ULTRASONIC FLOWMETER FOR FLUID MEASUREMENT

by

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Ultrasonic Flowmeter for Fluid Measurement
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Accurate, absolute fluid flow measurement is a necessary requirement in applied fluid mechanics. Although simple in concept an accurate, absolute flow fluid measurement device, has escaped development by even the most astute hydraulic engineer. Several devices have been developed in recent years in an attempt to meet this measurement requirement. One of the more promising of these new devices is the ultrasonic flowmeter.

In this study the ultrasonic flowmeter is analyzed as a fluid measurement device. Its history, advantages, limitations, uses, and basic theory are presented. The equations, sequence of operation, and sources of error are presented for an ultrasonic flowmeter developed and manufactured by the Tokyo Keiki Seizosho Company Ltd., of Tokyo, Japan.

Discharge rate comparison tests were conducted using an ultrasonic flowmeter on a 24 inch inside diameter asbestos-cement pipe and on a 24 inch inside diameter steel pipe. The purpose of the comparison testing was to determine if the ultrasonic flowmeter could measure the discharge rate within the accuracy claimed by the manufacturer. The discharge rate as determined by the flowmeter was compared against the discharge rate as determined from a group of calibrated Venturi meters. The test results indicate the flowmeter performed unsatisfactorily when installed on the asbestos-cement pipe because of not knowing the velocity of sound in the non-homogenous pipe wall material. Test results indicate the flowmeter can measure discharge rate accurately when installed on a steel pipe. The flowmeter indicated an obvious error in measurement when installed on the steel pipe. This error was a "zero drift"; the flowmeter indicated a discharge through an empty pipe. This "zero drift" detracted from the overall performance of the flowmeter when installed on the steel pipe. It is believed that this error can be corrected by the manufacturer.

The information gained in this study may provide a basis for further research into the uses and reliability of ultrasonic flowmeters.

This abstract is approved as to form and content.

Signed J. Ernest Flack

Faculty member in charge of dissertation

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INTRODUCTION

Effective use of water resources requires controlled flow in the conveyance system. Closely related to this control is the requirement for accurate flow measurement. There have been a number of flow measurement devices developed in recent years attempting to meet this requirement. Of these newer devices, the ultrasonic* flowmeter is one of the more promising.

Ultrasonic flowmeters transmit a pressure pulse diagonally through the fluid. Measurement of either the travel time or the change in frequency of the pressure pulse permits the determination of the flow rate.

Like all measurement devices, an ultrasonic flowmeter possesses advantages, limitations, and uses. Two of the more important advantages are; the flowmeter has the capability of velocity measurement within one percent of the true velocity, and the flowmeter introduces no energy loss in the fluid. Its major limitation is its high cost. Ultrasonic flowmeter applications range from measuring the flow of blood in a vein to measuring flows in large rivers such as the Columbia River.

Ultrasonic flowmeter systems are built based on a number of methods. One of the commonly used methods employs what is called a sing-around system. This system was developed by the Tokyo

*Ultrasonic flowmeter is the more common name although the names acoustic flowmeter and sonic meter are also used. Hereafter, the term ultrasonic flowmeter will be used exclusively.

Keiki Seizosho Company Ltd., of Tokyo, Japan. Distribution of their meters in the United States is by the Badger Meter Manufacturing Company of Milwaukee, Wisconsin. In this system the change in frequency of a sound pulse caused by the velocity of the fluid is measured and related to the fluid velocity. The development of the theory, equations relating the change in frequency to the velocity of the fluid, operation sequence, and sources and magnitude of errors are presented in this thesis.

An ultrasonic flowmeter measures the average velocity along the sound path. Some means must be employed to convert this average velocity to a discharge rate. There are two methods to do this. The first and most used method is to apply a velocity correction factor to the velocity measured by the flowmeter to convert it to the mean velocity for use in the continuity equation. This method requires that the velocity distribution throughout the flow be known. The other method uses a finite number of velocity measurements and a numerical integration procedure to integrate accurately the velocity across the flow area. In this method the velocity distribution does not need to be known. Since a pipe is the most commonly used conveyance conduit, equations based on a circular cross-section are presented for both methods.

Discharge comparison tests were conducted with an ultrasonic flowmeter installed on an asbestos-cement pipe and on a steel pipe to determine if the ultrasonic flowmeter could measure the discharge rate within the accuracy claimed by the manufacturer.

The discharge rate indicated by the flowmeter was compared with a group of calibrated Venturi meters. The test results on the asbestos-cement pipe were considered as not acceptable, whereas, the test results on the steel pipe were acceptable. Data is presented for both test groups. The asbestos-cement pipe data is analyzed and explanations made as to why the flowmeter data were not acceptable.

Conclusions based on these test results are presented.

MEASUREMENT HISTORY

Probably since the beginning of civilization man has attempted to find a simple, practical method of measuring fluid discharge. Man is still trying.

The Romans probably made the first attempt to measure fluid discharge when they attempted to measure water delivered to their consumers. They related the discharge rate to the cross-sectional area of a pipe. The unit of discharge was the quinaria, the area of a circle 5/4 of a digit in diameter, one digit being 1/16 of a Roman foot(1)*. At first standard size pipes were used to bring water to the consumer. The water flowed continuously. Even though the Roman did not understand why, he soon discovered that the flow rate could be increased by altering the outlet end of the pipe. As a result, a standard tube was eventually inserted into the inflow end of each supply pipe. This made the method more of a flow controller rather than a meter. As crude

*Numbers such as (1), refer to the bibliography on page 93.

as the method was by today's standards, it was an attempt at measuring fluid discharge.

Basically because of a lack of understanding of the principles involved, developments in measuring devices came slowly. In 1717, Marguis Giovanni Poleni presented an equation for the discharge from an open tank through a rectangular opening(2). The equation is similar to today's sharp-crested weir equation. Henri de Pitot in 1732 described a device, which is presently known as a Pitot tube, to measure the velocity of flow(2). The continuity equation had been developed by this time, so knowing the area of flow the discharge could be computed. In 1790 Reinhard Woltman described the application of a spoke-vane type of current meter to measure river flows(2).

Despite an increase in knowledge of hydraulics it was not until 1888 that an American civil engineer named Clements Herschel obtained a patent(3) for a Venturi meter. Actually, an Italian scientist, Giovanni Battista Venturi, discovered the phenomenon of a pressure decrease in a throat of a pipe on which Herschel based the Venturi meter. This development was significant, for even today the Venturi meter is the primary pipe flow measurement device.

There have been numerous other discharge measurement methods, each with its own advantages and limitations, invented and used with acceptable results both for closed conduit and free-surface flow. During the last few years many new and promising methods have been advanced and developed, each possessing its own particular advantages and limitations. One of the more promising of these newer methods is the ultrasonic flowmeter.

ULTRASONIC FLOWMETER HISTORY

The first recorded history of an ultrasonic flow rate measurement was on July 31, 1931 when Antonio Feorenzi[3] received a patent for an acoustic method that measured fluid discharge. On October 1, 1935[4] and again on March 21, 1939[5], H. E. Hartig obtained patents from the United States Patent Office for an acoustic flow measurement device. Since then many other patents [6], [7], [8], [9] have been issued for ultrasonic flow measurement devices.

OSKAR RUTEN MARCH 1931 GERMAN PATENT

Ultrasonic flowmeter systems are built based on the following principles.

(1) Beam deflection - This system is based on the deflection of an ultrasonic sound beam as it is transmitted normal to the direction of the fluid. The measured deflection is caused by and directly related to the velocity of the fluid[10].

(2) Phase-shift - This system is based on the change in phase between two ultrasonic sound pulses transmitted simultaneously and traveling diagonally through the fluid in opposite directions. The measured change in phase between the two sound pulses is directly related to the velocity of the fluid[11].

(3) Transit time - This system is based on the acual travel time for two ultrasonic sound pulses transmitted simultaneously and diagonally through the fluid along the same path but in opposite directions. Measuring the two travel times the velocity of the fluid can be computed. In this system the velocity of sound in the fluid must be known quite accurately[12].

(4) Sing-around - This system is based on the difference in frequency between two ultrasonic sound pulses. One pulse is transmitted diagonally downstream through the fluid for a set time interval. After the first transmission is complete, a second pulse is transmitted for the same set time interval and along the same path as the first pulse, but in the opposite direction. The measured difference in frequency between these two sound pulses is directly related to the velocity of the fluid[13].

About 1953 the California Department of Water Resources asked the U. S. Geological Survey to explore the possibility of using an ultrasonic method for water measurement. A couple of years later the U. S. Corps of Engineers became interested in such a flowmeter.

A flowmetering system was conceived and built that measured the phase-shift between the received and generated sound pulses. It was installed in the Sacramento River in July of 1959 and tested for the next two years. In 1961, testing was stopped because the flowmeter did not attain acceptable performance.

Based on experience from this flowmeter a new system was designed. The basic differences between the new and the original flowmeters were the elimination of analog computer components, and measuring the travel times of the two sound pulses instead of the phase-shift. The original flowmeter provided a direct read out of velocity. The new flowmeter outputed the basic parameters namely, the travel times of the sound pulses, and the recorded stage needed to compute the area of the cross-section. The computation of discharge was done by other means.

The new flowmeter was tested during 1962 in the Three Mile Slough, near Rio Vista, California. Two more flowmeters were built with only minor design refinements. One was installed in the Delta-Mendota Canal near Tracy, California by the U.S. Geological Survey in August of 1963 and the other by the U.S. Corps of Engineers on the Snake River near Clarkston, Washington in September of 1963. Test work with modifications continued until 1965. The U.S. Geological Survey concluded that

> "the acoustic-velocity-metering system developed under a cooperative agreement between the U.S. Geological Survey, the California Department of Water Resources, and the U.S. Corps of Engineers does not possess the calibration stability required for this application. However, other systems, now in commercial production may have the desired performance characteristics"(14).

In 1955 Sevengel, Hess, and Waldorf published two papers[15], [16] that described the use of an ultrasonic flowmeter for discharge measurement. The tests were conducted in a 16 foot wide by 25 foot high rectangular intake conduit to Safe Harbor Power Plant. The system measured the phase-shift to determine the velocity from which the discharge was computed. The ultrasonic sound pulse was generated and transmitted across the conduit by two 30 foot transducer rods. One rod was attached to each side of the conduit. The results of those tests indicated that the ultrasonic flowmeter measured the discharge within plus or minus one percent of the discharge determined by Piezometer Discharge Meters.

An ultrasonic flowmeter system using the rod-type transducers was built into the Corps of Engineer's Sutton Dam. Tests were conducted in June 1961 in the 5 foot-8 inches wide by 10 foot-0 inches high rectangular sluice. A good signal was transmitted across still water but noise created by the flowing water during sluice operation completely obliterated the ultrasonic sound pulse and prevented measurement of the phase-shift[17].

In 1955 Kritz[18] described the use of an ultrasonic flowmeter that used small pin-like transducers to generate the sound pulse that traveled in a small beam across the conduit. This type of transducer is used today because it can be used in a conduit of any cross-sectional shape.

Two transducers of this type were tested in Sutton Dam. The test results were essentially the same as for the rod-type transducers; a good signal in still water but the signal was completely obliterated during sluice operation[17].

In 1961 a manufacturer of underseas ultrasonic equipment became interested in developing an ultrasonic flowmeter using devices they had developed to measure the speed of vehicles through water. They investigated the phase-shift system but did not recommend it. In 1964 they recommended an ultrasonic flowmeter based on the transit time system. They now have an ultrasonic flowmeter based on this system commercially available.

About the same time an electronics manufacturer in Japan was developing an ultrasonic flowmeter based on the sing-around system. They sold their first flowmeter in the spring of 1964. As of September, 1968 over 200 of these flowmeters have been sold. Recent annual sales of 60 to 70 flowmeters were reported in Japan[19].

CHAPTER II

ULTRASONIC FLOWMETER CHARACTERISTICS

Like all fluid measurement devices, an ultrasonic flowmeter has particular measurement characteristics. It possesses its own advantages, limitations, and uses.

ADVANTAGES

An ultrasonic flowmeter has a number of advantages over present flow measurement devices.

Since none of the flowmeter projects into and obstructs the flow, the flowmeter is protected from flow damage and does not introduce any energy loss in the fluid.

An ultrasonic flowmeter does not require flow calibration. Flow calibration is inherent and is based on the dimension of the conduit and the properties of the fluid. Based on these dimensions and properties, the electronics of the flowmeter are calculated, set, and checked before the flowmeter is installed. A "check system" is built into the flowmeter to allow periodic checking of some of the electrical circuits within the flowmeter.

An ultrasonic flowmeter has rapid response time and can update its output every few seconds. Typically about 60 flow measurements are computed every second. These measurements are averaged over a period of time, about five seconds, before being transmitted to the output device.

The velocity of the fluid is a linear function over the entire flow range of the parameters measured by the flowmeter. This is not the case for a number of other measurement devices.

The ultrasonic flowmeter can have a measurement accuracy of one percent or better. The larger the sound path length and the greater the velocity of flow the greater the accuracy.

The flowmeter can be used to measure fluids containing particles such as sewage and slurries. The fluid cannot, however, contain solids or air bubbles comparable in size to the wave length of the sound pulse[20].

Some of the flowmeters are small enough to be portable and in some cases can be installed without flow stoppage.

The same main electrical unit, the major cost in a flowmeter, can be used with several pairs of transducers to measure flows in a system of conveyance conduits. For example, if a pumping plant has a number of discharge conduits, the discharge can be measured with one main electrical unit and a set of transducers on each discharge conduit. The main electrical unit switches from one conduit to another until flowmeter measurements have been taken on all the conduits.

Some advantages that will become more important with more effective use of water are that an ultrasonic flowmeter can measure reverse flow, operate over a wide flow range, and measure flow rates that are too large for standard measurement devices such as venturis, propeller meters, orifice plates, and flumes. With conveyance systems now being designed for larger flows and for bidirectional flow, ability to measure large flows in either direction becomes necessary. A flow rate ratio, low flow to high flow, measurement requirement of 1 to 50 is not uncommon today. The standard measurement devices are not adequate for these requirements.

LIMITATIONS

Possible limitations to the ultrasonic flowmeter may be the effects of high concentrations of entrained air, in some cases its dependence upon velocity distribution, relative high cost as compared to other fluid measurement equipment presently available, and uncertainty as to its accuracy and reliability.

Generally speaking, on a properly designed hydraulic structure an ultrasonic flowmeter can be located so that entrained air should not be a problem.

The dependence of an ultrasonic flowmeter upon velocity distribution can be corrected by locating it where the velocity distribution is known. By applying a velocity correction factor to the flowmeter's velocity, to obtain the mean velocity, the discharge can be computed using the continuity equation. If the flowmeter cannot be so located this dependency can be corrected by multiple velocity measurement within the conduit. By applying these measurements to a numerical integration technique that actually integrates the velocity across the flow area the discharge can be computed directly.

If the ultrasonic flowmeter is generally accepted as a flow measurement device and becomes a "shelf Item" the cost per unit would probably decrease. With increased use its accuracy can be verified and its reliability checked.

USES

The ultrasonic flowmeter is being used in a number of interesting ways. One of the more interesting, is an attempt to measure blood flow in veins and arteries where total flows of fractions of cubic centimeters per second are being investigated[21]. At the other extreme, the flowmeter is being used to measure exceedingly large flows. A flowmeter is presently in operation in the Columbia River near The Dalles, Oregon. To date it has measured flows up to 500,000 cubic feet per second satisfactorily[22]. In the near future a flowmeter is to be installed in the harbor at Portland, Oregon that will measure tidal flows and the net flow of the Columbia River into the Pacific Ocean. The majority of any future ultrasonic flowmeter applications should fall in between these two extremes and be capable of producing acceptable results.

CHAPTER III

SING-AROUND SYSTEM

As stated earlier, ultrasonic flowmeters have been built based on four different systems, beam deflection, phase-shift, transit time, and sing-around.

In the beam deflection and phase-shift systems the parameters are difficult to measure, and are easily influenced by local disturbances and certain properties of the system. Because of this, beam deflection and phase-shift systems are not used to the same extent as are the transit time and sing-around systems.

Equations will be developed for the sing-around system.

Theory

The distance, L, an object travels in the time, T, can be computed from the equation

$$L = \int_{0}^{T} V \, dt \qquad (1)$$

where V is the velocity of the object as a function of time. If the average velocity of the object in the time, T, is V_a, Equation (1) becomes

$$L = V_a T \qquad (2)$$

Equation (2) can be written

$$V_a = \frac{L}{T} \qquad (3)$$

In applying Equation (3) to an ultrasonic flowmeter, L is the length of the sound path between the transducers, T is the time required for the sound pulse to travel from one transducer to the other, and V_a is the average velocity of the sound pulse along the sound path. The distance between transducers is a constant for a particular installation and can be easily measured. Since the flowmeter measures the time required for the sound pulse to travel from one transducer to the other, the flowmeter actually computes the average velocity along the sound path by using Equation (3). The fact that the flowmeter may actually measure frequency, the reciprocal of time, does not alter the above.

V_a in Equation (3) is composed of two velocities. One is the velocity of the sound pulse in the fluid, C, and the other is the velocity component of the fluid along the sound path, V_p. Therefore,

$$V_a = C + V_p \tag{4}$$

where V_p is positive when in the same direction as the sound pulse.

Substituting Equation (4) into Equation (3) and rearranging

$$T = \frac{L}{C + V_p} \quad . \tag{5}$$

EQUATIONS

To better understand the equations used in a flowmeter employing the sing-around system, reference is made to Figure 1, where the transducers are installed flush with the conduit boundary.

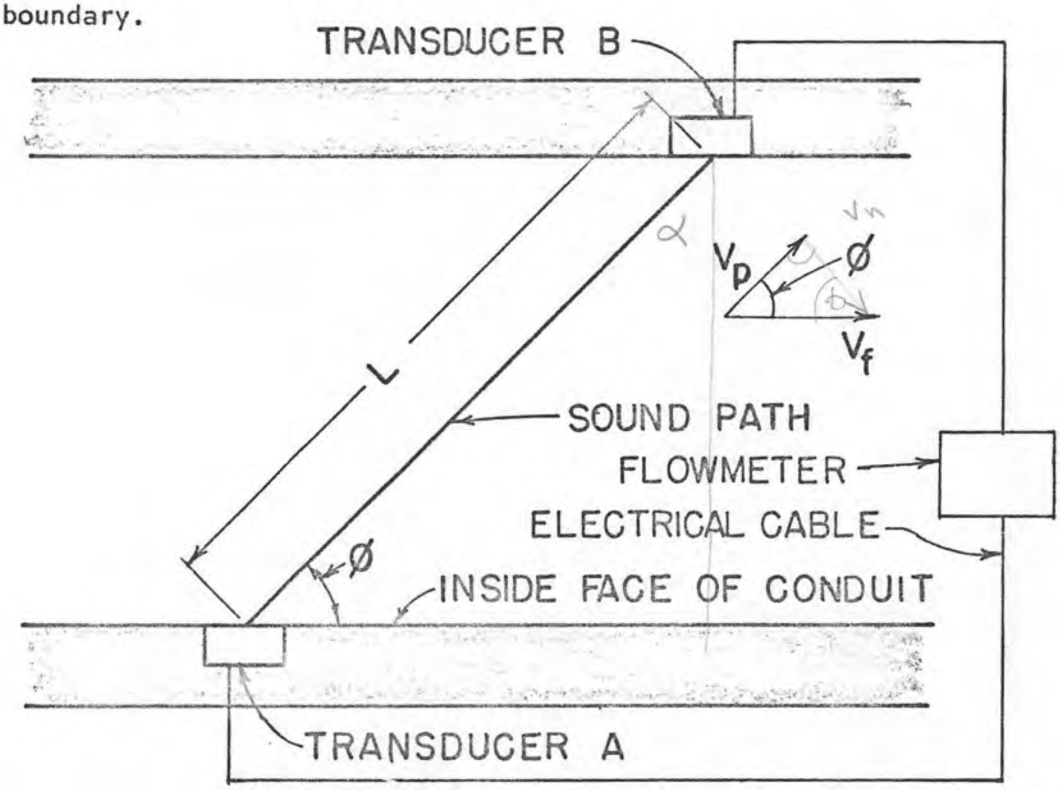


FIGURE 1

In Figure 1 an energy pulse is transmitted from the flowmeter to transducer A, through the fluid to transducer B, and back to the flowmeter. Neglecting, for now, the time required for the pulse to travel between the flowmeter and the transducers, Equation (5) will be

$$T_a = \frac{L}{C+V_p} \cdot \tag{6}$$

Similarly, an energy pulse is transmitted from the flowmeter to transducer B, through the fluid to transducer A, and back to the flowmeter. Again neglecting the time required for the pulse to travel between the flowmeter and the transducers, Equation (5) will be

$$T_b = \frac{L}{C - V_p} \tag{7}$$

where

C = velocity of sound in the fluid,

L = distance between the transducers along the sound path,

V_p = velocity component of the fluid along the sound path,

T_a = time required for the energy pulse to make a complete cycle with the pulse traveling through the fluid from transducer A to transducer B, and

T_b = time required for the energy pulse to make a complete cycle with the pulse traveling through the fluid from transducer B to transducer A.

The reciprocal of Equations (6) and (7) are

$$f_a = \frac{1}{T_a} = \frac{C + V_p}{L} \tag{8}$$

and

$$f_b = \frac{1}{T_b} = \frac{C - V_p}{L} \tag{9}$$

where f_a and f_b are the respective cycle frequencies of cycle times T_a and T_b. The frequency difference between Equations (8) and (9) is

$$\Delta' f = f_a - f_b = \frac{2 V_p}{L} \quad . \tag{10}$$

Since L is a constant for a particular installation, Equation (10) can be written

$$V_p = K\Delta f \quad . \qquad (11)$$

Equation (11) states that the change in frequency is directly dependent on the flow velocity. Another important fact is that the change in frequency is independent of the velocity of sound in the fluid. Changes in any factor, such as the mineral content or the temperature of the fluid have no effect on the frequency difference.

The installation recommended by the manufacturer has the transducers installed on the outside of the conduit as shown in Figure 2.

