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GENERAL CONSIDERATIONS OF FLOW IN BRANCHING CONDUITS *

By

Thomas J. Rhone[1]
M. ASCE

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INTRODUCTION

In late 1968, the Executive Committee of the Hydraulics Division of the ASCE approved the organization of the Task Committee on Branching Conduits. This Task Committee was given the assignment of summarizing and advancing the state of knowledge pertaining to flow phenomena in branching conduits and manifolds; to prepare a report for ASCE publication on standards useful to designers for branching conduits, complete with bibliography; to make recommendations and to encourage research leading to definition of design parameters; and to encourage preparation and publication of papers on the subject. Since work was being done on conduit systems for navigation locks by a committee of the Waterways and Harbors Division, the Task Committee was not required to study that aspect of branching conduits. Also to reduce the time involved, it was decided to direct the activities of the Task Committee to larger conduits, thus excluding the more standard plumbing fittings and air ducts.

Six papers have been prepared by the Task Committee. The first, "Junction Losses in Laminar Transitional Flows," by Donald K. Jamison and James R. Villemonte, was published in the Journal of the Hydraulics Division, Volume 97, Hy 7, July 1971 (Proc. Paper 8258). The second, "Dividing Flow in Branches and Wyes," by James V. Williamson and Thomas J. Rhone, was published in the Journal of the Hydraulics Division, Volume 99, Hy 5, May 1973 (Proc. Paper 9729). The other four papers, three of a technical nature and this one of general considerations are presented at this Hydraulics Division Specialty Conference.

In general the nomenclature and terminology used by the Committee conform to that recommended by the British Hydromechanics Research Association reports.(3)* The terminology used for the various configurations is shown on Figure 1.

The purposes of investigations on branches are to determine energy losses; pressure fluctuations, to determine whether the pressures are

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[1] Hydraulic Engineer, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado.
* Numbers refer to references in the appendix.

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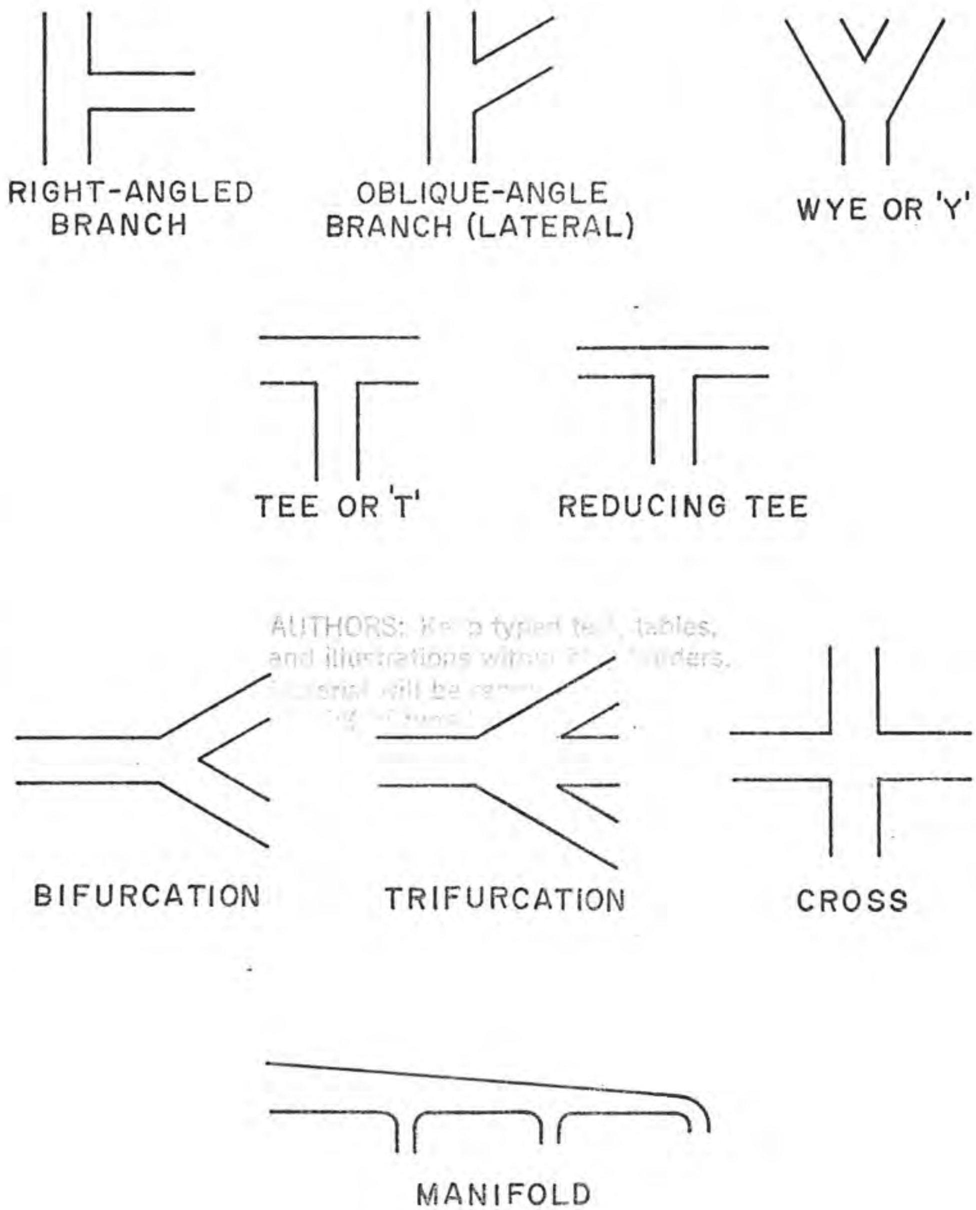


