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RESEARCH ON COAXIAL JET AIR MIXING

FINAL REPORT - PHASE I

John W. Shue

John K. Stauffer

Thermodynamics Laboratory
CONVAIR, A Division of General Dynamics
Convair, San Diego

June 1960

An Experimental Research Program
for
The Office of Naval Research
Department of the Navy

Office of Naval Research Contract Nonr 2854(00)

CONVAIR
A DIVISION OF GENERAL DYNAMICS CORPORATION
SAN DIEGO

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I. SUMMARY

Convair-San Diego, is currently conducting an experimental research program on the subsonic turbulent mixing of an unheated free jet of air with the surrounding moving stream under imposed longitudinal pressure gradients. The program is divided into three phases: (1) Phase I includes investigations of previous work performed in the field, construction of the test set-up, and the experimental development of a mixing tube imposing a constant longitudinal static pressure; (2) Phase II includes experimental investigations to obtain velocity, pressure, and turbulence parameters which characterize this subsonic turbulent mixing; and (3) Phase III includes experimental investigations to obtain the above parameters for two other mixing tubes; one imposing an increasing pressure gradient, and the other imposing a decreasing pressure gradient.

A mixing tube configuration (Figures 1 and 2) imposing a constant longitudinal static pressure over a length of approximately 40 primary nozzle diameters (D_p = 0.70") was experimentally developed. The primary nozzle is the smaller driving jet. This jet pump configuration has an initial velocity ratio, $\alpha = {}^{V_s}/V_p = 0.0719$ and a calculated initial area ratio, $\phi = {}^{A_p}/A_s = 0.0104$ based on experimental results.

The contour producing the constant longitudinal static pressure exhibits a linear area variation over the mixing region.

FOREWORD

The work presented herein was performed in the Thermodynamics Group of the Engineering Department of Convair, San Diego, A Division of General Dynamics Corporation. The work is being performed for the Office of Naval Research under the technical supervision of Dr. G. B. Matthews of ONR (Code 461) under contract Nonr 2854(00). The principal investigator for this program is Mr. John W. Shue, assisted by Mr. John K. Stauffer. Technical assistance is obtained from Dr. Paul Weyers, and Mr. Robert E. Forrette, both of Convair.

II. INTRODUCTION

Jet mixing occurs in a large number of problem areas of engineering such as jet pumps, combustion chambers, ejectors, etc. Significant attention has been given to jet pumps both through theoretical and experimental analyses. The status of jet pump theory to 1950 was summarized by Kastner(1) as follows:

> "Previous investigations may be roughly divided into two classes -- the first comprising the results of those workers who appear to have been chiefly interested in the performance of the ejector as a whole, and the second, the work of those who have studied the processes occurring in free jets and the mixing of one gaseous stream with another . . . . A theoretical approach to the problem must necessarily be concerned with conditions arising when two jets of fluid, whose initial pressure and specific volume are known, unite, but a solution, when achieved, should be in such a form as to enable the performance of a complete ejector to be predicted, and to be compared with the results of experiment, when the inlet and outlet conditions vary widely."

Although a large number of theoretical and experimental jet pump investigations have been performed since 1950, none has given any significant insight into the nature of the losses occurring in the mixing process despite the fact that this process is a primary determinant of the ejector performance.

In order to establish a valid basis for the design of mechanisms involving turbulent mixing, a practical theory of turbulent mixing must be developed. This theory would provide an experimentally verifiable prediction of the heat, mass, and momentum transfer involved in the mixing process under specified boundary conditions or imposed pressure gradients.

As an insight into this problem of turbulent mixing, Convair is conducting experimental investigations and evaluations of coaxial mixing. Within the scope of this program, Convair intends:

1 - to obtain velocity, pressure, and turbulence parameters which characterize the subsonic mixing of a primary jet of air at ambient temperature with a surrounding secondary ambient stream under the influence of imposed constant, increasing and decreasing pressure gradients;

2 - to correlate the results of the experimental and theoretical studies; and

3 - to determine the influence of the imposed longitudinal pressure gradients on coaxial jet mixing.

The special problem of an axially symmetric jet in a uniform stream was studied by Squire and Trouncer (2). The mixing jet was divided into three distinct regions (Figure 10). After mixing has started at the boundary of the two streams, an undisturbed conical core of fluid of uniform velocity exists for a certain distance downstream. Kuethe (3) showed that the length of this initial core extends about 4.44 diameters of the nozzle. This core defines region I. In region II, called the transition mixing region, the jet velocity along the axis decreases and the flow pattern begins to reach a steady state condition. In region III, the velocity profiles appear similar. It has been observed by Corrsin (4) that similarity of the velocity profiles is achieved at about 10 diameters downstream in a free jet. It will be determined in phase II if this similarity is also achieved in a free jet under an imposed constant pressure.

Squire and Trouncer (2) presented an integrated momentum analysis which is based on Prandtl's momentum transfer theory. This theory assumes dimensionless, cosine-shaped velocity profiles and a mixing length proportional to the width of the mixing region. With this assumption, the entire flow field can be computed with the known velocity ratio of the two streams. The validity of this method was checked by Landis and Shapiro (5) with the conclusion that this method is satisfactory to obtain representations of the turbulent mixing processes for small density variations. The validity of the method of Squire and Trouncer for the mixing under a known imposed longitudinal pressure will be determined in phase II.

Corrsin (4) found that, in a fully developed turbulent jet with axial symmetry, a completely turbulent flow exists only in the core region out to a radius at which the velocity is about one-half the maximum velocity of the cross section. Outside of this core is an annular transition region and outside of this transition region is a laminar flow region. It was noticed from oscillograph records of the velocity fluctuation near the edge of the jet that the flow was intermittent. This intermittency may be defined by specifying that the flow possesses the ordinary irregular fluctuations for a certain time and the rest of the time the velocity fluctuations are slow and of small magnitude. This intermittency is believed to be a phenomenon for turbulent flow near a free stream and to be due to the interaction of large eddies with the free stream. The intermittency in the constant pressure mixing process will be determined if time permits after the velocity, pressure, and turbulence parameters are obtained.

The technical discussions of the turbulence theory, traversing, and hot-wire anemometry equipment and techniques, will be included in the final report of phase II.

III. NOMENCLATURE

Symbols

A	cross sectional area
A^*	cross sectional area of airstream when $M = 1.0$
D	diameter
K	empirical diffusion constant (see ref. 9)
L	mixing tube length
M	Mach number
P	static pressure
P_t	total pressure
p	differential static pressure - $(p_{wall} - p_{\infty})$
$r_{1/2}$	radius where the local velocity is one-half the maximum velocity at a cross section (jet in still air)
R	radius
V	velocity
W_a	weight flow
α	velocity ratio at initial plane - V_s/V_p
μ	mass ratio $(\rho AV)_s/(\rho AV)_p$
ϕ	area ratio at initial plane - A_p/A_s

Subscripts

1	measured radii and static pressures
2	calculated radii and static pressures for new contour
s	mixing tube conditions (secondary duct)
p	driving jet (primary nozzle)
∞	ambient

IV. EXPERIMENTAL-PROGRAM - PHASE I

Many investigators have presented theoretical solutions for particular ejector designs. Most noteworthy of these were Keenan, Neumann, and Lustwek (6), who presented designs incorporating a constant-area mixing section and a constant-pressure mixing section, Helmbold (7), who presented a theory for constant-pressure mixing, and Szczeniowski (8), who presented a theoretical analysis which was conducted to determine an optimum contour for the mixing section of a jet pump. None of these theories were completely satisfactory in designing a constant pressure mixing tube.

