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FLOW QUALITY IMPROVEMENT AT MACH 8 IN THE VKF 50-INCH HYPERSONIC WIND TUNNEL B

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ARO, Inc.

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FOREWORD

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This technical report has been reviewed and is approved.

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ABSTRACT

Flow quality within the 50-in. hypersonic tunnel at a nominal Mach number of 8 is discussed. The nozzle and throat were recently remachined to closer tolerances which resulted in improved test section flow quality. Measurements of the contoured nozzle ordinates and Mach number distributions are presented along with results from method of characteristics solutions of design and actual measured wall contours.

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TABLE

NOMENCLATURE

M	Mach number
$M_{\mathbb{C}}$	Mach number on axial centerline of tunnel
p_o	Stilling chamber pressure, psia
p_o'	Total pressure behind normal shock wave, psia
T_o	Stilling chamber temperature, °R
y	Ordinate perpendicular to axial centerline of tunnel, in.
Δy	Ordinate measured minus design ordinate, in.
Z	Measure of curvature defined in Fig. 4, in.
γ	Specific heat ratio
δ	Boundary-layer thickness, in.
δ^*	Boundary-layer displacement thickness, in.

SECTION I
INTRODUCTION

The initial calibration of the 50-in. hypersonic Mach 8 tunnel (Gas Dynamic Wind Tunnel, Hypersonic (B)) in 1959 showed that the flow was nearly uniform everywhere excluding a small core in proximity to the axial centerline. At that location a sine-wave-shaped distribution in Mach number with an amplitude several times the off-center deviation was evidenced. This flow situation was quite common to axisymmetric supersonic wind tunnels and was more or less accepted until 1963 when the initial calibration of the Mach 10 tunnel (Gas Dynamic Wind Tunnel, Hypersonic (C)) showed negligible centerline focusing. Of course, Tunnel C had a much thicker boundary layer because of its higher Mach number, lower expansion angle, and increased length. The thicker boundary layer was thought to perhaps absorb any machining errors more readily.. With the use of the AEDC high-speed digital computer (IBM 7074), after the formation of Scientific Computing Services, and with the advent of increased precision requirements of wind tunnel testing, it was decided to investigate the disturbance focusing problem in Tunnel B. The problem has been solved to the extent that the flow quality in Tunnel B is as good or better than that of Tunnel C and is discussed herein.

SECTION II
WIND TUNNEL

Tunnel B is an axisymmetric, continuous, variable-density, hypersonic wind tunnel with a 50-in.-diam test section. Interchangeable throats provide nominal test Mach numbers of 6 and 8. At Mach 6, the stilling chamber pressure can be varied from 10 to 300 psia. Stagnation temperatures up to 1260°R are available. At Mach 8, the stilling chamber pressure can be varied from 50 to 900 psia at a stagnation temperature up to 1360°R.

Details of Tunnel B and associated equipment are shown in Fig. 1. As illustrated, the tunnel is equipped with a mechanism which can inject a model into the test section for a test run and then retract it into a chamber where model cooling or changes can be accomplished while the tunnel is running.

The aerodynamic design and operation of the tunnel is discussed in Ref. 1. The coordinates of the nozzle were obtained by adding a boundary-layer displacement thickness (δ^*) to an inviscid expansion determined by the method of characteristics. The inviscid design is basically that of Cresci (Ref. 2) where an initial expansion section is required to produce radial flow (that of a spherical source). The downstream portion of the nozzle accepts the radial flow and produces uniform parallel flow at the exit as shown in Refs. 1 and 2. The boundary-layer displacement thickness was determined by the Sivells-Payne method of Ref. 3. Both the Cresci and the Sivells-Payne schemes have been programmed on the AEDC high-speed digital computer (IBM 7074). Table I contains an abbreviated listing of coordinates applicable to the new throat and the remachined downstream contour of Tunnel B.

The test section Mach number distribution was measured using a top-window-mounted, cantilevered rake containing 17 impact pressure probes, 3/32-in. in diameter, spaced 1 in. apart. The rake was carefully aligned so that the center probe was on the geometrical longitudinal tunnel centerline when traversed fore and aft. This was considered important because of the inherent focusing of flow in axisymmetric wind tunnels.

Mach number was calculated from

$$\frac{p_o'}{p_o} = \left[\frac{(\gamma + 1)M^2}{(\gamma - 1)M^2 + 2}\right]^{\frac{\gamma}{\gamma-1}} \left[\frac{\gamma + 1}{2\gamma M^2 - (\gamma - 1)}\right]^{\frac{1}{\gamma-1}}$$

The specific heat ratio, γ, was taken to be 1.4. The precision of p_o' and p_o measurements was estimated to be within 1 percent of the reading.

SECTION III
RESULTS AND DISCUSSION

The aerodynamic design and the flow quality associated with the 50-in. hypersonic tunnel is discussed in Ref. 1. The reference indicates that along the axial centerline of the tunnel in an area of frequent model testing, there was a nonuniformity in Mach number of approximately 0.3. Figure 2 illustrates the centerline Mach number distribution near the midpoint of the 54-in.-long test section (p_o = 600 psia). This nonuniformity was confined to the tunnel centerline and was shown (Ref. 1) to be somewhat detrimental to local measurements on some wind tunnel models.

