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LOW-VELOCITY AIR TESTING APPLIED
TO HYDRAULIC PROBLEMS

BY

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INTRODUCTION

The title of my paper is "Low-Velocity Air Testing Applied to Hydraulic Problems." It will be presented from the viewpoint of the hydraulic engineer since my professional experience has been almost exclusively in this field of engineering.

Scope of Paper

The discussion will concern the use of low-velocity air in testing closed hydraulic systems, or testing in which air can be substituted for water without introducing any appreciable error due to compressibility. It will deal with the advantages, disadvantages, errors to be expected, and the cautions to be observed when the hydraulic engineer employs this method of testing.

Definition of Low-Velocity Air Testing

For the purpose of this paper, low air velocities will be considered those which for all practical purposes yield the same results as hydraulic tests. These velocities usually range up to about 250 feet per second or about 25 percent of sonic speed, depending upon the nature of the particular problem.

History of Air Testing

Air testing, or aerodynamic testing as it is commonly termed, in itself is not new, but the technique of using low-velocity air as a fluid in obtaining solutions to hydraulic problems is of fairly recent development. We find references to aerodynamic testing in the early part of the twentieth century, but these usually deal either directly with aircraft research or pertain to fluid mechanics research and not to testing of the type under discussion at this time. In this early research work the experimental data from tests using different fluids, including air and water, were combined to illustrate a fundamental law or principle rather than to prove that air could be substituted for water in determining the flow characteristics of hydraulic systems. It has been only within recent years that low-velocity air testing has been used in solving problems of this nature. Among the first to make use of this method, and a pioneer in this field, was Dr. C. Keller of the Swiss firm, Escher Wyss Company. Some of Dr. Keller's work was published as early as 1937. In 1939 he was co-author of an article on air testing of turbines published in the Escher Wyss News and entitled, "A Method for Determining the Cavitation Factor by Air Tests." In the same year this engineering periodical published another article "New Method of Aerodynamic Research," which cited some of Dr. Keller's work and discussed low-velocity air testing of hydraulic and steam-operated machines. Everything set forth in this article is just as applicable today when we find leading engineering organizations, universities, and private industries using air testing as a low-cost useful tool to solve some of their hydraulic problems.

Instruments, test equipment, and measuring techniques are beyond the scope of this paper but they offer no problem in low-velocity air testing because they have been highly developed through the extensive aerodynamic work pertaining to aircraft design. On the other hand, much work still can be done towards defining the limits where aerodynamic testing can be substituted for hydraulic testing. Some of the limits already established will be discussed later.

Increasing Use and Advantages of Low-Velocity Air Testing

There are numerous reasons why low-velocity air testing is gaining popularity with hydraulic engineers. The following advantages contribute mainly to this popularity:

a. Because of the low density of air the structural requirements of the test facilities are a minimum

b. For the same reason power requirements to circulate the test fluid are comparatively low

c. Absolute fluid tightness is not essential but more easily attained. Wetting problem nonexistent which permits use of a wide variety of materials

d. Atmosphere serves both as a supply reservoir and a catch basin

e. Test procedure usually greatly simplified, but requires certain types of more highly developed and sensitive instruments

f. Reynold's numbers can be made about the same for either air or water in a given model. Use of a larger model to test at a higher Reynold's number might be advantageous in some cases

g. The relationships for non-compressible fluids can be applied with negligible error if the air velocities are kept below certain values (less than 1/4 sonic speed)

I am sure that you will agree without further explanation that all except the last item are advantages which result directly when air is used instead of water for studying the flow characteristics of closed hydraulic systems. However, without proof you might question whether or not the simple relationships for an incompressible fluid are applicable when air is used in place of water. I will endeavor to supply this proof without going into extensive mathematical details.

Indicated Disadvantages

Before continuing with the discussion, however, it would seem appropriate to mention some of the disadvantages of using air as a test medium and to emphasize that the discussion today applies principally to systems of short length where friction is not a major consideration. Air has a comparatively low bulk modulus, it does not become discontinuous as in the case of liquids when the vapor pressures of the liquids are reached, and since it is a gas there is no free surface. From these properties it would seem that air could not be used to replace a liquid where effects of compressibility, cavitation, and gravity are predominating factors. This is not always the case but one must be sufficiently familiar with the dynamics of gaseous flow in order to recognize when such studies are applicable. The following discussion concerning the use of the equations for incompressible flow will indicate the limits where compressibility is of little or no consequence. A logical and valid conclusion without the aid of mathematics, would be that the velocity of sound for the test medium should not be exceeded in any event, since beyond this point it is not valid to assume the condition of adiabatic changes. A more elaborate theoretical treatment of the problem is required in such cases.

A pertinent question at this point would be, how near sonic velocity can the speed of the air be without introducing errors of appreciable magnitude?

Application and Limitations of Formulas for Incompressible Flow

It can be shown that large errors are introduced by using velocities near sonic when the simpler hydraulic relationships are applied. This being the case, it would appear that the first problem of a hydraulic engineer wishing to use air instead of water for testing a hydraulic system would be to determine the maximum air velocity for his particular study.

In most problems, if the test velocities are kept low and there are no large changes in pressure or velocity, it will not be necessary to make an evaluation of the compressibility effects. However, if there is some question as to whether or not the compressibility effects should be of concern this evaluation can be made as will now be outlined. The problem may or may not be easy depending upon how difficult it is to establish approximate expressions for the flow conditions as regards the relationships for pressures and velocities for both incompressible and compressible flow. The maximum permissible velocity for the problem can be determined by setting up the expressions for incompressible and compressible flow for the pressures at two carefully selected points, computing the pressure change from one point to the other for both types of flow, and plotting these against the respective velocities at the reference point.

If the velocity of the air is kept within the range where the pressure difference between the two selected points is essentially the same for both types of flow, then the simpler hydraulic relationships can be used in analyzing the test data from a hydraulic system using air instead of water as the test medium.

The velocity of the air which will give results within a given percent of accuracy in a given system can be found by considering the following two general equations for incompressible and compressible flow which are derived from the Bernoulli relationship between the two points.

$$\frac{h_1}{h_o} = 1 - \frac{1}{2gh_o} \left(V_1^2 - V_o^2\right) \qquad \text{(incompressible flow)}$$

and

$$\frac{h_1}{h_o} = \left[1 - \frac{K-1}{2} \frac{\left(V_1^2 - V_o^2\right)}{C_o^2}\right]^{\frac{K}{K-1}} \qquad \text{(compressible flow)}$$

where h is pressure head, V is velocity, g is acceleration of gravity, K is the gas constant, C is the acoustic velocity, and the subscripts o and 1 refer to the reference station and selected station, respectively. For the type of testing now being considered all velocities are much less than sonic and all pressures will be near atmosphere. Therefore, the term $\frac{K-1}{2} \frac{\left(V_1^2 - V_o^2\right)}{C_o^2}$ will be less than unity and the right side of the equation can be expanded into a convergent series by means of the bionomical theorem and may be written

$$\frac{h_1}{h_o} = 1 - \frac{K}{2C_o^2} \left(V_1^2 - V_o^2\right) \left[1 - \frac{\left(V_1^2 - V_o^2\right)}{4C_o^2} - \frac{K-2}{24} \frac{\left(V_1^2 - V_o^2\right)^2}{C_o^4} \cdots\right]$$

also V_1 can be expressed in terms of V_o as, $V_1 = \beta V_o$, where β is the ratio of flow areas $\frac{A_o}{A_1}$. Then

