Head losses occurring through smooth pipe fittings, liner folds and fusion joints

Ellis Dale Hart

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HEAD LOSSES OCCURRING THROUGH SMOOTH PIPE
FITTINGS, LINER FOLDS AND FUSION JOINTS

by

Ellis Dale Hart

A Dissertation Presented in Partial Fulfillment
Of the Requirements for the Degree
PhD in Engineering

COLLEGE OF ENGINEERING AND SCIENCE
LOUISIANA TECH UNIVERSITY

May 2004
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We hereby recommend that the dissertation prepared under our supervision by Ellis Dale Hart entitled Head Losses Occurring Through Smooth Pipe Fittings, Liner Folds and Fusion Joints be accepted in partial fulfillment of the requirements for the Degree of PhD in Engineering.

Supervisor of Dissertation Research
Head of Department

Recommendation concurred in:

Advisory Committee

Approved:

Dean of the Graduate School

Approved:

Dean of the College

27 February 2004

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(5/03)
ABSTRACT

This dissertation has involved laboratory and analytical studies of pipe head losses which were caused by:

(a) smooth wye and tee fittings of 4-inch and 6-inch diameter with corresponding 4-inch and 6-inch laterals,

(b) pipe liner folds created by inadequate stretching of the liner during placement, and

(c) fusion joints which protrude a short distance into the pipe causing a small but unknown head loss. Though the individual loss was found to be small, cumulative losses could prove worthy of design consideration.

The velocity and head loss measurements were made using either a 4-inch or 6-inch model diameter pipe. Having made the model measurements, appropriate procedures were applied to "scale" the acquired data to larger diameters. The modeling and scaling procedures are described in detail.

The "fittings" scaling diameter dimension was limited to a trunk line diameter of 12-inches because it is the largest size for smooth pipe wyes and tees manufactured. The manufacture of these smooth fittings is described in detail.

The liner fold scaling was also limited to 12-inches because the largest available model discharge was approximately 1.4 cfs. As the model pipe was scaled upward, the head loss approached zero at the 12-inch dimension.
Useful information was gathered in the fusion joint measurements. However, it was not possible to scale the results to larger diameters because the protrusion apparently grows slightly with increasing pipe diameter. The scaling allows only the change in one dimension, which would have been the pipe diameter but not the corresponding protrusion. This problem is discussed in detail in the fusion joint portion of the thesis.

It should also be pointed out the liner fold dimensions were also held constant during scaling. This restriction was considered acceptable as it is not possible to predict the fold size in any particular pipe diameter. This scaling was restricted to 12-inch diameters also, the reason being the head loss approached zero as the diameter increased (causing a simultaneous decrease in velocity).

The acquired and computed data should be useful to the trenchless technology industry as it allows predictions of possible line losses associated with these three phenomena. A series of example calculations for a typical line length of sewer pipe are included to indicate the relative effect of various conditions in a pipe and liner.
APPROVAL FOR SCHOLARLY DISSEMINATION

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Author

Ellis Lyle Hart

Date 16 April 2004
Dedicated to my wife, Barbara Ann
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I am especially indebted to my wife, Barbara Ann, for her support and encouragement during my period of study at Louisiana Tech University.
**NOTATION**

T ...................... temperature, °F

ρ ...................... density, slugs/ft³, kg/m³

μ ...................... dynamic viscosity, lb-sec/ft², N-sec/m²

ν ...................... kinematic viscosity, ft²/sec, m²/sec

γ ...................... specific weight, lb/ft³, N/m³

Δp ...................... pressure loss, lb/ft², N/m²

p ...................... pressure, lb/ft², N/m²

h ...................... head loss, ft, m

D ...................... inside pipe diameter, ft, m

F ...................... force, lb, N

m ...................... mass, slugs, kg

V ...................... velocity, ft/sec, m/sec

L ...................... length, ft, m

A ...................... area, ft², m²

V ...................... volume, ft³, m³

Q ...................... volume flowrate (discharge), ft³/sec, m³/sec

g ...................... acceleration of gravity, ft/sec², m/sec²

K ...................... loss coefficient, dimensionless
CHAPTER 1

INTRODUCTION/LITERATURE REVIEW

Introduction

Description of Problem

Head losses are created in pipe flow by certain obstructions common to waste discharge.

A number of obstructions affect sewer flow, and three of them are identified and studied in this report. The three types of losses studied are those created by:

(a) wyes and tees which connect laterals to the main line,
(b) butt fusion beads in HDPE pipes,
(c) liner installation errors.

Because of the lack of head loss coefficient data in the literature for some of the conditions that occur in lined or unlined pipelines, it is difficult to be precise about the expected flow capacity changes after pipe rehabilitation.

The development of a test facility and test program to examine the head loss coefficients caused by various conditions in sewer pipes before and after relining is described. There are a number of obstructions, such as lateral connecting wyes and tees, in waste flow whose head loss value or head loss coefficient, K, have not been identified for use by the designer. In many cases, these values are relatively small. When the main line pipe diameter is scaled upward, the loss values are even smaller. The design liquid temperature will have an effect on the design head loss factor. In addition, a great number
of fittings may be placed in the line, causing an additive loss situation. For example, in a residential area there could be 10 or more individual losses per city block caused by sanitary fittings such as sanitary tees. The fittings evaluated in the laboratory are of the “injection molded” type (described elsewhere).

**Other Head Loss Causes**

Errors in liner placement can, in many cases, cause obstructions to flow. A liner which is installed around a curve or whose diameter is larger than that of the host pipe or is not stretched properly may “crinkle” or fold along the pipe wall in the manner of an accordion and interfere with the flow. Inspections after installation would reveal these obstructions. Expected flow rates could then be recalculated. HDPE pipes are joined by butt fusion which produces a joint typically as strong as the pipe [1]. However, the fusing of the pipe creates a bead which, in turn, creates a small pressure loss of unknown magnitude unless the bead is removed. In a long pipe, the number of beads can be large. There are arguments in practice about whether it is necessary to remove this bead.

**Model Considerations**

A number of considerations were to be made before commencing with the model study. The most important was to determine if full or partial conduit flow should be used in the study. Considerations regarding this issue include the following:

1. If partial flow modeling was used, at what circumference location should the model lateral enter the main line pipe model? There would be some commonly used entrance points, such as 2 o’clock, in which it would be possible that no losses could be recorded.
This possibility brought up the question, of whether a number of lateral entrances need to be studied if partial flow were used.

(2) It is common knowledge that these smaller diameter PVC pipes do occasionally flow full. The sewer line is normally designed for 50 years. During that time the pipe interior losses may increase due to loss of smoothness caused by debris attachment to the interior wall, increasing the likelihood of full conduit flow.

(3) If full conduit flow conditions were chosen for the model, then all discharges would record a pressure loss which the designer could use or ignore, based on the lateral placement point on the circumference of the mainline pipe.

(4) For the same velocity passing through a sanitary fitting, the head loss recorded would no doubt be conservative for partial flow conditions, but accurate for high flow conditions. The decision was made to conduct the study using full conduit flow.

(5) Partial flow test conditions could be considered at a later date possibly in cooperation with another hydraulics laboratory such as the U. S. Army Research and Development Center, Vicksburg, MS with which the university has cooperated in the past.

(6) The maximum flow capacity (i.e. with pipe flowing full) is a critical design parameter relative to sewer system overflows.
Literature Review

Introduction

It is the objective of this literature review to describe procedures and justifications used, in the research which may be unfamiliar to the reader. Pertinent sections of the references listed in the bibliography were studied before and during the course of this study. Those areas of interest are combined herein to give general coverage to the information necessary to carry out a meaningful research study. The primary objective of the study is to look at head losses when pipe flow crosses relatively small lengths of fittings, folds, and fusion beads (defined elsewhere) which either have been intentionally or otherwise inserted into the pipe flow.

The primary interest areas considered are:

(a) fluid mechanics, specifically, pipe flow and associated head losses,

(b) dimensional analysis as it applies to scaling pipe velocity and head loss in increasingly larger pipe diameters (up to a practical limit, to be discussed in the research discussion),

(c) trenchless technology as it applies to this study, acknowledging little information of this type exists at the present time.

(a) Fluid Mechanics

Expressing Minor Losses

Information under this heading comes primarily from references, [2], [3] and [4]. Any transition in pipe flow (such as a constriction, expansion, tee, etc.), has been seen to have an effect upon the total energy head (H) and piezometric head (p/γ). The
effect acts for a considerable distance downstream of the transition. Even so, for computational purposes, it is arbitrarily assumed that the full effect of the transition head loss is confined to the vertical transition (a to b, Figure A [4]. The actual transition occurs from points a to c.

![Figure A. Assumed minor head loss](image)

Thus, the assumed instantaneous head may be expressed:

\[ h_{\text{minor}} = K V^2 / 2g \] ........................(a)

Equation (a) is used extensively in the section devoted to head losses (minor losses) created by the interference with flow caused by wyes and tees in the pipe.

**Effect of Minor Losses**

In most pipe systems, the Moody-type friction loss, because of the pipe length, is designated the “major” loss because the loss is computed for the length of the pipe.
system. Additional point losses in the pipes are designated the “minor losses” [2].

Many types of minor losses are, for the most part, listed in hydraulic and fluid mechanics textbooks [2, 3, 4, and 5]. These minor losses include losses due to:

(a) wyes and tees,

(b) sudden reductions in pipe diameter, such as the occurrence of pipe liner folds (liner buckling),

(c) small obstructions to flow such as indentions created when plastic pipes are joined by the “fusing” process.

Because the flow pattern through these type fittings and other obstructions is quite complex, the theory is weak [2]. The losses are commonly measured experimentally and correlated with the pipe flow parameters. This procedure was used in this study.

The measured minor loss is usually given as a ratio of the head loss, h, through the devise (tee, wye, etc.) to the velocity head of the associated piping system. As presented above:

\[ h = \frac{KV^2}{2g} \] ..................(a)

Because \( h/(V^2/2g) \) is dimensionless, the coefficient K is dimensionless also. Because the velocity through a minor loss section will likely vary, so will the coefficient, K. It is therefore necessary to measure the coefficient for a number of flow conditions.

The data could then, perhaps, be resolved into a regression equation for use in different flow conditions. Where pertinent, this procedure was used in this report.
The value of K generally decreases with increasing pipe size [2] if the velocities are the same. An example is taken from Table ID, to illustrate the decreasing K value with increasing pipe diameter:

<table>
<thead>
<tr>
<th>Nominal pipe Diameter, in.</th>
<th>Pipe velocity, fps</th>
<th>head loss feet</th>
<th>( \frac{V^2}{2g} ) feet</th>
<th>K</th>
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<tr>
<td>4</td>
<td>10</td>
<td>0.24</td>
<td>1.55</td>
<td>0.15</td>
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<tr>
<td>8</td>
<td>10</td>
<td>0.13</td>
<td>1.55</td>
<td>0.08</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
<td>0.10</td>
<td>1.55</td>
<td>0.06</td>
</tr>
</tbody>
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Note that as the pipe diameter increases (column 1) at a given velocity (column 2), the coefficient K (column 5) decreases. This result agrees with data from reference [2]. In the dissertation study, the tee lateral diameter remained constant as the main pipe diameter increased. This procedure illustrates the effect of the main pipe's diameter increasing with all other dimensions held constant. As the ratio of lateral (tee) to trunk line decreases, so does the K value. Because K varies with velocity head (a function of the pipe diameter), a table of K values is necessary. This variance caused the creation of the K value tables of chapter 4.

**Basic Hydraulic Computations**

All “A” tables in the dissertation contain basic but essential hydraulic computations. In most cases the computations were carried out to a large number of decimal places because of the computer's ability to do so in the Excel section of Microsoft Desk. The final answers, however, were generally reduced to two decimal places because of questions of accuracy.

These hydraulic computations included:
(a) discharge, \( Q \), of flow passing through the test pipe for a selected valve opening.

The instruments and procedure used to acquire this information \( (Q) \) is discussed, in part elsewhere. The basic procedure was to weigh a timed amount of water flowing through the system and convert this to a discharge in ft\(^3\)/sec (m\(^3\)/sec).

This computation amounted to solving the following equation:

\[
Q = \frac{\text{wt of water, lb}}{\text{(time, sec)} \times \text{specific wt of water, lb/ft}^3} = \text{ft}^3/\text{sec}
\]

Freeman [5] measured his discharge in a somewhat similar manner except he measured the volume accumulated rather than the weight. What was gained in bypassing the scale measurement may have been lost in the possible lack of constant dimensions of the catch-tank.

(b) pipe velocity, \( V \), was then computed by the well known continuity equation.

Streeter [3], gives a nice illustration of the application of the continuity equation as it applies to a section of pipe flow:

At section 1 of a pipe carrying water (Figure B) the velocity is 3.0 ft/sec and the diameter is 2.0 ft. This same flow passes another section 2 where the diameter is 3.0 ft. Find the discharge and velocity at section 2.
Figure B. Volumetric flow, continuity equation

\[ Q = V_1 A_1 = 3.0 \pi = 9.42 \text{ cfs} \]

and

\[ V_2 = \frac{Q}{A_2} = \frac{9.42}{(2.25\pi)} = 1.33 \text{ ft/sec}. \]

The computations of the loss coefficient, \( K \), and the Reynolds number, \( R_e \), are presented elsewhere.

**Mechanical Properties of Water**

Freeman [5] has an excellent table in which he lists the mechanical properties of water, density, \( \rho \), dynamic viscosity, \( \mu \), and kinematic viscosity, \( v \). The values of these factors are given in increments of one-half degree values of temperature (°F). This table made it convenient to develop an equation for \( v \), which appears in all A and B tables of the dissertation. The value is usually not shown in the A tables as it had to be “hidden” to reduce the table size. Development of this equation is described in Appendix A, “Computer Enhancement-Kinematic Viscosity Application.”
(b) Dimensional Analysis

General

Chapter 3 is devoted to the presentation of the derivation and use of the necessary dimensionless terms required for scaling of smooth pipe and fittings. Chapter 5 of White's textbook *Fluid Mechanics* contains an excellent discussion on the subject of dimensional analysis [2].

Dimensional analysis is a method for reducing the number and complexity of experimental variables (such as $\rho$, $\gamma$, $V$, etc.) that affect a given physical phenomenon, by using a sort of compacting technique. If a phenomenon depends on $n$ variables, dimensional analysis will reduce the problem to only $k$ dimensionless variables, where the reduction $n-k$ is 1, 2, 3, or 4, depending on the problem complexity. Generally, $n-k$ equals the number dimensions that govern the problem.

In fluid mechanics, the four basic dimensions are mass $M$, length $L$, time $T$, and temperature, $\Theta$.

Dimensional analysis for this study is presented in chapter 3, Dimensional Analysis. In that chapter, six dimensional variables are used to determine the dimensionless variables $Re$, known as the Reynolds number for scaling pipe velocities. The other dimensionless variable is labeled, "the Z Factor," because it has no known name. It is used to scale the head losses, $h$, with increasing diameter (smooth pipes and fittings).