As a basis for the design of the constant- pressure mixing tube to be used in Convair's test facility, the theory proposed by Helmbold was used to establish the basic design. Since Helmbold had designed and tested a jet pump with a nearly constant pressure mixing section (9), it was decided to use his results as a basis for developing the mixing tube. Identical velocity ratios and area ratios were used in order to simplify direct comparison of the data. A larger primary nozzle diameter was used in order to obtain a slightly larger mixing tube to facilitate traversing and data handling.

In Helmbold's original design computation of 1953, he used a numerical value of $K^2 = 0.00432$ for the diffusion constant which was derived from information given in the first German edition of Schlichting's "Boundary Layer Theory" which later turned out to be in error. The correct value is $K^2 = 0.0068$ according to Helmbold. The calculated results for the original constant pressure contour together with the experimental data are given in Table I. Tabulated contours and experimental data are also given in Table I for the two modifications to the original mixing tube. The corrected value of K^2 was used.

The Mach number of the primary jet was chosen as $M_p = 0.460$ in order that the data may be directly comparable to that of Helmbold. The temperature ratio between the primary and secondary streams is unity.

V. APPARATUS, INSTRUMENTATION, AND TEST SET-UP

Since the constant pressure contour was to be developed experimentally, sectional wood construction using blocks of hardwood along the axis was chosen for ease in making modifications to the contour, length, and instrumentation. A schematic diagram of the jet pump is shown in Figure 1 and a picture of the completed test stand is shown in Figure 2. Alignment was attained through recessed step joints and four tie rods. Protective wood sealer was used to minimize wood expansion.

The basic requirements of the jet mixing problem stipulate a flat velocity profile in both the primary and secondary streams at the initial plane of the mixing tube. To obtain this flat velocity profile, both the internal and external contours of the primary nozzle and the internal contour of the bellmouth were designed according to the theory of the design of the contraction cone for a wind tunnel by Tsien (10). The primary nozzle was machined from aluminum and the bellmouth was fabricated from Fiberglass.

Static pressure taps of 1/16 inch in diameter are located in the mixing section at one-inch intervals along the horizontal plane on one side and at two-inch intervals along the vertical plane on top of the mixing tube. Several static taps are located along the diffuser section to establish the complete profile.

The mixing tube static pressure measurements are obtained from an inclined alcohol differential manometer. Inclination of 10:1 allows a reading discrimination to within 0.01 inch of alcohol. The inclined manometer board was calibrated against the micromanometer and each pressure measurement was corrected accordingly. Photographs were taken of the tube bank during each of the runs and the data was obtained from these photographs.

A sensitive pressure regulator is used to control the primary nozzle airflow. Measurements are made from an orifice plate. The bellmouth airflow is measured by means of four static pressure taps equally spaced around the bellmouth throat and manifolded together. The micromanometer is used to measure the bellmouth static pressure.

The bellmouth with the primary nozzle inserted was calibrated by using Convair's vacuum facility and a calibrated flowmeter (Figure 3). The primary nozzle was not operating during the calibration runs.

VI. DEVELOPMENT OF THE CONSTANT PRESSURE MIXING TUBE

Operation of the jet pump configuration based upon Helmbold's design (9) using the corrected value of K^2, a design velocity ratio, $\alpha = 0.069$, and a design area ratio of $\phi = 0.01$, did not produce a constant longitudinal pressure profile over the mixing region. Figure 6 presents a documentation of this mixing tube using a value of the velocity ratio near the design value, and values of the velocity ratio above and below the design value. None of the off-design values of the velocity ratio produced a longitudinal pressure profile that was constant over the complete mixing section.

It has not been determined why Helmbold's configuration did not produce a constant pressure. His original configuration using the lower value of the diffusion constant produced a pressure that was closer to constant than this corrected configuration. In order to ascertain the magnitude of change required in the mixing tube configuration, the primary nozzle was translated to several positions fore and aft of the initial plane. These tests indicated that the length of the mixing tube would have to be increased. In addition to these tests, a new contour was calculated using the test data ($\alpha = 0.0703$) and the wall static pressure at the initial plane. This method for data correction assumes that the total pressure is equal to ambient pressure over the mixing length. Therefore, it is only applicable during the free mixing region or until the primary jet expands to the wall. The subscript 2 is used to represent the new calculated radii which produces the constant static pressure and the subscript 1 to represent the measured radii and pressures from the test results. With the assumption that the total pressure is equal to ambient over this mixing length, the corrected radius would be obtained from:

$$R_2^2 = R_p^2 + \frac{A_2/A^*}{A_1/A^*} \left(R_1^2 - R_p^2\right)$$

in which

$$A_2/A^* = f\left(p_2/p_t\right)$$

$$A_1/A^* = f\left(p_1/p_t\right) .$$

R_p is the radius of the expanding primary airstream calculated from the half maximum velocity radius (Ref. 9) which is

$$r_{1/2} = 0.0931 \; L .$$

This method was used to calculate the new area contour to the point where the primary jet started to reach the mixing tube wall. Beyond this point the total pressure cannot necessarily be assumed ambient. The curves were faired from the last calculated point above into the cylindrical section or diffuser.

The original contour based upon Helmbold's design was modified using this method. This second design involved a mixing section that was four inches longer than the original mixing tube. Documentation of this mixing tube is shown in Figure 7. A velocity ratio of $\alpha = 0.0729$ produced the most constant pressure profile for this configuration but a decreasing gradient still existed. As a point of interest, this second design has a conical section from station 5 to station 16 and produced a decreasing pressure gradient that was approximately of exponential form.

This second configuration was modified by using the same method described above and the data obtained from the second configuration ($\alpha = 0.0729$). The third configuration required the additional extension of the mixing section by three inches. To simplify fabrication, the mixing section was extended into the cylindrical section. Consequently, no cylindrical section exists on the third configuration.

The documentation of the third configuration is shown in Figure 8. The slight rise in pressure between stations 10 and 20 for $\alpha = 0.0719$ indicates that the second contour may have been slightly overcorrected. The amount of the rise was not considered intolerable since its magnitude borders on the accuracy of the instrumentation. During the initial portion of phase II, the primary nozzle will be shifted into the mixing tube to determine if decreasing the effective length of the mixing tube will affect this slight rise in the wall static pressure. The dip in pressure occurring in the transition region between the mixing section and the diffuser will be eliminated by additional recontouring.

A significant observation that may be helpful in designing jet pumps with constant pressure mixing sections is shown in Figure 5. The mixing tube area varies linearly with the length over the entire mixing region until the beginning of the transition region to the diffuser. Further investigations of this observation will be made during phase II.

Figure 4 presents the contours and mixing tube longitudinal static pressures for the three configurations tested.

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8 - Szczeniowski, B., "Theory of the Jet Syphon", National Advisory Committee for Aero., TN 3385, Wash. May 1955.