$$\frac{h_1}{h_o} = 1 - \frac{K}{2C_o^2} V_o^2 (\beta^2 - 1)\left[1 - \frac{V_o^2}{4C_o^2}(\beta^2 - 1) - \frac{(K-2)}{24}\frac{V_o^4}{C_o^4}(\beta^2 - 1)^2 \cdots\right]$$

or

$$h_1 - h_o = \frac{-1}{2g} V_o^2 (\beta^2 - 1)\left[1 - \frac{1}{4}\frac{V_o^2}{C_o^2}(\beta^2 - 1) - \frac{(K-2)}{24}\frac{V_o^4}{C_o^4}(\beta^2 - 1)^2 \cdots\right]$$

since $\frac{h_o k}{C_o^2} = \frac{1}{g}$

also for incompressible flow

$$h_1 - h_o = -\frac{1}{2g} V_o^2 (\beta^2 - 1)$$

Examination of these equations shows that the relative magnitude of the compressibility effects will be reflected only in the second and subsequent terms within the brackets and that it depends on three factors: (1) the velocity of the air in the test system, (2) the sonic velocity at the pressure in the test system, and (3) the shape of the flow passage.

A quick estimate of the probable error introduced by using air instead of water may be made for a particular test set-up by substituting approximate values of V_o, C_o, and β in the second term within the bracket. For example, let $V_o = 250$ ft/sec, $C_o = 1000$ ft/sec, and $\beta = 2$. This error would be $\frac{1}{4}\left(\frac{250}{1000}\right)^2 (4 - 1)$ or $\frac{3}{64} = 0.047$ or 4.7%. The effect of the third and subsequent terms is insignificant. Examination shows that error would be reduced to about 1% if V_o was limited to 50 ft/sec. However, pressure intensity and pressure differentials might be more difficult to measure and more precise instruments required.

Examples to Determine Limiting Velocity

One of the least complicated examples for determining the permissible test velocity is that for steady flow past a solid body held stationary in a uniform stream such as a Pitot tube which might be used in making a test. In this case the points selected are in the undisturbed flow upstream from the body and on the leading edge of the body where stagnation pressure exists. Expressions for this case are,

$$h_s - h_o = \frac{V_o^2}{2g} \quad \text{(incompressible flow)} \quad \text{where } \beta = 0$$

and

$$h_s - h_o = \frac{V_o^2}{2g}\left[1 + \frac{V_o^2}{4C_o^2} - \frac{(K-2)}{24}\frac{V_o^4}{C_o^4}\ldots\right]$$

(compressible flow at subsonic velocity)

The subscripts o and s refer to the station in the undisturbed flow and at the stagnation point, respectively. Assuming various values for V_o (less than sonic), computing values of $h_s - h_o$ and plotting the $(h_s - h_o)$ vs V_o terms for both cases, the following graph is obtained, (Figure 1). An examination of the graph discloses that the values for both conditions are essentially the same for velocities up to about 250 feet per second. For this type of study then, one would conclude that comparable results could be obtained with air providing the value of V_o was kept below about 250 feet per second and that reliable results could be expected from a Pitot tube for this velocity range. However, if other points in such a system are selected, it is possible that the value of V_o would have to be less in order to hold the error to an equivalent minimum. Compressibility effects influence the results from many test instruments. Flow through an orifice is another example. The accuracy of the formula for incompressible flow through an intake orifice will vary depending upon the pressures under which it operates and the reference pressure used in making the computation. The four lines on the graph of Figure 2 show the percent error in quantity for four possible conditions. The error is a minimum when the base pressure is that in the pipe downstream and results are compared with those obtained by the equation for compressible flow using the specific volume for the downstream pressure. With the low velocities employed in the air tests now being discussed, the pressure differentials are small and the ratio of downstream pressure to upstream pressure so near unity that the error is small in any case. I might add that the mean pressure could be used and would result in even less error in the case where the quantity is based on the specific volume at the downstream pressure. It may be concluded from this illustration that the equation for incompressible flow for an intake orifice may be used without introducing much error if the pressure differential across the orifice is kept small, not more than 1 foot of water.

Examples for stream tubes in general and for flow in a venturi meter may be found in "Fluid Mechanics" by Dodge and Thompson. The evaluation of the compressibility effects on the accuracy of data taken from the test structure and on any instruments which are to be used in making the tests might be only the initial phase of a study in which air is substituted for water. In most cases the need for this initial work can be eliminated by keeping the test velocities as low as possible and still provide accurately measureable quantities. With a little experience the hydraulic engineer is able to recognize whether or not the initial investigation of the compressibility effects is necessary.

There are other factors not apparent in the equations which might influence the accuracy of the results or make them qualitative only. Specific examples will be cited later to illustrate some of these factors which have been discovered mainly through experience.

Hydraulic Problems Studied by Low-Velocity Air Tests

Air has been used successfully in hydraulic problems of the following nature:

a. Design of water passages and runners and impellers of hydraulic turbines and pumps

b. The study of operating characteristics of hydraulic turbines and pumps including the efficiency and cavitation factor

c. The study and determination of losses in and the capacities of water distribution systems

d. The determination of the losses in and the capacity of comparatively large water tunnels

e. The study of the mechanics of turbulent flow and its application to liquids (turbulence loss, development, and decay below screens)

f. The study of the hydraulic characteristics of large outlet valves

g. The study of the hydraulic characteristics of complex passages such as those of hydraulic operating systems of large valves

h. The study of the pressure distribution and losses for various shapes of penstock inlets

i. The capacities and hydraulic characteristics of certain types of fluid meters (nozzles, orifices, etc.)

j. The study of the diffusion of air jets and its application to such structures as submerged sluice gates

Testing Pertaining to Turbine and Pump Design

The air testing in connection with turbine design seems to have been done mainly by German and Swiss engineers in the late thirties. A great deal of their work was published in the Swiss technical paper "Escher Wyss News," which contained the following comparison between aerodynamic and hydraulic tests, (Figure 3). The method seems not to have been adopted by manufacturers in the United States for we find these companies still using water for testing their models. The same is true of United States pump manufacturers.

Testing Pertaining to Large Water Tunnels

An unusual instance where air has been used instead of water to determine the flow characteristics of a system of water tunnels before they were placed in operation and checked by hydraulic tests afterward was discussed in papers given by two French engineers, G. Remenieras and P. Bourgingnon at the 1949 meeting of the International Association for Hydraulic Structures Research in Grenoble, France. The work consisted of passing air through the tunnels taking measurements of pressure changes, ascertaining the loss coefficients and computing the tunnel capacities. The agreement was very good when the results were checked after the system was placed in operation. The air tests in this case actually proved the adequacy of parts of the system before construction of the entire system was completed as would have been necessary for water tests. Such tests permit an on-the-spot check of such a system before the contractor has moved from the site and any deficiency could be corrected at a minimum cost.

Testing Pertaining to Turbulence

Currently, work is being done at the University of Iowa laboratory to study fundamental laws dealing with turbulence. Air is used instead of water because suitable instruments have been developed for measuring turbulence in air and instruments for measuring turbulence in water are still in the experimental stage. The diffusion of an air jet and its application to submerged sluice gates is another of the University's projects.

Testing Pertaining to Hydraulic Outlet Structures

The air testing of hydraulic equipment with which I am most familiar is, of course, that done in the Bureau of Reclamation Hydraulic Laboratory at the Denver Federal Center. This type of testing was first employed in the laboratory to study the flow characteristics of a diffuser cone. Later it was used to investigate the hydraulic properties of existing and proposed designs of outlet valves to study the deficiencies and advantages of the physical arrangement and dimensions of the water passages as regards capacity and possible occurrence of cavitation.