The basic rule of dimensional homogeneity can be stated as follows [2]:

*If an equation truly expresses a proper relationship between variables in a physical process, it will be dimensionally homogeneous: that is each of its additive terms will*
have the same dimensions. Chapter 3 has full details and examples of dimensional analysis.

(e) Trenchless Technology

The pipes used in this study consisted of polyvinyl chloride pipe (PVC), and high density polyethylene pipe (HDPE). The studies did not make pipe measurements of losses due to pipe length, but rather measurements of several types of fittings inserted within these pipes. The pipes and fittings were of the smooth type and therefore lent themselves to evaluation using smooth pipe equations and procedures.

Rehabilitation has been revolutionized through the use of trenchless technology (TT) methods and procedures [11]. The areas of research discussed in the dissertation pertain to existing TT procedures. “It is essential that a thorough evaluation of the sewer system, including the assessment of …., and the hydraulic conditions be conducted” [11].

The TT processes are now becoming more generally accepted as viable forms of rehabilitation, and owners and engineers are becoming more familiar and confident with the methods. However, there are still certain issues which need further study. One of the areas of concern is “the appropriateness of current design methodologies” [12]. “Design questions should be addressed to give designers the ability to select, design, and specify rehabilitation systems with confidence. If a rehabilitation method can be shown to cost less, last as long, and reduce the negative social and environmental effects of open-cut, then it should be considered as a preferred
alternative,” [12]. It is believed that research, such as described here, will contribute
to making more precise design a reality.
CHAPTER 2

TEST FACILITIES AND PROCEDURES

Test Facilities

Figure 1 presents a sketch of the general test facility layout. The flow is drawn from a sump into 4-inch (102mm) schedule 80 and schedule 40 PVC pipes.

**Pump.** The pump is a 102-mm submersible type rated at 494 gpm (1.10 cfs, 0.031 cms). Under the shown layout, a maximum flow rate of 1.41 cfs (0.040 cms) was achieved. The pump is of cast-iron construction, carbon vs. ceramic mechanical seal, 3-phase, 230 volt, 10.14 metric horsepower electric motor. It is rated for continuous duty.

**Piezometers.** The piezometers were installed on each side of each test fitting for differential pressure measurements, as will be discussed later. Because of the thin wall of the pipe, small squares of the same dimension pipe were cut and then drilled and tapped. They were next glued to the pipe wall to attach the piezometers as shown in Figure 3. Next ¼-inch (3 mm) piezometer holes were drilled inside the threaded openings in these squares, through the pipe wall. The inside surface of these holes was checked and smoothed where necessary. Nylon tubing was attached to the piezometers, each of which terminated at the recording station (see Figure 2).
**Figure 1.** Test facility

**Recording Station.** The recording station is shown in Figure 2. The open shunt valve allows the pressures to remain equalized until the differential pressure is to be measured with the valve closed. Between the shunt valve and the differential pressure transducer, tees connect each line to a bleed valve (not shown).
Further bleeding can be made at the transducer bleed screws near the pressure transducer diaphragms

**Differential Pressure Transducer**

The transducer, shown in Figure 2, is an Omega PX2300 wet/wet type. Its output is 4 to 20 mA corresponding to a pressure range of 0 to 5 psid (0 to 3515.5 kgs/m²). Claimed accuracy is 0.25% of full scale. Other ranges may be and were used, such as 0 to 1 psid.

**Display Meter** The display meter, also shown in Figure 2 is an Omega DP24-E panel meter with a red LED display. It can display any engineering unit from –1999 to 1999. Decimal places can be specified from none to three. It is simple to calibrate before testing.

Figure 3. Gate control valve
**Gate Control Valve**

Flow is controlled by a 4-inch (102 mm) gate valve inserted into the line just upstream of the pipe discharge point. The valve was calibrated so that the number of valve turns could be correlated with the system discharge. Figure 3 shows the gate valve during the time of calibration. See also Appendix B.

**Weigh Tank** The weigh tank, shown in Figure 4, has dimensions 3m x 6m x 7m. It is of steel construction, sitting on a Toledo model type 38-1700 weighing scale. The manufacturer claims perceptible movement to be caused by a 114-gram weight change. It has a 4536-kg capacity, with no springs. When the tank is full of water, the fluid weight is approximately 3600 kg.

![Figure 4. Weigh tank and scale](Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.)
Figure 5. General laboratory scene including recording station

Pipe Section

Figure 5 presents the test pipe section. Also shown is the location of the recording station (see also Figure 2). The tested pipes were of nominal diameters 4 and 6 inches.

Test Procedure The study, discussed subsequently, consisted of measurement of losses created by flow past three types of sanitary line fittings, fusion joints, and line folds. In the model, the main line pipe had a nominal diameter of either 4- or 6-inches (102- or 152-mm). The submersible pump could produce a maximum flow of 1.41 ft³/sec (0.04m³/sec). This allowed a maximum velocity through the pipes of about 16 ft/sec and 7 ft/sec through the 4-inch and 6-inch test lines, respectively. Piezometers were placed on each side of the fitting being tested (see Figure 7).

Measurements were made through the full range of discharges, with minimum flow about 0.30 ft³/sec (0.008 m³/sec). Vibrations and chattering occurred at the gate valve at
flows below this value, due to the small valve openings. The discharge was determined by timing the flow into the weigh tank and the fluid weight was divided by the time of filling and specific weight, i.e. \( \frac{wt}{(\text{time} \times \gamma)} \).

Some problems were experienced in bleeding the piezometer lines, at the recording station, when bubbles occurred between the tee (which allowed flow to the bleed valve) and the differential pressure transducer. Though the bleed screws on the transducer were open, the bubbles sometimes would not pass. Usually this problem could be overcome by closing the bleed valves as well as the shunt valve, thereby creating full pressure behind the bubble with the result that it would pass through the pressure transducer bleed screws.

Once the lines were free of bubbles, the differential pressures were read in psid (kgs/m²). These values were then converted to head loss in feet (meters). The recorded and reduced data are listed in tabular form in the following sections.
CHAPTER 3

DIMENSIONAL ANALYSIS

General

Basically, dimensional analysis is a method for reducing the number and complexity of experimental variables that affect a given physical phenomenon [2]. This simplification is accomplished by using a sort of compacting technique. If phenomena depend on $n$ dimensional variables, dimensional analysis will reduce the problem to $k$ dimensionless variables. The difference in these values gives the number of different (basic) dimensions that govern the problem.

The available basic dimensions are $\text{M, L, T}$ & $\Theta$ in the SI system or $\text{F, L, T}$ & $\Theta$ in English units. The abbreviations are $\text{M} =$ mass, $\text{L} =$ length, $\text{T} =$ time, $\Theta =$ angle and $\text{F} =$ force.

Purpose

The basic purpose of dimensional analysis is to reduce the number of variables by grouping them in dimensionless form. Dimensional analysis provides scaling laws that can convert (scale) data from a cheap, small model to design information for an expensive, large prototype.

If this scaling law is valid, a condition of similarity exists between model and prototype. This similarity is achieved, for example, if the Reynolds number (to be defined), is the same for the model and the prototype. The Reynolds number is dimensionless and is the combination of the variables:

Velocity, $V$, pipe diameter, $D$, liquid density, $\rho$, viscosity, $\mu$, arranged in the form:
\[ R_e = \frac{\rho V D}{\mu} \]  \hspace{1cm} (1)

A check will show this term is unit-less. If the geometry is complicated, other similarity parameters may be necessary, like the ratio of orifice diameter to pipe diameter.

If the numerical value of the Reynolds number is the same for the model (m) and prototype (p), then we can equate them:

\[ \rho_p V_p D_p / \mu_p = \rho_m V_m D_m / \mu_m \]  \hspace{1cm} (2)

Having made model measurements and knowing the prototype pipe diameter, density and viscosity, the prototype velocity could be written:

\[ V_p = \frac{(\rho_m V_m D_m \mu_p)}{(\mu_m \rho_p D_p)} \]  \hspace{1cm} (3)

In essence, the process simplifies computations by reducing the number of dimensional variables into a smaller number of dimensionless groups (such as the example Reynolds number).

**Dimensionless Parameters**

The necessary dimensionless parameters (such as the Reynolds number), must be determined analytically. If \( n \) = the number of dimensional variables required and if \( j \) = the number of pertinent dimensions \( (F,L,T,\theta) \) then we will derive \( k \) dimensionless variables in our computations:

\[ k = n - j \]  \hspace{1cm} (4)

**Procedure**

1. Count the number of pertinent variables required to define the problem.

   Suppose there were five variables: \( F, L, V, \mu, \) and \( \rho \). Then \( n = 5 \).

2. Determine the number of dimensions involved. Suppose they are \( M, L \) and \( T \).

   This gives \( j = 3 \).
3. We can reduce the problem to \( k \) dimensionless parameters.

\[
k = n - j = 5 - 3 = 2 \text{ dimensionless parameters} \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \ Quad
two dimensionless variables. Repeat the procedure with the remaining unused variable.

This procedure will be repeated in detail in the following section using the appropriate variables for this study. The final results will include \( j \) dimensionless parameters. These parameters (equations) will be used to solve for the scaled velocities, \( V \) and the head losses, \( h \).

The number of dimensionless variables can, in some cases, be reduced by mathematical manipulation. The dimensional analysis for this study follows. The procedure comes primarily from [2]. Other references include [3] and [4].
Dimensional Analysis for Study

Introduction

The pressure drop for flow through smooth pipes and fittings is a function of the average flow velocity, \( V \), density, \( \rho \), viscosity, \( \mu \), pipe diameter, \( D \), and pipe length, \( L \). That is, \( \Delta p = f(V, \rho, \mu, L, D) \) so that \( n = 6 \).

The pi theorem will be used to rewrite this function in dimensionless form. These six variables are made up of three, \( (k = 3) \) primary dimensions, \( M, L, \) and \( T \). Therefore, we should expect to develop three dimensionless parameters, i.e., \( j = n - k = 6 - 3 = 3 \) dimensionless pi groups. The dimensions of all pertinent variables are listed in many hydraulic and fluid mechanics texts [2, 3, and 4].

Procedure

1. First list the six variables (see Appendix C) and their dimensional properties:

<table>
<thead>
<tr>
<th>( \Delta p )</th>
<th>( V )</th>
<th>( \rho )</th>
<th>( \mu )</th>
<th>( L )</th>
<th>( D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ML^{-1} )</td>
<td>( LT^{-1} )</td>
<td>( ML^{-3} )</td>
<td>( ML^{-1} T^{-1} )</td>
<td>( L )</td>
<td>( L )</td>
</tr>
</tbody>
</table>

2. Find three variables that do not form a pi product. Try \( \rho, \mu, \) & \( D \).

3. Conduct pi check using \( \rho, \mu, D \):

\[
\rho^a \mu^b \cdot D^c = (ML^{-3})^a(ML^{-1}T^{-1})^b(L)^c = M^0 L^0 T^0
\]

Mass: \( a + b = 0, \ a = -b \)

Length: \( -3a - b + c = 0 \)

Time: \( -b = 0; \ a = 0; \ c = 0 \). These do not form a pi group, so we have our repeating variables.

4. Compute the three dimensionless variables by including, individually, \( \Delta p, V \) & \( L \) as multiples of the basic three variables, \( \rho, \mu, \) & \( D \).

(a) \( \Pi_1 \): Use \( \Delta p \) as the add-on variable:
\[ \rho a^b b c^d \Delta p = (ML^{-3})^a (ML^{-1})^b (L)^c (ML^{-1}T^{-2})^d \]

Mass: \( a + b + 1 = 0 \)

Length: \(-3a - b + c - 1 = 0\)

Time: \(-2b - 2 = 0; \quad b = -2, \quad a = 1, \quad c = 2.\)

Therefore: \( \Pi_1 = \frac{\Delta p}{\mu^2} \) ......................................................(6)

(b) \( \Pi_2 \): Next use \( V \) as the add-on variable:

\[ \rho a^b b c^d \Delta V = (ML^{-3})^a (ML^{-1}T^{-1})^b (L)^c (LT^{-1})^d \]

Mass: \( a + b = 0, \quad a = -b \)

Length: \(-3a - b + c + 1 = 0\)

Time: \(-b - 1 = 0; \quad b = -1, \quad a = 1, \quad c = 1\)

Therefore: \( \Pi_2 = \frac{VD}{\mu} \) ......................................................(7)

(c) \( \Pi_3 \): The final add-on variable will be \( L \):

\[ \rho a^b b c^d \Delta L = (ML^{-3})^a (ML^{-1}T^{-1})^b (L)^c (L)^d \]

Mass: \( a + b = 0, \quad a = -b \)

Length: \(-3a - b + c + 1 = 0\)

Time: \(-b = 0, \quad a = 0, \quad c = -1\)

Therefore: \( \Pi_3 = \frac{L}{D} \) ......................................................(8)

4. The three dimensionless parameters are functions of each other, i.e.:

\[ \rho D^2 \Delta p / \mu^2 = f(\rho V D / \mu, \ L/D) \] ......................................................(9).

Because the pressure loss, \( \Delta p \), is proportional to the length \( L \) we can pull \( L/D \) out of the functional relationship, giving:

\[ D^2 \Delta p / \mu^2 = (L/D) f(\rho V D / \mu) \]

Divide both sides of this equation by \( L/D \) and substitute \( \Delta p = \gamma h, \gamma = \rho g \) and
\[ v = \mu / p. \] This gives:

\[ D^3 g h / v^2 L = f (V D / v) \] \hspace{1cm} (10)

These two dimensionless parameters are the Reynolds number and the other term, named for convenience "Parameter Z"[2]. They will be applied to the scaling of the data acquired in some of the following model studies.

The Reynolds number \((V D / v)\) will be used to scale the model velocities to those of the larger diameter prototype pipes. That is, letting subscript \(m\) represent the model data and \(p\), the scaled prototype values, we have:

\[ V_p = V_m D_m v_p / v_m D_p \] \hspace{1cm} (11)

In the same manner, the resulting predicted head loss, \(h\), through the larger prototype pipe is predicted by the "Z Parameter" as follows:

\[ h_p = (g_m h_m D_m^3 L_p v_p^2) / (L_m v_m^2 g_p D_p^3) \] \hspace{1cm} (12)

Equation (11) will be applied in the following sections to scale the model velocities to prototype values. Equation 12 will then be applied to determine the scaled energy losses.

**Study Application**

The prototype head loss, \(h_p\), of equation 12, will be modified for use in this study in the following two ways:

(a) **Acceleration of gravity, \(g\)** The acceleration of gravity, \(g\), varies only ± 0.3% over the entire surface of the earth [2] and therefore will be considered constant for all applications of equation (12).

(b) **Fitting length, \(L\)**: The head loss, \(h\), across the fitting is considered a "form" loss. This consideration is justified considering the fact that the
piezometers in the model were placed just outside the ends of the fitting under study. In the scaled computations, the head loss was considered to occur over approximately the same length as that of the model.

