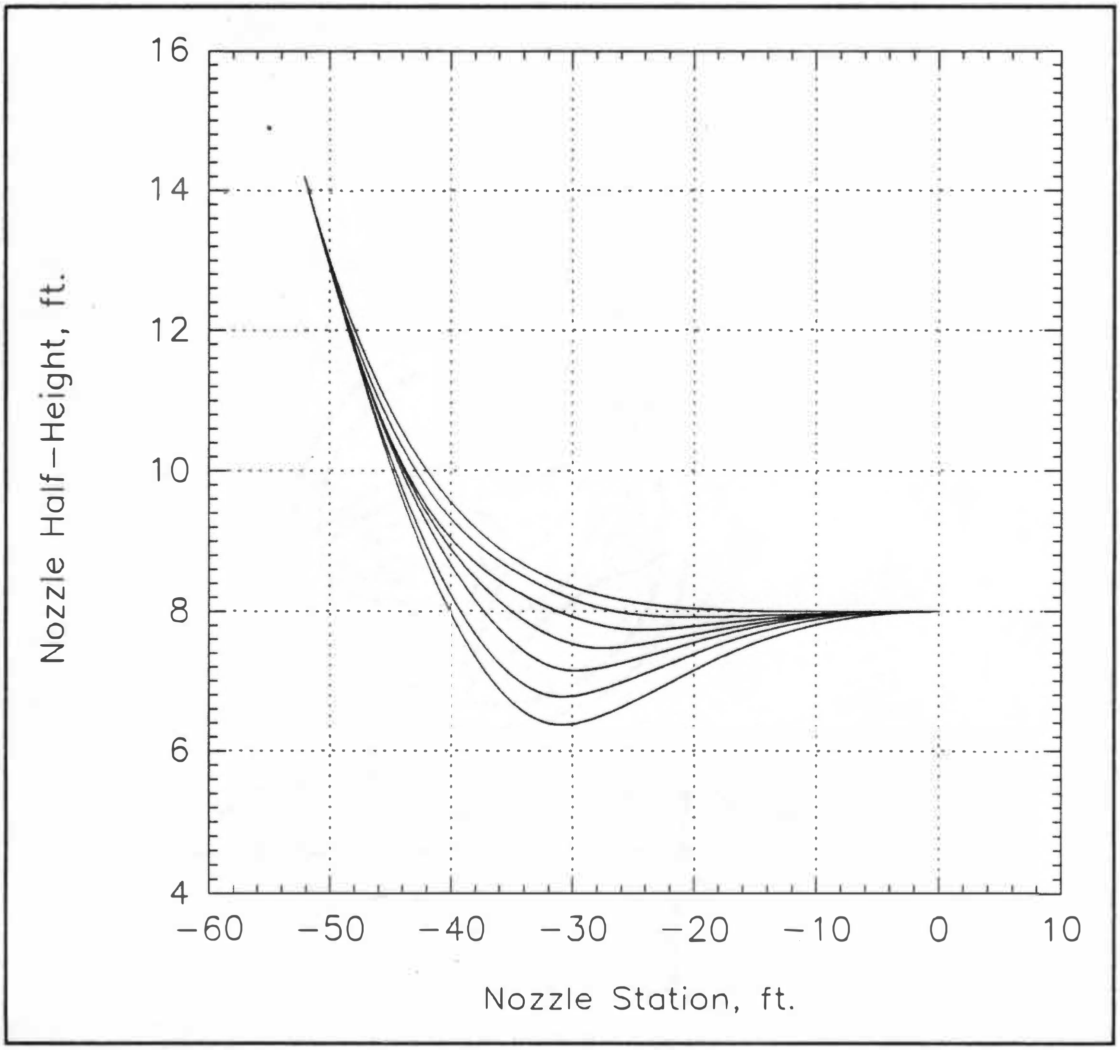
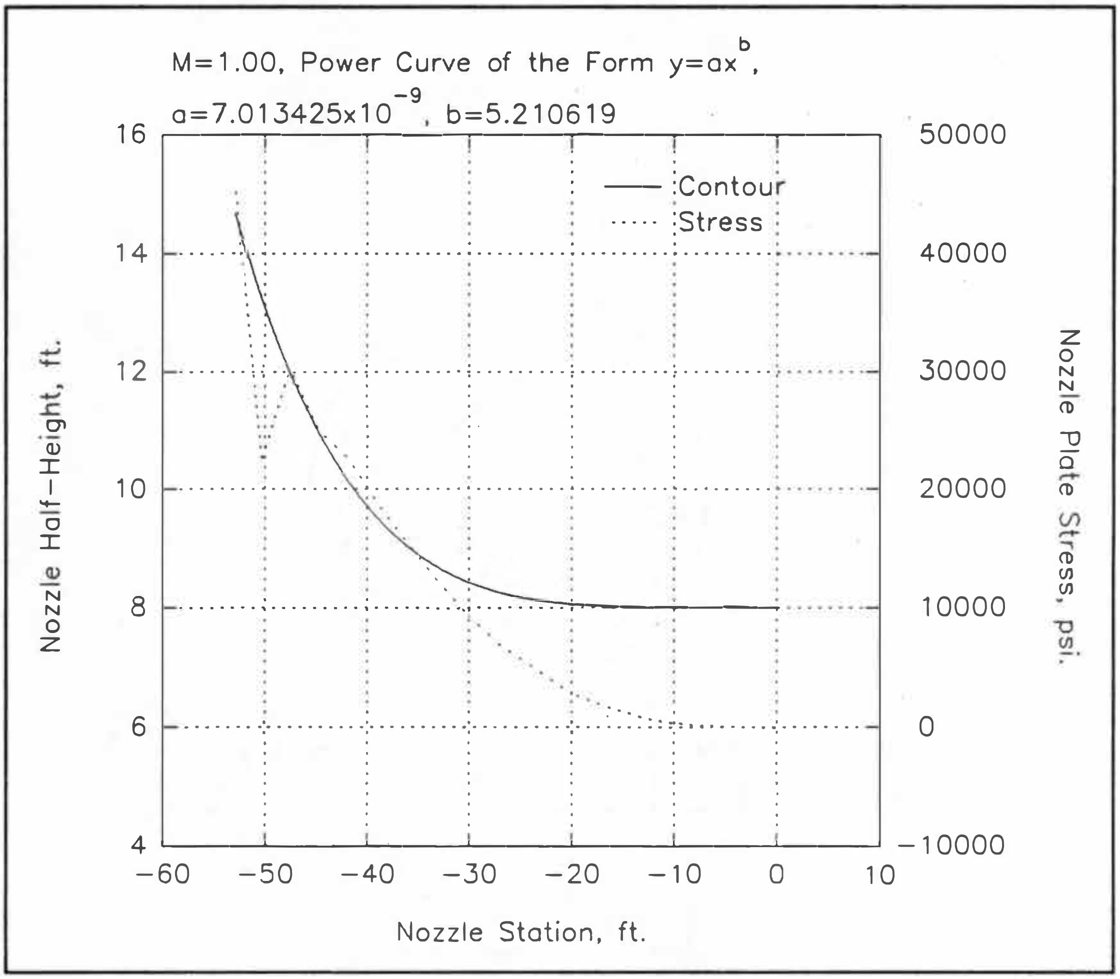
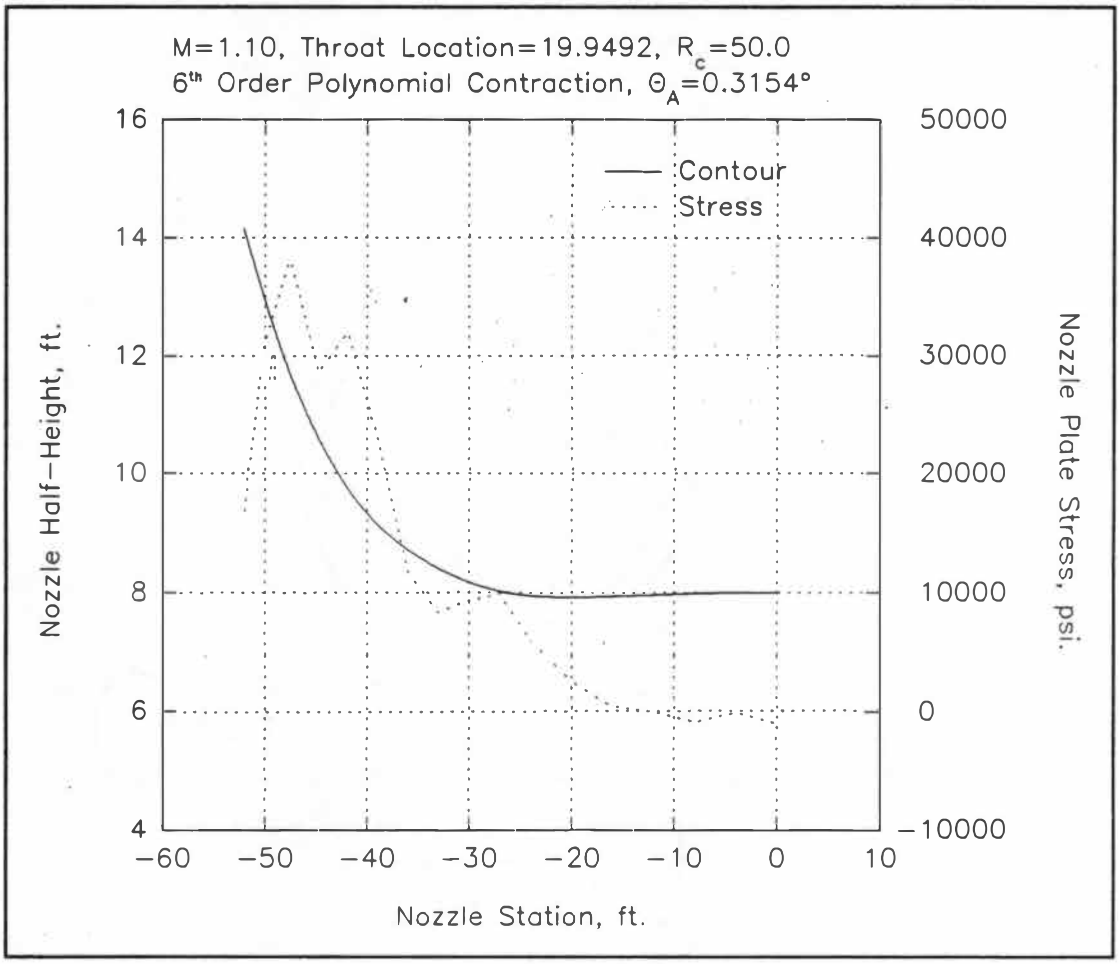