The axisymmetric Tunnel B nozzle is fabricated in several sections (Fig. 2): a throat section, five contoured sections, and a cone-frustum test section. The centerline focused nonuniformity of concern occurs at station 270. Characteristics associated with the disturbance (obtained from the design inviscid flow field) are illustrated in Fig. 2. If a contour error were to exist, it would have to be either near station 120 or in the throat section as shown in the figure.

The first step in seeking flow improvement was to build a new throat section as part of a general maintenance and modernization program as indicated in Ref. 1. The old throat had a radius of curvature to throat radius ratio of 5, and was defined by an analytical expression (a cubic for the entrance and a semicubic for the supersonic portion, Ref. 1). The new throat section was designed to have a radius of curvature to throat radius ratio of 20 and was defined by (1) the method of characteristics (Ref. 4) where the flow was supersonic, (2) transonic theory (Ref. 5) at the throat, and (3) a cubic for the entrance region. These changes in aerodynamic design of the throat region were believed to give better assurance that radial flow would be achieved at the inflection point, and the improved flow experienced at Mach 10 (Ref. 1) was partly attributed to the larger radius of curvature.

As shown in Fig. 2, however, the replacement of throat sections did not improve the flow uniformity. A slight over-all level shift was caused by a small change in throat diameter. The conclusion then was that an axisymmetric error existed in the contour near station 120. Figure 3 shows the results of a simple experiment where an axisymmetric disturbance, consisting of three layers of stairstep-fashioned pressure-sensitive tape (Scotch® No. 33), was affixed to the wall at station 117 (a fabrication joint). Centerline Mach number disturbance with an amplitude of five times that obtained with no tape resulted (Fig. 3), indicating that a contour error of a few thousandths of an inch was probably present in this vicinity.

Since absolute ordinate measurements of the nozzle near station 120 would be difficult to obtain without tunnel disassembly, a simple curvature gage was used to inspect the contour. The gage was 24 in. in length, with a dial indicator at the midpoint. Two legs at each end (1 in. apart) insured that the gage was always aligned with the tunnel centerline. The results of these measurements along with the calculated desired curvature are shown in the lower curve in Fig. 4. The measurements were repeatable to 0.001 in.

Although Fig. 4 shows only relative changes along the nozzle, it does imply that the contour, when assembled, was not within the specified ±0.002 tolerance. Based on these measurements along with some diametrical measurements, it was decided to remachine the contour (excepting the throat section) to as close a tolerance as possible with the available equipment. Curvature measurements after machining, given in the upper curve in Fig. 4, indicated a much better contour than before. Also, additional absolute ordinate measurements from station 60 to 160 showed that the contour was now within the ±0.002-in. tolerance.

Figure 5 shows the final centerline calibration with a total deviation of 0.09 in Mach number, whereas the deviation before machining was 0.24. The off-center Mach number is within 0.02 compared to 0.04 prior to remachining. Over-all axial and lateral gradients proved to be essentially nonexistent in the test region.

The method of characteristics using the AEDC digital computer was the basic tool for obtaining the inviscid outermost streamline onto which the turbulent boundary-layer displacement thickness was added. Given this inviscid streamline and an initial line of known flow (from transonic theory), the computer can generate a characteristics network, thereby defining the downstream flow. The results of two solutions of this type are presented in Fig. 6a. The first computation was applied to the inviscid design contour to serve as a basis of comparison for the second. As expected, the computed flow is shown to be very close to that desired. The second computation retained the identical inviscid boundary from the throat to station 109. From station 109 to 146, however, deviations of the measured wall from the design wall were applied to the inviscid outermost streamline, just as if the boundary layer conformed to the wavy wall but provided no cushioning. The top curve in Fig. 6a shows the streamline perturbation Δy in a region AB which has a direct effect on $M_{\mathbb{C}}$ in region A′B′. The points presented on the two curves between AB and A′B′ are in correspondence with respect to characteristics. The computed centerline Mach number distribution based on the perturbed streamline is in fair agreement with the measured Mach number, thereby indicating that small contour deviations can produce centerline nonuniformities on the order of those measured.

Thus far only test section centerline flow has been discussed. As mentioned previously, off-centerline flow is highly uniform. Figure 6b shows a lateral distribution at station 270 where, according to Fig. 6a, the centerline Mach number deviates most from that desired. The agreement between calculated and measured Mach numbers is considered excellent within the 32-in.-diam usable core. Of course, outside of the 32-in. test core a real boundary layer of thickness δ cannot be compared to the ficticious, but useful, concept of divorcing viscous and nonviscous flows. The reason for the drop in Mach number near the wall in the computed curve is the fore-shortened nozzle. Lateral distributions at all stations are typically the same except for less severe centerline focusing.

All measurements and calculations in this report are based on a design condition of a fixed stilling chamber pressure and temperature at Mach 8, namely 600 psia and 1310°R, respectively. The tunnel is being operated successfully over a stilling chamber pressure range of 50 to 900 psia. The quality of flow within this range is essentially the same as that presented, except for an over-all level change in Mach number. The average Mach number is 7.85 at 50 psia, 8.00 at 600 psia, and 8.02 at 900 psia.