The following information relative to manufacturing by "injection molding" was provided by Mr. Dewey Manus, Technical Director, Charlotte Pipe Company, Charlotte, NC:

1. The mold consists of an inner and outer stainless steel surface, held together by core pins.
2. The heated, PVC compound is poured, under pressure, into the mold.
3. The compound is held, under pressure, in the mold while it is being cooled by circulating water.

Molded wyes and tees are formed in this manner up to and including diameters of 12 inches, (305 mm). The molded surfaces are very smooth.

At this time, wyes and tees of diameters greater than 12 inches are "fabricated". This fabrication involves cutting larger diameter pipe and welding it back together in the configuration required by the installation. This study is restricted to fittings which are "injection molded", (i.e., not fabricated) to a maximum diameter of 12 inches.

Because of this limitation on fitting diameter, it is assumed that the model and prototype lengths ($L_m$ and $L_p$) are of approximately the same length. Because of assumptions a and b, equation 12 may be expressed as follows:

$$h_p = h_mD_m^3v_p^2/D_p^3v_m^2$$

....................................................... (12a)

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For the "fittings" sections (4A-4D) of the study, equation 12a is used to scale from the model head loss value to prototype head loss, in all cases.
CHAPTER 4

WYES AND TEES

Introduction

In the sanitary disposal industry there are a number of types of connectors which merge
the waste flow from homes, businesses and factories to the collecting trunk line. In many
situations which permit, the modern trend is to install PVC (polyvinyl chloride) pipe and
connectors (also referred to as “fittings”). This section, Wyes and Tees, describes
equipment, measurements, and results of head loss across the connectors. The four types
of connectors tested are shown in Figure 6 and described in the following Laboratory
Measurements section. A fitting will be referred to by its upstream and downstream
trunk line diameters followed by the lateral diameter. For example, an 8x8x6 fitting
would have:

(a) an upstream trunk line diameter: 8-inches (203 mm),
(b) a downstream trunk line diameter: 8-inches (203 mm),
(c) a lateral line diameter: 6-inches (152 mm).

General

Figure 6 presents the four types of fittings used in the tests. The 4x4x4 and 6x6x6 fittings
were selected because 4-inch and 6-inch laterals are common diameters used in
connections to homes, businesses and light industry. It should be pointed out that after a
test series such as a 4x4x4 tee model is run, the trunk line diameter can be scaled without
affecting the lateral size. That is why, in all four sets of model measurements, the
diameter of the model trunk line and the joining lateral were the same dimension. The
procedure for scaling to larger trunk diameters will be discussed later.

Figure 6. Wye and tee fittings, L to R: 4x4 Tee, 4x4 Wye, 6x6 Tee, 6x6 Wye

Laboratory Measurements

Laboratory measurements were made of the pressure losses across the smooth fittings at
measured pipe velocities in, for example, the 4x4x4 tee fitting shown in Figure 6. A
liquid conveying system is considered “smooth” if its wall friction factor $f$, for a
recorded Reynolds number ($R_e$), falls on or very near the smooth pipe curve of the
Moody diagram [3].

The smooth fittings tested were:

(a) 4-inch (102 mm) tee – Figure 6,
(b) 4-inch (102 mm) wye – Figure 6,
(c) 6-inch (152 mm) tee – Figure 6, and
(d) 6-inch (152 mm) wye – Figure 6.

In all cases, the model trunk lines and their laterals were of the same diameter. Each of the four test sections were similar, differing however, in that there were two lateral diameters (4-inch and 6-inch) and two lateral entrance angles (45° and 90°). Also, there were slightly different locations of the piezometers relative to the fitting. As stated previously, the lateral bleed valves were opened during each test run. Although it was determined that this step was unnecessary, it was continued for each test to insure that the conditions were uniform.
Section 1. 4x4x4 Tee Tests Results

General

Figure 7 presents a sketch of the first fitting tested; a 4x4x4 tee. The meaning of each of these three numbers is defined in the preceding section. In the testing program, the three diameters of the test fitting were always the same, either 4-inch (103 mm) or 6-inch (152 mm). In this testing, all three were nominally 4 inches in diameter.

Piezometers were installed on each side (upstream-downstream) of the fitting to be tested. Tubing was attached to each piezometer, the upstream tubing terminated at the upstream port of the differential pressure transducer (see Figure 2). The downstream tubing was attached to the downstream port of the differential pressure transducer.

![Diagram of 4x4x4 tee test section](image)

**Figure 7. Test section for 4x4x4 tee**

The shown tee lateral, which originates at a residence or business/factory, intersects the trunk line at a right angle. The lateral is represented in the model by a short length of 102 or 152 mm pipe (Figure 7 and 9) depending on the diameter lateral being tested. The laboratory lateral pipe was capped and a bleed valve inserted. A typical lateral section with its cap can be seen in Figure 9. Experiments showed that the loss across the fitting
was the same with, or without, lateral bleeding. The lateral was, however, bled during each test run.

Data - Measured and Computed

The recorded data were entered into a prepared spreadsheet table. Table 1A contains the recorded “Input” entry values. Note nine model tests were conducted at discharges, Q, ranging from 0.30 to 1.40 cfs (0.09 to 0.43 cms).

Table 1A 4X4X4 Tee Model Data

<table>
<thead>
<tr>
<th>INPUT</th>
<th>COMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tst #</td>
<td>T°F</td>
</tr>
<tr>
<td>401</td>
<td>71</td>
</tr>
<tr>
<td>402</td>
<td>71</td>
</tr>
<tr>
<td>403</td>
<td>71</td>
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<tr>
<td>407</td>
<td>71</td>
</tr>
<tr>
<td>408</td>
<td>71</td>
</tr>
</tbody>
</table>

The “Input” data, left to right, Table 1A, were:

(a) test number,
(b) test date,
(c) fluid temperature,
(d) pressure differential in psid,
(e) fluid weight of the test run,
(f) time required to reach the measured fluid weight.

The “Computation” section, also of Table 1A, presents:

(a) head loss in feet, h, computed by multiplying pressure loss in psi by 2.307ft/psi,
(b) discharge, Q, determined by dividing the total fluid weight by filling time in seconds, and the specific weight of the fluid, \( \gamma \), i.e., \( \frac{wt}{(time*\gamma)} \),

(c) velocity, \( V \), computed by dividing Q by the pipe area; \( \frac{Q}{Area} \),

(d) velocity head = \( \frac{V^2}{2g} \), ("hidden"),

(e) loss coefficient, \( K \), computed by dividing head loss by velocity head; \( \frac{h}{V^2/2g} \),

(f) kinematic viscosity, \( \nu \), computed from an equation derived from a \( \nu \) vs. temperature equation ("hidden"),

(g) Reynolds number, \( R_e = \frac{VD}{\nu} \).

As noted, some of the data columns were "hidden." This "hiding" is a spreadsheet feature which retains the hidden value for computations but allows reduction of print space.

**Table 1B 4x4x4 Tee Scaled Data**

The pertinent model data were then entered into the scaling table (Table 1B). The inside diameters of the prototype trunk lines (these are the main line dimensions to be scaled to) are entered in the left column A (shaded area), in inches and feet. Model values from data Table 1A are entered into cells C1 – I4 of Table 1B. The remaining entries are the model temperature, \( (Temp_m) \) and the design temperature, \( (Temp_p) \) in cells K2 and K6, respectively. Cells K1 and K5 contain the computed (see Appendix A) model and prototype viscosities, respectively. The computed densities and absolute viscosities are also listed but not used in the computations.
The remaining (darkened) cells contain equations which compute the scaled pipe velocity, (cells C5 through 15) for the scaled 8-inch pipe and cells and C7 through 17 for the scaled 12-inch pipe velocities. In the same manner, cells C6 through 16 compute the scaled values of head loss in the 8-inch pipe and cells C8 through 18 do likewise for the 12-inch pipe.

**Table 1B Computational Procedure**

The above discussed model data for the 4x4x4 tee consists of, discharge, $Q_m$, diameter, $d_m$, velocity, $V_m$, and head loss, $h_m$, taken from table 1A. They have been entered respectively in table 1B cells C1-I4. For example, to compute the 8-inch prototype pipe velocity (cell C5), equation 11 was written into the cell. In other words, the Reynolds number ($R_e$) for the 4-inch model was equated to the 8-inch prototype $R_e$. The equation was then solved for the velocity of the 8-inch prototype pipe ($V_p$):

$$V_p = \frac{V_m D_m}{\nu_m}$$

To compute the corresponding head loss ($h_p$) for the 8-inch pipe in cell C6, the same procedure was applied except equation 12 was used. Equation 12 has been designated the “$Z$ factor,” [2] derived in Chapter 3, (Dimensional Analysis).
\[
    h_p = \frac{(g_m m D_m^3 L_p v_p^2)}{(L_m v_m^2 g_p D_p^3)}
\]

\[\text{(12)}\]

**Computational Example**

A typical set of hand calculations are carried out for comparison with the data in Table 1B.

The computations will be made using English units, the answer will then be converted to SI units. The example is taken from Table 1B:

Given: fluid temperatures, \(T_m = 71.0^\circ F, T_p = 55.0^\circ F\) (cells K2 and K6)

Use column E for comparison: \(Q_m = 1.333 \text{ cfs}\), then \(d_m = 0.333 \text{ ft}\), \(V_m = 15.306 \text{ fps}\), \(\Delta h = 0.588 \text{ ft}\).

We will scale to prototype diameter: 1.00 ft, (cell A8).

Equation 11
\[
    V_p = V_m \left(\frac{d_m}{d_p}\right) \left(\frac{v_p}{v_m}\right) = 15.306 \left(\frac{0.333}{1.0}\right) \left(\frac{1.31 \times 10^{-5}}{1.05 \times 10^{-5}}\right) = 6.36 \text{ ft/sec (1.94 m/sec)}
\]

Equation 12:
\[
    h_p = h_m \left[\left(\frac{D_m^3 v_p^2}{v_m^2 D_p^3}\right)\right] = [0.59 \times 0.333^3 \times (1.31 \times 10^{-5})^2] / [1.05 \times 10^{-5}]^2 \times (1.0)^3 = 0.034 \text{ ft (0.01 m)}
\]

These two solutions may be compared with the values in cells E7 and E8 of Table 1B.

**Data Plot**

The velocity and head loss data for the 4-, 8-, and 12-inch pipes (with 4-inch laterals) were taken from Table 1B and plotted as head loss vs. velocity in Figure 8. In order to present a uniform plot, the maximum velocity was restricted to 10 ft/sec (3.05 m/sec). As would be expected, the head loss in Table 1B decreased with increasing pipe diameter.

To present a uniform plot, the equations of head loss vs. velocity were computed by the
“Chart Wizard” program of the Excel Microsoft package. These equations are presented in Figure 8, (Head loss vs. pipe velocity, 4 inch (102 mm) tee lateral).

Note that the greatest losses, for a given velocity, occur in the smaller, 4-inch (102 mm) pipe. This results would be expected, mathematically, noting the scaling equation for head losses \( h_p \), equation 12), decreases as a factor of the ratio of the cube of the model diameter \( d_m \), to the cube of the larger, prototype diameter \( d_p \).

For a given head loss, the required velocity in the 8-inch (203 mm) pipe would be greater than that in the 4 inch pipe by approximately 45% (using the 4-inch velocity as base).

For the 12 inch (305 mm) pipe, the velocity would need to be greater by about 65%, same procedure.
Figure 8. Head loss vs. pipe velocity, 4-inch (102 mm) tee lateral.
Minor Loss Coefficient, $K$

Those losses which occur in pipelines due to bends, elbows, tees, valves, etc., are called *minor losses*, [3]. This term may sometimes be a misnomer because in many situations they are more important than the losses due to pipe friction. This can be especially true in the case of smooth pipe such that used in this study.

Because the flow pattern in fittings and valves is quite complex, the theory is weak [2]. The measured minor loss is usually given as a ratio of the head loss, $h_{\text{tee}}$, through the device (a tee in this case), to the velocity head, $V^2/2g$ of the associated piping systems (see equation 13 below). That is, the head loss varies as the square of the velocity.

Although this is substantially true for all minor losses in turbulent flow, it is not exact. The discrepancies in this approximate analysis must be accounted for. The accounting is accomplished by inserting a loss coefficient, $K$, into the minor loss equation to account for discrepancies in the approximate analysis [2]:

$$h_{\text{tee}} = K(V^2/2g)$$

(13)

The loss coefficient $K$, was computed for the model 4-inch pipe and is given in Table 1A for each test. The coefficient is relatively constant throughout the test series until the velocity drops substantially. To compare the loss coefficients $K$, the value for the 8-inch and 12-inch tees are computed and listed in the following Table 1C.

Not all runs in which $K$ went to zero were listed.
Table 1C 4-in Tee K Values

<table>
<thead>
<tr>
<th>Dia</th>
<th>V</th>
<th>V^2/2g</th>
<th>h_{es}</th>
<th>V</th>
<th>V^2/2g</th>
<th>h_{es}</th>
<th>V</th>
<th>V^2/2g</th>
<th>h_{es}</th>
</tr>
</thead>
<tbody>
<tr>
<td>4&quot;</td>
<td>16.16</td>
<td>4.05</td>
<td>0.67</td>
<td>0.165</td>
<td>8&quot;</td>
<td>10.02</td>
<td>1.56</td>
<td>0.13</td>
<td>0.062</td>
</tr>
<tr>
<td>4&quot;</td>
<td>16.13</td>
<td>4.04</td>
<td>0.65</td>
<td>0.160</td>
<td>8&quot;</td>
<td>9.88</td>
<td>1.52</td>
<td>0.12</td>
<td>0.082</td>
</tr>
<tr>
<td>4&quot;</td>
<td>16.14</td>
<td>4.04</td>
<td>0.65</td>
<td>0.160</td>
<td>8&quot;</td>
<td>9.51</td>
<td>1.40</td>
<td>0.11</td>
<td>0.080</td>
</tr>
<tr>
<td>4&quot;</td>
<td>15.94</td>
<td>3.94</td>
<td>0.65</td>
<td>0.164</td>
<td>8&quot;</td>
<td>9.92</td>
<td>1.24</td>
<td>0.10</td>
<td>0.083</td>
</tr>
<tr>
<td>4&quot;</td>
<td>15.34</td>
<td>3.65</td>
<td>0.59</td>
<td>0.161</td>
<td>8&quot;</td>
<td>7.78</td>
<td>0.94</td>
<td>0.08</td>
<td>0.066</td>
</tr>
<tr>
<td>4&quot;</td>
<td>14.4</td>
<td>3.22</td>
<td>0.53</td>
<td>0.165</td>
<td>8&quot;</td>
<td>5.69</td>
<td>0.50</td>
<td>0.04</td>
<td>0.076</td>
</tr>
<tr>
<td>4&quot;</td>
<td>12.55</td>
<td>2.45</td>
<td>0.42</td>
<td>0.170</td>
<td>8&quot;</td>
<td>2.13</td>
<td>0.07</td>
<td>0.01</td>
<td>0.184</td>
</tr>
</tbody>
</table>

**Velocity vs. Head Loss Table**

It was desired to develop a table which would simplify the determination of the head loss created by a particular velocity through the fitting, whether it be of 4-, 8-, or 12 inch diameter.