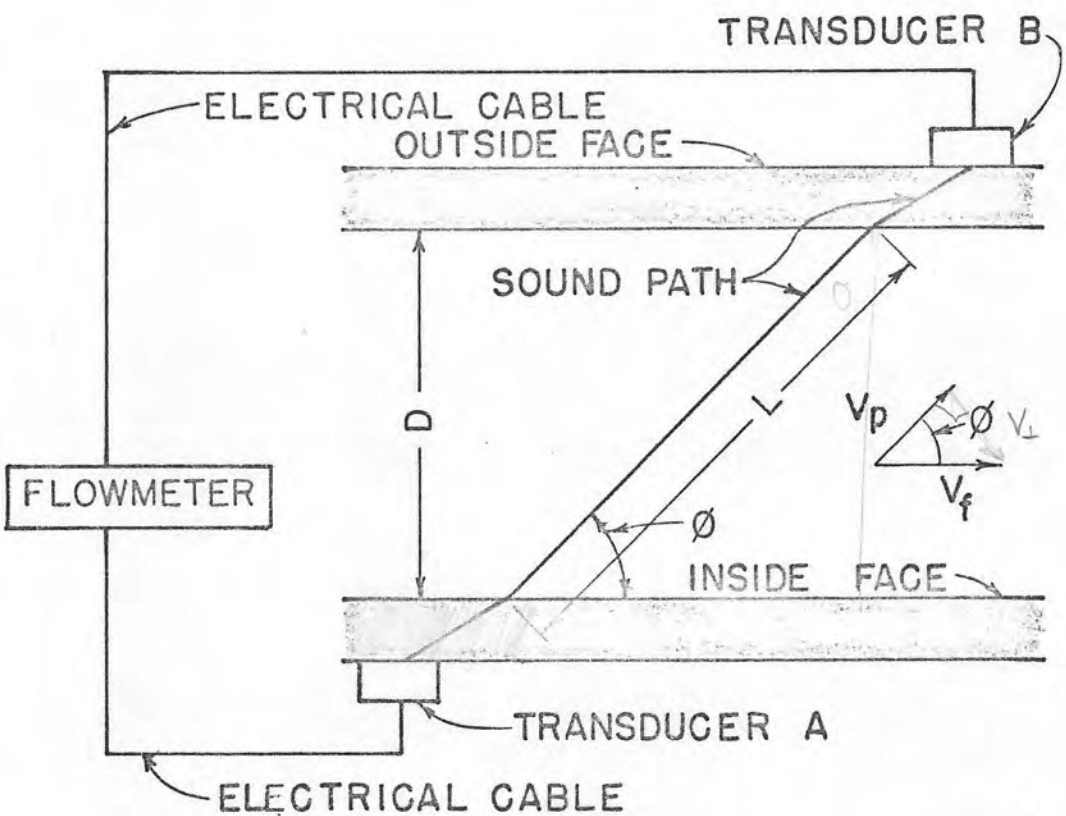


FIGURE 2

Equations (6) and (7) give only travel times of the sound pulse through the fluid in the different directions. With the transducers installed on the outside of the conduit, an additional time must be added for the sound pulse to travel through the walls of the conduit. Also, the time for the electrical pulse to travel from the flowmeter to the transmitting transducer and from the receiving transducer to the flowmeter must be added. These additional times, called the loop time delay, T_d, is a constant for a particular installation and applies to the travel times in both directions. Equations (6) and (7) should then be modified to

$$T_a = T_d + \frac{L}{C + V_p} \qquad (12)$$

and

$$T_b = T_d + \frac{L}{C - V_p}. \qquad (13)$$

Noting from Figure 2 that

$$L = \frac{D}{\operatorname{Sin} \phi}$$

and substituting for L in Equations (12) and (13) and getting a common denominator

$$T_a = \frac{T_d \operatorname{Sin} \phi (C + V_p) + D}{\operatorname{Sin} \phi (C + V_p)} \qquad (14)$$

and

$$T_b = \frac{T_d \operatorname{Sin} \phi (C - V_p) + D}{\operatorname{Sin} \phi (C - V_p) \cancel{+ D}} \qquad (15)$$

The change in frequency between Equations (14) and (15) is

$$\Delta f = \frac{1}{T_a} - \frac{1}{T_b} \quad . \tag{16}$$

Substituting Equations (14) and (15) into Equation (16) and getting a common denominator

$$\Delta f = \frac{-2 D V_p \operatorname{Sin} \emptyset}{C^2 T_d^2 \operatorname{Sin}^2 \emptyset - V_p^2 T_d^2 \operatorname{Sin}^2 \emptyset + D^2 + 2 D C T_d \operatorname{Sin} \emptyset} \quad . \tag{17}$$

Since T_d is very small, $V^2\ T_d{}^2\ \operatorname{Sin}^2\ \emptyset$ will be small and can be neglected without serious error. Equation (17) becomes

$$\Delta f = \frac{-2 D V_p \operatorname{Sin} \emptyset}{C^2 T_d^2 \operatorname{Sin}^2 \emptyset + D^2 + 2 D C T_d \operatorname{Sin}^2 \emptyset} \quad . \tag{18}$$

Factoring the denominator and substituting

$$V_p = V_f \operatorname{Cos} \emptyset$$

where V_f is the velocity in the direction of flow, into Equation (18)

$$\Delta f = \frac{-2 D V_f \operatorname{Sin} \emptyset \operatorname{Cos} \emptyset}{(D + C T_d \operatorname{Sin} \emptyset)^2} \quad . \tag{19}$$

Rearranging Equation (19)

$$\Delta f = -2 D V_f \operatorname{Sin} \emptyset \operatorname{Cos} \emptyset (D + C T_d \operatorname{Sin} \emptyset)^{-2} . \tag{20}$$

Defining f_o as the sing-around frequency, where $V_p = 0$ in Equation (14)

$$f_o = \frac{C \operatorname{Sin} \emptyset}{D} \left(1 + \frac{C T_d \operatorname{Sin} \emptyset}{D}\right)^{-1} \quad . \tag{21}$$

Rearranging and squaring Equation (21)

$$\left(\frac{f_o D}{C \operatorname{Sin} \emptyset}\right)^2 = \left(1 + \frac{C T_d \operatorname{Sin} \emptyset}{D}\right)^{-2} \quad . \tag{22}$$

Substituting Equation (22) into Equation (20) and simplifying

$$\Delta f = 2 V_f D \text{ Cot } \emptyset \left(\frac{f_0}{C}\right)^2. \qquad (23)$$

The only difference between Equations (10) and (23) is the inclusion of the loop time delay constant, T_d, in Equation (23).

The manufacturer recommends two installation forms, the Z-form and the V-form as shown in Figure 3. A Z-installation form is with the transducers located on opposite conduit walls. A V-installation form is with the transducers located on the same side of the conduit with the sound pulse reflected off the far inside face towards the receiving transducer. The V-form has certain advantages over the Z-form. The V-form gives a better averaging of the velocity of the fluid and makes the influence of T_d, loop time delay constant, on the equations less.

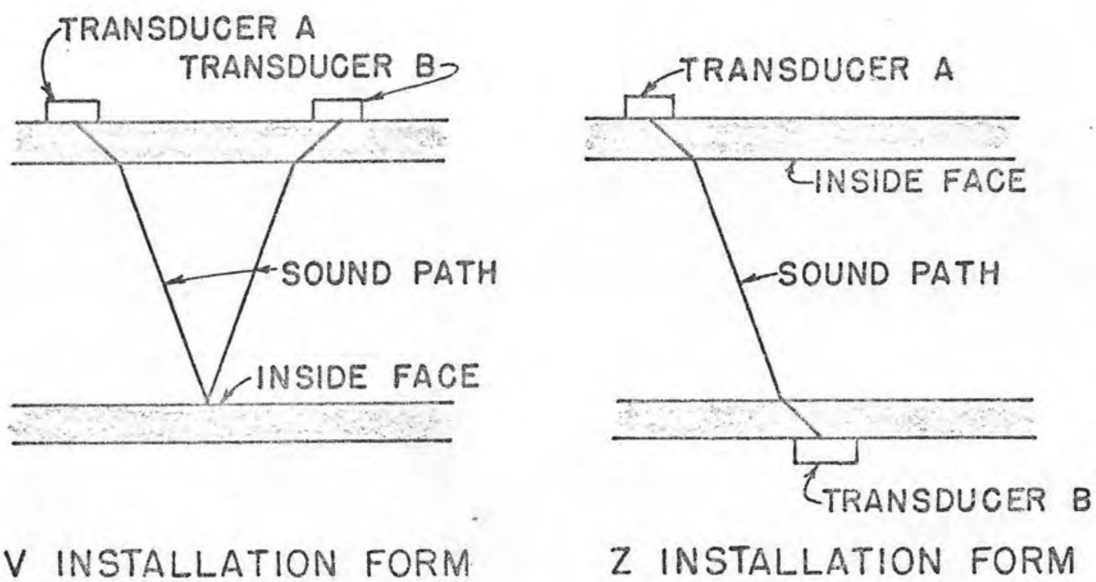


FIGURE 3

To consider the two possible installation forms, Equation (23) should then be modified to

$$\Delta f = 2 I V_f D \operatorname{Cot} \phi (\frac{f_o}{C})^2 \tag{24}$$

where I = 1 for a Z-installation form and I = 2 for a V-installation form. Rearranging Equation (24)

$$V_f = \frac{\Delta f}{2 I D \operatorname{Cot} \phi} (\frac{C}{f_o})^2 \quad . \tag{25}$$

For a given installation, D, I, and ϕ are constants. If C/f_o can reasonably be assumed constant, Equation (25) can be written

$$V_f = K \Delta f \ .$$

Since the velocity of sound, C, in water can vary from 4600 to 5200 feet per second a range of approximately 20 percent it is not readily apparent that C/f_o can be assumed constant.

Equation (21) can be written

$$\frac{C}{f_o} = \frac{C T_d \operatorname{Sin} \phi + D}{\operatorname{Sin} \phi} \quad .$$

Whether C/f_o is a constant depends upon three possibilities. The first possibility is

$$D \gg T_d C \operatorname{Sin} \phi$$

for which

$$\frac{C}{f_o} \approx \frac{D}{\operatorname{Sin} \phi}$$

which states that C/f_o is dependent upon the physical dimensions of the system. The second possibility is that

$$D = T_d C \sin \phi$$

from which

$$\frac{C}{f_o} = K \frac{D}{\sin \phi}$$

where $K = F(T_d, C)$ which requires that T_d and C remain constant, have small changes, or have off setting changes. The last possibility is that

$$D < T_d C \sin \phi$$

from which

$$\frac{C}{f_o} \approx T_d C$$

and from which C/f_o depends greatly on the values of C and T_d.

To determine which one of the above is more correct, one has to determine the difference between Equations (10) and (23). The only difference between the equations is the inclusion of T_d in Equations (13) and (14) which lead to Equation (23). Since Equation (11) is completely independent of C/f_o, the only effect C/f_o can have is through the effect of T_d. If T_d is less than one percent of either T_a or T_b then the maximum effect C/f_o can have on Equation (23) is less than one percent. If an average value of C is used, the maximum effect will be even less.

OPERATION SEQUENCE

A schematic diagram of an ultrasonic flowmeter sing-around operation is shown in Figure 4.

At the start of an operation cycle, the flowmeter is set in the up count mode. That is, the sound pulse will travel from transducer A to transducer B and the reversible counter will add the frequencies that are sent to it.

The operation is started by the transmitter sending an electric pulse through the switch to transducer A. At transducer A the electric pulse is converted to a sound pulse and directed through the fluid to transducer B. When the sound pulse reaches transducer B it is converted back into an electric pulse and sent through the switch which sends it to the frequency multiplier. Upon arriving at the frequency multiplier the frequency of the pulse is multiplied and sent to the reversible counter which adds the frequencies. The frequency multiplier also sends a signal to the transmitter to start another pulse. The flowmeter remains in the up count mode with the pulse traveling in a loop, hence the term sing-around, for a set count time interval.

After reaching the set count time interval, the timer switches the flowmeter to the down count mode. Now the sound pulse will travel from transducer B to transducer A and the reversible counter will subtract frequencies that are sent to it. The process is similar to the up count mode and takes places for the same set count time interval.

After completion of the set count time interval in the down count mode, the frequency count left in the reversible counter is the change in frequency of the sound pulse caused by the velocity of the fluid.

The frequency difference in the reversible counter is then sent to the relay memory where it is converted to an integer digital value. From here the digital value is sent to a digital to analog converter, which converts the digital number to an equivalent electrical current, multiplies it by the appropriate factors and sends it to the output unit. Also from the relay memory the digital value is sent to the counter gate where it is multiplied by the cycle time and other appropriate factors to obtain the volume of flow measurement, with output at the totalizer.

Since the process operates for a set time interval the velocity of the fluid outputed is the average velocity during that time interval. If this total process takes about five seconds as many as 3,000 velocities, depending upon the sound path length, will be measured and averaged before being outputed.

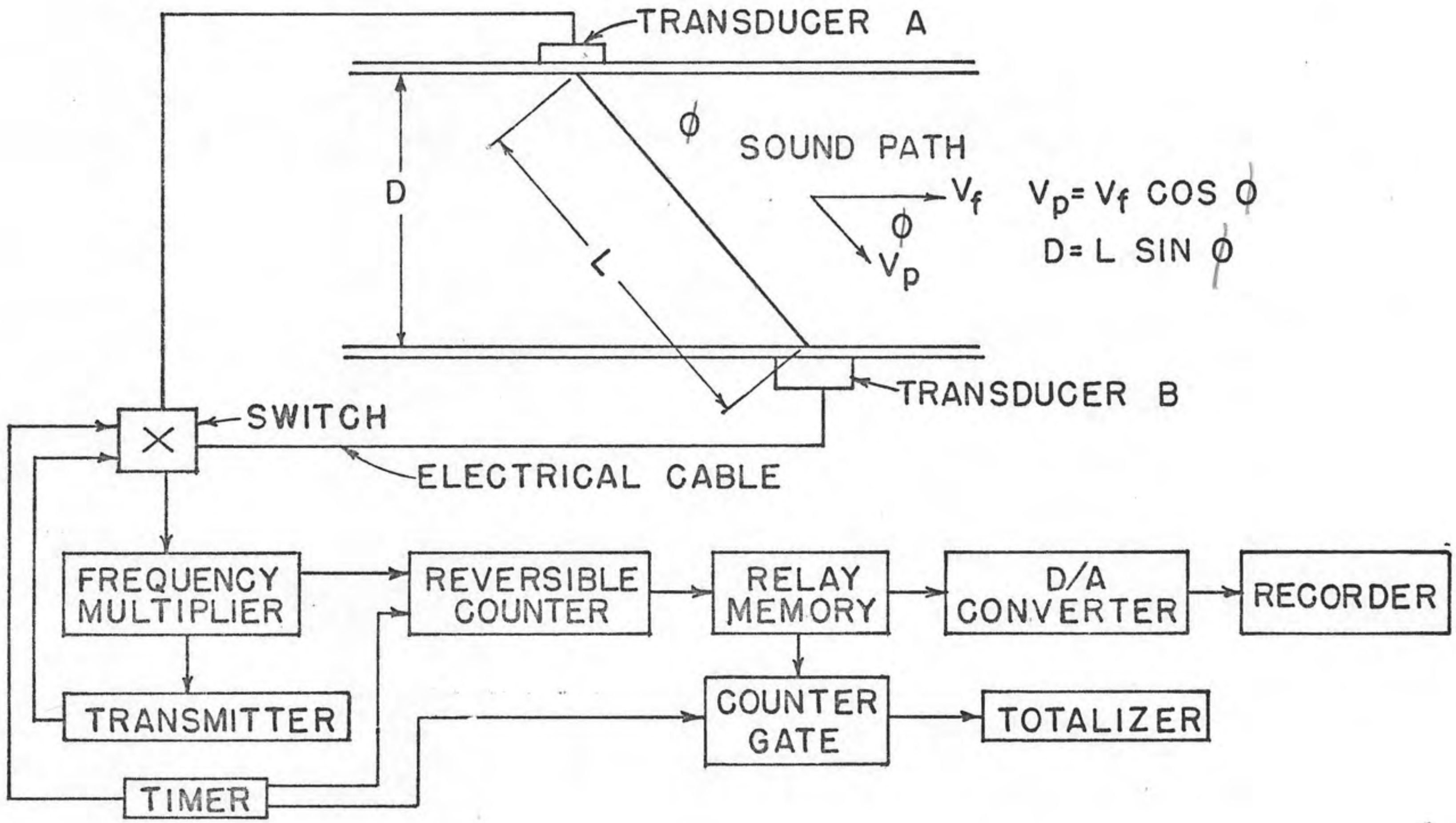

TRANSDUCER A
SOUND PATH
D
L
V_f
V_p
$V_p = V_f \cos \phi$
$D = L \sin \phi$
TRANSDUCER B
SWITCH
ELECTRICAL CABLE
FREQUENCY MULTIPLIER
REVERSIBLE COUNTER
RELAY MEMORY
D/A CONVERTER
RECORDER
TRANSMITTER
COUNTER GATE
TOTALIZER
TIMER

FIGURE 4

SOURCES OF ERROR

The ability of an ultrasonic flowmeter using the sing-around system to measure accurately the velocity of the fluid depends upon two sources of error; namely, the scale factor error and the instrument error. Scale factor errors are those errors caused by the difference between the actual and assumed values used in setting up the flowmeter. Instrument errors are those errors related to the components within the flowmeter that measure the frequency difference and convert this difference to a velocity.

Scale factor error

Scale factor errors are caused by the difference between the assumed and actual factors used in the calculations to set up the flowmeter. As a result, once the system is defined, the errors can be computed and are constant. The errors within this category can be separated into the following:

1) conduit measurement error,
2) transducer measurement error,
3) conduit wall thickness measurement error,
4) velocity of sound error in the conduit wall, and
5) velocity of sound error in the fluid

Conduit measurement error - this error is the result of the error in measuring the distance across the conduit perpendicular to the velocity of flow - distance D in Figure 2.

Transducer measurement error - the distance between the transducers is computed using Snell's law of refraction, and trigometeric principles. The distance between the transducers is set based on this calculation. The transducer measurement error is caused by the measurement error in setting this distance.

Conduit wall thickness measurement error - this error is the result of the error in measuring the conduit wall thickness.

Velocity of sound error in the conduit wall - this error is the result of the difference between the actual and assumed value used for the velocity of sound in the conduit wall.

Velocity of sound error in the fluid - this error is the result of the difference between the actual and assumed value for the velocity of sound in the fluid.

Since the scale factor error can control the overall error of the ultrasonic flowmeter, the manufacturer has specified the accuracy at which these measurements must be made and velocities of sound known. The manufacturer has specified the following:[23]

1) Conduit measurement must be with $\pm$0.2 percent of the actual measurement.
2) The transducers must be set within $\pm$0.1 percent of the calculated distance.
3) The conduit wall must be measured within $\pm$ 0.7 percent of the actual measurement
4) The velocity of sound within the conduit wall must be known within $\pm$2.0 percent of the actual value.
5) The velocity of sound in the fluid must be known within $\pm$0.4 percent of the actual value.

Based on these specified accuracies, the percent error for the error sources within the scale factor error for various path lengths is shown in Figure 5*. Since some of the errors are positive and others negative, the square root of the sum of the squares of the individual errors was used to compute the total scale factor error shown in Figure 5.

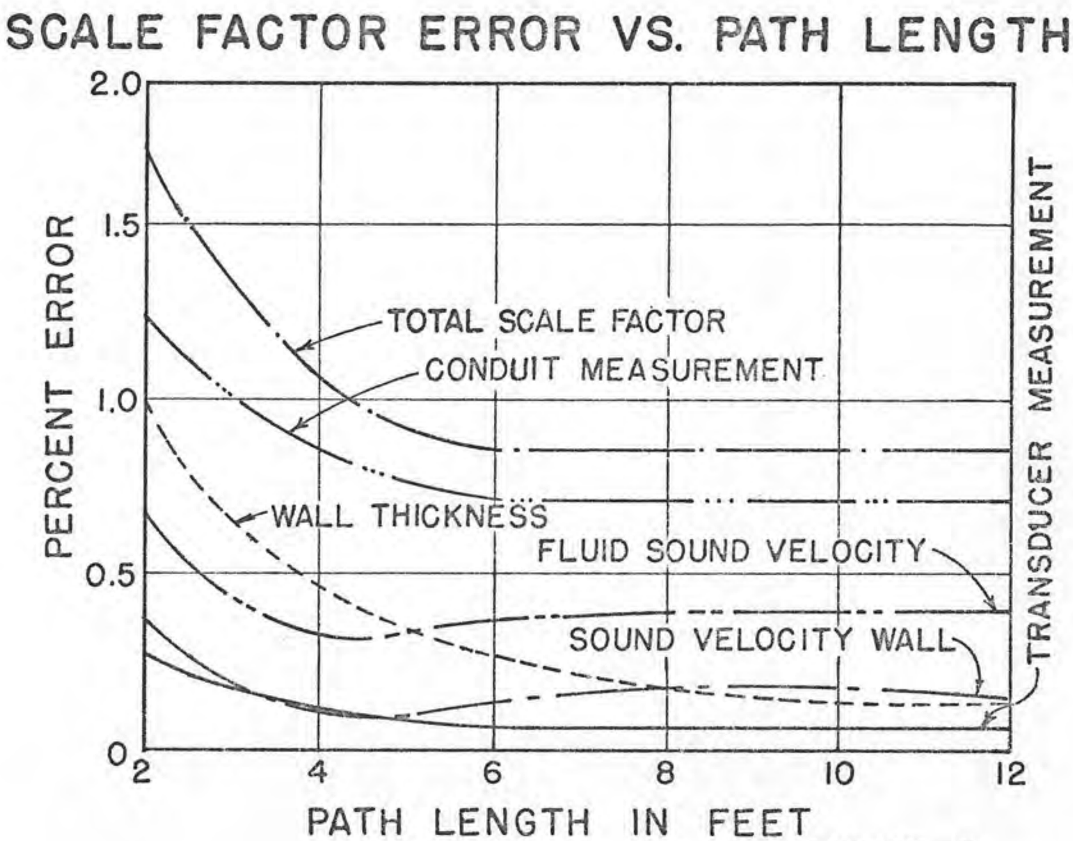


FIGURE 5

*The original calculations used in Figures 5 and 8 through 22 were done by the manufacturer[23]. These calculations were in meteric units and based on a steel pipe conduit. The results of these calculations were presented in a table form where the percent error was shown for various pipe diameters. Shown in these figures is a modification of the original calculations. The modifications consisted of changing from meters to feet units and expressing the percent error as a function of the sound path length instead of pipe diameter. In this way, these figures apply to flow in any steel conduit regardless of shape and whether the flow is free surface or pressure flow.

Instrument Errors

Sources of error with this group can be separated into the following:

1) memory value error,

2) design constant error,

3) frequency multiplier stop interval error,

4) digital to analog (D/A) conversion error, and

5) transducer mis-match error

Some of the errors within the instrument error group; namely, memory value and frequency multiplier stop interval errors, tend to correct themselves over a period of time. Therefore there are two types of errors that are of interest. One type includes the memory value and frequency multiplier stop interval errors and the other does not. The error that does include these errors is associated with a velocity measurement and is referred to as an instantaneous error. The other error that does not include the memory value and frequency multiplier stop interval errors is associated with a totalized velocity times time measurement and is referred to as an integrated error.

Memory value error - The relay memory only stores the integer value of the difference in sound frequency. The memory value error occurs because the frequency difference that cannot be directly converted into the relay memory is discarded. For example, if the actual value in the relay memory is 50.3, the 0.3 is dropped. The error is self correcting over a period of time and therefore does not affect the integrated error.

Design constant error - The frequency multiplier is a number the sound pulse frequencies are multiplied by before entering the reversible counter. The maximum frequency multiplier is calculated by dividing the maximum change in frequency into the maximum relay memory value. The design constant error is the result of rounding this frequency multiplier calculation to a necessary integer value.

Frequency multiplier stop interval error - There is a time delay of three sound waves between the received sound pulse and before another sound pulse is transmitted. To account for this delay an average time delay is added to the loop time delay constant. This error is the result of assuming the time delay is a constant when in fact it is a variable. It is a function of the frequency of the received sound pulse. Since an average value is used for the time delay, this error is self correcting over a period of time and does not enter into the integrated error.

Digital to analog (D/A) conversion error - This is a circuity error in converting the digital value in the relay memory to an electrical current. This error is estimated at 0.5 percent regardless of sound path length or velocity of flow. Since the pulses that lead to the integration flow do not pass through this circuit this error does not enter into the integrated error.

Transducer mis-match error - For clarity, transducer mis-match error can be divided into two parts; the error caused by the difference in amplitude, and the error caused by the difference frequency between the two transducers.

