University of Minnesota
St. Anthony Falls Hydraulic Laboratory

Project Report No. 178

COOLING WATER INTAKE MANIFOLD (HEADER) STUDY FOR THE JAMES H. CAMPBELL ELECTRIC POWER GENERATING PLANT, UNIT NO. 3

by

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ABSTRACT

A seven-junction cooling water intake manifold was studied in a physical model and by hydraulic analysis. The manifold, also referred to as a "header", is one of four to be embedded in the bottom of Lake Michigan approximately 3500 ft offshore from the James H. Campbell Plant. Each header supports and collects water from seven dual screen intake risers (subject of a separate study). The primary objective of the study was to determine flow contribution from each of seven risers and piezometric pressures along the header. It was found that the flow rates ranged from 92 percent to 112 percent of the average flow per riser. To achieve a higher degree of uniformity, an analysis was made to determine how much additional headloss had to be generated in each intake riser in order to produce identical withdrawal rates in all seven risers. A similar study was made for a partially balanced system where withdrawal rates would not fall outside the 95 to 105 percent limits. In that case, headloss generators were required in the two most downstream risers. Sharp edged nozzles were designed for Risers 6 and 7, and experimentally tested. The total piezometric pressure change through the partially balanced riser-manifold system at a total withdrawal rate of 206 cfs was determined to be 13.8 inches of water relative to the lake. The total energy headloss between the lake and the downstream end of the manifold was determined to be 10.7 inches of water.

Listing of Studies
for the James H. Campbell
Unit No. 3 Cooling Water Intake

1. H. Stefan and A. Fu, "Headloss Characteristics of Six Profile-Wire Screen Panels," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota, Project Report No. 175, September 1978, 71 pages.
2. H. Stefan and A. Fu, "Collector Well Study for the Cooling Water Intake System of the James H. Campbell Electric Power Generating Plant, Unit No. 3," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota, Project Report No. 176, November 1978, 46 pages.
3. H. Stefan, W. Q. Dahlin, J. F. Ripken, A. Wood. and T. Winterstein, "Experimental Flow Studies with the Dual-Screen Cooling Water Intake Assembly ("Riser") for the James H. Campbell Electric Power Generating Plant, Unit No. 3," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Project Report No. 177, December 1978, 130 pages.
4. H. Stefan, C. Shanmugham, and S. Dhamotharan, "Cooling Water Manifold Intake (Header) Study for the James H. Campbell Electric Power Generating Plant, Unit No. 3," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota, Project Report No. 178, January 1979, 59 pages.
5. John M. Killen and H. Stefan, "Hydraulic Analysis of Alternative Cooling Water Intake Designs for the James H. Campbell Electric Power Generating Plant, Unit No. 3," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota, External Memorandum No. 161, December 1978, 22 pages.

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I. INTRODUCTION AND OBJECTIVE

The Cooling Water Intake System of the James H. Campbell Power Generating Plant, Unit No. 3 owned by Consumer Power Company, Jackson, Michigan and designed in cooperation between Commonwealth Associates, Inc., Jackson, Michigan and Johnson Division UOP Inc., St. Paul, Minnesota will be located in Lake Michigan, about 3500 ft offshore and in about 35 ft of water.

Several elements of the Campbell Unit No. 3 cooling water intake have been studied analytically and experimentally by the authors at the St. Anthony Falls Hydraulic Laboratory in order to provide guidance in the design and to produce anticipated performance data. The Campbell Unit No. 3 intake differs considerably from other intake structures in the Great Lakes. It is designed for a maximum intake velocity of 0.5 ft/sec thru a screen opening. It uses 56 individual, cylindrical screen elements of 4.5 ft diameter, 4.0 ft length and of 3/8 in. screen opening.

The initial conceptual design of the Campbell Unit No. 3 intake is shown in Fig. I-1. An 18.0 ft diameter intake pipe leads to shore. The lake water enters through 56 screens which are mounted with a horizontal axis on 28 risers. Seven risers are connected to each of four individual headers. The headers are of 8.0 ft diameter and arranged in the shape of a cross.1) After passing through the screen, the water flows horizontally in a short T assembly, down a vertical pipe and horizontally through a header into the well and from there into the intake pipe leading to the plant. The headers are buried in the lake bottom. Only the upper portions of the 28 risers supporting the screens emerge from the lake bottom.

Separate studies have been conducted for the screens, risers, headers, and collector well. Only the header study will be described herein.

The header study was conducted to provide design information on headloss in the header system, flow contributions of the individual risers and the possible presence of undesirable flow characteristics in the header.

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1) The final design selected for construction is a branching pipe system. It does not use a collector well. It is described in External Memorandum No. 161 referenced as item number five on page iii.

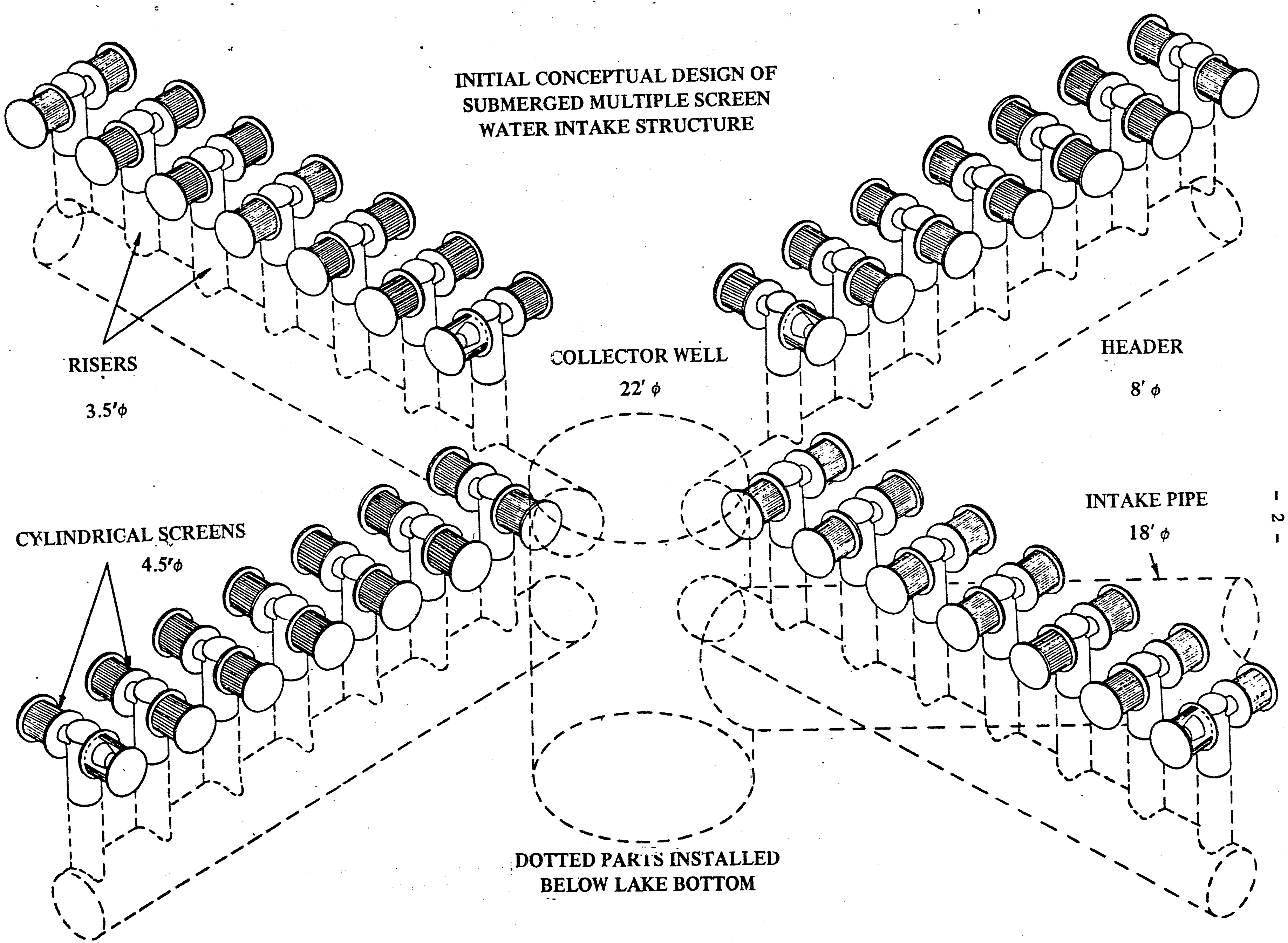


Fig. I-1. Initial Conceptual Design of the James H. Campbell Unit No. 3 Cooling Water Intake.

The following specific questions were addressed:

a. What will be the withdrawal rate through each of the seven risers?

b. What measures could be taken to make the flow contribution from each riser uniform or more nearly uniform?

c. What will be the piezometric headloss through the system of seven risers and the header? What will be the piezometric head at the end of the header relative to the lake?

d. Will undesirable (e.g. helical) flow patterns develop in the header?

A hydraulic scale model study and hydraulic analysis were used to provide answers to these questions. It was agreed a priori that the study would assume static lake conditions and clean screens at all risers. The results of the study therefore apply strictly only when lake currents are absent and when lake surface conditions are calm. Frequency distributions of current velocities measured at the site were analyzed elsewhere.

II. MODEL DESIGN AND OPERATION

With the objective of investigating the characteristics of the internal flow through the seven individual risers and the header of the intake unit, a simplified 1:12 scale model was designed and constructed. The risers used in this model are scaled versions of the prototype, but have been somewhat simplified to facilitate their construction and assembly. In particular, the screens and endplates have been omitted. The design of the simplified risers has been developed by a series of trials comparing the piezometric pressure drop produced by a single riser in the complete scale model and the simplified model for a range of discharges corresponding to Reynolds numbers from 40,000 to 200,000. The simplified model whose piezometric pressure loss most nearly matched that of the complete scale model with screens and endplates was designated as Type D. Seven units of this Type D were used in setting up the header model. Sketches of the scale model of the riser and the Type D simplified model are shown in Figures II-1 and II-2. The piezometric pressures at

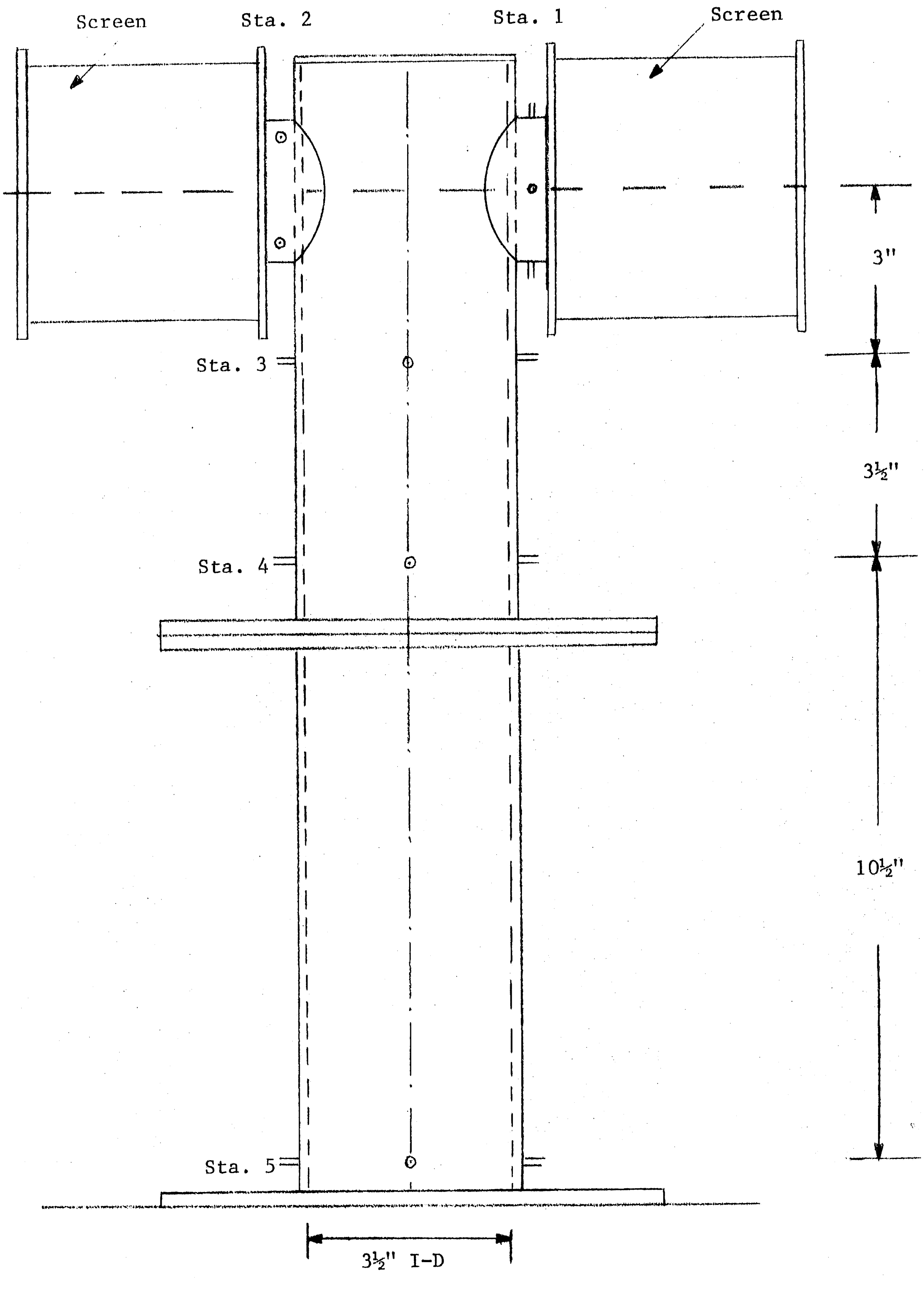


Fig. II-1 - Complete Single Riser Model and Location of Pressure Taps - Scale 1:12.

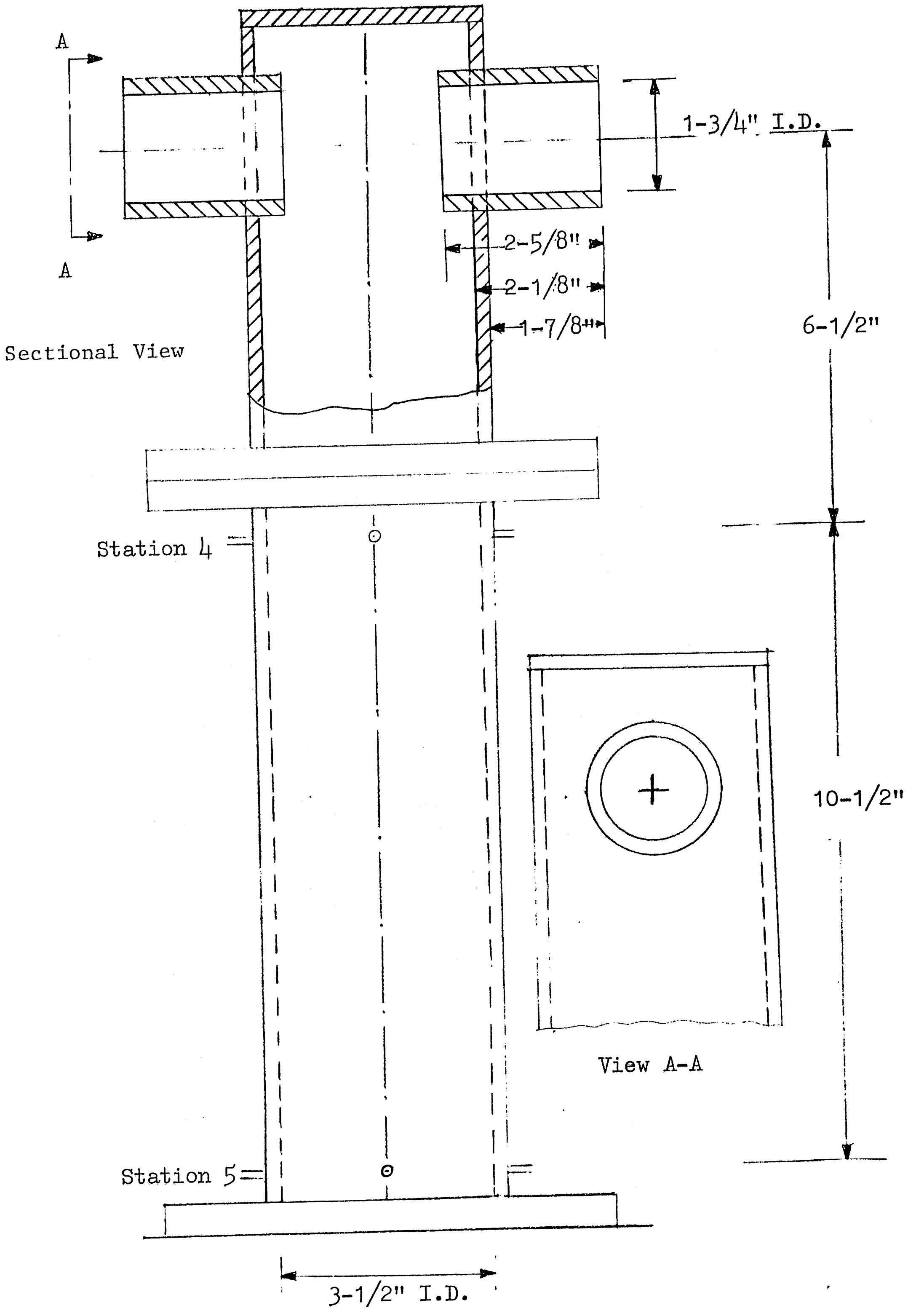


Fig. II-2 - Simplified Riser Model - Type D - Scale 1:12.

station 5 for both the models are shown in Figures II-3 and II-4. The locations of the pressure taps are designated as stations 1 through 5 on the scale model and as stations 4 and 5 on the simplified model. Each station consisted of four taps spaced 90° apart around the circumference, and connected together by a ring of plastic tubing. Photographs of the simplified risers are shown in Figures II-5 and II-6 in their inverted positions.