The created listing is presented as Table 1D, *Velocity vs. Head Loss, 4-in Tee*. In the table, it can be seen that a listing of velocities, for each fitting diameter, is given in increments of 0.5 fps (152 mm/sec).

Corresponding to each of these velocities a head loss is presented. For instance, given a 12 inch diameter pipe in which the design velocity is 5.5 fps; a head loss through the fitting would be 0.02 feet (6 mm). These values were derived using the equations of Figure 8 which were, themselves, derived from the Microsoft-Excel-Chart Wizard program.
**Table 1D Velocity vs. Head Loss, 4-in Tee**

<table>
<thead>
<tr>
<th>Dia (4in)</th>
<th>V</th>
<th>hL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dia (4in)</td>
<td>2.0</td>
<td>.07</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>2.5</td>
<td>.07</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>3.0</td>
<td>.07</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>3.5</td>
<td>.07</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>4.0</td>
<td>.07</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>4.5</td>
<td>.08</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>5.0</td>
<td>.09</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>5.5</td>
<td>.10</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>6.0</td>
<td>.11</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>6.5</td>
<td>.12</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>7.0</td>
<td>.14</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>7.5</td>
<td>.16</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>8.0</td>
<td>.17</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>8.5</td>
<td>.19</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>9.0</td>
<td>.22</td>
</tr>
<tr>
<td>Dia (4in)</td>
<td>9.5</td>
<td>.24</td>
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</table>

### 8x8x4 TEE:

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<th>hL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dia (8in)</td>
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<td>.01</td>
</tr>
<tr>
<td>Dia (8in)</td>
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<td>.01</td>
</tr>
<tr>
<td>Dia (8in)</td>
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<td>.02</td>
</tr>
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<td>.02</td>
</tr>
<tr>
<td>Dia (8in)</td>
<td>4.0</td>
<td>.03</td>
</tr>
<tr>
<td>Dia (8in)</td>
<td>4.5</td>
<td>.03</td>
</tr>
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<td>Dia (8in)</td>
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<td>.04</td>
</tr>
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<td>.04</td>
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<td>Dia (8in)</td>
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<td>.05</td>
</tr>
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<td>.05</td>
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<td>.06</td>
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<td>.07</td>
</tr>
<tr>
<td>Dia (8in)</td>
<td>8.0</td>
<td>.08</td>
</tr>
<tr>
<td>Dia (8in)</td>
<td>8.5</td>
<td>.09</td>
</tr>
<tr>
<td>Dia (8in)</td>
<td>9.0</td>
<td>.10</td>
</tr>
<tr>
<td>Dia (8in)</td>
<td>9.5</td>
<td>.12</td>
</tr>
<tr>
<td>Dia (8in)</td>
<td>10.0</td>
<td>.13</td>
</tr>
</tbody>
</table>

### 12x12x4 TEE:

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<th>hL</th>
</tr>
</thead>
<tbody>
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<td>.00</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
<td>2.5</td>
<td>.00</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
<td>3.0</td>
<td>.01</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
<td>3.5</td>
<td>.01</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
<td>4.0</td>
<td>.01</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
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<td>.02</td>
</tr>
<tr>
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<td>.02</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
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<td>.03</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
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<td>.03</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
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<td>.04</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
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<td>.04</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
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<td>.05</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
<td>8.0</td>
<td>.06</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
<td>8.5</td>
<td>.07</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
<td>9.0</td>
<td>.08</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
<td>9.5</td>
<td>.09</td>
</tr>
<tr>
<td>Dia (12&quot;)</td>
<td>10.0</td>
<td>.10</td>
</tr>
</tbody>
</table>

**Comparison With Other Research**

Measurements were made by others [8] of head losses resulting from flow across tees. The report states "the data presented are accurate for Reynolds numbers, \(R_e\), 1 \(x\) \(10^5\) to 2 \(x\) \(10^5\)." One of the test conducted by this writer was a 4x4x4 tee at \(R_e = 1.1 \times 10^5\) (see test #408, Table 1A). This LaTech test was, therefore, a good candidate for comparison. This author's data will be referred to as the "LaTech Study" (designated the model study) and the referenced study results as the "ASCE Study," (prototype data). The comparison will be made of the resulting head loss, \(h\), of each study.
Latech Study (Model-Table 1B)  
\[ \text{Find } V_p \text{ using } Re \text{ using equation 11 of Chapter 3. Assume } v_p = v_m \text{ since temperatures were not given by the ASCE paper, then} \]
\[ V_p = \frac{V_m d_m}{d_p} = \frac{(3.43)(0.333)}{0.1148} = 9.95 \text{ fps} \]

ASCE Study  
\[ \text{Find head loss, } h_p, \text{ using equation 12a of Chapter 3:} \]
\[ h_p = h_m \left( \frac{D_m^3}{D_p^3} \right) = 0.07 \left( \frac{0.333}{0.1148} \right)^3 = 1.71 \text{ ft} \]

LaTech Study: 
Find \( V_p \) using \( Re \) using equation 11 of Chapter 3. Assume \( v_p = v_m \) since temperatures were not given by the ASCE paper, then
\[ V_p = V_m d_m / d_p = (3.43)(0.333)/(0.1148) = 9.95 \text{ fps} \]

Find head loss, \( h_p \), using equation 12a of Chapter 3:
\[ h_p = h_m \left( \frac{D_m^3}{D_p^3} \right) = 0.07 \left( \frac{0.333}{0.1148} \right)^3 = 1.71 \text{ ft} \]

ASCE Study
The loss coefficient, \( \zeta_{13} \) (this term, which is represented by \( "K" \) in the LaTech study, is given in the ASCE study as equation 24, page 1362:
\[ \zeta = 0.99 - 0.24*(r/d)^{1/2} \]

here: \( r = \text{radius of curvature of the wall at joining edges} \ (r = 0 \text{ mm for both test series}) \).

This reduces equation 15 to
\[ \zeta = 0.99 \]

Apply the minor loss equation for tees and other fittings [2, 3, 4], letting \( \zeta = K \):
\[ h_p = K*(V_p^2/2g) = 0.99*(9.95^2/64.4) = 1.52 \text{ ft} \]

The percent difference between the two values is
\[ \Delta\% = [(1.71 - 1.52)/1.71]*100 = 11\% \]

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The ASCE study pipe ends and the tee shoulders were flush while there was a space between the shoulders and pipe ends in the LaTech study. This difference would account for at least a portion of the larger LaTech head loss.
Section 2 6x6x6 Tee Test Results

General

Figure 9 presents a photograph of the second tee fitting tested. It is a 6x6x6 tee model in place for testing. The shown distances between piezometers and the upstream piezometer/lateral centerline are typical of those of each test series. Both the trunk line and lateral diameters (6-in, 152 mm) are larger than the preceding 4x4x4 tee test series. Two different size tee tests were required to determine the loss conditions across tees with differing lateral diameters. The 4-in (102 mm) and 6-inch laterals were considered to be the most popular sizes in use in small, PVC pipe lines.

In this type of study, the model portion usually consists of trunk and lateral diameters of the same dimension. Once the model measurements have been completed, the trunk line...
diameters are scaled while the lateral diameter is held constant. The two separate sets of model units (4x4x4 and 6x6x6) were required because the trunk line and lateral cannot be scaled simultaneously. Therefore, following the model tests, the trunk line was, in both cases, scaled upward, in increments, to 12 inches, (305 mm). As stated previously, it is the largest known diameter of wyes and tees fabricated in the earlier described manner, (see page 26 of Chapter 3).

**Data – Measured and Computed**

As with the 4x4x4 tee model tests, the recorded data for the 6x6x6 tee model were entered into a prepared spreadsheet table. Table 2A contains the recorded “Input” entry values. The similar entries of Table 1A are discussed in Section 1 under the heading, “Data-Measured and Computed.” The maximum discharge in Table 1A and Table 2A are approximately the same [1.40± cfs (0.04 cms)]. However, because of the larger pipe diameter used in the second test series (Section 2) the velocities are much smaller, \( V_{max6} = 7.12 \text{ fps vs. } V_{max4} = 16.16 \text{ fps} \). This, of course, agrees with the continuity equation [3], \( V = Q/A \).

To obtain a rough comparison of the difference in head losses, look at test number 407 of the 4-inch series (Table 1A) where the Reynolds number, \( R_e \), equals 291,000. Compare this to the Reynolds number of test number 602 (Table 2A). In this case, the 6-inch series, \( R_e = 307,000 \). These values are the most comparable of the two test series:

<table>
<thead>
<tr>
<th>4-inch test #407</th>
<th>6-inch test #602</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_e = 291,000 )</td>
<td>( R_e = 307,000 )</td>
<td>6.0</td>
</tr>
<tr>
<td>( K = 0.15 )</td>
<td>( K = 0.12 )</td>
<td>20.0</td>
</tr>
<tr>
<td>( V^2/2g = 1.30 \text{ ft. (hidden)} )</td>
<td>( V^2/2g = 0.77 \text{ ft.} )</td>
<td>41.0</td>
</tr>
</tbody>
</table>
The K values are relatively close, the primary cause of the difference in head loss, h, being the difference in velocity head. That is, for the 55% difference in h (using the 4-inch data as base) there is a velocity head difference of 41%.

Data Tables

The following two tables (2A and 2B), contain the data recorded, reduced and scaled for the model 6x6x6 tee. The resulting model data were then scaled up to trunk line diameters of 8 inches (203 mm) and 12 inches (304 mm). The scaling is followed by a appropriate set of hand calculations for comparison with the computer derived data. As mentioned previously, some data columns may be “hidden” in order to prevent the tables from over-running the required page margins. The explanation of the data recorded in each of the two tables can be found in Section 1, 4x4x4 Tee tests and analysis.

Table 2A, 6x6x6 Model Tee Data

Note in Table 2A eight model tests were conducted at velocities ranging from 1.5 to 7.1 fps (0.45 to 2.16 mps). Note the temperature of the water in these model tests was 64°F, the lowest of any test conducted and 7° lower than the 4x4x4 tee tests. The difference caused a rise of the kinematic viscosity, from 1.05x10^{-5} ft^2/sec, (4x4x4 tee) to 1.15x10^{-5} ft^2/sec, (6x6x6 tee), for a difference of about 9%. These viscosities are given in Tables 1B and 2B, respectively. The maximum Reynolds number for the 4x4x4 tests was 514,000 compared to the maximum value for the 6x6x6 tests of 311,000.
Table 2A Model Data 6x6x6 Tee

<table>
<thead>
<tr>
<th>Test#</th>
<th>T°F</th>
<th>h-psi</th>
<th>Wt-#</th>
<th>t-sec</th>
<th>h-ft</th>
<th>Qft</th>
<th>V-fps</th>
<th>(v^2/2g)</th>
<th>K</th>
<th>Re</th>
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</thead>
<tbody>
<tr>
<td>600</td>
<td>64</td>
<td>0.040</td>
<td>4040</td>
<td>46.05</td>
<td>0.092</td>
<td>1.41</td>
<td>7.115</td>
<td>0.786</td>
<td>0.12</td>
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<td>601</td>
<td>64</td>
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<td>4036</td>
<td>45.81</td>
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<td>1.41</td>
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<td>0.793</td>
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<td>7.037</td>
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<td>0.587</td>
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<td>64</td>
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<td>4045</td>
<td>56.6</td>
<td>0.081</td>
<td>1.15</td>
<td>5.801</td>
<td>0.523</td>
<td>0.15</td>
<td>253,296</td>
</tr>
<tr>
<td>605</td>
<td>64</td>
<td>0.030</td>
<td>4037</td>
<td>58.6</td>
<td>0.069</td>
<td>1.11</td>
<td>5.591</td>
<td>0.485</td>
<td>0.14</td>
<td>244,119</td>
</tr>
<tr>
<td>606</td>
<td>64</td>
<td>0.025</td>
<td>4038</td>
<td>80.21</td>
<td>0.058</td>
<td>0.81</td>
<td>4.083</td>
<td>0.259</td>
<td>0.22</td>
<td>178,271</td>
</tr>
<tr>
<td>607</td>
<td>64</td>
<td>0.030</td>
<td>4035</td>
<td>214.2</td>
<td>0.069</td>
<td>0.30</td>
<td>1.528</td>
<td>0.036</td>
<td>1.91</td>
<td>66,716</td>
</tr>
</tbody>
</table>

Table 2B, 6x6x6 Tee Scaled Data

The pertinent model data were then entered into the scaling table (Table 2B). The inside diameters of the prototype trunk lines (these are the trunk line dimensions which are to be scaled upward) are entered in the left column A, in inches and feet, under the heading, “Dia”. Model values from data Table 2A are entered into cells C1 – K4 of Table 2B. The remaining entries to be made are the model temperature, and the design temperature, in cells M2 and M6, respectively. Cells M1 and M5 contain the computed (see Appendix A for details) model and scaled kinematic viscosities, respectively. The computed densities and absolute viscosities are also computed, but not used in the computations.
The remaining (darkened) cells contain implanted equations which compute the scaled pipe velocity, (cells C5 through K5) for the scaled 8-inch pipe and cells C7 through K7 for the scaled 12-inch pipe velocities.

In the same manner, cells C6 through K6 compute the scaled values of head loss in the 8-inch pipe. Cells C8 through K8 do likewise for the scaled 12-inch pipe.

**Table 2B Computational Procedure**

The information pertinent to this section is covered, by the same title in Section 1, except the table number now is 2B instead of 1B. The computational procedure of both tables is the same.

**Computational Example**

A typical set of hand-calculations are carried out for comparison with the data in Table 2B. The computations will be made using English units, the answer will be converted to SI units. The example is given using data from Table 2B:

**Given:** fluid temperatures, $T_m = 64^\circ F, \ T_p = 55^\circ F$. (cells M2 and M6, respectively).

From column F choose: $Q_m = 1.41$ fps, then $d_m = 0.502$ ft, $V_m = 7.144$ fps, $\Delta h = 0.081$ ft.

Scale to prototype diameter: 1.00 ft. (cell A8).
This example will be solved using equations 11 and 12a of Chapter 3.

Equation 11 (Chapter 3):
\[ V_p = V_m \left( \frac{d_m}{d_p} \right) \left( \frac{v_p}{v_m} \right) = 7.144 \times \frac{0.502/1.0}{1.308 \times 10^{-5}/1.15 \times 10^{-5}} = 4.08 \text{ fps (1.24 mps)}. \]

Equation 12a (Chapter 3):
\[ h_p = \frac{V_m^2}{D_p^3} v_p^2 = \frac{(0.081 \times 0.502^3 \times 1.308^2) / (1.0^3 \times 1.15^2)}{0.013 \text{ ft.} = 4 \text{ mm}}. \]

These two solutions \((V_p \text{ and } h_p)\) may be compared with the solutions given in cells F7 and F8 respectively of Table 2B.