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10 - Tsien, Hsue-Shen: "On the Design of a Contraction Cone for a Wind Tunnel", Journal Aero. Sciences., Feb. 1943

CONSTANT PRESSURE MIXING TUBE CONFIGURATION

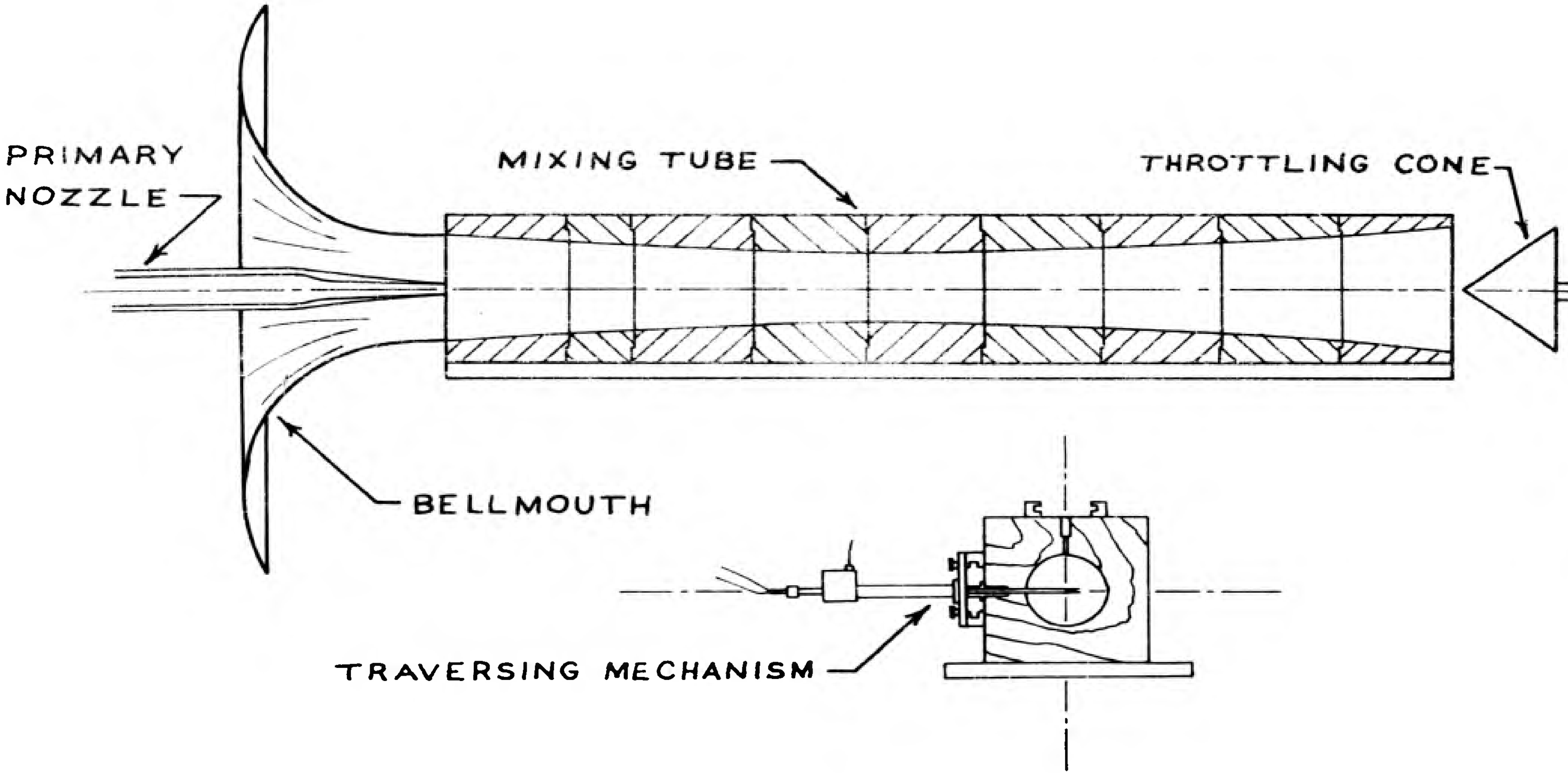


FIGURE 1

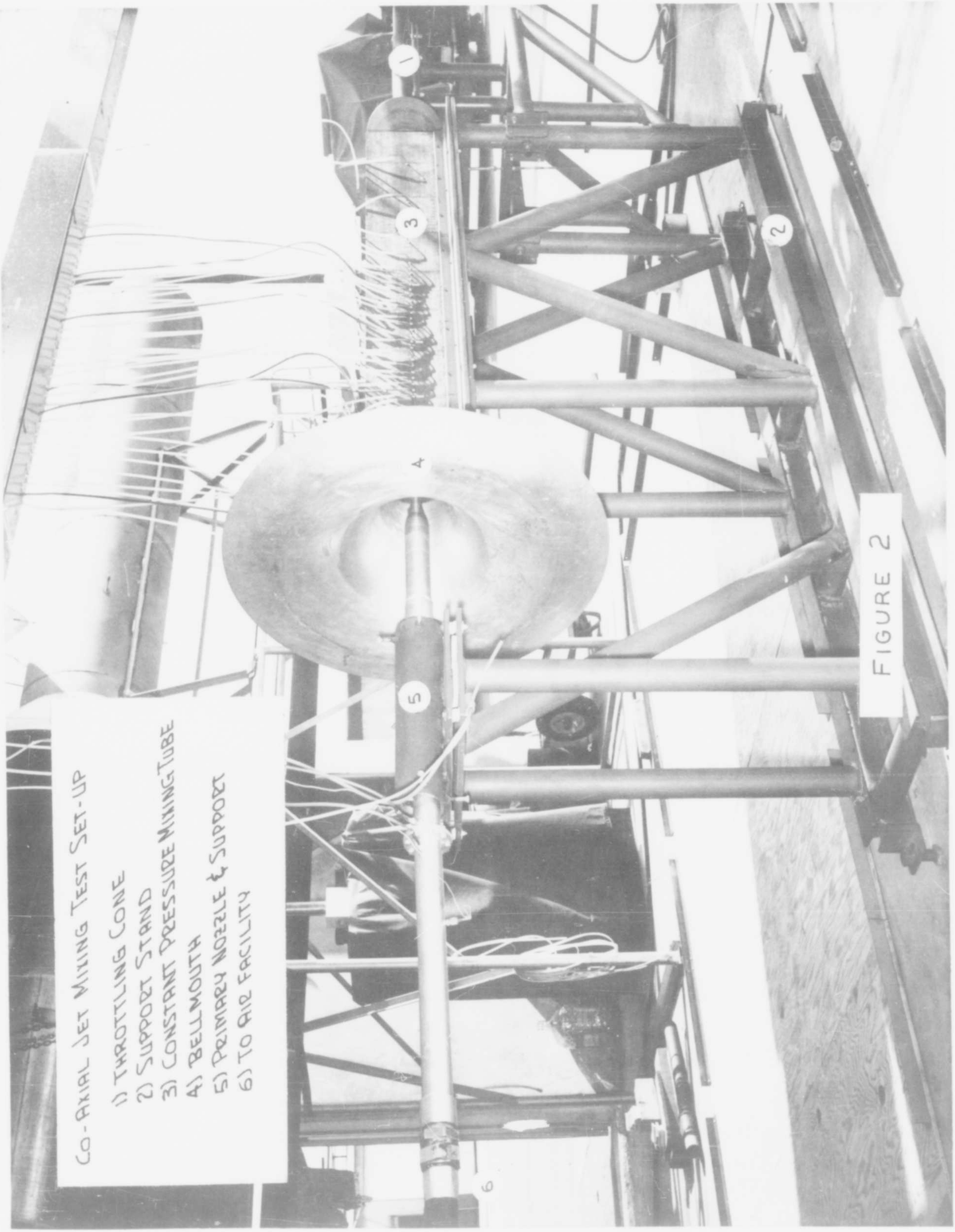
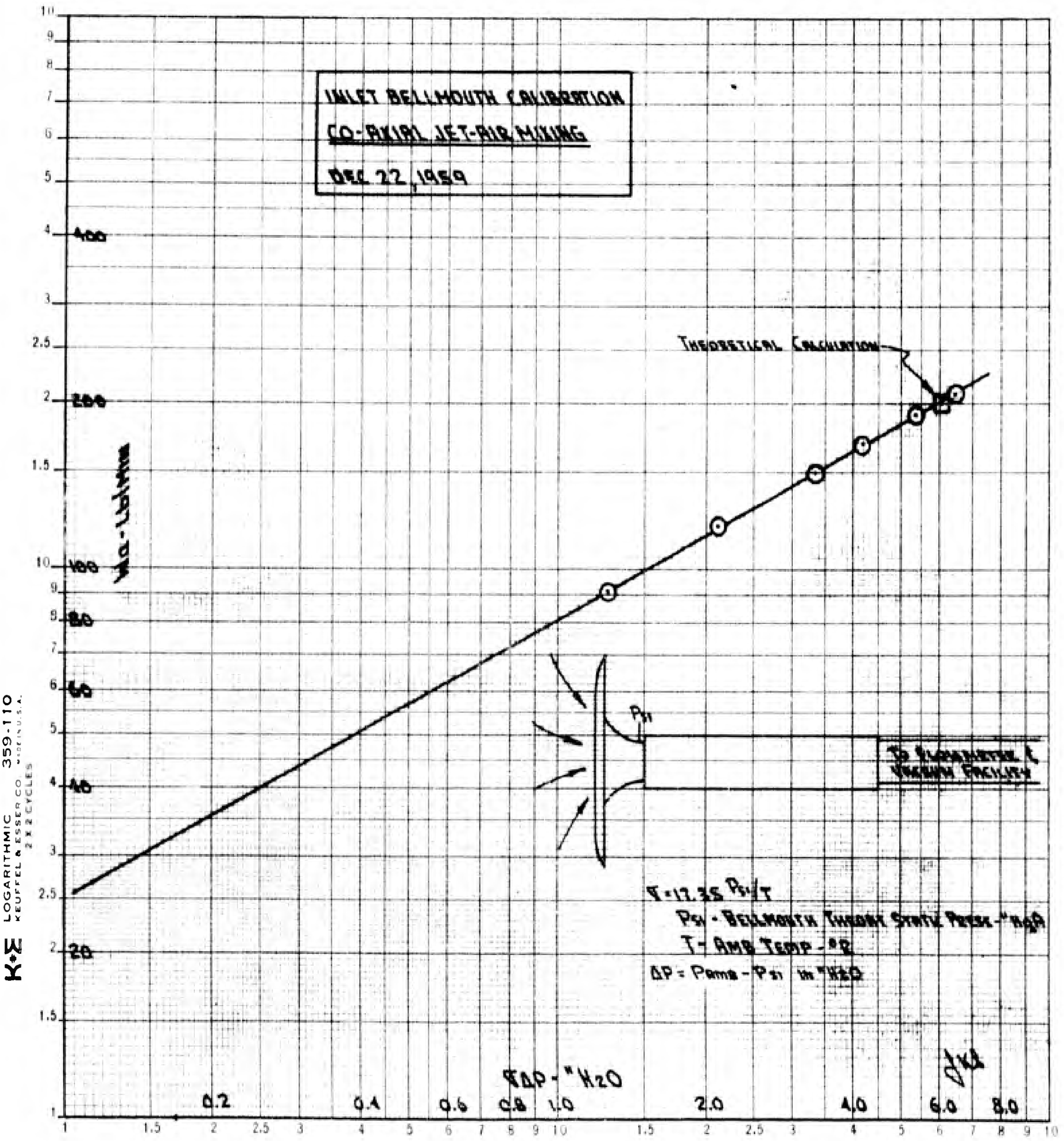

Co-Axial Jet Mixing Test Set-Up
1) Throttling Cone
2) Support Stand
3) Constant Pressure Mixing Tube
4) Bellmouth
5) Primary Nozzle & Support
6) To Air Facility
1
2
3
4
5
6

FIGURE 2

FIGURE 3


INLET BELLMOUTH CALIBRATION
CO-AXIAL JET-AIR MIXING
DEC 22, 1959
THEORETICAL CALCULATION
Wa - Lb/Min
400
200
100
80
60
40
20
P_S1
TO FLOWMETER & VACUUM FACILITY
Ψ = 12.35 Psi/T
Psi - BELLMOUTH THROAT STATIC PRESS - "HgA
T - AMB TEMP - °R
ΔP = Pamb - Ps1 in "H2O
ΨΔP - "H2O
0.2
0.4
0.6
0.8
1.0
2.0
4.0
6.0
8.0
JKL
K+E LOGARITHMIC 359-110
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 X 2 CYCLES