The complete assembly of the header model of the intake unit is shown in Figure II-7. The ground level tank in which the model was installed was 40' x 16½' x 1½'. As the depth of the tank was not sufficient to accommodate the risers and headers in their normal position, the whole assembly was inverted as shown in Figures II-5, 6, and 7. The hydraulic characteristics of the internal flow in the model were not affected in any way by this inversion.

The pressure tap locations in the header model were designated as stations 1 to 22. Their locations are shown in Figure II-8. As in the case of the individual riser models, each of these stations consisted of four pressure taps located 90° apart on the circumference and connected together by plastic tubing. The ambient pressure in the tank was registered by a single tube designated as station 23 leading from the tank. The leads from these 23 stations were taken to a manometer board with scale graduations of inches and tenths. The tops of all the manometer tubes were connected together by a manifold so that an aspirator could be used to bring the levels of water in the tubes to any desired and convenient reading position on the manometer board.

Closeup views of the complete header model with seven risers installed in the empty tank and the tank filled with water are given in Figures II-9 and II-10. The placement of the header model in the tank is shown in Figures II-11 and II-12.

A pump withdrew the water from the tank through the risers and header and discharged it back into the tank sufficiently far away from the model to avoid measurable disturbance near the risers. The water level in the tank was maintained constant by means of an overflow weir at the end of the tank and a supplemental water supply to the tank from a separate feeder pipe. Discharge through the system was measured by a 4" orifice in the 6" pipeline on the discharge side of the pump. Two manometers were used with the orifice

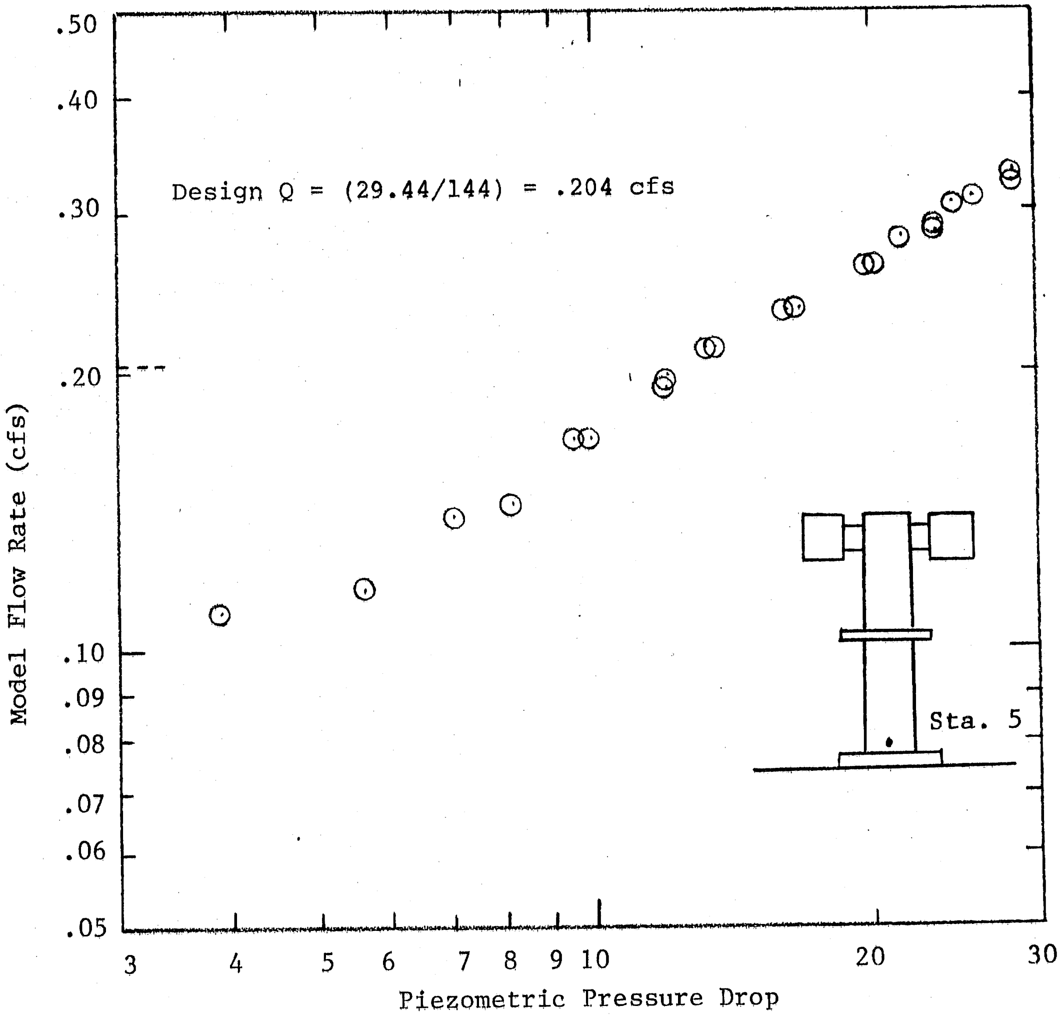


Fig. II-3 - Piezometric Pressure Drop (Inches of Water) Between Ambient and Station 5. Complete 1:12 Scale Riser Model.

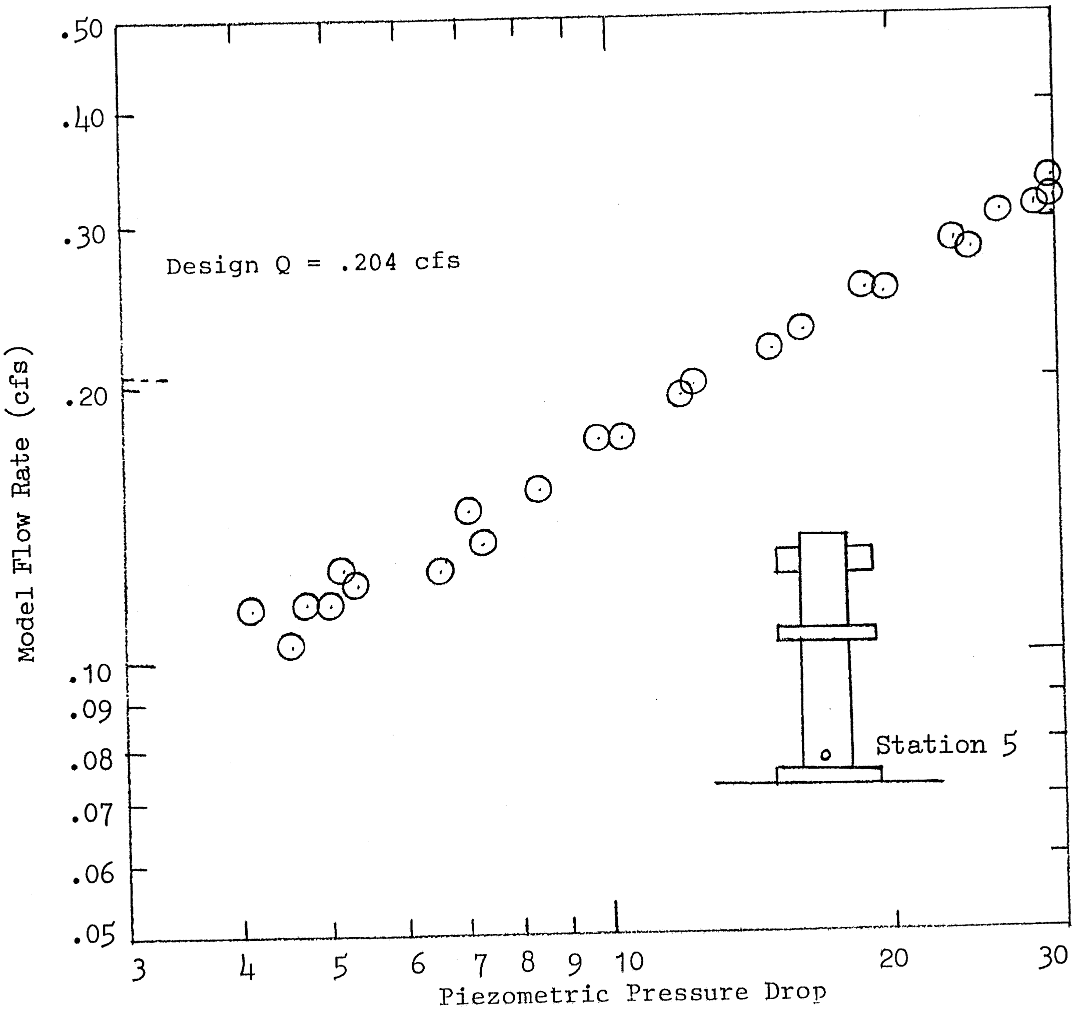
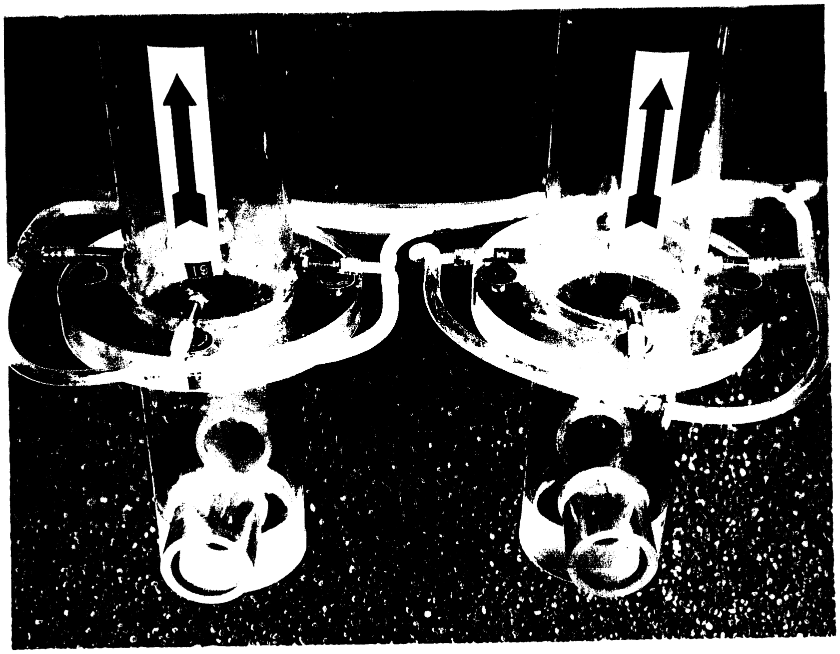


Fig. II-4 - Piezometric Pressure Drop (Inches of Water) Between Ambient and Station 5.

1:12 Simplified Model - Type D

Fig. II-5 - Side View of Two of the Seven Simplified Intake Risers.

Fig. II-6 - Front View of the Simplified Intake Riser No. 1 at End of Header.



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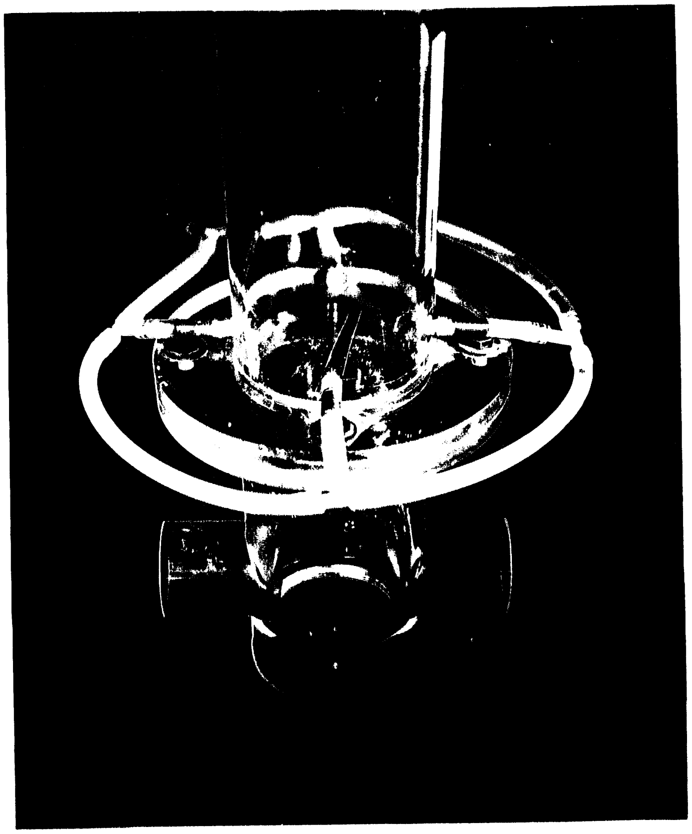