**Minor loss Coefficient, K**

The procedure used to compute the minor loss coefficient, \(K\), is explained in Section 1, same title. Table 2C lists the \(K\) values for the three pipe diameters (6-, 8- and 12-inches) along with the velocity, \(V\), velocity head, \(V^2/2g\) and head loss, \(h\). The plot of these data are discussed following the “Data Plot” section.

**Table 2C 6x6x6 K Values**

<table>
<thead>
<tr>
<th>Trk dia</th>
<th>V fps</th>
<th>(V^2/2g) ft</th>
<th>(h_{tee}) ft</th>
<th>K</th>
<th>Trk dia</th>
<th>V fps</th>
<th>(V^2/2g) ft</th>
<th>(h_{tee}) ft</th>
<th>K</th>
<th>Trk dia</th>
<th>V fps</th>
<th>(V^2/2g) ft</th>
<th>(h_{tee}) ft</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>6&quot;</td>
<td>7.11</td>
<td>0.79</td>
<td>0.09</td>
<td>0.12</td>
<td>8&quot;</td>
<td>6.09</td>
<td>0.58</td>
<td>0.05</td>
<td>0.09</td>
<td>12&quot;</td>
<td>4.06</td>
<td>0.26</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>6&quot;</td>
<td>7.14</td>
<td>0.79</td>
<td>0.08</td>
<td>0.10</td>
<td>8&quot;</td>
<td>6.11</td>
<td>0.58</td>
<td>0.05</td>
<td>0.08</td>
<td>12&quot;</td>
<td>4.08</td>
<td>0.26</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>6&quot;</td>
<td>7.04</td>
<td>0.77</td>
<td>0.09</td>
<td>0.12</td>
<td>8&quot;</td>
<td>6.02</td>
<td>0.56</td>
<td>0.05</td>
<td>0.09</td>
<td>12&quot;</td>
<td>4.02</td>
<td>0.25</td>
<td>0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>6&quot;</td>
<td>6.15</td>
<td>0.59</td>
<td>0.08</td>
<td>0.14</td>
<td>8&quot;</td>
<td>5.26</td>
<td>0.43</td>
<td>0.05</td>
<td>0.10</td>
<td>12&quot;</td>
<td>3.51</td>
<td>0.19</td>
<td>0.01</td>
<td>0.07</td>
</tr>
<tr>
<td>6&quot;</td>
<td>5.80</td>
<td>0.52</td>
<td>0.08</td>
<td>0.16</td>
<td>8&quot;</td>
<td>4.98</td>
<td>0.38</td>
<td>0.05</td>
<td>0.12</td>
<td>12&quot;</td>
<td>3.31</td>
<td>0.17</td>
<td>0.01</td>
<td>0.08</td>
</tr>
<tr>
<td>6&quot;</td>
<td>5.59</td>
<td>0.49</td>
<td>0.07</td>
<td>0.14</td>
<td>8&quot;</td>
<td>4.79</td>
<td>0.36</td>
<td>0.04</td>
<td>0.11</td>
<td>12&quot;</td>
<td>3.19</td>
<td>0.16</td>
<td>0.01</td>
<td>0.07</td>
</tr>
<tr>
<td>4.08</td>
<td>0.26</td>
<td>0.06</td>
<td>0.22</td>
<td>0.14</td>
<td>8&quot;</td>
<td>3.49</td>
<td>0.19</td>
<td>0.03</td>
<td>0.17</td>
<td>12&quot;</td>
<td>2.33</td>
<td>0.08</td>
<td>0.01</td>
<td>0.11</td>
</tr>
</tbody>
</table>

**Data Plot**

The velocity and head loss data for the 6-, 8-, and 12-inch pipes (with 6-inch laterals, described as “the 6x6x6 model data”) were taken from Table 2B and plotted as head loss.
vs. velocity in Figure 10. The graph was produced in the same manner as the 4x4x4 model data plot of Figure 8. The resulting plots are for each size trunk line (6-, 8-, and 12-inches) in the form of head loss vs. pipe velocity.

![6-in Tee Velocity vs. Head Loss](image)

**Figure 10.** Head loss vs. pipe velocity through 6x tees

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The regression line equations are shown in the figures (Figures 8 and 10). Note, as the pipe diameter, D, decreases, (for a given velocity), the head loss, h, increases. This change conforms to head loss equation 12a which states, as the ratio $D_m^3/D_p^3$ decreases, the head loss also decreases. This change of course, in our case, assumes the model diameter is smaller than that of the prototype diameter.

**Pipe Velocity vs. Loss Coefficient, K**

Figure 11 presents a graph which allows the comparison of the of the loss coefficient, K, with the change in velocity (due to the change in pipe diameter). For example, at a velocity of 4.0 fps the K value for a 6x6x6 tee is approximately 0.23. For the 12x12x12 tee, the K value is approximately 0.051. These differing values cause a percent difference in K (using $K = 0.23$ as base) of:

$$\Delta K = [(0.23-0.051)/0.23]*100 \approx 78\%$$

From this equation, we conclude, for a given velocity, the loss coefficient $K$, decreases with increasing pipe diameter.
Figure 11. Pipe velocity vs. 6x tee fitting loss coefficient K
**Comparison With Other Research**

As discussed in Section 1 (4x4x4 Tee Tests and Analysis), research of this nature was conducted by others [8]. The referenced report states "the data presented are accurate for Reynolds numbers, $R_e$, $1 \times 10^5$ and $2 \times 10^5$.

As in the 4x4x4 tee tests, one of the LaTech tests for 6x6x6 tees fell between these two $R_e$ values. From Table 2A, (Model Data 6x6x6 tee), it can be seen that test #606 was conducted at $R_e \approx 1.8 \times 10^5$. This LaTech laboratory test was therefore a good candidate for comparison. As in the Section 1 comparison above, these data will be referred to as the LaTech Study" (designated the model study). The study being compared will again be referred to as the “ASCE Study,” (prototype data). The comparison will be made of resulting head loss, $h$, of each study.

It is pointed out in advance, in this computation, the interior configurations were not the same, which was not the case in the 4x4x4 tee dimensions. Here, the ASCE study tee had joining corners of zero radius. However, the LaTech test tee had a zero degree corner on the downstream end of the lateral entrance but a large radius on the upstream side. With this difference in mind, the comparison will again be made.

<table>
<thead>
<tr>
<th>LaTech Study (Model)</th>
<th>ASCE Study (Prototype)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_m$ (cell K3 Table 2B) = 4.08 fps</td>
<td>$V_p$ = unknown</td>
</tr>
<tr>
<td>$d_m$ (cell (cell K2) = 0.502 ft</td>
<td>$d_p$ = 0.1148 ft (35 mm)</td>
</tr>
<tr>
<td>$h_m$ (cell K4) = 0.058 ft</td>
<td>$h_p$ = unknown</td>
</tr>
<tr>
<td></td>
<td>$v_p$ = unknown (do not include $v$)</td>
</tr>
</tbody>
</table>
LaTech study(model):

Find $V_p$ using $R_e$ assuming $v_p = v_m$ since temperatures were not given by the ASCE group, then

$$V_p = \frac{V_m d_m}{d_p} = (4.08)^*(0.0.502)/(0.1148) = 17.84 \text{ fps}$$

Find prototype head loss, $h_p$, using equation 12a of Chapter 3:

$$h_p = h_m \left( \frac{D_m^3}{D_p^3} \right) = 0.058(0.502^3/0.1148^3) = 4.85 \text{ ft}.$$ 

ASCE Study(prototype):

The loss coefficient, $\zeta$, is given by the ASCE Study authors’ equation:

$$\zeta = 0.99 * (r/d)\frac{1}{2} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots
Section 3 4x4x4 Wye Test Results

General

Figure 12 presents a photograph of the smaller, 4-inch (103 mm) wye fitting. The wye lateral makes a 45-degree angle with the main trunk line direction. The inside diameters of the trunk and lateral lines were 4 inches (0.333 ft or 103 mm). This dimension is also shown in Table 3A, Model Data, 4x4x4 Wye.

![Diagram of the 4x4x4 wye with piezometers](image)

**Figure 12. 4x4x4 wye with piezometers**

The piezometers shown in Figure 12 were installed upstream and downstream of the fitting at distances shown in the figure. As with previous fittings, tubing was attached to the two piezometers, each terminating at the upstream and downstream ports of the
differential pressure transducer which is shown in Figure 2. The laboratory lateral pipe
was capped and a bleed valve inserted as shown in Figure 12 above.

**Data – Measured and Computed**

As in previously discussed procedure, the recorded data were entered into a spreadsheet
table. In this study, the recorded data and corresponding reduced data are entered in
Table 3A, Model Data 4x4x4 Wye. Eight model tests were conducted at discharges, Q,
ranging from 0.30 to 1.4 cfs (0.09 to 0.43 cms).

**Table 3A, 4x4x4 Wye Model Data**

Table 3A contains data from eight model tests conducted at velocities ranging from 3.40
to 16.07 fps (1.04 to 4.90 mps). The Reynolds number ranged from 108,185 to 510,813,
very close to the Re range for the 4x4x4 tee tests of Table 1A (109,302 to 513,727).

<table>
<thead>
<tr>
<th>INPUT</th>
<th>Table 3A. Model Data 4x4x4 Wye</th>
<th>Dia=0.333 ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test #</td>
<td>T-°F</td>
<td>h-psi</td>
</tr>
<tr>
<td>420</td>
<td>71</td>
<td>0.220</td>
</tr>
<tr>
<td>421</td>
<td>71</td>
<td>0.220</td>
</tr>
<tr>
<td>422</td>
<td>71</td>
<td>0.210</td>
</tr>
<tr>
<td>423</td>
<td>71</td>
<td>0.200</td>
</tr>
<tr>
<td>424</td>
<td>71</td>
<td>0.210</td>
</tr>
<tr>
<td>425</td>
<td>71</td>
<td>0.165</td>
</tr>
<tr>
<td>426</td>
<td>71</td>
<td>0.090</td>
</tr>
<tr>
<td>427</td>
<td>71</td>
<td>0.030</td>
</tr>
</tbody>
</table>

The “Input” and “Computation” columns of Table 3A are the same as those described for
Table 1A, “Section A, 4x4x4 Tee Tests and Analysis”.

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Table 3B, 4x4x4 Wye Scaled Data

The pertinent model data were, as in previous sections, entered into “Table 3B, 4x4x4 wye scaled data.” The inside diameters of the prototype trunk lines (these are the main line dimensions to be scaled to) are entered in the left column A, in inches and feet. Values from Table 3A are entered into cells C1 through K4 of Table 3B. The remaining entries in the table are the model temperature and the design temperature in cells M2 and M6, respectively. Cells M1 and M5 contain, respectively the computed (see Appendix A) model and prototype viscosities. The computed densities and absolute viscosities are also listed, but not used in the computations.

Table 3B 4x4x4 Wye Scaled Data.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.047E-05</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>71.00</td>
</tr>
<tr>
<td>3</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.038E-05</td>
</tr>
<tr>
<td>4</td>
<td>Dia</td>
<td>h_model</td>
<td>0.51</td>
<td>0.48</td>
<td>0.46</td>
<td>0.48</td>
<td>0.38</td>
<td>0.21</td>
<td>0.07</td>
</tr>
<tr>
<td>6</td>
<td>0.67</td>
<td>h_model</td>
<td>0.10</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.07</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>7</td>
<td>12&quot;</td>
<td>V_model</td>
<td>6.70</td>
<td>6.62</td>
<td>6.41</td>
<td>6.98</td>
<td>5.06</td>
<td>3.78</td>
<td>1.42</td>
</tr>
<tr>
<td>8</td>
<td>1.00</td>
<td>h_model</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The remaining (darkened) cells contain equations which compute the scaled pipe velocity, (cells C5 through K5) for the 8-inch pipe and (cells C7 through K7) for the 12-inch pipe, respectively. In the same manner, cells C6 through K6 compute the scaled values of head loss in the 8-inch pipe and cells C8 through K8 do likewise for the 12-inch pipe.
Table 3B Computational Procedure

The information pertinent to this section is covered, under the same title, in Section 1, except the table number is now 3B instead of 1B. The computational procedure of both tables is the same.

Computational Example

A typical set of hand calculations are carried out for comparison with the data given in Table 3B. The computations will be made using English units; the final answer will then be converted to SI units. The example is given using data from Table 3B:

Given: Fluid temperature – Tm = 71°F, Tp = 55°F.

From column F copy: Qm = 1.38 cfs, Dm = 0.333 ft., Vm = 15.89 fps, Ah = 0.48 ft.

Scaling: Choose to scale to a pipe diameter of 12-inches, 1.0 ft. (305 mm), see cell A8.

The Reynolds number, Re, as in previous examples, is used to derive the prototype velocity (equation 11). The model data for these computations will be taken from column F. The prototype head loss value, h will then be solved using equation 12a.

\[ V_p = V_m (D_m/D_p)(v_p/v_m) = 15.89(0.333/1.00)(1.308/1.047) = 6.61 \text{ fps} \]

Compare this value to that of cell F7, Table 3B.

\[ h_p = (h_mD_m^3v_p^2/D_p^3v_m^2) = (0.48*0.333^3*1.308^2)/(1.00^3*1.047^2) = 0.028 \approx 0.03 \text{ ft.} \]

Compare this value to that of cell F8, Table 3B.

Data Plot

The velocity and head loss data for the 4-, 8-, and 12-inch pipes (with 4-inch laterals, described as the “4x4x4 wye model data”) were taken from Table 3B and plotted as head loss vs. velocity in Figure 13. The graph was produced in the same manner as
the 4x4x4 model data plot of Figure 8. The resulting plots are for each size trunk line (4-, 8-, and 12-inches) connected to 4-inch wye laterals.

The head loss vs. pipe velocity curves is relatively parallel for the 8- and 12-inch pipes in Figure 13. However, for the 4-inch pipe, the curve climbs at a much steeper rate. This phenomenon was also evident in Figures 8 and 10, especially Figure 8. This difference, no doubt, is due to the smaller 4-in model pipe having a smaller diameter and a higher velocity. In the Darcy equation, the head loss is directly proportional to the velocity squared and inversely proportional to the pipe diameter. i.e.:

\[ h_f = f(L/D)V^2/2g \]
Figure 13. Head loss vs. pipe velocity through 4x wyes
Major Loss Coefficient, K

The procedure used to compute the minor loss coefficient, K, is explained in Section 1, same title. Table 3C lists the K values for the three pipe diameters (4-, 8- and 12-inches) along with the velocity, V, velocity head \( V^2/2g \) and head loss, h.

