West Pakistan
Water and Power Development Authority

ADDENDUM

TARBELA DAM PROJECT
POWER TUNNEL PENSTOCK MANIFOLD
HYDRAULIC MODEL STUDY
(BYPASS RELIEF BRANCH)

CIVIL ENGINEERING DEPARTMENT

Engineering Research Center
Colorado State University
Fort Collins, Colorado

July 1967

Prepared for
Tippetts-Abbett-McCarthy-Stratton
New York, New York

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FINAL REPORT

OF

HYDRAULIC MODEL STUDY

OF

POWER TUNNEL PENSTOCK MANIFOLD
BYPASS RELIEF BRANCH

TARBELA DAM PROJECT
INDUS RIVER
WEST PAKISTAN

Prepared for
Tippetts - Abbett - McCarthy - Stratton
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by

J. F. Ruff

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PREFACE

The Engineering Research Center at Colorado State University is located between Horsetooth Reservoir of the Colorado Big Thompson Project and College Lake. The laboratories of the Center are strategically placed to utilize the high head, 250 feet, available from the reservoir and the storage capacity of the lakes. The Center is the focal point for research and graduate education.

There are five principal parts to the Center: the offices for staff and graduate students, the hydraulics laboratory, the fluid dynamics laboratory, the hydromechanical laboratory and the outdoor hydraulics - hydrology laboratory. The research activities of the Center are in fluid mechanics, hydraulics, hydrology, ground-water, soil mechanics, hydrobiology, geomorphology and environmental engineering.

The hydraulics laboratory includes 50,000 square feet of floor space in which basic and applied research activities are undertaken. The floor of the laboratory is constructed over a large sump system, having one acre-foot capacity, which permits recirculation of water through the various research facilities. Generally, pumps are used for recirculation but the high head and large flow capacity from the reservoir can also be utilized.

The Center includes well equipped machine and woodwork shops. All research facilities of the Center are constructed on site and in the case of this model study, necessary metal work and all the plastic work were done by personnel in the shops. The shop personnel are particularly well experienced in the art and skill of model construction.

This model study was undertaken by Colorado State University in close coordination with Tippetts-Abbett-McCarthy-Stratton (TAMS) of New York, for whom this work was done. The urgent need of hydraulic information for purposes of planning and design was recognized from the beginning and all information obtained from the model studies relevant to those purposes were transmitted to TAMS in advance of this report. Decisions affecting model construction tests or testing program, or time schedules were made with mutual consent through assessment of appropriate information and consideration and accord with project planning.

Grateful acknowledgment is hereby expressed by the writer to personnel at TAMS for their cooperation, to personnel of the shops for their ingenious contributions in solving model construction problems, particularly in the plastic works, and to others contributing to the model study and the preparation of this report.

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SUMMARY

A hydraulic model study of a portion of the Tarbela Dam penstock manifold was performed. The portion tested included only branch 4 with a butterfly valve and bypass relief branch installed. Pressures were measured and recorded and velocity distributions were observed at several locations.

The bypass relief branch and connection exhibited satisfactory hydraulic performance. No abrupt pressure changes or unusual velocity distributions were observed. The branch connection has no detrimental effects on the flow approaching the turbine scroll case inlet. The butterfly valve installed upstream from the bypass relief branch connection exhibited no detrimental effects on pressures and velocities either at the bypass relief branch connection or the turbine scroll case inlet.

Form loss coefficients were calculated for the bypass relief branch connection including the reducing bend and for the branch 4 header. The coefficients are given for bypass and header in Figures 7 and 8, respectively.

A minimum distance "d" to prevent backsplash from the jet issuing from the bypass relief valve could not be determined because of limitations of model. Fillets installed in the hood reduced the backsplash but did not completely eliminate it.

This report is an addition to a comprehensive study of the penstock manifold. It describes the construction of branch connection and reducing bend approach to the bypass relief valve, details of the tests performed on this section of the manifold when installed in branch 4, and methods used to calculate the branch loss coefficients.

INTRODUCTION

This report is an addition to the report entitled "Tarbela Dam Project - Power Tunnel Penstock Manifold - Hydraulic Model Study" hereinafter referred to as the Penstock Report. The Penstock Report was a comprehensive study of pressure and velocity distributions throughout the manifold and branches leading to the turbine. Included in the report was a section discussing the tests and results for the basic design of the bypass relief branch. The bypass relief branch was modified and this report describes the tests performed on the modified branch and their results.

Description of Bypass Relief Branch

Details of the prototype bypass relief branch are shown in Figure 1. The axis of the bypass branch intersects each branch header with an internal angle of 53^0 - 01' - 33". The connection reduces the diameter from 16-ft. to 10-ft. The bend is formed from a conical transition and reduces the conduit to 8-ft. approaching the bypass relief valve. The basic differences between the bypass relief branch previously tested and this one are:

(1) a change from 45^0 to 53^0 - 01' - 33" in the internal angle between the centerline of the branch and the header,

(2) a reduction in the conduit diameter from 10-ft. to 8-ft. through a reducing bend instead of a reduction just upstream of the valve,

(3) the axis of the leaf of the open butterfly valve upstream from the bypass relief branch connection is oriented in the plane formed by the centerlines of the header and bypass branch conduits rather than vertical or horizontal.

Scope of the Model Study

The purpose of the model study was to evaluate the hydraulics of flow through the bypass relief branch for various ratios of the discharge through the bypass to the total discharges approaching the branch. The specific objectives are:

(1) measure static and dynamic pressures at the boundaries of the conduits,

(2) calculate the junction loss coefficients for the bypass relief branch connection,

(3) determine the effect of the bypass relief branch connection on velocity distributions approaching the turbines,

(4) determine the effects of the butterfly valve on pressures and velocity distributions immediately downstream from the valve,

(5) determine a minimum dimension "d" for backward projection of the hood covering the bypass valve to prevent backsplash. The dimension "d" is measured from the downstream face of the relief valve and is shown in Figure 1.

Model Criteria

The same criteria applies to this model as for the first model. The Reynolds number $\frac{Vd}{\nu}$ and Euler number $\frac{\Delta p}{\rho V^2}$ are significant. The Reynolds number governs the friction losses and the Euler number governs the form losses.

The geometric scale ratio 1:24 was chosen to construct the model. The modified bypass relief branch connection could then replace the original section of penstock without major modification to the model.

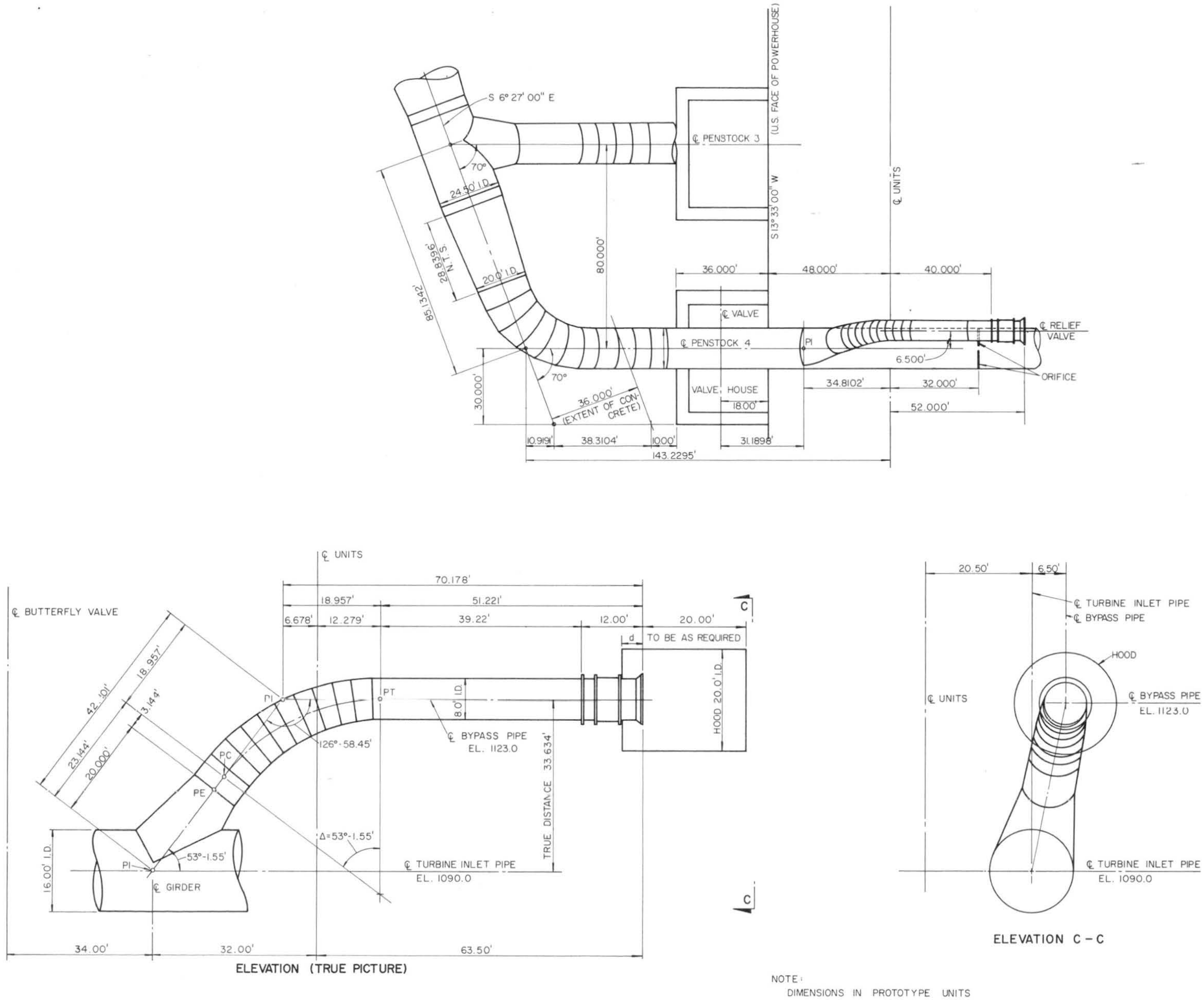


FIG. 1 DETAILS OF BYPASS RELIEF BRANCH

THE MODEL

Model Construction

The bypass relief branch connection, the bypass bend and a segment of branch 4 conduit were fabricated from plexiglass and acrylic resin tubes as shown in Figure 2. This section was designed to be interchangeable with the basic branch connection previously tested.

The locations of the many piezometers used to measure the pressures at the boundary of the bypass relief connection and conduit are shown in Figures 3 and 4. The locations at which velocity traverses were made are also shown in Figure 4. For locations of piezometers in the manifold other than those specificially found in the modified bypass relief branch refer to Figures 12, 13, 14, 15, and 16 in the Penstock Report.

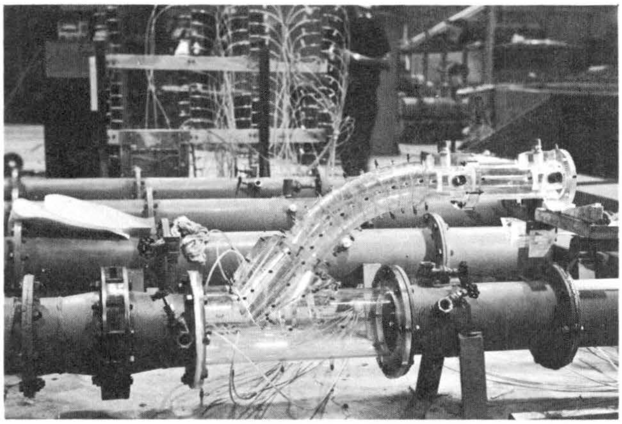


Fig. 2 Photo of completed branch connection

Water was supplied by a 20-in. deep well, turbine pump. A calibrated orifice plate was installed in branch 4 to measure the discharge through the branch. The reducing bend approach to branch 4 was calibrated to measure the total discharge supplied to the branch connection. The discharge measured at the orifice was subtracted from total discharge to determine the discharge passing through the bypass relief branch.