In one case there was a question as to the time required for the closing and opening cycle of an outlet needle valve when operated hydraulically. The speed of the cycle was governed mainly by the capacity of the flow passages of the operating mechanism. A very simple representation of this mechanism was constructed of wood and sheet metal and tested with air. The results proved very satisfactory and were obtained with less work and in only a fraction of the time required for hydraulic tests.

Latest tests in the laboratory have included the study of the pressure distribution in the rectangular entrance to an outlet conduit having a radial gate for regulation, and the determination of loss coefficients for a complicated system of branching penstocks. Comparison of the results of these air studies with water studies have not been made available to date.

Miscellaneous Items Affecting Low-Velocity Air Tests

Some very interesting facts pertinent to air-testing were brought to light during the studies just discussed.

In the initial air tests on diffusers, an unexpected discrepancy was noted in the results when compared with those of water tests, (Figure 4). The air tests indicated considerable more loss in the diffusers than did water. In an attempt to introduce an additional loss ahead of the diffuser to study its effect upon the action of the diffuser, a wire mesh wastebasket was held over the inlet to the test apparatus shown as Case I in Figure 4. A decrease in loss was indicated immediately. It was concluded that turbulence was almost nonexistent without the basket placed in the incoming air stream because of the arrangement which used the entire volume of the laboratory as a supply reservoir and thus flow conditions were not correctly represented. The apparatus was rearranged as shown for Case II and the tests repeated.

With the air supply passing through the screen before flowing through the diffusers of the new arrangement there was a marked change in the results and good agreement was found between the aerodynamic and hydraulic tests. This situation of having a virtually turbulence-free fluid at the beginning of the model, which first occurred inadvertently in the air test, rarely, if ever, is encountered in a hydraulic problem. It is the reverse of the case in aerodynamic works where the turbulence-free conditions of the atmosphere can best be only approximated in wind tunnels. The plot of Figure 4 illustrates the error which might be introduced by improper turbulence.

Several items of interest were discovered in the air tests made in the Bureau laboratory pertaining to the design of outlet valves. The tests concerned, the Ensign Balanced valve, needle valves, and the more recent development, the hollow-jet valve. In the case of the balanced valve, extensive air tests were made on the existing design and proposed alterations to eliminate cavitation (Figure 5). The tests were completed before a hydraulic model could be put in operation and were used as an expedient to obtain design information while the hydraulic model was being constructed. The air tests were later checked by water testing of a scale model and in general found to be in excellent agreement. When materials could not be obtained for making the indicated alterations because of war restrictions, the tests were used as a guide in operating the valves at openings which would permit a minimum of cavitation. The operation at these openings proved highly successful in reducing the cavitation damage. I could give a discussion on the construction of air models, but this would be a paper in itself. However, it might be mentioned here that the use of modeling clay in this type of air testing might be likened to the use of an eraser in drafting.

From the results of the tests on the balanced valve, it may be shown that very reliable quantitative data will be obtained from hydraulic systems in which there is little chance for vapor pressures to occur when air is used as a test fluid. On the other hand, when vapor pressure is likely to occur in the hydraulic system the data are not so reliable quantitatively but are extremely useful qualitatively. Figures 6, 7, and 8 illustrate this. A comparison of pressure factors for computing pressure intensities at given points for various operating conditions show excellent agreement in the case of the streamlined design and sizeable discrepancies in the design where cavitation was a problem. The more general condition of flow leading to discrepancies of this nature is that where separation is present.

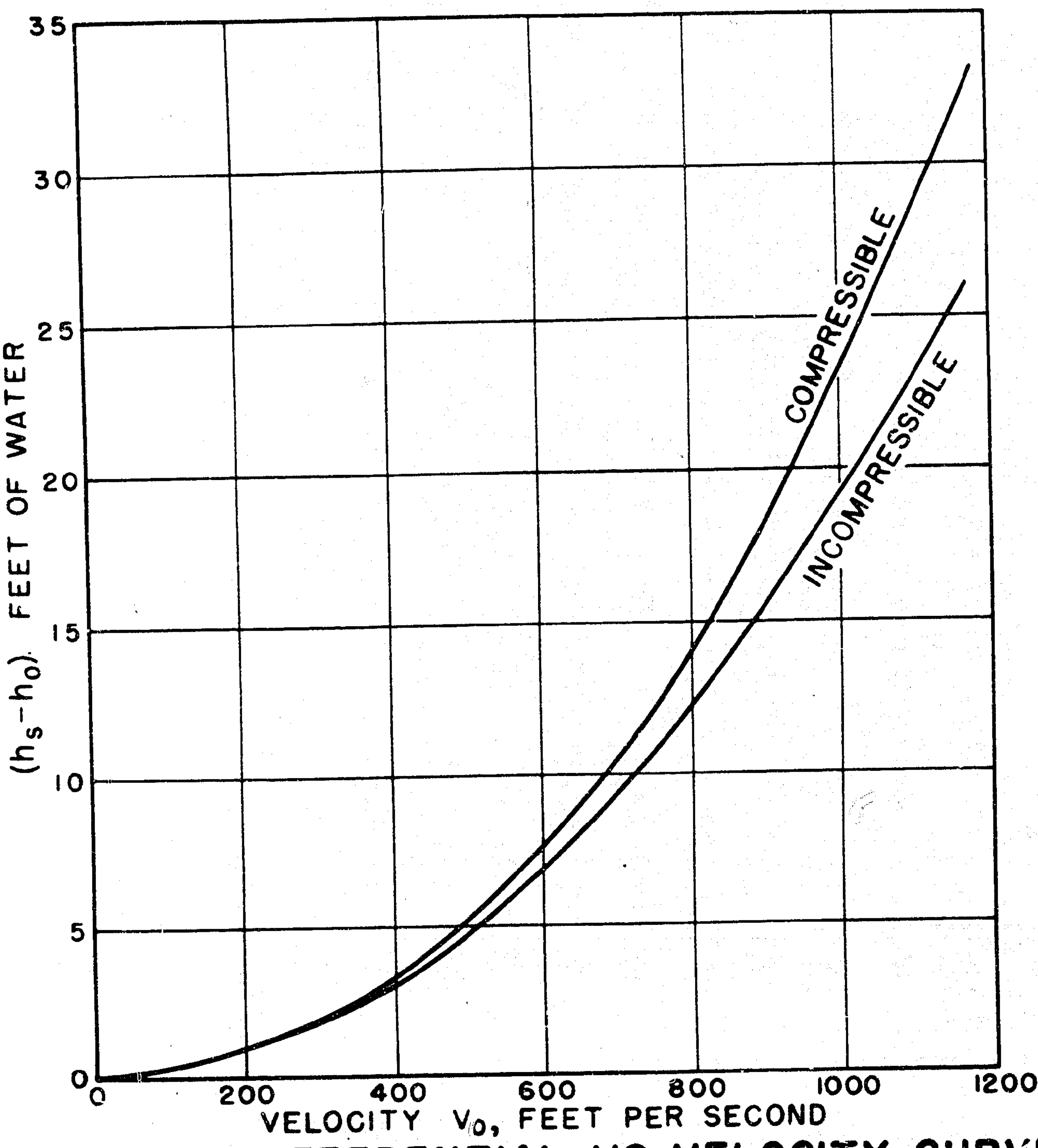
Another interesting fact noted during the same study when two small valves were calibrated using both air and water, was the importance of selecting the correct points for measuring pressures or pressure drops which would represent the actual hydraulic conditions. In the case of the hollow-jet valve shown on Figure 9, it was necessary to install an additional piezometer in order to measure the effective head on the valve, mainly because the use of air actually represented a submerged condition which was not the case in the hydraulic tests. Without this piezometer the results would have been misleading and would not have compared with those from the water tests.

