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** Department of Mechanical Engineering, Colorado State University.

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**** National Bureau of Standards Cryogenic Engineering Laboratory, Boulder, Colorado.

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TABLE OF CONTENTS

ABSTRACT

This is a report of an exploratory study of low quality steam and water mixtures flowing in a Venturi tube. Analysis of the experimental results indicate the flow pattern may be tending to change from separated, slugging flow at the entrance to annular flow at the throat. Correlations indicate the venturi may be calibrated for use as a quality meter if the mass flow rate is known.

LIST OF SYMBOLS

$\dot{m}$	Mass rate of flow of fluid, lb_m/sec.
ΔP	Pressure drop in Venturi between stations indicated in the subscript.
x	Quality, or fraction of total mass which is vapor.
A_E	Total cross-sectional area of entrance, f^2.
A_T	Total cross-sectional area of throat, f^2.

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Although there have been many studies of steam and water flow and general studies of liquid and gas flow, almost all of the previous studies have been made under conditions where the major portion of the pressure drop is due to fluid friction (1), (2), (6) or where the flow becomes critical (3), (4). In the steam and water flow in Venturi tubes, the major portion of the pressure drop results from the change of momentum of the fluid. In addition to investigating the pressure drop in 2 phase flows in rapidly changing cross-sectional areas, the results of this study may be used to determine the usefulness of the Venturi tube as a fluid meter in liquid-vapor flow.

TEST PROCEDURES AND RESULTS

In this preliminary portion of the program, controlled quantities ($\dot{m}$) and qualities (x) of steam and water mixtures flowed through the Venturi tubes No. 1 and No. 2 shown in Figure No. 1.[†] Quality was controlled and computed from electrical input data; that is, the energy supplied to form the vapor. Short sections of glass pipe upstream and downstream from the Venturi tube permitted observations of the flow at these points.

The flow pattern, as defined in reference (2) entering the Venturi tube, was separated with intermittent disk-like, predominately liquid slugs, for all runs with the slugs considerably greater in number and annular in appearance on the downstream side of the Venturi tube. Damped pressure and differential thermocouple temperature readings were taken at approximately

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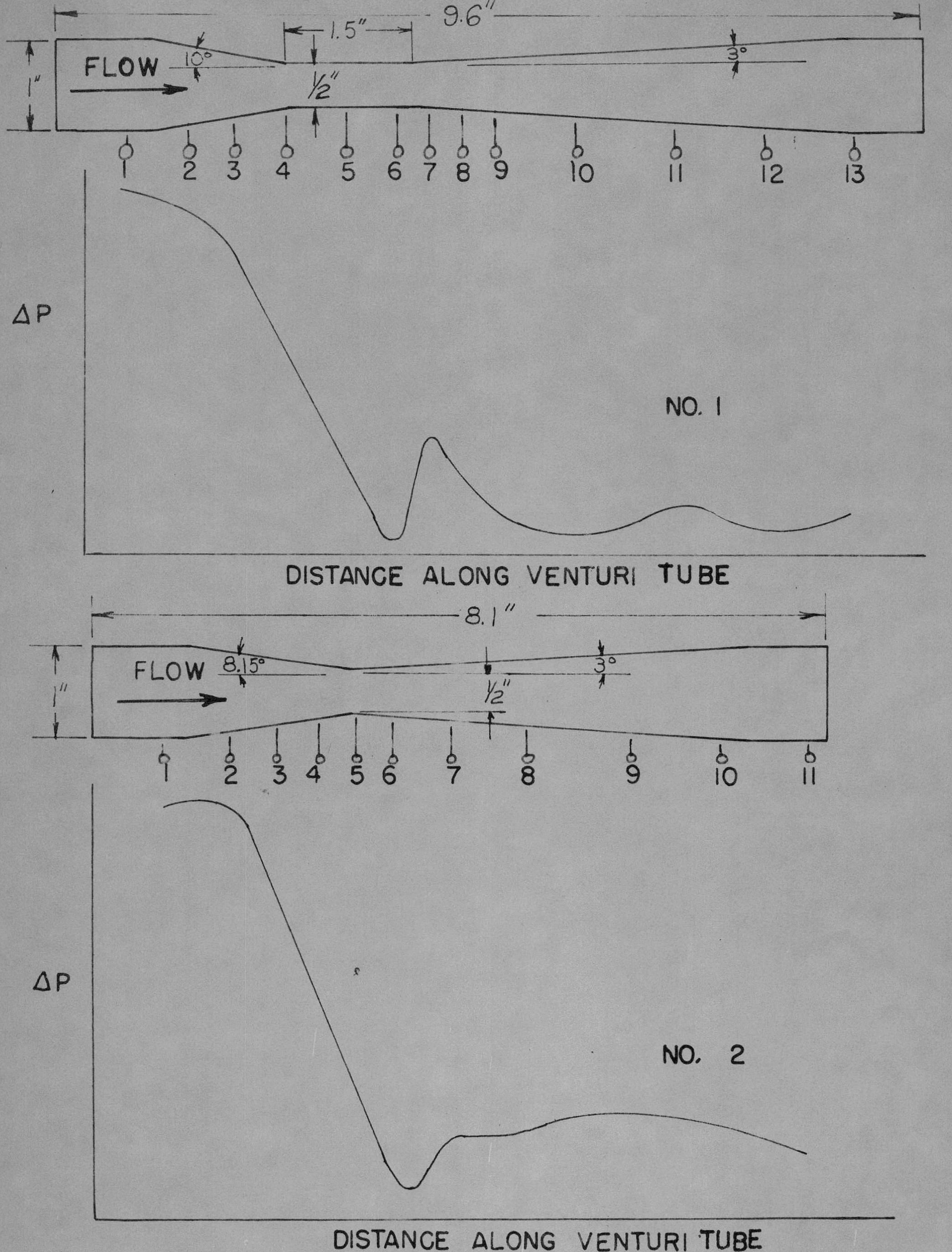
† See Appendix for further details.



THE RANGE OF MASS FLOW IS FROM 0.100 TO 0.210 LB./SEC.
THE PERCENT QUALITY RANGE IS FROM 0.18 TO 9.10%

PLOT SHOWING TYPICAL PRESSURE PROFILES
FIGURE NO. 1

3/4 inch spacing in the Venturi tube and the general shape of the pressure patterns are shown in Figure No. 1. Temperature data indicated no measurable temperature differences in Venturi tube No. 2 and a one or two (^{o}F) temperature rise in the throat of Venturi tube No. 1, falling again to equilibrium temperature at the exit.†

DISCUSSION AND ANALYSIS

A good correlation was obtained from pressure drops, as shown in Figure No. 2. Pressure drops from the entrance to the throat exit produced the best correlation.

In order to make a mathematical analysis of the flow, the liquid velocity profile was determined from Pitot tube measurements and the entrance liquid-gas velocities were computed neglecting the effect of the slugs. These velocity values showed reasonably good agreement with the Lockhart-Martinelli correlation (1). The momentum pressure drop was computed by trial and error assuming the pressure drops from the entrance to the throat for the liquid and gas were equal. This represents the computed pressure drop neglecting compressibility, friction and phase change. The results are shown in Table 1.† It is interesting to note that these pressure drops are as small as one-eighth of those which would be predicted for homogeneous flow assuming an effective velocity.

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† See Appendix for further details.