Table 3C 4-inch Wye K Values

<table>
<thead>
<tr>
<th>Trk Dia</th>
<th>( V^2/2g ) ft.</th>
<th>( h_{wye} ) ft.</th>
<th>K</th>
<th>Trk Dia</th>
<th>( V^2/2g ) ft.</th>
<th>( h_{wye} ) ft.</th>
<th>K</th>
<th>Trk Dia</th>
<th>( V^2/2g ) ft.</th>
<th>( h_{wye} ) ft.</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>4&quot;</td>
<td>4.01</td>
<td>0.51</td>
<td>0.13</td>
<td>8&quot;</td>
<td>1.57</td>
<td>0.10</td>
<td>0.06</td>
<td>12&quot;</td>
<td>0.70</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>4&quot;</td>
<td>3.97</td>
<td>0.51</td>
<td>0.13</td>
<td>8&quot;</td>
<td>1.53</td>
<td>0.09</td>
<td>0.06</td>
<td>12&quot;</td>
<td>0.68</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>4&quot;</td>
<td>3.92</td>
<td>0.48</td>
<td>0.12</td>
<td>8&quot;</td>
<td>1.43</td>
<td>0.09</td>
<td>0.06</td>
<td>12&quot;</td>
<td>0.64</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>4&quot;</td>
<td>3.67</td>
<td>0.46</td>
<td>0.13</td>
<td>8&quot;</td>
<td>1.25</td>
<td>0.09</td>
<td>0.07</td>
<td>12&quot;</td>
<td>0.56</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>4&quot;</td>
<td>3.20</td>
<td>0.48</td>
<td>0.15</td>
<td>8&quot;</td>
<td>0.89</td>
<td>0.07</td>
<td>0.08</td>
<td>12&quot;</td>
<td>0.40</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>4&quot;</td>
<td>2.29</td>
<td>0.38</td>
<td>0.17</td>
<td>8&quot;</td>
<td>0.50</td>
<td>0.04</td>
<td>0.08</td>
<td>12&quot;</td>
<td>0.22</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>4&quot;</td>
<td>1.28</td>
<td>0.21</td>
<td>0.16</td>
<td>8&quot;</td>
<td>0.07</td>
<td>0.01</td>
<td>0.14</td>
<td>12&quot;</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>4&quot;</td>
<td>0.18</td>
<td>0.07</td>
<td>0.38</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3C Comments

Table 3C shows that the loss coefficient K, decreases with increasing pipe diameter. Recall that \( K = h/V^2/2g \). Calculations show the head loss, h, decreases at a greater rate than does the velocity head as the diameter increases.

Example:

Looking at the first row of Table 3C the 4- to 8-inch change in pipe velocity head is 61\% whereas the 4- to 8-inch change head loss is 80\%, causing a reduction in K of 54\%.
Section 4 6x6x6 Wye Test Results

General

Figure 14 presents a photograph of the larger, 6-inch (152 mm) wye fitting. The wye lateral makes a 45-degree angle with the main trunk line direction. The inside diameters of the trunk and lateral lines were approximately 6 inches (0.50 feet or 152 mm). The measured inside diameters are given later in this section in Table 4A, Model Data 6x6x6 Wye.

Figure 14. 6x6x6 Wye with piezometers

The distance between the upstream and downstream piezometers in Figure 14 was 18.6 inches (472 mm). The distance from the downstream piezometer (P2), to the centerline of the lateral was 8.20 inches (208 mm). This distance leaves the distance from the
lateral centerline to the upstream piezometer (P1) equal to 10.4 inches (208 mm). As described in previous sections, tubing was attached to each piezometer. The tubing from the upstream piezometer terminated at the upstream port of the differential transducer (see Figure 2). The tubing from the downstream piezometer led to the downstream port of the differential transducer (also Figure 2). As in other model fittings, the lateral pipe was capped and a bleed valve inserted as shown in Figure 14 above.

**Data – Measured and Computed**

As discussed in the previous three sections (sections 1, 2, and 3), the recorded data were entered into a spreadsheet table. In this portion of the study, the recorded model data are entered in Table 4A, “Model Data 6x6x6 Wye.” Nine model tests were conducted at discharges, Q, ranging from 0.30 to 1.41 cfs (0.008 to 0.04 cms).

**Table 4A, 6x6x6 Wye Model Data**

Table 4A contains data from nine model tests which were conducted at velocities ranging from 1.51 to 7.12 fps (0.46 to 2.17 mps). The Reynolds number, Re, ranged from 67,500 to 319,250 and compared well with the range of 66,700 to 310,000 for the 6-inch (Table 2A) tee study. The “Input” and “Comp” columns of Table 4A are the same as those described for Table 1A.
Table 4A Model Data 6x6x6 Wye

<table>
<thead>
<tr>
<th>Tst #</th>
<th>L-ft^1</th>
<th>T^°F</th>
<th>h-psi</th>
<th>wt-#</th>
<th>t-sec</th>
<th>Tst #</th>
<th>L-ft^1</th>
<th>T^°F</th>
<th>h-psi</th>
<th>wt-#</th>
<th>t-sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>658</td>
<td>1.583</td>
<td>66</td>
<td>0.045</td>
<td>4036</td>
<td>45.98</td>
<td>0.104</td>
<td>1.41</td>
<td>7.12</td>
<td>0.132</td>
<td>319,246</td>
<td></td>
</tr>
<tr>
<td>657</td>
<td>1.583</td>
<td>66</td>
<td>0.050</td>
<td>4033</td>
<td>46.03</td>
<td>0.115</td>
<td>1.41</td>
<td>7.11</td>
<td>0.147</td>
<td>319,046</td>
<td></td>
</tr>
<tr>
<td>656</td>
<td>1.583</td>
<td>66</td>
<td>0.050</td>
<td>4050</td>
<td>52.33</td>
<td>0.115</td>
<td>1.24</td>
<td>6.28</td>
<td>0.189</td>
<td>281,819</td>
<td></td>
</tr>
<tr>
<td>655</td>
<td>1.583</td>
<td>66</td>
<td>0.045</td>
<td>4036</td>
<td>53.30</td>
<td>0.104</td>
<td>1.22</td>
<td>6.14</td>
<td>0.177</td>
<td>275,402</td>
<td></td>
</tr>
<tr>
<td>654</td>
<td>1.583</td>
<td>66</td>
<td>0.040</td>
<td>4037</td>
<td>56.84</td>
<td>0.092</td>
<td>1.14</td>
<td>5.76</td>
<td>0.179</td>
<td>258,314</td>
<td></td>
</tr>
<tr>
<td>653</td>
<td>1.583</td>
<td>66</td>
<td>0.035</td>
<td>4036</td>
<td>63.34</td>
<td>0.081</td>
<td>1.02</td>
<td>5.17</td>
<td>0.195</td>
<td>231,749</td>
<td></td>
</tr>
<tr>
<td>651</td>
<td>1.583</td>
<td>66</td>
<td>0.030</td>
<td>4032</td>
<td>80.34</td>
<td>0.069</td>
<td>0.81</td>
<td>4.07</td>
<td>0.269</td>
<td>182,529</td>
<td></td>
</tr>
<tr>
<td>652</td>
<td>1.583</td>
<td>66</td>
<td>0.025</td>
<td>4033</td>
<td>112.15</td>
<td>0.058</td>
<td>0.58</td>
<td>2.92</td>
<td>0.437</td>
<td>130,789</td>
<td></td>
</tr>
<tr>
<td>650</td>
<td>1.583</td>
<td>66</td>
<td>0.025</td>
<td>4036</td>
<td>217.5</td>
<td>0.058</td>
<td>0.30</td>
<td>1.51</td>
<td>1.640</td>
<td>67,496</td>
<td></td>
</tr>
</tbody>
</table>

1. Distance between piezometers

**Table 4B, 6x6x6 Wye Scaled Data**

The pertinent model data were, as in previous sections, entered into the scaling table, Table 4B, "6x6x6 Wye scaled data." The inside diameters of the prototype trunk lines (these are the main line dimensions to be scaled to) are entered in the left column A, in inches and feet. Model values from Table 4A are entered into cells C1 through K4 of Table 4B. The remaining entries in the table are the model temperature (cell M2) and the design temperature (cell M6). Cells M1 and M5 contain, respectively, the computed model and prototype kinematic viscosities (see Appendix A). The computed densities and absolute viscosities are also listed but not used in the computations.
Table 4B 6x6x6 Wye Scaled Data

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Q&lt;sub&gt;mod&lt;/sub&gt;</td>
<td>1.41</td>
<td>1.22</td>
<td>1.14</td>
<td>1.02</td>
<td>0.81</td>
<td>0.58</td>
<td>0.30</td>
<td>1.119E-05</td>
</tr>
<tr>
<td>2</td>
<td>d&lt;sub&gt;mod&lt;/sub&gt;</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>66.00</td>
</tr>
<tr>
<td>3</td>
<td>V&lt;sub&gt;mod&lt;/sub&gt;</td>
<td>7.12</td>
<td>6.14</td>
<td>5.76</td>
<td>5.17</td>
<td>4.07</td>
<td>2.92</td>
<td>1.51</td>
<td>2.188E-05</td>
</tr>
<tr>
<td>4</td>
<td>Dia</td>
<td>0.10</td>
<td>0.10</td>
<td>0.09</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
<td>1.940</td>
</tr>
<tr>
<td>5</td>
<td>h&lt;sub&gt;mod&lt;/sub&gt;</td>
<td>0.26</td>
<td>0.40</td>
<td>0.57</td>
<td>0.55</td>
<td>0.55</td>
<td>2.27</td>
<td>1.32</td>
<td>1.308E-05</td>
</tr>
<tr>
<td>6</td>
<td>V&lt;sub&gt;mod&lt;/sub&gt;</td>
<td>4.18</td>
<td>3.60</td>
<td>2.38</td>
<td>2.03</td>
<td>2.39</td>
<td>1.71</td>
<td>0.88</td>
<td>1.308E-05</td>
</tr>
<tr>
<td>7</td>
<td>h&lt;sub&gt;mod&lt;/sub&gt;</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>1.940</td>
</tr>
</tbody>
</table>

The remaining (darkened) cells contain equations which compute the scaled pipe velocity, (cells C5 through K5) for the 8-inch pipe and cells C7 through K7 for the 12-inch pipe velocity, respectively. In the same manner, cells C6 through K6 compute the scaled values of head loss, h, in the 8-inch pipe and cells C8 through K8 do likewise for the 12-inch pipe.

**Table 4B Computational Procedure**

The information pertinent to this section is covered, under the same title, in Section A, except the table number is now 4B instead of 1B. The computational procedure of both tables is the same.

**Computational Example**

A typical set of hand-calculations are carried out for comparison with the data given in Table 4B. The computations will be made using English units; the final answer will then be converted to SI units. The example is given using data from column C, Table 4B:

**Given:** Fluid temperature – T<sub>m</sub> = 66°F, T<sub>p</sub> = 55°F.

From column C copy: Q<sub>m</sub> = 1.41 cfs, D<sub>m</sub> = 0.502 ft, V<sub>m</sub> = 7.12 fps, Δh<sub>m</sub> = 0.10 ft.
Scaling: Choose to scale to a pipe diameter of 8-inches, 0.667 ft (cells A5 and A6) or 17 mm.

The example will be solved for the head loss, $\Delta h_{\text{scaled}}$ using equation 12a, as before.

The Reynolds number, $Re$ is common to both the model and the prototype, therefore, use the equality $Re_{\text{model}} = Re_{\text{proto}}$ (equation 11).

Eqn 11: $V_p = V_m(D_m/D_p)(v_p/v_m) = 7.12[(0.50/0.667)(1.308/1.119)] = 6.26 \text{ fps, 1.9 mps.}$

Compare this value to that of cell C5, Table 4B.

Next, solve for the “scaled” head loss, $h$, for a pipe of diameter 8-inches:

Eqn 12a: $h_p = h_m D_m^3 v_p^2 / D_p^3 v_m^2 = (0.10*0.50^2*1.308^2)/(0.667^3*1.119^2) = 0.058 \approx 0.06 \text{ ft, 18 mm.}$

Compare this value to that of cell C6, Table 4B.

Data Plot

The velocity and head loss data for the 6-, 8-, and 12-inch pipes (with 6-inch laterals, described as the “6x6x6wye model data”) were taken from Table 4B and plotted as head loss vs. velocity in Figure 15. The graph was produced in the same manner as the 4x4x4 tee model data plot of Figure 8. The resulting plots are for each size trunk line (6-, 8-, and 12-inch), connected to 6-inch wye laterals.

In the plot of Figure 15, it can be seen the head loss values climb with velocity as was the case in Figures 8, 10 and 13. The curves are slightly concave upward indicating the head loss rate increases slightly with increasing velocity. The plot accuracy is good as each coefficient of determination, $R^2$, is close to unity [6].
Figure 15 presents the changing head loss, h, with changing velocity.
**Minor Loss Coefficient, K**

The procedure used to compute the minor loss coefficient, K is explained in Section A, same title as this section title. Table 4C lists the K values for the three pipe diameters (6-, 8-, and 12-inches) along with the velocity, V, velocity head \(V^2/2g\) and head loss, \(h\).

![Table 4C 6-Inch Wye K Values](image)

Table 4C shows that the loss coefficient K, grows slowly until a certain (not shown) decreasing control valve opening is reached. After that point is reached, the value of K increases rapidly. There are fewer values shown in the 8-inch and 12-inch sections because some of the velocities and/or head loss values were rounded to zero.

From Table 4C, it can also be stated, in general, (reading from bottom to top):

- The head loss, \(h\), climbs with increasing velocity while the K value decreases. The 12-inch head loss values are difficult to interpret, probably because we are dealing with very small, rounded data.
- Though carrying the values to greater decimal places might help explain the curves of Figure 15, it is doubtful that such precision can be justified.

This completes the “fittings” study.
CHAPTER 5

LINER FOLDS

Introduction

Pipeline rehabilitation has been revolutionized in recent years. Modern rehabilitation involves basically, pipeline repairing, or replacement by a number of methods which precludes digging out the old pipe. One of these methods is designated the Cured-In-Place Pipe (CIPP) procedure.

The CIPP is a system in which a thin, flexible tube of polymer or glass fiber fabric is impregnated with resin and forced into position on the inner wall of a defective pipeline. The resin then cures, attaching to the host pipe inner wall and hardening the liner material. The uncured liner may be installed by winch or inverted by water or air pressure, with or without the aid of a turning out winch [11].

The procedure produces a strong, smooth interior surface which increases flow efficiency. In addition, CIPP can eliminate or reduce inflow of storm water, infiltration of groundwater, infiltration of pollutants, surface settlement caused by soil migration into the pipe, corrosive attack, and pipe irregularities/defects/joints in sewer collection systems. These systems (CIPP lining of defective pipes) can restore or increase hydraulic flow by smoothing surfaces. CIPP can be used in both circular and non-circular shapes
Detailed information on CIPP considerations and methods of installation are given in references [11] and [12].