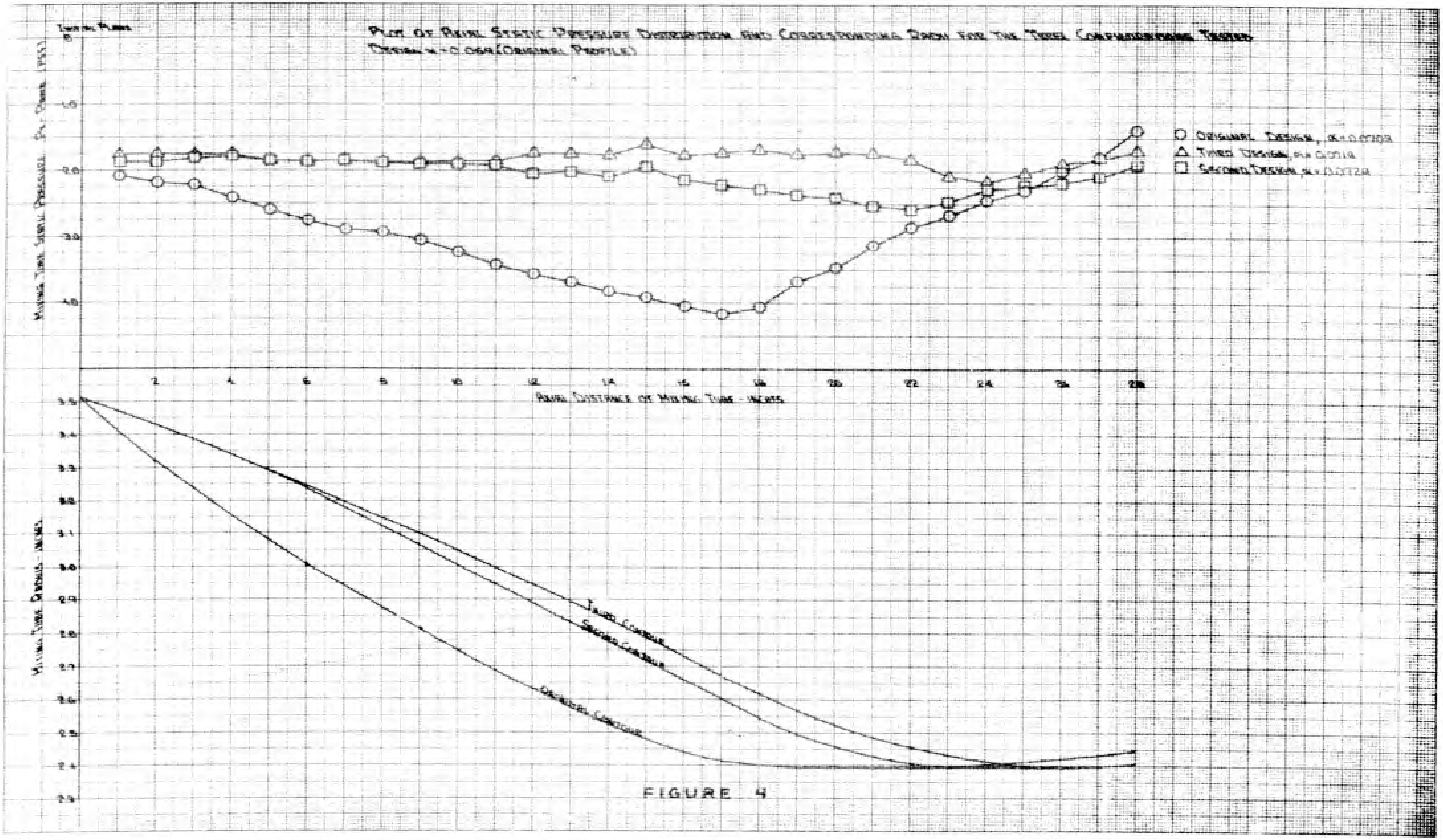

Plot of Axial Static Pressure Distribution and Corresponding Radii for the Three Configurations Tested
Design α = 0.068 (Original Profile)
Throat Plane
○ Original Design, α = 0.0703
△ Third Design, α = 0.0719
□ Second Design, α = 0.0728
Mixing Tube Static Pressure - In. Gauge (PSI)
0
1.0
2.0
3.0
4.0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Axial Distance of Mixing Tube - Inches
Mixing Tube Radius - Inches
3.5
3.4
3.3
3.2
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
Third Contour
Second Contour
Original Contour

FIGURE 4

AXIAL STATIC PRESSURE DISTRIBUTION AND CORRESPONDING AREA DISTRIBUTION COMPARISON

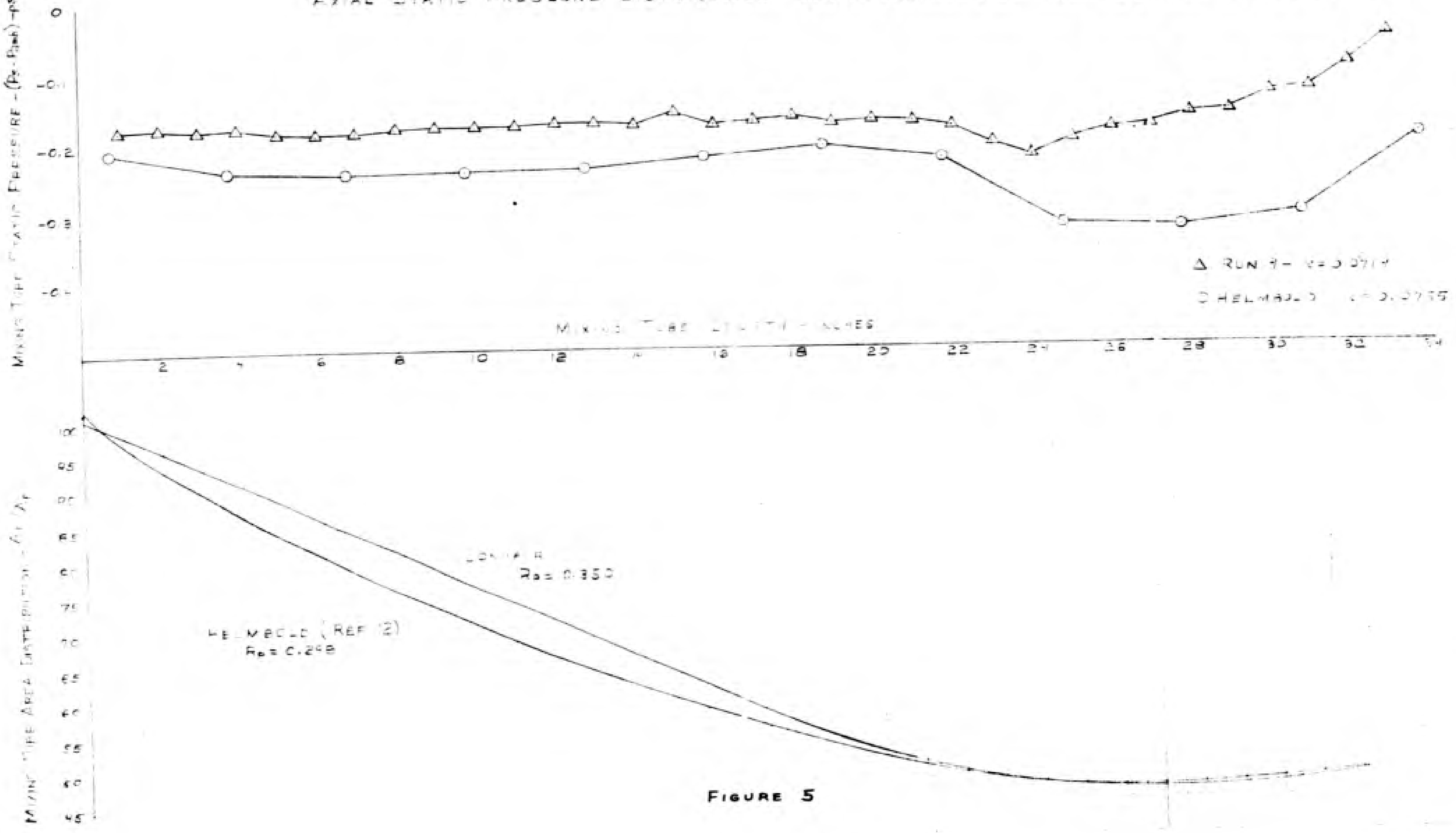


FIGURE 5

FIGURE 6

AXIAL STATIC PRESSURE DISTRIBUTIONS FOR CONSTANT PRESSURE MIXING TUBE

(ORIGINAL DESIGN)