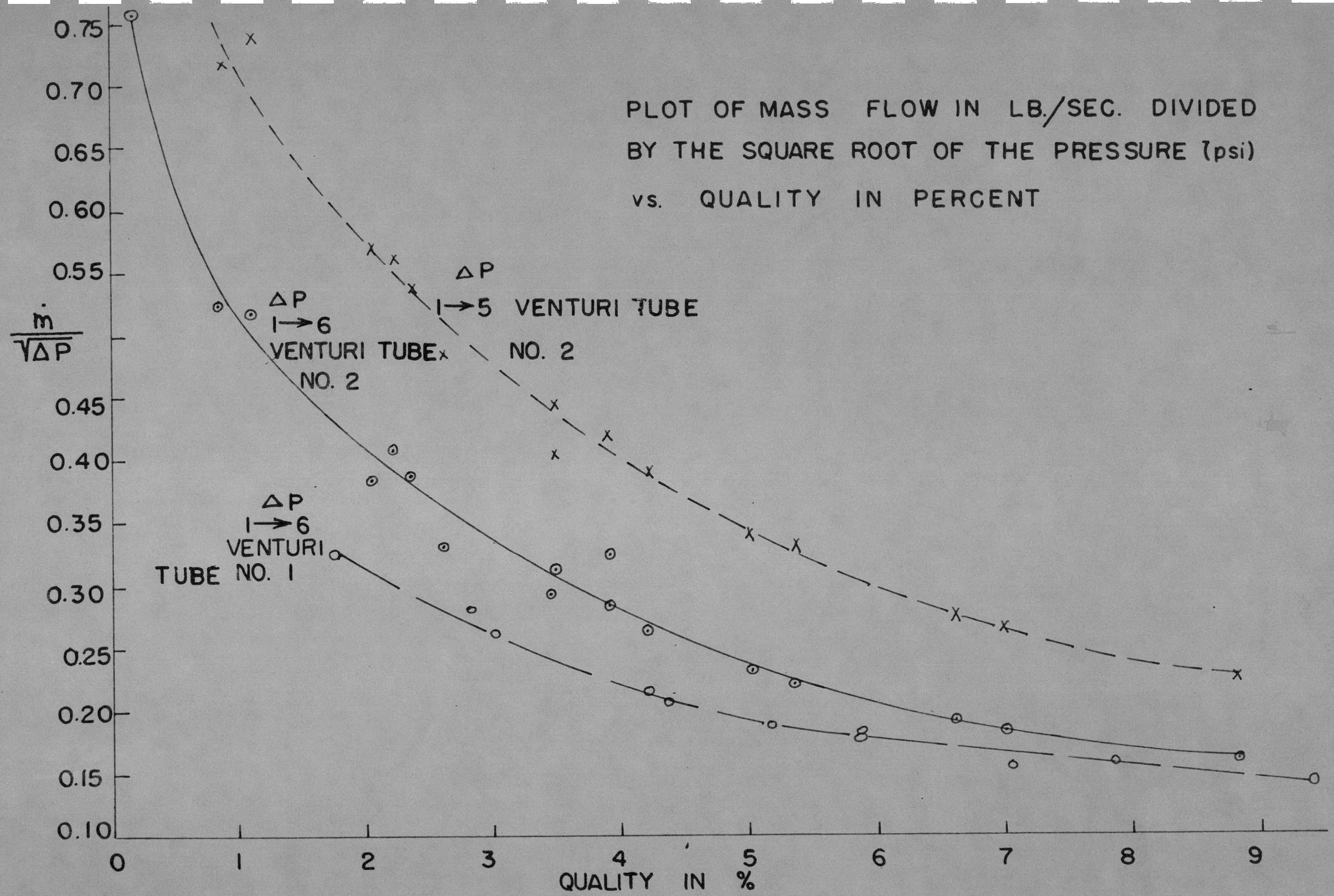
PLOT OF MASS FLOW IN LB./SEC. DIVIDED BY THE SQUARE ROOT OF THE PRESSURE (psi) vs. QUALITY IN PERCENT
$\frac{\dot{m}}{\sqrt{\Delta P}}$
0.75
0.70
0.65
0.60
0.55
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0
1
2
3
4
5
6
7
8
9
QUALITY IN %
ΔP $1 \rightarrow 5$ VENTURI TUBE NO. 2
ΔP $1 \rightarrow 6$ VENTURI TUBE NO. 2
ΔP $1 \rightarrow 6$ VENTURI TUBE NO. 1

FIGURE NO. 2

$\dot{m}$ LBm/sec	χ% No. 1	χ% No. 2	No. 1 Experimental ΔP 1⟶6 (psi)	No. 1 Calculated Momentum ΔP 1⟶6	No. 2 Experimental ΔP 1⟶5	No. 2 Calculated Momentum ΔP 1⟶5	No. 2 Experimental ΔP 1⟶6	Entrance $\frac{A \text{ Liquid}}{A_E}$ Calculated	Throat $\frac{A \text{ Liquid}}{A_T}$ Calculated
	3.90	3.49	0.112	0.039	0.060	0.047	0.101	15.4%	36.8%
0.099	5.86	5.00	0.208	0.100	0.086	0.056	0.183	14.1%	26.2%
-0.100	7.84	6.96	0.314	0.154	0.140	0.140	0.297	12.3%	20.9%
	9.40	8.81	0.488	0.215	0.195	0.199	0.380	12.2%	17.9%
	2.80	2.21	0.217	0.040	0.047	0.042	0.090	21.5%	48.0%
0.122	4.34	3.90	0.397	0.082	0.084	0.081	0.140	17.5%	34.9%
-0.129	5.84	5.33	0.531	0.142	0.134	0.132	0.305	16.5%	27.4%
	7.06	6.61	0.700	0.165	0.195	0.172	0.397	16.4%	25.6%
	1.76	0.88	0.307	0.082	0.053	0.038	0.099	31.6%	50.8%
0.163	2.97	2.35	0.388	0.084	0.094	0.087	0.182	25.3%	48.2%
-0.165	4.19	3.46	0.617	0.147	0.137	0.139	0.319	21.0%	36.8%
	5.16	4.20	0.848	0.153	0.177	0.171	0.387	20.8%	36.0%
		0.17			0.041	0.053	0.076	50.3%	78.7%
0.210		1.09			0.081	0.069	0.162	31.0%	58.3%
		2.02			0.137	0.135	0.301	28.8%	52.6%
		2.60			0.187	0.168	0.400	24.3%	42.0%

EXPERIMENTAL AND CALCULATED PRESSURE DROPS AND AREA RATIOS FOR VENTURI TUBES

TABLE NO. 1

Agreement between the computed and measured values is within the range of experimental accuracy for these exploratory tests for $\Delta P_{1 \rightarrow 5}$ for Venturi tube No. 2. However, for $\Delta P_{1 \rightarrow 6}$ with Venturi tubes No. 1 and No. 2, computed values which should approximately equal $\Delta P_{1 \rightarrow 5}$ varied far from the experimental results. Since all three pressure drops correlate well in Figure 2, these data lead to two observations. First, one may conclude that the analytical treatment omits significant factors or that the assumed mode of flow changes. Second, the sources of the analytical error must be a function of the correlating parameters.

More detailed calculations show that neglecting wall friction, phase change or compressibility will not account for the differences noted. In considering alternate mechanisms, $\Delta P_{1 \rightarrow 6}$ patterns for both venturies suggest a vena contracta effect for the gas. A flow mechanism which would produce a pressure curve similar to a vena contracta would be a system in which the flow pattern tended to change from separated flow at the entrance to annular flow, with a liquid annulus, at the throat. The horizontal velocity component of the liquid in the throat may be quite low and its flow cross-sectional area increased to a value considerably greater than that shown in Table 1. Thus, the experimental ΔP measurements downstream of the throat entrance may primarily represent the gas velocity pattern.[†]

[†] See Appendix for further details.

Another explanation for the discrepancies in Table 1 may be that the flow pattern tends to become homogeneous in the throat and the pressure readings downstream of the entrance to the throat, accordingly, approach the considerably higher homogeneous pressure drop.

It would appear that slugging is a result of intermittent liquid "sealing off" the flow area followed by a pressure build-up of gas forcing a liquid slug to form. This occurrence is much more probable at the throat with its smaller cross-sectional area. The marked increase in the number of slugs appearing downstream of the Venturi substantiaties this explanation. Also, the annular appearance of the downstream slugs indicates a tendency for a change in the mode of flow at the throat. If the previous hypothesis is true then the quality (x) must be a measure of the tendency for this flow pattern to change because correlation is possible with (x).

The downstream recovery of both Venturi tubes is poor with pressure oscillations in the downstream portion. This pressure pattern is typical of a cavitating Venturi (5).

In examining the general pressure pattern for Venturi tube No. 1, an unexpected result is the essentially linear portion from the entrance to the end of the throat. A change of slope would normally be expected at the entrance to the throat. Again, a changing flow pattern could explain this behavior with the water cross-section controlling the flow cross-section area of the gas which, in turn, may be the major factor in producing the measured Venturi tube pressure drop.

CONCLUSIONS

Correlations from this exploratory study suggest that a Venturi tube may be successfully calibrated for use as a quality measuring meter if the total mass flow rate is known. The downstream pressure tap should be located near the throat exit.

Preliminary calculations indicate the flow pattern at the Venturi tube throat may be changing from separated flow to annular flow with the annular flow pattern much more pronounced in the long-throated Venturi tube.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to Professors H. B. Mummert and J. T. Strate for their assistance on this project and to Mr. E. Yellin for his work in the early stages of the project.

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6. Griffith, P. and Wallis, G. B., "Two Phase Slug Flow", A.S.M.E. Preprint 60-HT-28.

APPENDIX

LIST OF SYMBOLS USED IN THE APPENDIX

A_ℓ	Cross-sectional area of liquid flow, ft^2
h	Height of liquid-vapor interface, ft
$\dot{m}$	Mass rate of flow of fluid, lb_m/sec
ΔP	Pressure drop in Venturi between stations indicated by subscript
V_g	Velocity of gas, ft/sec
V_ℓ	Velocity of liquid, ft/sec
V_{EFF}	Effective velocity, ft/sec
x	Quality or fraction of total mass which is vapor
ρ_g	Weight density of gas, lb_m/ft^3
ρ_ℓ	Weight density of liquid, lb_m/ft^3
v	Specific volume of homogeneous mixture

SLUGGING

The slugging flow upstream and downstream from the Venturi tubes are somewhat different. On the upstream side the slugs are well defined disk-like formations of water moving down the glass tube. The downstream slugs are shaped as an annulus and are longer and less well defined. The slugs resulting from Venturi tube No. 1 are more frequent than those resulting from Venturi tube No. 2. At the higher mass flows with Venturi tube No. 1, the downstream slugs are so frequent that it is almost continuously annular flow. The velocity of the downstream slugs appear greater than those upstream. It was observed that the number of slugs per minute increased as the mass flow and quality increased. In Figure No. A1 is shown the apparent pattern of slugs in the Venturi tubes. Between slugs the pattern is similar except that the top is not covered with water so that the pattern oscillates from a complete annulus as slugs pass through the Venturi tube to separated flow between the slugs.

The slugs were counted when they filled the entire glass tube. It was found that the number of slugs per minute both upstream and downstream stayed constant for any one mass flow and power setting. See Table No. A1 which shows the number of slugs per minute with the various mass flows and power settings.

Fluctuations between the annular and separated shapes shown.