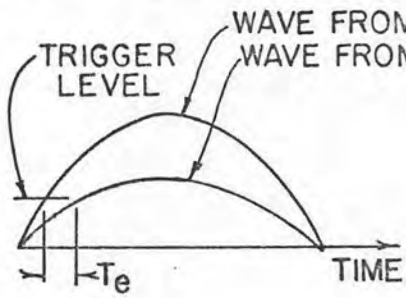


FIGURE 6

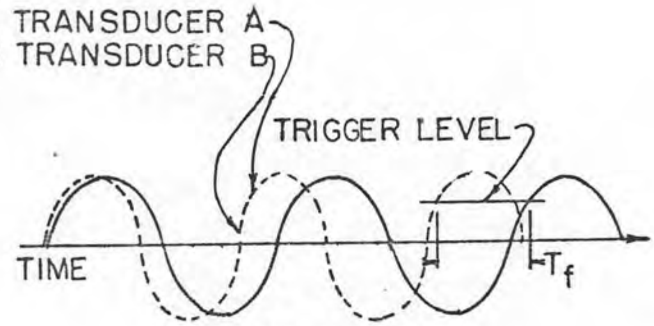


FIGURE 7

As shown in Figure 6, if the amplitude of the two waves as transmitted by the transducers is different, it will take different times for the waves to reach the trigger level. The trigger level is the level at which the sound pulse is transformed into an electric pulse within the transducer and sent to the flowmeter. Also, as shown in Figure 7 if the frequency between the two waves as transmitted by the transducers is different, it will take different times for the third wave to reach the trigger level. The third wave is used as the trigger wave. These time differences, T_e and T_f, are the errors due to transducer mis-match in amplitude and frequency respectively. Actually the transducers are mis-matched both in amplitude and frequency with the two time differences adding. When the flowmeter is measuring a small change in frequency due to a small flow velocity, this error can be significant.

Since it is impossible to give an error without defining the system, various error magnitudes have been calculated* based on the following conditions:

Conduit material----------steel

Sound path lengths--------2 feet through 14 feet

Flow velocities-----------1.5 through 6.0 feet per second

Figures 8 through 19 show the relationship of the various instrument errors and the scale factor errors for various velocities. Figures 20 through 22 show the relationship of the total combined instantaneous and integrated errors for various path lengths and various maximum velocities.

The following observations about the sources of error in an ultrasonic flowmeter can be made:

(1) The largest source of error in path lengths greater than 7 feet is in scale factor error.

(2) The path length must be at least 7 feet in length to insure accuracy within one percent.

(3) The error at the same flow velocity is essentially the same regardless of the maximum design velocity.

(4) As the path length and velocity of flow decrease, the instrument measurement errors increase rapidly.

(5) The difference between the instantaneous and integrated errors is small. This is because memory value, frequency multiplier stop interval, and digital to analog conversion errors which do not enter into the integrated error are small.

*See footnote page 29.

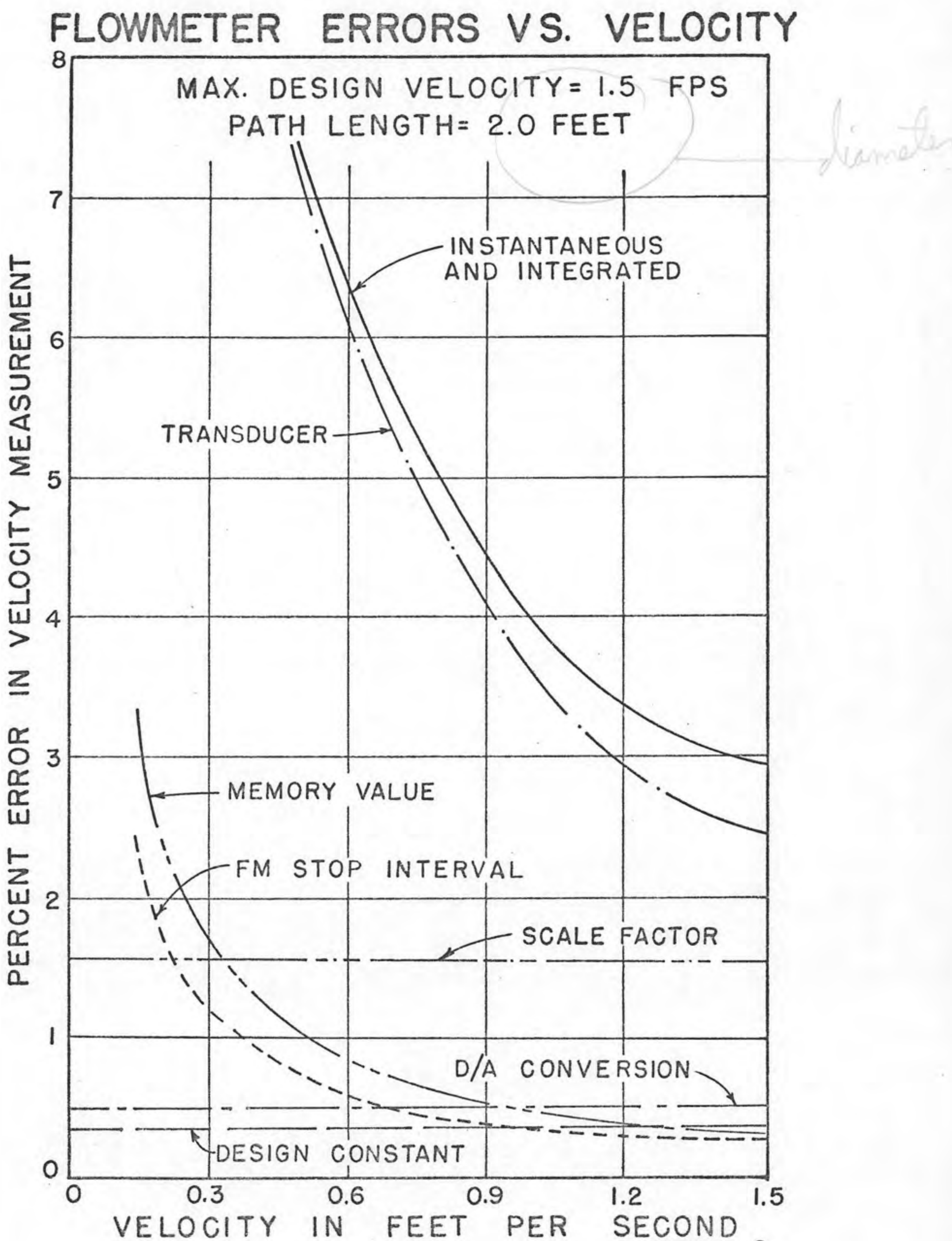

FLOWMETER ERRORS VS. VELOCITY
MAX. DESIGN VELOCITY= 1.5 FPS
PATH LENGTH= 2.0 FEET
diameter
INSTANTANEOUS AND INTEGRATED
TRANSDUCER
MEMORY VALUE
FM STOP INTERVAL
SCALE FACTOR
D/A CONVERSION
DESIGN CONSTANT
PERCENT ERROR IN VELOCITY MEASUREMENT
VELOCITY IN FEET PER SECOND
0
1
2
3
4
5
6
7
8
0.3
0.6
0.9
1.2
1.5

FIGURE 8

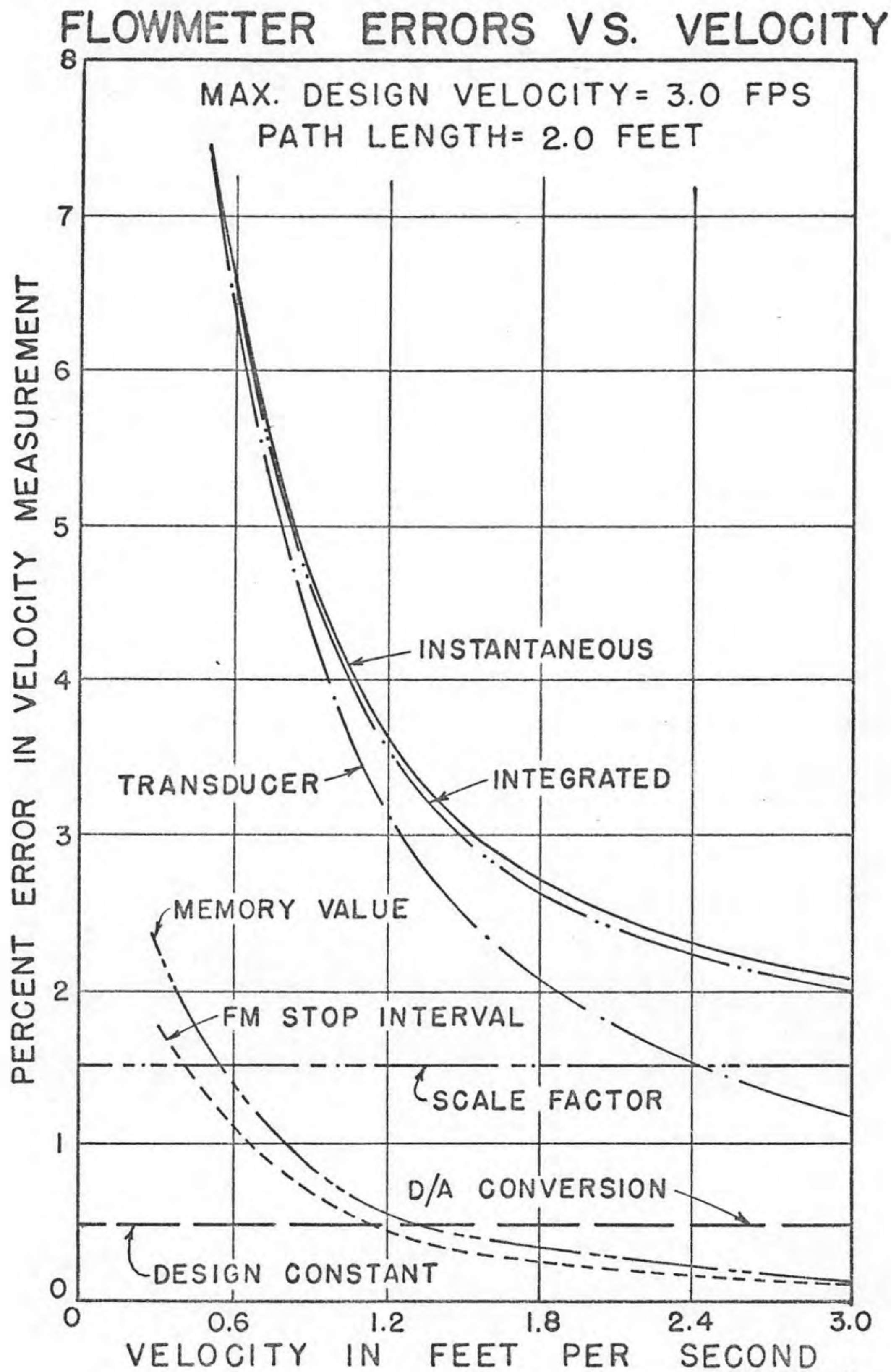

FLOWMETER ERRORS VS. VELOCITY
MAX. DESIGN VELOCITY= 3.0 FPS
PATH LENGTH= 2.0 FEET
INSTANTANEOUS
TRANSDUCER
INTEGRATED
MEMORY VALUE
FM STOP INTERVAL
SCALE FACTOR
D/A CONVERSION
DESIGN CONSTANT
PERCENT ERROR IN VELOCITY MEASUREMENT
VELOCITY IN FEET PER SECOND
0
1
2
3
4
5
6
7
8
0
0.6
1.2
1.8
2.4
3.0

FIGURE 9

FLOWMETER ERRORS VS. VELOCITY

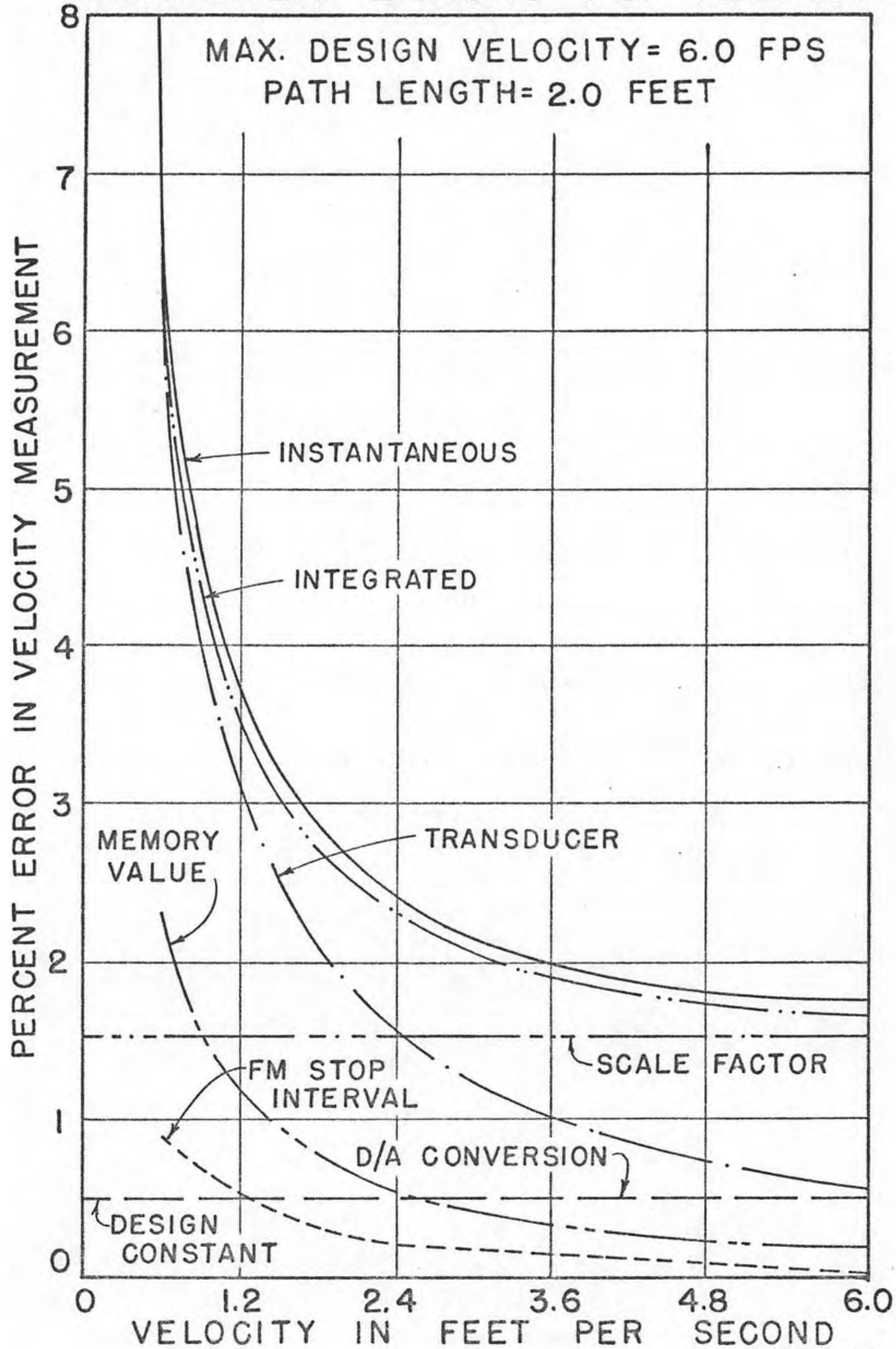


FIGURE 10

FLOWMETER ERRORS VS. VELOCITY

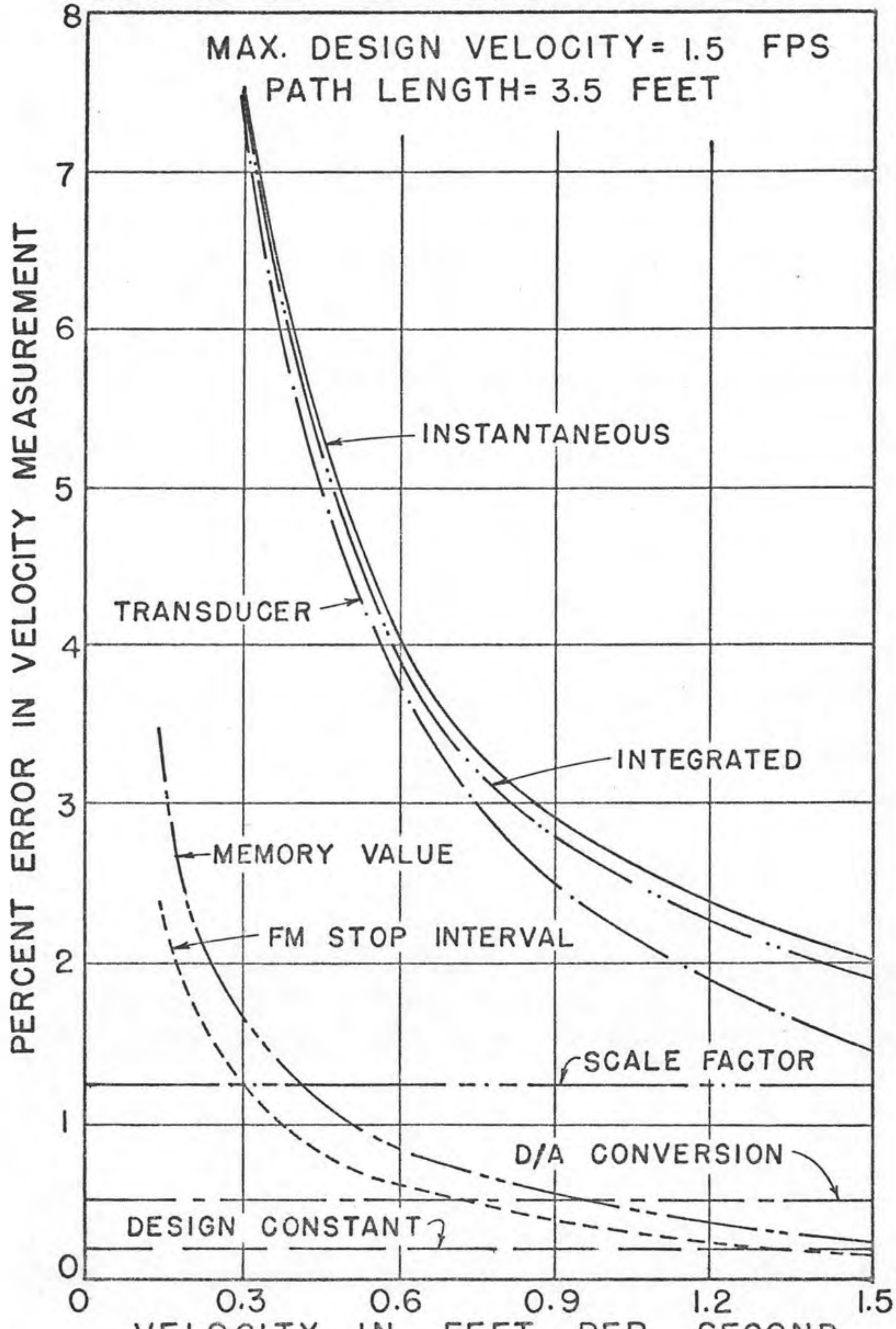


FIGURE II

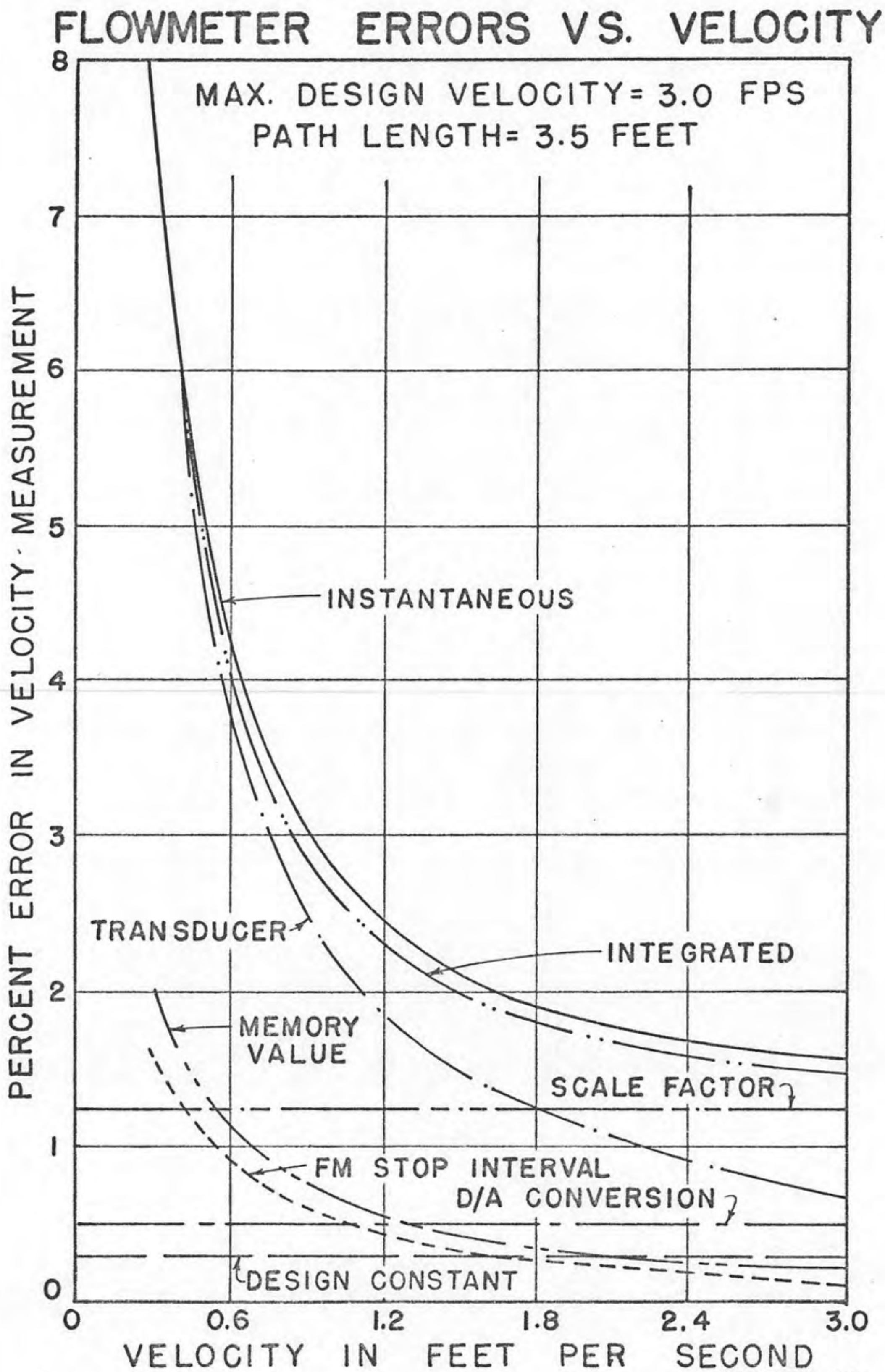

FLOWMETER ERRORS VS. VELOCITY
MAX. DESIGN VELOCITY = 3.0 FPS
PATH LENGTH = 3.5 FEET
INSTANTANEOUS
TRANSDUCER
INTEGRATED
MEMORY VALUE
SCALE FACTOR
FM STOP INTERVAL
D/A CONVERSION
DESIGN CONSTANT
PERCENT ERROR IN VELOCITY MEASUREMENT
VELOCITY IN FEET PER SECOND
0
1
2
3
4
5
6
7
8
0.6
1.2
1.8
2.4
3.0