**Pipe Liner “Folds”**

After the liner is inserted into the host pipe the resin-saturated material cures by application of hot water or steam to form a new pipe of slightly smaller inside diameter [12]. Ideally, the liner will take the same general shape as the original pipe. The liner is designed to fit snugly against the wall of the host pipe. If the liner is not stretched properly, “folds” in the liner can occur. A fold is an intrusion into the flow passage which creates a head loss accompanied by a reduction in flow capacity. It is the purpose of this section to look at the head loss, \( h \), created by folds.

In this study, three simulated folds of different diameters, and therefore, different head loss factors- are considered. A drawing of a “fold” cross-section is presented in Figure 16. For this initial study, the effects of single, perpendicular to flow, folds of differing diameters were studied. Although folds parallel to flow are more common in CIPP installations, their effect on flow is more easily estimated using calculations of changes in

![Figure 16. Pipe liner fold](image-url)
“wetted perimeter.” Perpendicular folds can occur if the liner is not stretched fully in the longitudinal direction and when liners are installed around sharp bends in a pipe.

**Test Program**

Three sets of tests were run with differing fold diameters, d. The head loss across the folds were measured in the same manner as described in Chapter 4. Three sets of folds were inserted into the test section of the pipe. The d/D ratio (see Figure 16) of each fold tested was as follows:

Fold #1 = d/D = 0.471 ft/0.502 ft = 0.938,

Fold #2 = d/D = 0.429 ft/0.502 ft = 0.854,

Fold #3 = d/D = 0.393 ft/0.502 ft = 0.782.

![Figure 17. Open test section](image-url)
Test Facility

The general test facility is the same as the system described in Chapter 2. Some minor differences were necessary which will be described in this section. Figure 17 presents the test pipe with the open test section. A short attachment section of pipe containing a portion of the test instrumentation was inserted therein (see Figure 18). This section facilitated the closing of the pipe uniformly, in proper alignment, before the hardening of the epoxy.

![Attachment section](image)

**Figure 18. Attached liner fold test section**

Figure 18 presents the closed, epoxied, test section including the approximate location of the test "fold."

The simulated folds were fabricated by slicing small PVC pipe sections (see Figure 19). The inside diameter of the folds are presented above. Each PVC pipe section was carefully sliced down the middle as shown in Figure 19B. Grooves were then spliced
into the half-tube section to allow forming the tubing around the inside of the pipe diameter. After attachment and drying of the epoxy, a layer of epoxy was brushed around the fold to cover the resulting grooves. The fold section, ready for insertion in the pipe is also shown in Figure 19C.

Figure 19. Pipe “fold” preparation sequence

Inspection following each test series showed the fold sections to be attached to the inside wall with no loose sections.

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Section 5 Fold #1 Test Results

Introduction

Three model tests were conducted in a 6-inch (0.502 ft) diameter pipe as shown in Figures 17 and 18. The test setup is discussed in the first portion of this section, titled “Pipe Liner Folds.” The fold depth, k, was 0.015 ft, resulting in a fold opening diameter, d, of 0.47 ft and a d/D ratio of 0.94.

The resulting model data are given in Table 5A. The definition of the data in Table 5A are the same as those described for Table 1A, “Data Measured and Computed.”

Table 5A Model Data, Fold #1

<table>
<thead>
<tr>
<th>TABLE 5A Model Data Fold #1</th>
<th>Dia= 0.502 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA</td>
<td>COMP</td>
</tr>
<tr>
<td>Tst</td>
<td>T°F</td>
</tr>
<tr>
<td>700</td>
<td>72</td>
</tr>
<tr>
<td>701</td>
<td>72</td>
</tr>
<tr>
<td>702</td>
<td>72</td>
</tr>
<tr>
<td>703</td>
<td>72</td>
</tr>
<tr>
<td>704</td>
<td>72</td>
</tr>
<tr>
<td>705</td>
<td>72</td>
</tr>
<tr>
<td>706</td>
<td>72</td>
</tr>
</tbody>
</table>

As in previous sections, the model data from Table 5A are listed in Table 5B, “Scaled Data, Fold #1.” In Table 5B the fold diameter, d_{fold} and pipe diameter, d_{pipe}, (also designated D elsewhere) are listed in the heading for reference. In this case, the value of d_{fold} is 0.471 feet.

Table 5B, Model Fold #1, Scaled Data

The pertinent model data were entered into the scaling table (Table 5B). The discussion of the table, model entries and prototype scaling computations are the same as those
discussed in the section headed Table 1B, 4x4x4 Tee Scaled Data. The shaded area of Table 5B contains the scaled data.

**Table 5B Scaled Data, Fold #1**

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Q&lt;sub&gt;model&lt;/sub&gt;</td>
<td>1.40</td>
<td>1.39</td>
<td>1.38</td>
<td>1.21</td>
<td>1.14</td>
<td>1.10</td>
<td>0.80</td>
<td>kin viscosity</td>
<td>1.03E-05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>d&lt;sub&gt;model&lt;/sub&gt;</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>Temp</td>
<td>72</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>V&lt;sub&gt;model&lt;/sub&gt;</td>
<td>7.06</td>
<td>7.01</td>
<td>6.99</td>
<td>6.12</td>
<td>5.76</td>
<td>5.56</td>
<td>4.03</td>
<td>abs viscosity</td>
<td>2.01E-05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>dia</td>
<td>h&lt;sub&gt;model&lt;/sub&gt;</td>
<td>0.16</td>
<td>0.17</td>
<td>0.15</td>
<td>0.15</td>
<td>0.14</td>
<td>0.10</td>
<td>0.08</td>
<td>den</td>
<td>1.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>8&quot;</td>
<td>V&lt;sub&gt;p&lt;/sub&gt;</td>
<td>5.72</td>
<td>5.68</td>
<td>5.66</td>
<td>5.84</td>
<td>5.49</td>
<td>5.30</td>
<td>3.04</td>
<td>kin viscosity</td>
<td>1.31E-05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>12&quot;</td>
<td>V&lt;sub&gt;p&lt;/sub&gt;</td>
<td>6.43</td>
<td>6.46</td>
<td>6.44</td>
<td>5.99</td>
<td>5.86</td>
<td>3.83</td>
<td>2.96</td>
<td>abs viscosity</td>
<td>1.31E-05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.0&quot;</td>
<td>V&lt;sub&gt;p&lt;/sub&gt;</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>den</td>
<td>1.94</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Computational Example**

A typical set of hand calculations are carried out for comparison with the data in Table 5B. The computations will be made using English units, the answer will then be converted to SI units. From Table 5B:

**Given:** T<sub>m</sub> (cell M2) = 72°F, T<sub>p</sub> (cell M6) = 55°F.

Model data (column C): Q<sub>m</sub> = 1.40 cfs, d<sub>m</sub> = 0.502 ft, V<sub>m</sub> = 7.05 fps, h<sub>m</sub> = 0.16 ft

Scale to prototype diameter 0.667 ft., 8-inches, (cells A5 and A6).

Prototype velocity, Equation 11:

\[ V_p = V_m(D_m v_p)/(v_m D_p) = 7.05*(0.502*1.31\times10^{-5})/(0.667*1.03\times10^{-5}) = 6.74 \text{ ft/sec} \]

\[ = 2.05 \text{ m/sec}. \]

Prototype head loss, Equation 12a:

\[ h_p = (h_m D_m^2 v_p^2)/(D_p^3 v_m^2) = (0.16*(0.502^2*[1.31\times10^{-5}]^2)/(0.667^3*[1.03\times10^{-5}]^2) = 0.11 \text{ ft}. \]

\[ = 0.03 \text{ m}. \]

The two answers, in English units, may be compared to Table 5B cells C5 and C6.
Data Plot

The velocity and head loss data for fold #1 were taken from Table 5B and plotted as Figure 20, “Head Loss vs. Pipe Velocity-Fold #1.” The fold indentation k, and the pipe diameter, D, could not be scaled simultaneously. Therefore, the curves represent head loss, h, with expanding pipe diameter, D, in which the indentation k, is held constant. Under these conditions, as would be expected, for a common velocity, the head loss, h, increases with decreasing pipe diameter as k/D increases with decreasing pipe diameter, D.
Figure 20. Head loss vs. pipe velocity, fold #1
Section 6 Fold #2 Test Results

Introduction

The model test was conducted in a 6-inch (0.502 ft) diameter pipe as shown in Figures 17 and 18. The test setup is discussed in the first portion of this section, titled “Pipe Liner Folds.” The fold depth, k, was 0.037 ft, resulting in a fold opening diameter d, of 0.43 ft. and a d/D ratio of 0.85.

The resulting model data are given in Table 6A. The description of the data in this table are the same as those described for Table 1A, Data “Measured and Computed.”

Table 6A Model Data, Fold #2

<table>
<thead>
<tr>
<th>DATA</th>
<th>COMPUTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tst</td>
<td>T°F h-psi</td>
</tr>
<tr>
<td>720</td>
<td>70 0.14</td>
</tr>
<tr>
<td>721</td>
<td>70 0.13</td>
</tr>
<tr>
<td>722</td>
<td>70 0.11</td>
</tr>
<tr>
<td>723</td>
<td>70 0.09</td>
</tr>
<tr>
<td>724</td>
<td>70 0.08</td>
</tr>
<tr>
<td>725</td>
<td>70 0.06</td>
</tr>
<tr>
<td>726</td>
<td>70 0.04</td>
</tr>
<tr>
<td>727</td>
<td>70 0.035</td>
</tr>
</tbody>
</table>

As in previous sections, the model data from Table 6A are listed in Table 6B, “Model Fold #2.” In Table 6B, the fold diameter, d_fld and pipe diameter, d_pipe (also designated D elsewhere) are listed in the heading for reference. In this case the value of d_fld is 0.429 feet.

Table 6B, Model Fold #2, Scaled Data

The pertinent model data were entered into the scaling table, (Table 6B). The discussion of the table, model entries and prototype scaling computations are the same as those.
discussed in the section headed, Table 1B, 4x4x4 tee scaled data. The shaded area of Table 6B contains the scaled data.

### Table 6B Scaled Data, Fold #2

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$Q_{\text{model}}$</td>
<td>1.38</td>
<td>1.24</td>
<td>1.21</td>
<td>1.14</td>
<td>1.02</td>
<td>0.78</td>
<td>0.57</td>
<td>kin vism</td>
<td>1.06E-05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$d_{\text{model}}$</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>Tempm</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$V_{\text{model}}$</td>
<td>6.98</td>
<td>6.26</td>
<td>6.12</td>
<td>5.78</td>
<td>5.17</td>
<td>3.92</td>
<td>2.86</td>
<td>abs vism</td>
<td>2.07E-05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>dia</td>
<td>0.32</td>
<td>0.30</td>
<td>0.25</td>
<td>0.21</td>
<td>0.18</td>
<td>0.14</td>
<td>0.09</td>
<td>denm</td>
<td>1.94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>8&quot;</td>
<td>$V_{\text{model}}$</td>
<td>6.48</td>
<td>5.81</td>
<td>5.68</td>
<td>5.37</td>
<td>4.79</td>
<td>3.94</td>
<td>2.66</td>
<td>kin vism</td>
<td>1.31E-05</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.667&quot;</td>
<td>$h_{\text{model}}$</td>
<td>0.21</td>
<td>0.18</td>
<td>0.16</td>
<td>0.13</td>
<td>0.12</td>
<td>0.09</td>
<td>0.06</td>
<td>Tempm</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>12&quot;</td>
<td>$V_{\text{model}}$</td>
<td>4.32</td>
<td>3.87</td>
<td>3.79</td>
<td>3.58</td>
<td>3.20</td>
<td>2.43</td>
<td>1.77</td>
<td>abs vism</td>
<td>1.31E-05</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.0&quot;</td>
<td>$h_{\text{model}}$</td>
<td>0.05</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.02</td>
<td>denm</td>
<td>1.94</td>
<td></td>
</tr>
</tbody>
</table>

**Computational Example**

A typical set of hand calculations are carried out for comparison with the data in Table 6B. The computations will be made using English units, the answer will then be converted to SI units.

**Given:** $T_m$ (cell M2) = 70°F, $T_p$ (cell M6) = 55°F.

Model data (column F): $Q_m = 1.24$ cfs, $d_m = 0.502$ ft, $V_m = 6.26$ fps, $h_m = 0.30$ ft.

Scale to prototype diameter 1.00 ft, 12-inches, (cells A7 and A8).

**Prototype velocity, Equation 11:**

$$V_p = \frac{V_m(D_m v_p)}{(v_mD_p)} = 6.26*(0.502*1.31*10^{-5})/(1.00*1.06*10^{-5}) = 3.88 \text{ fps} = 1.18 \text{ mps}$$

**Prototype head loss, Equation 12A:**

$$h_p = (h_mD_m^3v_p^2)/(D_p^3v_m^2) = 0.30*(0.502)^3*(1.31*10^{-5})^2/(1.00)^3*(1.06*10^{-5})^2 = 0.06 \text{ ft} = 0.02 \text{ m}$$

The two answers, in English units, may be compared to Table 6B cells F7 and F8.
Data Plot

The velocity and head loss data for fold #2 were taken from Table 6B and plotted as Figure 21, "Head Loss vs. Pipe Velocity-Fold #2." The fold indentation, k, and the pipe diameter, D, could not be scaled simultaneously. Therefore, the curves represent head loss, h, with expanding pipe diameter, D, in which the indentation, k, is held constant. Under these conditions, it would be expected, for a common velocity, the head loss, h, would increase with decreasing pipe diameter as k/D increases with decreasing pipe diameter, D.
Figure 21. Head loss vs. pipe velocity, fold #2
Section 7 Fold #3 Test Results

Introduction

Three model tests were conducted in a 6-inch (0.502 ft) diameter pipe as shown in Figures 17 and 18. The test setup is discussed in the first portion of this section, titled *Pipe Liner Folds*. The fold depth was 0.055 ft, resulting in a fold opening diameter, $d$, of 0.39 ft and a $d/D$ ratio of 0.78.

The resulting model data are given in Table 7A. The definition of the data in Table 7A is the same as that described for Table 1A, *Data Measured and Computed*.

As in previous sections, the model data from Table 7A are listed in Table 7B, *Model Data, Fold #1*. In Table 7B the fold diameter, $d_{fold}$ and pipe diameter, $d_{pipe}$, (also designated D elsewhere) are listed in the heading for reference. In this case the value $d_{fold}$ is 0.393 feet.