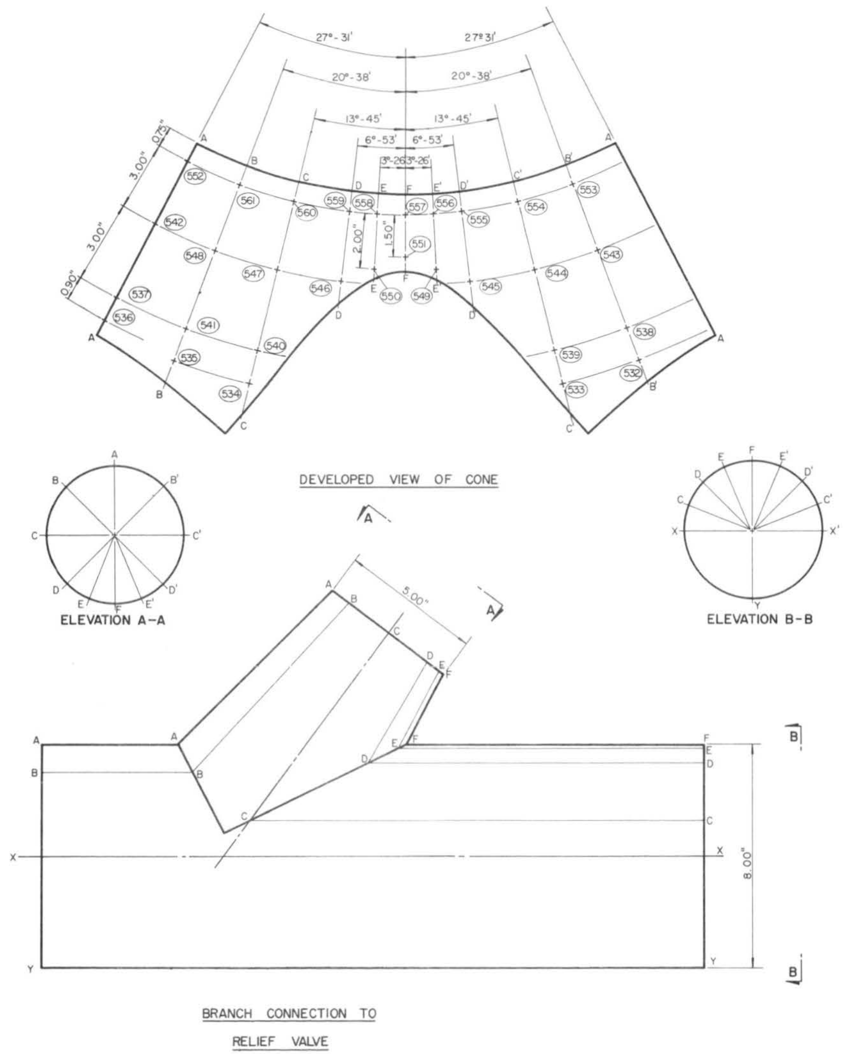
Instrumentation

Piezometric readings - The same electronic instrumentation was used to facilitate the reading of the many piezometers as was described in the Penstock Report. However, in place of piezometer banks, the individual piezometers were attached to the transducer through a valved manifold system.

For recording dynamic pressures a transducer was attached to the piezometer tap with a short tube to reduce the dampening effect of the tubing. The frequency was measured by using an electronic counter for frequencies greater than about 10 cps. For frequencies less than 10 cps the signal was recorded directly on a strip chart recorder with a frequency response up to 10 cps. An oscilloscope was used to observe the wave form and to measure the amplitude of the high frequency pressure signals.

Velocity traverses - The velocity profiles across the conduit were recorded directly on an X-Y plotter. The instrumentation was the same as that described under the heading "Velocity Traverses" in the Penstock Report.

Piezo No.	Elev. in ft.	Piezo No.	Elev. in ft.	Piezo No.	Elev. in ft.	Piezo No.	Elev. in ft.	Piezo No.	Elev. in ft.
501	99.93	516	99.27	530	99.69	545	99.88	560	100.25
502	99.85	517	99.69	531	99.93	546	99.95	561	100.33
503	99.56	518	99.87	532	99.64	547	100.08		
504	99.27	519	99.89	533	99.69	548	100.16		
505	99.69	520	99.92	534	99.82	549	99.95		
506	99.90	521	99.95	535	99.93	550	99.97		
507	99.93	522	99.93	536	99.95	551	99.99		
508	99.56	523	99.87	537	99.99	552	100.35		
509	99.27	524	99.56	538	99.90	553	100.20		
510	99.69	525	99.27	539	99.77	554	100.13		
511	99.90	526	99.69	540	99.86	555	100.04		
512	99.85	527	99.89	541	99.98	556	100.09		
513	99.65	527A	99.93	542	100.17	557	100.09		
514	99.77	528	99.56	543	100.10	558	100.12		
515	99.56	529	99.27	544	100.03	559	100.17		



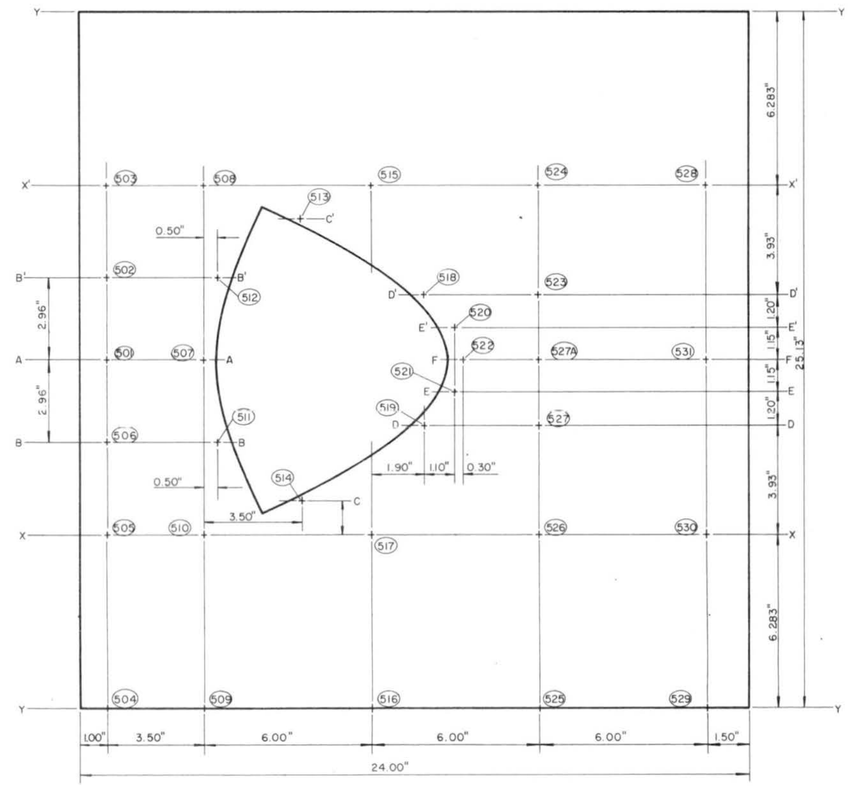
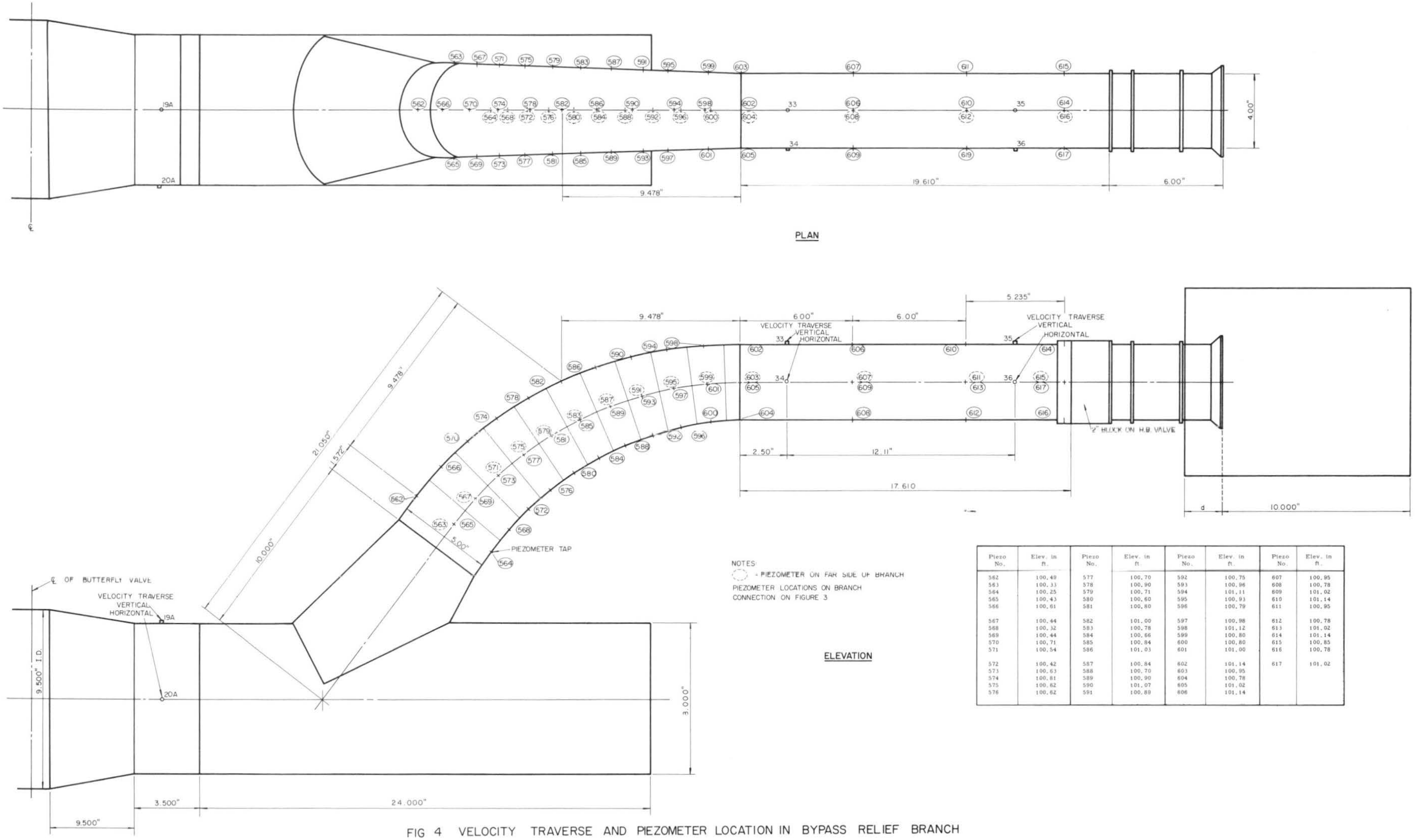


FIG. 3 PIEZOMETER LOCATIONS IN THE BYPASS RELIEF BRANCH CONNECTION



Piezo No.	Elev. in ft.	Piezo No.	Elev. in ft.	Piezo No.	Elev. in ft.	Piezo No.	Elev. in ft.
562	100.49	577	100.70	592	100.75	607	100.95
563	100.33	578	100.90	593	100.96	608	100.78
564	100.25	579	100.71	594	101.11	609	101.02
565	100.43	580	100.60	595	100.93	610	101.14
566	100.61	581	100.80	596	100.79	611	100.95
567	100.44	582	101.00	597	100.98	612	100.78
568	100.32	583	100.78	598	101.12	613	101.02
569	100.44	584	100.66	599	100.80	614	101.14
570	100.71	585	100.84	600	100.80	615	100.85
571	100.54	586	101.03	601	101.00	616	100.78
572	100.42	587	100.84	602	101.14	617	101.02
573	100.63	588	100.70	603	100.95		
574	100.81	589	100.90	604	100.78		
575	100.62	590	101.07	605	101.02		
576	100.62	591	100.89	606	101.14		

FIG 4 VELOCITY TRAVERSE AND PIEZOMETER LOCATION IN BYPASS RELIEF BRANCH

Model Test Program

Tests were performed on the bypass relief branch connection with pressure measurements made and velocity profiles taken at locations downstream from the butterfly valve. The flow approaching the branch connection was divided with approximately 0, 25, 40, 50, 60, 75, and 100% of the flow passing through the bypass. The bypass relief branch was installed only at branch 4.