BASIC CONFIGURATIONS
TERMINOLOGY
FIGURE I

high (impact) or low (cavitation); and the relation of hydraulic losses to structural considerations in large conduits, particularly as they influence the economics. Generally, losses at branches are relatively minor, but they become significant under certain conditions, such as low head cooling water systems in powerplants, and in hydroelectric conduits where the value of the power is considerable. In these cases individual efforts are made to reduce losses by modifying the branches. On the other hand, heating and air-conditioning systems usually consist of a variety of standard ducts and bends selected and assembled to meet a particular specification. Higher losses are often tolerated in the interest of ease of manufacture or assembly.

Current Trends

There is a current trend toward increasing the allowable design velocities in conduits. This practice is to offset the increasing costs of structural materials where the cost-benefit ratio can be improved. In structures where limited head is available and large quantities of water are needed higher flow velocities are especially advantageous. In any case the optimum design of a supply system is a favorable compromise of the energy losses on one hand and the construction costs on the other. Structural design and economic considerations also can cause deviation from an optimum hydraulic design. Escher Wyss and Krupp have successfully developed excellent hydraulic and structural designs for dividing flow structures.(7)

Pumped-storage projects are becoming an increasingly important part of the hydroelectric scheme as peak power producers. The hydraulic design of a two-directional hydraulic system is comparatively new and needs considerable improvement.

Included in the new technology of designing for higher velocities, larger flow quantities and two-way flow should be a careful analysis of bifurcations, wye branches, trifurcations, manifolds, etc., so that they are equally efficient for merging flow and dividing flow modes. In considering internal losses in the water conveyance system of a pumped-storage project, it should be noted that the head losses occur twice during a complete operational cycle, affecting economics by an increase in expense during the pumping cycle and a loss in revenue during the generating cycle. What may be a desirable configuration during one mode, might be objectionable during the opposite mode.

BRANCHING CONDUIT INVESTIGATIONS

Types of Flow

In general there are three types of branching conduits:

1. One or more branches from the side, top, or bottom of a main conduit. A manifold would be included in this category.

2. Symmetrical bifurcation at the end of a main conduit; usually the area of the two branches equals the area of the main conduit.

3. Symmetrical trifurcation at the end of a main conduit. Here also the area of the three branches equals the area of the main conduit.

The types of flow which have been investigated are dividing, combining, reverse combining, and reverse uniting, as shown on Figure 2.