Sketch showing apparent flow patterns at entrance and throat of venturi tube

Figure No. A1

Mass Flow Lb_m/Sec.	Power Added Kilowatts	Number of Slugs per Minute		
		Upstream	No. 2 Downstream	No. 1 Downstream
0.100	4.0	0 -0	14	31
0.100	6.0	0 -1	19	39
0.100	8.0	1 -2	30	49
0.100	9.6	1 -3	39	52
0.123	4.0	0 -0	39	42
0.123	6.0	0 -0	40	43
0.123	8.0	4 -5	40	60
0.123	9.6	13-15	42	72
0.165	4.0	0 -2	50	55
0.165	6.0	8 -10		65
0.165	8.0	15-17	52	76
0.165	9.6	20-25	65	94
0.210	4.0	0 -1	53	
0.210	6.0	22-25	54	
0.210	8.0	26-30	65	
0.210	9.6	35-40	75	

Table A1

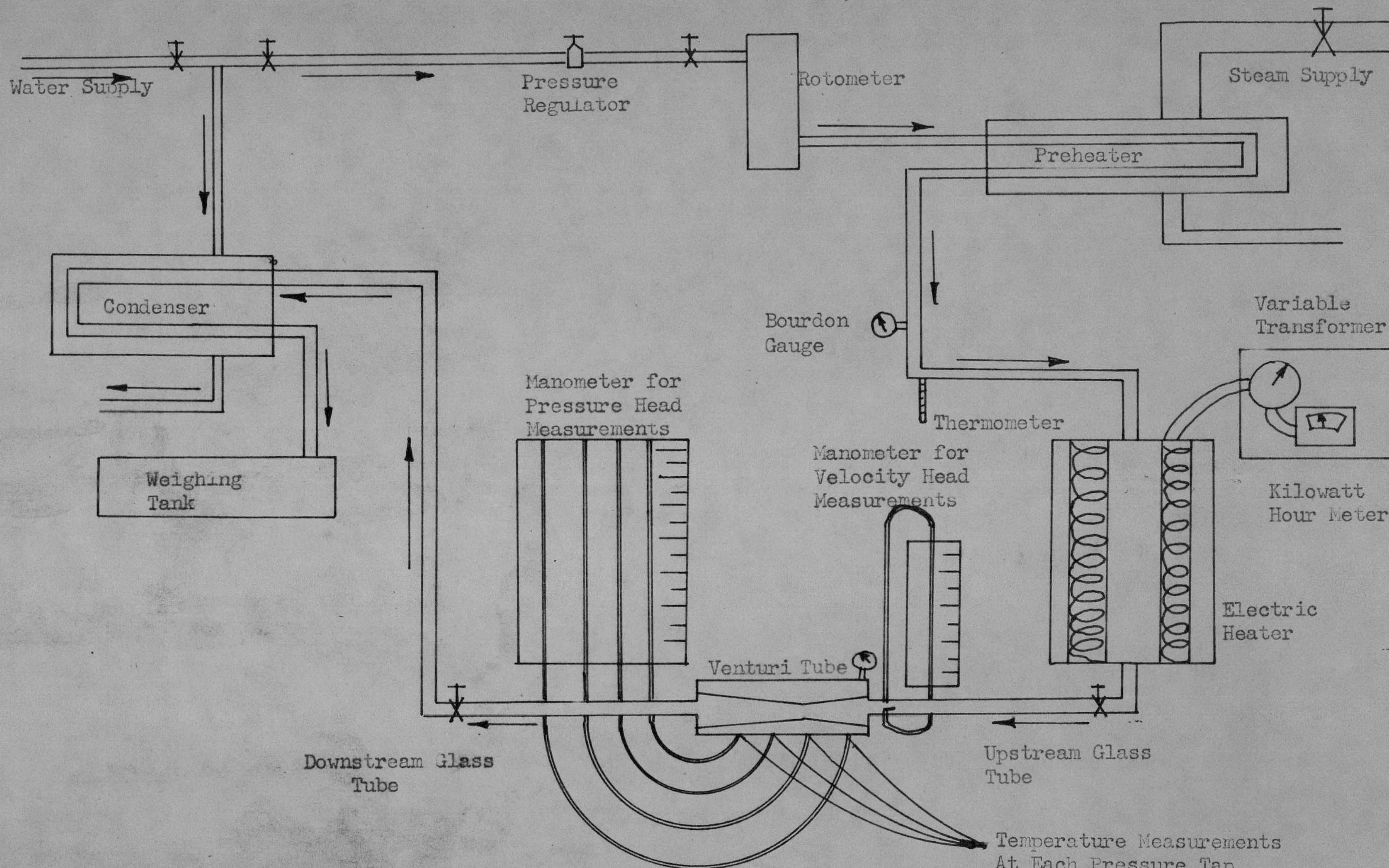
Numbers of Slugs Upstream and Downstream

EQUIPMENT AND TESTING

See Figure No. A2 for a schematic drawing of the equipment used in this study of two-phase flow. It may be seen that the cold supply water is put through a rotometer to obtain a rough setting of the mass flow desired. A more precise measurement of this mass flow is obtained by weighing the fluid discharged on a scale to which a stopclock is attached. In these tests, the clock stopped when fifty pounds of fluid had discharged into the weighing tank. Occasional fluctuations of pressure in the supply line were therefore averaged into the mass flow data.

After leaving the rotometer the water entered a closed heat exchanger where it was brought to near saturation temperature. The Bourdon gauge was set at 12 psi and the temperature of the fluid leaving the heat exchanger was read. The fluid then went to the three electric heaters where superheated steam is generated. The power settings of 4.0 KW, 6.0 KW, 8.0 KW and 9.6 KW were used to produce the different quality used in the runs.

After leaving the electric heaters the vapor and liquid pass through the glass tube at the end of which is a Pitot tube for measuring the velocity head. The total head tube was made from a hypodermic needle to minimize flow disturbances. It was made movable so that the velocity measurements could be made from the bottom of the tube up to the interface of the liquid and the gas. Errors were introduced here by the slugging flow for as a slug moves down the tube and enters the Pitot tube, the velocity head shows a distinct variation. With a large number of slugs moving down the tube the velocity head may be in error to some degree, however as Table No. A1 shows, for most runs, slugs were relatively infrequent upstream of the Venturi tube.