$\alpha = 0.067$

$M_p = 0.460 \qquad \epsilon = 0.0104$

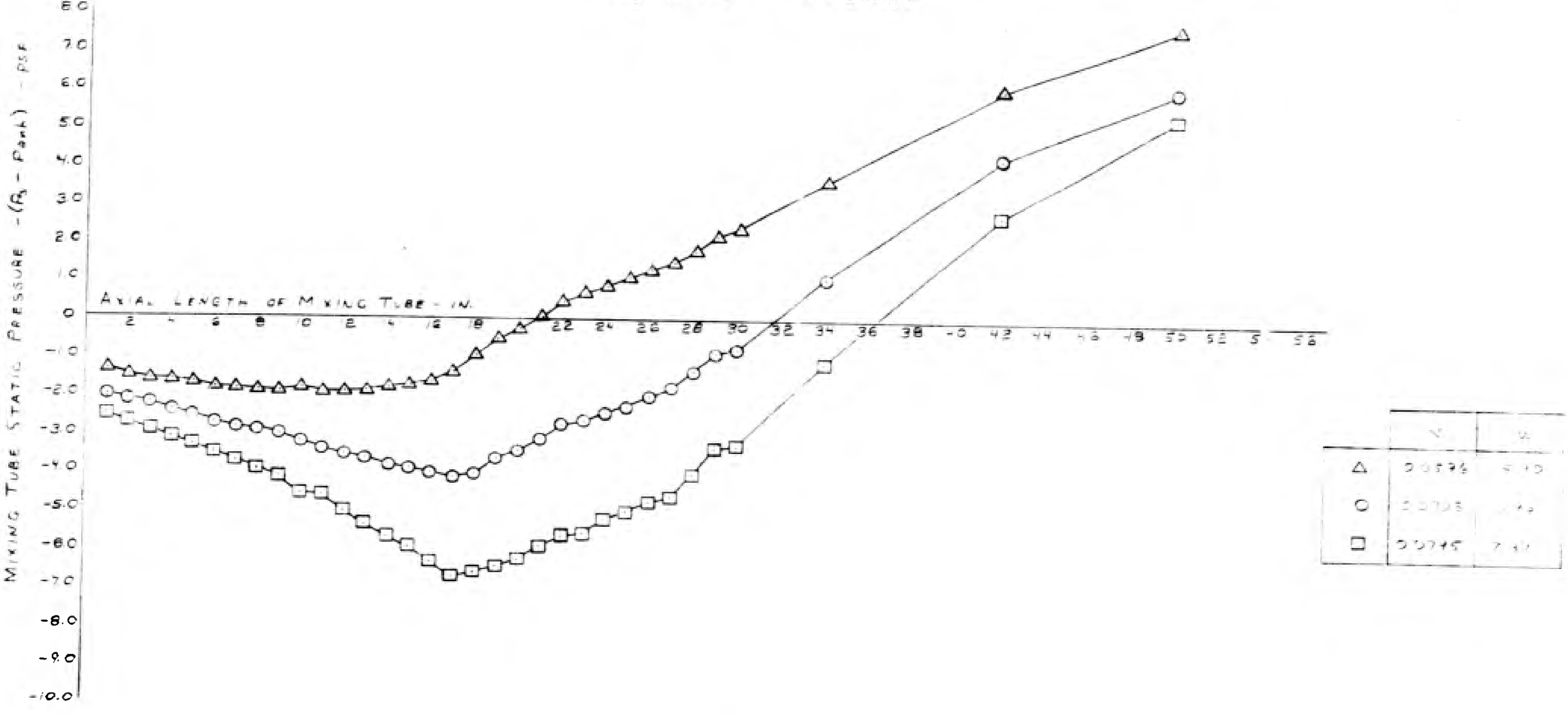


FIGURE 6

FIGURE 7

AXIAL STATIC PRESSURE DISTRIBUTIONS FOR CONSTANT PRESSURE MIXING TUBE

(CONTOUR NO. 2)