The head losses at a branch are a function of the amount of flow diverted into the branch, the angle of takeoff of the branch, the ratio of the area of the branch to the main conduit and the type of entry such as sharp cornered, rounded, or conical, and other considerations such as filler blocks, vanes, and deflectors.

The inlet conditions which affect losses are velocity distribution, swirl, asymmetry, etc. The effect of inlet and outlet conditions can be eliminated for experimental purposes by providing long straight pipes upstream of the branch to establish fully developed flow at the inlet and downstream to allow the flow to become fully developed after passing through the branch. It is doubtful whether these conditions were maintained in a number of the experiments.

Theoretical Considerations

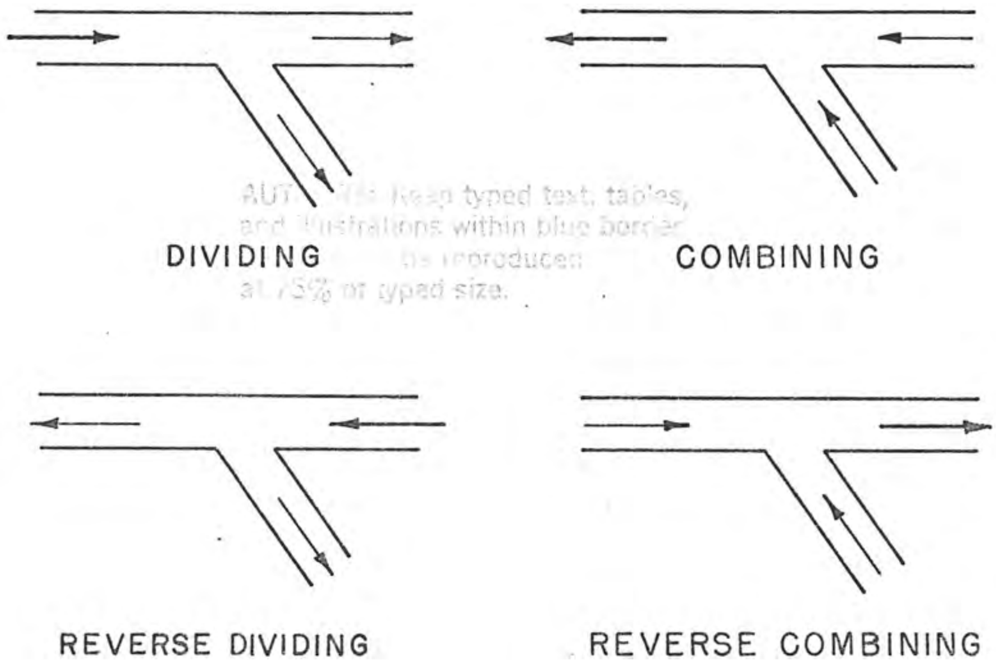
Theoretical investigations can be divided into the use of the free streamline theory and the use of the momentum principle.

1. Free streamline theory

This theory is based on the flow having a boundary which is a streamline at constant pressure. This theory is usually applied to divided flows in closed conduits by analyzing the situation where the flow emerges through a slot or orifice in the side of a pipe. Once the theoretical shape of the issuing jet has been established the pipe walls are shaped to follow the curve of the free streamlines as closely as possible to reduce the loss. Results from this theory have been confirmed by experiments for very simple flow configurations. Difficulty of application occurs with more elaborate fittings which are known to give lower head losses. The inclusion of tapered entrances to branch pipes, rounded corners, and guide vanes complicates the problem beyond the scope of the technique.

2. Momentum principle

The use of the momentum principle provides a more successful approach to the theoretical analysis of losses at branches and the results from these analyses usually agree well with experimental results. The losses are assumed to be partly due to the deflection of flow and partly to the reexpansion of the stream from a vena contracta formed just after the branch.



TYPES OF FLOW
FIGURE 2

The advantage of using momentum equations is that they may be generally applied to both dividing and combining flow. So far their reliability has been checked in cases of flow in branches at low Reynolds Number; their validity has not been checked widely using higher values of Reynolds Number. As with the free streamline theory, this technique cannot predict the performance if improvements are obtained by rounding corners or tapering the entry sections to a branch.