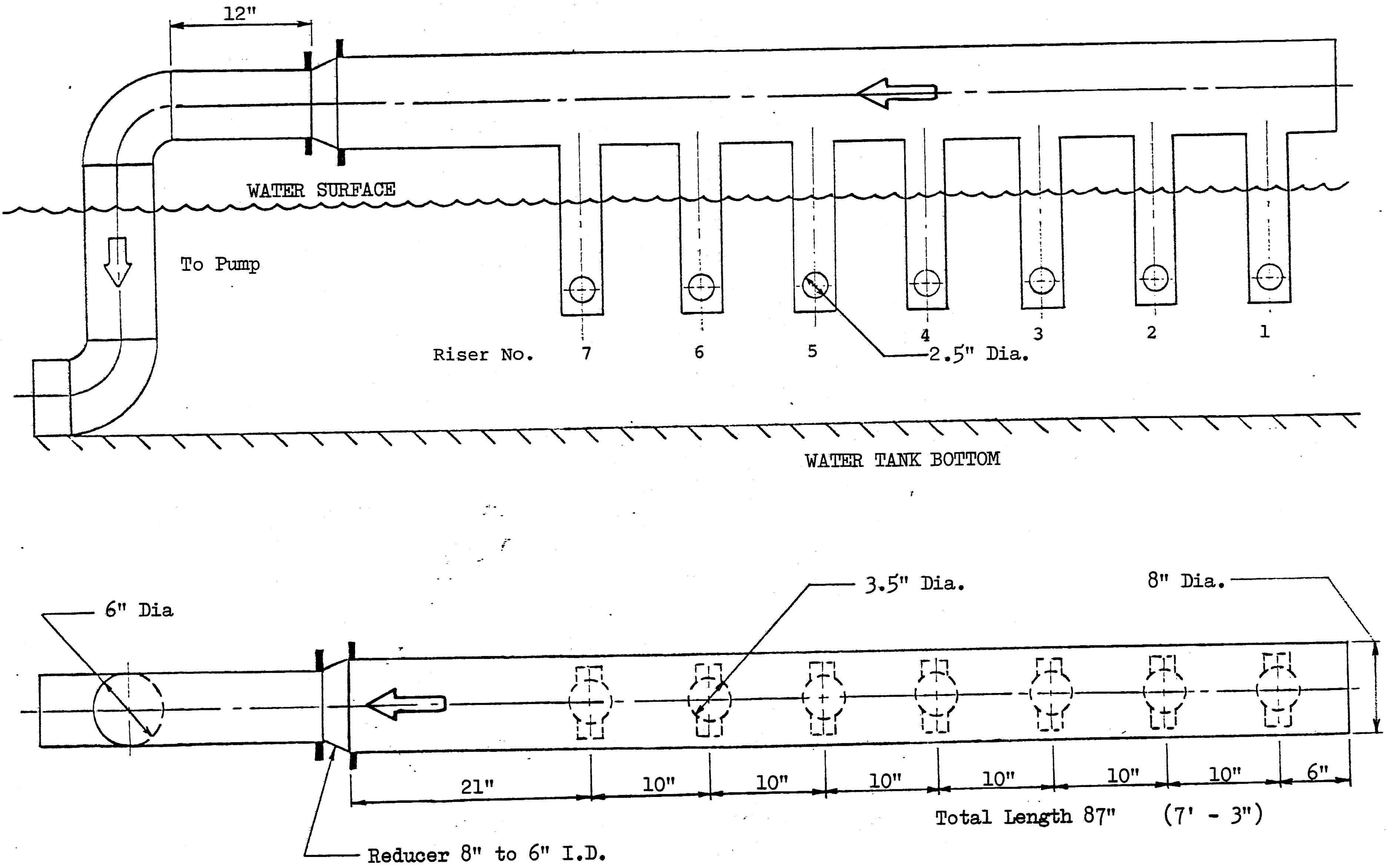


Fig. II-7 - SINGLE HEADER MODEL
Scale: 1:12

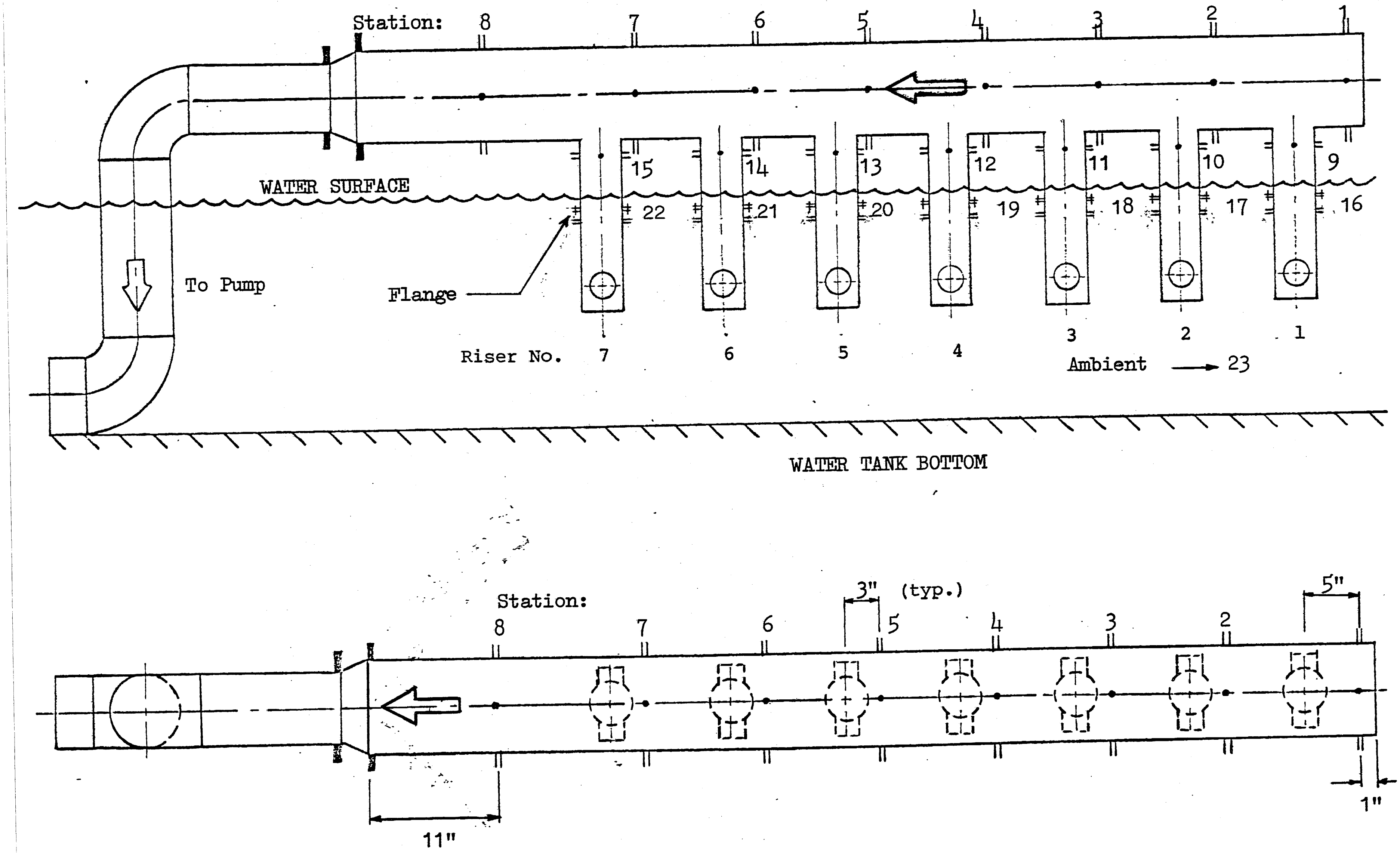
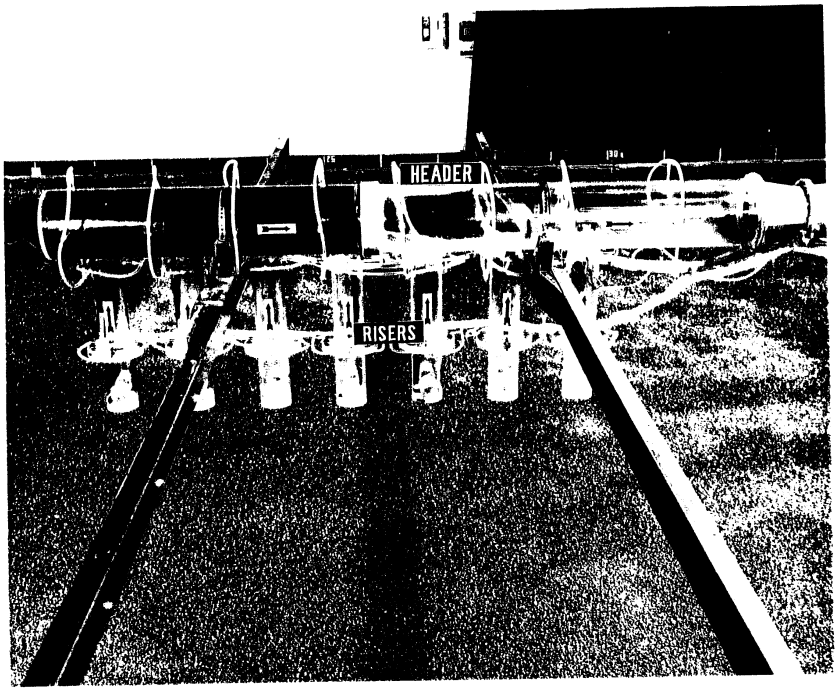


Fig. II-8 – Pressure Tap Locations on Header Model.
Scale: 1:12


HEADER
RISERS

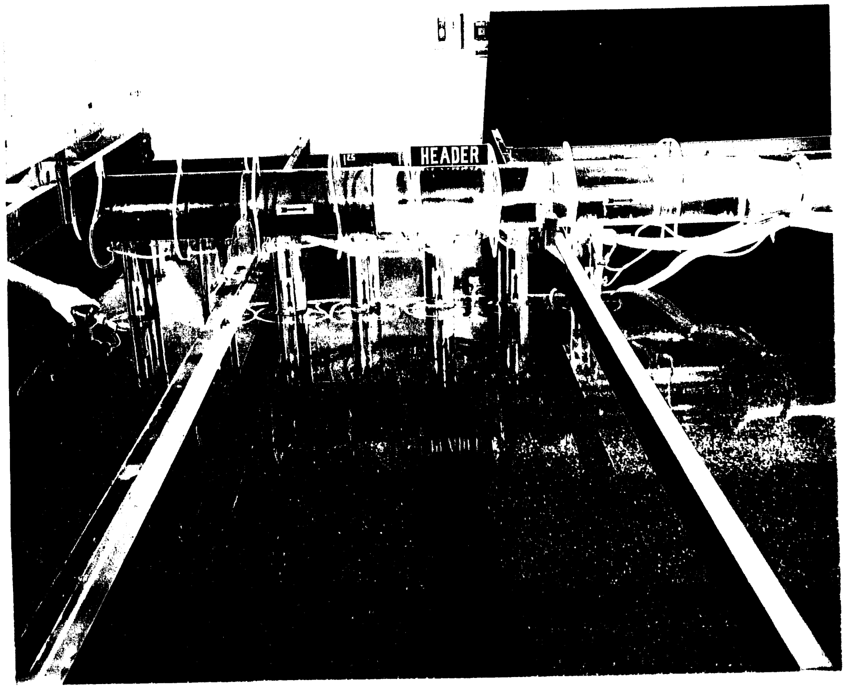
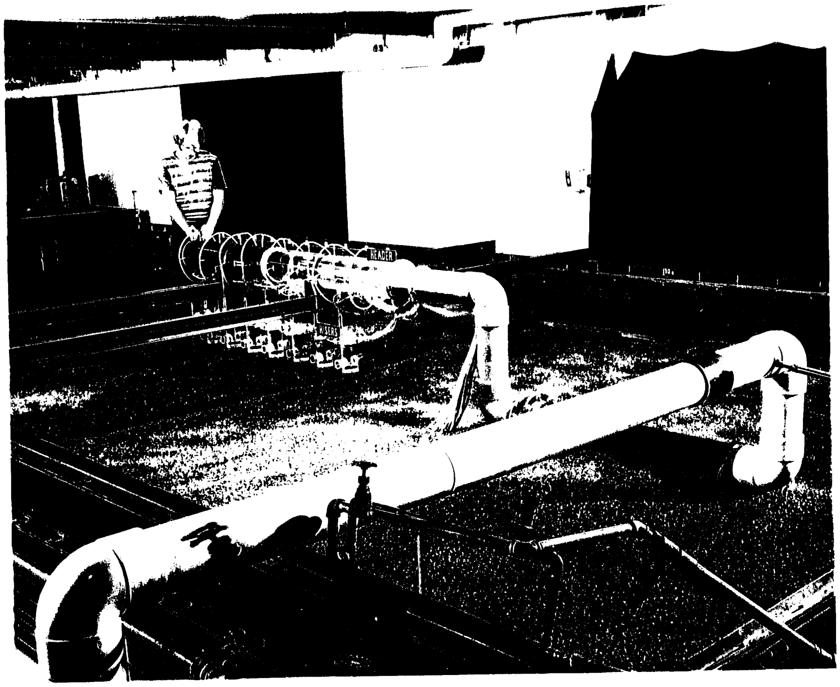
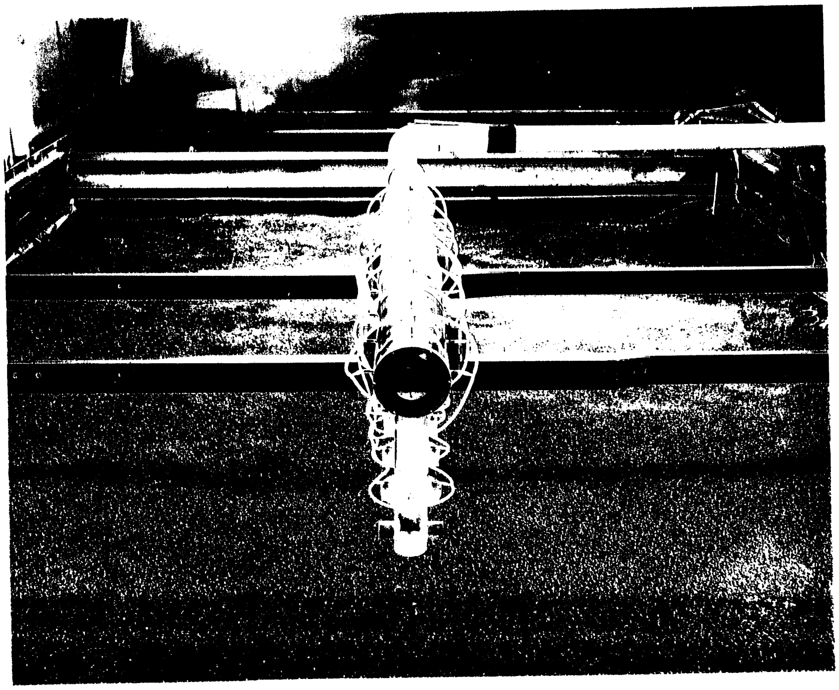

HEADER

Fig. II-11 - 1:12 Scale Inverted Header Model Installation in Dry Tank.

Fig. II-12 - Head-on View of 1:12 Scale Inverted Header Model in Dry Tank.


HEADER



meter - one with Meriam No. 3 (sp. gr. 2.97) as the manometric fluid for small rates of flow (up to about 0.5 cfs) and the other with mercury as the indicative fluid for higher discharges. The orifice meter had been calibrated against known flow rates for both the Meriam and mercury deflections in the manometers. The overall layout of the experimental installation is given in Fig. II-13.

Tests were run for a number of flow rates up to a maximum of 2.22 cfs. This corresponded to a maximum Reynolds number in the header of about 450,000. For each discharge, the piezometric heads at the 23 stations in the model were read on the manometer board. In order to take into account the fluctuations in the pressure readings, all piezometer tubes were read at a uniform pace and the entire set of readings was repeated three times in the same order. The mean of the three readings for each station was retained.

III. EXPERIMENTAL RESULTS FOR UNBALANCED HEADER

Figure III-1 shows the pattern of growth of the flow rate along the axis of the header as the flow from each of the risers is discharged into it. Figure III-2 indicates the piezometric head at various stations along the header for different total withdrawal rates. Figure III-3 shows the amount of actual flow drawn through the individual risers as a percentage of the ideal uniform flow per riser (29.44 cfs in the prototype) for various Reynolds number values at station 8 on the header.

The flow rate drawn by each riser was determined from the headloss between the ambient tank and the piezometric taps at the base of each riser (stations 9 to 15, Ref. Fig. II-8). A calibration obtained from testing the single simplified riser Type D was used to determine the values of flow corresponding to the piezometric headloss in each riser. The percentage of flow drawn by the separate risers increases in the direction of flow and also shows a slight dependence on Reynolds number.