SECTION IV
CONCLUSIONS

Based on this investigation of the flow in Tunnel B, the following results were obtained:

1. The semicubic throat discussed in Ref. 1 produced flow of equal quality to that of a more exotic aerodynamically designed throat with a larger radius of curvature.
2. Close tolerance machining is important, at least to point B (Fig. 6a), to keep centerline focusing to a minimum.
3. Masking or cushioning of the turbulent boundary layer is apparently small, with regard to machining errors of the type illustrated, even though the boundary layer is thick compared to the error.
4. The turbulent boundary layer scheme of Ref. 3 apparently predicted δ^* extremely well at all stations as evidenced by the level and lack of gradients in Mach number at design conditions.

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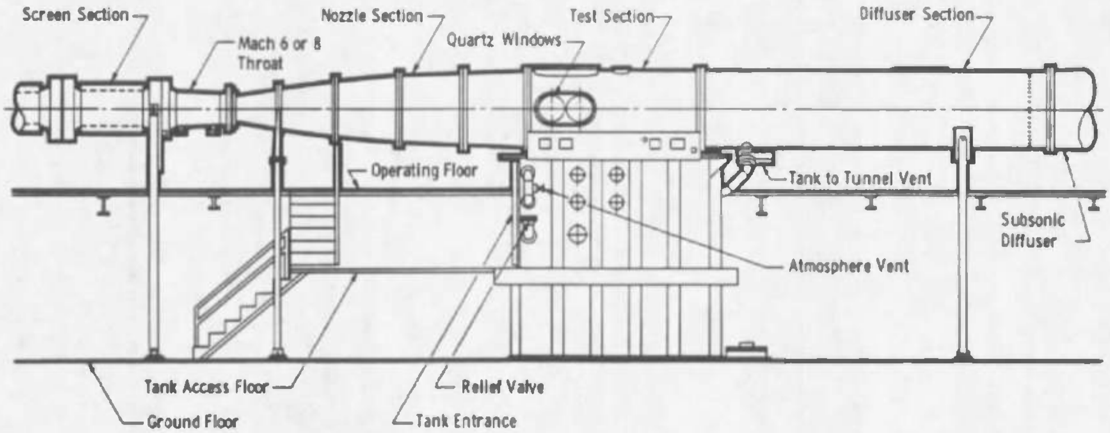
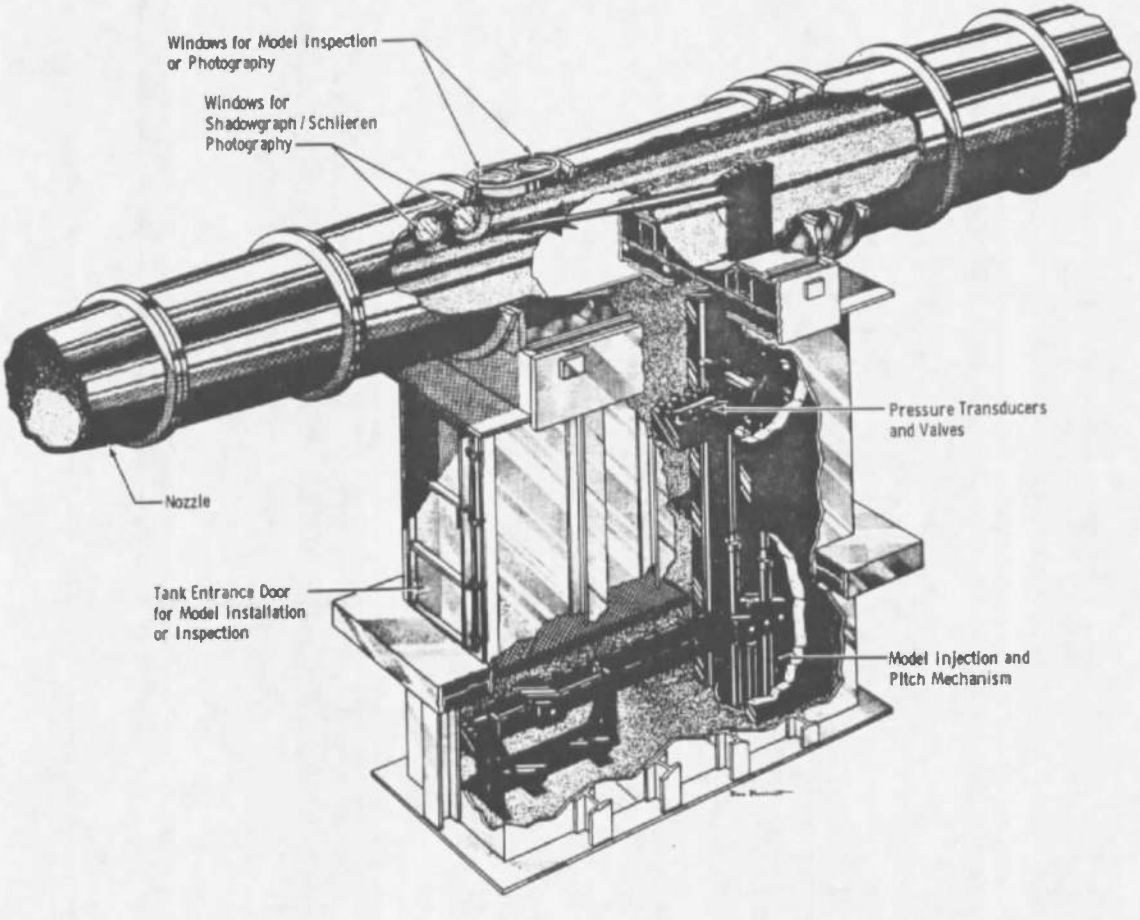