Experimental Studies

The British Hydromechanics Research Association,(3) has published a review of literature on the division and combination of flows in closed conduits. The review abstracts 60 references dating back to 1925. The stated purpose of the review was to provide an introduction to future experimental work and no attempt was made to correlate data. The report concluded that the majority of experimenters publish their results without attempting to analyze the problem or to relate the results to any theory. Some writers use a theoretical approach and compare this with experimental results of others. As might be expected this has proven difficult due to the diversity of conditions in which experiments have been performed and the methods of presenting the results.

Most of the information available on the losses in branching conduits is concerned with specific installations. The studies were performed as a design aid and the results were seldom suitable for generalization. The lack of generalized design data can be understood by considering the wide variety of configurations that are possible when the types of branches can vary from large air distribution systems to hydraulic structures to small plumbing fixtures.

The majority of the papers were of specific hydraulic structures and the investigator made the results available to the profession for what they were worth. The other papers were studies made in a sincere effort to increase the available technical knowledge of the subject. Many of the studies were performed with very small conduits, often less than 1 inch in diameter. The results are of doubtful value. Air was used as the flowing fluid in some studies but in most cases water was used. Many types of instrumentation were described but since some of the studies date back to 1930, or earlier, water and air manometers were the predominant means of pressure measurement. Velocities were generally a discharge-area ratio although occasionally careful Pitot tube traverses were made. The Reynolds Numbers of the flow, where reported, were always well into the turbulent range.

Supporting prototype field data were almost nonexistent. The small amount that was reported could not be considered supportive since it was usually very erratic. A conclusion offered in a Bureau of Reclamation study was that, based on careful studies of similar branches on small (3-inch-diameter) and large (10-inch-diameter) conduits, comparative head loss coefficients were smaller in the large conduits. They concluded that this indicated a full size structure would probably have smaller losses than a model would indicate.

In 1971 the British Hydromechanics Research Association published another reference, "Internal Flow, a Guide to Losses in Pipe and Duct Systems"(5) that presents experimentally measured pressure loss coefficients. The book contains results from an extensive 3-year experimental project combined with reliable data extracted from the literature. One section of the book is on the performance of dividing and combining tees, and in many respects provides parallel information to that being developed by our Task Committee.

Other experimental works of a general nature and described by Williamson and Rhone(7) were the early, and probably most comprehensive, experiments conducted for dividing and combining flows at the Hydraulic Institute of Munich Technical University from 1928 through 1931, similar experiments by Gardel at Lausanne, and some experiments of a general nature at the Iowa Institute of Hydraulic Research.

Some excellent comprehensive experimental studies on merging flow were performed by F. W. Blaisdell and P. W. Manson(2) and studies on combining and dividing manifold flow by J. S. McNown.(4) These studies and others, both theoretical and experimental are discussed in other papers of the Task Committee.

Branch Spacing

Villemonte describes a junction as basically a disturbance of a normal turbulence pattern of straight pipe flow. The turbulence in the straight through flow has a definite settling length before normal turbulence patterns are reestablished. The head loss pattern in a second branch depends on its exit location with respect to the disturbance caused by the upstream branch. McNown and McCaig state that, if the main conduit is large relative to the size of the combined laterals or outlets, the velocity head of flow in the main is negligible. The conduit then serves as a high-pressure, comparatively quiescent reservoir, and the pattern of flow at any lateral is like that of any other. If the conduit is relatively small, the velocity in the pipe is large, and the efficiency of the efflux depends in part upon this velocity. Muller and Stratmann(6) determined that it was advantageous with respect to the loss in the downstream branch of a manifold-type branch, to keep the spacing as close as possible. They also found that less loss occurred if as much flow as possible was diverted into the upstream branch. Their explanation for this anomaly was that it was due to the flow asymmetry of the velocity profile after the first branch. Their measurements indicated that the slower flowing boundary layer fluid was to a large extent led off into the first branch, the flow in the through portion was deflected to the side containing the second branch thus the branch flow was made up of relatively higher velocity flow.