Pressures and Velocities

Pressure data for the test runs are given in Appendix A-1. Velocity profiles taken at the locations shown in Figure 4 are given in Appendix A-2. The velocity profiles were recorded for all runs. The distributions were uniform in general and entirely satisfactory for all combinations of discharges through the bypass and branch 4.

The primary objectives of recording the velocities was to determine the distributions in the vicinity downstream from the butterfly valve and the approach to the turbines. The velocity profiles recorded at velocity traverse points 19A, 20A, 30 and 32 for test run 1-X are shown in Figure 5 (see Figure 4 for location of 19A and 20A and Figure 12 in the Penstock Report for locations 30 and 32). These depict the flow conditions downstream from the butterfly valve (profiles 19A and 20A) and at the turbines (profiles 30 and 32) for normal operation, i.e., with the bypass valve closed. Profile 20A, which is normal to the axis of the butterfly leaf, shows a small, almost sinusoidal, increase and decrease in the mean velocity near the center of the traverse. This was the only effect noted due to the butterfly valve. Similar conditions had previously been observed and reported in the Penstock Report. This disturbance is quickly damped out and its effects are not observed in the velocity profiles approaching the turbines (profiles 30 and 32). Some fluctuations in the velocity were noted and can be seen in the profiles shown in Figure 5 and those in the Appendix. These fluctuations were determined to be due to the pump (described later in this section) and the disturbance created by the pitot tube itself. The velocity fluctuations are, therefore, not considered to be detrimental or cause for concern.

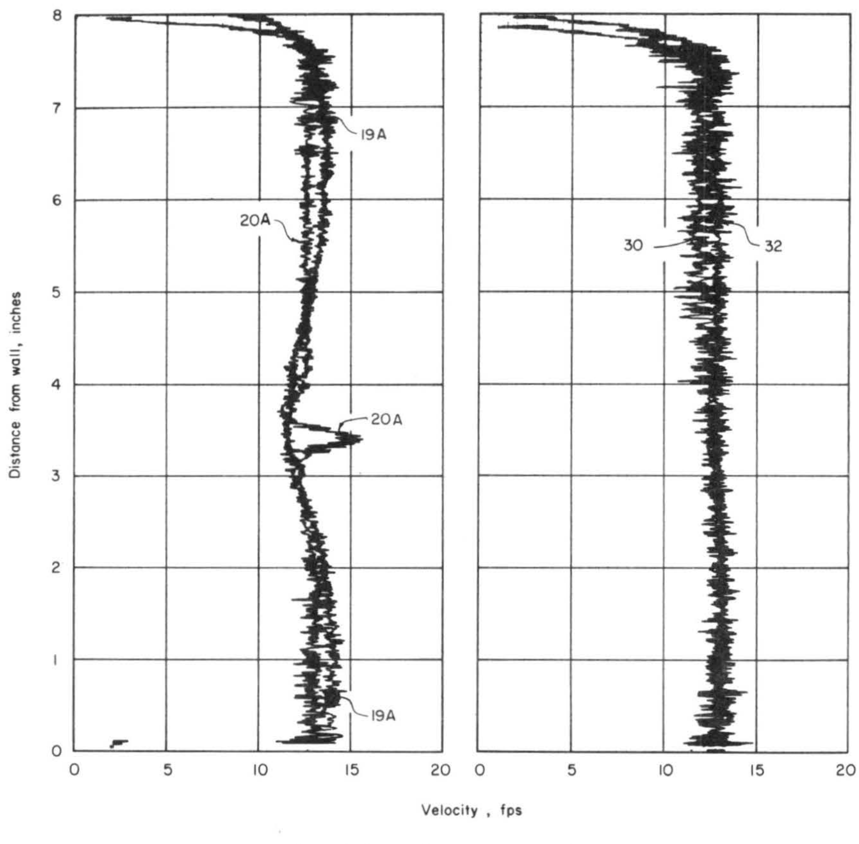


Fig. 5. Velocity profiles in branch 4 for run 1-X

Pressures at the bypass relief branch connection, bend and conduit were satisfactorily positive for all conditions of operation. Some reductions in the mean pressure were noted at piezometers 507, 532, 535 and 536, when 24.6% of the flow was discharging through the bypass. These pressures accompanied the local acceleration of the flow as it entered the bypass. The magnitude of these pressure reductions was not excessive, generally less than 1-ft. (model dimensions) and was not cause for concern.

When all the approaching flow was passing through the bypass, the water trapped in branch 4 downstream from the bypass relief connection formed a liquid boundary and caused a localized low pressure area to develop near the point of the crotch formed by the connection. The local pressure was recorded by piezometers 549, 550 and 551 which had pressures of 13.22, 14.46 and 14.65 ft. of water, respectively. The magnitude of the pressure is satisfactorily positive and not cause for concern but should be considered in the structural design.

A fluctuating component of pressure was superimposed on the static pressures described above. It was assumed that the principal component of the fluctuations was caused by the pump supplying water to the model. Tests were performed to substantiate this assumption. The model was filled with water and with the pump running all valves were closed. Pressure fluctuations were observed for this condition at piezometer taps 14, 197, 542 and 590. The minimum and maximum peak to peak pressure fluctuations observed at all locations ranged between about 0.3 and 2.5 ft. of water, respectively, with the average being about 1.4 ft. of water. The minimum and maximum detectable frequencies were 2.9 and 3.3 cps, respectively.

Different combinations of discharge through the bypass and branch 4 were then tested. Table I gives the peak to peak magnitudes about the mean pressure and the frequencies of the pressure fluctuations observed at the given piezometer locations. The maximum peak to peak fluctuation observed in the bypass relief branch connection was 1.01 ft. of water at piezometer 542. The minimum and maximum detectable frequencies were 2.9 and 3.5 cps, respectively. Random higher frequencies were noted but the magnitude of the signal was too small to be detected and differentiated from extraneous noise signals with the equipment available.

Form Loss Coefficients

Energy losses through the branch connection were found graphically by first plotting the mean piezometric heads and establishing the hydraulic grade line. Hydraulic grade lines for three test runs are shown in Figure 6. Points on the energy grade line were determined by adding the velocity head, calculated using a velocity distribution coefficient (α) equal to unity, to the average piezometric head determined at significant points on the hydraulic grade line.

The energy line in the bypass was established by projecting the line drawn through the points determined in the 4-in. conduit upstream to the P.T. of the reducing bend. From this point a friction slope calculated for the average conduit diameter through the bend was projected upstream to the P.C. of the bend. From the P.C. of the bend upstream to the P.I. of the bypass branch and header a friction slope for a 5-in. conduit was used.

The energy grade line in the header of branch 4 was determined by fitting a line with a friction slope equivalent to the theoretical losses on the section to the experimental points. These energy lines were projected upstream or downstream to the P.I. of the bypass branch and header.

TABLE I

DYNAMIC PRESSURES RECORDED IN BRANCH 4 AND THE BYPASS RELIEF BRANCH

Piezometer Number	Per Cent of Discharge in Branch 4	Per Cent of Discharge in Bypass	Pressure Fluctuation in ft of water			Frequency cps
			Maximum	Minimum	Average	
197	0	100	0.93	0.11	0.51	3.2
	50	50	0.50	0.11	0.25	3.2
	100	0	0.67	0.09	0.40	2.9
542	0	100	1.01	0.20	0.45	3.3
	50	50	0.59	0.20	0.37	3.5
	100	0	0.51	0.15	0.33	3.2
549	50	50	0.47	0.20	0.37	3.1
	100	0	0.78	0.22	0.46	3.2
590	0	100	0.71	0.15	0.37	3.2
	50	50	0.36	0.11	0.25	3.2
	100	0	0.68	0.14	0.40	3.1

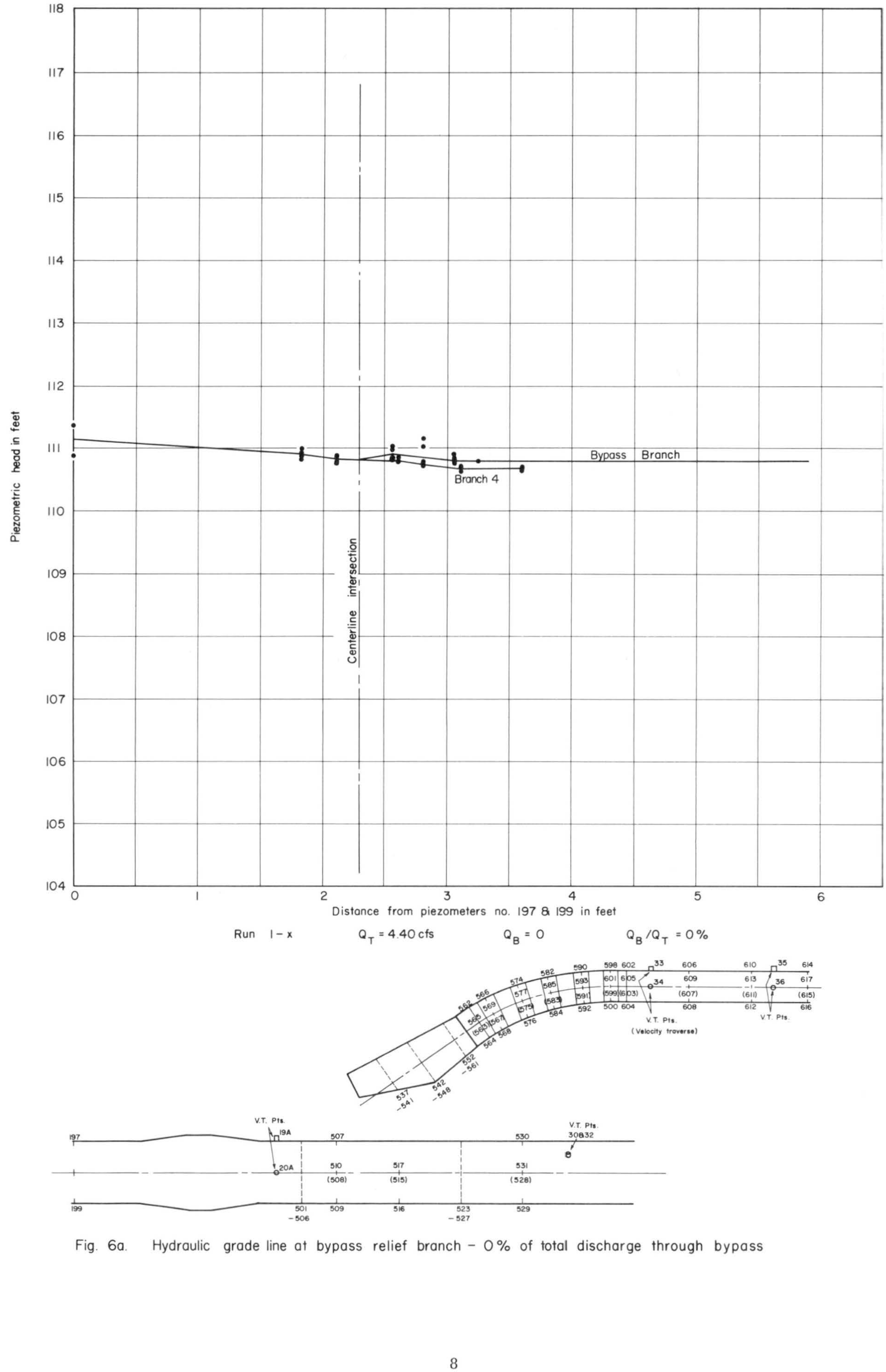


Fig. 6a. Hydraulic grade line at bypass relief branch – 0 % of total discharge through bypass