In another instance it was found necessary to remove what offhand appeared to be an essential part of the test valve in order to make it represent the hydraulic conditions which would be present in the field structure.

Conclusion

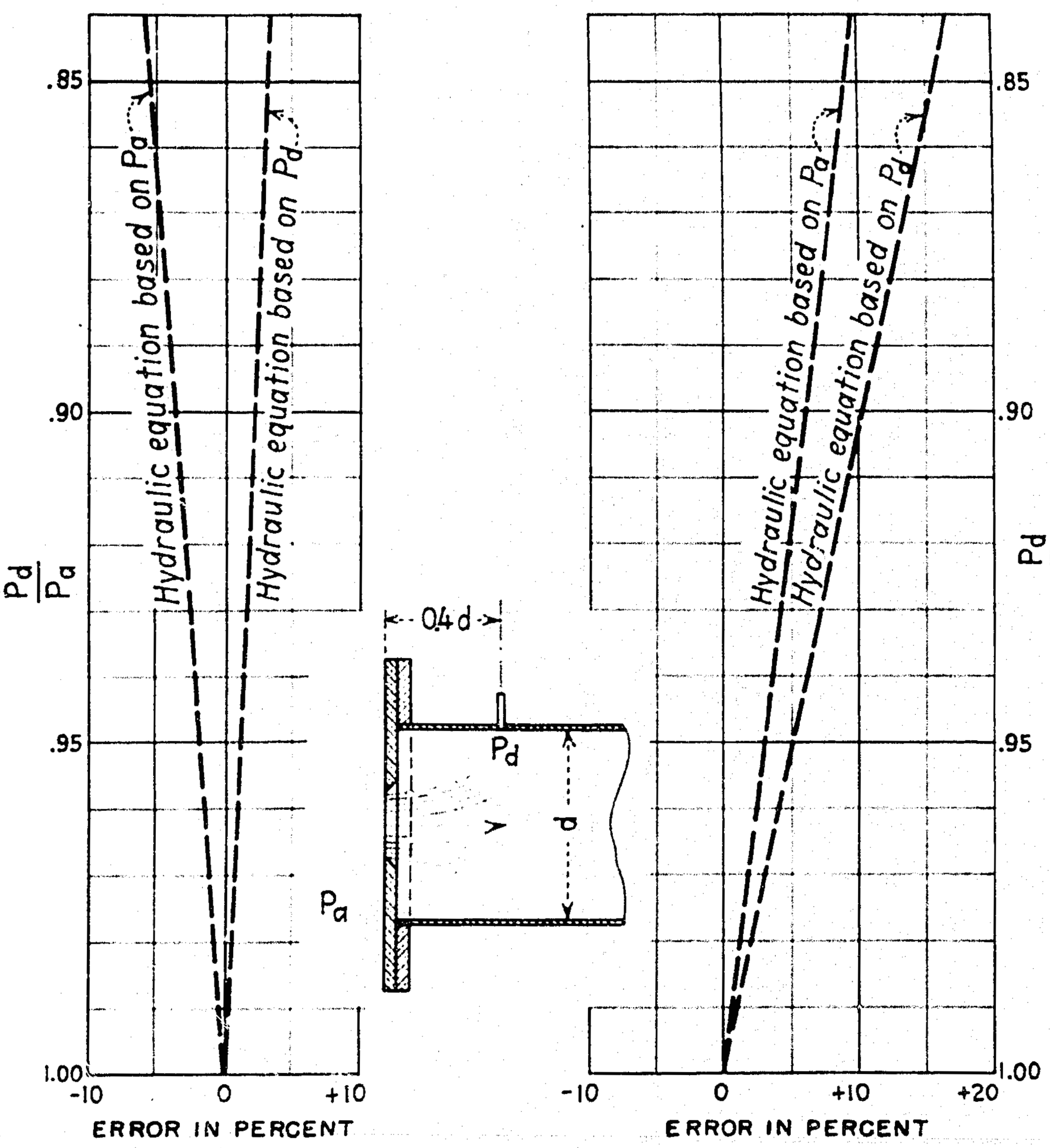
No doubt there are other factors involved in the proper representation of boundary conditions which influence the application and accuracy of air test results that have not been discussed in this paper. Those presented here are either readily apparent from an examination of the physical relationships involved or those encountered by the author in his work or in contacts with other engineers who have conducted low-velocity air tests for solving problems of a hydraulic nature. It would be interesting to hear from others who have had experience with or have knowledge of hydraulic problems being solved by low-velocity air testing.

In closing I would like to leave this thought. Although low-velocity air testing of hydraulic systems is a very useful, expeditious, and economical method of solving many hydraulic problems, it is doubtful if it will ever be used extensively or result in accomplishments of a sensational nature. It is used mainly as a substitute for hydraulic tests and serves as an expedient for urgent or preliminary studies. The final proof of the design of a hydraulic system will, therefore, in most cases still be its successful operation under hydraulic conditions.