a. Tunnel Assembly



b. Tunnel Test Section

Fig. 1 Tunnel B

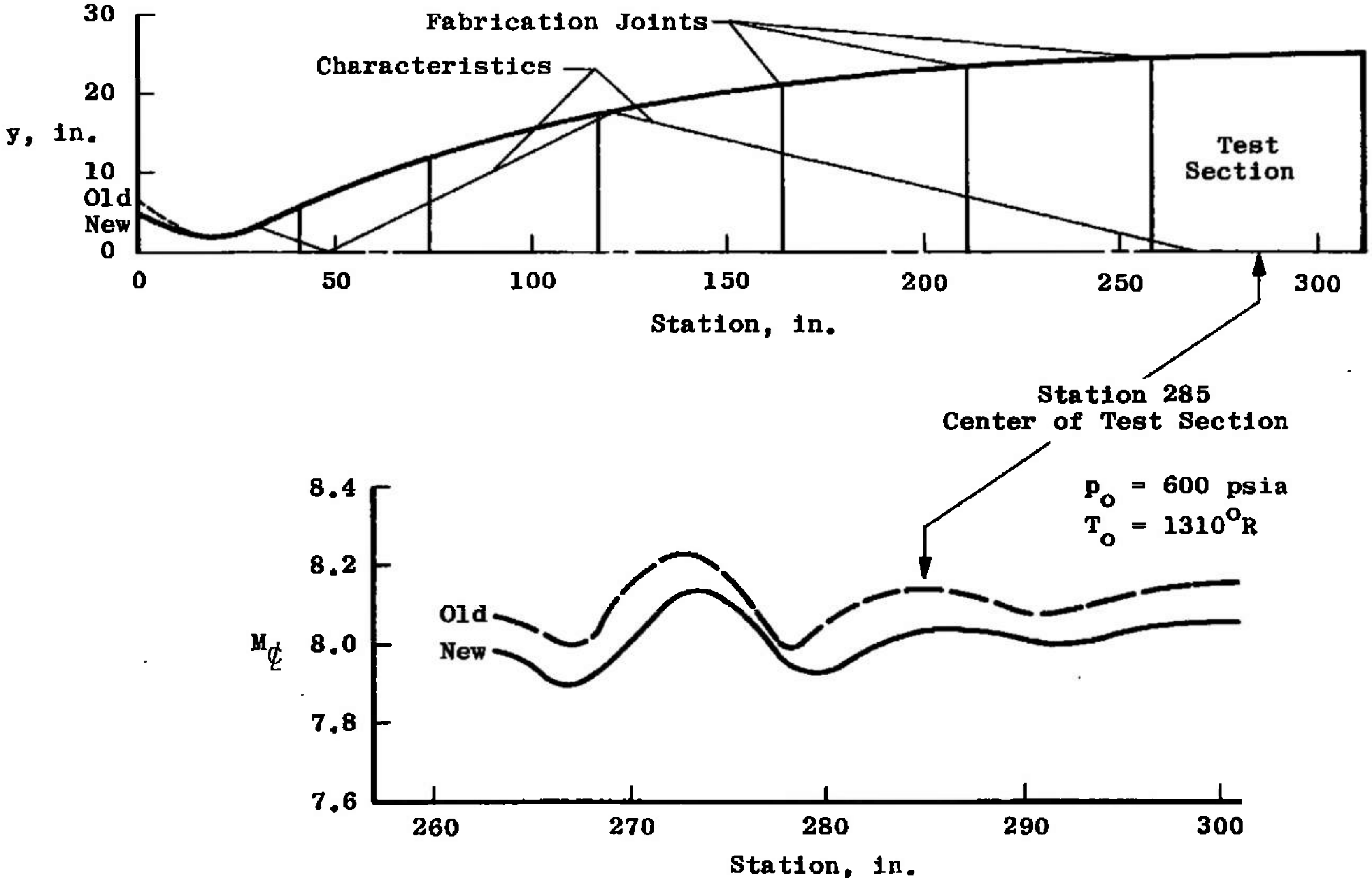


Fig. 2 Test Section Centerline