FIGURE 12

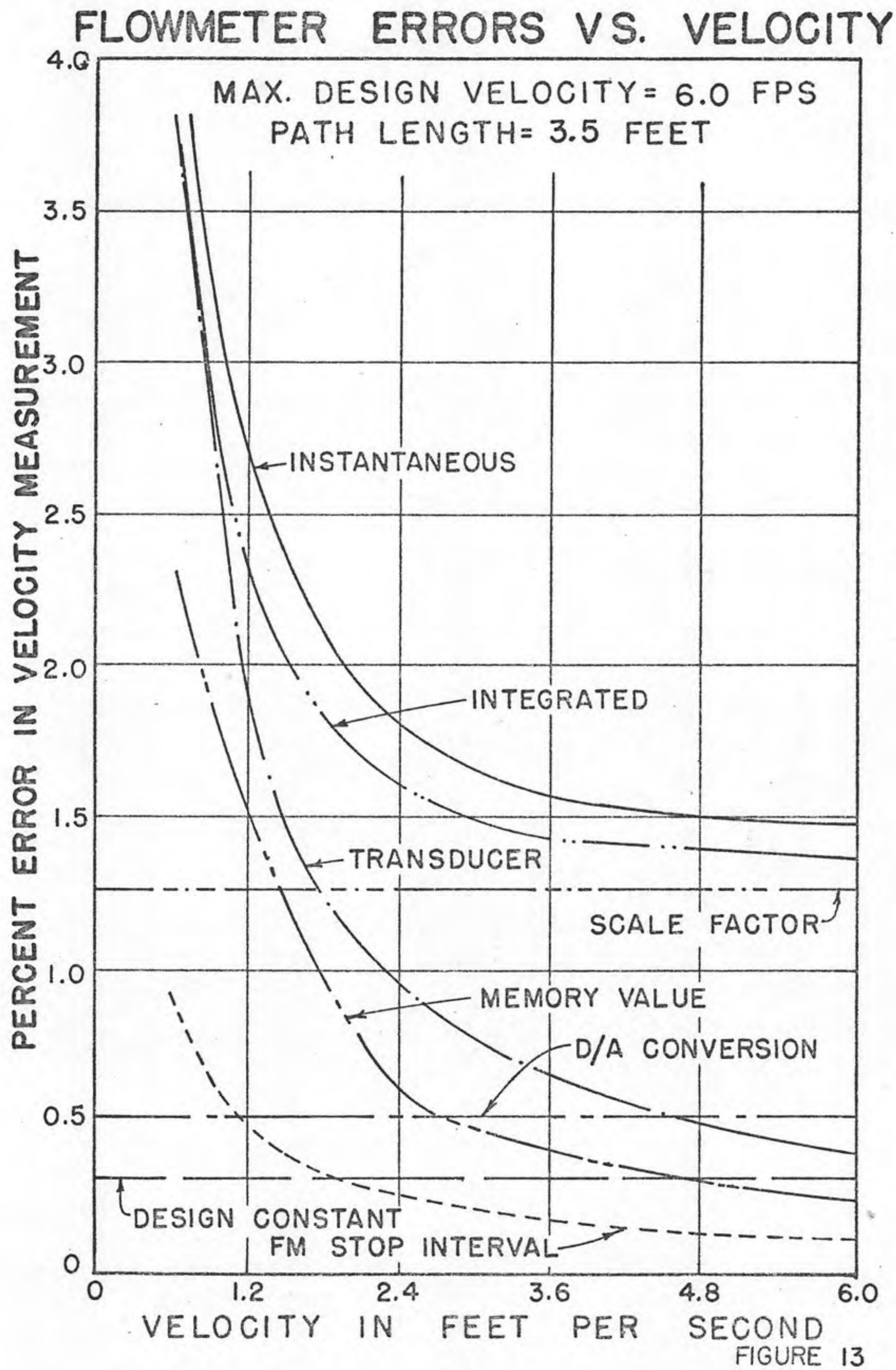

FLOWMETER ERRORS VS. VELOCITY
MAX. DESIGN VELOCITY= 6.0 FPS
PATH LENGTH= 3.5 FEET
INSTANTANEOUS
INTEGRATED
TRANSDUCER
SCALE FACTOR
MEMORY VALUE
D/A CONVERSION
DESIGN CONSTANT
FM STOP INTERVAL
PERCENT ERROR IN VELOCITY MEASUREMENT
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
1.2
2.4
3.6
4.8
6.0
VELOCITY IN FEET PER SECOND

FIGURE 13

FLOWMETER ERRORS VS. VELOCITY

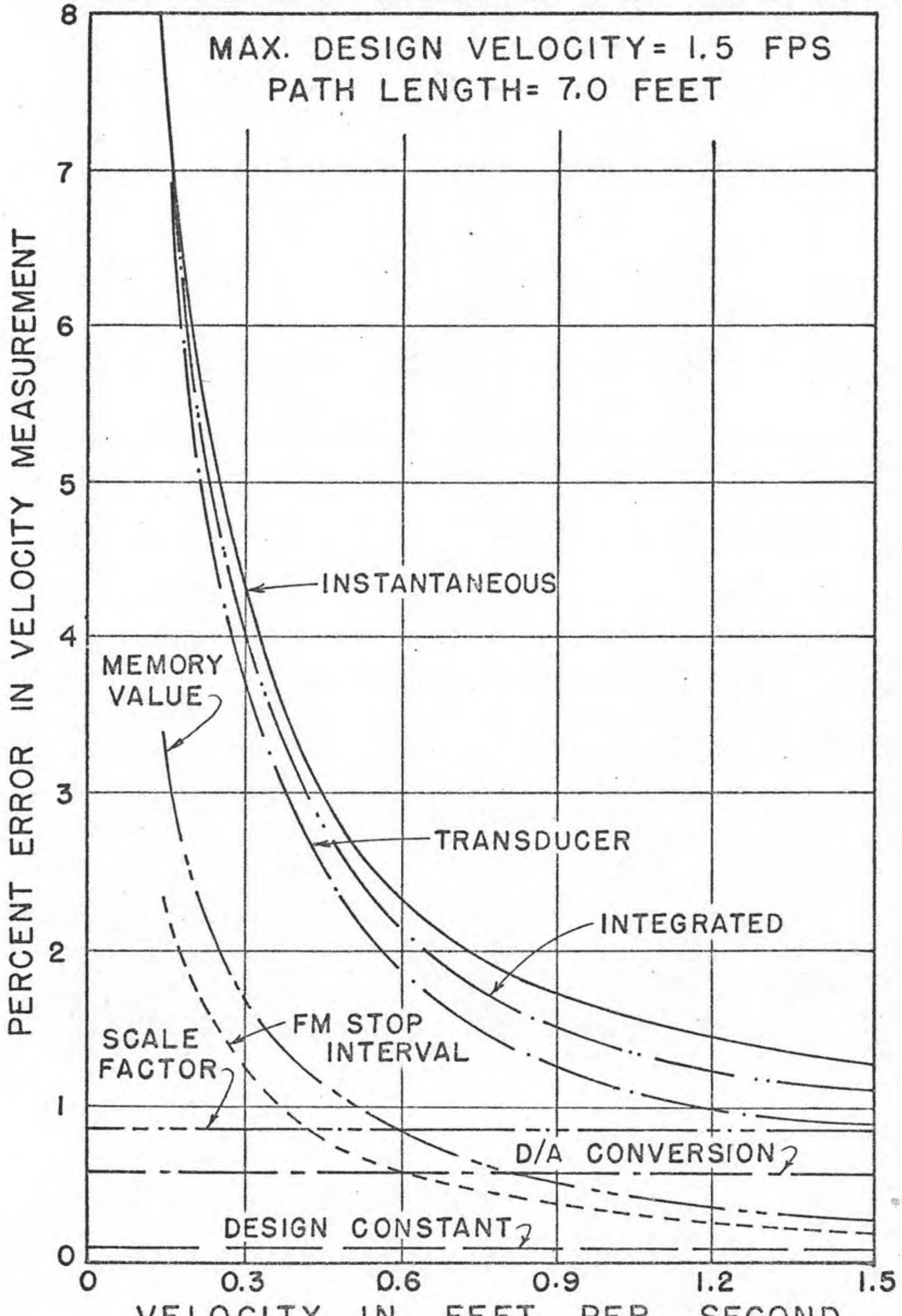


FIGURE 14

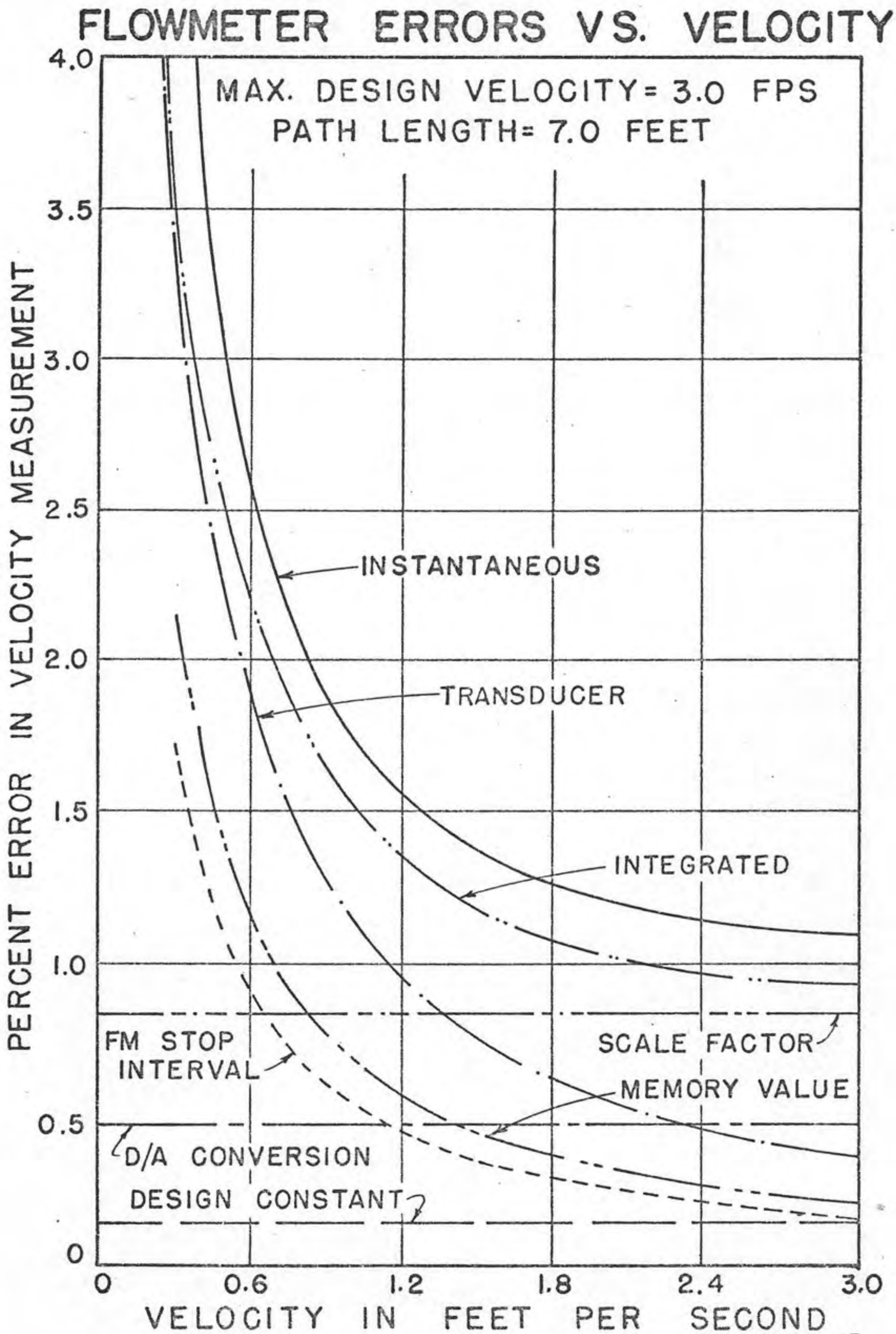

FLOWMETER ERRORS VS. VELOCITY
MAX. DESIGN VELOCITY= 3.0 FPS
PATH LENGTH= 7.0 FEET
PERCENT ERROR IN VELOCITY MEASUREMENT
VELOCITY IN FEET PER SECOND
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
0.6
1.2
1.8
2.4
3.0
INSTANTANEOUS
TRANSDUCER
INTEGRATED
FM STOP
INTERVAL
SCALE FACTOR
MEMORY VALUE
D/A CONVERSION
DESIGN CONSTANT

FIGURE 15

FLOWMETER ERRORS VS. VELOCITY

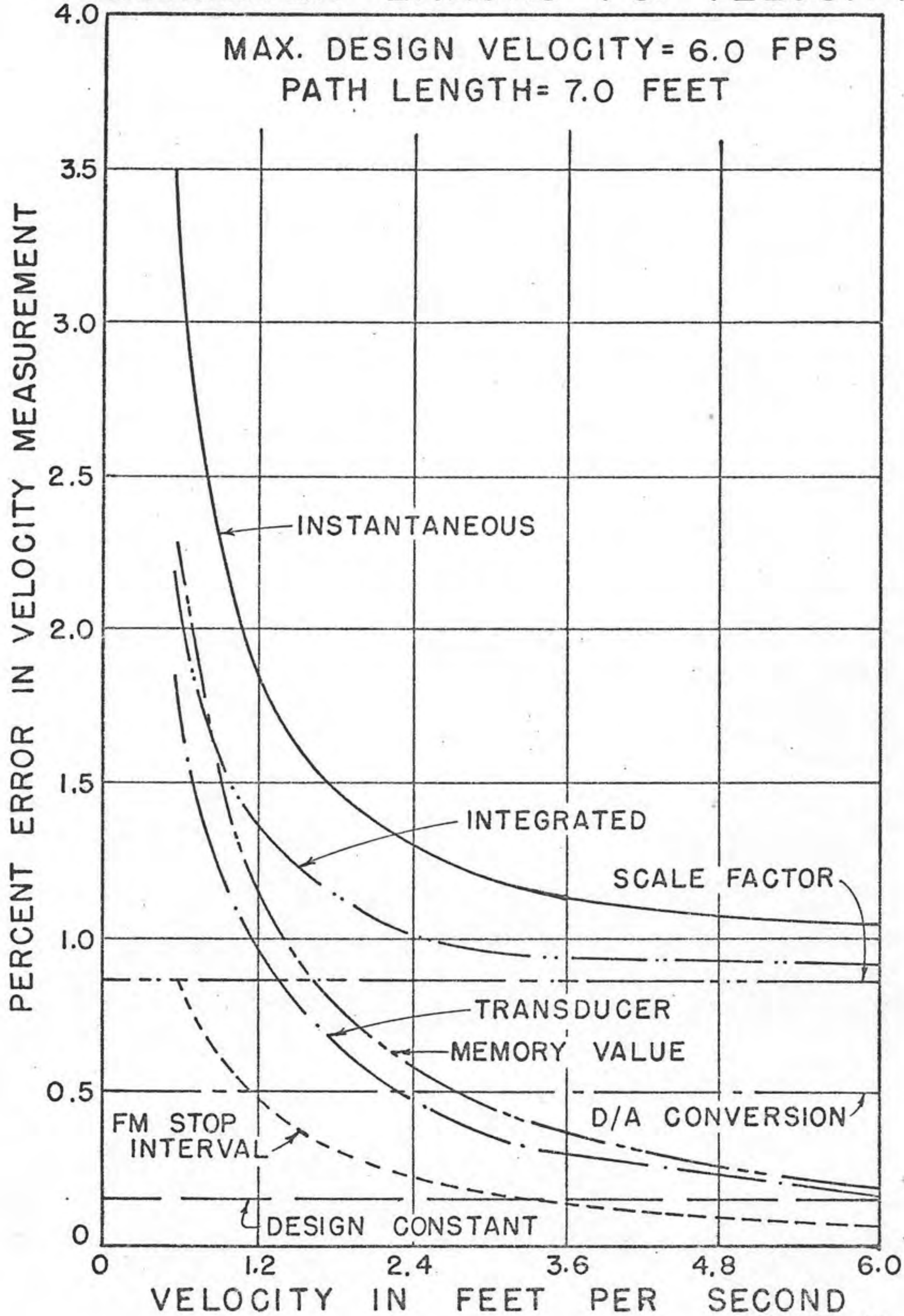
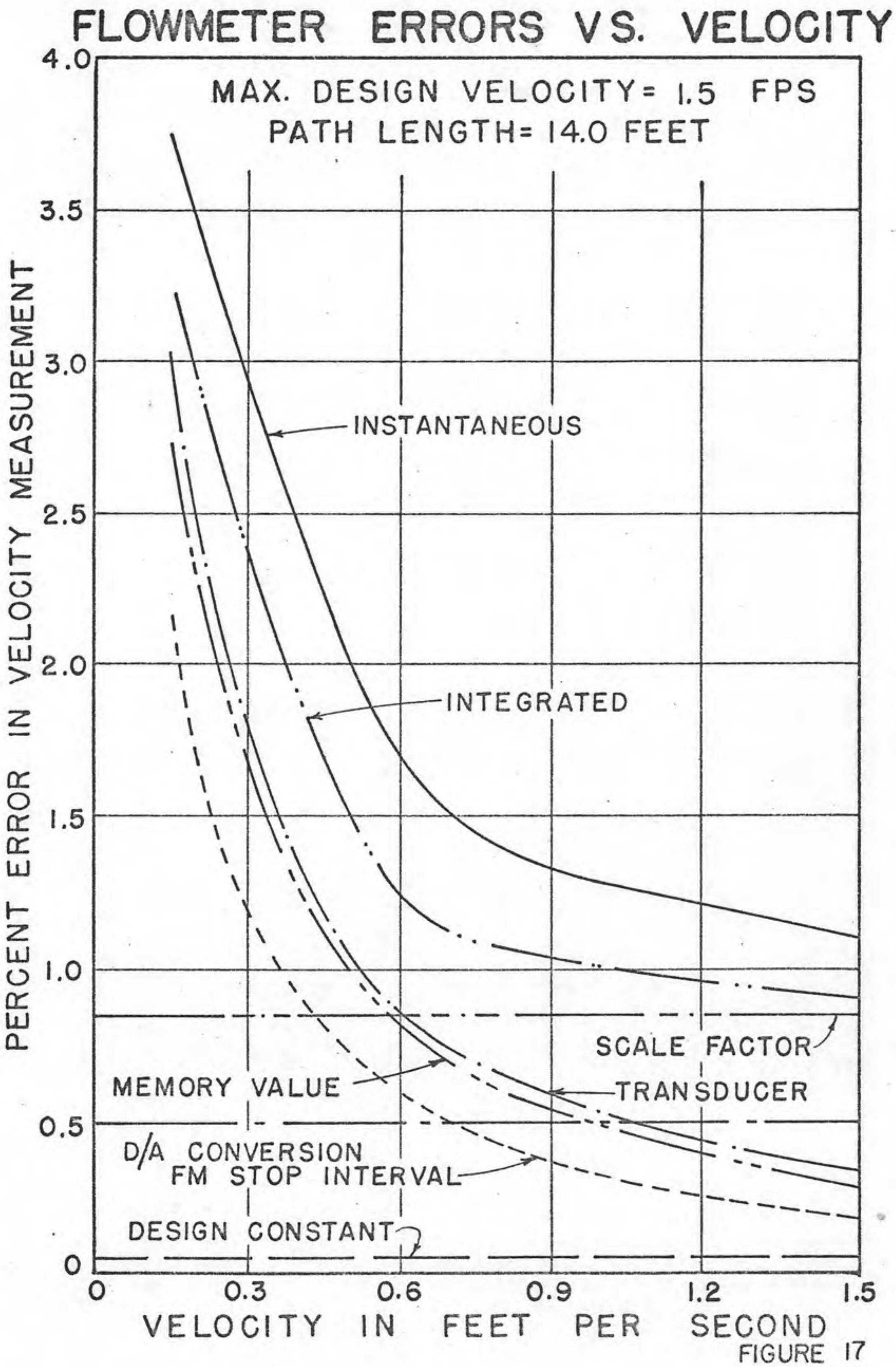


FIGURE 16


FLOWMETER ERRORS VS. VELOCITY
MAX. DESIGN VELOCITY= 1.5 FPS
PATH LENGTH= 14.0 FEET
PERCENT ERROR IN VELOCITY MEASUREMENT
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
INSTANTANEOUS
INTEGRATED
SCALE FACTOR
MEMORY VALUE
TRANSDUCER
D/A CONVERSION
FM STOP INTERVAL
DESIGN CONSTANT
0
0.3
0.6
0.9
1.2
1.5
VELOCITY IN FEET PER SECOND
FIGURE 17

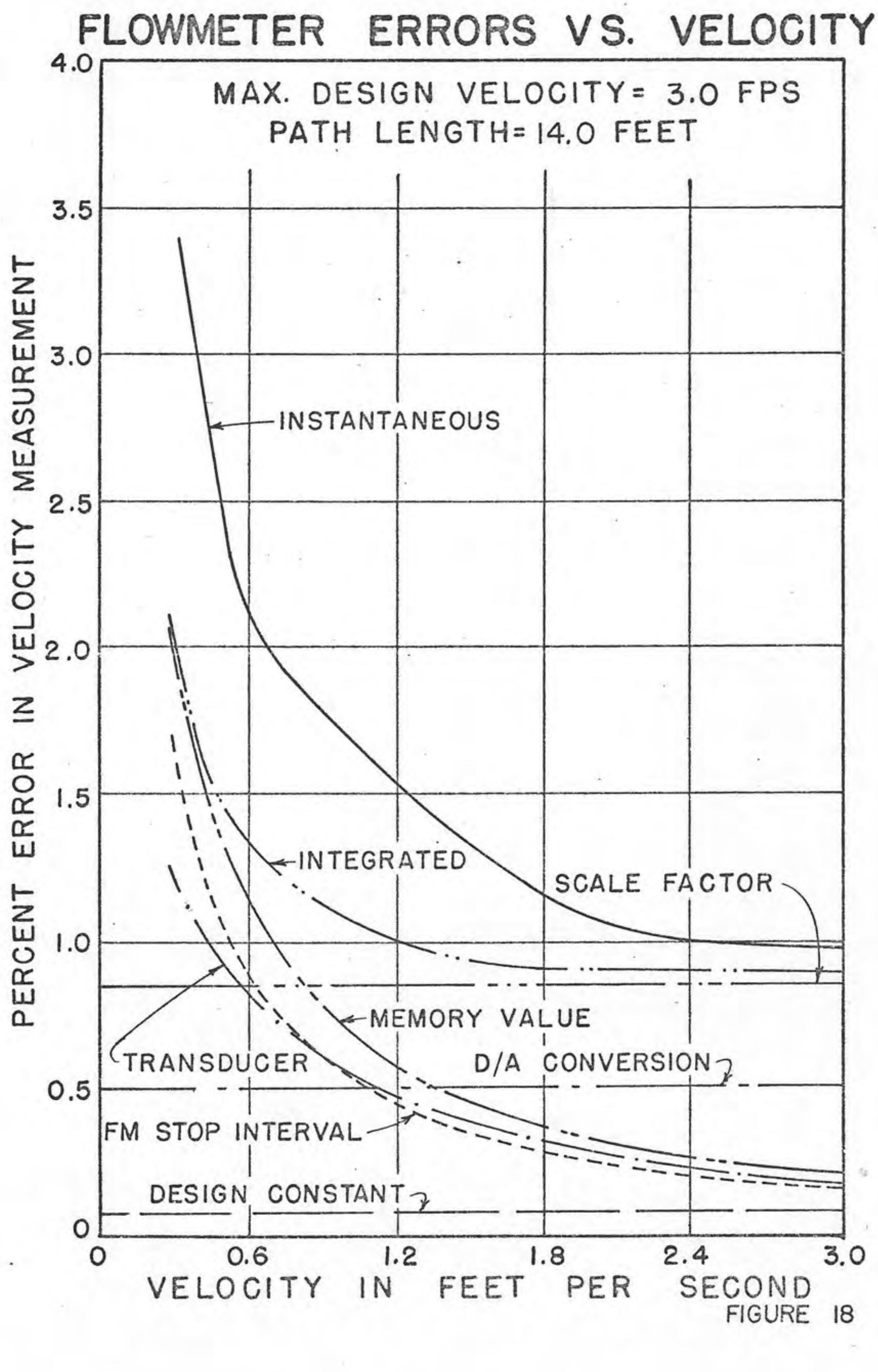

FLOWMETER ERRORS VS. VELOCITY
MAX. DESIGN VELOCITY= 3.0 FPS
PATH LENGTH= 14.0 FEET
PERCENT ERROR IN VELOCITY MEASUREMENT
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
INSTANTANEOUS
INTEGRATED
SCALE FACTOR
MEMORY VALUE
TRANSDUCER
D/A CONVERSION
FM STOP INTERVAL
DESIGN CONSTANT
0
0.6
1.2
1.8
2.4
3.0
VELOCITY IN FEET PER SECOND