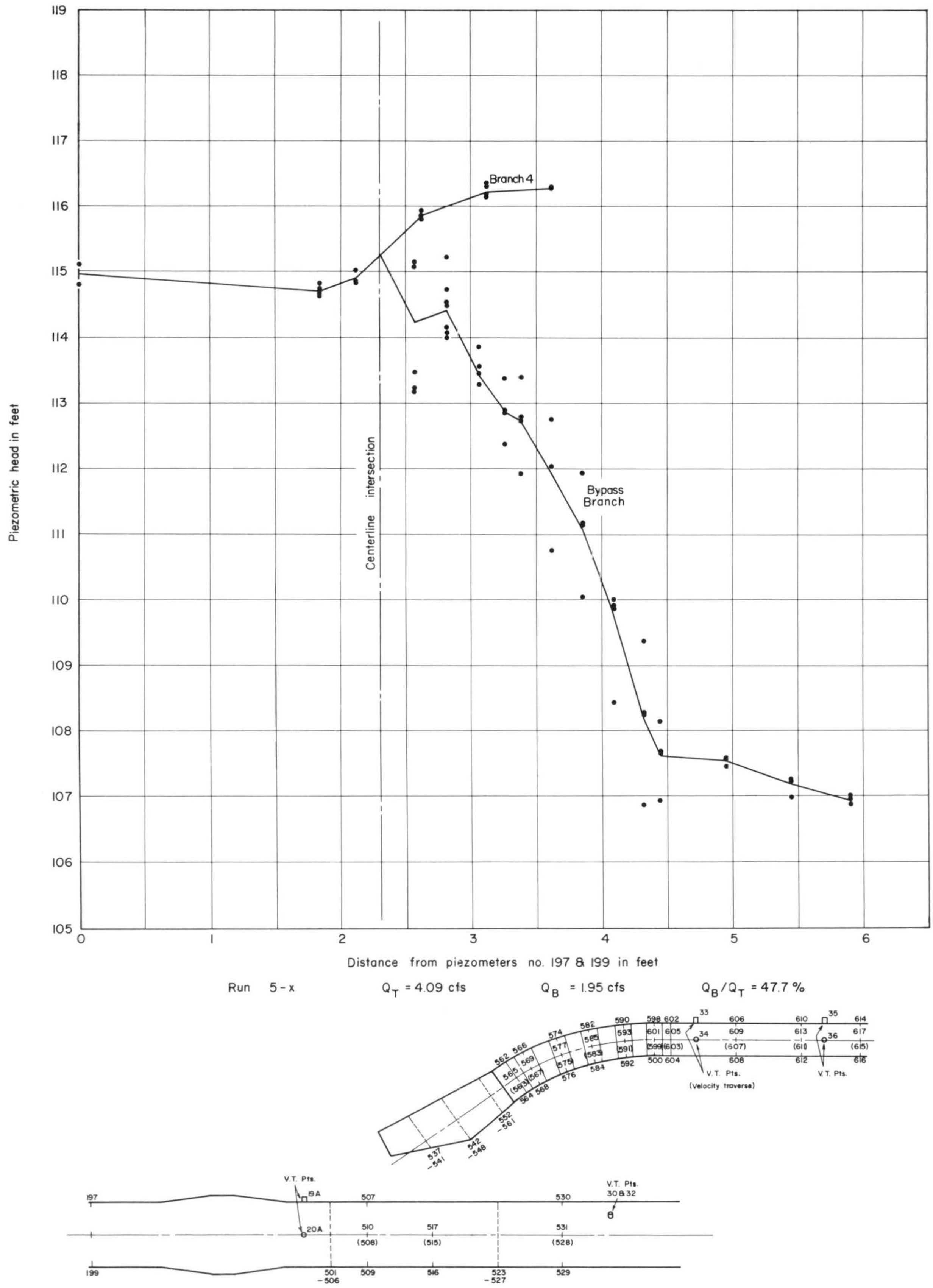


Fig. 6b. Hydraulic grade line at bypass relief branch —47.7% of total discharge through bypass

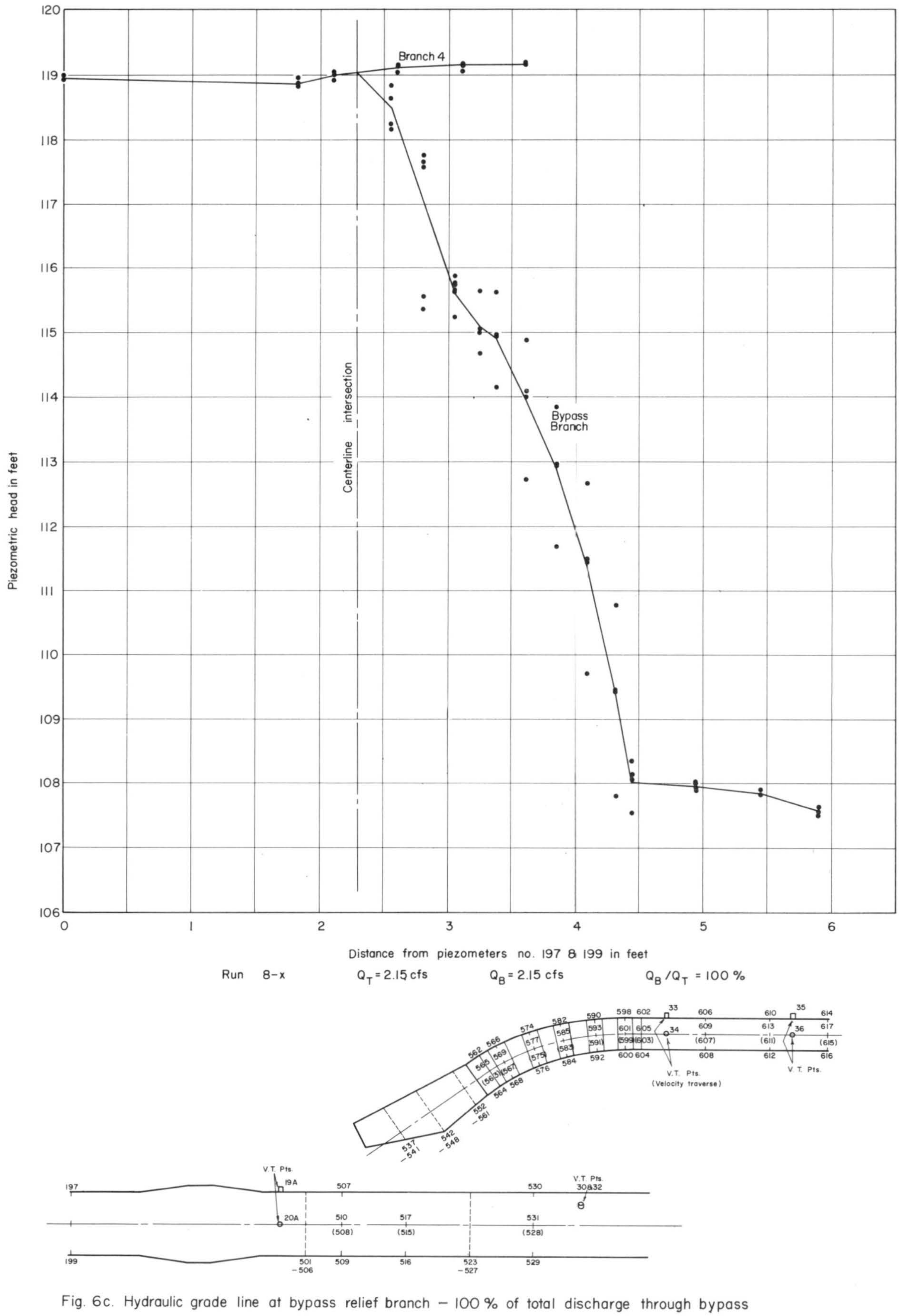


Fig. 6c. Hydraulic grade line at bypass relief branch — 100 % of total discharge through bypass

The various losses were then scaled from the graph and the form loss coefficients were found using the following equations:

$$H_{LB} = K_B \frac{V_d^2}{2g} \quad \text{and} \quad H_{LH} = K_H \frac{V_d^2}{2g}$$

in which

H_{LB} = head loss between sections at P.I. of header and branch and section at P.T. of reducing bend in feet of water,

H_{LH} = head loss between header sections in feet of water,

V_d = velocity at downstream sections in fps,

K_B = bypass loss coefficient,

K_H = header loss coefficient, and

g = gravitational acceleration = 32.2 ft/sec^2.

Loss coefficients are shown for the bypass and branch 4 header in Figures 7 and 8, respectively.

Bypass Relief Valve Hood

A cursory study of the bypass relief valve hood was made. The objective of this study was to determine a distance "d" (see Figure 1) for backward projection of the hood to prevent backsplash from the jet.

The model bypass relief valve differs slightly from a prototype valve of the same type. Since this difference may influence the results of the backsplash tests, the difference is described here. The model valve was built with a larger lip at the base of the conical section of the valve (a photograph of the valve was given in Figure 9 of the Penstock Report). Water discharging from the valve ports could conceivably impact on this lip and tend to be diverted outward at a greater angle. If this phenomenon did occur, the backsplash in the model could be greater than in the prototype and should be regarded in the analysis of these tests.

The hood was positioned with "d" dimensions of 10-ft. and 16-ft. (prototype dimensions). The backsplash with a "d" dimension of 16-ft. is shown in Figure 9. Limitations of the model prevented a backward projection of the hood of more than 16-ft.

In an attempt to provide a possible solution to the backsplash problem, annular triangular shaped fillets of the dimensions shown in Figure 10 were then placed in the model hood. The backsplash from the jet with the fillet having a minimum inside diameter of 16-ft. (prototype dimension) is shown in Figure 11. The backsplash from a jet with the fillet having a minimum inside diameter of 12-ft. is given in Figure 12. The fillets reduced the backsplash but did not completely eliminate it.