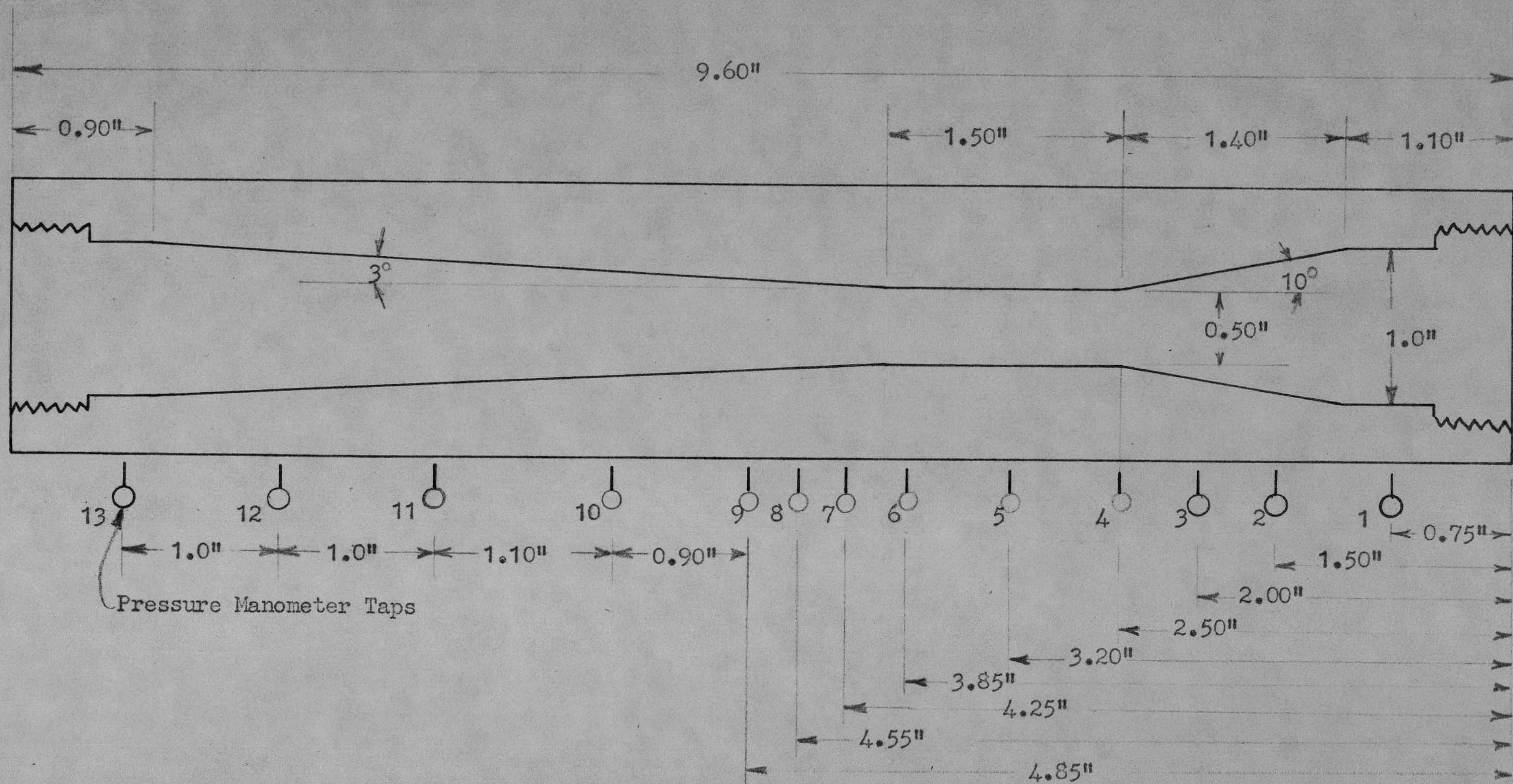


Schematic Drawing of Equipment

Figure No. A2

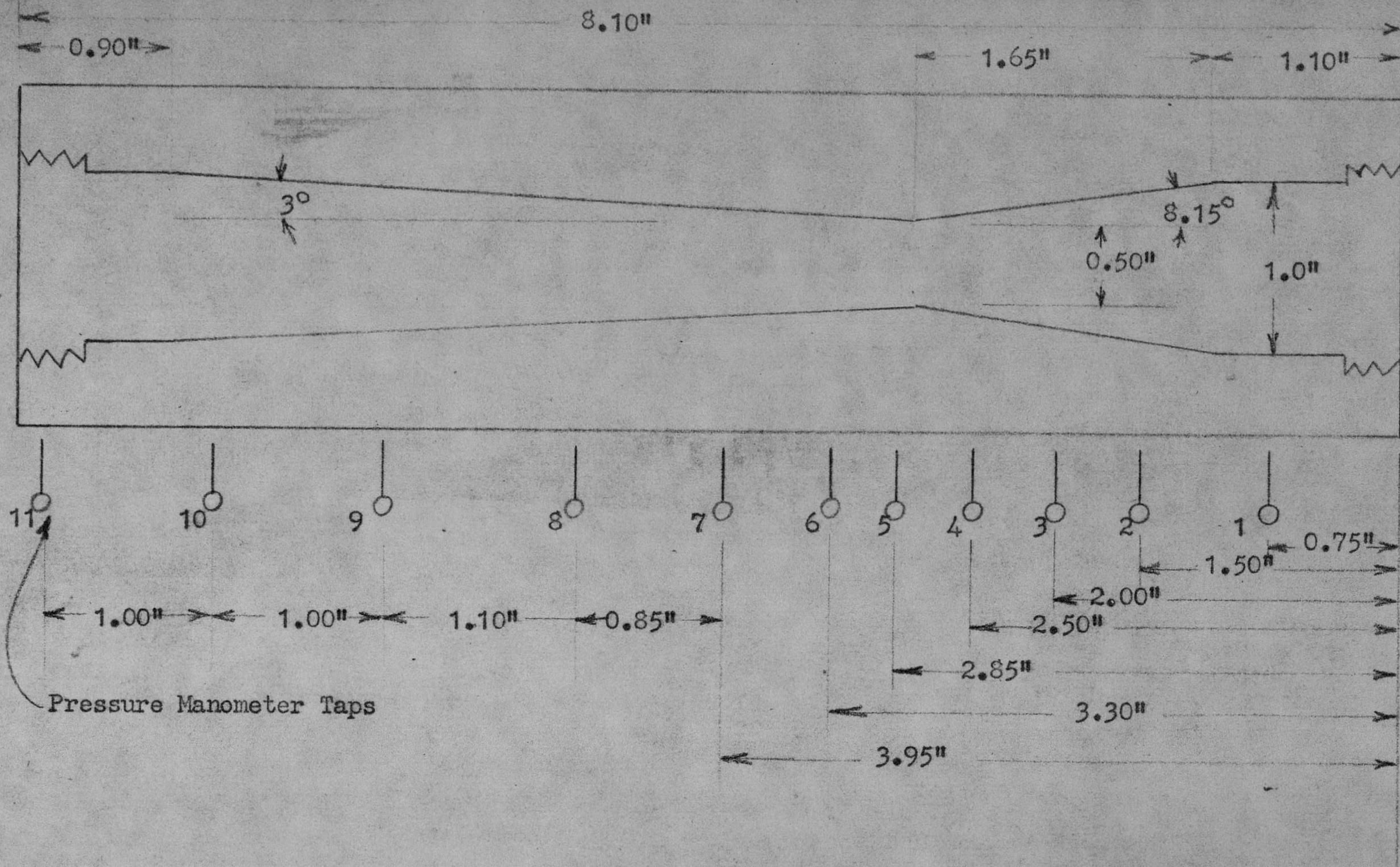
Immediately downstream from the velocity head needle, the liquid and vapor enters the Venturi tube, which is made of teflon. Its dimensions are shown in Figures No. A3 and A4. There are eleven pressure head taps on the bottom of the Venturi tube No. 2 and thirteen pressure taps on the bottom of Venturi tube No. 1. The Venturi tube has been turned forty-five degrees and no appreciable pressure variation was noted, so it was assumed there was not a vertical pressure gradient in the Venturi tube. On the sides of the Venturi tube holes have been drilled for temperature measurements. Thermocouples were installed with their junction on the Venturi tube centerline. Slugging made even differential temperature measurements difficult and only a general pattern was obtained as shown in Figure No. A14.

The downstream glass tube enables one to see the downstream slugging flow. Immediately downstream from this glass tube is a valve with which the pressure at the entrance to the Venturi tube was maintained at 5.0 ± 0.2 psi. The pressure varies to this extent due to the effect of the slugs. The liquid and gas then enter the condenser. From there it goes to the weighing tank and then to the drain.



Venturi Tube No. 1

Figure No. A3



Venturi Tube No.2

Figure No. A4

METHOD OF EFFECTIVE LIQUID VELOCITY DETERMINATION

Using the mass flow data, the effective liquid velocity is

$$V_{EFF} = \frac{(1-x)(\dot{m})(v)}{A_1} \qquad (1)$$

and the area of the liquid is

$$A_1 = 0.25 \cos^{-1} (1-2h) - (0.5-h)(h-h^2)^{\frac{1}{2}} \qquad (2).$$

The effective liquid velocity may also be found by using the velocity profile (Figure A13)

$$V_{EFF} = \frac{A_1V_1 + A_2V_2 + A_3V_3}{A_1 + A_2 + A_3} \qquad (3)$$

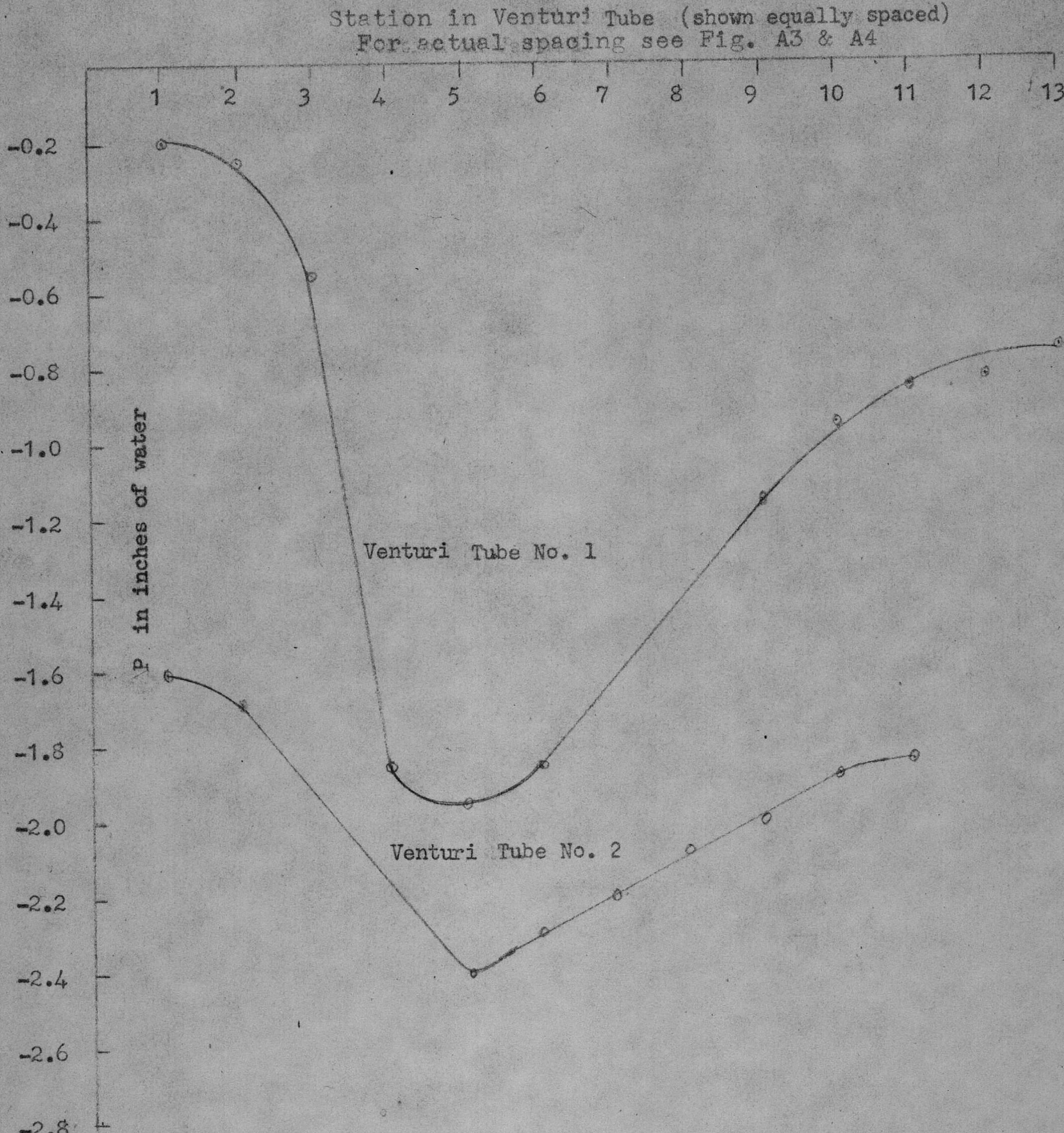
These equations involve a trial and error solution.