Taking the piezometric pressure at station 8 at the end of the header as the reference datum, piezometric pressure loss coefficients for stations 1 to 7 have been calculated as follows:

$$K_{8j} = \frac{(p_j/\gamma + z_j) - (p_8/\gamma + z_8)}{V_8^2/2g} \qquad \text{(III-1)}$$

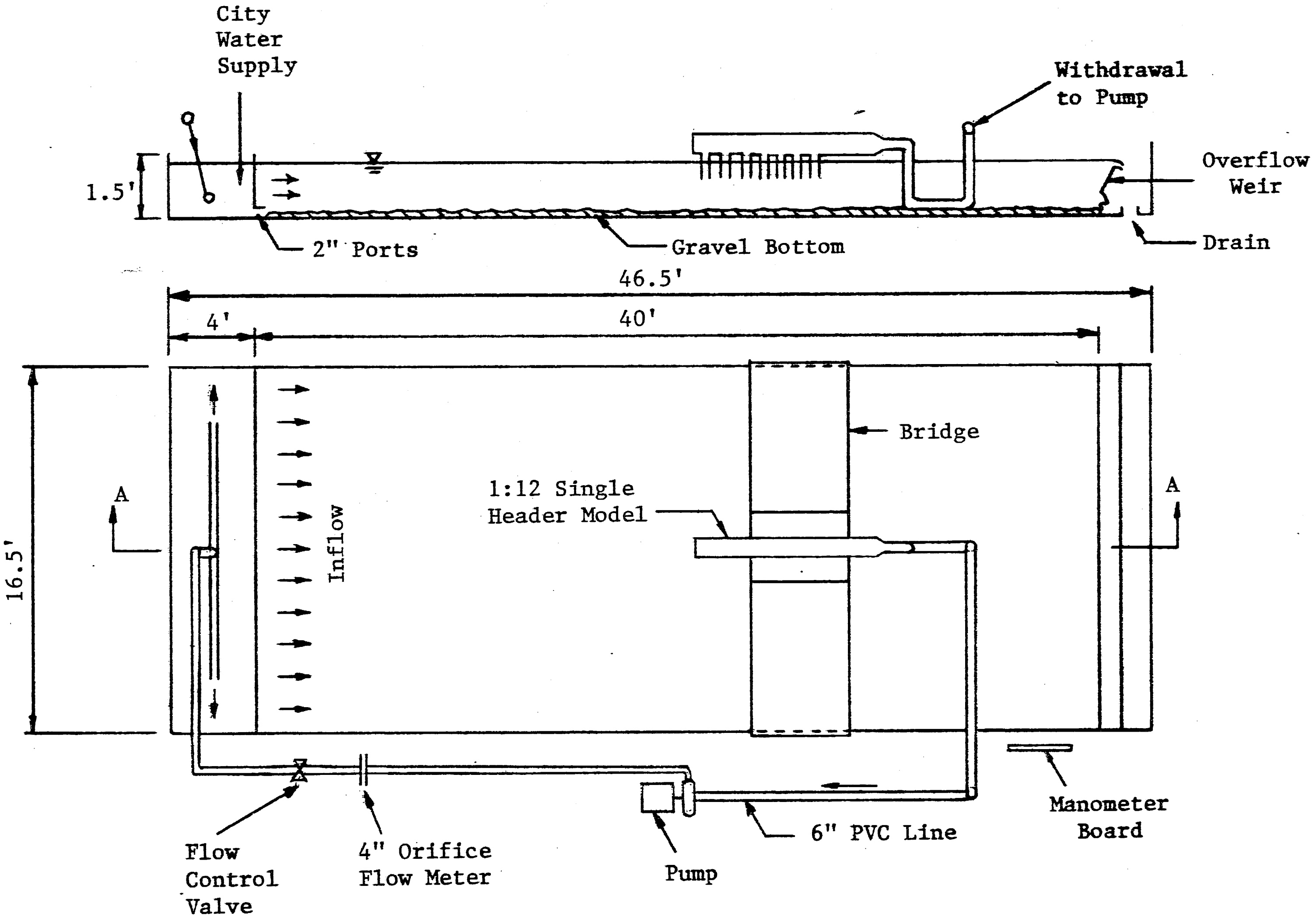


Fig. II-13 - Overall Layout of Experimental Installation for Header Model Experiments.

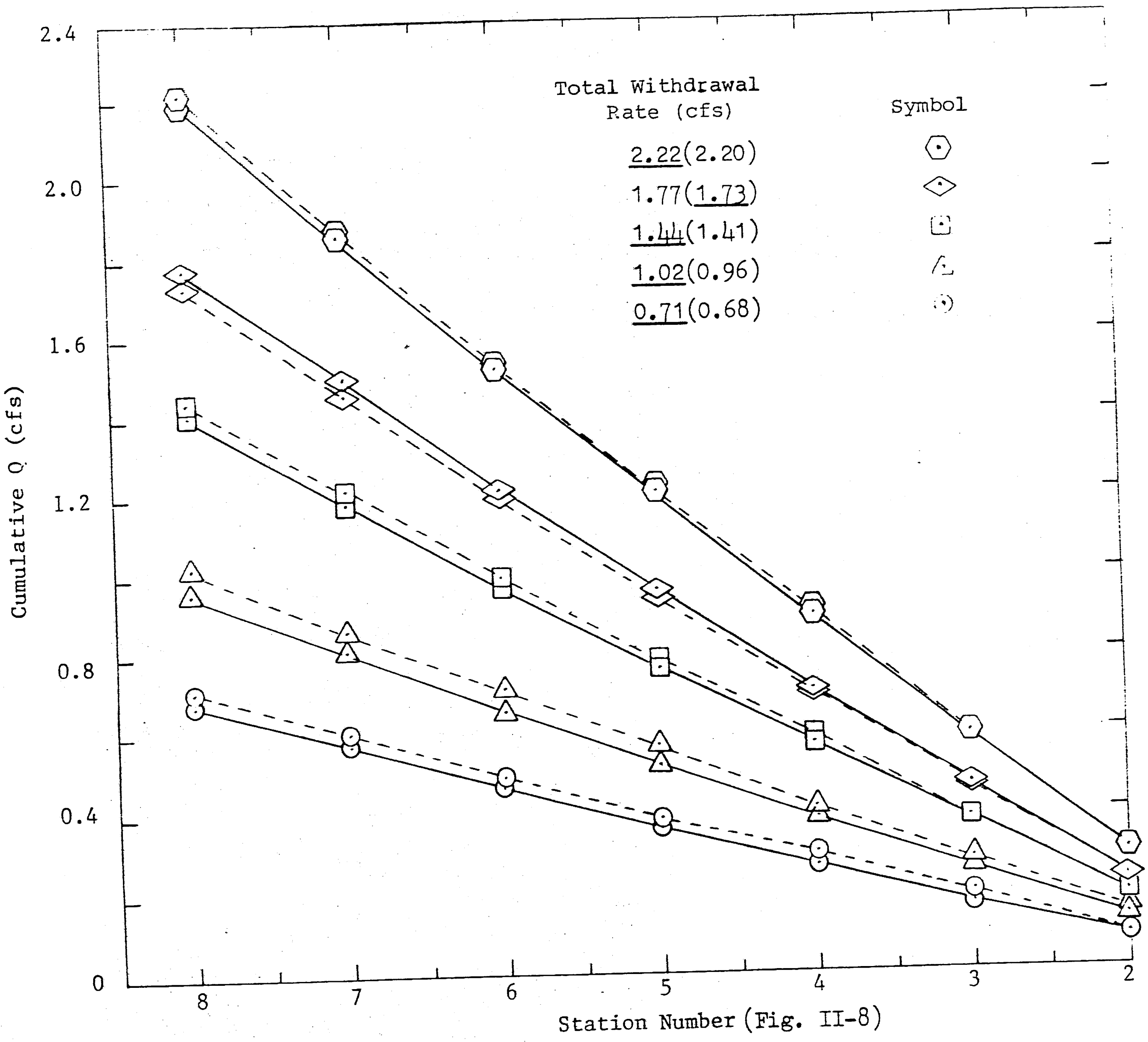


Fig. III-1 - Cumulative Model Flow Rates Along Axis of Header.

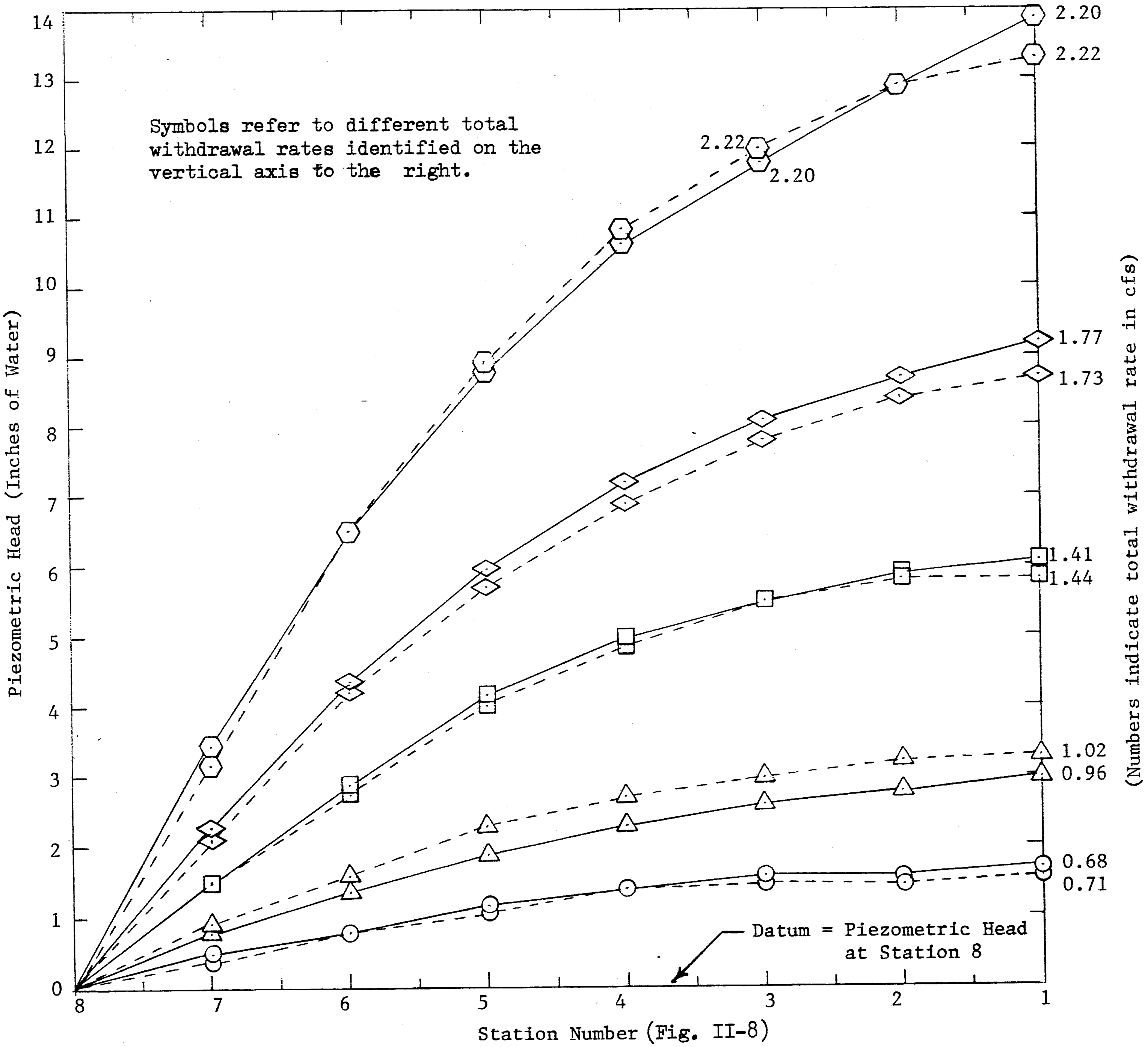


Fig. III-2 - Piezometric Heads Along Header Axis for Different Model Flow Rates.

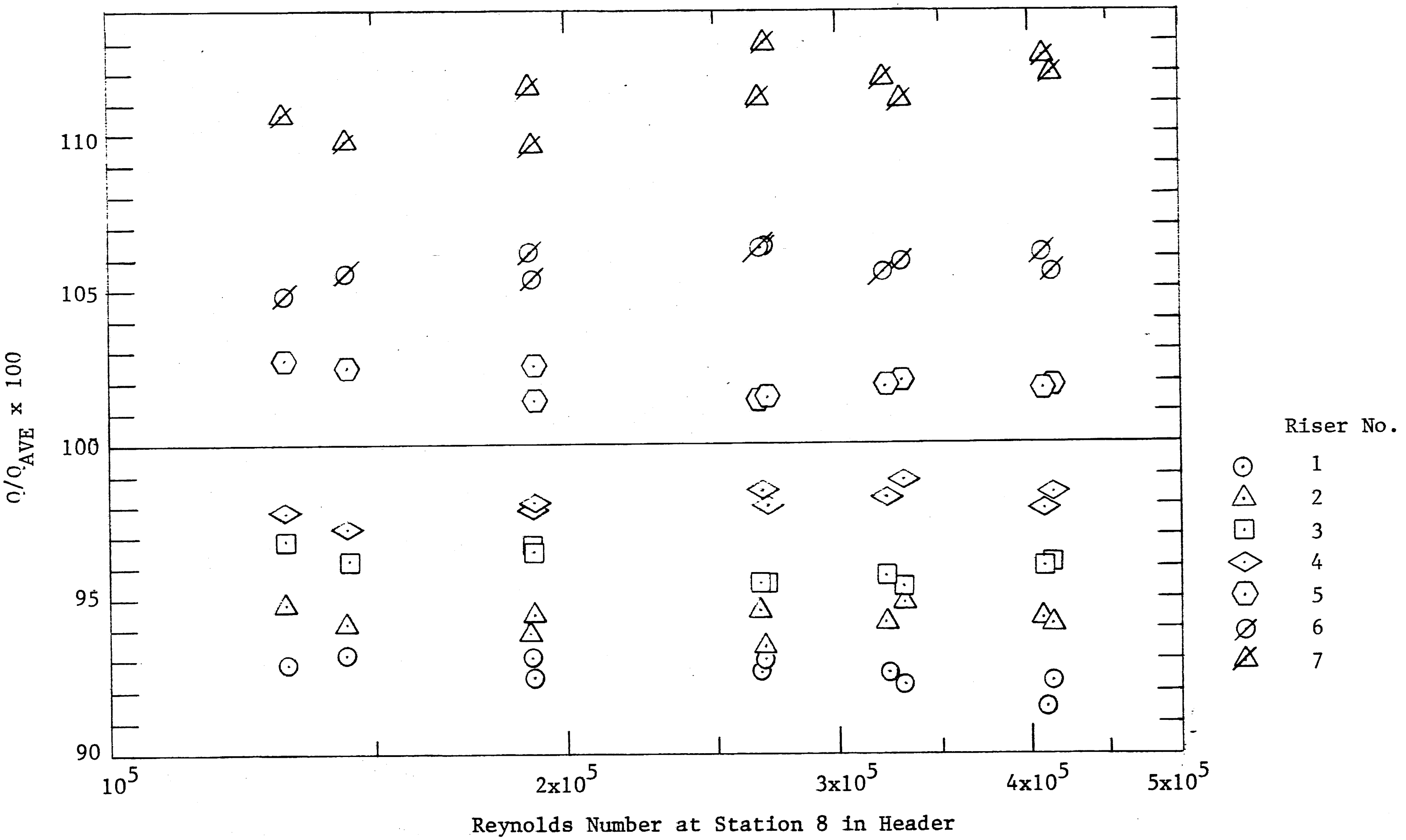


Fig. III-3 - Percentage of Withdrawal by Individual Risers Relative to the Average Withdrawal Rate (29.44 cfs per Riser) as a Function of Reynolds Number.

K_{8j} = piezometric pressure loss coefficient for station j with reference to station 8

p = static pressure

z = elevation

γ = sp. weight of water

V = velocity

g = acceleration due to gravity, and

j = suffix referring to station number

The variation of the piezometric pressure loss coefficients with station 8 Reynolds number is shown in Figure III-4 for stations 1 to 7.

The maximum value of the prototype Reynolds number at station 8 on the header, corresponding to a maximum flow rate of $Q_p = 29.44 \times 7 = 206.08$ cfs, is about 3.1×10^6. Though Reynolds numbers approximating this magnitude have not been reached in the model test, it appears from Fig. III-4 that the piezometric pressure loss coefficients vary little at high Reynolds numbers. Using the values of the coefficients read from Fig. III-4 at a Reynolds number value of 450,000, the piezometric pressure heads which can be anticipated in the prototype header have been computed. The results are shown in Table III-1.

Similarly, the prototype withdrawal rates for the seven individual risers must be estimated assuming that the percentages shown in Figure III-3 at a Reynolds number of 450,000 are not altered by an increase in Reynolds number. The trends shown in Figure III-3 justify such an assumption. The resulting prototype withdrawal rates for the unbalanced header are given in Table III-2.