FIGURE 18

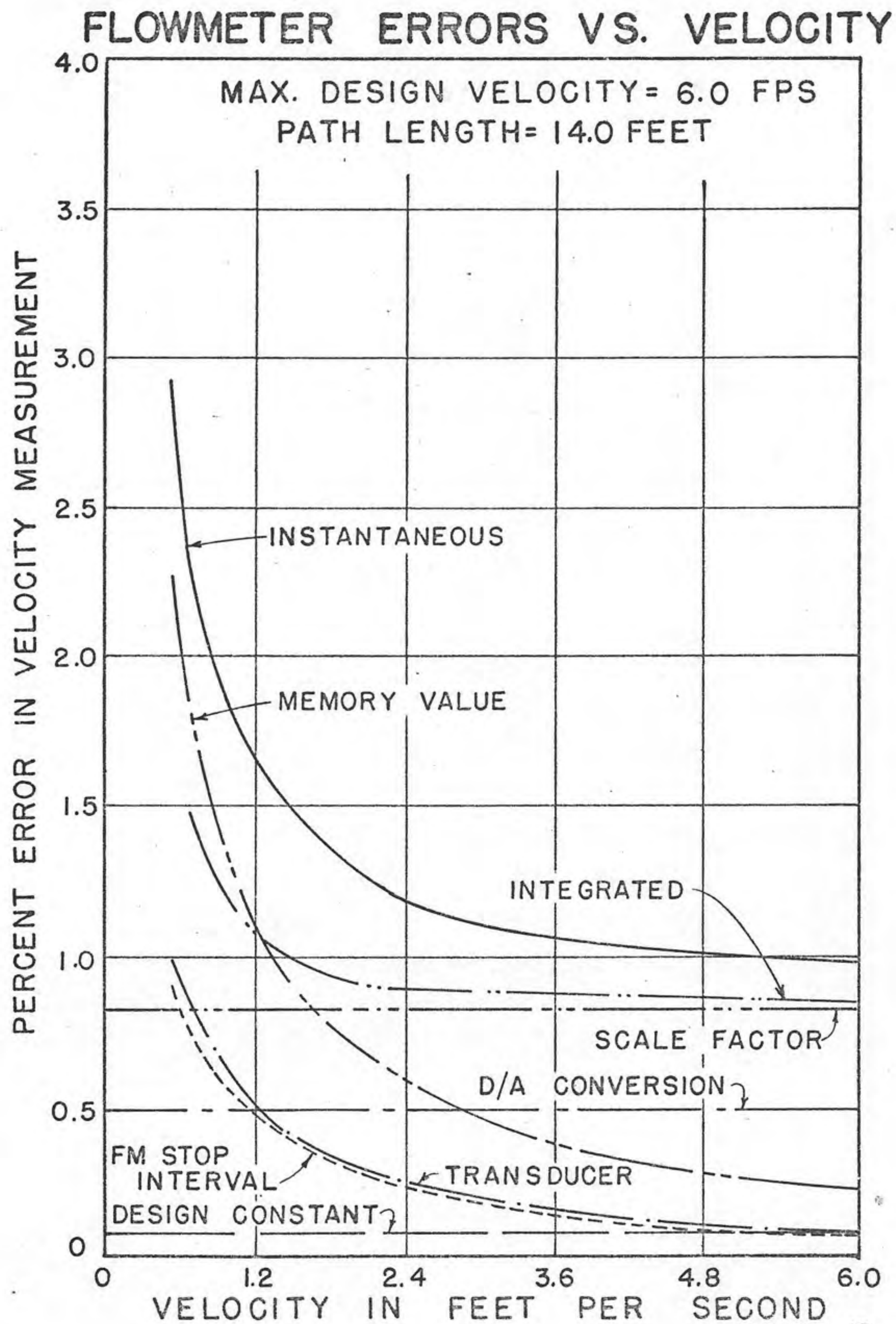

FLOWMETER ERRORS VS. VELOCITY
MAX. DESIGN VELOCITY= 6.0 FPS
PATH LENGTH= 14.0 FEET
PERCENT ERROR IN VELOCITY MEASUREMENT
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
INSTANTANEOUS
MEMORY VALUE
INTEGRATED
SCALE FACTOR
D/A CONVERSION
FM STOP INTERVAL
TRANSDUCER
DESIGN CONSTANT
0
1.2
2.4
3.6
4.8
6.0
VELOCITY IN FEET PER SECOND

FIGURE 19

INSTANTANEOUS AND INTEGRATED ERRORS VS. VELOCITY

MAX. DESIGN VELOCITY = 1.5 FPS

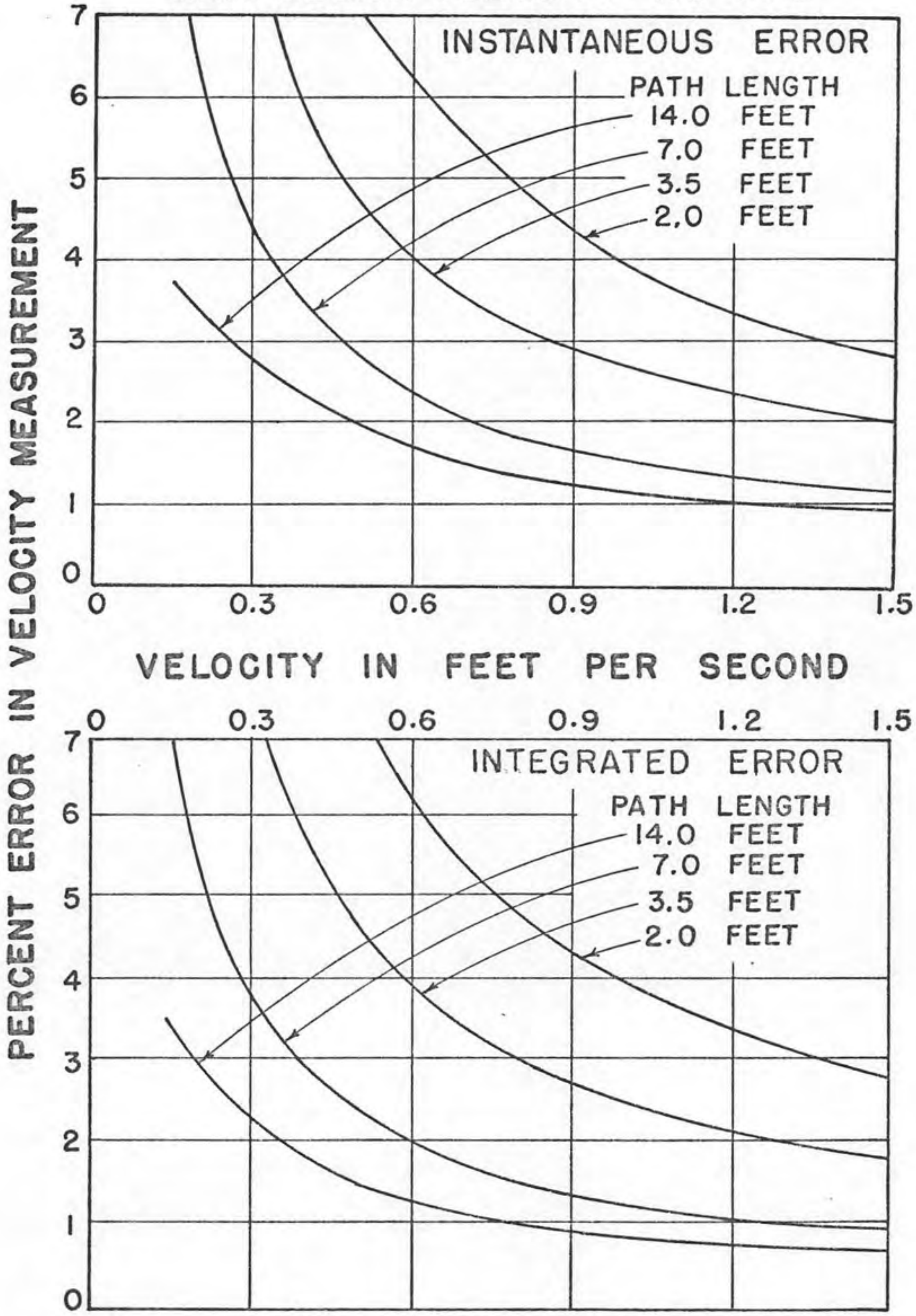


FIGURE 20

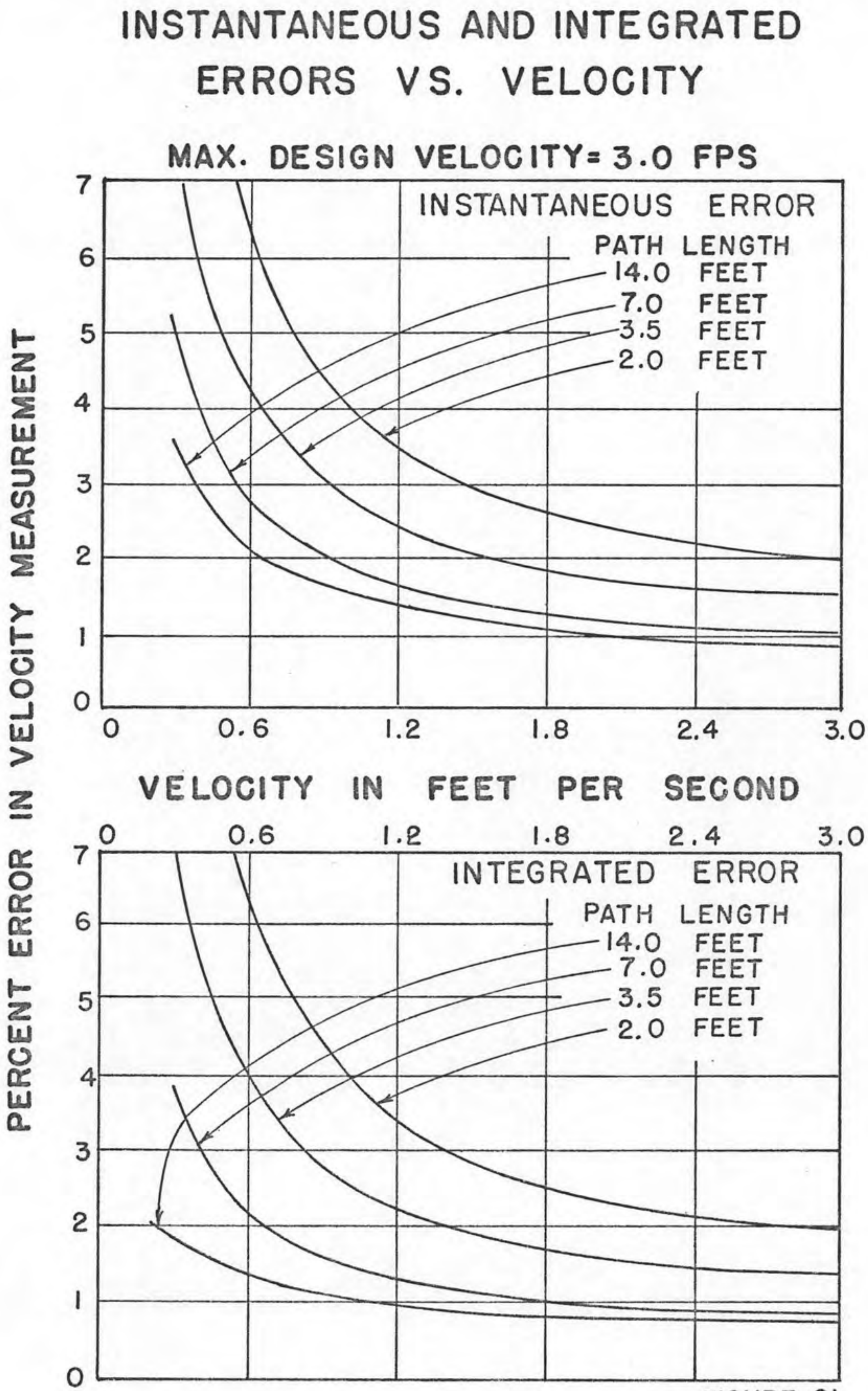

INSTANTANEOUS AND INTEGRATED
ERRORS VS. VELOCITY
MAX. DESIGN VELOCITY= 3.0 FPS
INSTANTANEOUS ERROR
PATH LENGTH
14.0 FEET
7.0 FEET
3.5 FEET
2.0 FEET
INTEGRATED ERROR
PATH LENGTH
14.0 FEET
7.0 FEET
3.5 FEET
2.0 FEET
PERCENT ERROR IN VELOCITY MEASUREMENT
VELOCITY IN FEET PER SECOND
0
0.6
1.2
1.8
2.4
3.0
0
1
2
3
4
5
6
7

FIGURE 21

INSTANTANEOUS AND INTEGRATED ERRORS VS. VELOCITY

MAX. DESIGN VELOCITY = 6.0 FPS

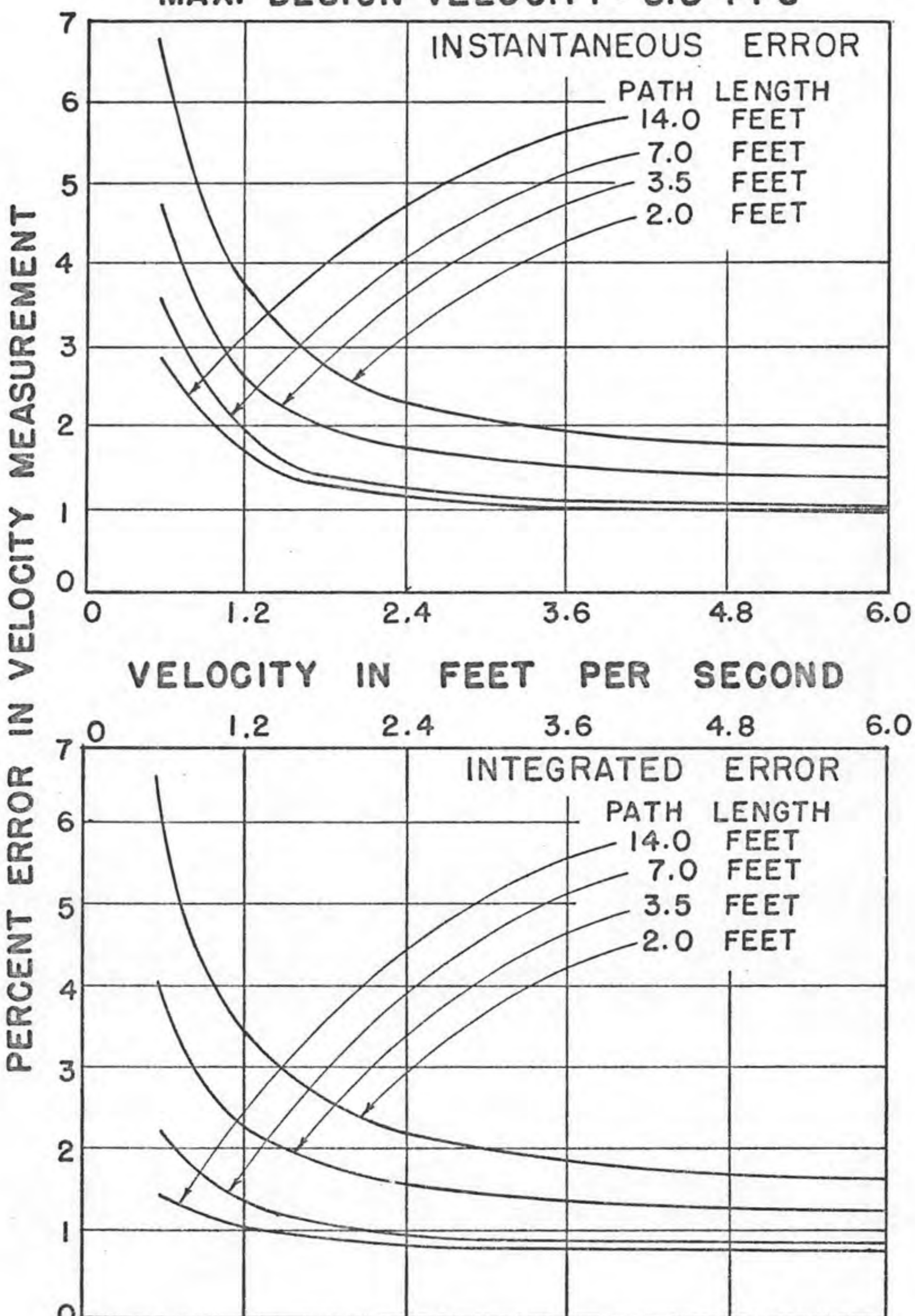


FIGURE 22

Q= AV

CHAPTER IV

VELOCITY CORRECTION FACTOR

Since an ultrasonic flowmeter measures the average velocity along the sound path, some means must be used to correct this velocity to the mean flow velocity before any flow discharge can be computed from the continuity equation. How this average velocity is corrected depends upon the velocity profile.

There are five distinct velocity profiles that are of interest. They are; (1) a fully developed laminar profile; (2) a fully developed turbulent non-varying profile; (3) a distorted non-varying profile; (4) a distorted profile that varies with time, and (5) a distorted profile that varies with time and is of unknown shape.

In the first three profiles, the average velocity along a single path can be corrected adequately to the mean velocity. In the last two, a multiple path approach must be used. In the multiple path approach a number of velocity measurements are made and using approximate integration techniques these velocities are integrated across the flow section.

Since a pipe is probably the most widely used conduit in a conveyance system, the remainder of this discussion will consider the velocity correction factor as applied to a full flow circular cross section. For other cross sections and for free surface flow, a similar approach can be used obtaining similar results.

SINGLE PATH

If a velocity profile is non-varying, the simplest and least expensive method of correcting the average velocity as determined by the flowmeter to the mean velocity, $\bar{V}$, used in the continuity equation is with a velocity correction factor. This velocity correction factor, K_f, is defined as the ratio of the average velocity along the sound path to the mean velocity

$$K_f = \frac{V}{\bar{V}} \qquad (27)$$

For a fully developed laminar flow profile, profile (1) above, the velocity correction factor is a constant and can be readily calculated. For laminar flow, the velocity at any point can be expressed as $V_y = V_c(1-y^2/r^2)$ where the variables are as shown in Figure 23.

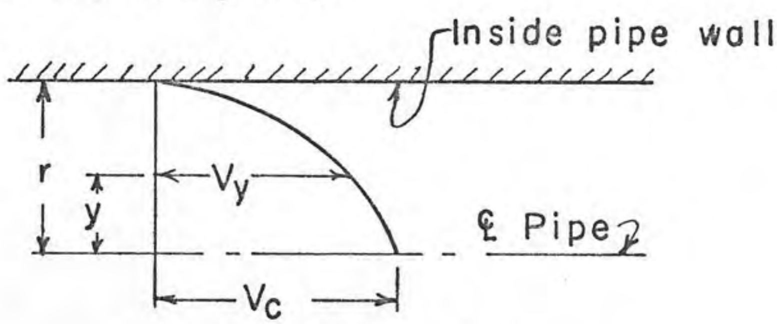


FIGURE 23

The average velocity, V, of the sound path is

$$V = \frac{1}{r}\int_0^r V_y\,dy \qquad (28)$$

The mean velocity, $\bar{V}$, is

$$\bar{V} = \frac{1}{\pi r^2}\int_0^r 2\pi r V_y\, y\,dy \qquad (29)$$

Performing the necessary integration, dividing Equation (29) into Equation (28) and simplifying, $K_f = 4/3$. If the equation of the velocity profile is exact, the relationship between the average to the mean velocities is exact.

For a fully developed turbulent velocity profile, profile (2) above, the velocity correction factor is not a constant because the equation of the velocity profile cannot be expressed exactly. In this case, the velocity correction factor can be computed by either of two methods. The first method is to model the conduit and determine the velocity of flow throughout the cross section. Then graphically determine the average velocity along the sound path and mean velocity across the flow section. Then divide the average velocity by the mean velocity to obtain the velocity correction factor. The other and most used method is to use an empirical velocity profile equation and integrate the equation across the flow section. Then dividing by the mean velocity yields the velocity correction factor. A number of equations have been developed for this purpose, some of which are,

(17)

$$K_f = \frac{2+\sqrt{f}}{2} \qquad (30)$$

(24)

$$K_f = 1 + \frac{0.19}{R_n^{0.1}} \qquad (31)$$

(25)

$$K_f = 1 + 0.01\sqrt{6.25 + \frac{431}{R_n^{0.237}}} \qquad (32)$$

(26)

$$K_f = 1.12 - 0.011\ \mathrm{Log}_{10} R_n \tag{33}$$

(27)

$$K_f = 1 + 0.4419\sqrt{f} \tag{34}$$

where

R_n = Reynolds number, and

f = Darcy friction factor.

The basic difference among all of these equations is in the empirical velocity profile equation and the simplifications used to reduce the equation to a usable form.

Various Reynolds numbers and the corresponding Darcy friction factor for smooth pipe were input into the above equations, the results are shown in Table 1.

TABLE 1

VELOCITY CORRECTION FACTORS FOR SMOOTH PIPE

Reynolds number	Darcy friction factor	Velocity Correction Factor EQ. 30	EQ. 31	EQ. 32	EQ. 33	EQ. 34
50,000	.0205	1.072	1.064	1.063	1.064	1.063
100,000	.0178	1.067	1.060	1.059	1.059	1.059
500,000	.0130	1.057	1.051	1.050	1.057	1.050
1,000,000	.0116	1.054	1.048	1.048	1.054	1.048
10,000,000	.008	1.045	1.038	1.040	1.043	1.040

As can be seen from Table 1, there is very little difference between the velocity correction factor as determined by the Equations 30 through 34. This is particularly so for Equations 31 through 34.

In actual practice, the velocity correction factor, K_f, is computed using one of the velocity correction equations, with the velocity correction factor based on mean velocity flow conditions and applied to the ultrasonic flowmeter equations as a constant.

For a constant but distorted profile, profile 3 above, the discharge rate can be computed by either of two methods. The first is to use a single path graphical approach as described above or a multiple path approach as described below and then compute the discharge directly.

MULTIPATH

For flow profiles, (4) and (5) above, that vary with time, a single path method cannot be used. A method must be used that actually integrates the velocity across the flow section.

The basic equation to determine the discharge rate through a circular section is

$$Q = \int_0^R \int_0^R \int_0^R dl\, dv\, dx \qquad (35)$$

where dv is the velocity in an area that is dl long and dx wide and R is the radius of the circle, see Figure 24. If dl, dv, and dx can be expressed as a function of the radius R, the discharge can be computed accurately by Equation (35).

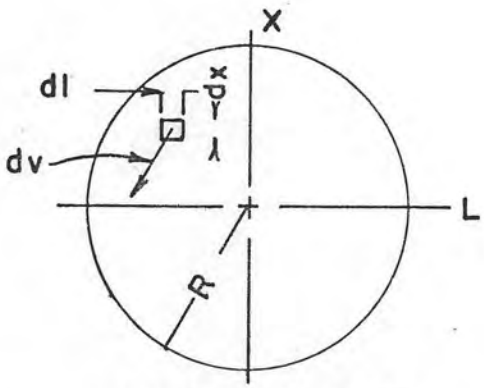


FIGURE 24

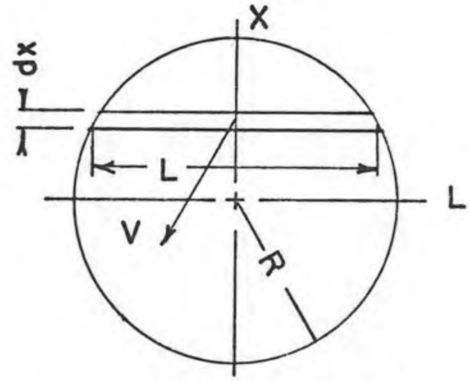


FIGURE 25

Since the ultrasonic flowmeter measures the average velocity, a fact explained earlier, along a sound path, in this case a chord, and the chord of a circle can be accurately measured, Equation (35) can be written

$$Q = \int_0^R L V \, dx \quad , \qquad (36)$$

where L is the length of the sound path, and V is the average velocity along the sound path, as shown in Figure 25.