Flow Disturbance

Since branching flow is a disturbance to the normal turbulence pattern of straight pipe flow, it follows that if a branch is not correctly shaped poor flow distribution might result and lead to adverse pressure distribution, vibration, and other damaging hydraulic conditions.

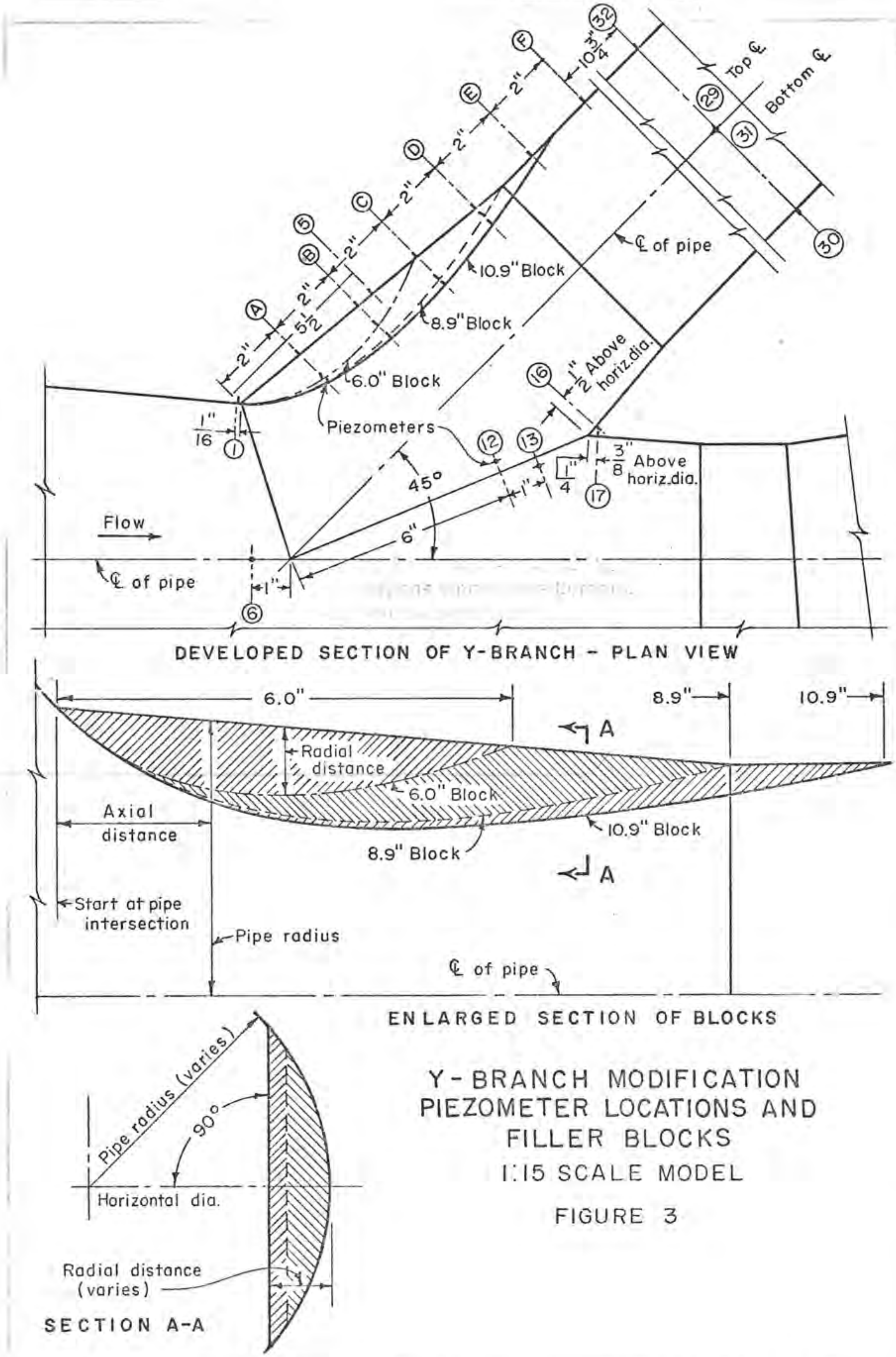
After one of the outlet works at Falcon Dam on the Rio Grande was placed in operation, it was reported that there was vibration and noise in the wye branch and a butterfly valve in the left branch tended to vibrate and move toward the closed position. Corrective measures were tried in the field but were found to be ineffective. The movements and sounds had a period of from 2 to 3 seconds. The sounds were referred to as cavitation sounds having a loud and heavy thumping or slapping nature. The conditions were believed to result from turbulence originating at the junction. A model used for calibration of the valves in the system was used to determine corrective measures for the branch.(1) To determine pressure variations and intensities, piezometers were installed in critical pressure zones, Figure 3. Pressure measurements showed that pressure variations and instantaneous low pressures were more severe when the flow was equally divided between the two legs of the branch. The fluctuations appeared to be the result of a zone of turbulence along the left side of the left branch. In the initial tests instantaneous pressures fluctuated from 48 feet of water above atmospheric to 16.5 feet of water below atmospheric. A review of test results from models of the penstock branches for Hoover Dam (Part VI, Bulletin No. 2, Boulder Canyon Project Final Reports) disclosed that when filler blocks were placed to occupy turbulent zones the turbulent flow was reduced. Several filler blocks were tested in the model and a block was recommended for prototype installation that decreased the magnitude of the fluctuations to approximately 19.5 feet of water and kept the minimum instantaneous pressures well above vapor pressure.