SOLUTION FOR PRESSURE DROPS

This solution assumes the pressure drops from the entrance to the throat for the liquid and for the gas are equal and that compressibility, frictional and phase change effects are negligible. Thus the pressure drop may be expressed as:

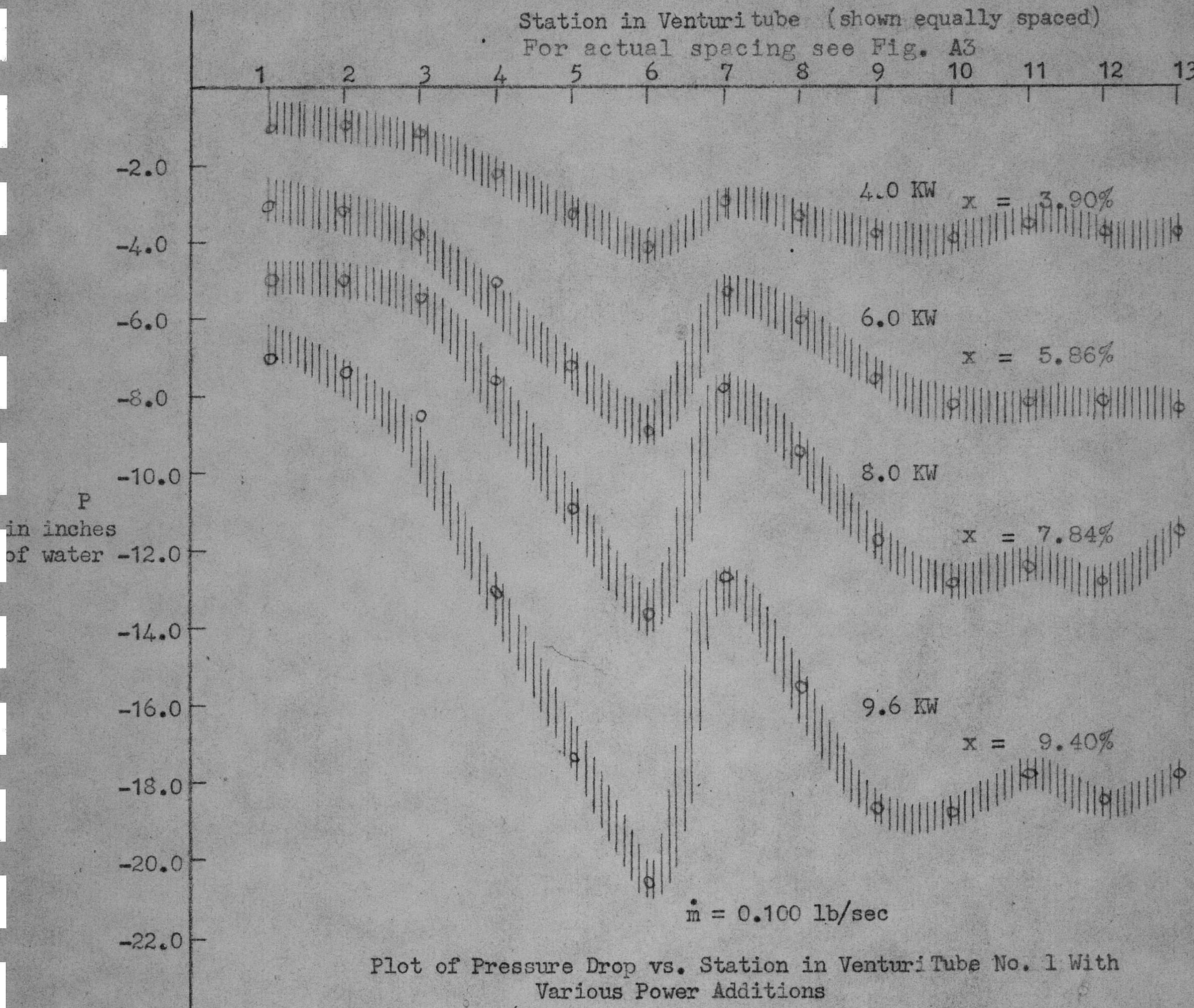
$${}_1\Delta P_{\ell_5} = \frac{\rho_\ell\left(V_{\ell 5}^2 - V_{\ell 1}^2\right)}{2g} = \frac{\rho_g\left(V_{g5}^2 - V_{g\ell}^2\right)}{2g} = {}_1\Delta P_{g_5} \qquad (4).$$

Equation (4) involves a trial and error solution also.



Single Phase Pressure Profiles for Each Venturi Tube

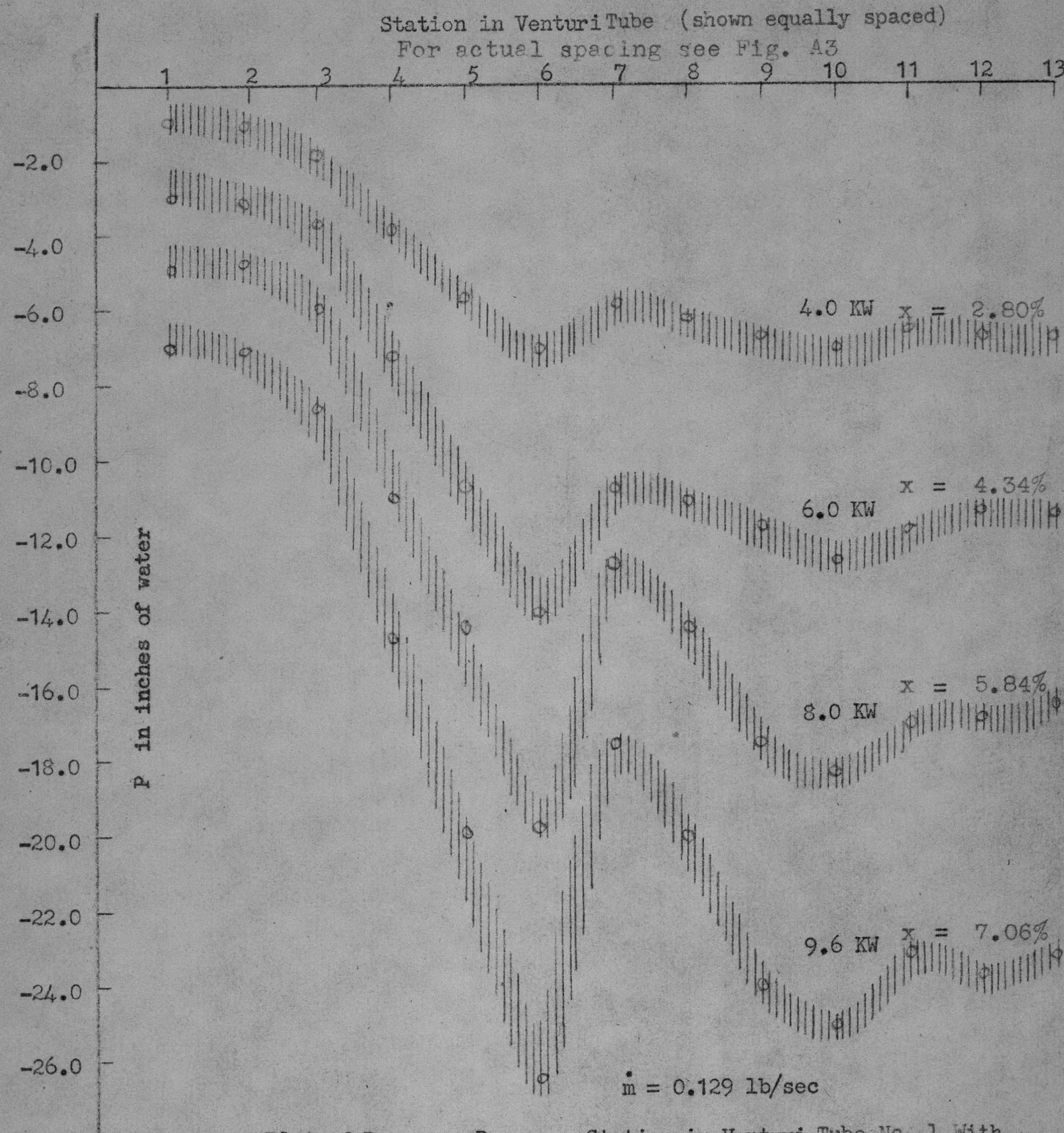
Figure No. A5



Plot of Pressure Drop vs. Station in Venturi Tube No. 1 With Various Power Additions

Figure No. A6

Dashed lines indicate pressure tap locations may not be at the critical points to determine the true pressure pattern shape.