If a numerical integration procedure could be employed to allow accurate integration of Equation (36) with a finite number of velocity measurements the discharge could be computed. There are a number of integration procedures available that can be used to develop this integration. Two of the more familiar are the Trapezodial Rule and the Simpson Rule. The best procedure to use is one that gives the best accuracy with the least number of velocity measurements.

One of the more accurate integration procedures with a minimum number of measurements is the Guassian Quadrature Integration Formula. This procedure can give an exact integration for any degree of a polynominal. The exact expression of this formula is

$$\int_B^A f(x)\,dx = \frac{B-A}{2} \sum_{i=1}^{n} W_i \; A_i + R \qquad (37)$$

where

A and B = the upper and lower limits of the integration respectively,

X_i = the specified Guassian distance,

$X_A = \frac{B-A}{2}(X_i) + \frac{B+A}{2}$, measured from the origin,

A_i = the ith measurement at X_A,

R = the remainder to be added to achieve exact integration, integration, and

W_i = the Guassian weight factors.

The values of X_A, at which measurements must be taken are specified and are symmerical about the center of the integration. The number of measurements needed for an exact integration is related to the highest order of X in the polynominal $y = a_1x^1 + a_2x^2 + \ldots + a_nx^n$. If n equals three, two measurements are required. For n equal to five and seven the number of measurements needed are three and four respectively.

In Equation (37), if R can be considered negligible and the axes transformed so that the lower limit of the integration is

A = 0, Equation (37) reduces to

$$\int_0^B f(x)\,dx \approx \frac{B}{2} \sum_{i=1}^{n} W_i\ A_i \qquad (38)$$

where $X_A = \frac{B}{2}(1+X_i)$.

Applying Equation (38) to Equation (36), Equation (36) can be written

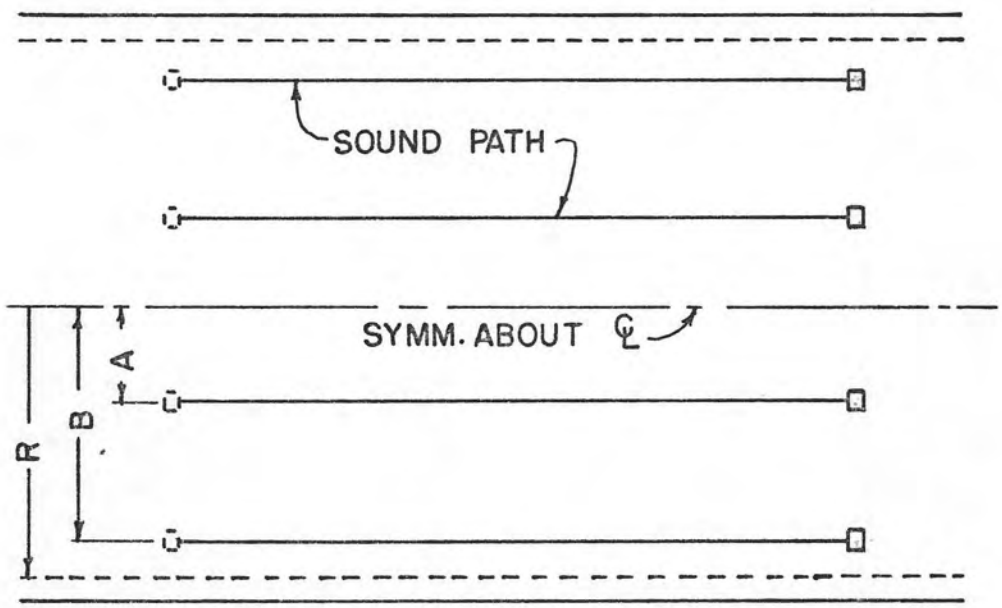
$$Q = R \sum_{i=1}^{n} W_i\ (VL) \qquad (39)$$

In the case of a circular cross-section, the product of the average velocity along the sound path, and the length of the sound path can be closely represented by a polynominal of no higher order than six, even for grossly distorted flow[28]. The largest contributing factor to this is that the chord length of a circle is a quadratic function of the diameter and when multiplied by the average velocity, the quadratic terms dominate the smaller higher terms of the average velocity. Another contributing factor is that the flowmeter measures the average velocity along the sound path and in the process smooths out any velocity distortions.

Since VL can be represented by a polynominal of no higher order than six, four velocity measurements are required. Therefore applying the Guassian weights factors to Equation (39) and noting what was stated earlier that the integration is symmerical about its centerline, Equation (39) can be written

$$Q = \left[0.1739(V_1 L_1 + V_4 L_4) + 0.3261(V_2 L_2 + V_3 L_3)\right] D \quad (40)$$

where D is the diameter of the circle and the V's and L's are measurements taken as shown in Figure 26.



A=0.3399 R
B=0.8611 R

FIGURE 26

There is nothing in Equation (40) that limits its use to a circle cross-section. It can be used on other cross sections with the L's and D replaced by appropriate values.

The accuracy of this procedure to handle distorted velocity profiles is shown in the following examples. The results are summarized in Table 2.

Shown in Figure 27 is a distorted hypothetical velocity profile plot looking in the downstream direction. The velocity contours are shown relative to the mean velocity. Since this is a hypothetical problem, the results of example (1) are taken as absolute. The examples are as follows:

1) The sound paths are taken vertically inclined downward looking downstream.
2) The sound paths are the same as in example (1) except the paths are rotated 45 degrees clockwise.
3) The sound paths are the same as in example (1) except the paths are rotated 45 degrees counterclockwise.
4) The sound paths are horizontal.
5) The sound paths are vertical as in example (1). The velocity profile is as shown at the most upstream transducer. At the most downstream transducer the velocity profile is rotated 90 degrees clockwise from that shown.
6) Same as example (5) except that the paths are inclined downward looking downstream.

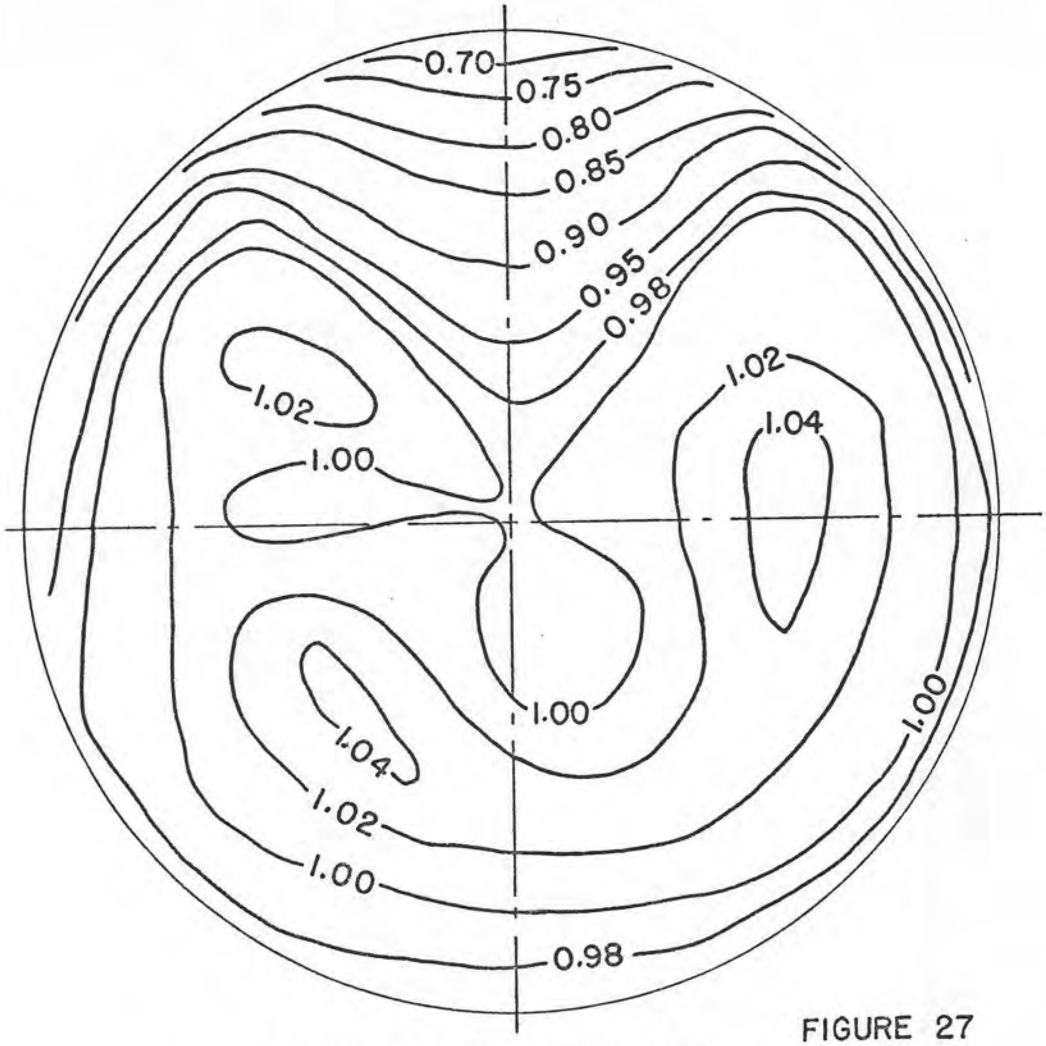


FIGURE 27

VELOCITY PLOT

VALUES RELATIVE TO MEAN VELOCITY

TABLE 2

DISCHARGE RATIOS

EXAMPLE NO.	1	2	3	4	5	6
RATIO*	0	1.008	0.992	0.996	1.031	-1.023

$$*\text{Ratio} = \frac{\text{Example 1 - Example No.}}{\text{Example 1}} \; 100$$

As can be seen in Table 2, this procedure integrates a distorted varying profile quite accurately. The disadvantage of using this procedure is the extra costs for additional transducers.

HAPTER V

.AMATION INSTALLATION

ger Meter Manufacturing Company of ultrasonic flowmeter to the U.S. ate the flowmeter's ability to offer requested that the flow- at least 12 inches, and pre- acility used for the demon- to measure accurately the dis- c or minus one percent, with which the flow- meter data could be compared. Equipment with this measurement accuracy requirements was available in the Bureau of Reclamation's hydraulic laboratory in Denver, Colorado.

Since the majority of conveyance systems are concrete pipe, and some asbestos-cement pipe was available at no cost, the offer was accepted with the proposal that the flowmeter be installed on a 24 inch inside diameter asbestos-cement pipe in the Bureau's hydraulic laboratory. It was felt that if the flowmeter performed satisfactorily under these conditions it would perform even better with steel pipe.

Since the Badger Company knew little about using an ultra- sonic flowmeter on an asbestos-cement pipe, they took three actions. First, they requested information from the manufacturer in Japan about their experience on installing the flowmeter on asbestos-cement pipe. Secondly, they contacted a pipe manu- facturer about the properties of asbestos-cement pipe. Thirdly, they purchased a section of asbestos-cement pipe and using it as a standpipe installed an ultrasonic flowmeter to it. The measured sing-around frequency of the sound pulse in non-flowing water was very close to the value calculated by Equation (21). Based on this test they considered the proposal feasible.

The flowmeter was installed on the asbestos-cement pipe in the Bureau's laboratory by Badger personnel on June 8, 1970. Flow comparison testing was started the next day. On June 25 Badger personnel returned in an effort to determine why the flowmeter was not performing satisfactorily. After some minor adjustments, the flowmeter still did not perform satisfactorily. The flowmeter was indicating a discharge that was considerably smaller than the actual discharge. Testing was stopped on June 26 pending an answer from Badger as to why the flowmeter was not working. Badger concluded in July that the flowmeter would not operate satisfactorily on asbestos-cement pipe because the sound transmission characteristics of the asbestos-cement were unpredictable. They suggested that a meaningful demonstration of the flowmeter's capabilities could be conducted on steel pipe where sound transmission through the steel would not be a problem.

The steel pipe installation was set up and Badger personnel returned and installed the flowmeter on October 24, 1970. Discharge comparison testing was started the next day and concluded on December 14, 1970. Test results indicated that the flowmeter can measure discharge accurately in a steel pipe.

On January 22, 1971 the plus 12 volt DC circuit within the flowmeter short-circuited and now is in the process of being repaired.

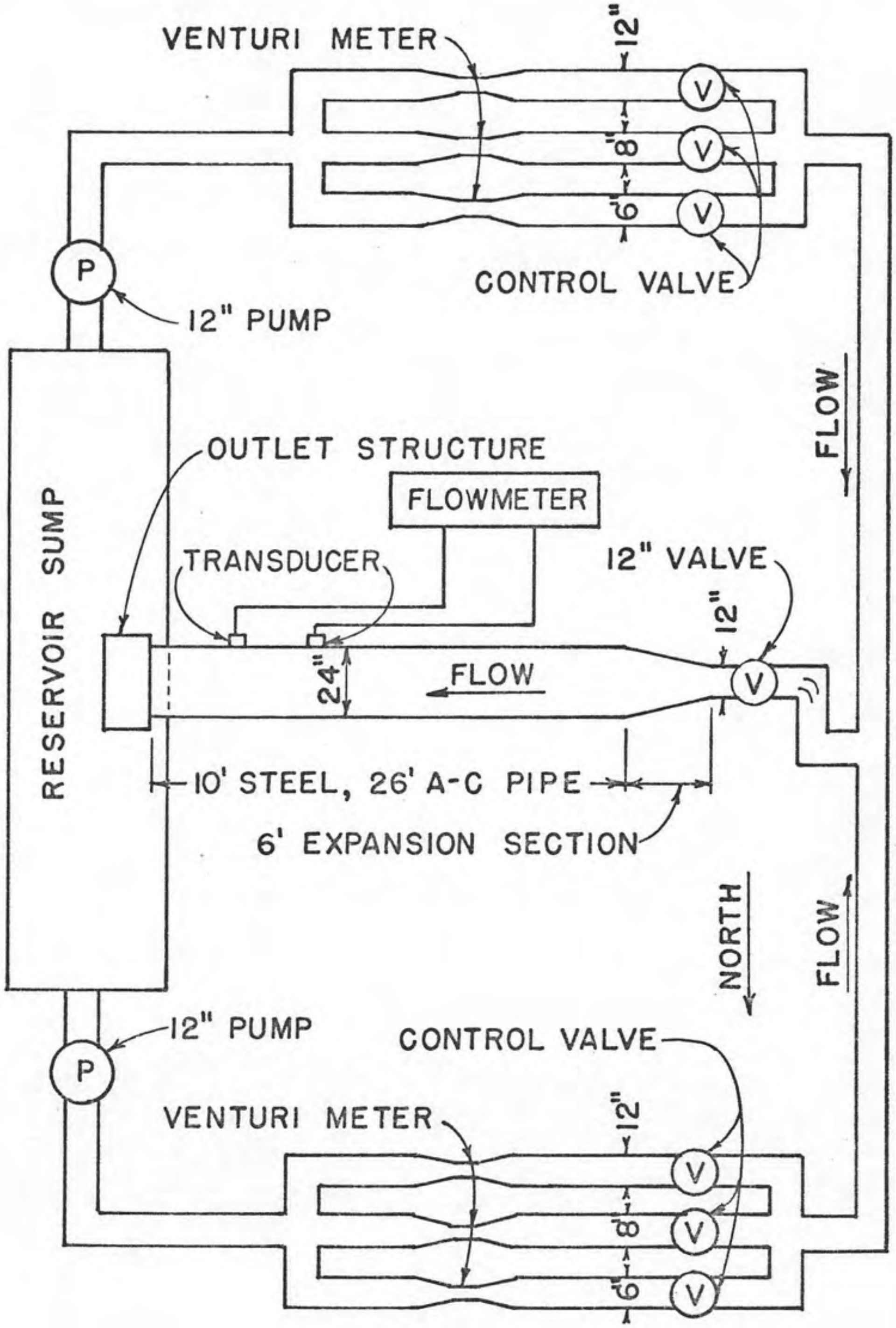
MODEL DESCRIPTION AND TEST PROCEDURE

An overall schematic of the model is shown in Figure 28. The laboratory uses a recirculating system where the water is pumped from a reservoir sump through a pipe system to the model where it is discharged back into the reservoir.

Discharge was measured by standard 6, 8, and 12 inch Venturi meters connected to a mercury differential manometer. The Venturi meters were calibrated and are believed to be accurate within plus or minus one percent.

The flowmeter was set up to measure the average velocity along one sound path. This average velocity was converted to the mean velocity in the continuity equation through the use of a velocity correction factor, see Chapter IV. For this installation Equation (34) was used. Therefore, a fully developed turbulent velocity flow profile was necessary.

The upstream transducer was set approximately 24 feet or 12 pipe diameters downstream from a 12 inch to 24 inch diameter expansion section. Just upstream from this was a 12 inch gate valve, that remained fully open through testing, followed by a 12 inch 90 degree single miter vaned elbow and two 12 inch 90 degree single miter non-vaned elbows. This arrangement was necessary because of the limited space available in the laboratory.



MODEL SCHEMATIC

(NO SCALE)

FIGURE 28

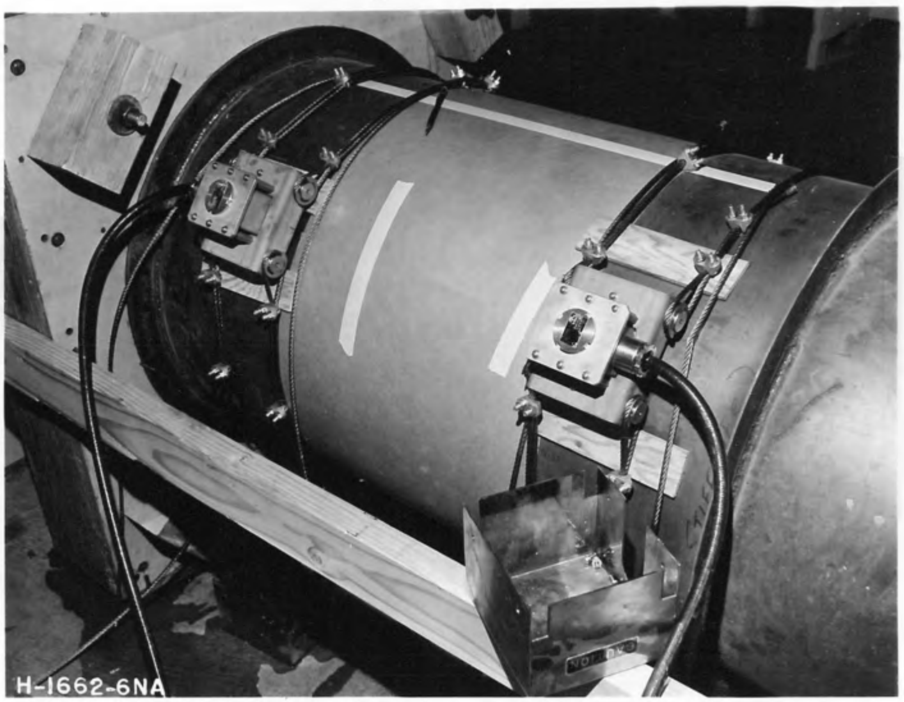
With this arrangement, the velocity profile was fully developed by the time it reached the upstream transducer.

Located approximately 6 feet or three pipe diameters downstream from the downstream transducer was an outlet structure which consisted of a wooden box without a floor over the reservoir sump. A series of wooden slots were positioned vertically at the pipe exit. Adjustment of the size of opening between the slots caused the pipe to flow full and allow the water to discharge as evenly as possible across the pipe cross-section. The steel and asbestos-cement pipes were smoothly connected so as not to disturb the velocity profile. In the case of the steel pipe test the upstream transducer was located approximately six inches from the pipe connection. See Figures 29 and 30 for further details.

A maximum discharge of 20 cubic feet per second of water could be delivered by the system to the model. For this case, pumps at each end of the reservoir were used. For discharges under 11.5 cubic feet per second only one pump was used. The minimum discharge was 0.5 cubic feet per second, the amount necessary to keep the pipe full with all of the slots placed in the outlet structure. The system had a maximum discharge variation, which was dependent upon a discharge rate, of about 0.3 cubic feet per second. The flow to the model was controlled by valves just downstream from the Venturi meters and by the pump speed.

OVERALL VIEW OF MODEL

FIGURE 29



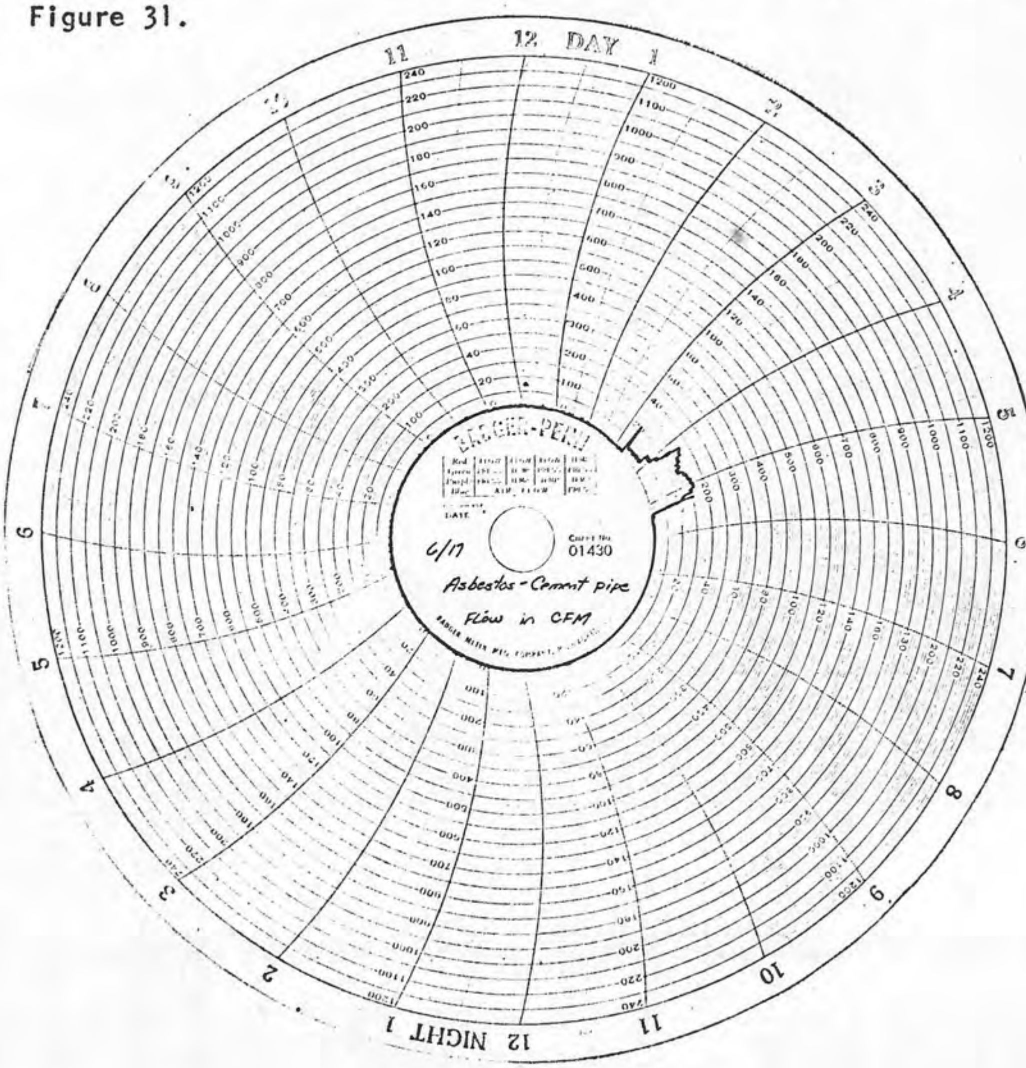
VIEW OF TRANSDUCERS INSTALLED ON STEEL PIPE

(FLOW IS FROM LEFT TO RIGHT)

FIGURE 30

The average inside and outside diameters of the asbestos-cement pipe were 23.955 inches and 30.086 inches respectively. The average inside diameter of the steel pipe was 24.090 inches with an average wall thickness of 0.075 inches.