PRESSURE DIFFERENTIAL VS VELOCITY CURVES FOR STAGNATION POINT IN COMPRESSIBLE AND INCOMPRESSIBLE FLOW OF AIR

FIGURE 1

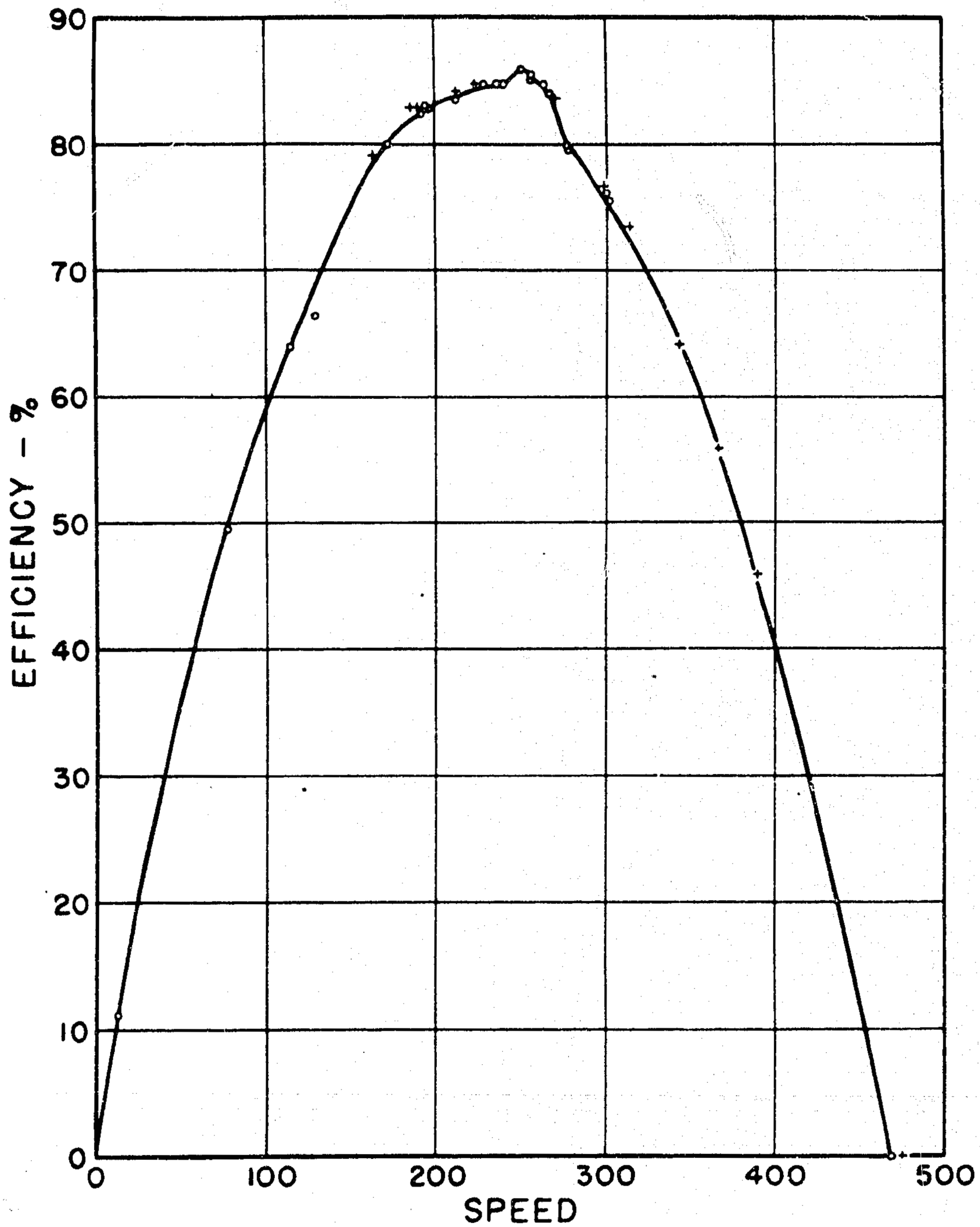


Variation from quantity obtained by Thermodynamic equation based on specific volume at P_d.

Variation from quantity obtained by Thermodynamic. equation based on specific volume at P_a.

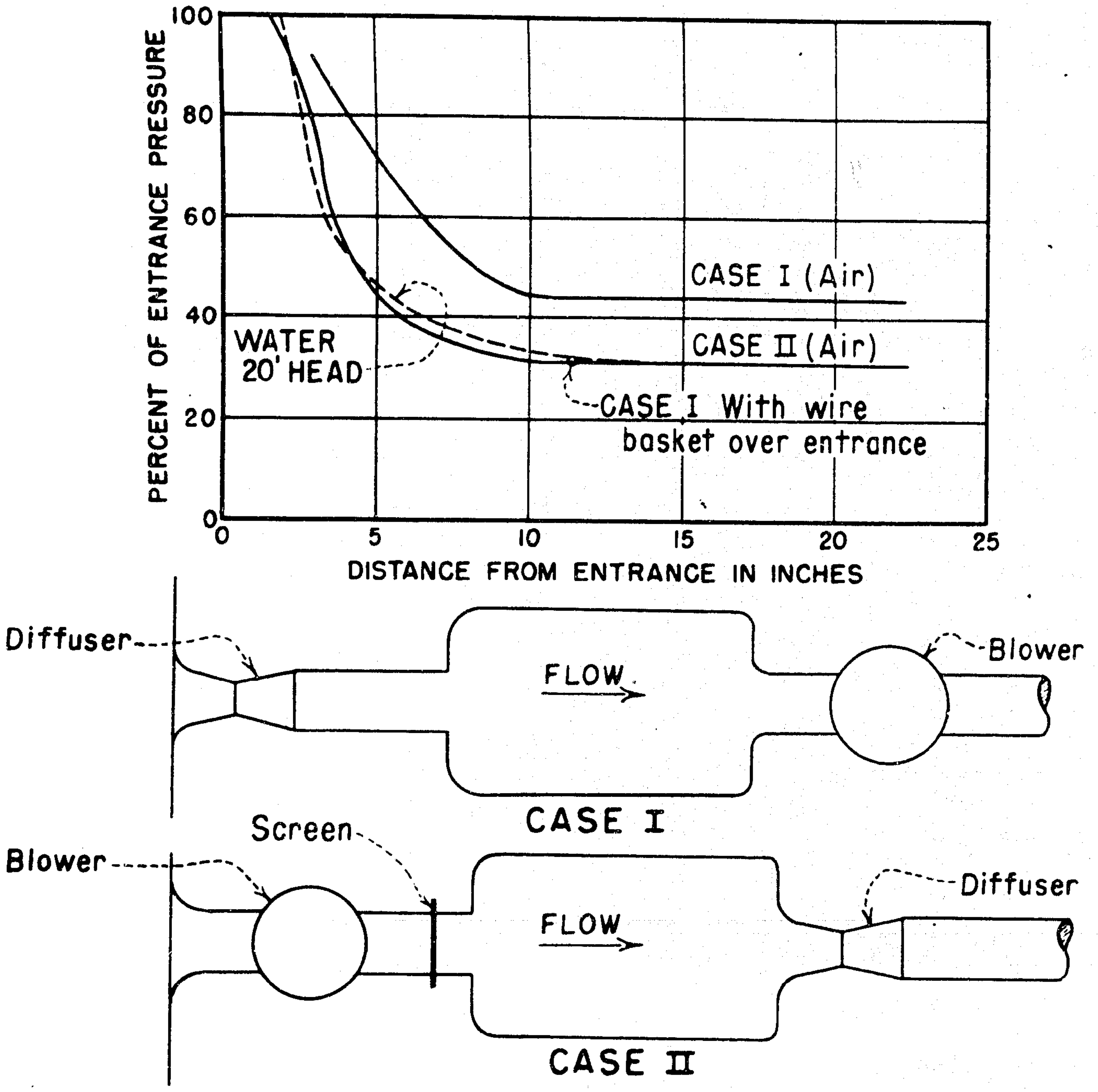
ERROR INTRODUCED BY USING HYDRAULIC INSTEAD OF THERMODYNAMIC EQUATION FOR OBTAINING FLOW OF AIR THROUGH AN INTAKE ORIFICE