Calibration with Old and New Throat Sections

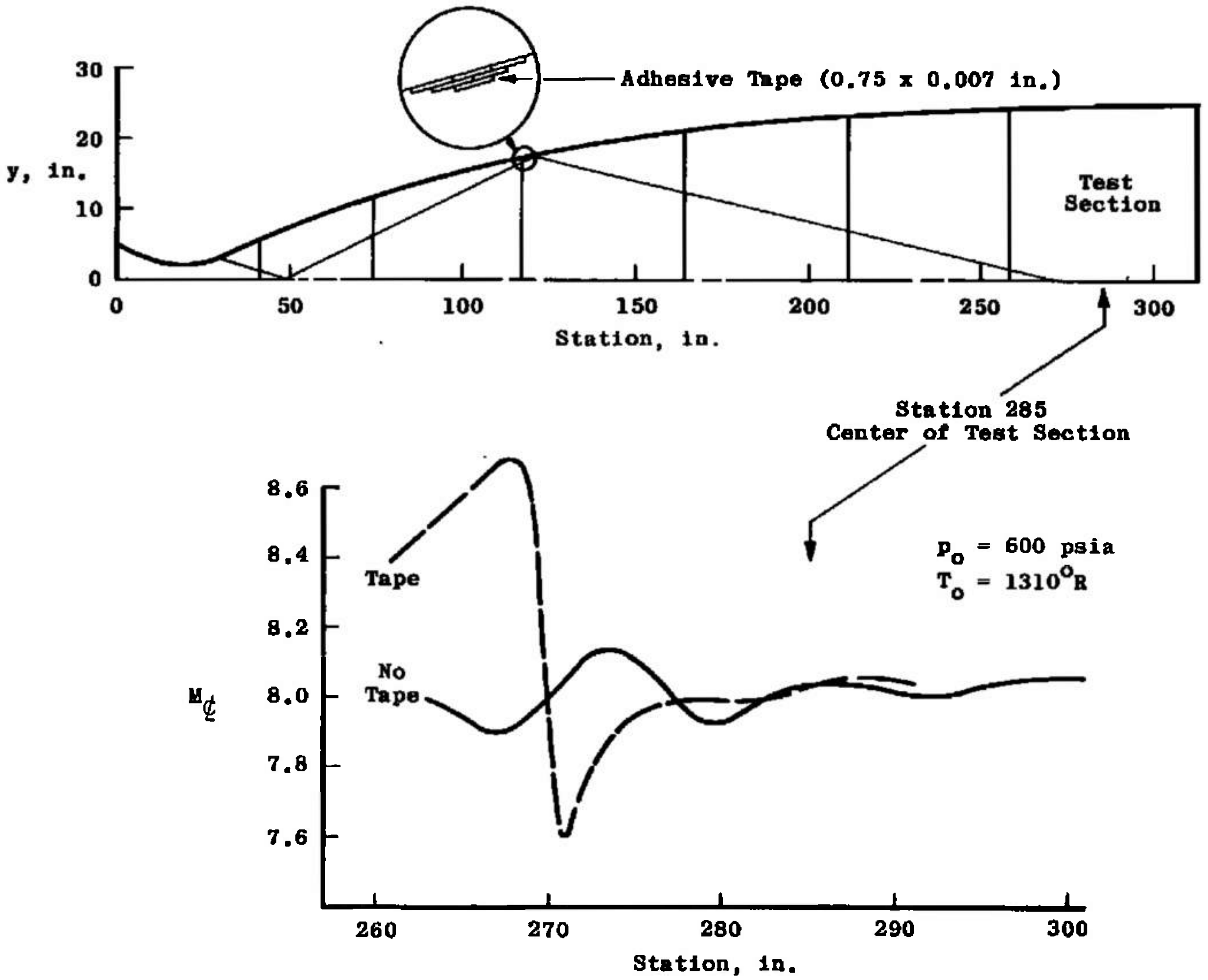


Fig. 3 Test Section Centerline Calibration