$M_p = 0.460 \qquad \phi = 0.0104$

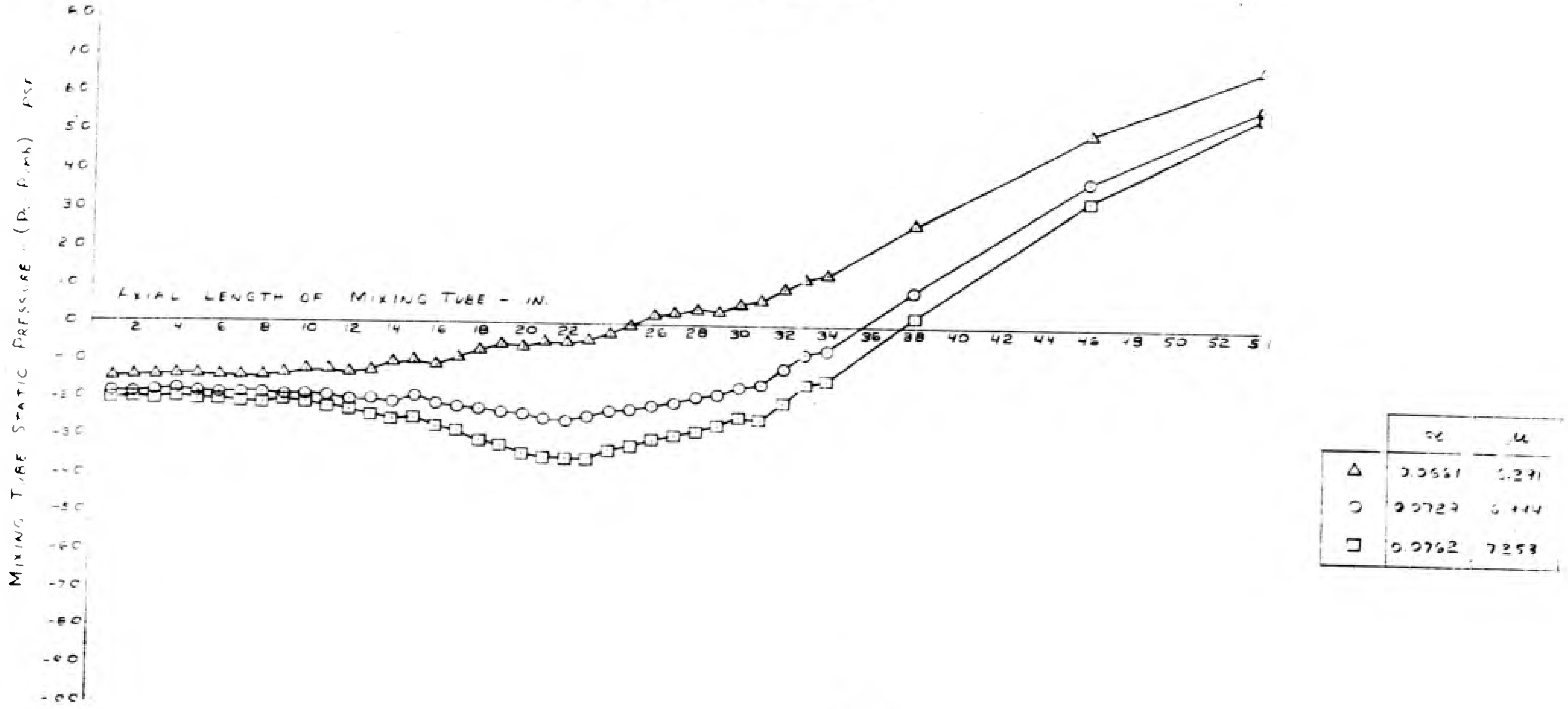


FIGURE 7

AXIAL STATIC PRESSURE DISTRIBUTIONS FOR CONSTANT PRESSURE MIXING TUBE (CONTOUR # 3)