Figure 7. Composite of nozzle contours from the sonic to the Mach 1.60 contour in increments of 0.10.



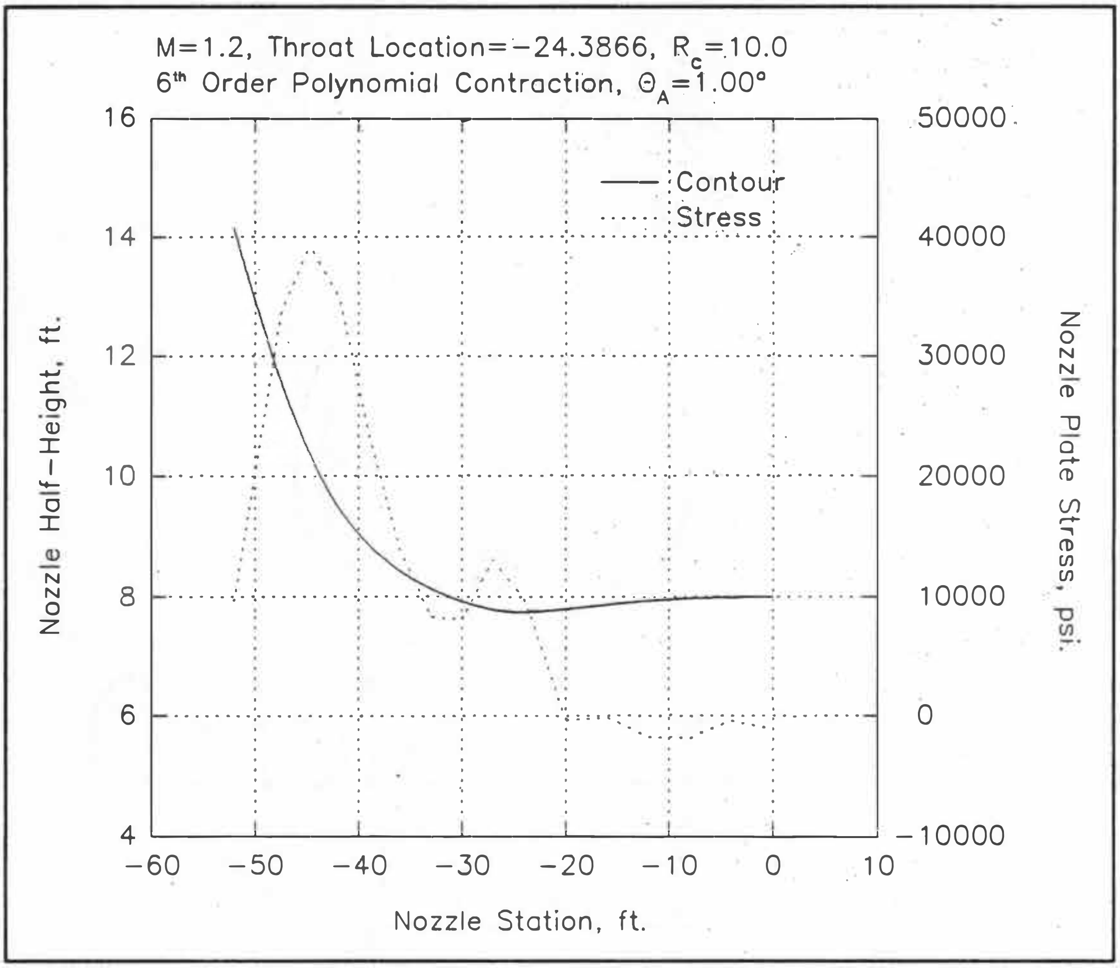
a. M=1.00

Figure 8. Nozzle contour and associated stress distribution.



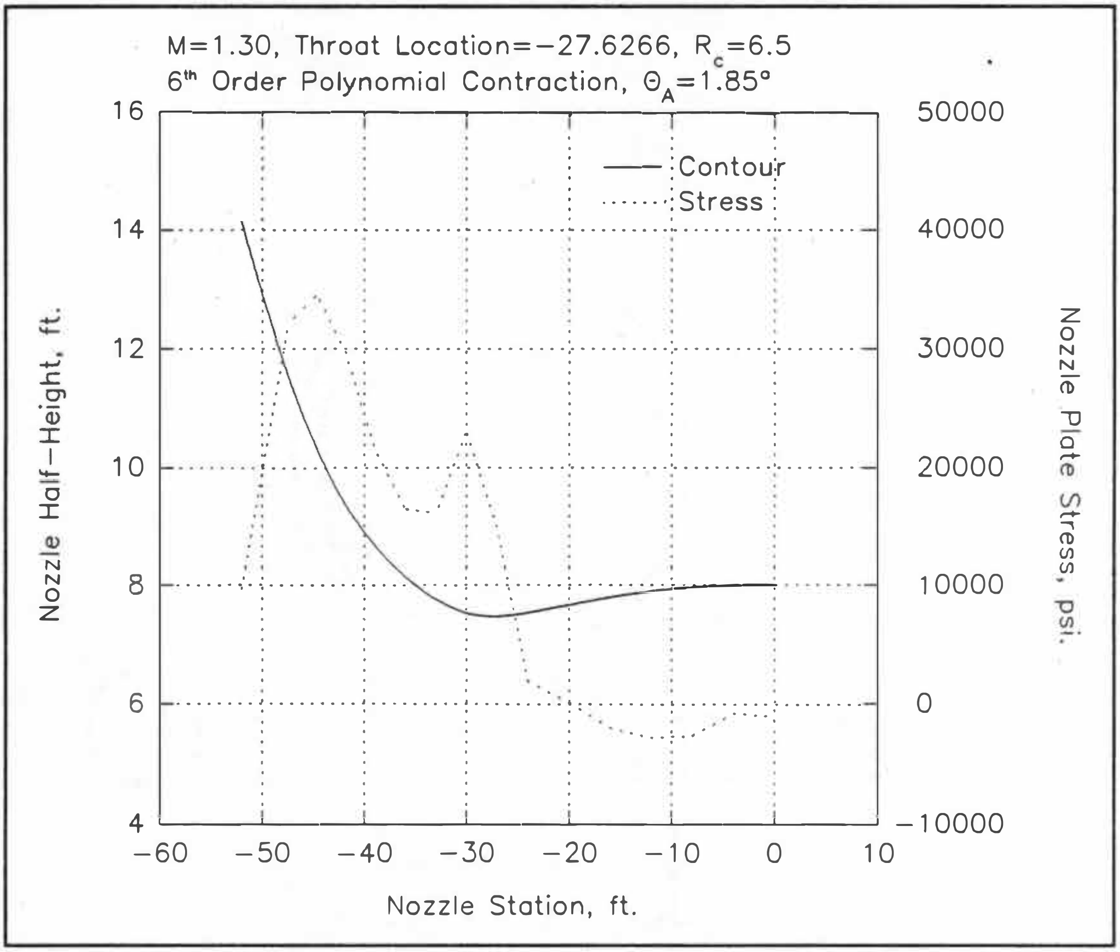
b. M=1.10

Figure 8. Continued.