Table III-1 gives the piezometric head with reference to station 8 on the header. To assess the performance of the total header-riser system, it is more useful to give piezometric heads with reference to the lake. In order to do this it is necessary to determine the piezometric pressure differential between the lake and station 1. Experiments with single risers gave a piezometric pressure loss coefficient of 5.6 between the lake and station 9. The header experiments indicated that between station 9 and station 1, the piezometric pressure loss coefficient was -0.2, giving a total loss coefficient of 5.4 between lake

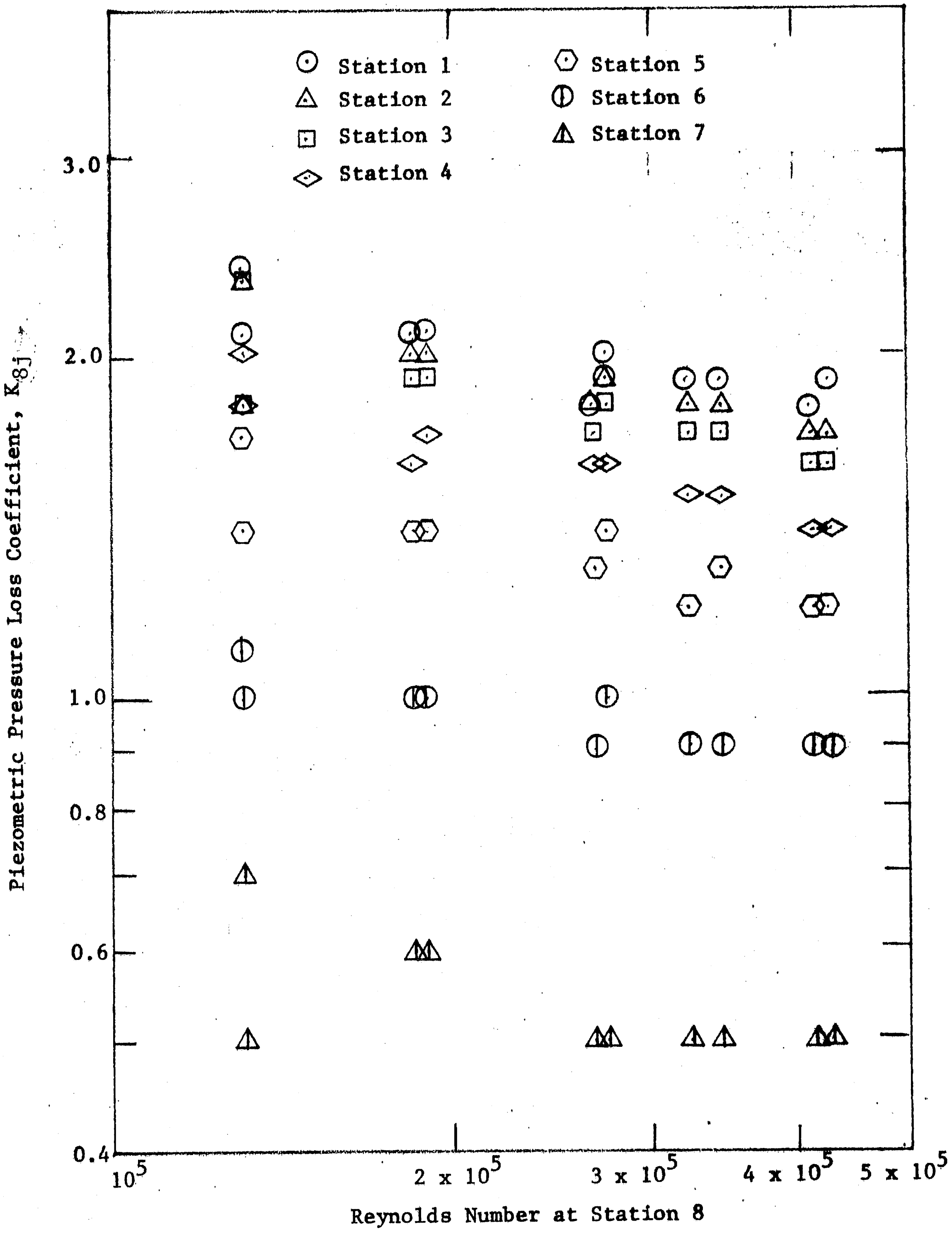


Fig. III-4 - Piezometric Pressure Loss Coefficients, K_{8j}, Between End of Header and Individual Stations along Header.

TABLE III-1

Computed Prototype Piezometric Headlosses at Stations 1 to 7 on the Header

Total Withdrawal Rate = 29.44 x 7 = 206.08 cfs

Dia. at Sta. 8 = 8 ft.

Velocity at Sta. 8 = 4.10 ft/sec

Velocity Head at Sta. 8 = 0.26 ft

Sta. No.	K_{8j} value from model test	Piezometric Pressure Loss with Reference to Sta. 8	
		Feet of Water	Inches of Water
1	1.83	0.48	5.7
2	1.70	0.44	5.3
3	1.57	0.41	4.9
4	1.40	0.37	4.4
5	1.19	0.31	3.7
6	0.89	0.23	2.8
7	0.50	0.13	1.6
8	0	0	0

TABLE III-2

Computed Prototype Withdrawal Rates of the Seven Risers on the Unbalanced Header

Total Withdrawal Rate = 29.44 x 7 = 206.08 cfs

Diameter at Sta. 8 = 8 ft.

Velocity at Sta. 8 = 4.10 ft/sec

Riser No.	Q/Q_{AVE}	Q cfs
1	92	27.1
2	94	27.7
3	96	28.3
4	98	28.9
5	102	30.0
6	106	31.2
7	112	33.0
Total		206.2 cfs

ambient and station 1. With a flow rate of 27.1 cfs in Riser No. 1, the piezometric pressure head at station 1 (upstream end of the header) is therefore calculated to be

$$-5.4\left(\frac{27.1}{9.62}\right)^2 \frac{1}{64.4} = -0.665 \text{ ft} = -8.0 \text{ inches of water}$$

with reference to lake stage. At station 8 (downstream end of header) the piezometric head is -13.7 inches of water with reference to lake level. Intermediate values between stations 1 and 8 are given in Table III-3.

The total energy headloss between the lake and station 8 for the unbalanced header and at a withdrawal rate of 206.08 cfs is

$$\frac{-13.7}{12} + \left(\frac{206.08}{8^2\ \pi/4}\right)^2 \frac{1}{64.4} = 0.881 \text{ ft}$$

$$= 10.6 \text{ inches of water}$$

Dye was injected into several of the risers. No helical flow patterns were observed in the header or the risers.

TABLE III-3

Computed Prototype Piezometric Pressure Heads Along Unbalanced Header (in Inches of Water Below Lake Stage)

Total Withdrawal Rate from Unbalanced Header = 206.08 cfs

Station No.	Piezometric Head (inches of water with referrence to lake level)
1	-8.0
2	-8.4
3	-8.8
4	-9.3
5	-10.0
6	-10.9
7	-12.1
8	-13.7

IV. HYDRAULIC ANALYSIS OF THE FULLY-BALANCED HEADER

To assure compliance with the design criteria it was considered to establish equal withdrawal rates from all seven risers. To this end, it was necessary to determine how much headloss had to be induced artificially in each riser to equalize the withdrawal rates. The purpose of the following computations is to determine these additional headlosses. The computations are shown in Table IV-1, wherein the subscript H attached to Q refers to header flow and subscript R to the riser flow.

The computed energy and piezometric headlosses along a fully balanced header are given in Table IV-1. The numbers in Table IV-1 have been obtained by application of the one-dimensional energy and continuity equations. Headlosses along the header axis and at each riser junction were derived from the unbalanced header experiments. The coefficients presented in Section V and explained in Appendices A and B were used.

To obtain the piezometric pressures with reference to the lake, it is necessary to examine riser 1 for full withdrawal at 29.44 cfs. The piezometric head at the bottom of the riser will be -9.8 inches relative to the lake and the piezometric pressure at station 1 on the header will be -9.4 inches. Adding to this the -5.9 inches along the header gives a total piezometric head differential between the lake and the end of the fully balanced header (station 8) equal to -15.3 inches. The energy headloss between the lake and station 8 is 15.3 - 3.1 = 12.2 inches of water. The totally balanced header system produces 1.6 inches more energy headloss than the unbalanced one (Section III).

The headloss which must be induced in each riser to balance all withdrawal rates is shown in line 13 of Table IV-1. Table IV-2 gives the piezometric heads and flow rates of the fully balanced header.

TABLE IV-1

Prototype Piezometric and Energy Grade Levels in the Fully Balanced Header

Equalized Flow Through Each Riser = 29.44 cfs
u_i = 3.06 ft/sec $u_i^2/2g$ = 1.74 inches

	Station No.							
	1	2	3	4	5	6	7	8
1. Header Flow Rate (cfs)	0	29.4	58.9	88.3	117.8	147.2	176.6	206.1
2. Velocity head in header, $u_j^2/2g$ (inches)	0	0.1	0.3	0.6	1.0	1.6	2.3	3.1
3. Q_R/Q_H		1.00	0.50	0.33	0.25	0.20	0.17	0.14
4. Header Loss Coefficient $K_{j-1,j}$		0.15	0.16	0.17	0.22	0.25	0.29	0.35
5. Headloss Along Header Across One Riser Junction (Inches of Water)		0.26	0.28	0.30	0.38	0.44	0.50	0.61
6. Cumulative Headloss Along Header (Inches of Water)	0	0.26	0.54	0.84	1.22	1.66	2.16	2.77
7. Energy Head (Inches of Water)	5.9	5.6	5.4	5.1	4.7	4.2	3.7	3.1
8. Piezometric Head (Inches of Water)	5.9	5.5	5.1	4.5	3.7	2.6	1.4	0
9. Exit Loss Coefficient for Riser K_{ij}		1.00	0.84	0.78	0.74	0.60	0.47	0.15
10. Riser Exit Loss (Inches of Water)		1.74	1.46	1.36	1.29	1.04	0.82	0.26
11. $-u_i^2/2g + u_j^2/2g$ (inches)		-1.64	-1.44	-1.14	-0.74	-0.14	+0.56	+1.36

TABLE IV-1 (Cont.)

	Riser No.						
	1	2	3	4	5	6	7
12. Piezometric Head at Bottom of Riser (Inches)	5.6	5.1	4.7	4.3	3.5	2.8	1.6
13. Required Additional Piezometric Headloss (Inches of Water)	0	0.5	0.9	1.3	2.1	2.8	4.0

TABLE IV-2

Essential Characteristics of Fully Balanced Header

Station No.	Piezometric Head (Inches of water with ref. to lake level)	Flow Rate (cfs)
1	-9.4	
2	-9.8	1 X 29.44 = 29.44
3	-10.4	2 X 29.44 = 58.88
4	-10.9	3 X 29.44 = 88.32
5	-11.6	4 X 29.44 = 117.76
6	-12.5	5 X 29.44 = 147.20
7	-13.8	6 X 29.44 = 176.64
8	-15.3	7 X 29.44 = 206.08

V. HYDRAULIC ANALYSIS OF THE PARTIALLY BALANCED HEADER - NOZZLE DESIGN FOR RISERS 6 AND 7.

1. Hydraulic Analysis

There are only three risers on the unbalanced header which withdraw more than the design flow rate of 29.44 cfs. The excess is 2% of design flow for riser No. 5, 6% for riser No. 6, and 12% for riser No. 7. The piezometric pressure adjustments required in risers 3 and 4 for full balancing are small and difficult to control with any degree of accuracy. Johnson Division, UOP Inc., indicated that reduction of the withdrawal rate in only risers 6 and 7 could comply with the design velocity criteria. The hydraulic analysis of the "Partially balanced header" will be presented herein.

The flows to be drawn through risers 6 and 7 were specified as 105% and 102% of the average riser flow. In order to analyse the flow situation under such partially balanced conditions, the flow through the risers and header is considered a manifold flow and equations are set up and solved for the flow rates in risers 1 through 5.

The numbering system shown in Fig. II-8 is used to designate the various points on the header and risers. Numbers 1 to 8 refer to the pressure taps on the header and 9 to 15 refer to the pressure taps in risers 1 to 7 nearest to the header. Considering risers 1 and 2, the loss in energy head at point 3 with reference to the ambient is made up of the loss in energy between ambient and point 9 on riser 1, the riser exit loss between points 9 and 2, and the loss in header between points 2 and 3. This should also be equal to the sum of the loss in head between ambient and point 10 on riser 2 and the riser exit loss between points 10 and 3. Designating the change in energy by the notation ΔE with suffixes to denote the points to which it refers, we can write

$$\Delta E_9 + \Delta E_{9-2} + \Delta E_{2-3} = \Delta E_{10} + \Delta E_{10-3} \quad \text{for risers 1 and 2} \qquad \text{(V-1)}$$

Similarly,

$$\Delta E_{10} + \Delta E_{10-3} + \Delta E_{3-4} = \Delta E_{11} + \Delta E_{11-4} \quad \text{for risers 2 and 3} \qquad \text{(V-2)}$$

$$\Delta E_{11} + \Delta E_{11-4} + \Delta E_{4-5} = \Delta E_{12} + \Delta E_{12-5} \quad \text{for risers 3 and 4} \qquad \text{(V-3)}$$

$$\Delta E_{12} + \Delta E_{12-5} + \Delta E_{5-6} = \Delta E_{13} + \Delta E_{13-6} \quad \text{for risers 4 and 5} \qquad \text{(V-4)}$$

In addition, designating by ΔQ the difference in the flows drawn through the risers under unbalanced and partially balanced conditions, we can write

$$\Delta Q_9 + \Delta Q_{10} + \Delta Q_{11} + \Delta Q_{12} + \Delta Q_{13} + \Delta Q_{14} + \Delta Q_{15} = 0 \qquad \text{(V-5)}$$

The flow corrections ΔQ_{14} and ΔQ_{15} are known:

$\Delta Q_{14} = 106 - 105 = 1\%$

$\Delta Q_{15} = 113 - 102 = 11\%$

The five unknowns ΔQ_9 to ΔQ_{13} can be obtained by solving the equations (V-1) to (V-5) simultaneously.

The energy losses ΔE in equations (V-1) through (V-5) are functions of the flow rates. As is customary in pipeflow analysis, they will be expressed in the form $K_i Q_i^2$, where Q_i will be taken as the volumetric flow in the riser. The derivation of the expanded equation (V-1) is given below. In the unbalanced condition equation (V-1) becomes:

$$(K_9 - 1.0)Q_9^2 + K_{9-2}Q_9^2 + K_{2-3}Q_{10}^2 = (K_{10} - 1)Q_{10}^2 + K_{10-3}Q_{10}^2 \qquad \text{(V-6)}$$

After the risers no. 6 and 7 have been partially balanced, the flow rates Q_9 and Q_{10} will have changed to $Q_9 + \Delta Q_9$ and $Q_{10} + \Delta Q_{10}$. The expanded equation is

$$(Q_9 + \Delta Q_9)^2 (K_9 - 1.0 + K_{9-2}) = (Q_{10} + \Delta Q_{10})^2 (K_{10} - 1 + K_{10-3} - K_{2-3}) \qquad \text{(V-7)}$$

By subtracting (V-6) from (V-7) and by retaining first order terms only, the following linear equation for ΔQ_9 and ΔQ_{10} is obtained.

$$Q_9 \Delta Q_9 \, (K_9 - 1 + K_{9-2}) = Q_{10} \Delta Q_{10} \, (K_{10} - 1 + K_{10-3} - K_{2-3}) \qquad \text{(V-8)}$$

Similarly, equation (V-2) through equation (V-4) can be reduced to:

$$Q_{10} \Delta Q_{10}(K_{10} - 1 + K_{10-3}) = Q_{11} \Delta Q_{11}(K_{11} - 1 + K_{11-4} - K_{3-4}) \qquad \text{(V-9)}$$

$$Q_{11} \Delta Q_{11}(K_{11} - 1 + K_{11-4}) = Q_{12} \Delta Q_{12}(K_{12} - 1 + K_{12-5} - K_{4-5}) \qquad \text{(V-10)}$$

$$Q_{12} \Delta Q_{12}(K_{12} - 1 + K_{12-5}) = Q_{13} \Delta Q_{13}(K_{13} - 1 + K_{13-6} - K_{5-6}) \qquad \text{(V-11)}$$

The five linear equations (V-5), (V-8), (V-9), (V-10), and (V-11) were solved for ΔQ_9, ΔQ_{10}, ΔQ_{11}, ΔQ_{12}, and ΔQ_{13}, with the result given in Table V-1.

Initial estimates of the flow rates (in percent) were those for the unbalanced header. The loss coefficients K were derived as follows. K_9 through K_{12} are the piezometric loss coefficients from ambient through each riser. A value of $K_9=K_{10}=K_{11}=K_{12} = 5.6$ was used.

The coefficients K_{9-2}, K_{10-3}, K_{11-4}, K_{12-5}, and K_{13-6} are exit loss coefficients for the flow from individual risers into the header. These coefficients are shown in Figure V-1. They were derived from the header experiments as shown in Appendix A. Data published by the British Hydromechanics Research Association (BHRA)[1] are also shown.

The coefficients are plotted versus the discharge ratio Q_R/Q_H, where Q_R is the withdrawal flow in a particular riser and Q_H is the volumetric flow rate in the header downstream from that riser. The data is for Reynolds numbers at station 8 from 250,000 to 350,000.

The coefficients K_{2-3}, K_{3-4}, K_{4-5}, K_{5-6}, and K_{6-7} are for the headloss along the axis of the header. They are presented in Figure V-2 and derived in Appendix B. Information from the BHRA is also shown.

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[1] Donald S. Miller, "Internal Flow. A Guide to Losses in Pipe and Duct Systems", British Hydromechanics Research Association, Cranfield, Bedford, 1971.