MPRI = .460
Φ = 0.0104

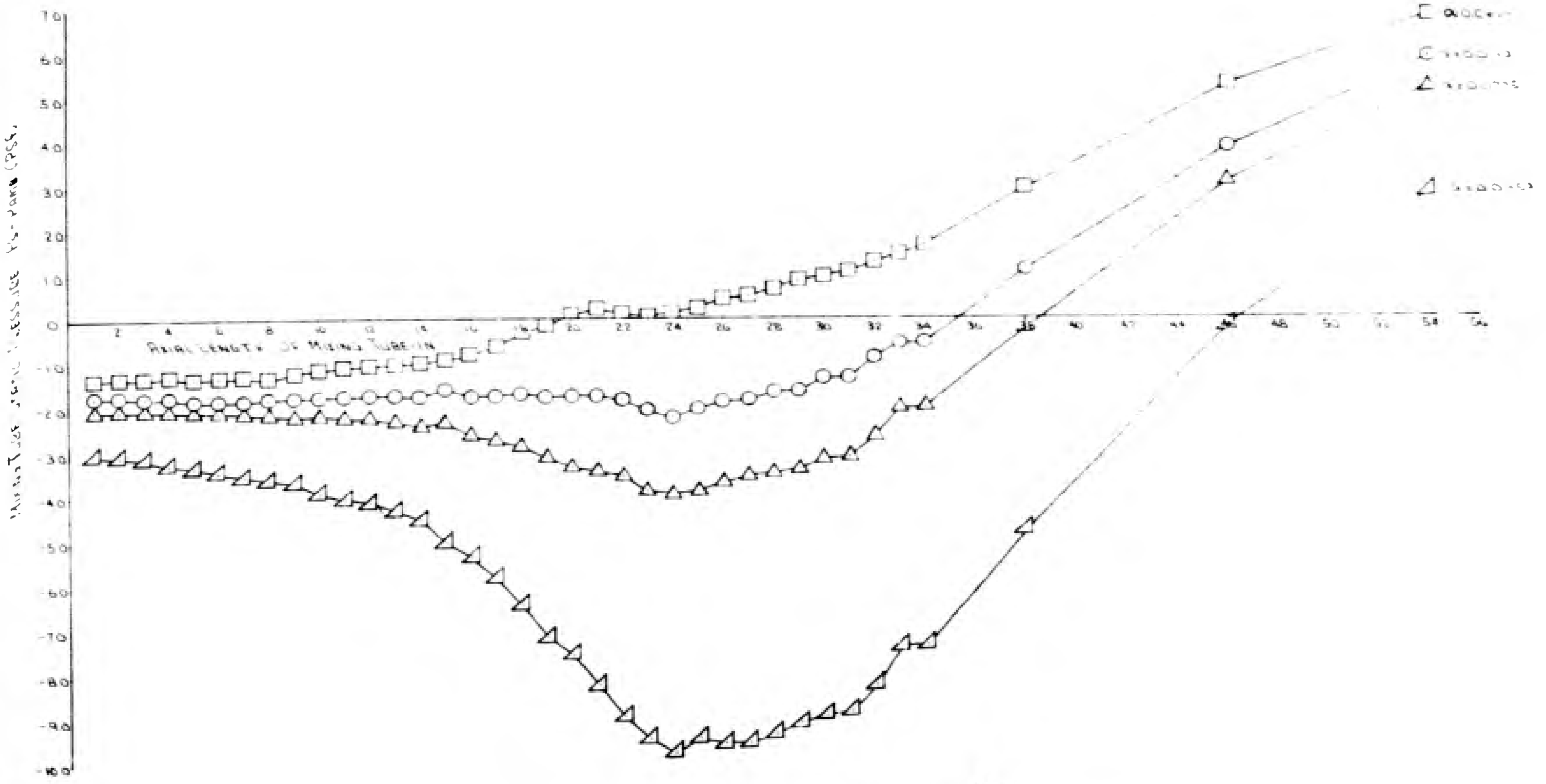
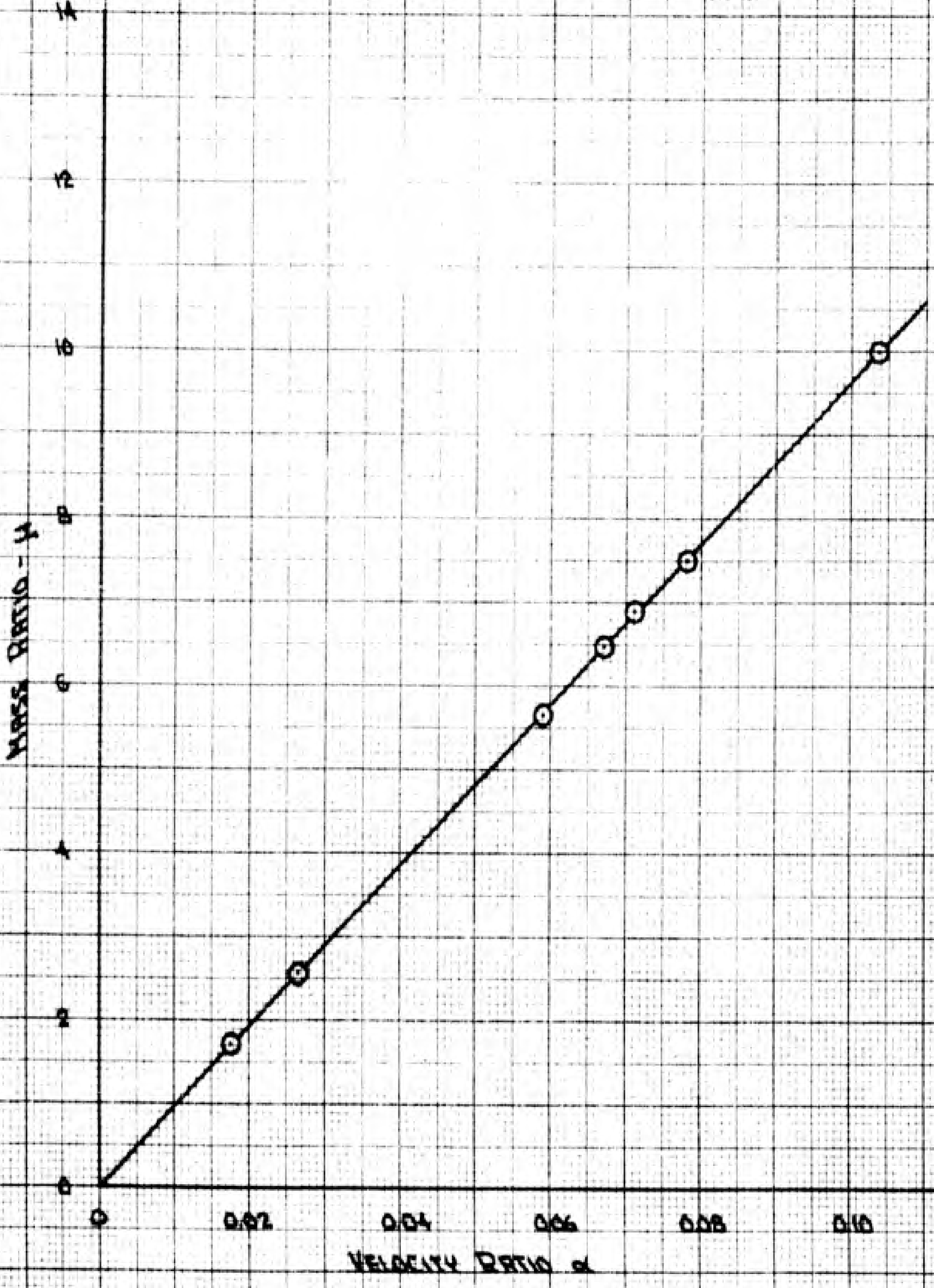
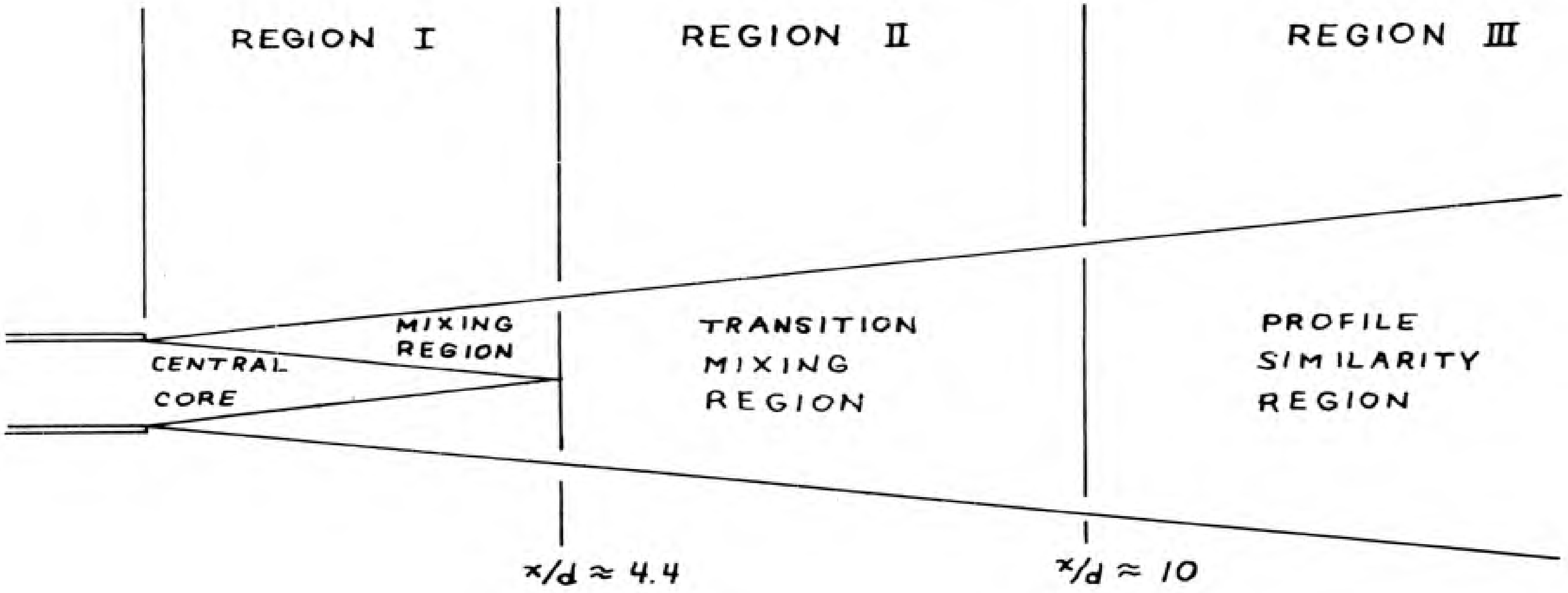