FIGURE 2



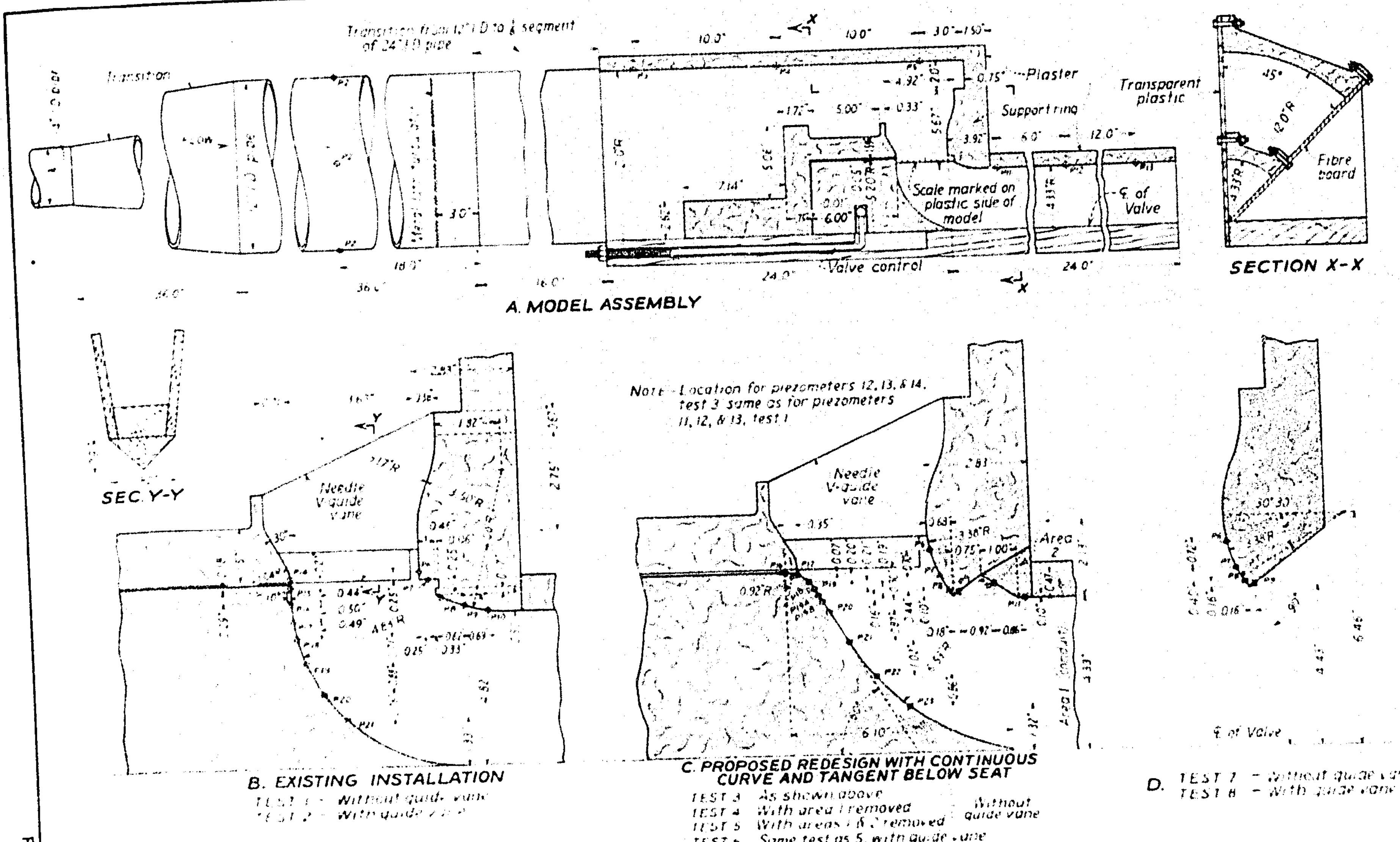
EFFICIENCY CURVES MEASURED ON THE SAME MODEL TURBINE DRIVEN ONCE WITH AIR (o) AND ONCE WITH WATER (+)