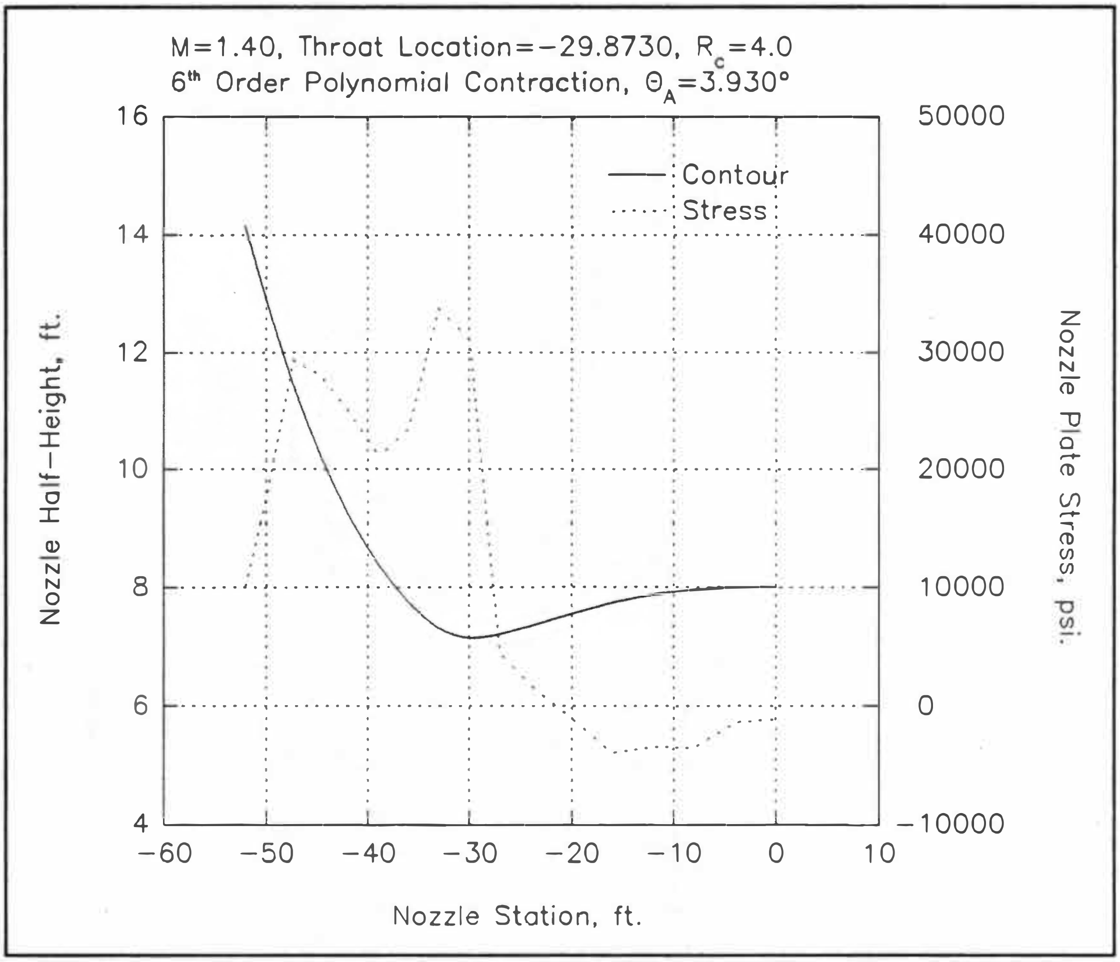
c. M=1.20

Figure 8. Continued.



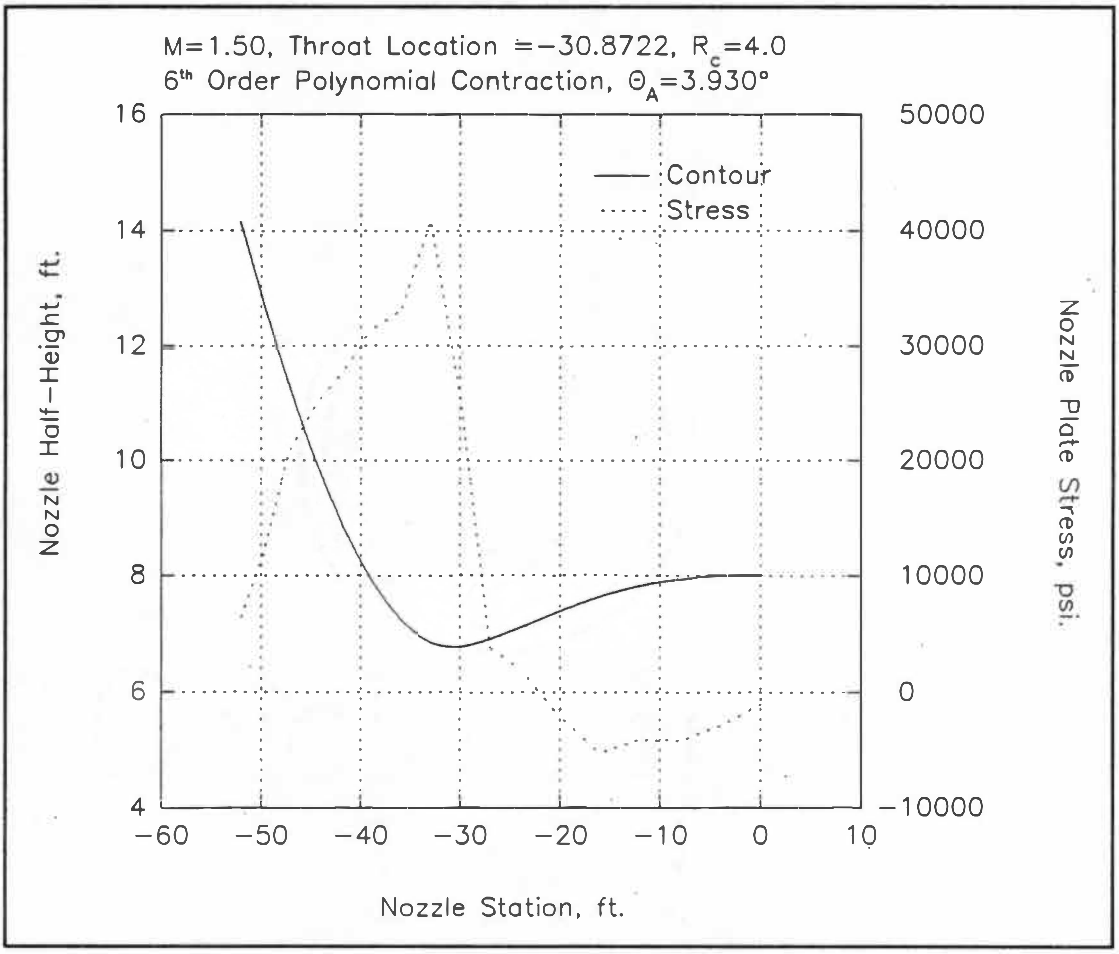
d. M=1.30

Figure 8. Continued.



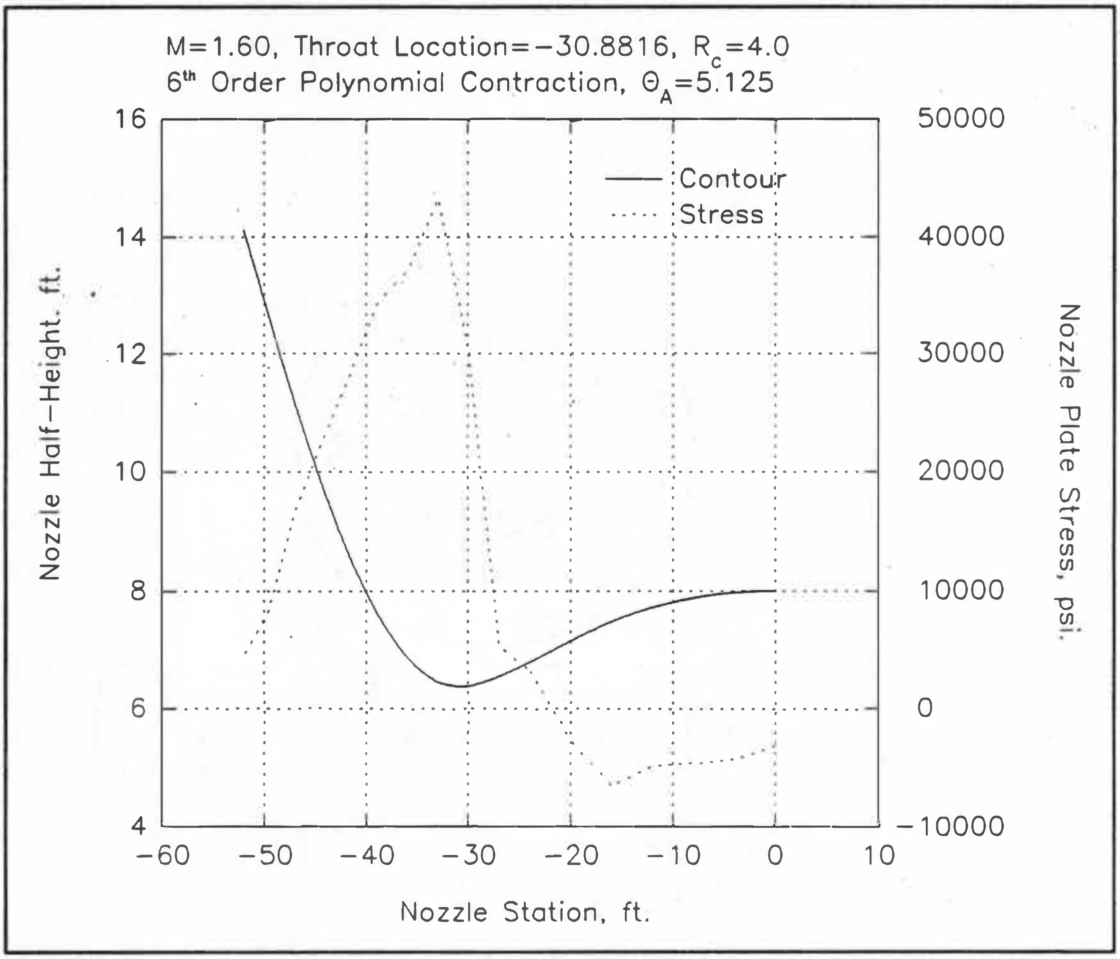
e. M=1.40

Figure 8. Continued.