with an Artificial Disturbance

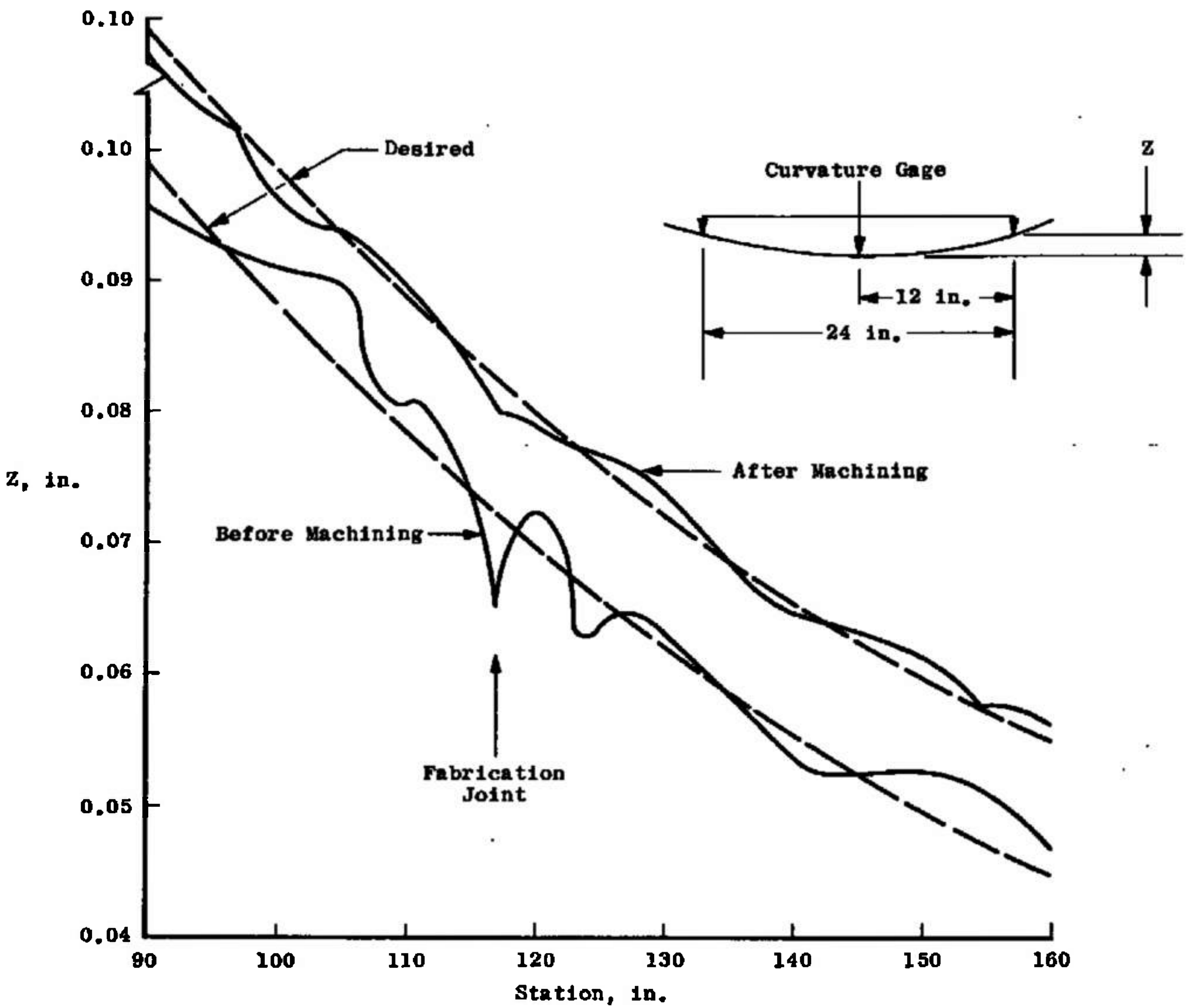


Fig. 4 Relative Smoothness of Nozzle before and after Remachining