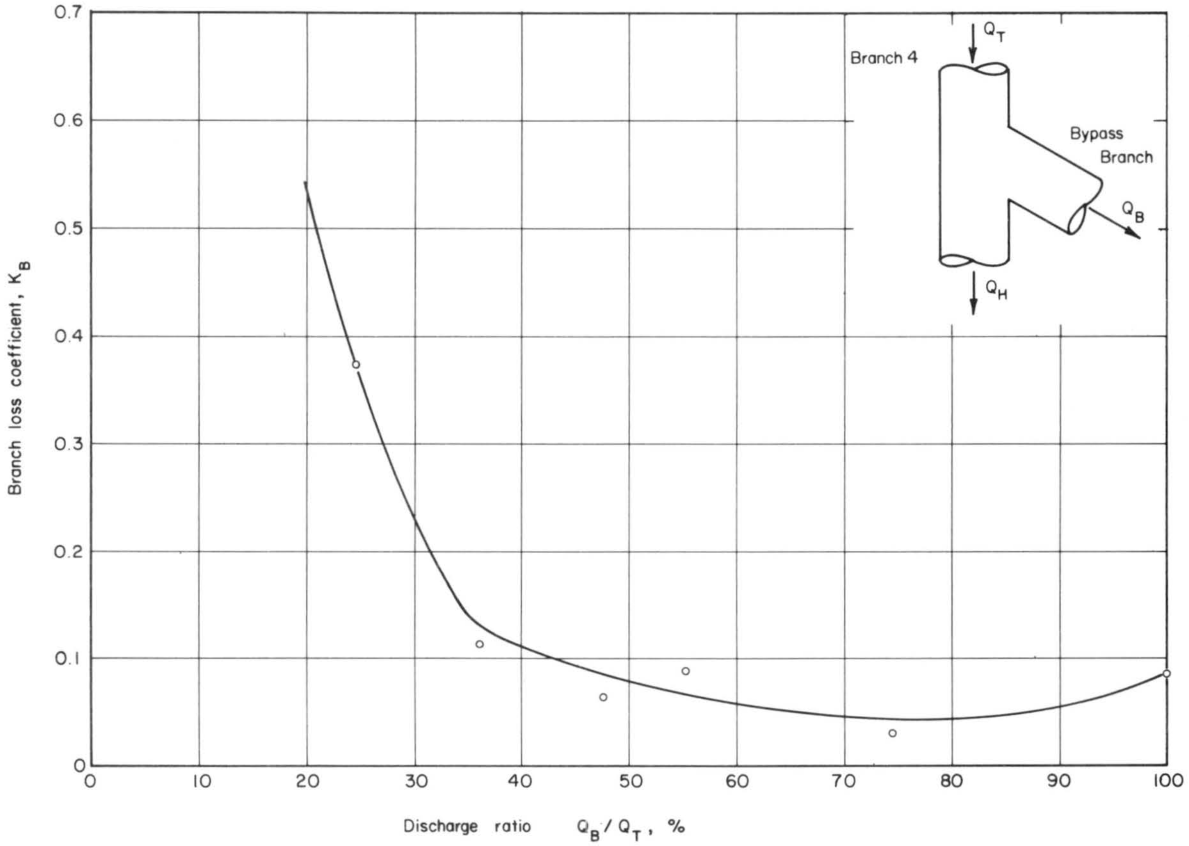


Fig. 7. Bypass relief branch loss coefficients

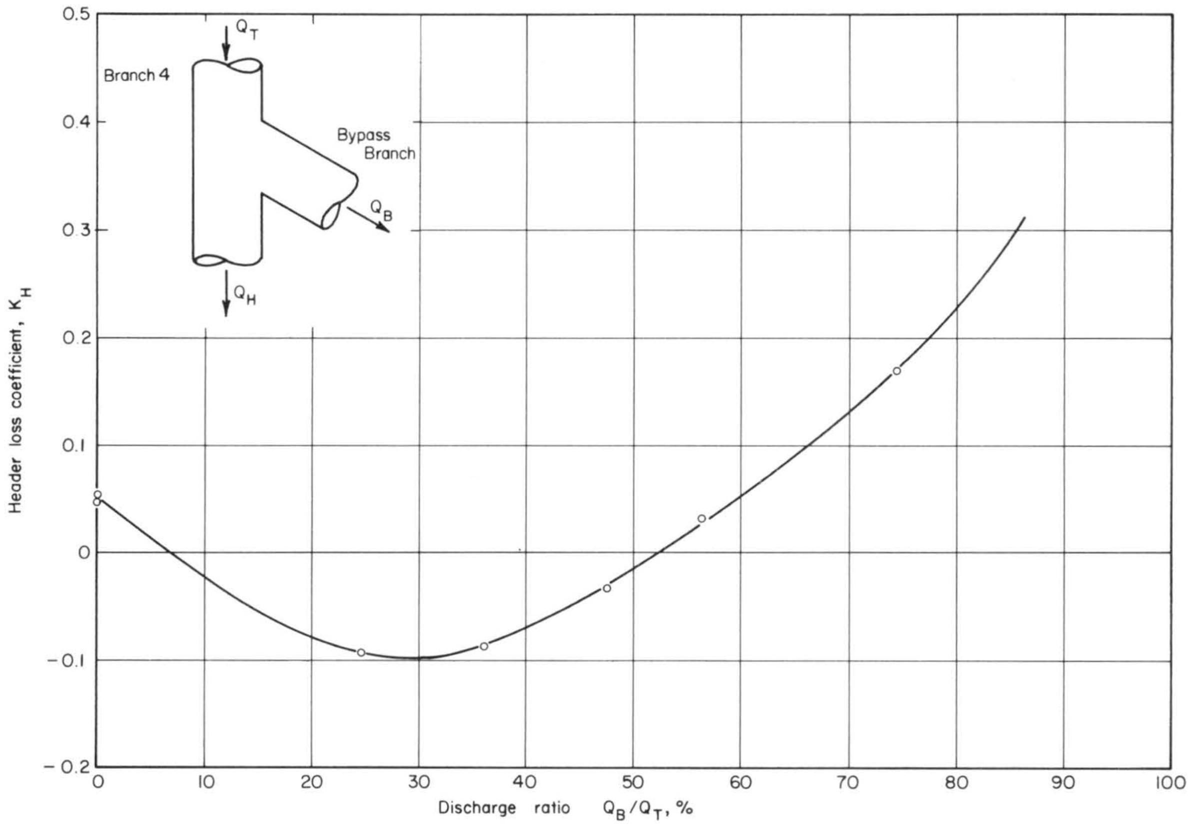


Fig. 8. Branch 4 header loss coefficients

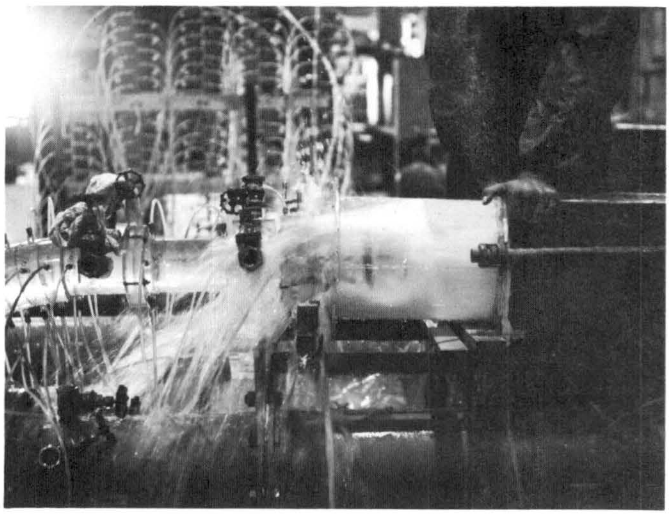


Fig. 9 Backsplash from hood with d = 16-ft.

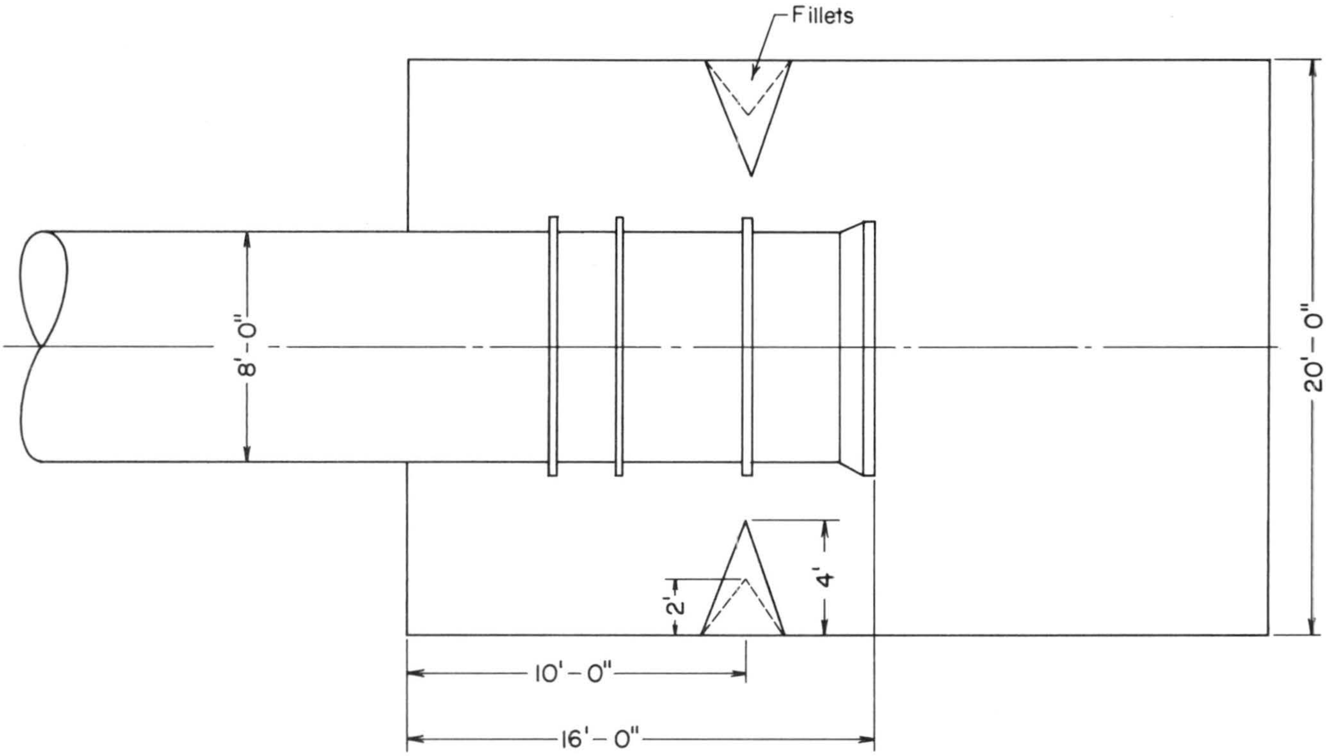


Fig. 10. Location of fillets in bypass relief valve hood.

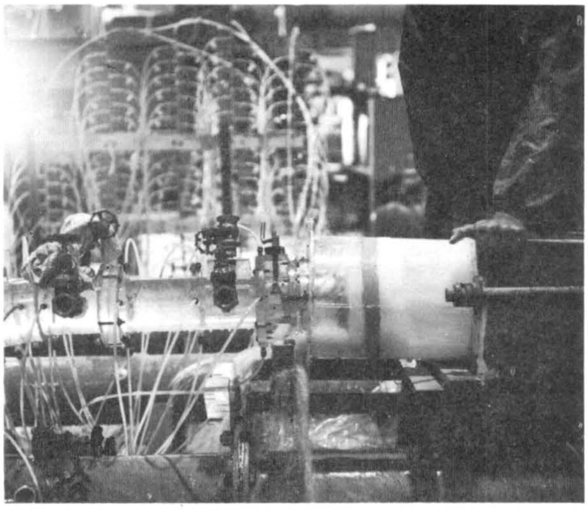


Fig. 11 Photograph of jet backsplash with fillet having a minimum diameter of 16-ft. installed in hood

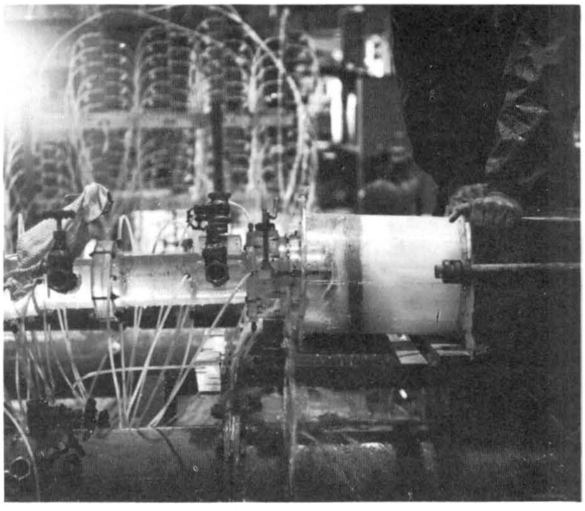


Fig. 12 Photograph of jet backsplash with fillet having a minimum diameter of 12-ft. installed in hood

CONCLUSIONS AND RECOMMENDATIONS

Pressure measurements recorded at the many piezometric taps indicated positive pressures at all locations throughout branch 4 and the bypass relief branch. Some pressure reduction which accompanied an acceleration of the flow was observed at the region where the flow enters the bypass conduit at the crotch of the connection. This reduction was not excessive or cause for concern but should be considered in the structural design. Pressure fluctuation measurements were made and recorded. Fluctuations with average amplitudes and frequencies on the order of 0.5 ft. of water and 3.1 cps, respectively, were found. Pump surges were also checked and indicated the same order of magnitude of amplitudes and frequencies as those found in Table I and, therefore, it was concluded that the fluctuations recorded could be attributed to the pump. No other measurable fluctuations or vibrations were detected in the model.

Velocity traverses made in conjunction with the pressure data indicated no unusual or unexpected profiles. The profile normal to the butterfly valve leaf axis (traverse point 20A) indicated a small local increase and decrease near the center of the profile. This was the only noticeable effect of having the butterfly valve installed and this small perturbation was quickly dissipated. The butterfly valve upstream from the bypass relief branch connection caused no detrimental effects to the flow conditions. Velocity traverses taken at the turbine scroll case inlet showed uniform velocity profiles. The profiles give evidence of satisfactory approach flow conditions and hydraulic operation.

The losses in the model were determined from a graphical analysis of the pressure data. The form loss coefficients for the bypass relief branch connection, including the reducing bend, are given in Figure 7. The form loss coefficients for the branch 4 header are given in Figure 8.

Limitations of the model prevented a determination of the distance "d" required to prevent backsplash from the jet issuing from the bypass relief valve. Sixteen feet was the maximum "d" that could be achieved in the model and considerable backsplash was evident as can be seen in Figure 9. Fillets installed in the hood reduced the backsplash (see Figures 11 and 12) but did not eliminate it completely. Fillets could provide a possible solution to the problem of backsplash, but a definite conclusion could not be drawn from this cursory investigation.