The flowmeter recorded a discharge rate on a chart in cubic feet per minute and an integrated flow on a totalizer in units of one hundred cubic feet. For a typical example of a chart see Figure 31.



TYPICAL FLOW CHART

FIGURE 31

Using Snell's law of refraction to locate the sound path and trigometeric principles, the Badger Company calculated the distance between the transducers. They installed the transducers on the pipe. Before the transducers were installed on the asbestos-cement pipe, the outside "waffle texture" surface of the pipe was sanded to smooth. In both the asbestos-cement installation and steel pipe installation the transducer face next to the pipe was coated with a thin layer of axle grease before installing the transducers on the pipe. The axle grease was applied to improve sound transmission at the inner face and to help account for the fact that the pipe surface was round whereas the transducer face was a plane. For the transducer installation on steel pipe see Figure 30.

All of the testing was conducted using what is call a V installation form, see page 21, except for the testing conducted on June 26, 1970. Testing on this day was conducted using what is called a Z installation form.

The test procedure was as follows:

1. Provide a flow through the system and allow the system to stabilize.
2. Record the average discharge as indicated by the flowmeter.
3. Record the mercury manometer differential connected to the Venturi meter, and convert this differential to discharge.

4. Alter the discharge either by changing the pump speed or the opening of the control valve.

5. Repeat the cycle.

CALCULATIONS

The calculations for installing the flowmeter on the asbestos-cement and steel pipes were based on the values shown in Table 3.

TABLE 3

INSTALLATION DATA

ITEM	ASBESTOS-CEMENT PIPE	STEEL PIPE
Pipe		
Average inside diameter, feet	1.9963	2.0075
Average wall thickness, feet	0.25545	0.00625
Assumed sound velocity, feet per second	10,760	10,760
Cable length, feet	16	16
Installation form	V	V
Flow		
Maximum discharge, cubic feet per second	20.0	20.0
Maximum velocity, feet per second	6.32	6.32
Mean velocity, feet per second	3.00	3.47
Minimum velocity, feet per second	0.40	0.40
Velocity correction factor, Equation 34	1.050	1.051
Sound velocity, feet per second	4,790	4,790
Transducer angle, degrees	40	40

Based on the values in Table 3, Snell's law of refraction, and flowmeter equations, the values shown in Table 4 were computed.

TABLE 4

INSTALLATION CALCULATION RESULTS

ITEM	ASBESTOS-CEMENT PIPE	STEEL PIPE
Transducer spacing, feet	2.286	1.380
Sound time through pipe wall, picoseconds	49.67	1.22
Loop time delay constant, picoseconds	120.7	23.8
Time sound wave in water, picoseconds	905.6	910.7
Transit cycle time, picoseconds	1026.3	934.5
Frequency, non-flowing water	974.31Hz	1070.06Hz
Maximum frequency shift	0.9443Hz	1.1305Hz
Count time, seconds	1.92	1.92
Total cycle time, seconds	5.12	5.12

TEST RESULTS

A total of 199 discharge comparison tests were conducted. Of this total, 118 were conducted on the asbestos-cement pipe and 81 tests were conducted on the steel pipe. For each test a percent difference was calculated. The percent difference being defined as the

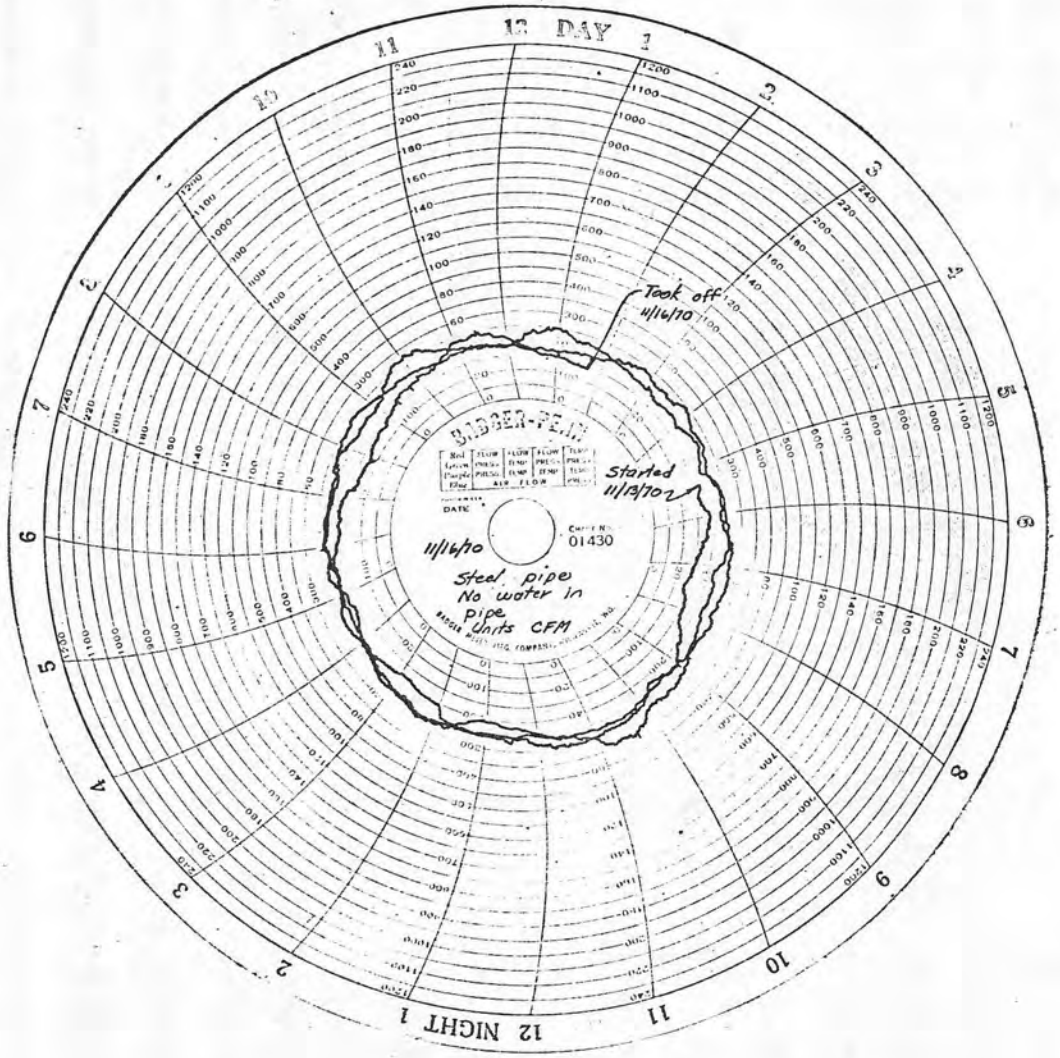
$$\frac{(\text{Venturi discharge-Ultrasonic Flowmeter discharge})100}{\text{Venturi discharge}}.$$

Tests on the asbestos-cement pipe were conducted over a discharge range from a minimum of 0.657 cubic feet per second to a maximum of 11.242 cubic feet per second. The percent difference between the Venturi and flowmeter varied from +45.8 to +5.5. The results of the asbestos-cement pipe tests are shown in Table 5 and Figure 36.

Tests on the steel pipe were conducted over a discharge range varying from a minimum of 0.422 cubic feet per second to a maximum of 17.570 cubic feet per second. The percent difference varied from +5.2 to -6.0. The overall algebraic average percent difference is +0.44. The square root of the sum of the squares of the percent difference is 0.25. The results of the tests are shown in Table 6 and Figure 37.

It should be noted that the steel pipe testing was done selectively. At various times the flowmeter indicated an obvious incorrect discharge rate. For example, see Figure 32.

This error became very apparent with no water in the pipe. The flowmeter would sometimes indicate a discharge rate as great as 7.0 cubic feet per second, about one-third of full scale, with no water in the pipe. It was present although not as apparent with the pipe completely full. It is believed that an instability in an electronic circuit within the flowmeter occurred producing this incorrect "zero drift" discharge reading. This "zero drift" may have been present when the flowmeter was installed on the asbestos-cement pipe, but for other reasons was not apparent.



TYPICAL FLOW CHART SHOWING "ZERO DRIFT"

FIGURE 32

Data were taken from the totalizer and converted to an average discharge rate. These were compared to an average discharge rate as recorded on the chart and found to be nearly the same. This indicates that the "zero drift" occurs within a circuit before or in the frequency multiplier circuit. The frequency multiplier circuit is the last circuit the instantaneous and integrated flows have in common.

Another interesting observation and possibly a clue in locating what caused this "zero drift" was that the flowmeter would record the actual discharge correctly, if the actual discharge through the pipe was greater than the discharge indicated because of the "zero drift". However, it would not indicate any discharge less than that controlled by the "zero drift". Suppose, for example, because of the "zero drift" the flowmeter indicated a discharge rate of 2.0 cubic feet per second. The flowmeter would measure and correctly record any discharge rate, as determined by the Venturi meters, greater than 2.0 cubic feet per second. However, the flowmeter would not indicate any discharge less than 2.0 cubic feet per second.

Badger was contacted after the "zero drift" became apparent. Some electronic components were replaced which were thought to be the problem. After installing the components the magnitude of the "zero drift" became less but was still present.

It was thought that the "zero drift" might be caused by voltage fluctuations within the electrical power source. A voltage regulator was installed between the flowmeter and the power source but with no apparent effect on the "zero drift".

It was in an attempt to determine more about the instability that the plus 12 volt DC circuit was short-circuited.

The Badger Company took this "zero drift" problem to the manufacturer in Japan for a solution. As of now, the problem is being worked on but not solved.

TEST RESULTS ANALYSIS

A justifiable conclusion based on the test results, disregarding the "zero drift", is that the flowmeter's performance was acceptable when installed on the steel pipe, and unpredictable and unacceptable when installed on the asbestos-cement pipe. The hydraulic conditions were very similar, the inside diameters nearly the same, and the flowmeter installation was essentially the same. Why the difference?

This difference can only be the result of two variables that were different, namely, the wall thickness and the wall material. All other variables in the system were near enough the same in each pipe test that their influence on the test results can be safely ignored. Of the two variables, wall thickness and wall material, wall thickness has the greatest influence on the flowmeter's performance. If the pipe wall is thin enough, the wall material will not have a significant influence on the results. However, if the pipe wall is thick, the wall material properties, such as the velocity of sound in the material, have to be known quite accurately if the flowmeter is to give acceptable results.

What constitutes a thin or thick wall is dependent upon the transit time ratio, the time for the sound pulse to travel through the wall to the total transit cycle time. If this ratio is small enough that it can be ignored when compared with other sources of error, see page 27, in the flowmeter, the wall would be classified as a thin wall in the sense of flowmeter application.

In the case of the steel pipe test, the transit time ratio was 0.0026. This installation would be classified as a thin wall installation with the wall material having little influence on the flowmeter's performance. This is evidenced by the test results. The installation calculations were based upon a velocity of sound in the steel pipe wall of 10,760 feet per second. A more realistic velocity of sound in steel may be about 16,000 feet per second[29]. This error in the assumed velocity of sound did not have an apparent effect on the test results.

For the asbestos-cement pipe installation, the pipe wall was 41 times thicker than the steel pipe wall. The transit time ratio was .096, a significant value. The asbestos-cement pipe would have to be classified as a thick wall installation where the wall material properties could influence the results. This is evidenced by the test results.

Some characteristics of asbestos-cement that could affect the results of the asbestos-cement pipe tests are:

1. the sound transmissibility of asbestos-cement,
2. the velocity of sound of the asbestos-cement, and
3. the sound transmission characteristics at the contact surface between the pipe surface and the transducer.

Intuitively one would expect sound transmission problems with a material as non-homogenous as asbestos-cement. Also, one would expect beam dispersion with a non-homogenous material.

Associated with beam dispersion is the loss of signal strength.

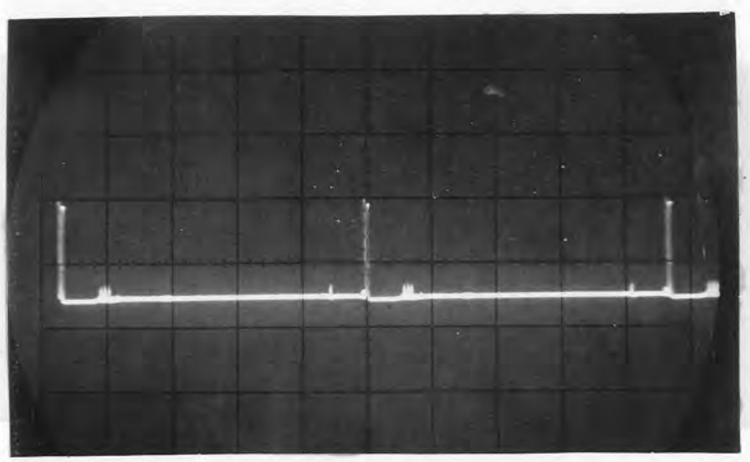
The first encountered beam dispersion was the outside "waffle texture" surface of the pipe. As explained earlier, the "waffles" were sanded, but even after sanding the surface of the pipe was rough with the "waffles" still easily visible. This surface probably caused some beam dispersion. Beam dispersion also occurred when the sound beam struck an asbestos fiber within the pipe wall. The sound beam was also dispersed when the beam was reflected at the far inside face of the pipe.

Using an oscilloscope, the transmitted and received sound signals were checked while the flowmeter was installed on the asbestos-cement pipe. Three distinct signals were received, all about the same relative strength and grouped close together. The signal strength was quite a bit lower than the transmitted signal indicating appreciable signal loss. The three signals are evidence of beam dispersion in the signal transmission through the asbestos-cement pipe walls. With this many signals and all of the same relative strength it is difficult to distinguish the main signal. Normally echoes and other miscellaneous noise patterns are small in signal strength and scattered so that separating the main signal is not a problem.

Another indication that sound transmission was a problem is that on June 25, 1970 the gain of the transmitting amplifier was increased by a factor of five through a small redesign. The average percent difference of tests conducted on June 11, 1970 and June 12, 1970 was approximately +20. (These test dates were used and not later ones because the percent difference was found to vary with time because of another factor. This will be discussed later.) The average percent difference on June 25, 1970 after the redesign was approximately +13. This indicates that a source of difference is in the signal strength.

It is unfortunate that some oscilloscope pictures were not taken showing the transmitted and received signals while the flowmeter was installed on the asbestos-cement pipe. After the flowmeter was installed on the steel pipe a request was made to reinstall the flowmeter on the asbestos-cement pipe so that pictures could be taken. If this had been done earlier sound transmission through asbestos-cement as a major source of error could be determined.

A picture of the transmitted and received signals when the flowmeter was installed on the steel pipe is shown in Figure 33.



TRANSMITTED AND RECEIVED SIGNALS

WITH FLOWMETER INSTALLED ON STEEL PIPE

FIGURE 33

In the installation calculations made by the Badger Company, the average velocity of sound through the asbestos-cement was assumed to be 10,760 feet per second. This value was based on an average modulus of elasticity and density for asbestos-cement supplied by an asbestos-cement pipe manufacturer. Using an oscilloscope and two accelerometers, tests were conducted to determine the velocity of sound in the asbestos-cement pipe. The results indicate that the velocity of sound varies with direction and the values along the pipe and circumferentially were 12,500 and 14,000 feet per second respectively, see Figure 34.

To show the effect of the velocity of sound in the calculations, assume a velocity of sound equal to 13,200 feet per second along the sound path. Also assume that sound transmission is not a problem and that the receiving transducer receives a strong, clear signal. Refer to Figure 35 where the values shown were taken from Table 4 for asbestos-cement pipe.

From Snell's refraction law we have

$$\frac{\text{Sin } \theta_1}{13{,}200} = \frac{\text{Sin } \theta}{4790}$$

and from geometry

$$2.286 = (1.9963 \tan \theta + 0.2554 \tan \theta_1)2.$$

Solving these equations simultaneously

$$\theta_1 = 65° - 18' \quad \text{and} \quad \theta = 19° - 15'.$$

The maximum change in frequency, from Equation (24), is

$$\Delta \text{ fmax} = 0.823 \text{ Hz.}$$

VELOCITY OF SOUND DETERMINATION IN ASBESTOS CEMENT

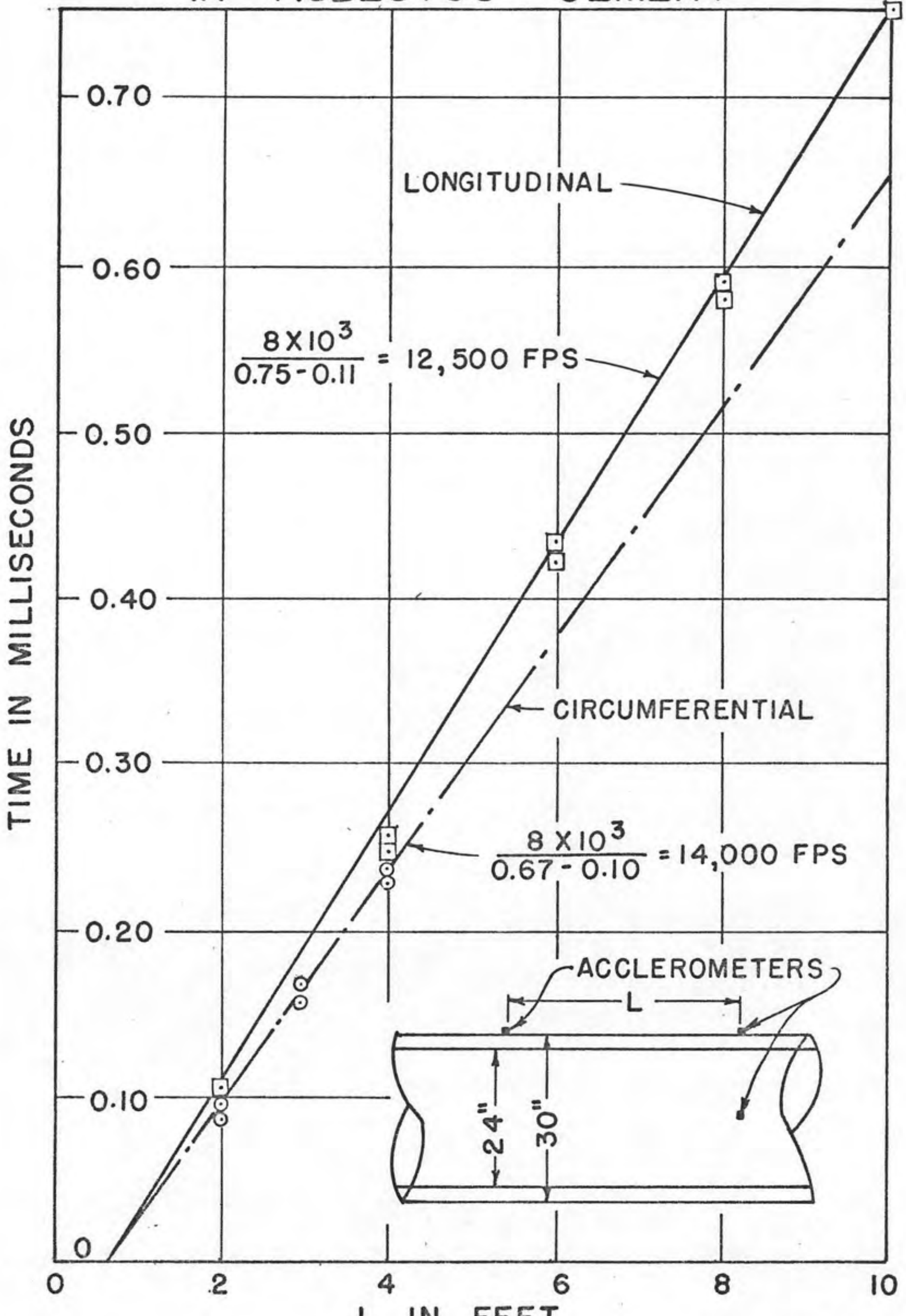


FIGURE 34

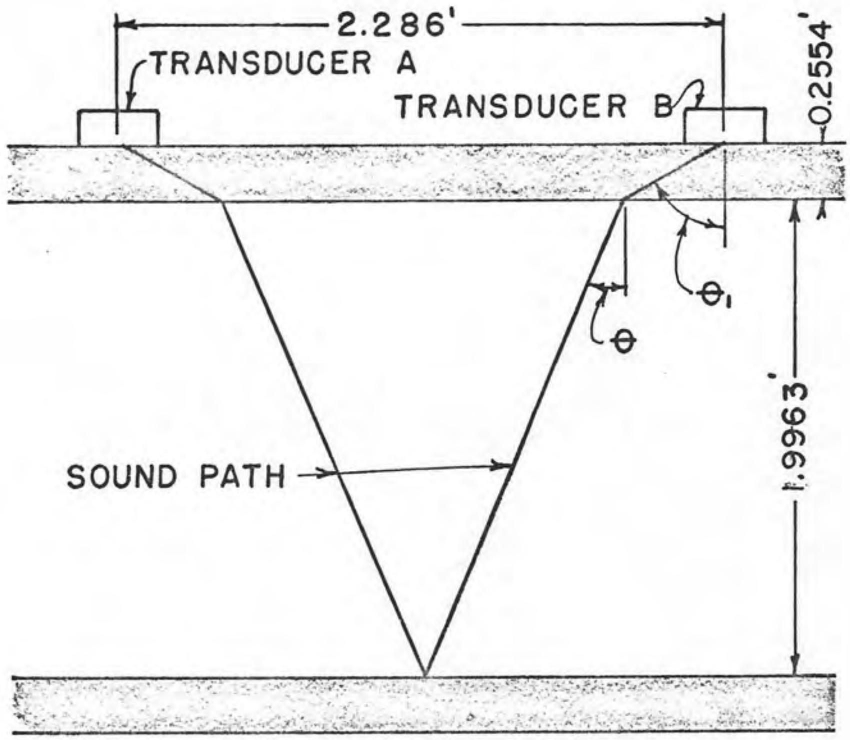


FIGURE 35

The flowmeter was set-up to have a maximum change in frequency of

$$\Delta \text{ fmax} = 0.9443 \text{ Hz}.$$

If the above is true, this indicates there would be about a 15 percent difference in the flowmeter's indicated discharge for the above difference in velocities of sound in the asbestos-cement.

Another indication that the velocity of sound through the asbestos-cement was a source of error is evidenced from the data. The average percent difference in the tests conducted on June 25, 1970, using a V installation form, see page 21, was +13. The average percent difference on tests conducted on June 26, 1970 using a Z installation form was +20. In each of the test groups, conditions were the same except that the sound pulse was in the water twice as long for the V-form as for the Z-form. The transit time ratio, the time for the sound pulse through the walls to the total transit cycle time, was 1.52 times as large for the Z-form as for the V-form. In the flowmeter application sense, the pipe became thicker with the material properties becoming more important. Since the average percent difference ratio of the tests, 20/13 = 1.5, and the transit time ratio, 1.52, are nearly the same and in the same direction this indicates that a source of error is in the velocity of sound in the asbestos-cement wall.