TABLE V-1

Flow Withdrawn Through the Risers Under Unbalanced and Partially Balanced Conditions

Riser No.	Flow Under Unbalanced Condition		Change Induced by Partial Balancing		Flow Under Partially Balanced Conditions		
		per cent		per cent		per cent	cfs
1	Q_9	92	ΔQ_9	+2.2	Q_9'	94.2	27.73
2	Q_{10}	94	ΔQ_{10}	+2.3	Q_{10}'	96.3	28.35
3	Q_{11}	96	ΔQ_{11}	+2.4	Q_{11}'	98.4	28.97
4	Q_{12}	98	ΔQ_{12}	+2.5	Q_{12}'	100.5	29.59
5	Q_{13}	102	ΔQ_{13}	+2.6	Q_{13}'	104.6	30.79
6	Q_{14}	106	ΔQ_{14}	-1.00	Q_{14}'	105.00	30.91
7	Q_{15}	112	ΔQ_{15}	-11.00	Q_{15}'	101.00	29.73

Total = 206.07 cfs

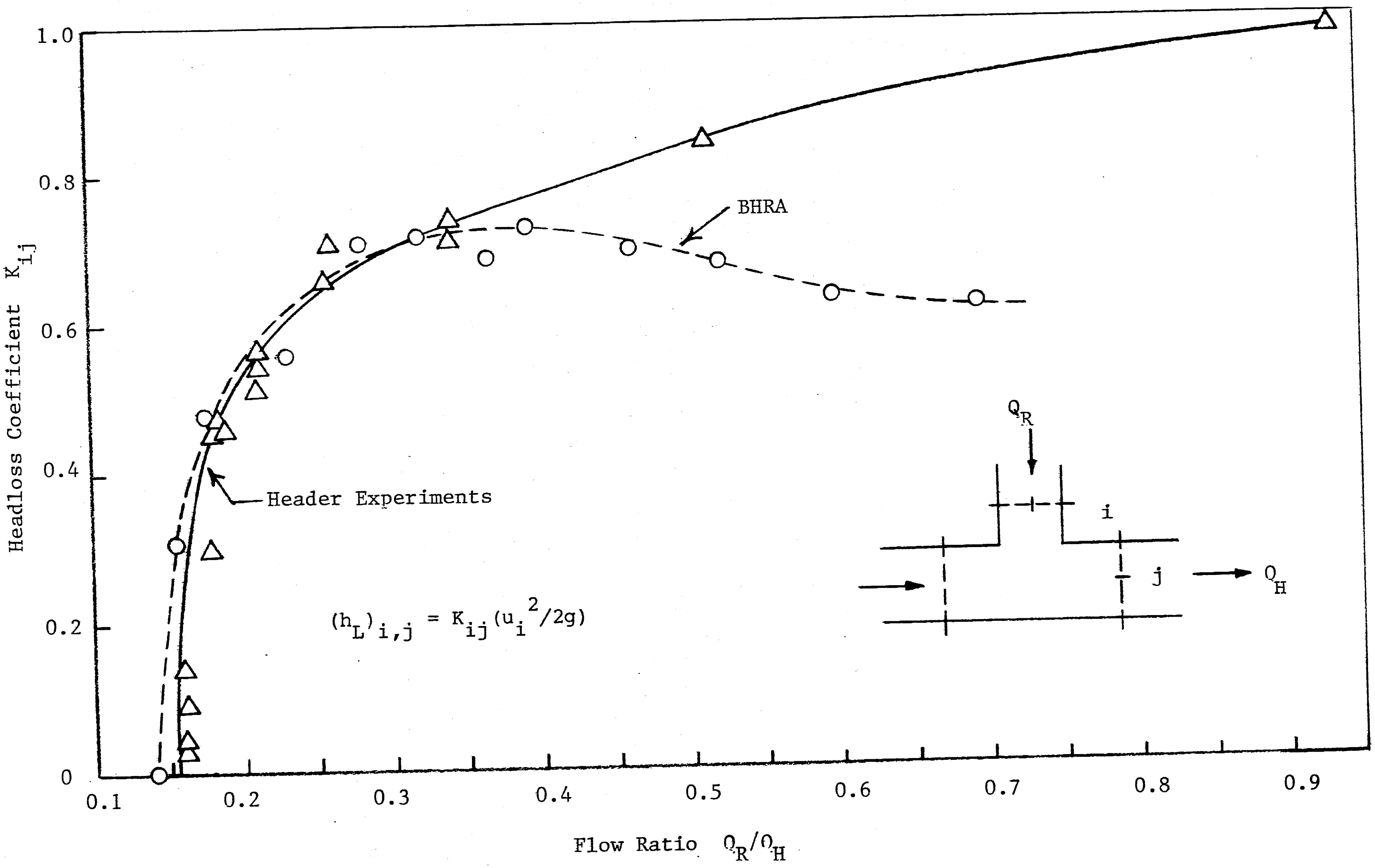

Fig. V-1 - Riser Exit Energy Loss Coefficients for Flow From Individual Risers Into the Header.

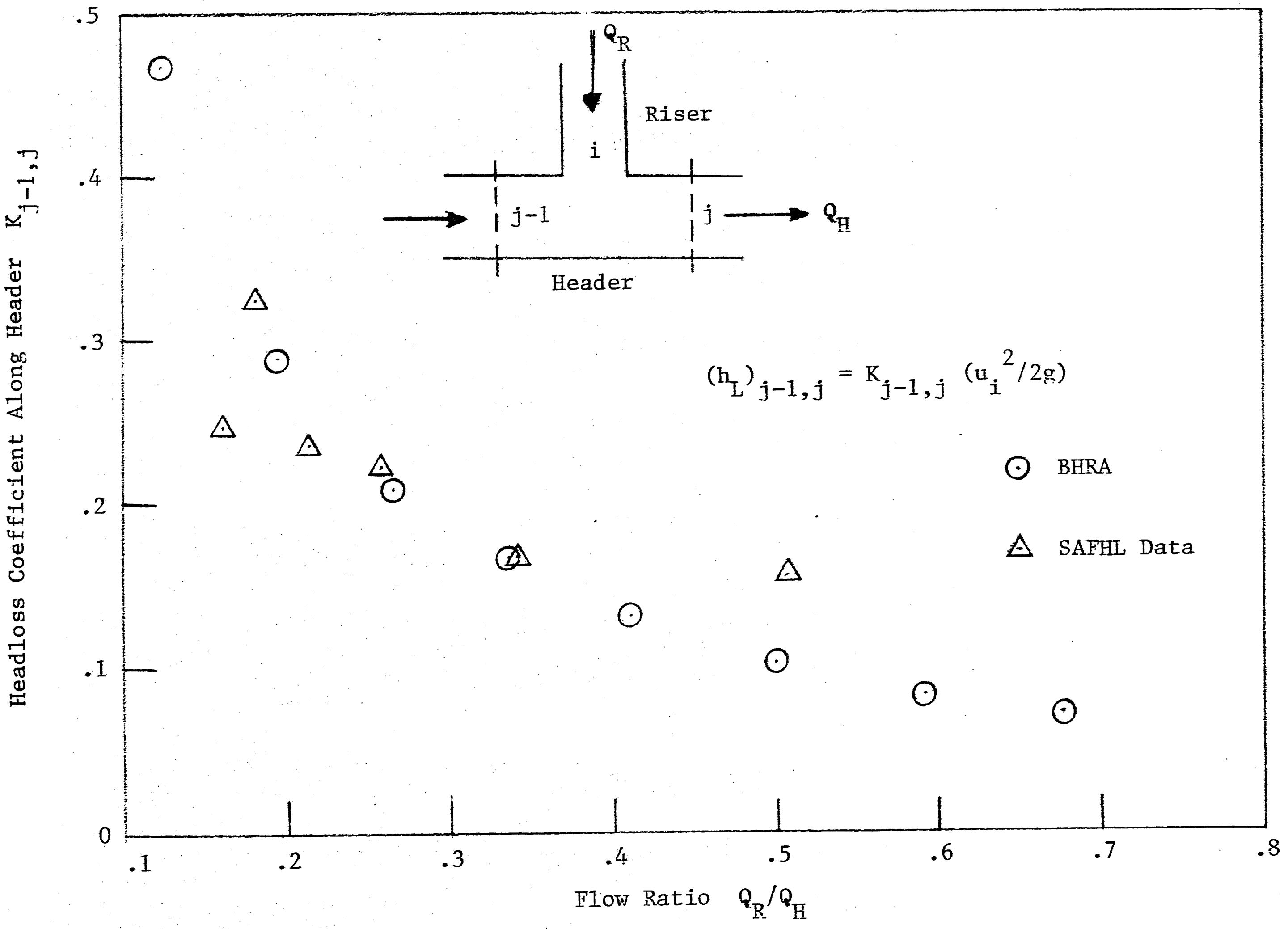

Fig. V-2 - Energy Loss Coefficients for Flow Along Header at Riser Junctions.

The coefficients have to be selected prior to the solution of the equation and the flow ratios Q_R/Q_H are estimated for that purpose. Good estimates of coefficients can be made since the flow rates in the riser are known a priori to within 1 to 3%.

The results of the analysis are shown in Table V-1. It can be seen that the reduction in withdrawal flow in risers 6 and 7 by 12 per cent of 29.44 cfs, causes an increase in withdrawal flow between 2 and 3 per cent in the remaining five risers. None of the withdrawal flows exceeds 105 per cent of 29.44 cfs or 30.91 cfs. The smallest withdrawal flow occurs in riser no. 1 and is 94.2 per cent of 29.44 cfs or 27.73 cfs.

2. Nozzle Design

In order to reduce the withdrawal rates in risers No. 6 and 7 it is necessary to install headloss generating devices in these two risers. Three different devices were considered for that purpose:

(a) an orifice plate,

(b) a simplified nozzle (sudden pipe contraction and expansion),

(c) cylinder installed transverse to the flow in riser.

The orifice was discarded because it would have required an opening only slightly smaller than the 42" dia. riser pipe. The contraction coefficient of such an orifice would not be well defined. A cylinder welded into the 42" pipe would be quite effective in producing an additional headloss. However, the separated flow over the cylinder was feared to be Reynolds number and approach flow dependent. The analysis of the flow would have been cumbersome. The flow through a nozzle with sharp edges upstream and downstream is relatively well defined and has been previously investigated. The energy headloss induced by the nozzle is mostly due to the expansion from the small to the large diameter pipe. The associated headloss coefficient is well established and equal to 1.0. The entrance loss coefficient has been previously investigated. Experimental measurements of the sharp edged entrance loss coefficient were made by J. Weisbach and can be found e.g. in J. K. Vennard, Elementary Fluid Mechanics, 4th Ed., 1961, p. 313.

The nozzle was chosen as the most suitable device for headloss generation in risers No. 6 and 7.

Before the nozzle dimensions could be chosen, the headloss which they had to produce needed to be calculated. This was accomplished by solving two energy equations similar to equations (V-1) to (V-4) for risers 6 and 7. The equations are:

$$Q_{13}^{2}(K_{13} - 1 + K_{13-6}) = Q_{14}^{2}(K_{14} - 1 + K_{14-7} - K_{6-7} + N_{14}) \qquad \text{(V-12)}$$

$$Q_{14}^{2}(K_{14} - 1 + K_{14-7} + N_{14}) = Q_{15}^{2}(K_{15} - 1 + K_{15-8} - K_{7-8} + N_{15}) \qquad \text{(V-13)}$$

The above equations contain a nozzle loss coefficient N in addition to the previously used coefficients for exit losses from the risers and losses along the header. The above equations were solved for N_{14} and N_{15} using $Q_{13} = 104.55\%$, $Q_{14} = 105\%$, and $Q_{15} = 101\%$, $K_{13} = K_{14} = 5.6$, $K_{13-6} = 0.55$, $K_{14-7} = 0.47$, $K_{15-8} = 0.1$, $K_{6-7} = 0.32$, $K_{7-8} = 0.25$. The solution was

$$N_{14} = 0.356 \quad \text{and} \quad N_{15} = 1.30$$

The additional headlosses required for the nozzles were:

Riser No. 6: $h_{L,14} = N_{14} * \dfrac{V_{14}^{2}}{2g} = 0.356 \cdot \left(\dfrac{30.91}{3.5^{2}\pi/4}\right)^{2} \dfrac{1}{64.4}$

$= 0.057$ ft $= 0.68$ inches of water

Riser No. 7: $h_{L,15} = N_{15} * \dfrac{V_{15}^{2}}{2g} = 1.3 \cdot \left(\dfrac{30.02}{3.5^{2}\pi/4}\right)^{2} \dfrac{1}{64.4}$

$= 0.197$ ft $= 2.36$ inches of water

The actual headloss in the nozzle is the sum of entrance loss and exit loss, which can be expressed in the form

$$h_{L} = \frac{V_{s}^{2}}{2g}\left[K_{c} + \left(1 - \frac{A_{s}}{A_{L}}\right)^{2}\right] \qquad \text{(V-14)}$$

In this formula A_s is the smaller area of the nozzle and A_L is the larger one (equal to the area of the 42" riser), K_e is the entrance loss coefficient and $V_s = Q_R/A_s$ is the flow velocity in the smaller part of the nozzle. The nozzle is schematically shown in Fig. V-3.

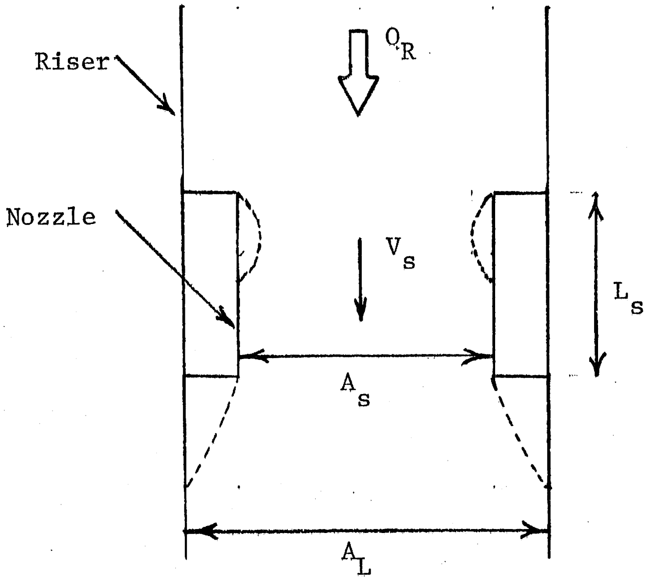

Fig. V-3 - Schematic of Flow Nozzle for Risers No. 6 and No. 7.

Equation V-14 is solved by trial and error, beginning with an assumed area ratio A_s/A_L and selection of an appropriate K_e value. The following nozzle area ratios and nozzle diameters were calculated:

Riser No.	6	7
Area Ratio	.72	0.55
Diameter D_s (inches)	35.8"	31.2"
Design D_s (inches)	36"	30"
Length of Nozzle (ft)	3.5'	4.5'

The calculated nozzle diameters were rounded to the nearest commercial sizes.

The nozzle lengths, shown above, were selected with the length of the entrance separation region in mind. The flow had to reattach before reaching the end of the nozzle. An experimental verification of this flow behavior was made subsequently.

VI. EXPERIMENTAL RESULTS FOR PARTIALLY BALANCED HEADER AND PROTOTYPE PREDICTIONS

1:12 scale models of the nozzles for risers No. 6 and No. 7 were built and experimentally tested in the header model. The dimensions of the experimental nozzles, built of lucite, and their location relative to the intake are shown in Figs. VI-1 and VI-2. The flow experiments previously described for the unbalanced header were repeated with different total flow rates. Piezometric heads were measured at all piezometric taps.

The experiments were also used to verify the nozzle loss coefficients and the reattachment of the flow within the nozzle itself. The results and observations with dye were satisfactory.

The piezometric head at various stations along the header for different total withdrawal rates is shown in Fig. VI-3. The total withdrawal rates were kept nearly the same as those used for the header experiments without any nozzles. The amount of actual flow drawn through the individual risers as a percentage of the ideal uniform flow per riser for various Reynolds number values at station 8 on the header is presented in Fig. VI-4. The measurements at the high Reynolds numbers compare favorably with the analysis (Section V).

As in the case of the unbalanced header experiments, the flow rate drawn by each riser was determined from the headloss in the individual risers between the ambient and the piezometric taps at the base of the risers. The calibration curve obtained by testing the single simplified riser Type D was used to read off the values of flow corresponding to the piezometric headloss in the risers. For the risers 6 and 7 fitted with nozzles, the additional headloss due to the nozzles is accounted for by computation prior to reading off the values of flow from the calibration curve. The riser flow percentage values in Fig. VI-4 show a slight dependence on Reynolds number as they did in the case of unbalanced header case discussed in Section III.