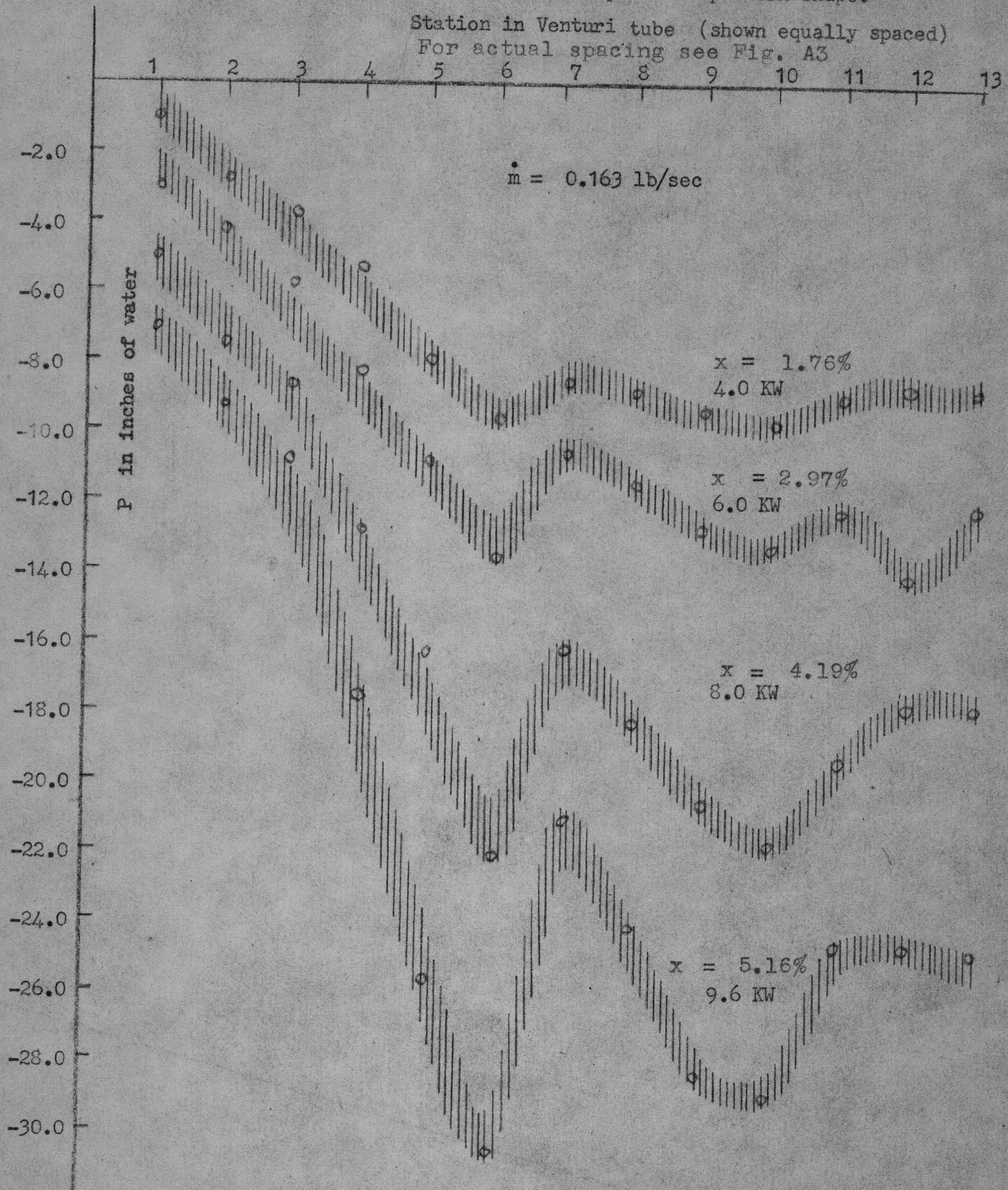
Plot of Pressure Drop vs. Station in Venturi Tube No. 1 With Various Power Additions

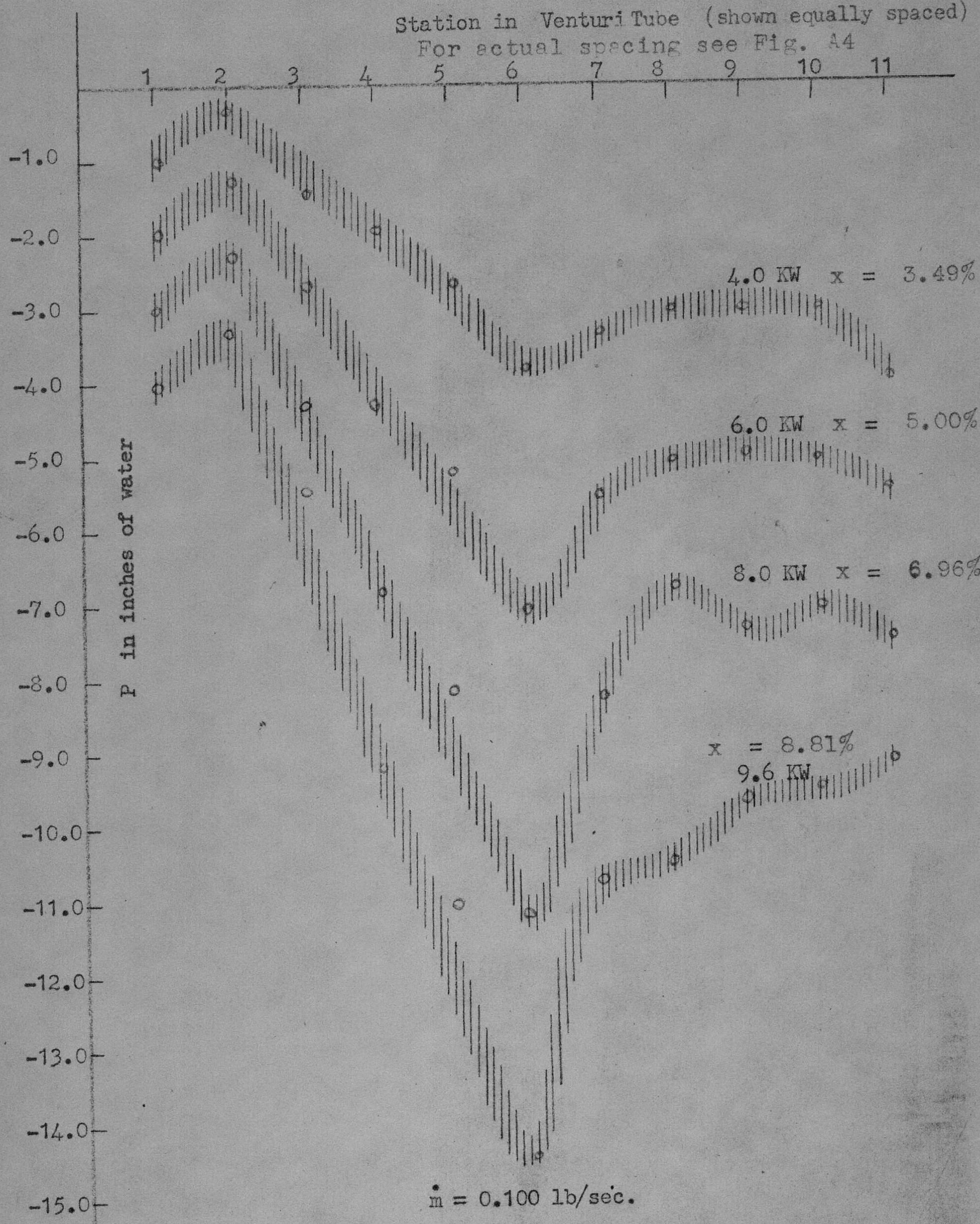
Figure No. A7
Dashed lines indicate pressure tap locations may not be at the critical points to determine the true pressure pattern shape.

Figure No. A8

Plot of Pressure Drop vs. Station in Venturi Tube No. 1 With Various Power Additions

Dashed lines indicate pressure tap locations may not be at the critical points to determine the true pressure pattern shape.