Prototype Tests

There is a paucity of information on tests on completed structures. Those performed by Sulzer at Lucendro Power Station(7) and by Escher Wyss at Olivone Power Station,(7) indicate reasonable consistency between model and prototype measurements. Conversely, other studies have shown considerable deviation from model investigations. The structures that showed the greatest inconsistencies were usually the converging manifolds in powerplants.

CONCLUSION

A review of the literature shows that the configurations of branches and manifolds used to combine or divide flows are many and diverse. The terminology and definitions used in describing the structure and the flow phenomena are equally varied and the attempts of experimenters to generalize on design criteria show how complex the problem is. One thesis that was repeated over and over was that the published information is adequate for preliminary designs but model investigations are essential to assure a satisfactorily operating structure. Well documented information on prototype operation is almost nonexistent and every attempt should be made to further the knowledge in this field. It is hoped that the work of the Task Committee will be of some aid in reducing the confusion in nomenclature and definition as well as providing some consistency in presenting the previously published experimental data. Recommended head loss coefficient curves developed



Y-BRANCH MODIFICATION
PIEZOMETER LOCATIONS AND
FILLER BLOCKS
1:15 SCALE MODEL

FIGURE 3

from an analysis of this data should be of significant assistance to the practicing design engineer.

APPENDIX

1. Ball, J. W., "Calibration of Hollow-Jet Valves and Vibration Studies of the Outlet Works Y-Branch, Falcon Dam." Report Hyd 474, U.S. Bureau of Reclamation, October 25, 1960.

2. Blaisdell, F. W. and Manson, Phillip W., "Energy Loss at Pipe Junctions," Journal of the Irrigation and Drainage Division, ASCE, Vol 93, No. 1R-3, September 1967.

3. Crow, D. A. and Wharton, F., "A Review of Literature on the Division and Combination of Flow in Closed Conduits," British Hydromechanics Research Association, January 1968.

4. McNown, John S., "Mechanics of Manifold Flow," Transactions ASCE, Vol 119, 1954.

5. Miller, D., "Internal Flow - A Guide to Losses in Pipe and Duct Systems." British Hydromechanics Research Association, Fluid Engineering, November 1971.

6. Muller, W. and Stratmann, H., "Pressure Losses in Branch Pipes and Distributors," Sulzer Technical Review, Vol 93, 1971. No. 4.

7. Williamson, J. V. and Rhone, T. J., "Dividing Flow in Branches and Wyes," Journal of the Hydraulics Division, ASCE, Vol 99 No. Hy 5, 1 May 1973.