f. M=1.50

Figure 8. Continued.



g. M=1.60

Figure 8. Continued.

while, for the contours approaching Mach 1.1 the point of maximum stress moves upstream. This occurs because of the slip joint at the upstream end of the nozzle plate. The slope of this joint is fixed at a slope appropriate for the Mach 1.6 contour and, as such, additional bending must take place in this region as the plate is retracted. Note that the stress pattern for Mach 1.00 contour is different from the other contours. The reason for the difference is the different way the contour is formed. The sonic contour is purely a power curve formulation and results in the maximum curvature occurring at the upstream end of the nozzle. As mentioned previously, the nozzle actuator jack lengths should progress in a monotonic nature from the lowest Mach number contour to the highest. Figure 9 shows the jack extension as a function of nozzle Mach number for each of the nozzle jacks. As can be seen, the jacks do not reverse direction in their progression to higher contours.

Figure 10 shows a composite of the nozzle plate stress for all the designed contours. Note the location of the peak stress for each Mach number. The Mach 1.60 contour exhibits a peak stress near the nozzle throat while the lower Mach number contours result in the peak stress nearer the upstream slip joint. This occurs because the slip joint is of a fixed slope closely matched to the Mach 1.60 requirements. Contours requiring less plate extension result in additional

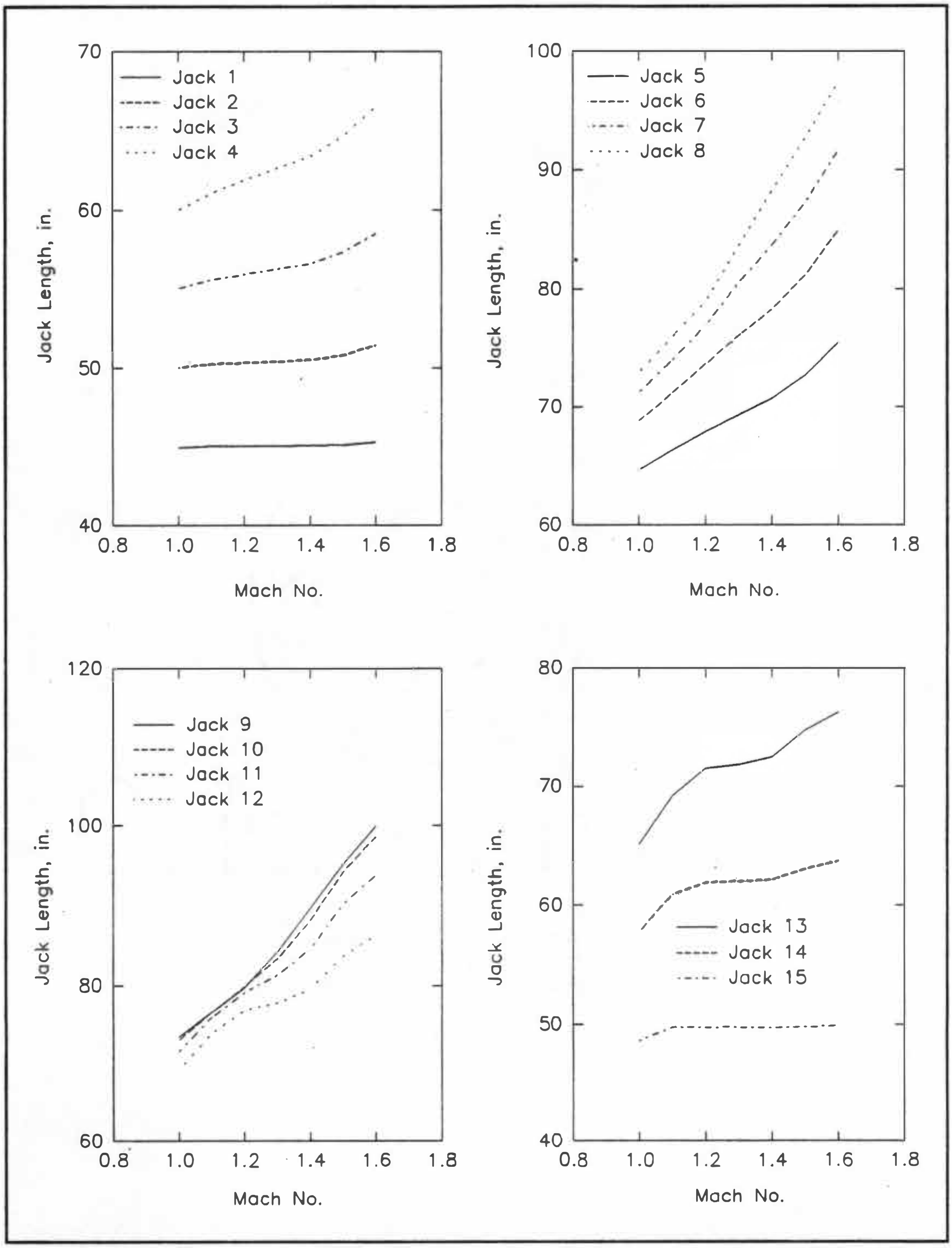


Figure 9. Nozzle actuator jack extension versus Mach number.

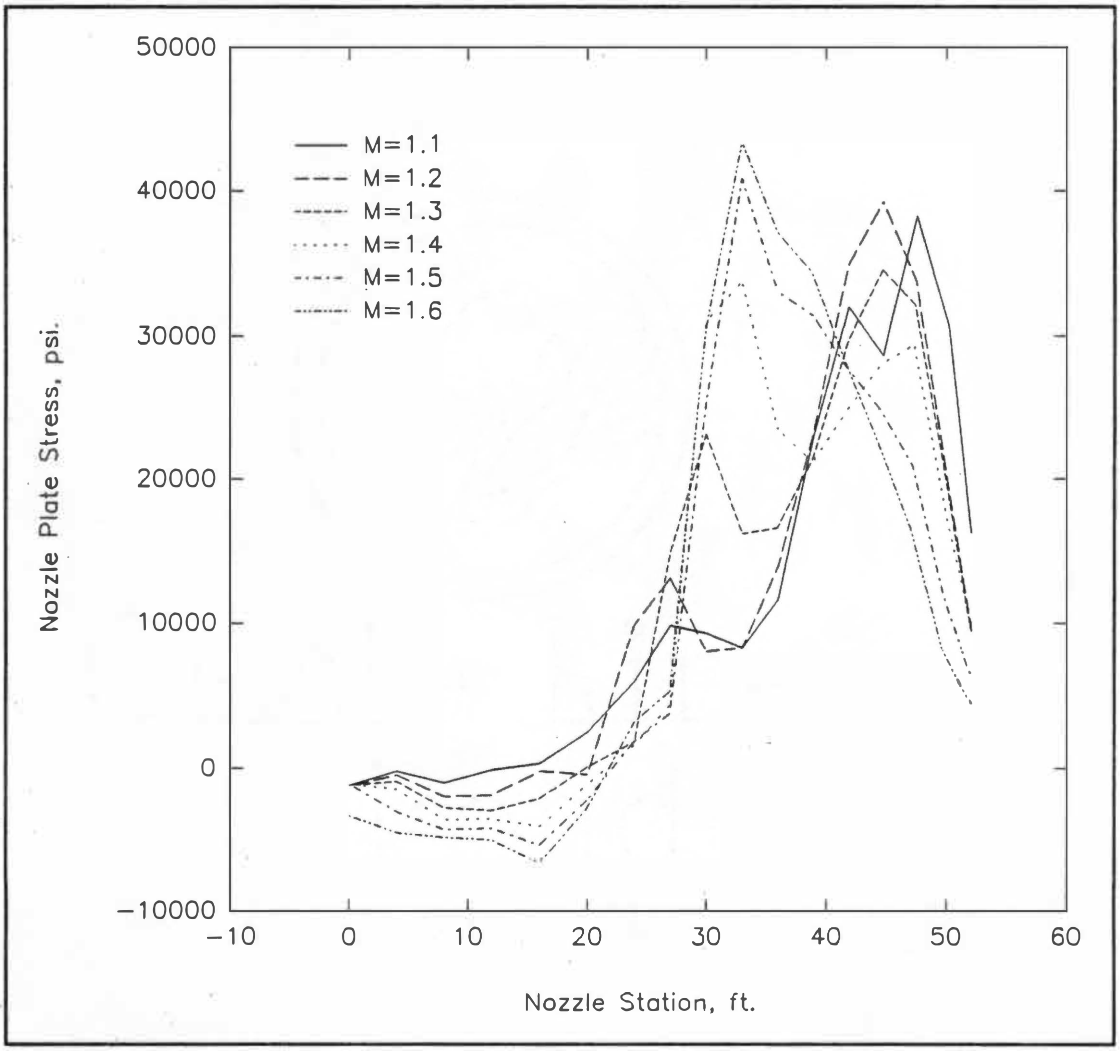


Figure 10. Composite nozzle plate stress for all designed contours.

bending in the upstream contraction region in order to accommodate the slip joint slope.