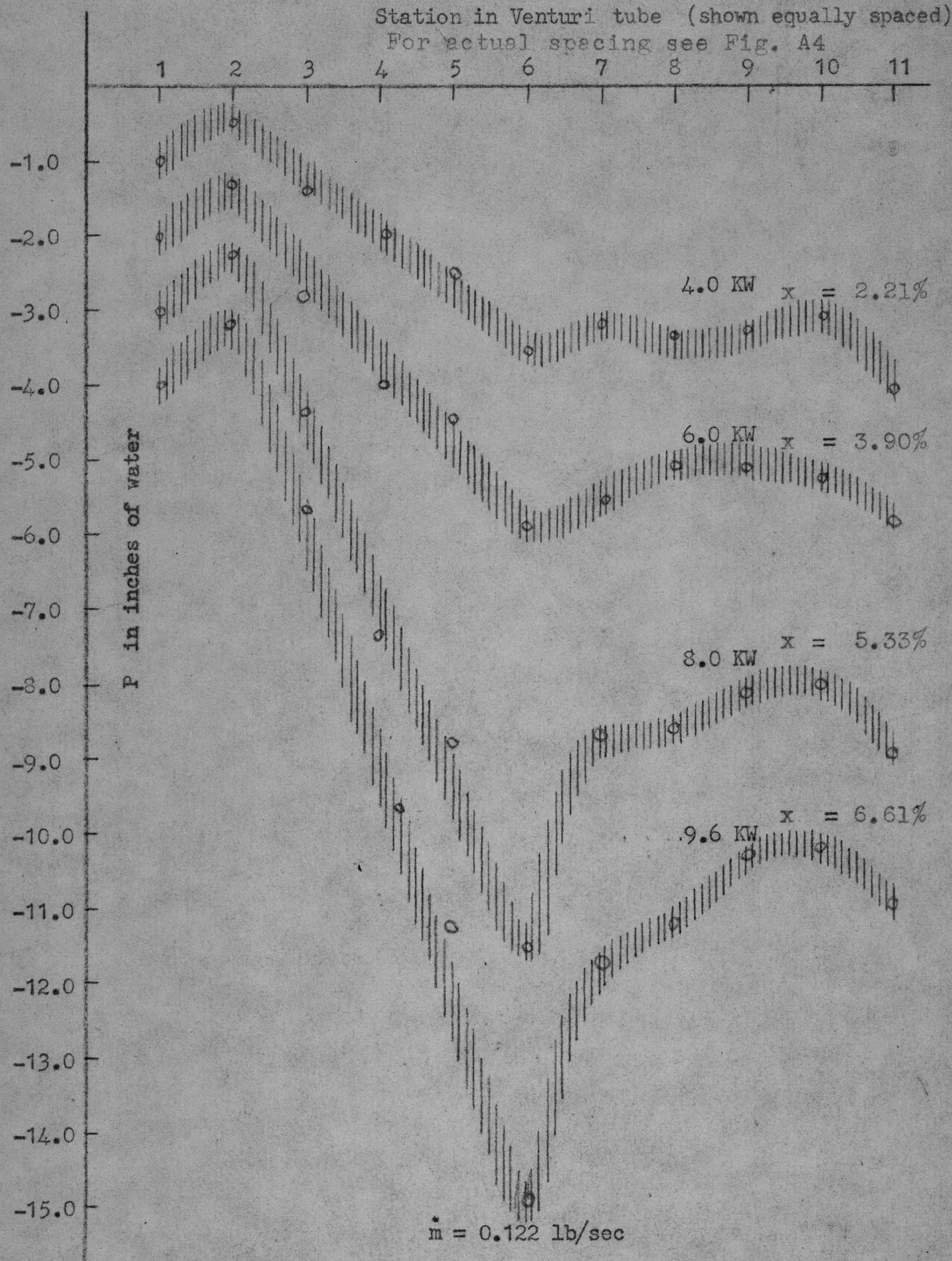




Plot of Pressure Drop vs. Station in Venturi Tube No. 2 With Various Power Additions

Figure No. A9

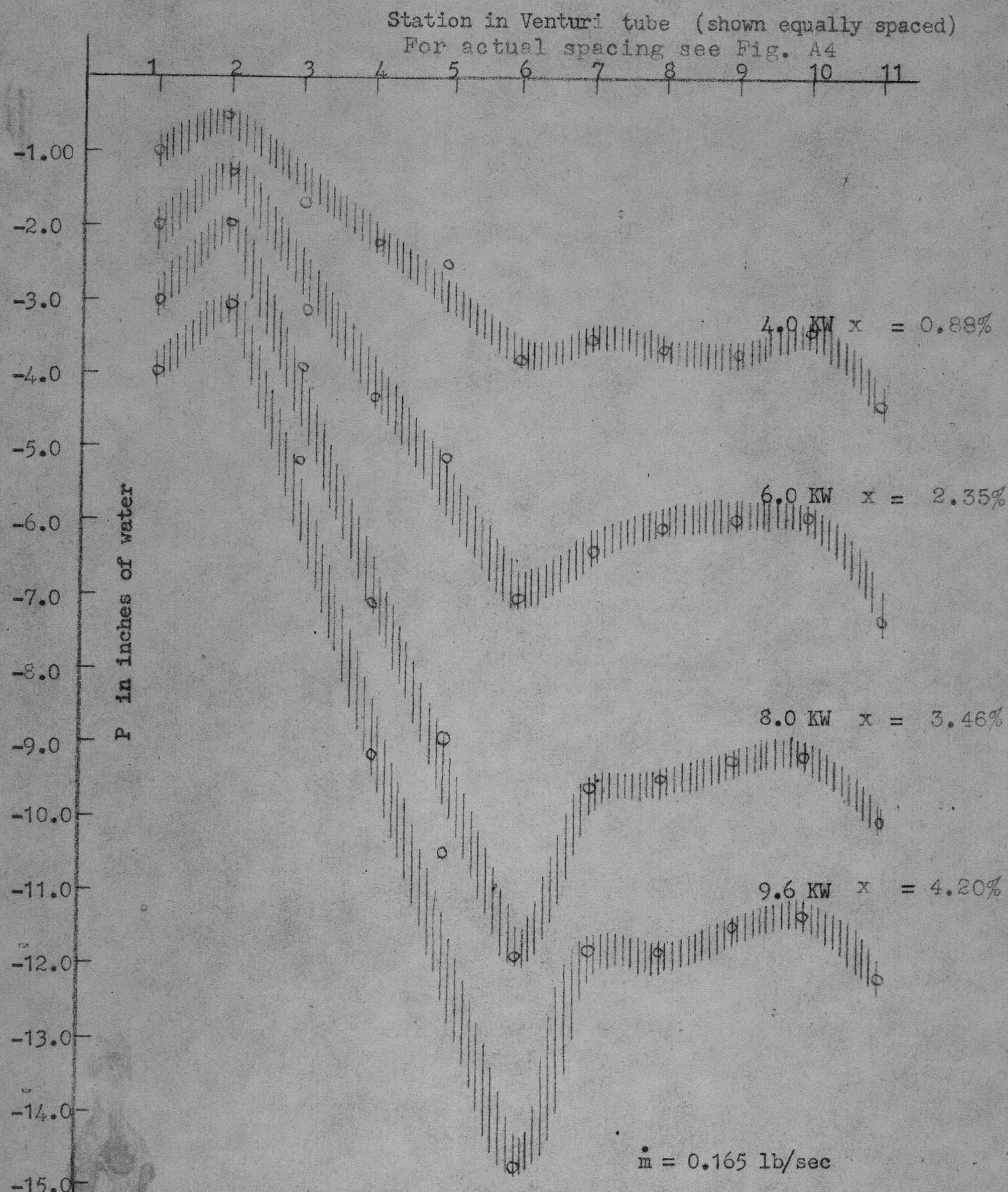
Dashed lines indicate pressure tap locations may not be at the critical points to determine the true pressure pattern shape.



Plot of Pressure Drop vs. Station in Venturi Tube No.2 With Various Power Additions

Figure No. A10

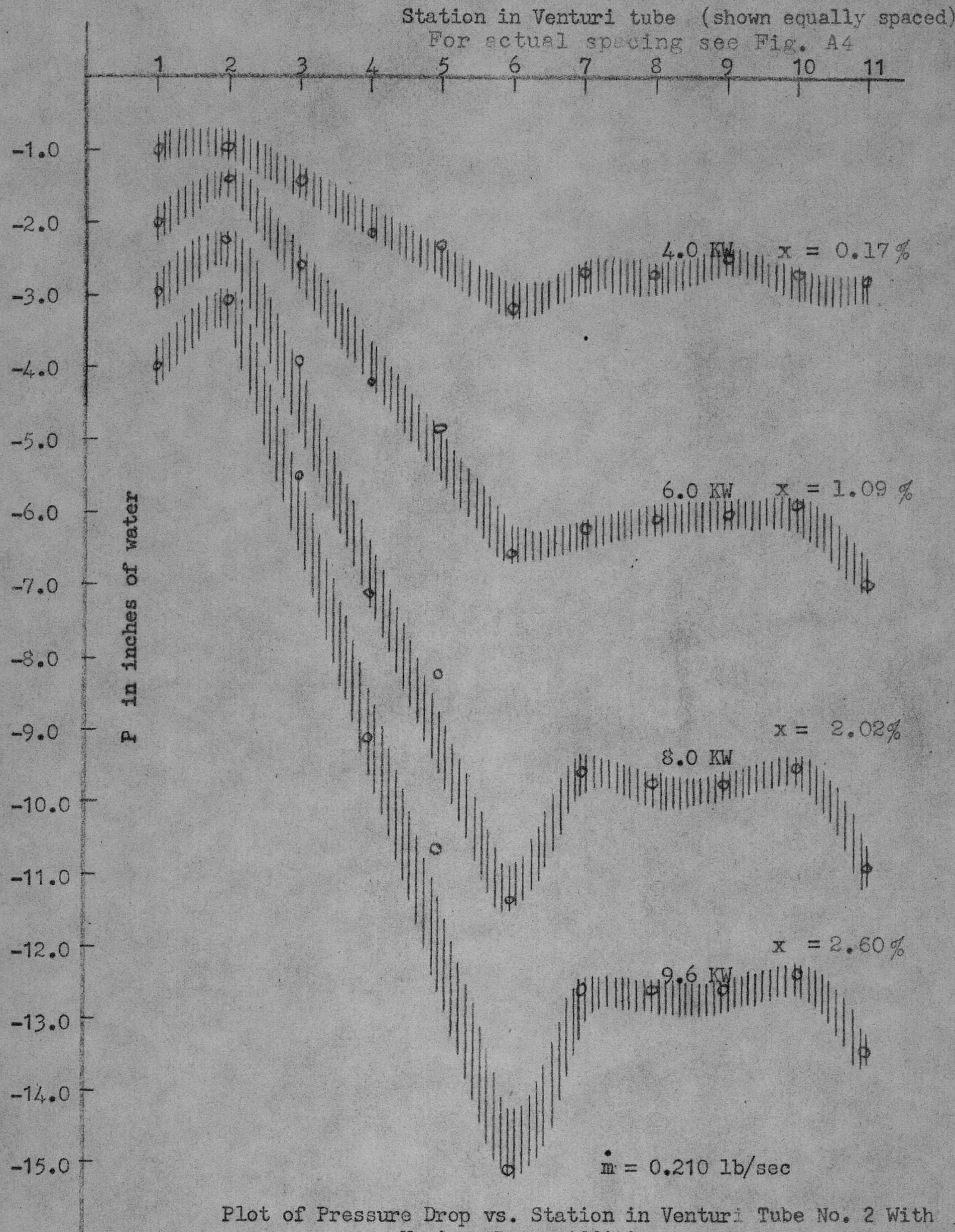
Dashed lines indicate pressure tap locations may not be at the critical points to determine the true pressure pattern shape.