FIGURE 3



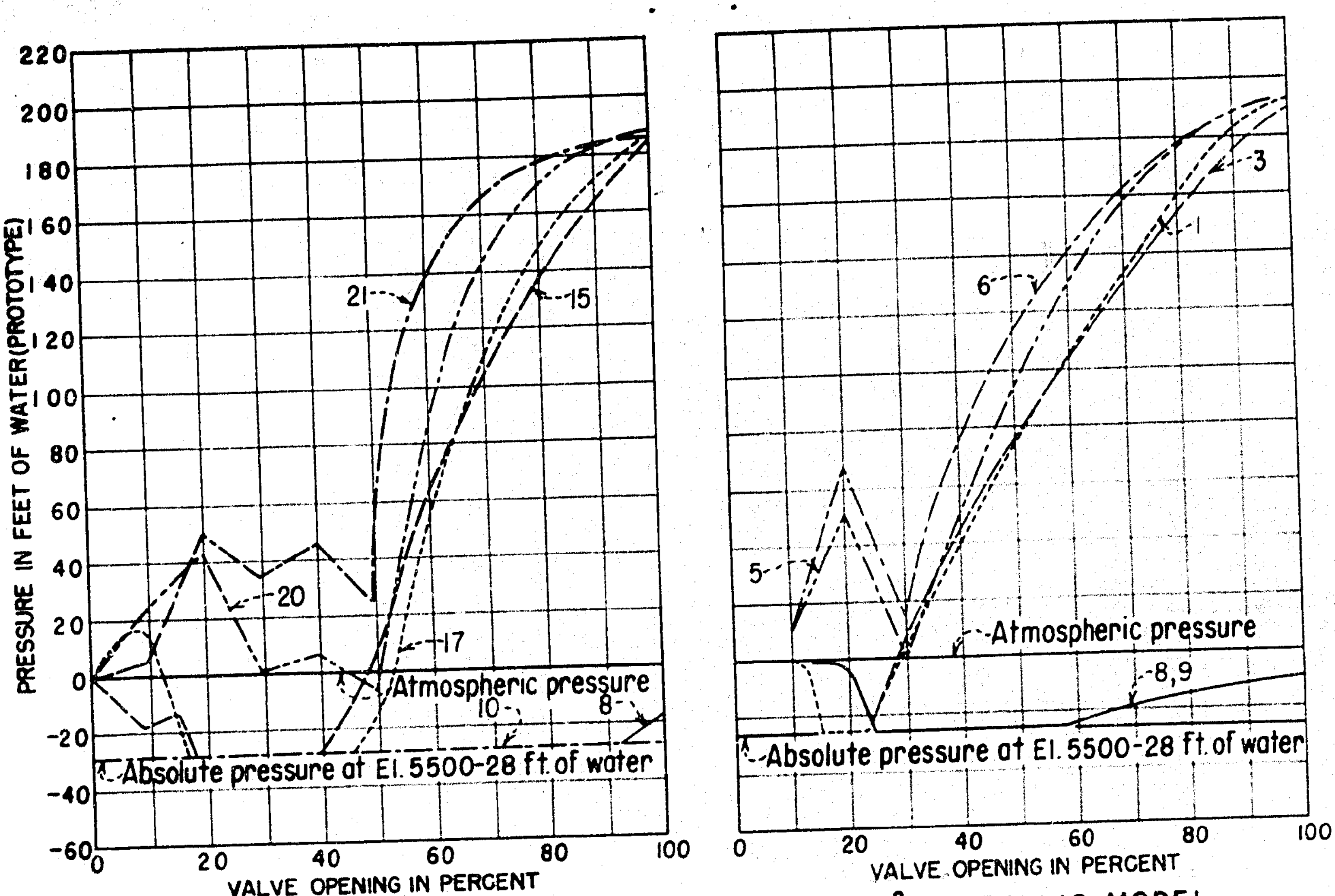
EFFECT OF TURBULENCE ON AIR TESTS

FIGURE 4



SHOSHONE DAM
58-INCH BALANCED VALVE
MODEL STUDIES - 1 TO 6 SCALE
ASSEMBLY AND DETAILS OF AERODYNAMIC MODEL

FIGURE 5



1:6 AERODYNAMIC MODEL

$1{:}8\frac{2}{3}$ HYDRAULIC MODEL

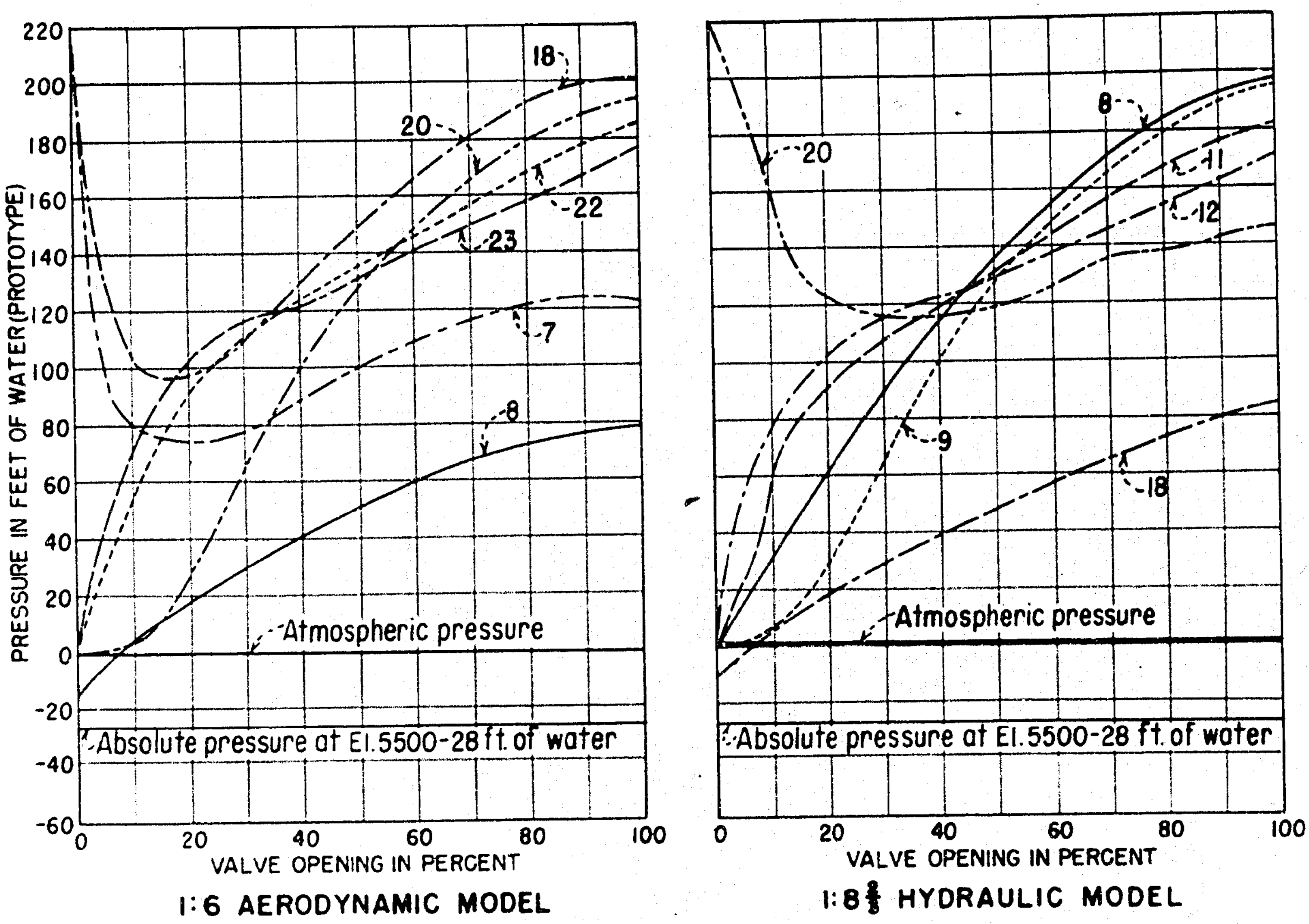
EXISTING OUTLET DESIGN

SHOSHONE DAM

58-INCH BALANCED VALVE

PRESSURES IN VALVES AND CONDUITS

FIGURE 6

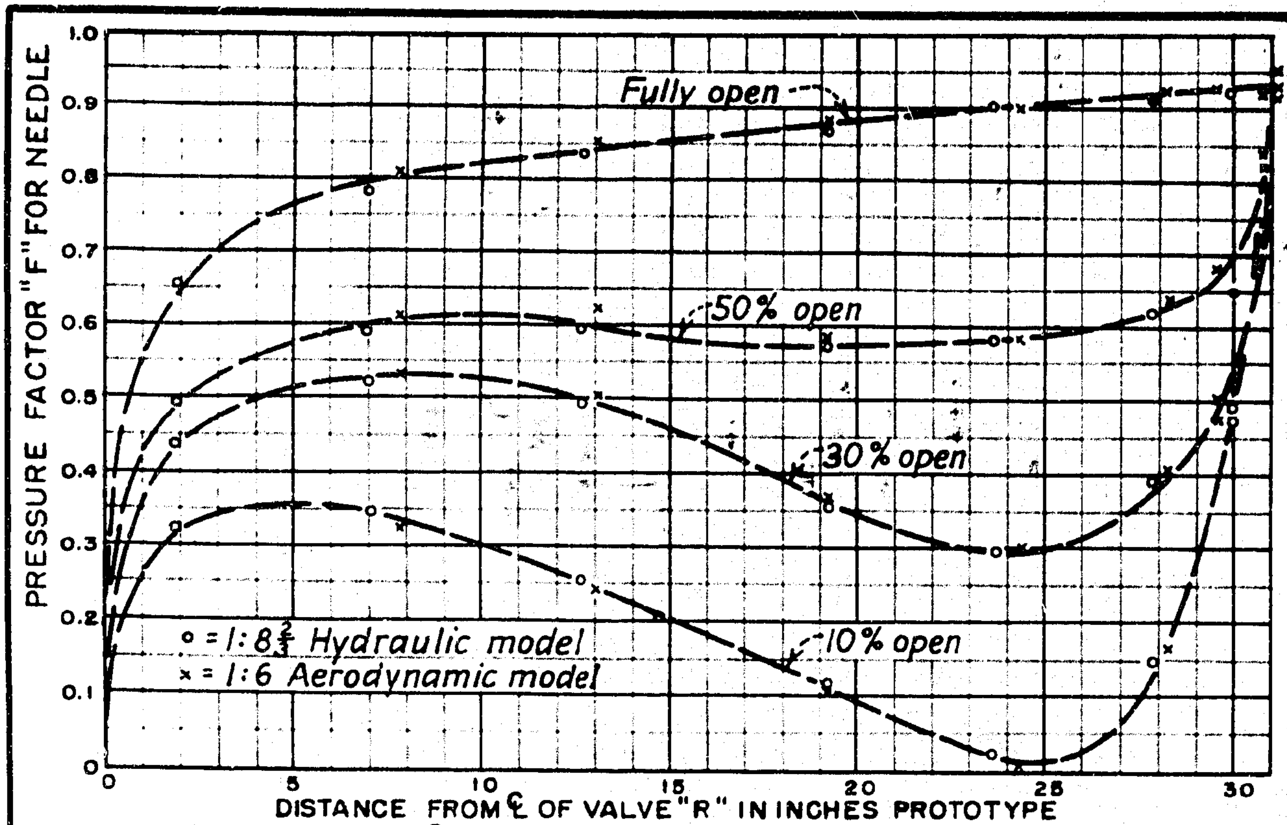