APPENDIX A - 1

PRESSURE HEADS ALONG MANIFOLD WALLS

PRESSURE HEADS ALONG MANIFOLD WALLS

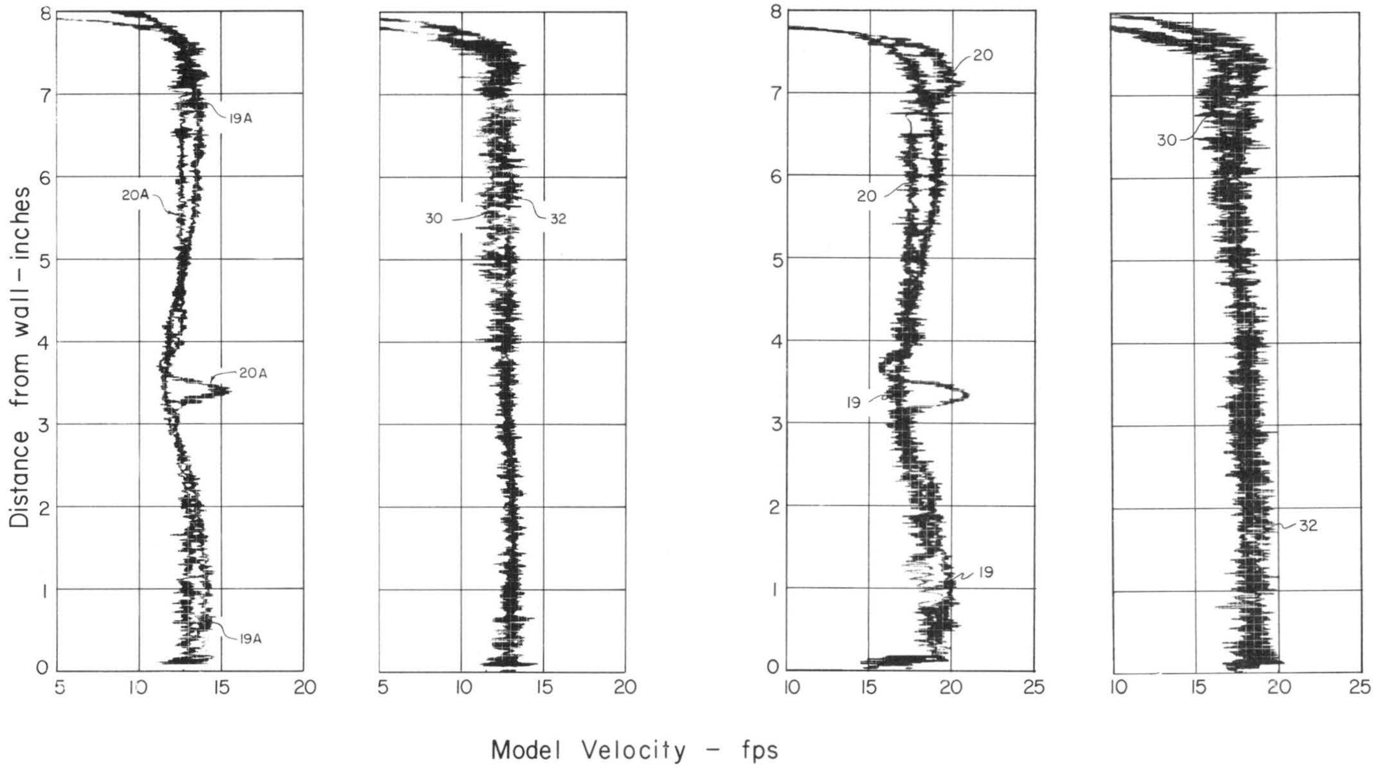
Pressure Heads in Feet of Water

Run #	1-x	2-x	3-x	4-x	5-x	6-x	7-x	8-x
Q Br. 4	4.40 cfs	5.65 cfs	5.20 cfs	3.54 cfs	2.14 cfs	1.58 cfs	0.70 cfs	0 cfs
Q Bypass	0 cfs	0 cfs	1.70 cfs	2.01 cfs	1.95 cfs	2.04 cfs	2.05 cfs	2.15 cfs
Temp.	70°F	70°F	71°F	70°F	70°F	70°F	70°F	71°F
Piezo. No.	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head
14	13.40	17.15	26.35	21.05	17.05	18.35	17.75	19.35
16	13.40	17.15	26.35	21.05	17.05	18.35	17.75	19.35
26	13.40	17.11	26.35	21.04	17.00	18.31	17.73	19.35
30	13.34	17.09	26.35	21.05	17.04	18.30	17.74	19.35
46	13.30	17.01	26.35	21.05	17.00	18.33	17.75	19.33
65	13.31	17.11	26.34	21.05	17.03	18.17	17.73	19.34
77	13.24	16.95	26.06	20.89	16.80	18.24	17.67	19.31
81	13.21	16.87	26.21	20.90	16.95	18.22	17.69	19.31
106	13.25	16.95	26.07	20.91	16.93	18.34	17.68	19.32
111	13.27	16.94	26.20	20.90	16.94	18.27	17.70	19.35
122	12.98	16.46	25.17	20.50	16.69	18.05	17.57	19.24
126	12.95	16.41	25.41	20.45	16.68	18.05	17.59	19.25
151	13.18	16.34	25.52	20.44	16.69	18.13	17.57	19.25
155	13.03	16.48	25.37	20.43	16.67	18.15	17.57	19.25
165	12.18	15.08	23.80	19.20	15.77	17.37	16.92	18.67
167	12.78	15.78	24.24	20.92	16.56	18.12	17.72	19.55
177	11.75	14.23	22.26	18.55	15.53	17.16	16.85	18.78
179	12.36	14.81	23.13	19.07	16.09	17.79	17.51	19.44
189	10.92	12.52	19.83	17.04	14.74	16.63	16.69	18.80
191	12.93	13.75	20.96	18.18	15.64	17.57	17.44	18.50
197	10.96	12.42	19.58	16.95	14.88	16.72	16.82	18.99
199	12.12	13.94	21.58	18.18	15.85	17.68	17.54	19.74
501	11.06	12.51	19.39	16.85	14.72	16.58	16.70	18.90
502	11.08	12.55	19.59	16.85	14.85	16.66	16.79	18.99
503	11.27	12.64	19.84	17.17	15.14	17.04	17.13	19.32
504	11.61	12.89	20.26	17.60	15.55	17.42	17.50	19.68
505	11.19	12.48	19.54	17.09	15.05	16.98	17.02	19.19
506	11.02	12.31	19.42	16.80	14.73	16.67	16.74	18.92
507	10.96	12.47	18.57	16.03	13.94	15.85	16.04	18.30
508	11.32	12.70	20.00	17.34	15.28	17.21	17.19	19.36
509	11.53	12.91	20.57	17.95	15.76	17.63	17.65	19.79
510	11.09	12.34	19.89	17.23	15.17	17.12	17.13	19.32
511	10.96	12.29	18.49	15.89	13.99	15.84	16.08	18.94
512	10.96	12.41	18.51	15.99	14.01	16.00	16.09	18.85
513	11.07	12.69	20.79	18.08	15.72	17.58	17.38	19.38
514	11.03	12.47	20.59	17.98	15.62	17.52	17.28	19.27
515	11.24	12.61	21.76	18.98	16.37	18.02	17.76	19.56
516	11.51	12.83	22.06	19.11	16.53	18.27	18.04	19.88
517	11.11	12.49	21.70	18.80	16.17	17.81	17.55	19.37
518	10.57	11.71	22.96	19.72	16.51	17.97	17.33	19.15
519	10.62	11.70	23.17	19.66	16.38	17.81	17.21	19.01
520	10.51	11.52	23.61	20.39	17.07	18.52	17.98	19.24
521	10.54	11.77	23.68	20.33	16.99	18.47	17.81	19.11
522	10.53	11.58	24.06	20.46	17.06	18.50	17.98	19.21
523	10.82	11.92	22.41	19.55	16.48	18.17	17.67	19.29
524	11.12	12.49	22.58	19.58	16.63	18.21	17.89	19.62
525	11.35	12.58	22.82	19.76	16.85	18.40	18.09	19.79
526	11.01	12.15	22.52	19.39	16.50	18.02	17.71	19.48
527	10.72	11.52	22.25	19.37	16.41	17.95	17.53	19.32
527a	10.73	11.94	22.52	19.44	16.47	17.98	17.58	19.29
528	11.13	12.29	22.52	19.61	16.71	18.32	17.90	19.64
529	11.40	12.77	23.08	19.96	17.00	18.66	18.22	19.90
530	10.97	12.35	22.46	19.47	16.58	18.21	17.85	19.49
531	10.78	11.88	22.16	19.24	16.37	17.99	17.55	19.24
532	11.26	12.54	18.10	15.37	13.26	14.92	15.57	18.88
533	11.38	12.95	20.52	17.93	15.52	17.32	17.23	19.24
534	11.20	12.76	20.58	17.77	15.43	17.23	17.01	19.12
535	10.87	12.17	17.66	15.05	12.97	14.68	15.21	18.52
536	10.92	12.28	17.89	15.78	13.38	15.13	15.31	18.32
537	10.90	12.18	17.70	15.17	13.18	14.91	15.14	18.26
538	10.92	12.32	18.16	15.23	13.57	15.70	16.00	18.73
539	11.20	12.74	20.42	17.72	15.32	17.02	16.89	19.06
540	11.17	12.70	20.32	17.57	15.28	17.06	16.78	18.78
541	10.86	12.29	17.59	15.16	13.25	15.33	15.93	18.18
542	10.58	12.00	17.43	15.19	13.83	15.76	15.78	17.59
543	10.63	12.04	17.50	15.27	14.04	15.79	15.68	17.48
544	10.74	12.15	18.71	16.72	13.49	16.06	15.88	17.62
545	11.13	12.79	21.25	18.01	14.89	16.10	15.45	15.50
546	11.20	12.66	22.47	18.77	15.27	16.14	14.94	15.61
547	10.71	12.08	18.44	16.54	14.40	16.01	15.76	17.50