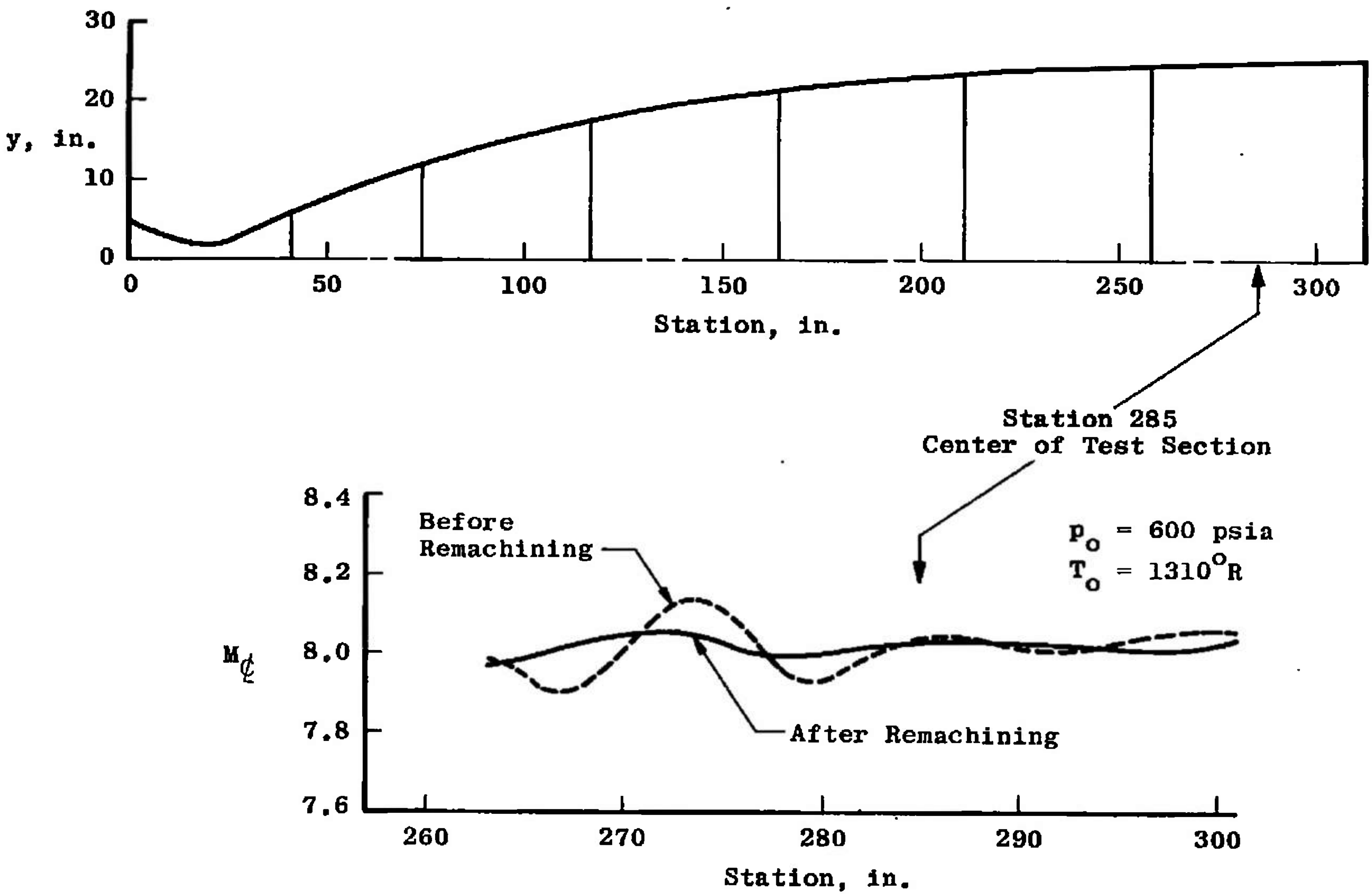
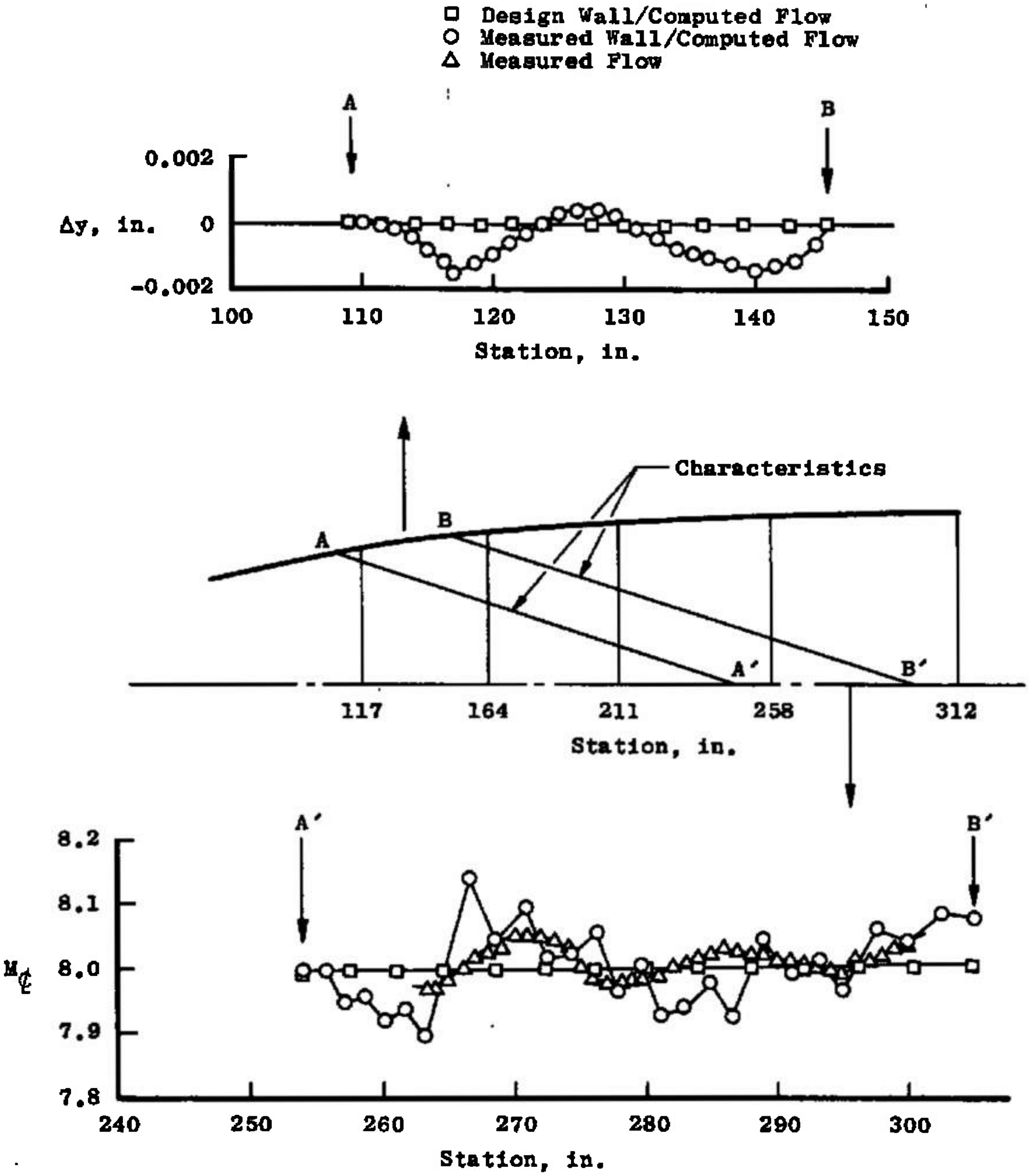
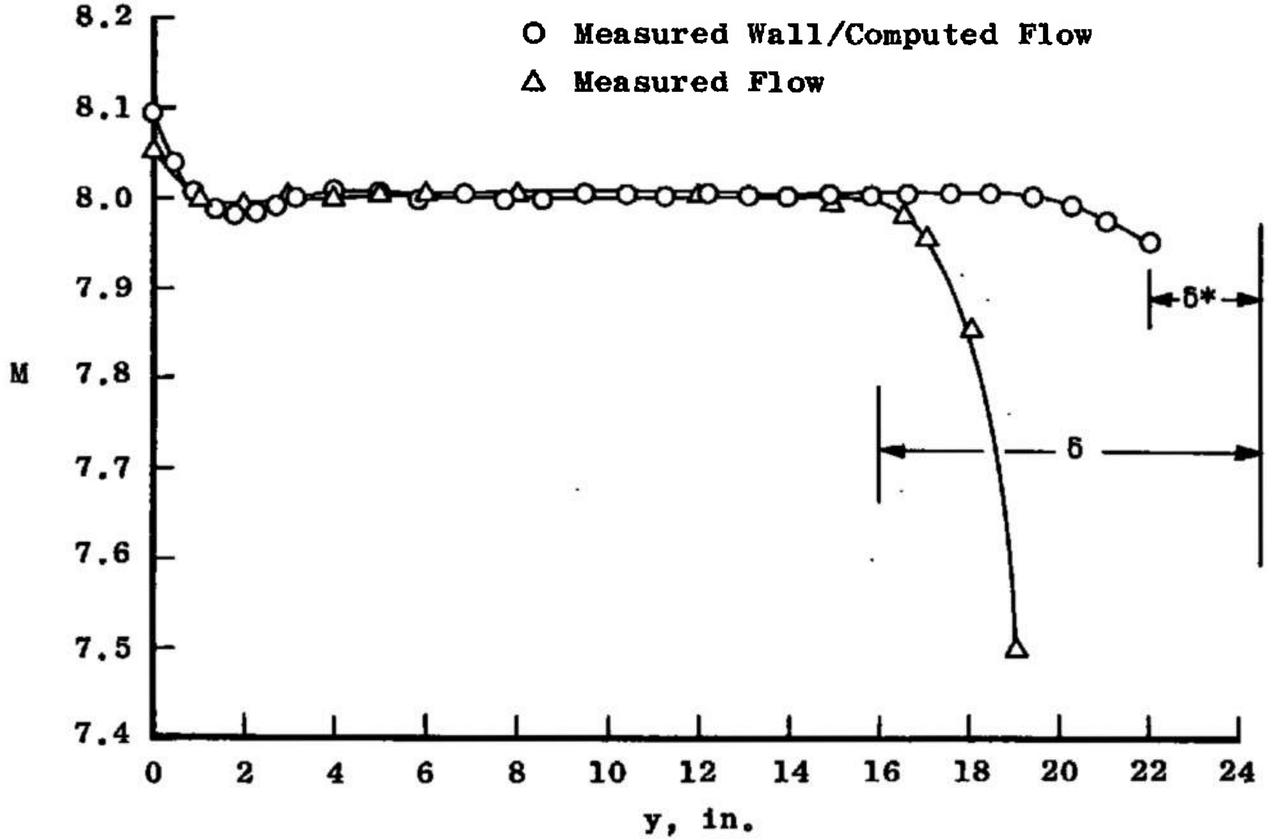