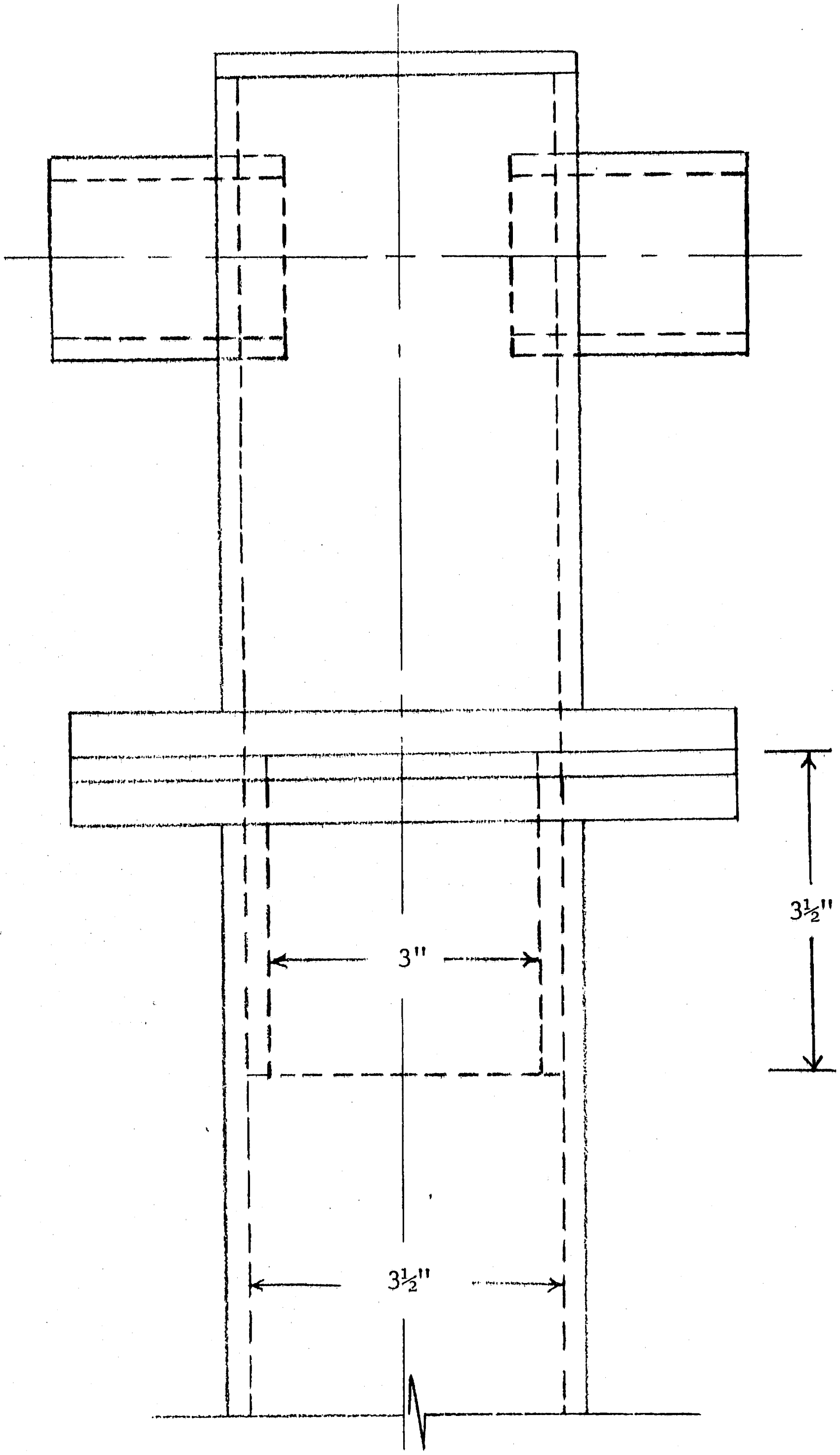

Fig. VI-1 - Scale Model (1:12) of Riser No. 6 with 3" Nozzle.

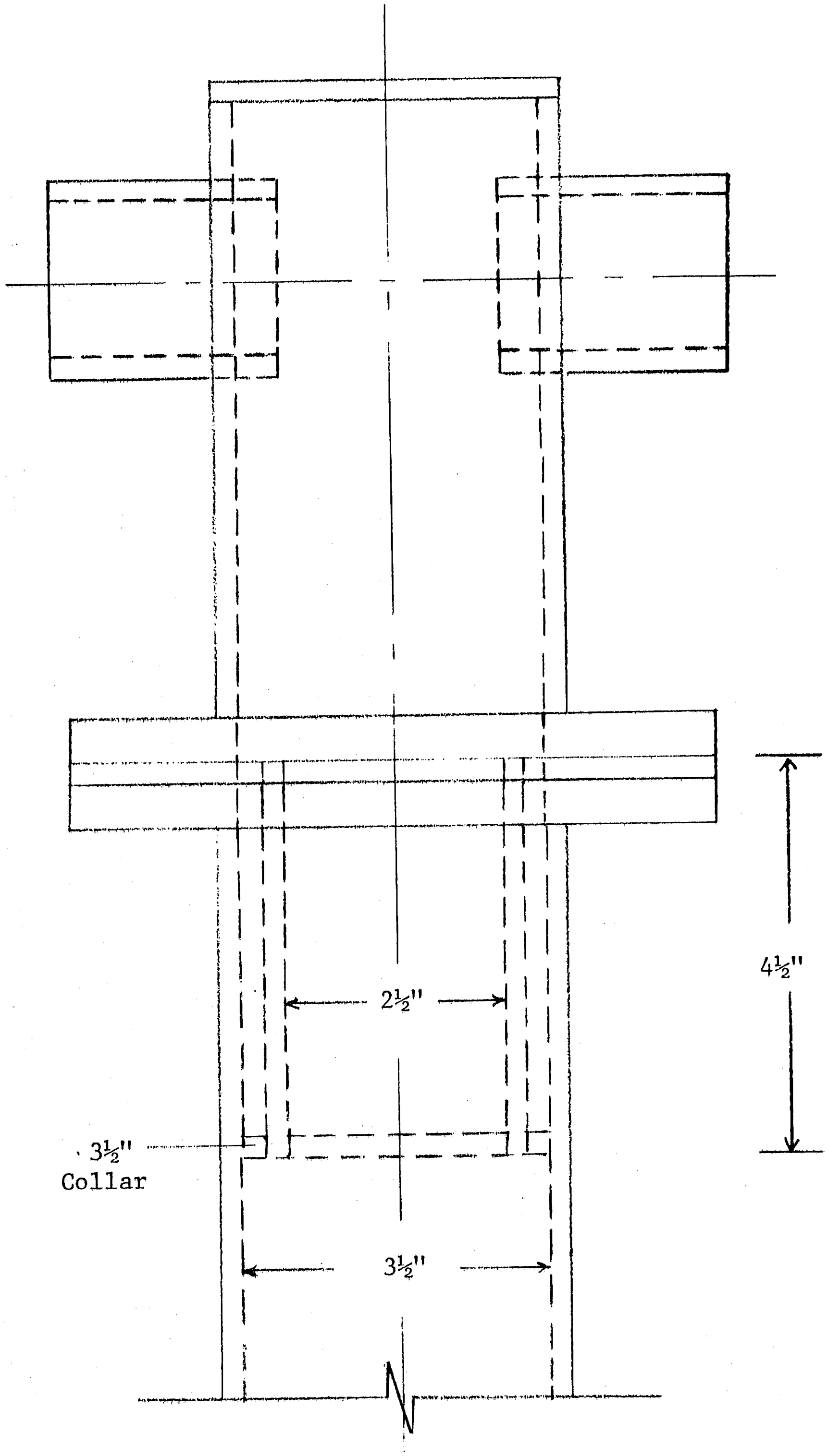

Fig. VI-2 - Scale Model (1:12) of Riser No. 7
with 2½" Nozzle.

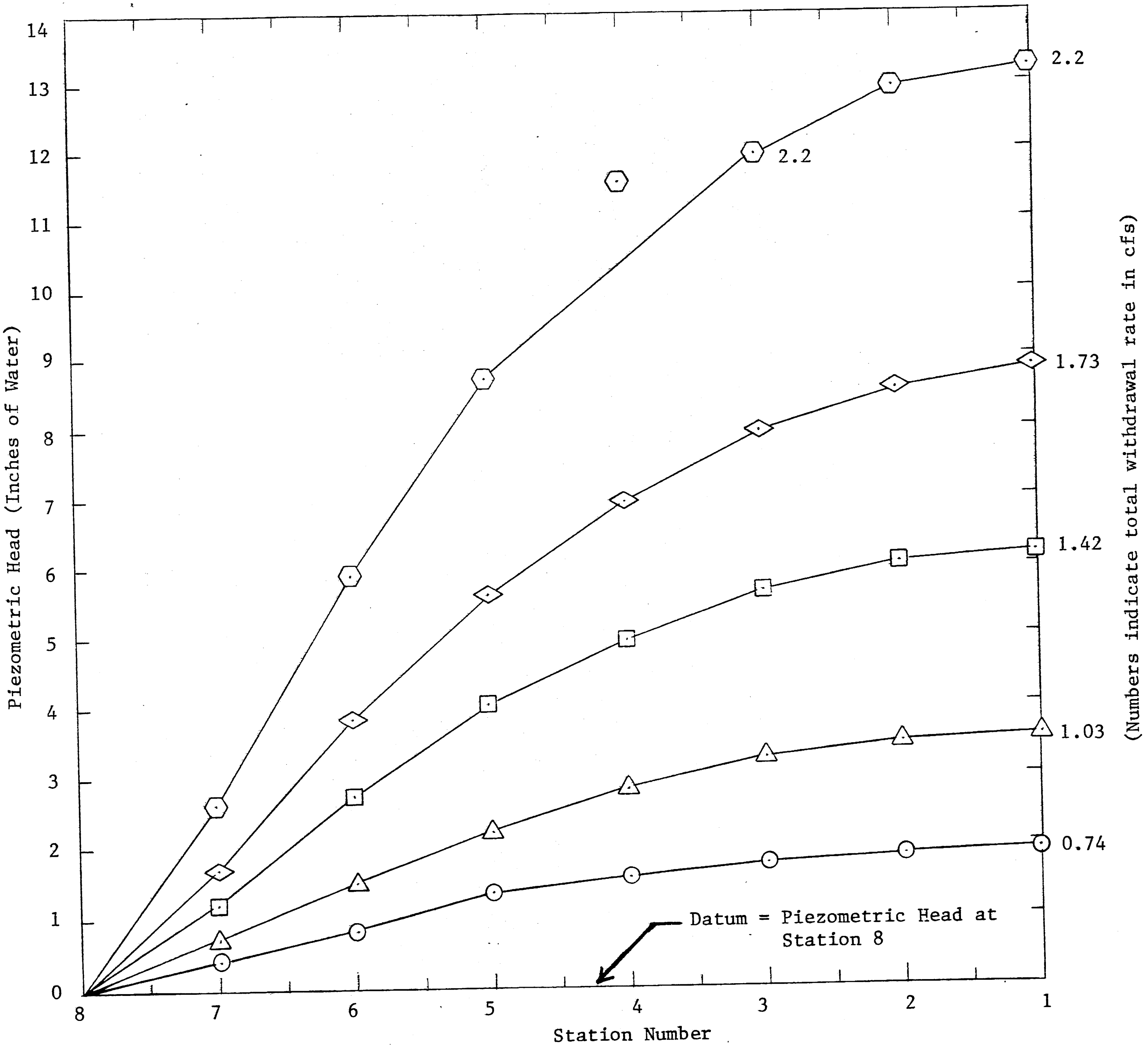

Fig. VI-3 - Piezometric Heads Along Header Axis with Nozzles in Risers 6 and 7 for Different Model Flow Rates.

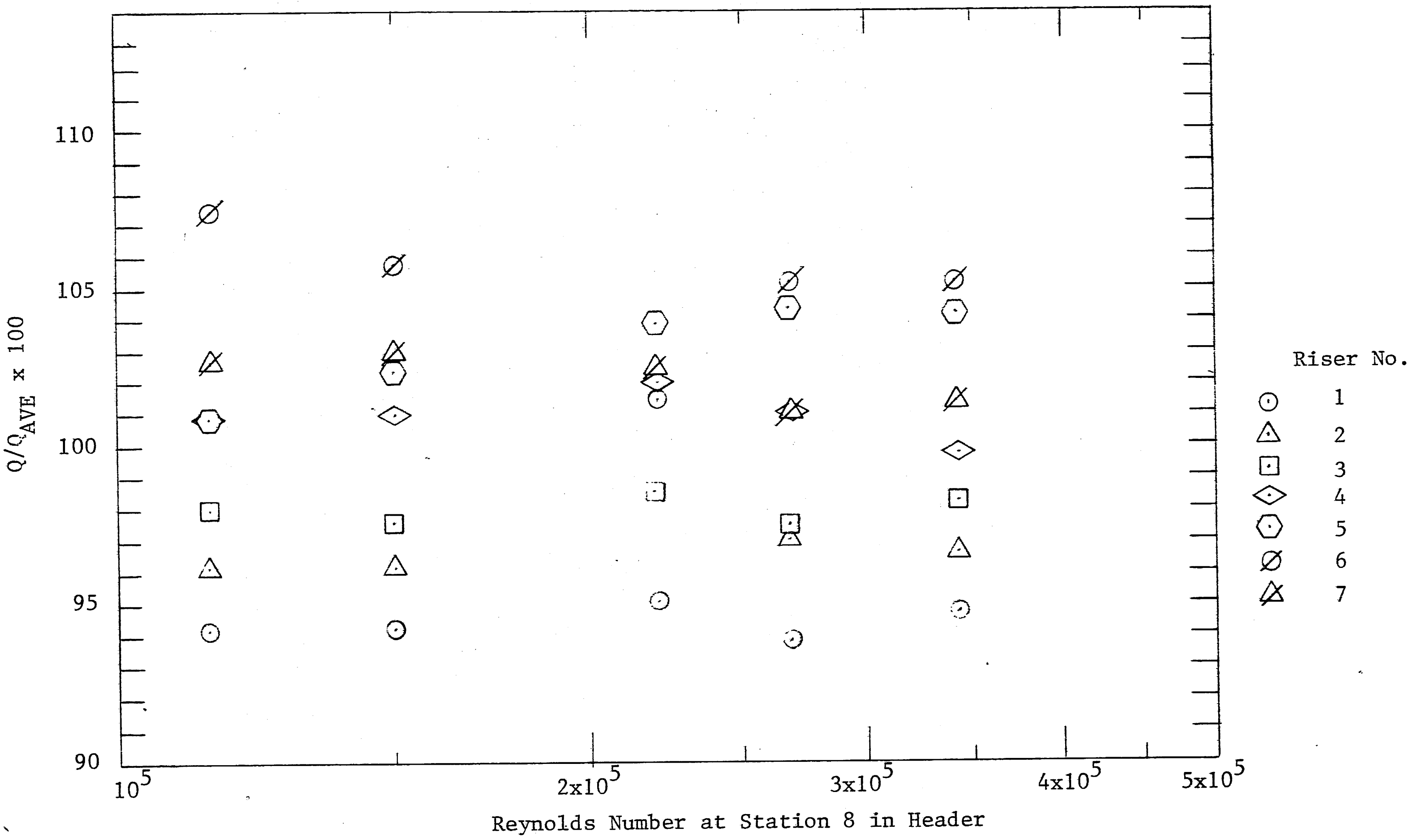

Fig. VI-4 - Percentage of Withdrawal by Individual Risers Relative to Average Withdrawal Rate as a Function of Reynolds Number for the Case of a Partially Balanced Header (Nozzles in Risers 6 and 7).

The variation of the pressure loss coefficient as a function of Reynolds number at station 8, is shown in Fig. VI-5 for stations 1 to 7. The piezometric pressure loss coefficients for stations 1 to 7 are calculated using equation (III-1),taking the piezometric pressure at station 8 at the end of the header as a reference datum.

As indicated in Section III, though maximum Reynolds number equal to that in the prototype (corresponding to the maximum total flow rate of 206.08 cfs) is not obtainable in the model test, it appears from Fig. VI-5 that the piezometric pressure loss coefficients do not vary much at high Reynolds number. Using the coefficients read from Fig. VI-5 at a maximum Reynolds number of 350,000, the piezometric head curve for the prototype header has been computed. These computed piezometric headloss values for stations 1 to 7 along the header are shown in Table VI-1.