Figure 11 shows the variation in the throat radius of curvature with nozzle Mach number. As can be seen, the radius of curvature varies from about 25 ft. at the Mach 1.60 contour to approximately 350 ft at the Mach 1.10 contour. The rather large radius of curvature for the Mach 1.10 contour is more a requirement for the upstream contraction than for the supersonic portion of the contour. Figure 12 shows the variation of the inflection point wall angle with nozzle Mach number. The progression is very smooth throughout the Mach number range. The inflection point Mach number is one of the primary variables used in defining the contour geometry and a smooth transition is imperative if a similar family of contours is to be obtained.

Figure 13 shows the variation of the parameter K/θ_A. As mentioned previously, it is desirable to keep this parameter between values of 2 and 4 if possible. Because of length constraints, K/θ_A falls below 2 for Mach numbers above 1.40. For the Mach 1.50 and 1.60 contours care was taken to ensure that the actuator jack positions were suitable to attain the desired contour.

Figure 14 shows the length of the nozzle from the throat

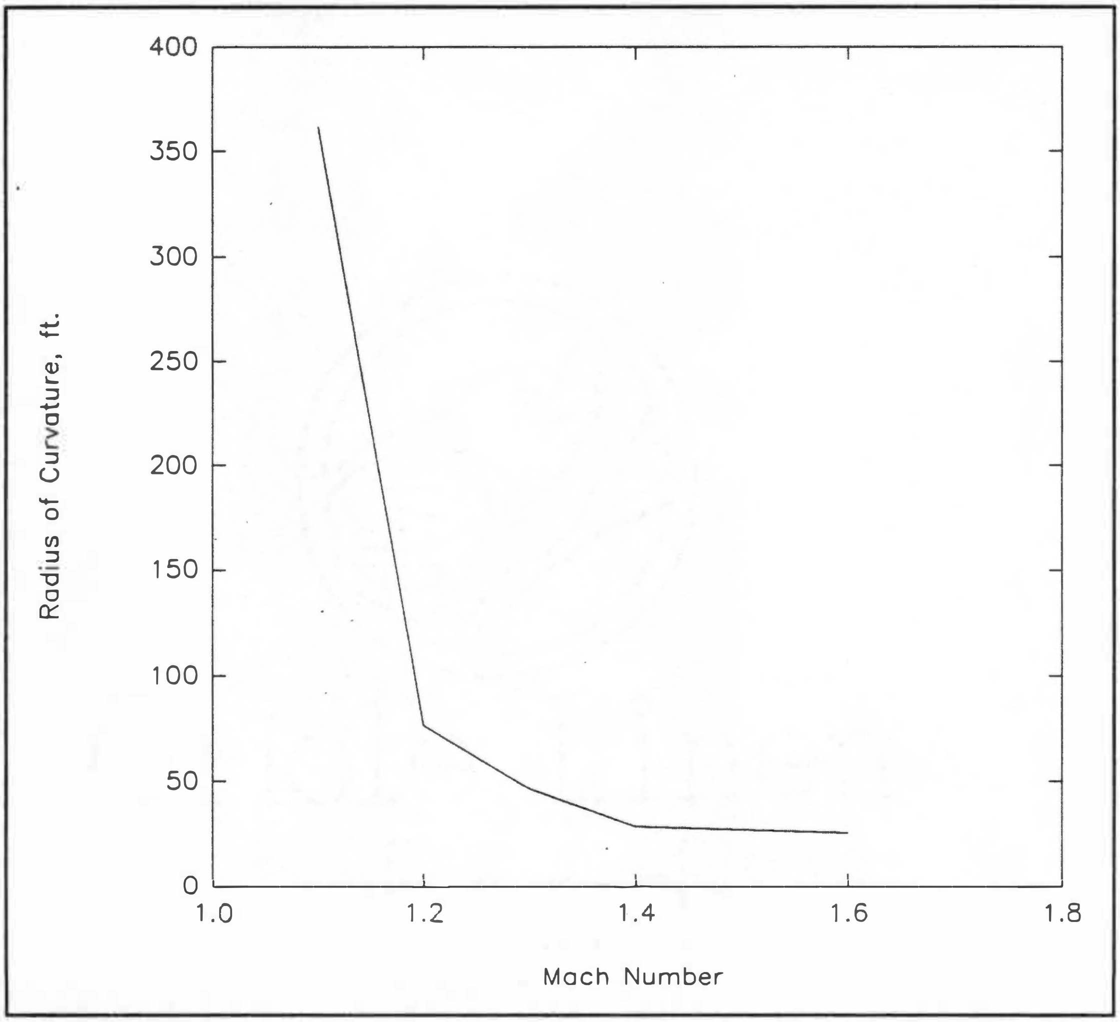


Figure 11. Variation of throat radius of curvature versus nozzle Mach number.

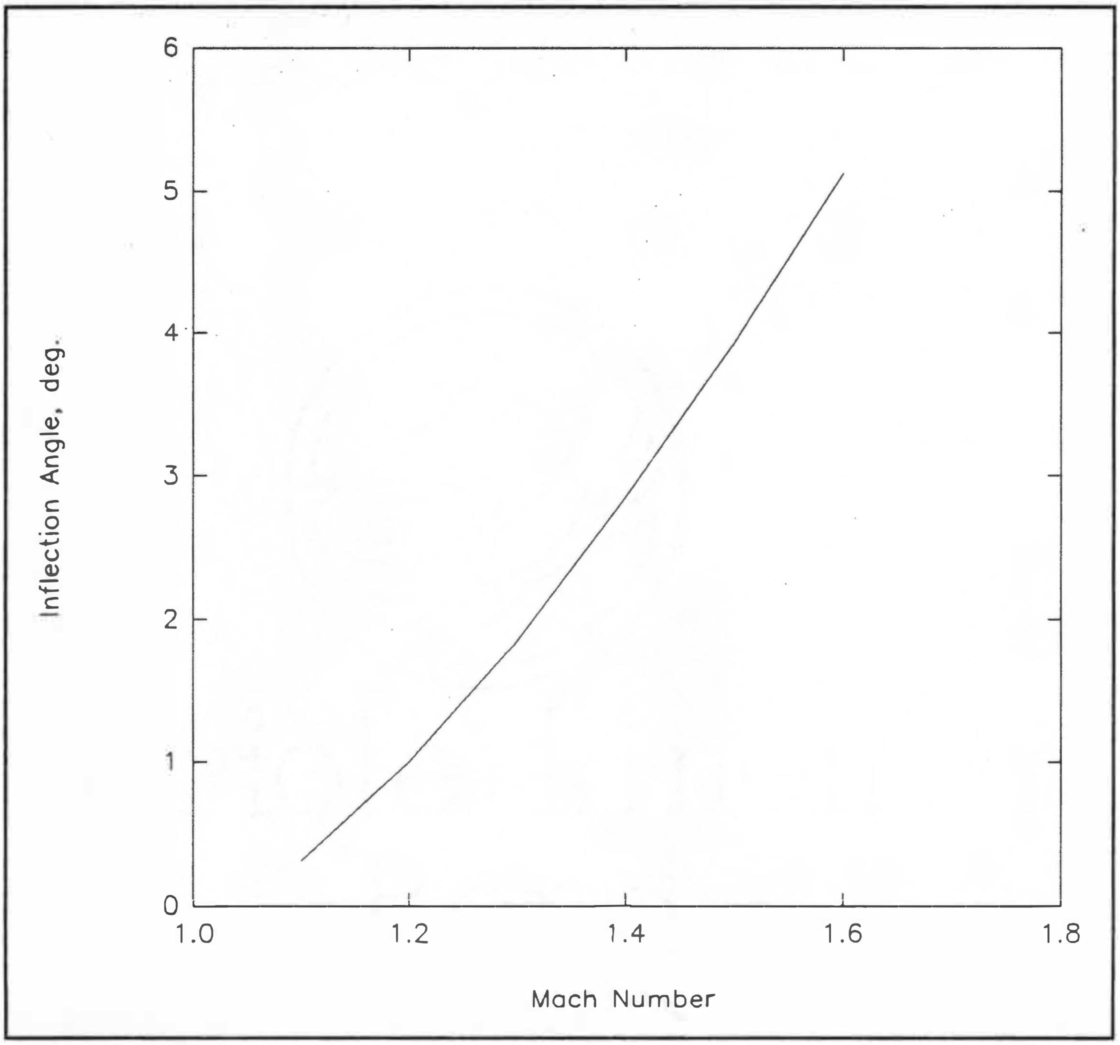


Figure 12. Variation of inflection point wall angle versus nozzle Mach number.