REVISED OUTLET DESIGN

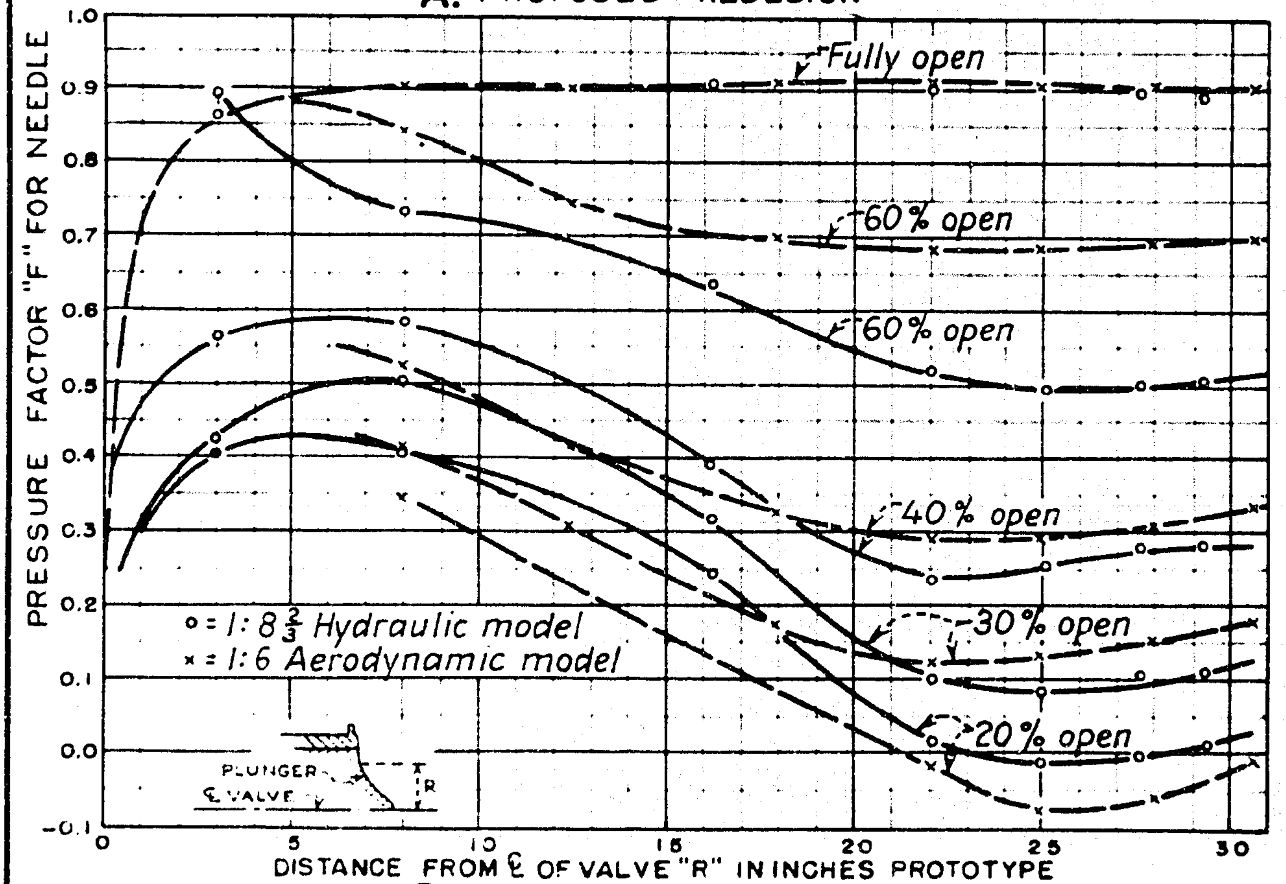
SHOSHONE DAM

58-INCH BALANCED VALVE
PRESSURES IN VALVES AND CONDUITS

FIGURE 7



A. PROPOSED REDESIGN

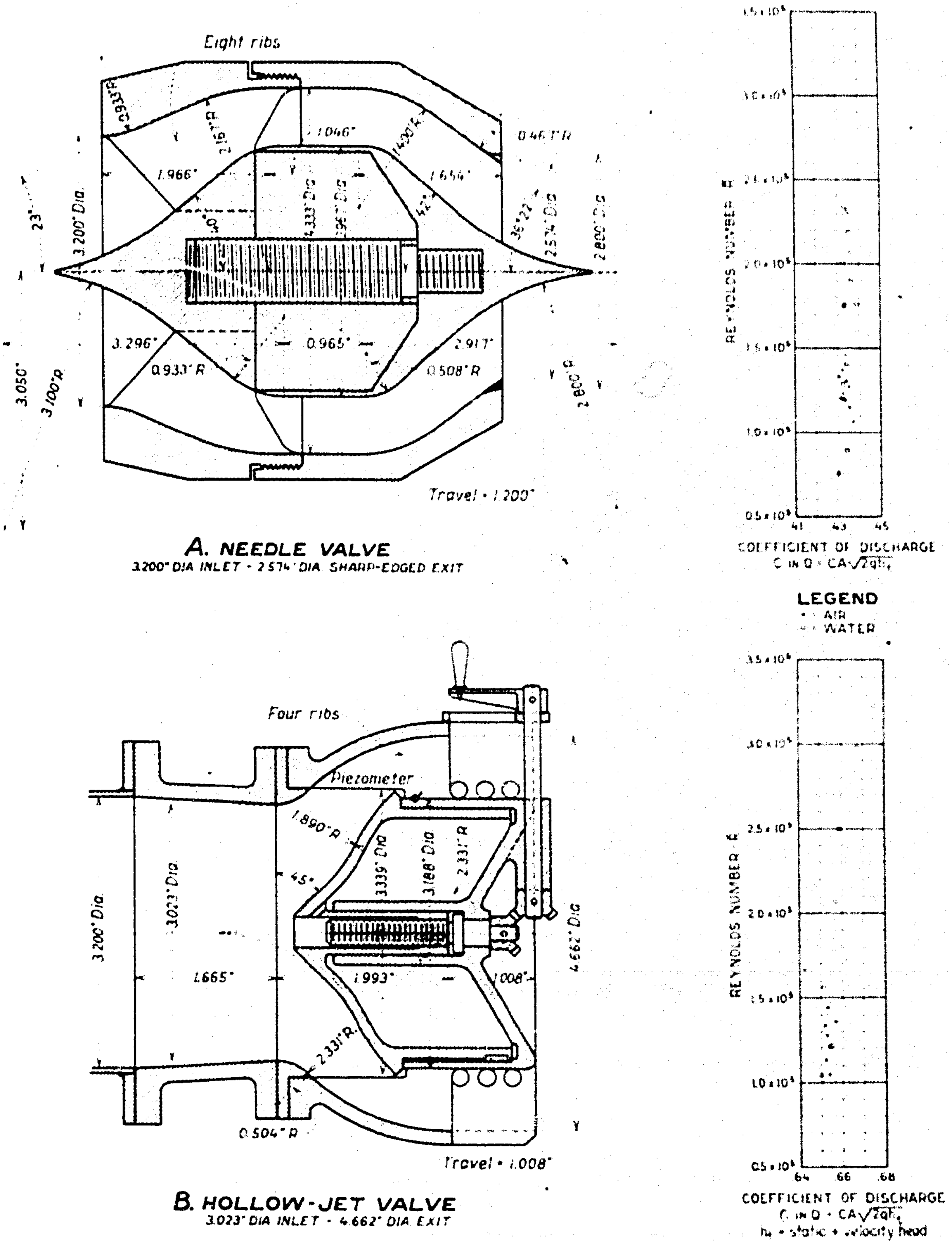


B. EXISTING INSTALLATION

SHOSHONE DAM

COMPARISON OF PRESSURE FACTORS
PROPOSED REDESIGN AND EXISTING OUTLET
AIR VERSUS WATER

FIGURE 8



DISCHARGE COEFFICIENTS FOR SMALL VALVES
USING AIR AND WATER AS FLUIDS

FIGURE 9