The transducers were installed on the asbestos-cement pipe on June 8, 1970. As explained earlier, the contact material between the pipe and the transducer face was axle grease. On June 10, 1970 and June 11, 1970 the average percent difference was +20, see Table 5. This percent difference continued to increase until on June 17, 1970 and June 18, 1970 the percent difference is +30, which indicates that the percent difference increased with time. On June 25, 1970 the transducers were removed from the pipe. It was noted that the axle grease had changed from a soft substance to a hard cake. Apparently the porous surface of the asbestos-cement pipe leached out the lighter greases leaving a hard ineffective cake. This would change the sound transmission characteristics at the contact surface and in the asbestos-cement pipe in the vicinity of the transducer. This could account for the increase in the percent difference with time.

TEST CONCLUSION

In the asbestos-cement pipe installation the ultrasonic flowmeter did not measure discharge to the accuracy expected. The test results were unpredictable and varied with time. However, the flowmeter proper was not the main source of error. The controlling factors that affect the flowmeter's performance was in the properties of the asbestos-cement in the pipe wall. The thickness of the pipe was such that the material properties of the pipe wall became very important. The three major sources of difference were; 1) the sound beam was dispersed when transmitted through the asbestos-cement and the main signal was difficult to detect at the receiving transducer, 2) the velocity of sound in the asbestos-cement was not known accurately, and 3) the sound transmissibility of the contact surface between the outside pipe surface and the transducer face was not adequate and varied with time.

Of the three, the largest source of error was in the velocity of sound in the asbestos-cement pipe wall. The velocity of sound in the asbestos-cement pipe was a variable, dependent upon direction in the pipe wall. To a certain extent this error can be corrected, but not to the extent that the flowmeter could indicate discharges accurately.

The second largest source of difference is in the contact surface between the outside pipe surface and the transducer face. Using axle grease as the contact medium between the pipe and the transducer is at best a temporary measure. If it had been known at the time, this difference could have been reduced by periodically removing the transducers and regreasing the contact surface. Eventually the asbestos-cement would have stopped leaching out the lighter components of the grease. For a permanent installation the manufacturer recommends that the transducers be epoxyed to the pipe. This is probably a more reliable method.

The smallest source of difference is in the dispersion of the sound beam as it travels through the asbestos-cement. This difference is not correctable in asbestos-cement because of its non-homogenous nature. This error would be present in any non-homogenous pipe wall material.

In the steel pipe installation the ultrasonic flowmeter did demonstrate that it could measure discharge quite accurately, within the accuracy claimed by the manufacturer, when installed on steel pipe. The pipe walls were thin enough that the pipe wall material properties did not affect the flowmeter's performance.

The ultrasonic flowmeter developed a "zero drift" that did affect its overall performance. It does not seem that this is a major drawback and with an effort by the manufacturer can be corrected.

In future installations the ultrasonic flowmeter's transducers should be installed in direct contact with the fluid stream. The largest source of error in installations with the transducers mounted on the outside of the conduit can be in transmitting the sound pulse through the conduit's wall.

TABLE 5

24 INCH INSIDE DIAMETER ASBESTOS-CEMENT PIPE

DISCHARGE COMPARISON TEST DATA

DATE	TEST NO.	DISCHARGE VENTURI CU.FT/SEC.	VENTURI CU.FT/MIN.	FLOWMETER CU.FT/MIN.	PERCENT DIFFERENCE
6/9/70	1	1.054	63.2	37	+41.4
	2	1.236	74.2	52	+30.0
	3	1.203	72.2	43	+40.5
	4	1.050	63.1	41	+35.0
	5	0.924	55.4	34	+38.5
	6	1.325	80.2	55	+32.7
6/10/70	1	2.260	135.6	103	+24.0
	2	2.900	174.0	135	+22.4
	3	3.600	216.0	173	+19.9
	4	2.916	175.0	135	+22.8
	5	3.456	207.4	165	+20.4
	6	3.616	217.0	172	+20.7
	7	5.006	300.4	225	+25.0
	8	4.442	266.5	218	+18.1
6/11/70	1	4.370	262.2	208	+20.6
	2	5.160	309.6	245	+20.8
	3	6.895	413.7	335	+19.0
	4	6.733	404.0	325	+19.5
	5	5.765	345.8	285	+17.6
	6	4.172	250.3	205	+18.1
	7	7.118	427.1	338	+20.8
	8	8.235	494.1	400	+19.0
	9	8.469	508.1	412	+18.9
	10	8.613	516.8	418	+19.1
	11	7.349	440.8	355	+19.4
	12	7.387	443.2	360	+18.7
	13	7.560	453.6	325	+28.3
	14	6.614	396.8	312	+21.3
	15	7.201	432.1	350	+18.9
	16	7.477	448.6	357	+20.4
	17	7.771	466.3	375	+19.5
	18	7.559	453.5	372	+17.9

TABLE 5

24 INCH INSIDE DIAMETER ASBESTOS-CEMENT PIPE

DISCHARGE COMPARISON TEST DATA

DATE	TEST NO.	DISCHARGE VENTURI CU.FT/SEC.	DISCHARGE VENTURI CU.FT/MIN.	DISCHARGE FLOWMETER CU.FT/MIN.	PERCENT DIFFERENCE
6/11/70	19	8.018	481.1	390	+18.9
	20	8.181	490.9	395	+19.5
	21	9.266	556.0	440	+20.8
	22	9.576	574.6	460	+19.9
	23	9.858	591.5	490	+17.1
	24	7.744	464.6	378	+18.6
	25	9.085	545.1	435	+20.1
	26	4.382	262.9	207	+21.2
	27	5.018	301.1	240	+20.2
	28	5.487	329.2	270	+17.9
	29	6.033	362.0	290	+19.8
6/12/70	1	4.160	249.6	185	+25.8
	2	4.553	273.2	205	+24.9
	3	5.977	358.6	278	+22.4
	4	5.491	329.5	255	+22.6
	5	5.809	348.5	270	+22.5
	6	7.204	432.2	342	+20.8
	7	7.542	452.5	360	+20.4
	8	7.879	472.7	375	+20.6
	9	8.328	499.6	395	+20.9
	10	8.663	519.8	408	+21.5
	11	9.537	572.2	435	+23.9
	12	8.478	508.7	380	+25.2
6/15/70	1	1.368	82.1	50	+39.1
	2	1.785	107.1	65	+39.3
	3	1.724	103.4	61	+41.0
	4	1.478	88.7	48	+45.8
	5	1.968	118.1	78	+33.9
	6	2.228	133.7	85	+36.4
	7	2.260	135.6	97	+28.4

TABLE 5

24 INCH INSIDE DIAMETER ASBESTOS-CEMENT PIPE

DISCHARGE COMPARISON TEST DATA

DATE	TEST NO.	DISCHARGE VENTURI CU.FT/SEC.	DISCHARGE VENTURI CU.FT/MIN.	DISCHARGE FLOWMETER CU.FT/MIN.	PERCENT DIFFERENCE
6/16/70	1	1.990	119.4	73	+38.9
	2	2.462	148.7	100	+32.8
	3	3.388	203.3	150	+26.2
	4	3.807	228.4	163	+28.6
	5	4.573	274.3	198	+27.8
	6	3.561	213.7	150	+29.8
	7	4.783	287.0	205	+28.6
	8	5.258	315.5	235	+25.5
	9	4.512	270.8	195	+28.0
	10	3.848	230.8	168	+27.2
	11	3.360	201.6	145	+28.1
6/17/70	1	1.078	64.7	40	+38.1
	2	2.185	131.1	80	+39.0
	3	3.748	224.9	165	+26.6
	4	3.321	199.3	138	+30.7
	5	3.564	213.8	155	+27.5
	6	3.803	228.2	165	+27.6
	7	2.867	172.0	115	+33.1
6/18/70	1	2.318	139.1	95	+31.6
	2	2.956	177.4	125	+29.5
	3	3.592	215.5	158	+26.6
	4	2.747	164.8	112	+32.0
	5	3.279	196.7	145	+26.3
	6	2.553	153.2	96	+37.3
	7	2.570	154.2	105	+31.9
6/25/70	1	3.834	230.0	208	+ 9.5
	2	4.923	295.4	265	+10.2
	3	5.030	301.8	285	+ 5.5
	4	7.035	422.1	325	+23.0
	5	7.168	430.1	350	+18.6
	6	5.994	359.6	300	+16.5
	7	3.586	215.2	195	+ 9.3

TABLE 5

24 INCH INSIDE DIAMETER ASBESTOS-CEMENT PIPE

DISCHARGE COMPARISON TEST DATA

DATE	TEST NO.	DISCHARGE VENTURI CU.FT/SEC.	VENTURI CU.FT/MIN.	FLOWMETER CU.FT/MIN.	PERCENT DIFFERENCE
6/25/70	8	1.559	93.5	80	+14.4
	9	1.778	106.7	95	+10.9
	10	1.994	119.6	108	+ 9.7
	11	0.657	39.4	33	+16.2
	12	3.493	209.6	188	+10.2
	13	4.548	272.9	237	+13.1
	14	5.147	308.8	263	+14.8
	15	3.844	230.6	200	+13.2
	16	2.745	164.7	147	+10.7
	17	4.925	295.5	259	+12.3
	18	7.165	429.9	372	+13.4
	19	7.697	461.8	398	+13.8
	20	8.220	493.2	430	+12.8
6/26/70	1	2.318	139.1	110	+20.0
	2	3.111	186.7	145	+22.3
	3	3.671	220.3	172	+21.9
	4	4.147	248.8	198	+20.4
	5	5.202	312.1	235	+24.7
	6	5.751	345.1	286	+17.1
	7	7.146	428.9	338	+21.1
	8	8.272	496.3	395	+20.4
	9	8.813	528.8	423	+20.0
	10	10.040	602.4	471	+21.8
	11	11.242	674.5	540	+19.9

24" ASBESTOS CEMENT PIPE TEST
DISCHARGE VS. PERCENT DIFFERENCE

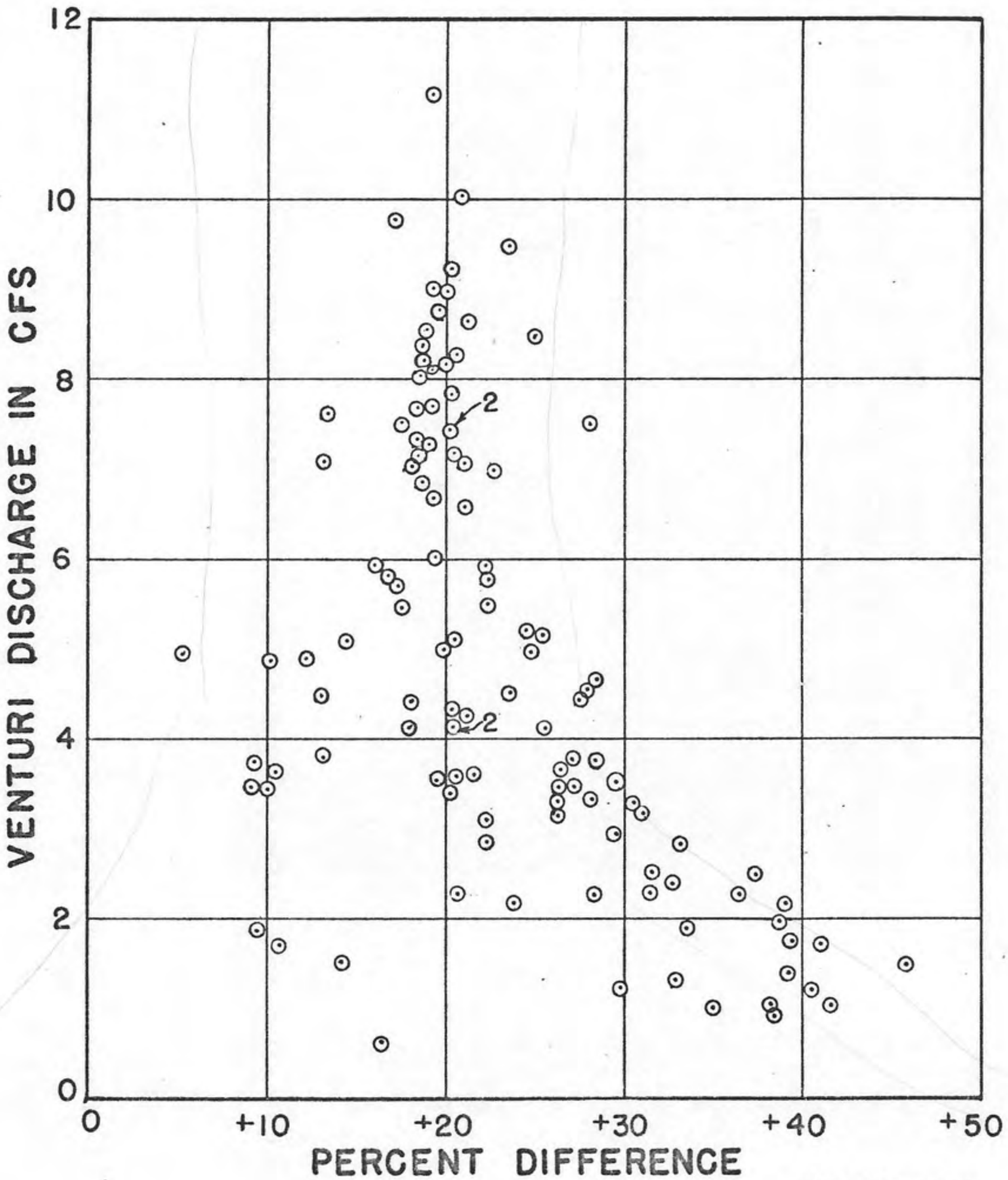


FIGURE 36

TABLE 6

24 INCH INSIDE DIAMETER STEEL PIPE

DISCHARGE COMPARISON TEST DATA

DATE	TEST NO.	DISCHARGE VENTURI CU.FT/SEC.	VENTURI CU.FT/MIN.	FLOWMETER CU.FT/MIN.	PERCENT DIFFERENCE
10/24/70	1	.422	25.3	25	+1.2
	2	.740	44.4	45	-1.3
	3	1.120	67.2	68	-1.1
	4	.952	57.1	55	+3.7
	5	1.433	86.0	85	+1.1
	6	1.825	109.5	105	+4.1
	7	1.916	115.0	112	+2.6
	8	2.195	131.7	130	+1.3
	9	3.200	192.0	182	+5.2
	10	3.877	232.6	238	-2.3
	11	4.337	260.2	260	+0.1
	12	5.809	348.5	345	+1.0
	13	7.067	424.0	420	+0.9
	14	7.768	466.1	465	+0.2
	15	8.991	539.5	540	+0.1
	16	10.138	608.3	605	+0.5
	17	11.287	677.2	675	+0.3
	18	11.643	698.6	705	-0.9
11/10/70	1	0.856	51.4	50	+2.6
	2	1.239	74.3	75	-0.9
	3	1.568	94.1	95	-1.0
	4	1.949	116.9	115	+1.7
	5	1.987	119.2	120	-0.7
	6	2.188	131.3	125	+4.8
	7	1.655	99.3	95	+4.3
	8	1.227	73.6	72	+2.2
11/11/70	1	.492	29.5	30	-1.6
	2	1.372	82.3	80	+2.8
	3	2.088	125.3	122	+2.6
	4	2.640	158.4	160	-1.0
	5	3.174	190.4	190	+0.2

TABLE 6

24 INCH INSIDE DIAMETER STEEL PIPE

DISCHARGE COMPARISON TEST DATA

DATE	TEST NO.	DISCHARGE VENTURI CU.FT/SEC.	VENTURI CU.FT/MIN.	FLOWMETER CU.FT/MIN.	PERCENT DIFFERENCE
11/11/70	6	3.700	222.0	220	+0.9
	7	3.940	236.4	235	+0.6
	8	4.633	278.0	275	+1.1
	9	5.168	310.1	312	-0.6
	10	5.335	320.1	325	-1.5
	11	8.185	491.1	480	+2.3
	12	8.423	505.4	520	-2.9
	13	9.453	567.2	580	-2.3
	14	10.435	626.1	650	-3.8
	15	11.239	674.3	715	-6.0
11/12/70	1	7.007	420.4	425	-1.1
	2	7.720	463.2	460	+0.6
	3	8.749	524.9	530	-1.0
	4	9.529	571.7	570	+0.3
	5	11.765	705.9	730	-3.4
	6	11.184	671.0	675	-0.6
	7	10.087	605.2	595	+1.7
	8	8.606	516.4	520	-0.7
	9	11.765	705.9	710	-0.6
	10	8.634	518.0	518	0.0
	11	7.422	445.0	445	0.0
	12	5.229	313.7	325	-3.6
11/13/70	1	2.439	146.3	145	+0.9
	2	2.960	177.6	180	-1.3
	3	3.800	228.0	225	+1.3
	4	4.251	255.1	260	-1.9
	5	4.851	288.6	290	-0.5
	6	5.182	310.9	310	+0.3
	7	3.271	196.3	205	-4.4
12/10/70	1	10.930	655.8	650	+0.9
	2	11.880	712.8	705	+1.1
	3	12.750	765.0	765	0.0

TABLE 6

24 INCH INSIDE DIAMETER STEEL PIPE

DISCHARGE COMPARISON TEST DATA

DATE	TEST NO.	DISCHARGE VENTURI CU.FT/SEC.	VENTURI CU.FT/MIN.	FLOWMETER CU.FT/MIN.	PERCENT DIFFERENCE
12/10/70	4	13.240	794.4	800	-0.7
	5	13.670	820.2	830	-1.2
	6	13.940	836.4	835	+0.2
	7	15.900	954.0	960	-0.6
	8	16.630	997.8	1000	-0.2
12/11/70	1	1.754	105.2	100	+5.0
	2	2.713	162.8	165	-1.4
	3	3.596	215.8	215	+0.3
	4	4.603	276.2	265	+4.04
	5	5.179	310.7	300	+3.4
	6	5.468	328.1	330	-0.6
	7	6.980	418.8	420	-0.3
	8	8.095	485.7	495	-1.9
	9	9.704	582.8	590	-1.3
	10	11.839	710.3	735	-3.5
12/14/70	1	16.110	966.6	920	+4.8
	2	17.570	1054.2	1060	-0.6
	3	16.180	970.8	920	+5.2

24" STEEL PIPE TEST
DISCHARGE VS. PERCENT DIFFERENCE

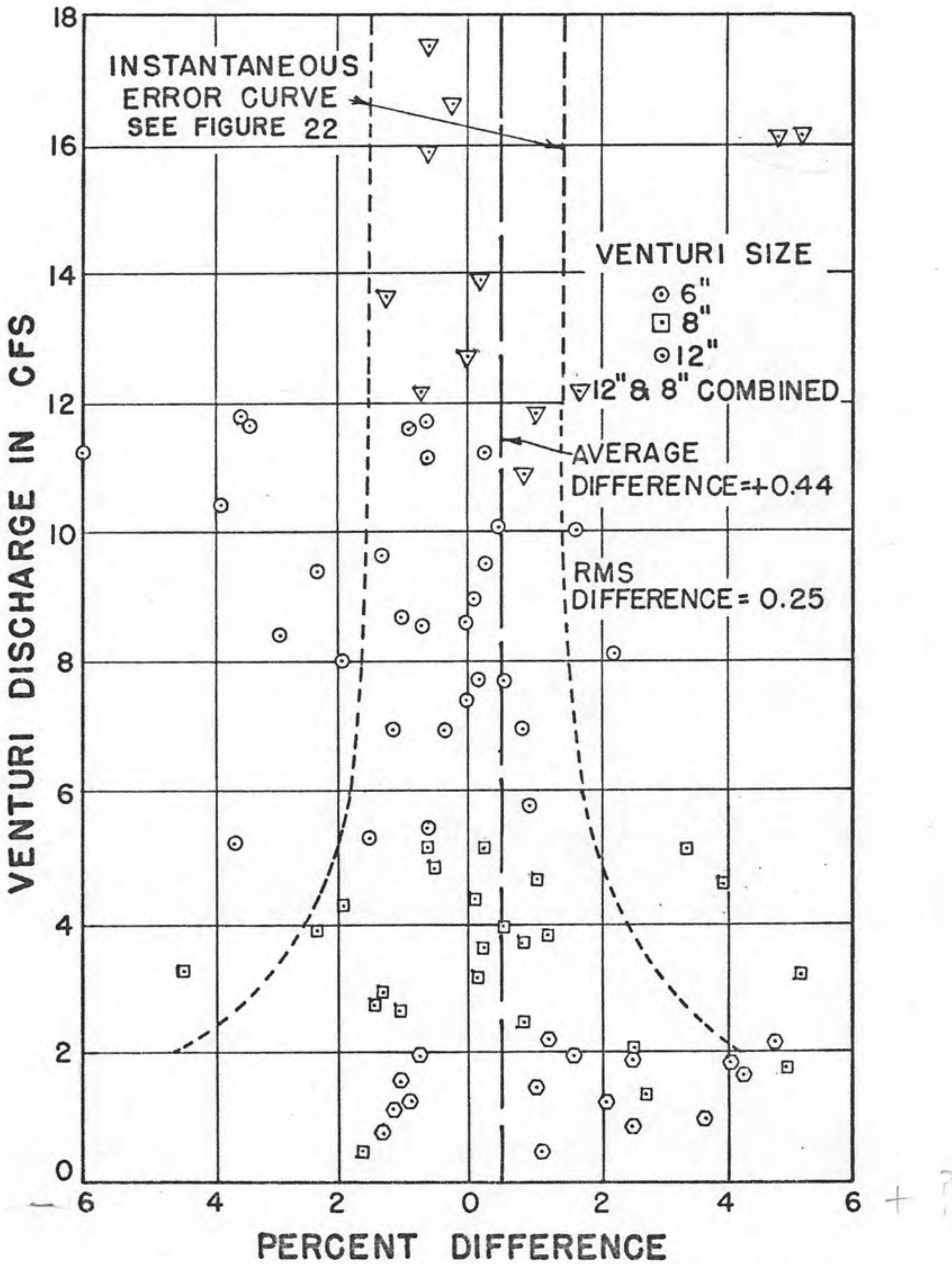


FIGURE 37

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APPENDIX

The following notation was used throughout this thesis:

A = Designation used to denote upstream transducer

B = Designation used to denote downstream transducer

C = Velocity of sound in the medium

D = Distance across the conduit perpendicular to the direction of flow

f_a = Frequency of the energy pulse cycle with the sound pulse traveling from transducer A to transducer B

f_b = Frequency of the energy pulse cycle with the sound pulse traveling from transducer B to transducer A

f = The difference in frequencies between two energy pulses

FPS = Feet per second

f_o = Sound pulse frequency through still water

I = Installation form factor

K = Flowmeter constant

K_f = Velocity correction factor, the ratio of the average velocity along the sound path to the mean velocity used in the continuity equation

L = Length of sound path

Q = Discharge rate in volume per time

T = Time

T_a = Time required for the energy pulse to make a complete cycle with the pulse traveling through the fluid from transducer A to transducer B

T_b = Time required for the energy pulse to make a complete cycle with the pulse traveling through the fluid from transducer B to transducer A

T_d = Loop time delay constant

V = Average velocity of the fluid along the sound path as determined by the ultrasonic flowmeter

V_a = Average velocity along sound path

V_f = Velocity of flow of the fluid

V_p = Component of the velocity of flow along the sound path

$\overline{V}$ = The mean velocity used in the continuity equation

$\emptyset$ = The angle between the sound pulse and the direction of flow