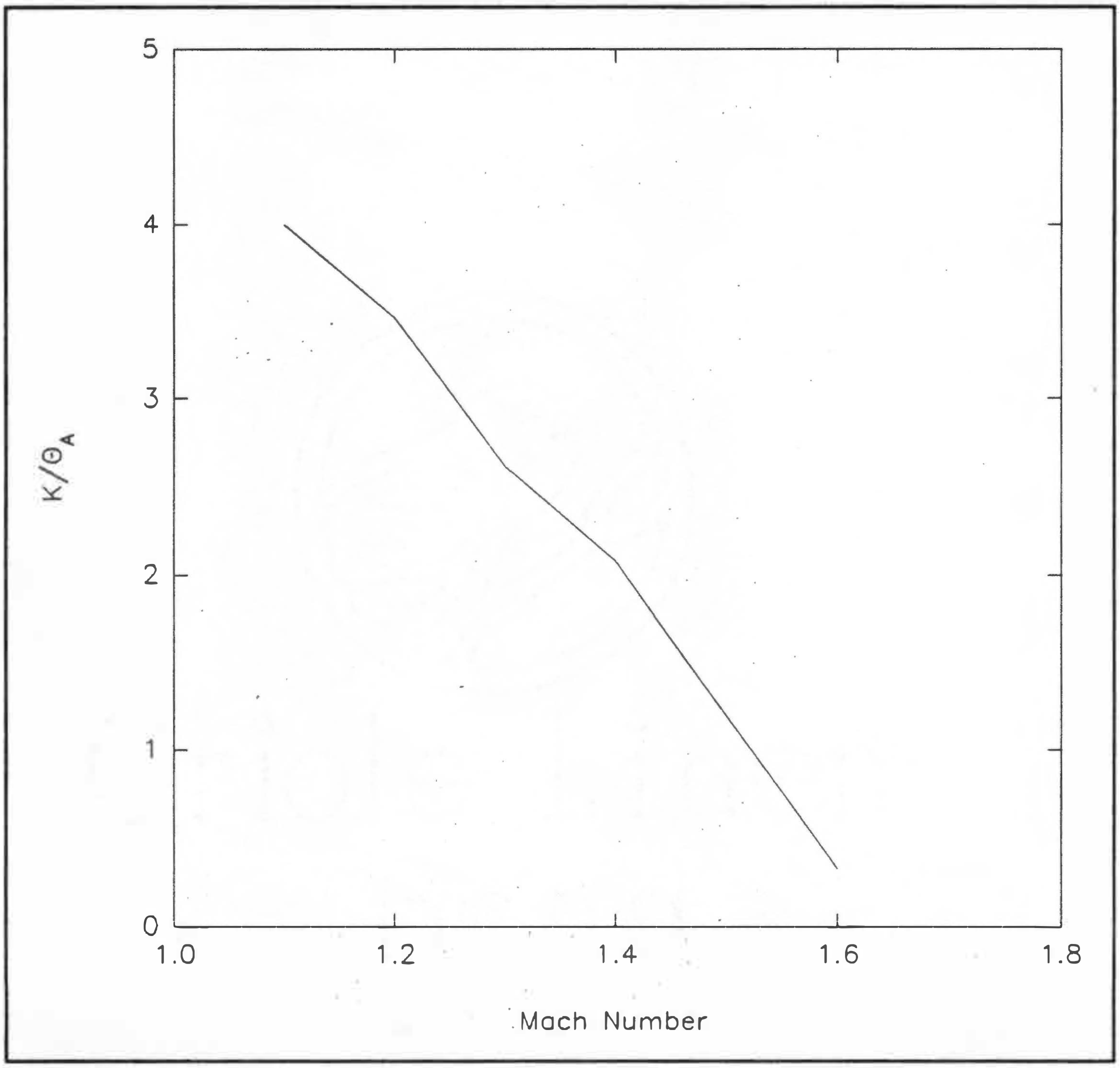


Figure 13. Variation of K/θ_A versus nozzle Mach number.

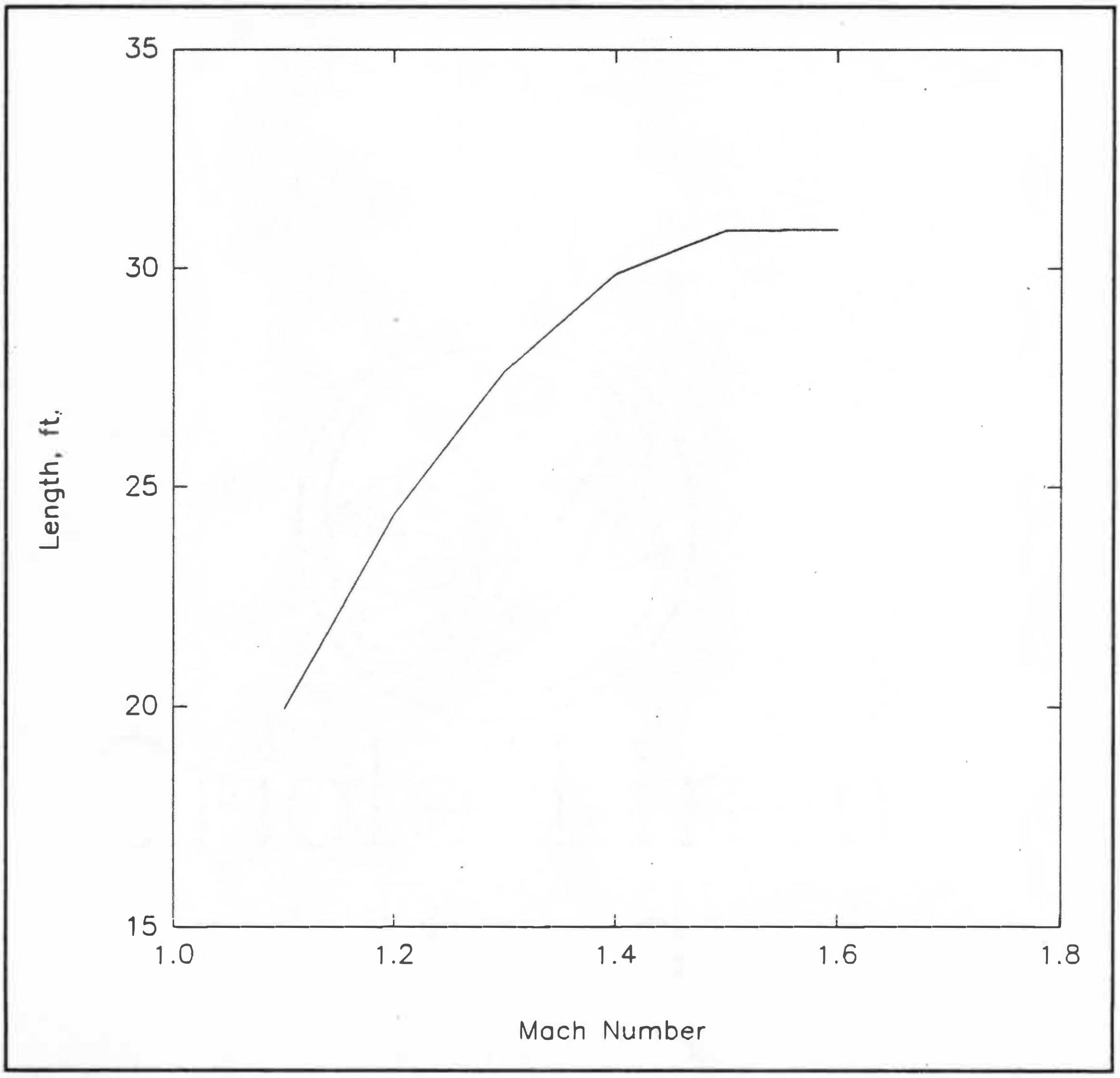


Figure 14. Length of nozzle from throat to exit versus nozzle Mach number.

to the exit as a function of the nozzle Mach number. Again, the transition is smooth as desired to assure a set of similar contour shapes.

Figure 15 presents the nozzle contour geometry in tabular form. At each support station is given the nozzle coordinates as well as the cubic polynomial coefficients describing the plate shape between each support location. Also shown is the curvature, bending stress, actuator jack length, and the plate length between support locations. The axial location of the nozzle throat is printed at the bottom of each figure.