Run #	1-x	2-x	3-x	4-x	5-x	6-x	7-x	8-x
Q Br. 4	4.40 cfs	5.65 cfs	5.20 cfs	3.54 cfs	2.14 cfs	1.58 cfs	0.70 cfs	0 cfs
Q Bypass	0 cfs	0 cfs	1.70 cfs	2.01 cfs	1.95 cfs	2.04 cfs	2.05 cfs	2.15 cfs
Temp.	70°F	70°F	71°F	70°F	70°F	70°F	70°F	71°F
Piezo. No.	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head
548	10.58	11.84	17.55	15.08	13.90	15.70	12.67	17.40
549	11.02	12.64	21.46	17.21	13.68	14.48	13.01	13.22
550	11.27	12.70	22.62	18.27	14.79	15.60	13.63	14.46
551	11.02	12.93	21.56	17.53	13.40	14.43	13.78	14.65
552	10.41	11.69	18.90	16.50	13.50	14.89	14.28	15.54
553	10.57	11.83	18.94	16.17	13.25	14.49	14.16	15.58
554	10.65	12.00	18.32	15.70	13.12	14.48	14.13	15.48
555	10.75	12.08	18.75	15.87	13.26	14.59	14.22	15.57
556	10.71	12.17	18.60	15.87	13.21	14.53	14.21	15.57
557	10.82	12.21	18.75	15.93	13.33	14.71	14.17	15.13
558	10.72	11.96	18.78	15.78	13.14	14.45	14.19	15.11
559	10.64	11.99	18.36	16.72	13.08	14.43	14.16	15.60
560	10.50	11.90	18.45	15.81	13.05	14.37	14.12	15.49
561	10.47	11.81	18.32	16.09	13.23	14.51	14.06	15.30
562	10.31	11.65	19.24	15.98	12.88	14.20	13.78	15.16
563	10.45	11.81	19.27	15.56	12.55	13.70	13.41	14.67
564	10.55	11.89	18.50	15.02	12.11	13.38	13.10	14.43
565	10.37	11.71	18.95	15.48	12.40	13.58	13.29	14.62
566	10.19	11.53	19.53	15.84	12.79	13.94	13.65	15.00
567	10.36	11.70	19.55	15.43	12.28	13.50	13.22	14.53
568	10.48	11.82	18.47	14.68	11.61	12.81	12.52	13.84
569	10.36	11.70	19.55	15.54	12.35	13.58	13.24	14.52
570	10.09	11.43	19.39	15.46	12.34	13.63	13.28	14.63
571	10.26	11.60	19.26	15.02	11.87	13.07	12.73	13.97
572	10.38	11.72	18.28	14.01	11.01	12.15	11.81	13.09
573	10.17	11.51	19.07	13.80	11.59	12.84	12.48	13.64
574	9.99	11.33	19.53	15.10	11.94	13.15	12.85	14.08
575	10.18	11.52	19.08	14.60	11.40	12.53	12.23	13.38
576	10.28	11.62	- -	13.37	10.22	11.20	11.01	12.19
577	10.10	11.44	18.84	14.56	11.33	12.48	12.17	13.39
578	9.90	11.24	18.94	14.65	11.50	12.64	12.27	13.42
579	10.09	11.43	18.93	14.18	10.99	12.04	11.68	12.82
580	10.20	11.54	17.66	13.05	9.93	10.82	10.52	11.58
581	10.00	11.34	18.28	13.91	10.71	11.70	11.50	12.62
582	9.80	11.14	19.01	14.12	10.91	11.99	11.70	12.85
583	10.01	11.35	18.44	13.53	10.34	11.41	11.06	12.16
584	10.14	11.48	17.62	12.63	9.37	10.12	9.95	11.02
585	9.96	11.30	18.46	13.49	10.32	11.28	11.01	12.10
586	9.77	11.11	18.60	13.72	10.51	11.53	11.22	12.30
587	9.96	11.30	18.01	12.97	9.73	10.71	10.38	11.43
588	10.10	11.44	16.95	11.73	8.51	9.29	9.04	9.99
589	9.90	11.24	18.06	12.90	9.53	10.56	10.40	11.37
590	9.73	11.07	- -	13.04	8.94	10.81	10.56	11.60
591	9.91	11.25	17.17	12.31	9.01	9.91	9.69	10.54
592	10.05	11.39	- -	10.87	7.66	8.30	8.07	8.95
593	9.84	11.18	17.11	12.13	8.90	9.77	9.52	10.52
594	9.69	11.03	17.32	12.16	8.92	9.71	9.47	10.35
595	9.87	11.21	16.96	11.49	8.24	8.99	8.73	9.72
596	10.01	11.35	15.97	- -	7.05	7.52	7.38	8.11
597	9.82	11.16	16.73	11.35	8.10	8.85	8.55	9.58
598	9.68	11.02	16.95	11.59	8.24	9.02	8.75	8.65
599	9.90	11.24	16.04	10.65	7.36	7.90	7.78	8.53
600	10.00	11.34	15.45	- -	6.06	6.35	7.24	7.00
601	9.80	11.14	16.07	10.48	7.24	7.65	7.60	8.44
602	9.66	11.00	15.74	- -	7.01	7.46	7.24	7.22
603	9.85	11.19	15.60	9.75	6.69	6.90	6.83	7.10
604	10.02	11.36	15.04	9.11	6.14	6.35	6.19	6.76
605	9.78	11.12	15.61	9.65	6.65	6.92	6.82	7.12
606	9.66	11.00	15.24	9.36	6.42	6.79	6.36	6.74
607	9.85	11.19	15.64	9.78	6.63	6.97	6.83	7.05
608	10.02	11.36	15.72	9.73	6.76	6.94	6.81	7.15
609	9.78	11.12	15.30	9.40	6.42	6.71	6.71	6.99
610	9.66	11.00	15.11	9.14	6.07	6.52	6.31	6.71
611	9.85	11.19	15.17	9.07	6.03	6.41	6.36	6.05
612	10.02	11.36	15.58	9.55	6.44	6.86	6.67	7.12
613	9.78	11.12	15.24	9.13	6.22	6.46	6.39	6.81
614	9.66	11.00	14.52	8.60	5.81	5.86	5.84	6.36
615	9.85	11.19	14.79	8.90	5.91	6.12	6.05	6.68
616	10.02	11.36	14.12	9.20	6.22	6.53	6.34	6.86
617	9.76	11.12	18.87	8.71	5.84	5.96	5.82	6.54