Fig. 5 Test Section Centerline Calibration before and after Remachining



a. Longitudinal Distribution

Fig. 6 Computer-Analysis of Centerline Focusing



b. Lateral Distribution

Fig. 6 Concluded

TABLE I
COORDINATES OF TUNNEL B (M – 8)

Sta, in.	y, in.	Sta, in.	y, in.	Sta, in.	y, in.	Sta, in.	y, in.
-9.5000	9.7500	46	7.4781	118	17.7526	190	22.3805
-7.9094	8.8030	49	8.1052	121	18.0257	193	22.5030
-5.9094	7.6823	52	8.7089	124	18.2901	196	22.6210
-1.9094	5.6899	55	9.2903	127	18.5460	199	22.7347
1.0906	4.4292	58	9.8501	130	18.7939	202	22.8441
3.0906	3.7074	61	10.3894	133	19.0341	205	22.9495
5.0906	3.0850	64	10.9091	136	19.2668	208	23.0509
7.0906	2.5662	67	11.4101	139	19.4924	211	23.1486
9.0906	2.1548	70	11.8934	142	19.7108	214	23.2425
11.0906	1.8548	73	12.3597	145	19.9225	217	23.3330
13.1906	1.6640	76	12.8101	148	20.1274	220	23.4200
15.1616	1.6047	79	13.2453	151	20.3257	223	23.5037
17.0435	1.6586	82	13.6659	154	20.5177	226	23.5841
18.8449	1.8110	85	14.0724	157	20.7034	229	23.6612
21.0968	2.1332	88	14.4652	160	20.8830	232	23.7352
22.9133	2.4660	91	14.8450	163	21.0567	235	23.8060
25.1865	2.9256	94	15.2121	166	21.2247	238	23.8737
27.0067	3.3104	97	15.5671	169	21.3871	241	23.9384
29.1074	3.7635	100	15.9106	172	21.5440	244	24.0001
31.5162	4.2892	103	16.2435	175	21.6960	247	24.0588
34.2533	4.8910	106	16.5656	178	21.8430	250	24.1147
37.3329	5.5714	109	16.8772	181	21.9848	253	24.1677
40.0906	6.1831	112	17.1787	184	22.1215	256	24.2179
43.0000	6.8275	115	17.4704	187	22.2534	258	24.2500
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13. ABSTRACT

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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Mach number distribution						
contoured nozzle ordinates						
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