Plot of Pressure Drop vs. Station in Venturi Tube No. 2 With Various Power Additions

Figure No. A11

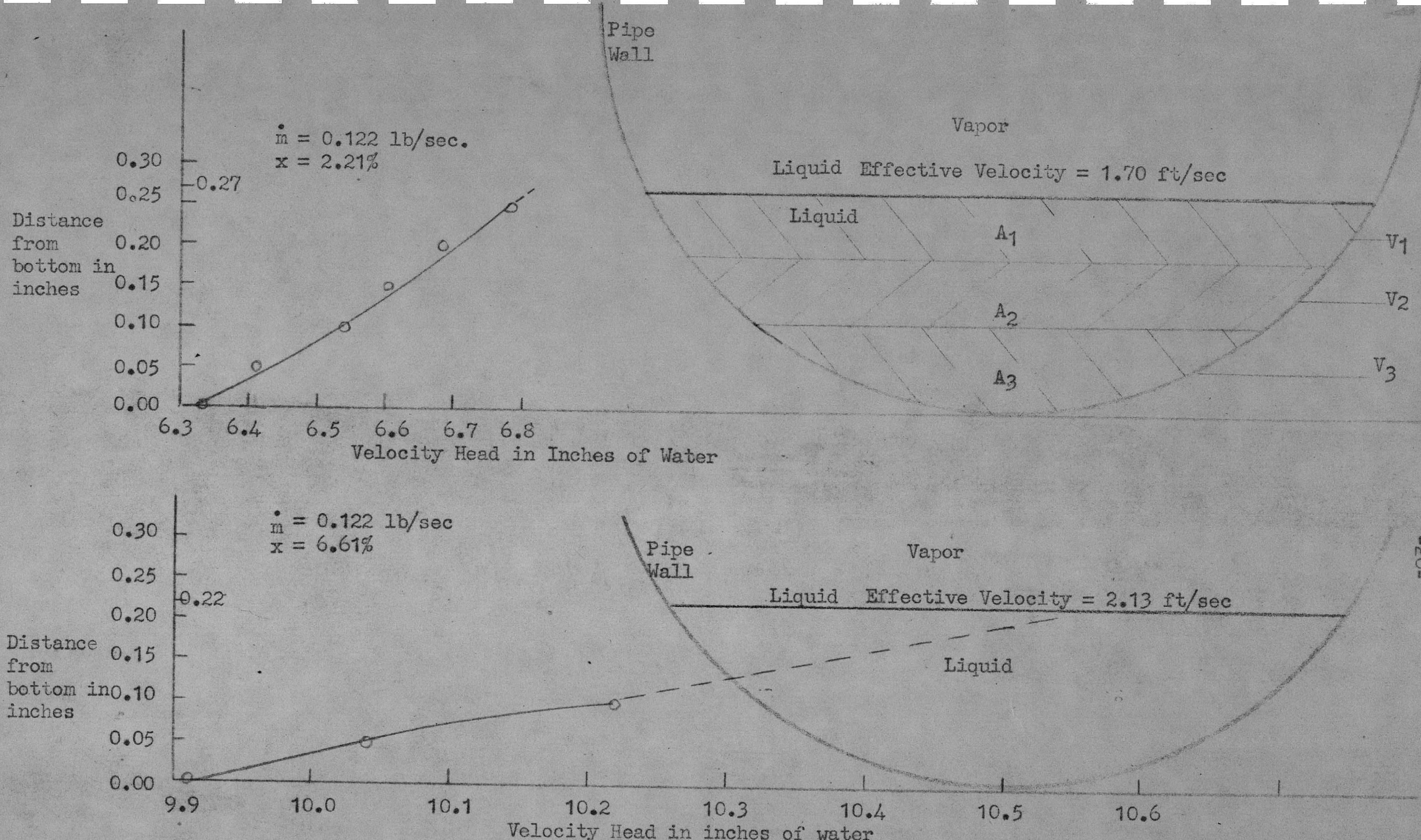
Dashed lines indicate pressure tap locations may not be at the critical points to determine the true pressure pattern shape.



Plot of Pressure Drop vs. Station in Venturi Tube No. 2 With Various Power Additions

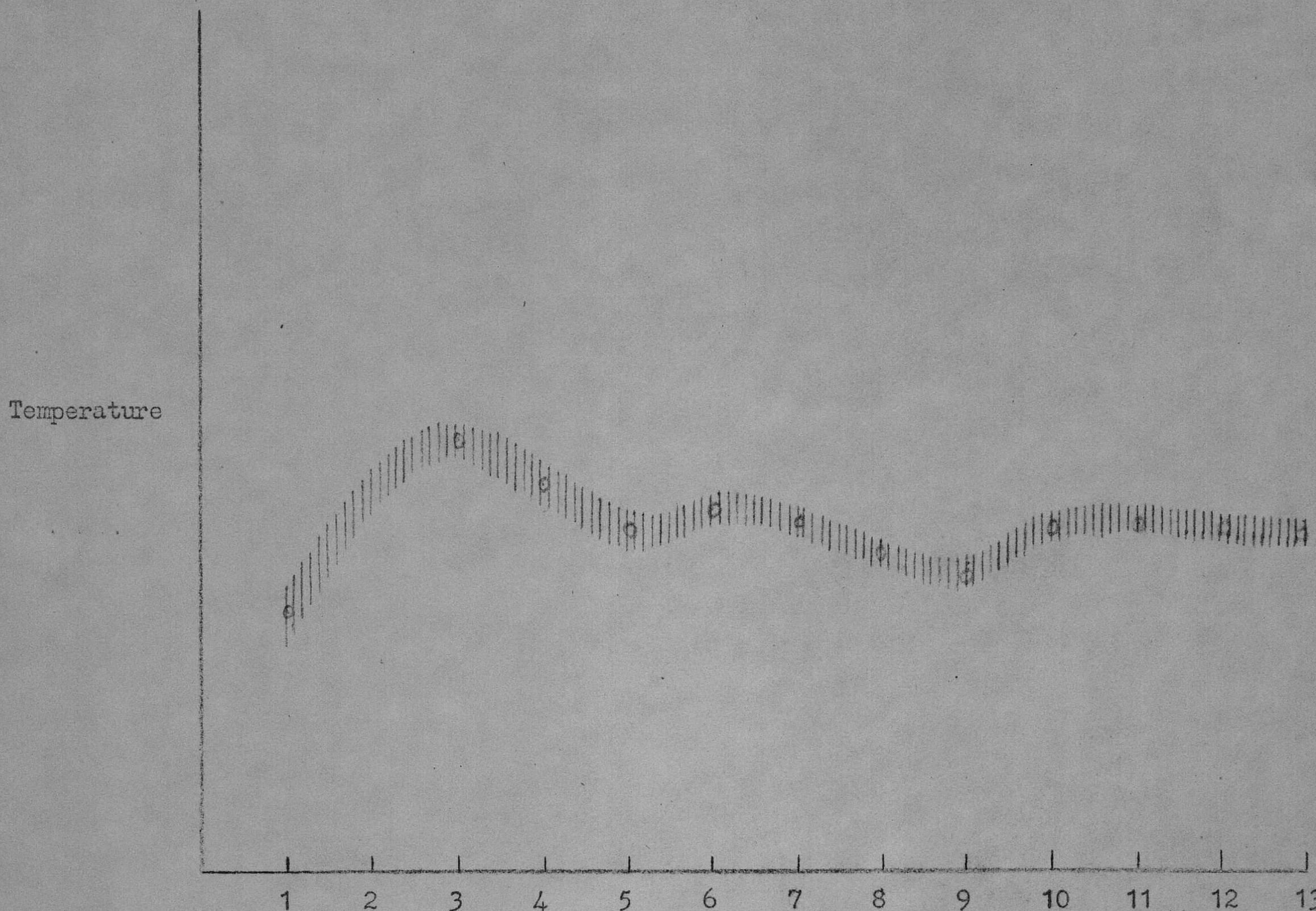
Figure No. A12

Dashed lines indicate pressure tap locations may not be at the critical points to determine the true pressure pattern shape.



Typical Velocity Profile of Liquid for Low and High Power Additions in Upstream One Inch Pipe

Figure No. A13



Station in Venturi Tube (shown equally spaced)
For actual spacing see Fig. A3

Typical Temperature Profile for Venturi Tube No. 1

Figure No. A14