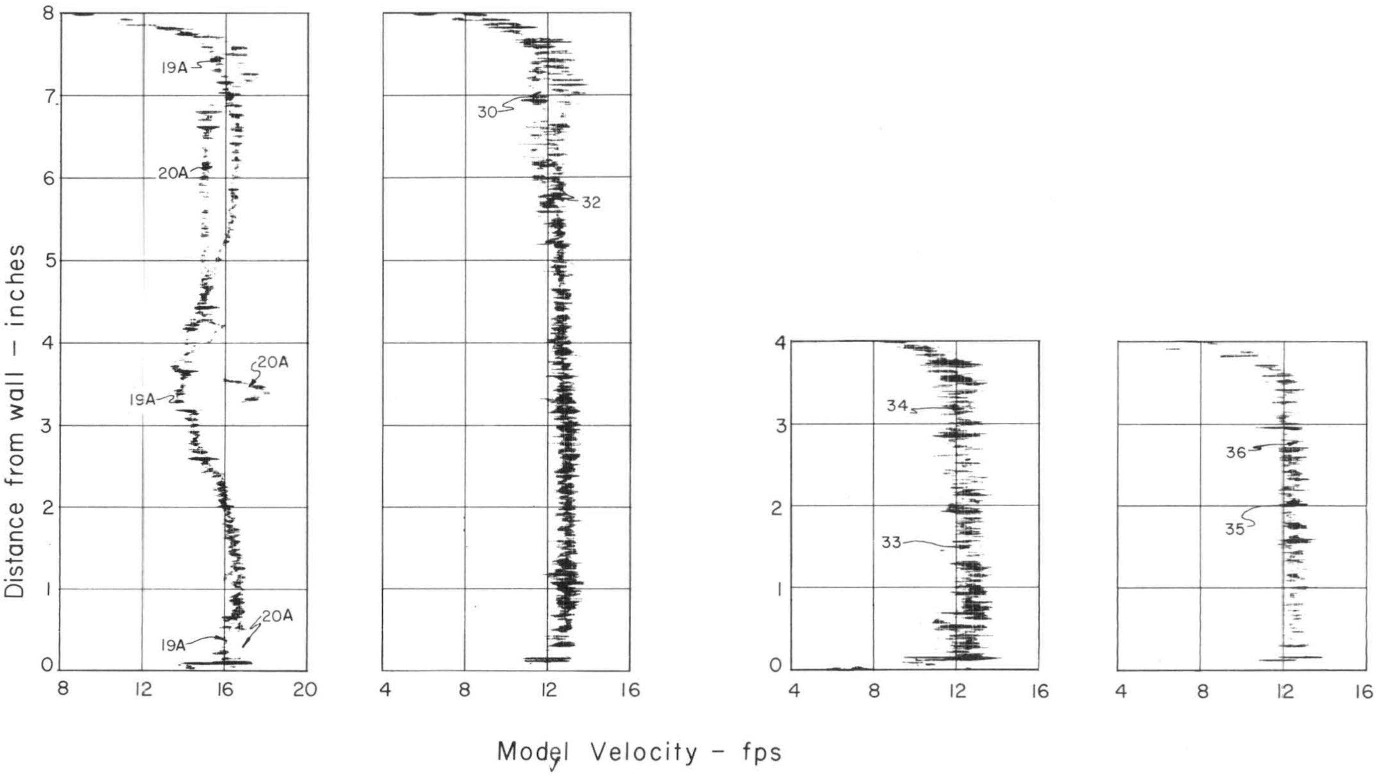
APPENDIX A - 2

VELOCITY DISTRIBUTIONS WITHIN MANIFOLD

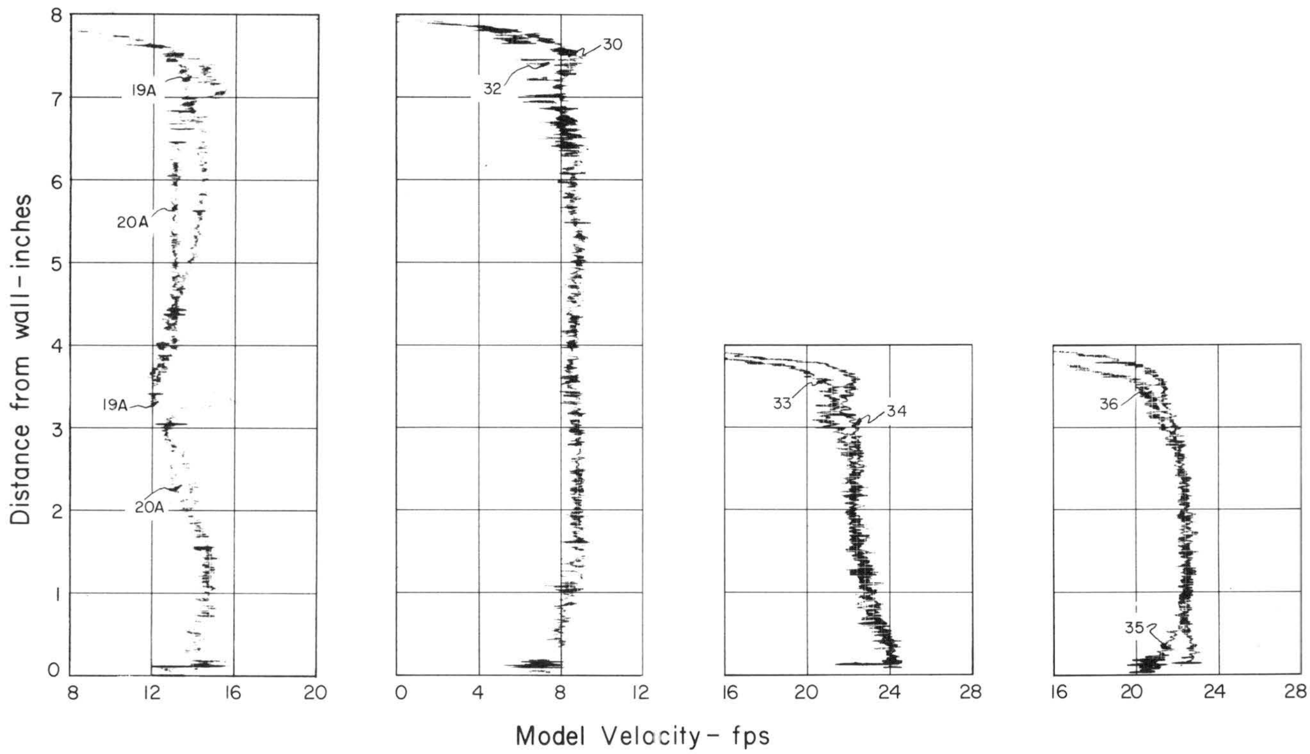


Run 1-x $Q_T = 4.40$ cfs $Q_B = 0$ $Q_B/Q_T = 0\%$

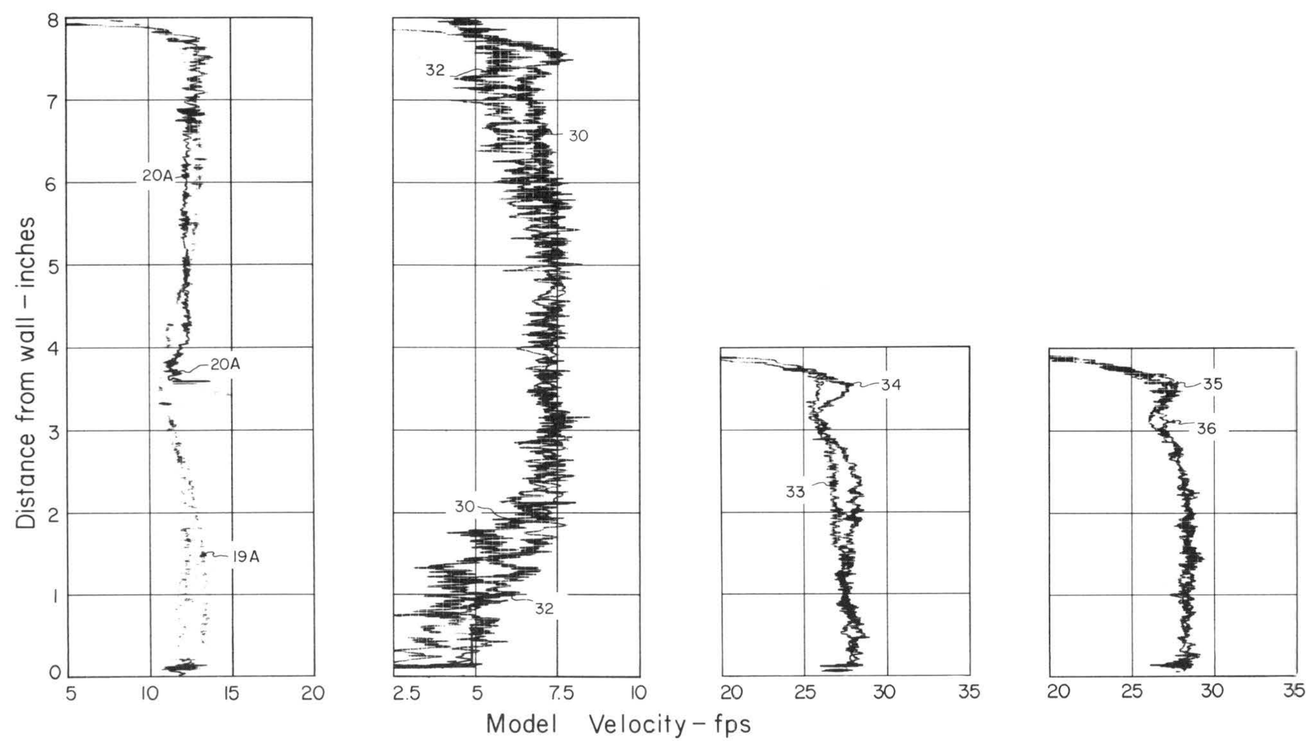
Run 2-x $Q_T = 5.65$ cfs $Q_B = 0$ $Q_B/Q_T = 0\%$



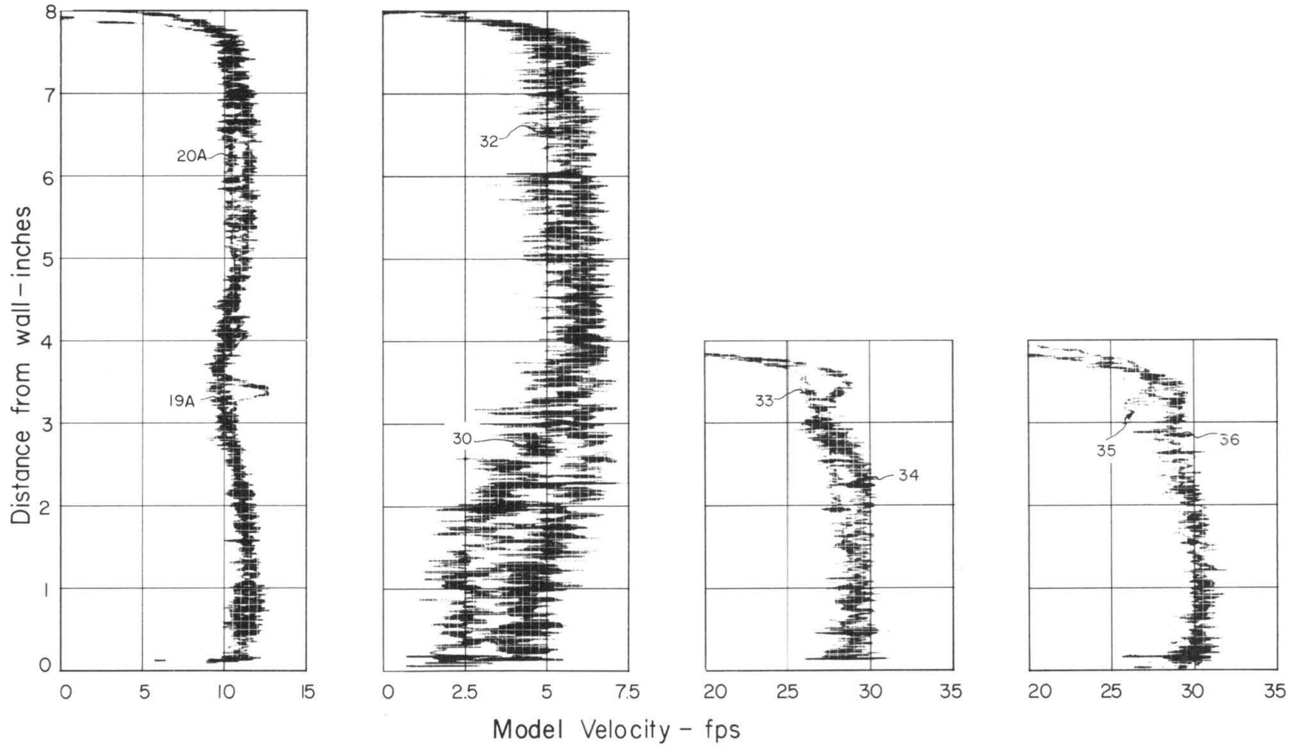
Run 3-x $Q_T = 6.90$ cfs $Q_B = 1.70$ cfs $Q_B/Q_T = 24.6\%$



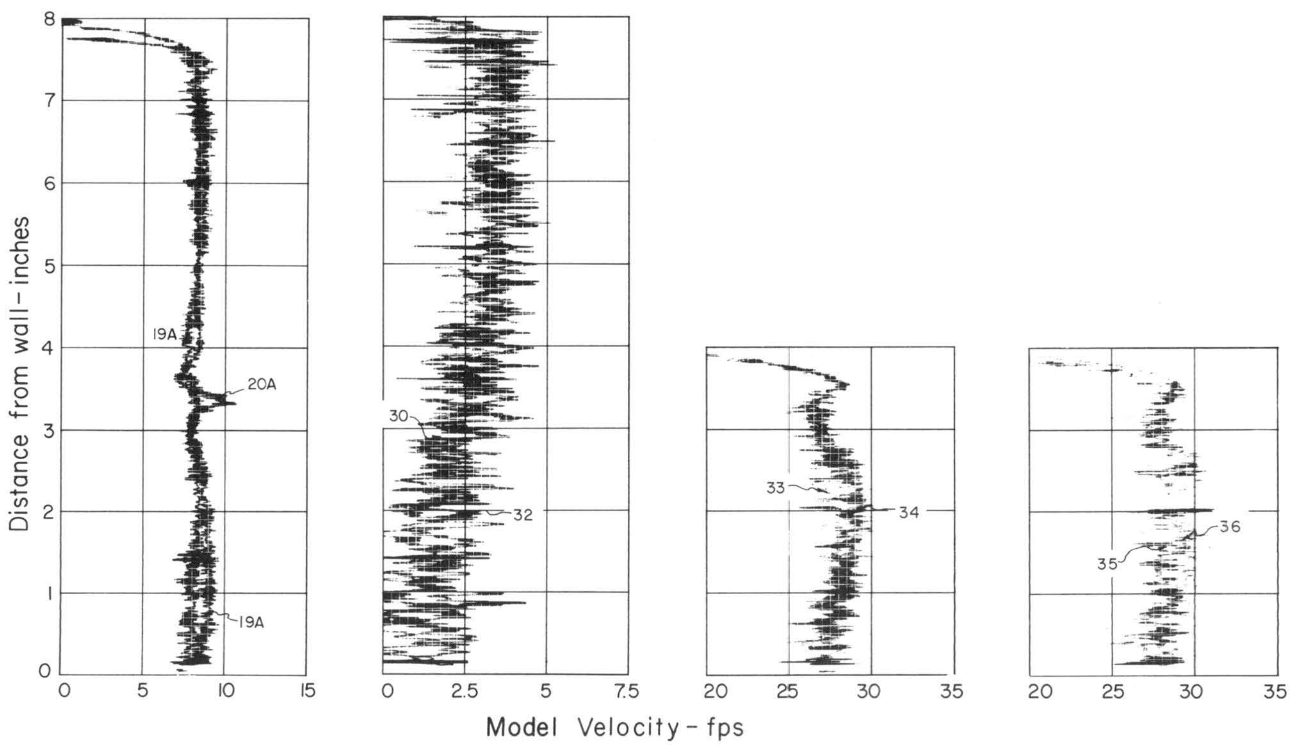
Run 4 – x Q_T = 5.55 cfs Q_B = 2.01 cfs Q_B/Q_T = 36.2 %



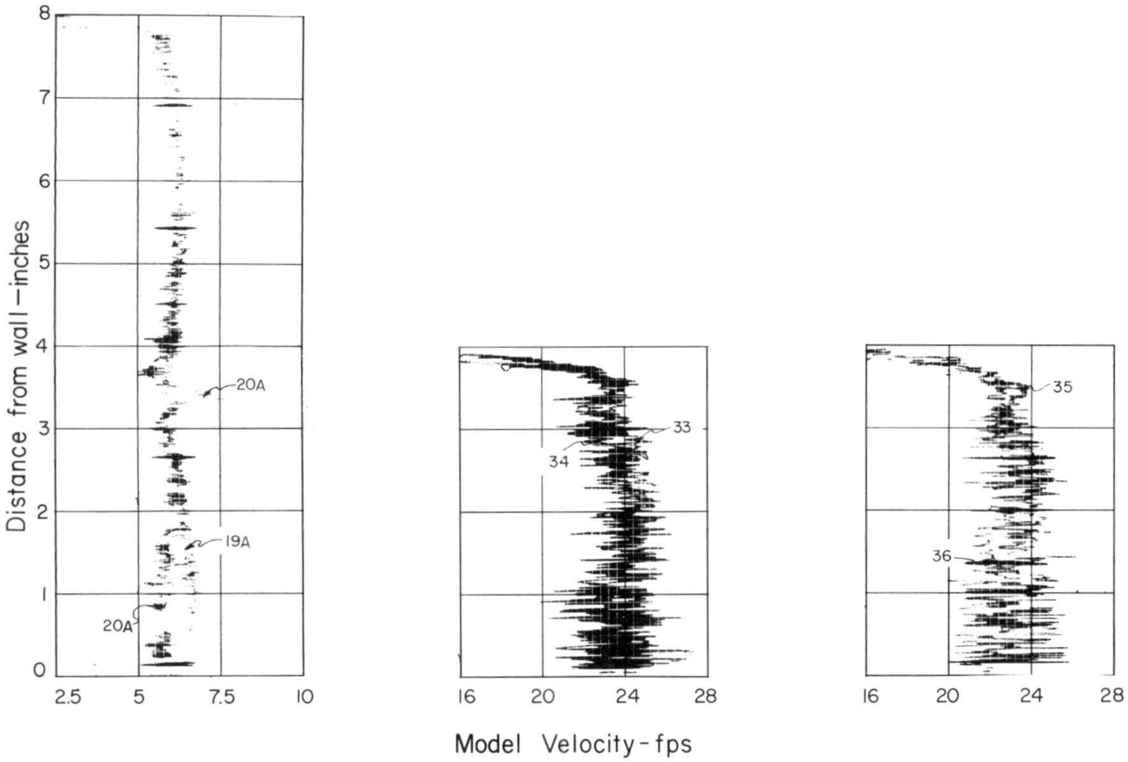
Run 5 – x Q_T = 4.09 cfs Q_B = 1.95 cfs Q_B/Q_T = 47.7 %



Run 6-x Q_T = 3.62 cfs Q_B=2.04 cfs Q_B/Q_T= 56.4%



Run 7-x Q_T =2.75 cfs Q_B =2.05 Q_B/Q_T= 74.5%



Run 8-x Q_T = 2.15 cfs Q_B = 2.15 cfs Q_B/Q_T = 100%