The withdrawal rates from the seven individual risers with nozzles installed in risers 6 and 7 were computed from the experimentally determined flow percentages at high Reynolds number, shown in Fig. VI-4, with the result shown in Table VI-2.

To obtain the piezometric pressure head distribution along the header with reference to the lake, it is necessary to calculate the piezometric headloss from ambient to station 1, as described in Section III. For the partially balanced header, that value is

$$-5.4\left(\frac{27.9}{9.62}\right)^2 \frac{1}{64.4} = -0.705 \text{ ft} = -8.5 \text{ inches of water}$$

Combining this figure with those in Table VI-1, one obtains the piezometric pressure heads given in Table VI-3.

The total energy head lost between the ambient and station 8 is

$$\frac{-13.8}{12} + \left(\frac{206.08}{8^2\pi/4}\right)^2 \cdot \frac{1}{64.4} = 0.889 \text{ ft}$$

$$= 10.7 \text{ inches of water}$$

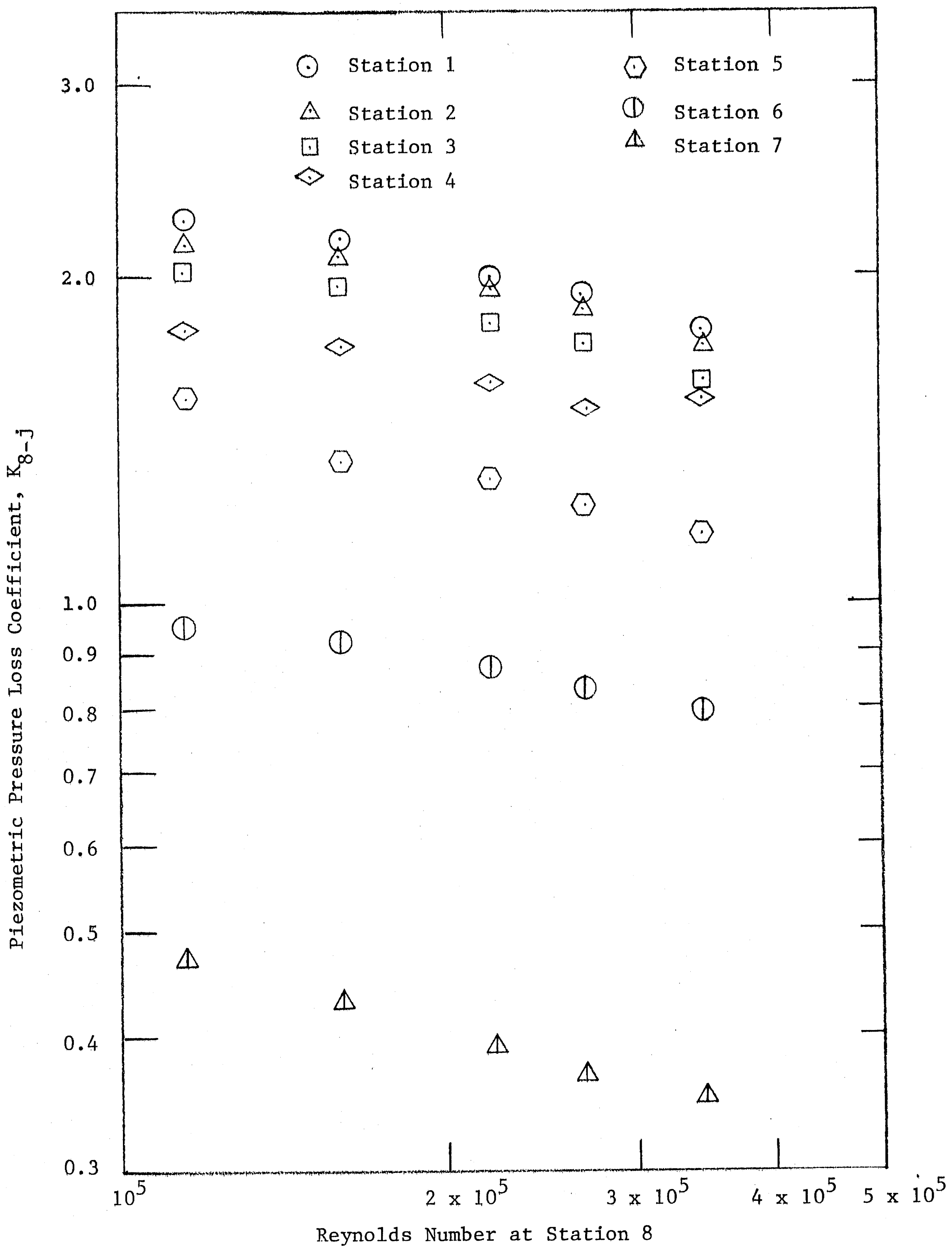

Fig. VI-5 - Piezometric Pressure Loss Coefficients, K_{8-j}, Between End of Header and Individual Stations Along Header for the Partially Balanced Header Case.

TABLE VI-1

Computed Prototype Piezometric Headlosses at Stations 1 to 7 on the Header for the Case with Nozzles in Risers 6 and 7

Total Withdrawal Rate = 29.44 * 7 = 206.08 cfs
Dia. at Station 8 = 8 ft
Velocity at Station 8 = 4.10 ft/sec
Velocity Head at Station 8 = 0.26 ft

Station No.	K_{8j} Value from Model Test	Piezometric Pressure Loss with Reference to Station 8	
		Feet of Water	Inches of Water
1	1.70	0.44	5.30
2	1.60	0.42	5.0
3	1.51	0.39	4.7
4	1.43	0.37	4.5
5	1.19	0.31	3.7
6	0.79	0.20	2.5
7	0.35	0.10	1.3
8	0	0	0

TABLE VI-2

Computed Prototype Withdrawal Rates of the Seven Risers on the Partially Balanced Header

Total Withdrawal Rate = 29.44 x 7 = 206.08 cfs
Diameter at Station 8 = 8 ft
Velocity at Station 8 = 4.10 ft/sec

Riser No.	Q/Q_{AVE}	Q cfs
1	95	27.9
2	97	28.4
3	98	28.9
4	100	29.4
5	104	30.7
6	105	31.0
7	101	29.9
Total		206.2

TABLE VI-3

Computed Prototype Piezometric Pressure Heads Along Partially Balanced Header (in Inches of Water with Ref. to Lake Level)

Total Withdrawal Rate from Partially Balanced Header = 206.08 cfs

Station No.	Piezometric Head (inches of water with ref. to lake level)
1	-8.5
2	-8.8
3	-9.1
4	-9.3
5	-10.1
6	-11.3
7	-12.5
8	-13.8

VII. CONCLUSIONS

Experimental data from the 1:12 scale model study of the intake manifold header and hydraulic analysis were used to predict withdrawal rates of individual risers, piezometric pressure heads along the header and total energy head loss between the lake and the downstream end of the header.

Results for the unbalanced header are given in Tables III-2 and III-3.

Results for a completely balanced header are given in Table IV-2.

Results for a partially balanced header are given in Table VI-2 and VI-3.

These findings are summarized in Table VII-1.

Nozzles have been designed for insertion in risers 6 and 7 to limit the withdrawal rate in any riser. The geometry of the nozzles is shown in Fig. VI-1 and Fig. VI-2. The increase in total energy headloss in the total system induced by the nozzles is negligible.

Headloss requirements for a fully balanced header have been calculated (Section IV).

No helical flow pattern was observed in the header.

TABLE VII-1

Summary of
Prototype Piezometric Pressure Heads and
Riser Withdrawal Rates

① Unbalanced header

② Partially balanced header

③ Fully balanced header

Station No.	Piezometric pressure head with reference to lake stage (inches of water)			Riser No.	Riser withdrawal rates cfs		
	①	②	③		①	②	③
1	-8.0	-8.5	-9.4				
2	-8.4	-8.8	-9.8	1	27.1	27.9	29.44
3	-8.8	-9.1	-10.4	2	27.7	28.4	29.44
4	-9.3	-9.3	-10.9	3	28.3	28.9	29.44
5	-10.0	-10.1	-11.6	4	28.9	29.4	29.44
6	-10.9	-11.3	-12.5	5	30.0	30.7	29.44
7	-12.1	-12.5	-13.8	6	31.2	31.0	29.44
8	-13.7	-13.8	-15.3	7	33.0	29.9	29.44
Total energy headloss (inches)	-10.7	-10.8	-12.2				

APPENDIX A

Riser Exit Energy Loss Coefficients

The riser exit energy headloss coefficients, designated by the notation K_{ij}, i being a point on the riser nearest to the header and j an adjacent point on the header downstream, have been derived from the laboratory tests carried out on the 1:12 header model. The loss coefficient K_{ij} for flow in the direction i to j is defined as the ratio of the total headloss between i and j to the mean velocity head of the riser flow at i; that is,

$$K_{ij} = \frac{(h_i + u_i^2/2g) - (h_j + u_j^2/2g)}{u_i^2/2g}$$

where h, u, and g are the piezometric head, velocity, and gravitational acceleration, respectively.

Results obtained in the riser Reynolds number range of 200,000 to 350,000 are tabulated in Table A-1 and also plotted as a function of Q_i/Q_j in Fig. V-1. The values of these coefficients read from the charts given by D. S. Miller, BHRA (Ref. on p. 31), are given in Table A-2 and shown plotted in Fig. V-1.

TABLE A-1

Riser Exit Loss Coefficients K_{ij} for Riser Reynolds Numbers Greater Than 250,000

(Computed from Model Test Data)

Riser Number	Riser Reynolds Number	Q_i/Q_j	K_{ij}
1	284,000	1.000	0.94
	292,000	1.000	0.99
2	289,000	0.505	0.84
	301,000	0.508	0.84
3	295,000	0.340	0.74
	306,000	0.340	0.71
4	253,000	0.259	0.72
	302,000	0.258	0.66
	312,000	0.258	0.71
5	201,000	0.210	0.70
	206,000	0.211	0.62
	261,000	0.211	0.57
	312,000	0.211	0.51
	324,000	0.211	0.54
6	253,000	0.180	0.47
	271,000	0.180	0.45
	324,000	0.179	0.47
	338,000	0.181	0.30
7	268,000	0.160	0.09
	285,000	0.159	0.14
	343,000	0.160	0.04
	359,000	0.161	0.03

TABLE A-2

Riser Exit Loss Coefficients K_{ij}

(Read from BHRA Charts)

$$\text{Area Ratio} = \frac{A_i}{A_j} = 0.1914$$

Q_i/Q_j	K_{ij}
0.11	-1.21
0.13	-0.43
0.14	0
0.155	+0.30
0.175	0.47
0.205	0.52
0.230	0.55
0.260	0.54
0.280	0.70
0.320	0.71
0.365	0.68
0.390	0.72
0.460	0.69
0.520	0.67
0.595	0.62
0.690	0.61

APPENDIX B

Headloss Coefficients Along Header

The headloss coefficients along header designated by the notation $K'_{j-1,j}$, $j-1$, and j being adjacent points on the header on either side of a riser, is defined as the ratio of the headloss between points $j-1$ and j expressed as a ratio of the mean velocity of the combined flow (in our case at point j); that is,

$$K'_{j-1,j} = \frac{\left(h_{j-1} + \frac{u_{j-1}^{2}}{2g}\right) - \left(h_j + \frac{u_j^{2}}{2g}\right)}{u_j^{2}/2g} \qquad \text{(B-1)}$$

h and u standing for piezometric head and velocity, respectively. It can also be written as

$$K'_{j-1,j} = \frac{h_{j-1} - h_j}{u_j^{2}/2g} + \left(\frac{Q_{j-1}}{Q_j}\right)^{2} - 1 \qquad \text{(B-2)}$$

The values of $K'_{j-1,j}$ have been computed from the results of tests on the 1:12 header model conducted in the laboratory and tabulated in Table B-1.

When considering individual risers, it will be more useful to express the headloss between stations on the header on either side of the riser in terms of the mean velocity head in the riser. The corresponding headloss coefficient will then be given by

$$K_{j-1,j} = \frac{\left(h_{j-1} + \frac{u_{j-1}^{2}}{2g}\right) - \left(h_j + \frac{u_j^{2}}{2g}\right)}{u_i^{2}/2g} \qquad \text{(B-3)}$$

where u_i is the velocity in the riser.

The coefficients $K_{j-1,j}$ and $K'_{j-1,j}$ will be related by the equation

$$K_{j-1,j} = K'_{j-1,j} \left(\frac{Q_j}{Q_i}\right)^2 \left(\frac{A_i}{A_j}\right)^2 \qquad \text{(B-4)}$$

where A represents the area of cross-section. Average values of $K_{j-1,j}$ and the corresponding $K'_{j-1,j}$ calculated for each riser are also shown in Table B-2.

Values of $K_{j-1,j}$ have been plotted in Fig. V-2 against the ratio Q_i/Q_j where Q_i is the flow in the riser between points j-1 and j. The values of these coefficients as read from the charts given by D. S. Miller, BHRA (Ref. on p. 31) are given in Table B-2 and also shown plotted in Fig. V-2.

TABLE B-1

Headloss Coefficients Along Header

(Computed from Model Test Data)

Riser No.	Q_i/Q_j	$K'_{j-1,j}$	$K_{j-1,j}$
1	1.000	2.742	
	1.000	5.020	
	1.000	6.862	
	1.000	2.058	
Average	1.000	4.171	0.153
2	0.504	1.084	
	0.507	0.997	
	0.508	1.344	
	0.505	0.925	
Average	0.506	1.088	0.156
3	0.339	0.642	
	0.337	0.594	
	0.340	0.433	
	0.340	0.411	
Average	0.340	0.520	0.165
4	0.258	0.435	
	0.259	0.393	
	0.258	0.375	
	0.258	0.400	
Average	0.258	0.401	0.221
5	0.211	0.311	
	0.211	0.263	
	0.211	0.278	
	0.211	0.292	
Average	0.211	0.286	0.235
6	0.180	0.320	
	0.180	0.291	
	0.181	0.245	
	0.179	0.292	
Average	0.180	0.287	0.324

TABLE B-1 (Cont.)

Riser No.	Q_i/Q_j	$K'_{j-1,j}$	$K_{j-1,j}$
7	0.160	0.163	
	0.159	0.188	
	0.161	0.206	
	0.160	0.130	
Average	0.160	0.172	0.246

TABLE B-2

Headloss Coefficients Along Header

(Read from BHRA Charts)

Area Ratio = A_i/A_j = 0.1914

Q_i/Q_j	$K'_{j-1,j}$	$K_{j-1,j}$
0.125	.2	0.469
0.195	.3	0.289
0.265	.4	0.209
0.335	.5	0.168
0.410	.6	0.131
0.500	.7	0.103
0.590	.8	0.084
0.675	.9	0.072

APPENDIX C

Summary of the Experimental Data on Energy Loss in Nozzles

In order to study the effect of introducing nozzles in risers 6 and 7, a series of tests was run with each of these two risers running individually. As the average maximum prototype flow through each riser of 29.44 cfs corresponds to 0.204 cfs in the model, the tests were run to cover a range of flow rates from 0.2 to 0.3 cfs.

Expressing the total energy head lost in the nozzle as the sum of the losses due to sudden contraction and subsequent expansion, the headloss h_L in the nozzle can be written as

$$h_L = \frac{u_s^2}{2g} \left[K_e + (1 - u_L/u_s)^2\right]$$

where u is the velocity and the suffixes L and s refer to the larger (riser) and the smaller (nozzle) cross-sections, respectively, and K_e is the coefficient of loss at the entrance. The computed values of K_e and the corresponding values read from BHRA charts and used in the analysis are given in Table C-1.

TABLE C-1

Nozzle Contraction Loss Coefficients

Riser No.	Model Test Data			From BHRA Chart
	Riser Reynolds Number	Header Reynolds Number	K_e	
	(10^5)	(10^5)		
6	0.533	0.233	0.22	Riser Dia. = 3.5"
	0.640	0.280	0.20	Nozzle Dia. = 3.0"
	0.720	0.315	0.14	Area Ratio = 0.7347
	0.795	0.348	0.19	K_e = 0.10
7	0.533	0.233	0.21	Riser Dia. = 3.5"
	0.640	0.280	0.20	Nozzle Dia. = 2.5"
	0.720	0.315	0.18	Area Ratio = 0.5102
	0.795	0.348	0.22	K_e = 0.23