16T FLEX NOZZLE - MACH 1.10
PLATE PROPERTIES: E= .30D+08 I= 9.8260 THICKNESS= .8500

CALCULATED CUBICS BETWEEN JACK POINTS ($Y = A + B*X_m + C*X_m^2 + D*X_m^3$) WHERE $X_m = (X-X_i)$
X_i = Axial location of i^{th} jack downstream of location of interest

JACK	X	A	B	C	D	CURVATURE	STRESS	JACK LEN.	S	
0	.00000000	8.00000000	.00000000	-.00052821	.00003701	-.00008803	-1122.	.0000	.0000	0
1	3.99999435	7.99391727	-.00244923	-.00008410	-.00002843	-.00001402	-179.	45.0138	4.0000	1
2	7.99997263	7.98095556	-.00448647	-.00042521	.00002394	-.00007087	-904.	50.2670	8.0000	2
3	11.99990441	7.95773921	-.00673881	-.00013788	.00005936	-.00002298	-293.	55.6418	12.0000	3
4	15.99982342	7.93237733	-.00499265	.00057443	-.00007197	.00009574	1221.	61.0439	16.0000	4
5	19.99979334	7.91699203	-.00385152	-.00028914	.00067187	-.00004819	-614.	66.3543	20.0000	5
6	23.99956890	7.93995334	.02617809	.00777282	-.00100370	.00129414	16500.	71.2070	24.0000	6
7	26.99706961	8.06122882	.04571885	-.00125295	.00067821	-.00020817	-2654.	73.5173	27.0000	7
8	29.99358787	8.20522367	.05648105	.00484382	.00039897	.00080346	10244.	75.5572	30.0000	8
9	32.98507581	8.42821417	.09615472	.00842437	-.00073809	.00138481	17656.	76.3114	33.0000	9
10	35.96544635	8.77008141	.12667563	.00182502	.00083182	.00029699	3787.	75.9320	36.0000	10
11	38.93653984	9.18437275	.15953485	.00923923	.00000854	.00148290	18907.	75.2799	39.0000	11
12	41.88514559	9.73532550	.21409962	.00931479	.00227619	.00145153	18507.	73.9098	42.0000	12
13	44.78709106	10.49069908	.32528786	.02913088	-.00033891	.00417523	53234.	70.3907	45.0000	13
14	47.56697356	11.61279662	.47803083	.02630449	-.00118776	.00321965	41051.	61.7324	48.0000	14
15	50.20671268	13.03612089	.58509173	.01689839	-.00200047	.00181094	23089.	49.8728	51.0000	15
16	52.05000000	14.15950000	.61661500	.00583607	.00000000	.00059986	7648.	.0000	53.1587	16

THROAT LOCATION = 21.5330
COUNT = 5

a. M=1.10

Figure 15. Nozzle contour geometry.

16T FLEX NOZZLE - MACH 1.20
PLATE PROPERTIES: E= .30D+08 I= 9.8260 THICKNESS= .8500

CALCULATED CUBICS BETWEEN JACK POINTS $(Y = A + B*X_m + C*X_m^2 + D*X_m^3)$ WHERE $X_m = (X-X_i)$
X_i = Axial location of i^{th} jack downstream of location of interest

JACK	X	A	B	C	D	CURVATURE	STRESS	JACK LEN.	S	
0	.00000000	8.00000000	.00000000	-.00055790	.00003040	-.00009298	-1186.	.0000	.0000	0
1	3.99999249	7.99301915	-.00300404	-.00019311	-.00005837	-.00003218	-410.	45.0246	4.0000	1
2	7.99994475	7.97417821	-.00735036	-.00089349	.00000346	-.00014890	-1899.	50.3483	8.0000	2
3	11.99970049	7.93070595	-.01433165	-.00085197	.00006483	-.00014195	-1810.	55.9662	12.0000	3
4	15.99914018	7.86390728	-.01803529	-.00007408	-.00000893	-.00001234	-157.	61.8656	16.0000	4
5	19.99845779	7.79002223	-.01905638	-.00018123	.00040215	-.00003019	-385.	67.8780	20.0000	5
6	23.99804842	7.73663536	-.00114623	.00464412	.00017030	.00077402	9869.	73.6451	24.0000	6
7	26.99760399	7.77957792	.03130636	.00617658	-.00026245	.00102792	13106.	76.8953	27.0000	7
8	29.99412086	7.92178678	.06124395	.00381731	.00001334	.00063265	8066.	78.9590	30.0000	8
9	32.98613942	8.13956042	.08443668	.00393708	.00030673	.00064923	8278.	79.7694	33.0000	9
10	35.97144474	8.43487769	.11612459	.00668410	.00053670	.00109186	13921.	79.9352	36.0000	10
11	38.94183018	8.85285356	.16996070	.01146672	.00075354	.00183120	23348.	79.1754	39.0000	11
12	41.87683251	9.46951722	.25646562	.01810162	.00050483	.00274200	34961.	76.8861	42.0000	12
13	44.73904147	10.36370540	.37182659	.02243640	-.00004823	.00307923	39260.	71.5321	45.0000	13
14	47.49065866	11.55569989	.49332379	.02203826	-.00096715	.00264927	33778.	61.8961	48.0000	14
15	50.12460686	12.99031046	.58408463	.01439600	-.00122882	.00154480	19696.	49.7530	51.0000	15
16	52.05000000	14.15950000	.61661500	.00729811	.00000000	.00075014	9564.	.0000	53.2527	16

THROAT LOCATION = 24.1206
COUNT = 4

b. M=1.20

Figure 15. Continued.

16T FLEX NOZZLE - MACH 1.30
PLATE PROPERTIES: E= .30D+08 I= 9.8260 THICKNESS= .8500

CALCULATED CUBICS BETWEEN JACK POINTS $(Y = A + B*X_m + C*X_m^2 + D*X_m^3)$ WHERE $X_m = (X-X_i)$
X_i = Axial location of i^{th} jack downstream of location interest

JACK	X	A	B	C	D	CURVATURE	STRESS	JACK LEN.	S	
0	.00000000	8.00000000	.00000000	-.00054049	.00001093	-.00009008	-1149.	.0000	.0000	0
1	3.99998958	7.99205163	-.00379934	-.00040935	-.00007156	-.00006822	-870.	45.0362	4.0000	1
2	7.99989497	7.96572597	-.01050861	-.00126802	-.00000617	-.00021130	-2694.	50.4497	8.0000	2
3	11.99938568	7.90301896	-.02094726	-.00134207	.00003195	-.00022353	-2850.	56.2985	12.0000	3
4	15.99804042	7.79984196	-.03014746	-.00095885	.00008453	-.00015959	-2035.	62.6349	16.0000	4
5	19.99591036	7.66939238	-.03376106	.00005497	.00006971	.00000915	117.	69.3263	20.0000	5
6	23.99380739	7.53975236	-.02999708	.00089110	.00068003	.00014832	1891.	76.0082	24.0000	6
7	26.99306363	7.47614655	-.00630011	.00700987	.00043485	.00116824	14895.	80.5351	27.0000	7
8	29.99216472	7.53203318	.04746086	.01092231	-.00035510	.00181425	23132.	83.6344	30.0000	8
9	32.98294352	7.76217587	.10321052	.00773620	.00003608	.00126904	16180.	84.2907	33.0000	9
10	35.95894101	8.13879725	.15015805	.00805833	.00030578	.00129888	16561.	83.4512	36.0000	10
11	38.91285513	8.66054653	.20566604	.01076810	.00055938	.00168655	21504.	81.3595	39.0000	11
12	41.82817247	9.36550738	.28246821	.01566045	.00050419	.00232619	29659.	77.8884	42.0000	12
13	44.67510741	10.30823844	.38336799	.01996662	.00012868	.00270910	34541.	71.8355	45.0000	13
14	47.42086197	11.51406827	.49518235	.02102657	-.00086835	.00252206	32156.	61.9520	48.0000	14
15	50.05499768	12.94847100	.58340078	.01416448	-.00116270	.00152131	19397.	49.7012	51.0000	15
16	52.05000000	14.15950000	.61661500	.00720572	.00000000	.00074064	9443.	.0000	53.3339	16

THROAT LOCATION = 27.4251
COUNT = 4

c. M=1.30

Figure 15. Continued.

16T FLEX NOZZLE - MACH 1.40
PLATE PROPERTIES: E= .30D+08 I= 9.8260 THICKNESS= .8500

CALCULATED CUBICS BETWEEN JACK POINTS ($Y = A + B*X_m + C*X_m^2 + D*X_m^3$) WHERE $X_m = (X-X_i)$
X_i = Axial location of i^{th} jack downstream of location of interest

JACK	X	A	B	C	D	CURVATURE	STRESS	JACK LEN.	S	
0	.00000000	8.00000000	.00000000	-.00050449	-.00001285	-.00008408	-1072.	.0000	.0000	0
1	3.99998672	7.99110559	-.00465284	-.00065873	-.00008289	-.00010978	-1400.	45.0475	4.0000	1
2	7.99982348	7.95665188	-.01390071	-.00165337	.00000251	-.00027548	-3512.	50.5586	8.0000	2
3	11.99895748	7.87477939	-.02700339	-.00162320	-.00002056	-.00027024	-3446.	56.6376	12.0000	3
4	15.99663987	7.73957343	-.04096633	-.00186983	.00011367	-.00031086	-3963.	63.3589	16.0000	4
5	19.99228459	7.55328559	-.05046384	-.00050726	.00010697	-.00008422	-1074.	70.7211	20.0000	5
6	23.98713639	7.35041447	-.04922657	.00077474	.00014620	.00012865	1640.	78.2822	24.0000	6
7	26.98401459	7.21378177	-.04064315	.00208920	.00139100	.00034734	4429.	83.6854	27.0000	7
8	29.98298835	7.14820234	.00941581	.01460388	.00017060	.00243366	31029.	88.2381	30.0000	8
9	32.97743639	7.31192714	.10133867	.01613647	-.00050750	.00264851	33768.	89.6832	33.0000	9
10	35.94568837	7.74162453	.18352054	.01161732	-.00008355	.00184237	23490.	88.1801	36.0000	10
11	38.87705776	8.37731313	.24929982	.01088253	.00030722	.00165691	21126.	84.6125	39.0000	11
12	41.76295194	9.19478385	.31955370	.01354231	.00035548	.00195075	24872.	79.6133	42.0000	12
13	44.58443916	10.21219269	.40406337	.01655130	.00034251	.00219868	28033.	72.4828	45.0000	13
14	47.31751850	11.44715601	.50165149	.01935962	-.00083077	.00230419	29378.	62.1201	48.0000	14
15	49.94922676	12.88629651	.58286146	.01280055	-.00083573	.00137579	17541.	49.6447	51.0000	15
16	52.05000000	14.15950000	.61661500	.00753350	.00000000	.00077433	9873.	.0000	53.4566	16

THROAT LOCATION = 29.6441
COUNT = 4

d. M=1.40

Figure 15. Continued.