FIGURE 8

FIGURE 9

VARIATION OF MASS RATIO WITH VELOCITY RATIO





SCHEMATIC DRAWING OF MIXING JET

FIGURE 10

TABLE I

AXIAL STATIC PRESSURE DISTRIBUTION AND CORRESPONDING RADII FOR THE THREE CONFIGURATIONS TESTED

(Initial plane located at Station 0)
$M_p = 0.460$

ORIGINAL DESIGN $\alpha = 0.069$			MODIFICATIONS				
Axial Station inches	Run 4, $\alpha = 0.0703$		Axial Station inches	First Modification Run 8, $\alpha = 0.0729$		Second Modification Run 9, $\alpha = 0.0719$	
	Radius inches	Δp_s psf		Radius inches	Δp_s psf	Radius inches	Δp_s psf
0	3.515		0	3.515		3.515	
1	3.410	- 2.08	1	3.472	- 1.87	3.472	- 1.78
2	3.320	- 2.18	2	3.430	- 1.89	3.430	- 1.76
3	3.240	- 2.28	3	3.382	- 1.82	3.382	- 1.80
4	3.160	- 2.42	4	3.342	- 1.78	3.342	- 1.78
5	3.080	- 2.59	5	3.290	- 1.87	3.292	- 1.86
6	3.010	- 2.76	6	3.238	- 1.89	3.245	- 1.88
7	2.945	- 2.89	7	3.180	- 1.87	3.197	- 1.86
8	2.875	- 2.93	8	3.121	- 1.89	3.149	- 1.80
9	2.815	- 3.05	9	3.063	- 1.93	3.100	- 1.79
10	2.750	- 3.23	10	3.007	- 1.92	3.050	- 1.79
11	2.690	- 3.42	11	2.947	- 1.95	3.000	- 1.78
12	2.635	- 3.57	12	2.890	- 2.05	2.949	- 1.74
13	2.575	- 3.68	13	2.834	- 2.02	2.896	- 1.74
14	2.525	- 3.83	14	2.775	- 2.11	2.842	- 1.77
15	2.480	- 3.92	15	2.720	- 1.95	2.788	- 1.60
16	2.440	- 4.05	16	2.662	- 2.16	2.733	- 1.78
17	2.415	- 4.16	17	2.603	- 2.23	2.676	- 1.73
18	2.400	- 4.06	18	2.545	- 2.28	2.619	- 1.69
19	2.395	- 3.68	19	2.497	- 2.36	2.568	- 1.77
20	↓	- 3.48	20	2.459	- 2.40	2.525	- 1.74
21		- 3.13	21	2.429	- 2.53	2.486	- 1.76
22		- 2.87	22	2.408	- 2.58	2.455	- 1.84
23	2.397	- 2.67	23	2.395	- 2.48	2.431	- 2.08
24	2.405	- 2.45	24	↓	- 2.32	2.413	- 2.26
25	2.410	- 2.30	25		- 2.28	2.400	- 2.03
26	2.420	- 2.01	26		- 2.18	2.396	- 1.88
27	2.430	- 1.80	27	2.397	- 2.08	2.397	- 1.84
28	2.445	- 1.38	28	2.405	- 1.90	2.405	- 1.68
29	2.460	- 0.90	29	2.410	- 1.85	2.410	- 1.64
30	2.480	- 0.78	30	2.420	- 1.65	2.420	- 1.38
34	2.815	+ 1.08	31	2.430	- 1.59	2.430	- 1.34
42	3.310	+ 4.25	32	2.445	- 1.13	2.445	- 0.99
50	3.980	+14.60	33	2.460	- 0.74	2.460	- 0.57
			34	2.480	- 0.64	2.480	+ 0.56
			38	2.815	+ 0.96	2.815	+ 1.08
			46	3.310	+ 3.87	3.310	+ 3.82
			54	3.980	+ 5.83	3.980	+ 5.86