16T FLEX NOZZLE - MACH 1.50
PLATE PROPERTIES: E= .30D+08 I= 9.8260 THICKNESS= .8500

CALCULATED CUBICS BETWEEN JACK POINTS $(Y = A + B*X_m + C*X_m^2 + D*X_m^3)$ WHERE $X_m = (X-X_i)$
X_i = Axial location of i^{th} jack downstream of location of interest

JACK	X	A	B	C	D	CURVATURE	STRESS	JACK LEN.	S	
0	.00000000	8.00000000	.00000000	-.00050367	-.00007339	-.00008395	-1070.	.0000	.0000	0
1	3.99995566	7.98724459	-.00755194	-.00138435	-.00004913	-.00023071	-2941.	45.0938	4.0000	1
2	7.99953994	7.93175155	-.02098282	-.00197387	.00000357	-.00032876	-4192.	50.8575	8.0000	2
3	11.99784013	7.81652912	-.03659422	-.00193104	-.00004612	-.00032119	-4095.	57.3372	12.0000	3
4	15.99373718	7.63652639	-.05423367	-.00248395	.00012166	-.00041217	-5255.	64.5968	16.0000	4
5	19.98598028	7.38816416	-.06824813	-.00102688	.00016251	-.00016996	-2167.	72.7052	20.0000	5
6	23.97628876	7.10980803	-.06833919	.00091857	.00009949	.00015203	1938.	81.1730	24.0000	6
7	26.97002076	6.91612092	-.06016326	.00181213	.00112480	.00030039	3830.	87.2605	27.0000	7
8	29.96684388	6.78237011	-.01899601	.01192459	.00083055	.00198636	25326.	92.6289	30.0000	8
9	32.96483541	6.85497775	.07480247	.01939454	-.00034390	.00320548	40870.	95.1511	33.0000	9
10	35.93867219	7.23990321	.18070538	.01632644	.00001925	.00259303	33061.	94.1649	36.0000	10
11	38.86216903	7.90821512	.27628248	.01649526	-.00007872	.00246200	31391.	90.1212	38.9999	11
12	41.71638774	8.82933496	.36807692	.01582118	-.00003774	.00217931	27786.	83.6787	42.0000	12
13	44.48990121	9.97109865	.45451579	.01550719	-.00014948	.00195005	24863.	74.7784	45.0000	13
14	47.17793367	11.30199604	.53423888	.01430176	-.00071518	.00163559	20854.	63.0075	48.0000	14
15	49.78774579	12.78095725	.59261825	.00870230	-.00057411	.00092343	11774.	49.7520	51.0000	15
16	52.05000000	14.15950000	.61661500	.00480592	.00000000	.00049398	6298.	.0000	53.6492	16

THROAT LOCATION = 30.7062
COUNT = 4

e. M=1.50

Figure 15. Continued.

16T FLEX NOZZLE - MACH 1.60
PLATE PROPERTIES: E= .30D+08 I= 9.8260 THICKNESS= .8500

CALCULATED CUBICS BETWEEN JACK POINTS $(Y = A + B*X_m + C*X_m^2 + D*X_m^3)$ WHERE $X_m = (X-X_i)$
X_i = Axial location of i^{th} jack downstream of location of interest

JACK	X	A	B	C	D	CURVATURE	STRESS	JACK LEN.	S	
0	.00000000	8.00000000	.00000000	-.00152395	-.00004568	-.00025399	-3238.	.0000	.0000	0
1	3.99987208	7.97269473	-.01438349	-.00207216	-.00001247	-.00034525	-4402.	45.2683	4.0000	1
2	7.99877824	7.88124239	-.03155311	-.00222181	-.00000775	-.00036975	-4714.	51.4640	8.0000	2
3	11.99543853	7.71915113	-.04968109	-.00231470	-.00006547	-.00038436	-4901.	58.5069	12.0000	3
4	15.98819034	7.47971822	-.07129188	-.00309896	.00014965	-.00051258	-6535.	66.4810	16.0000	4
5	19.97498202	7.15571919	-.08886257	-.00130904	.00023882	-.00021561	-2749.	75.4989	20.0000	5
6	23.95878807	6.79603220	-.08748809	.00154520	.00010884	.00025460	3246.	84.9437	24.0000	6
7	26.94875841	6.55116851	-.07532637	.00252144	.00130876	.00041669	5313.	91.6443	27.0000	7
8	29.94377060	6.38334324	-.02500148	.01428069	.00070304	.00237789	30318.	97.4191	30.0000	8
9	32.94150842	6.45566711	.07943971	.02060331	-.00023920	.00340163	43371.	99.9269	33.0000	9
10	35.91153465	6.86708150	.19508204	.01847207	-.00000285	.00291093	37114.	98.5960	36.0000	10
11	38.82148647	7.59110876	.30201468	.01844719	-.00023353	.00269721	34389.	93.7971	39.0000	11
12	41.65013268	8.58771654	.40023618	.01646551	-.00024314	.00219599	27999.	86.2839	42.0000	12
13	44.39190759	9.80383945	.48459750	.01446562	-.00035914	.00175700	22402.	76.2824	45.0000	13
14	47.05262419	11.18885925	.55363636	.01159889	-.00071034	.00129448	16505.	63.6825	48.0000	14
15	49.64875370	12.69191689	.59874447	.00606648	-.00037045	.00063855	8142.	49.9136	51.0000	15
16	52.05000000	14.15950000	.61661500	.00339787	.00000000	.00034925	4453.	.0000	53.8142	16

THROAT LOCATION = 30.7689
COUNT = 4

f. M=1.60

Figure 15. Continued.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

A new set of nozzle contours have been designed for the 16T nozzle. As was shown in Chapter 4, the actuator supported plate differs from the method of characteristics contour by no more than 0.01 in. Because of the very close agreement between the physical and ideal contour shapes, the flow quality from the nozzle contours should match the method of characteristics flow field very closely. However, there are always errors associated with locating the actuator jacks and in the calibration of the plate position itself. Typically, the order of magnitude of these errors is approximately 0.015 in. for a nozzle of this size. It is difficult to measure the plate position more accurately than this value with available measurement equipment. For these reasons, it is expected that the resultant flow uniformity at the nozzle exit will be of lessor quality than what the method of characteristics calculation predicts. It is recommended, therefore, that the initial calibration of the flow field after the contours are installed be accomplished with the capability to make corrections to the contours using the influence coefficient correction techniques mentioned previously. If deemed necessary, these corrections should be accomplished with a restriction applied to the maximum allowable correction amount. In no case should the individual jack corrections be allowed to be so large that the jacks no longer move in a monotonic fashion while progressing in Mach number contour. Of course, if the corrections are of a lessor amount than the ability to set the contour, it is questionable whether they will accomplish any valuable results. It is the author's experience that this type of contour correction procedure should be approached cautiously.

The nozzle contours designed in this study were calculated assuming a nozzle stagnation pressure of 1000 psfa. The assumed stagnation pressure only influences the boundary layer calculation and the resulting displacement thickness which is used as a correction to the inviscid contour calculation. The assumed pressure is representative of typical tunnel operating pressures but there are frequent excursions from this pressure. For this reason, it may be advisable to design a series of contours for each Mach number to compensate for different displacement thicknesses. This capability exists with the present control system, but has not been utilized to date. The need may not arise in the future either, but it should be remembered that the capability is there.

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VITA

William Everett Milam was born in Baytown, Texas on December 31, 1950. He attended elementary schools in Riverside, California, Rancho Cordova, California, and Devine, Texas. He graduated from Englewood High School in Jacksonville, Florida in 1969. In 1970 he entered the United States Air Force and served for four years at which time he received an honorable discharge. In 1975 he entered the University of Florida and in December, 1978 received a Bachelor of Science in Mechanical Engineering with Honors. In January, 1979 he began employment at Arnold Engineering Development Center where he still employed. He has pursued courses leading to a Master of Science at the University of Tennessee Space Institute intermittently since he began employment at AEDC. In August, 1992 he received a Master of Science in Mechanical Engineering from the University of Tennessee.