Table 7A Model Data, Fold #3

<table>
<thead>
<tr>
<th>Tst#</th>
<th>T°F</th>
<th>h-psi</th>
<th>wt#</th>
<th>t-sec</th>
<th>h-ft</th>
<th>Q-cfs</th>
<th>V-fps</th>
<th>$V^2/2g$</th>
<th>$K$</th>
<th>$Re$</th>
</tr>
</thead>
<tbody>
<tr>
<td>740</td>
<td>71</td>
<td>0.14</td>
<td>4050</td>
<td>46.75</td>
<td>0.31</td>
<td>1.391</td>
<td>7.03</td>
<td>0.77</td>
<td>0.41</td>
<td>337,060</td>
</tr>
<tr>
<td>741</td>
<td>71</td>
<td>0.14</td>
<td>4039</td>
<td>46.8</td>
<td>0.32</td>
<td>1.385</td>
<td>7</td>
<td>0.76</td>
<td>0.42</td>
<td>335,786</td>
</tr>
<tr>
<td>742</td>
<td>71</td>
<td>0.13</td>
<td>4039</td>
<td>53.65</td>
<td>0.3</td>
<td>1.208</td>
<td>6.11</td>
<td>0.58</td>
<td>0.52</td>
<td>292,913</td>
</tr>
<tr>
<td>743</td>
<td>71</td>
<td>0.12</td>
<td>4041</td>
<td>56.77</td>
<td>0.28</td>
<td>1.143</td>
<td>5.77</td>
<td>0.62</td>
<td>0.53</td>
<td>276,952</td>
</tr>
<tr>
<td>744</td>
<td>71</td>
<td>0.1</td>
<td>4040</td>
<td>63.25</td>
<td>0.22</td>
<td>1.025</td>
<td>5.18</td>
<td>0.42</td>
<td>0.53</td>
<td>248,516</td>
</tr>
<tr>
<td>745</td>
<td>71</td>
<td>0.07</td>
<td>4040</td>
<td>82.08</td>
<td>0.16</td>
<td>0.79</td>
<td>3.99</td>
<td>0.25</td>
<td>0.65</td>
<td>191,504</td>
</tr>
<tr>
<td>746</td>
<td>71</td>
<td>0.05</td>
<td>4033</td>
<td>112.5</td>
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<td>0.576</td>
<td>2.91</td>
<td>0.13</td>
<td>0.88</td>
<td>139,541</td>
</tr>
</tbody>
</table>

Table 7B Model Fold #3, Scaled Data

The pertinent model data were entered into the scaling table (Table 7B). The discussion of the table, model entries and prototype scaling computations are the same as those discussed in the section headed, Table 1B, "4x4x4 tee scaled data."
The shaded area of Table 7B represents the scaled data.

### Table 7B Scaled Data, Fold #3

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Q&lt;sub&gt;model&lt;/sub&gt;</td>
<td>1.39</td>
<td>1.38</td>
<td>1.21</td>
<td>1.14</td>
<td>1.03</td>
<td>0.79</td>
<td>0.58</td>
<td>kin vis&lt;sub&gt;m&lt;/sub&gt;</td>
<td>1.05E-05</td>
</tr>
<tr>
<td>2</td>
<td>d&lt;sub&gt;model&lt;/sub&gt;</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>Temp&lt;sub&gt;m&lt;/sub&gt;</td>
<td>71</td>
</tr>
<tr>
<td>3</td>
<td>V&lt;sub&gt;model&lt;/sub&gt;</td>
<td>7.03</td>
<td>7.00</td>
<td>6.11</td>
<td>5.77</td>
<td>5.18</td>
<td>3.99</td>
<td>2.91</td>
<td>abs vis&lt;sub&gt;m&lt;/sub&gt;</td>
<td>2.04E-05</td>
</tr>
<tr>
<td>4</td>
<td>dia</td>
<td>8&quot;</td>
<td>0.31</td>
<td>0.32</td>
<td>0.30</td>
<td>0.28</td>
<td>0.22</td>
<td>0.16</td>
<td>0.12</td>
<td>den&lt;sub&gt;m&lt;/sub&gt;</td>
</tr>
<tr>
<td>5</td>
<td>8&quot;</td>
<td>V&lt;sub&gt;p&lt;/sub&gt;</td>
<td>6.82</td>
<td>6.50</td>
<td>5.87</td>
<td>5.36</td>
<td>4.81</td>
<td>3.71</td>
<td>2.70</td>
<td>kin vis&lt;sub&gt;p&lt;/sub&gt;</td>
</tr>
<tr>
<td>6</td>
<td>0.667'</td>
<td>h&lt;sub&gt;p&lt;/sub&gt;</td>
<td>0.20</td>
<td>0.21</td>
<td>0.19</td>
<td>0.18</td>
<td>0.14</td>
<td>0.10</td>
<td>0.07</td>
<td>Temp&lt;sub&gt;p&lt;/sub&gt;</td>
</tr>
<tr>
<td>7</td>
<td>12&quot;</td>
<td>V&lt;sub&gt;p&lt;/sub&gt;</td>
<td>4.35</td>
<td>4.33</td>
<td>3.78</td>
<td>3.57</td>
<td>3.21</td>
<td>2.47</td>
<td>1.80</td>
<td>abs vis&lt;sub&gt;p&lt;/sub&gt;</td>
</tr>
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<td>8</td>
<td>1.0&quot;</td>
<td>h&lt;sub&gt;p&lt;/sub&gt;</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>den&lt;sub&gt;p&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

### Computational Example

A typical set of hand calculations are carried out for comparison with the data in Table 7B. The computations will be made using English units, the answer will then be converted to SI units. From Table 7B:

Given: T<sub>m</sub> (cell M2) = 71°F, T<sub>p</sub> (cell M6) = 55°F.

Model data (column C): Q<sub>m</sub> = 1.39 cfs, d<sub>m</sub> = 0.502 ft, V<sub>m</sub> = 7.03 fps, h<sub>m</sub> = 0.31 ft

Scale to prototype diameter 0.667 ft., 8-inches, (cells A5 and A6).

Prototype velocity, Equation 11:

\[
V_p = \frac{V_m (D_m v_p)}{(v_m D_p)} = \frac{7.03 \times (0.502^3 \times 1.31 \times 10^{-5})}{(0.667^3 \times 1.05 \times 10^{-5})} = 2.02 \text{ m/sec.}
\]

Prototype head loss equation 12a:

\[
h_p = \frac{(h_m D_m^3 v_p^2)}{(D_p^3 v_m^2)} = \frac{(0.31 \times (0.502^3 \times [1.31 \times 10^{-5}]^2)}{(0.667^3 \times [1.05 \times 10^{-5}]^2)} = 0.06 \text{ ft.}
\]

The two answers, in English units, may be compared to Table 7B cells C5 and C6.
The velocity and head loss data for fold #3 were taken from Table 7B and plotted as Figure 22, “Head Loss vs. Pipe Velocity-Fold #3.” The fold protrusion k, and the pipe diameter, D, could not be scaled simultaneously. For this reason, the curves represent head loss, h, with expanding pipe diameter, D, in which the protrusion, k, is held constant. Under these conditions, as would be expected, for a common velocity, the head loss, h, increases with decreasing pipe diameter as k/D increases with decreasing pipe diameter, D.
Conclusions

As stated previously, the fold protrusion is held constant while the pipe diameter is scaled upward. For a given constant protrusion into the flow (in the form of a uniform ring), the
the head loss, \( h \), decreases with increasing pipe diameter. This feature is shown in Figures 20, 21, and 22.

Figure 23 is a presentation of the folds (#1, #2 and #3) in the \( D = 6 \)-inches model pipe. As would be expected, the losses increase, for a given velocity with increasing protrusion of the “fold”.

![Head Loss vs. Pipe Velocity - Comparison](image)

**Figure 23. Comparison of head loss by fold diameter**

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CHAPTER 6

FUSION JOINT PROTRUSIONS INTO PIPE

General

Horizontal directional drilling (HDD) is a procedure often used for the installation of utilities when surface disruption is not a feasible option. The procedure typically involves the use of butt fusion of sections of either PVC or HDPE pipe. HDPE pipe has been the more popular of the two because the fusion procedure has been more widely available for HDPE pipe and it is a more flexible, lighter material. In addition, it will absorb water hammer, does not give off toxic fumes when heated, and has a 25-year, above-ground usage.

For many diameters, HDPE pipe is joined by butt fusion, which produces a joint as strong as the pipe, eliminating the leakage or breakage that might occur with PVC glued joints. Another advantage gained by using HDPE is the short curing time. Complete curing and full joint strength is attained in 20 minutes or less [1].

A brief summary of the procedure used in “butt fusion” is as follows:

1. Clean each pipe end with a clean cotton cloth.
2. Square (face) the ends of each pipe to be fused.
3. Check line-up of pipe ends. Check heater plate for proper temperature, i.e.:
   400° – 425°F........coated plates,
   375° -400°F........uncoated plates.

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4. Insert heater plate between aligned ends and bring ends firmly in contact with the heater plate, without applying pressure while achieving melt pattern. Watch for proper melt.

5. Remove heater plate after achieving proper melt bead.

6. Bring melted ends together rapidly. Do not slam. Apply enough pressure to form a “double roll-back bead” (see Figure 24).

7. Allow the butt fusion joint to cool properly (until finger can remain comfortably on bead).

The above procedure was provided by a local, north Louisiana contractor. The double roll-back bead can be seen in Figure 24.

Figure 24 Double roll-back bead, 6-inch pipe

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Liner Differences in the 4-inch and 6-inch Pipes

The inside lining in the two pipes tested differed considerably. The 4-inch pipe was cast with no inside liner. The 6-inch pipe had an inside attached, smooth liner of about 1/32 inch (< 1 mm) thickness. Because of this liner difference, it was not possible to scale the 4-inch section up to the 6-inch section or visa versa for a check on the difference in head loss, h, created by the two different protrusions. The difference in wall roughness apparently over-shadowed the protrusion difference.
Section 8 Fusion Test #1 Results

Introduction
Two model tests were conducted in nominal 4-inch and 6-inch HDPE pipes. A typical 6-inch pipe section is shown in Figure 25. The procedure for fusing these pipes together is discussed in the preceding section. The protrusion depth, k, shown in Figure 25, was approximately 3 mm (~0.1 inch).

Hydraulic Considerations
The formed melt bead creates a small obstruction to flow on the inside wall of the pipe. Many of the fused pipe systems are made of 20- or 30-feet lengths and can be thousands of feet long. Therefore, it can be assumed that a summation of the losses created by the melt bead might be significant. The purpose of this portion of the research program was to attempt to define the hydraulic head loss, h, created by these melt beads.

Research Considerations
When one “scales” from one pipe diameter to a usually larger one, all other cross-section dimensions are held constant. Thus one must assume the melt bead diameter remains constant while the pipe diameter is increased (or decreased). From the research conducted on a limited number of pipes, the protrusion increased with increasing diameter. Nevertheless, some scaling is carried out to give a general idea of the melt bead effect on changing pipe diameters. Additional difficulty in predicting a fixed protrusion, k, is the likely difference in personnel application of fusion pressure and pressure application time, and the degree of heat applied. Figure 25 presents the cross-section of a pipe section containing a fusion joint. For the tested “4-inch” pipe, the
protrusion of the bead melt, $k$, was about 3mm. For the “6-inch” pipe the protrusion was about 4mm.

$k_{4\text{-inch}} \approx 3\text{mm}, \ k_{6\text{-pipe}} \approx 4\text{mm}$

**Figure 25.** Fusion sealed joint.

**Model Data, Table 8A**

The resulting model data for the nominal 4-inch pipe are given in Table 8A, “Fusion #1-(4-inch).” The definition of the data in this table are the same as those described for Table 1A, “Data Measured and Computed.”

**Table 8A Model Fusion #1**

<table>
<thead>
<tr>
<th>Tst</th>
<th>T</th>
<th>h-psi</th>
<th>Wt#</th>
<th>t-sec</th>
<th>h-ft</th>
<th>Q-cfs</th>
<th>V-fps</th>
<th>V(^2/2g)</th>
<th>K</th>
<th>R,</th>
</tr>
</thead>
<tbody>
<tr>
<td>930</td>
<td>72</td>
<td>0.010</td>
<td>4040</td>
<td>46.87</td>
<td>0.023</td>
<td>1.41</td>
<td>15.32</td>
<td>3.65</td>
<td>0.006</td>
<td>508,943</td>
</tr>
<tr>
<td>931</td>
<td>72</td>
<td>0.008</td>
<td>4040</td>
<td>48.55</td>
<td>0.0185</td>
<td>1.39</td>
<td>16.10</td>
<td>3.54</td>
<td>0.005</td>
<td>501,508</td>
</tr>
<tr>
<td>932</td>
<td>72</td>
<td>0.015</td>
<td>4040</td>
<td>54.64</td>
<td>0.0346</td>
<td>1.19</td>
<td>12.86</td>
<td>2.57</td>
<td>0.013</td>
<td>427,255</td>
</tr>
<tr>
<td>933</td>
<td>72</td>
<td>0.015</td>
<td>4040</td>
<td>54.58</td>
<td>0.0346</td>
<td>1.19</td>
<td>12.88</td>
<td>2.57</td>
<td>0.013</td>
<td>427,724</td>
</tr>
<tr>
<td>934</td>
<td>72</td>
<td>0.018</td>
<td>4040</td>
<td>59.06</td>
<td>0.0415</td>
<td>1.10</td>
<td>11.90</td>
<td>2.20</td>
<td>0.019</td>
<td>395,279</td>
</tr>
<tr>
<td>935</td>
<td>72</td>
<td>0.017</td>
<td>4040</td>
<td>66.64</td>
<td>0.0392</td>
<td>0.97</td>
<td>10.55</td>
<td>1.73</td>
<td>0.023</td>
<td>350,318</td>
</tr>
<tr>
<td>936</td>
<td>72</td>
<td>0.017</td>
<td>4030</td>
<td>80.55</td>
<td>0.0392</td>
<td>0.80</td>
<td>8.70</td>
<td>1.18</td>
<td>0.033</td>
<td>288,105</td>
</tr>
<tr>
<td>937</td>
<td>72</td>
<td>0.018</td>
<td>4038</td>
<td>110.59</td>
<td>0.0415</td>
<td>0.59</td>
<td>6.35</td>
<td>0.63</td>
<td>0.066</td>
<td>210,992</td>
</tr>
<tr>
<td>938</td>
<td>72</td>
<td>0.031</td>
<td>4040</td>
<td>205.68</td>
<td>0.0715</td>
<td>0.32</td>
<td>3.42</td>
<td>0.18</td>
<td>0.395</td>
<td>113,503</td>
</tr>
</tbody>
</table>

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Table 8B. Model Fusion #1, Scaled Data

As in previous sections, the model data from Table 8A are listed in Table 8B, “Scaled Data, Fusion #1.” In this table, the diameter (dia) is the inside diameter of the pipe itself and “k” is the depth of the fusion bead into the pipe. The outer portion of this fusion is shown in Figure 24.

As stated previously, data can be scaled in one parameter only. In this case that parameter is the diameter, D, of the pipe. The k value must be held constant. A fixed k value for different diameters is not usually the case, as k apparently grows with increasing D. However, for a rough comparison, the scaling was carried out.

With this in mind, the model data, as before, were entered into the scaling table (Table 8B). The discussion of the table, model entries and prototype scaling computations are the same as those discussed in the section headed, Table 1B, “4x4x4 tee scaled data.”

The shaded area of Table 8B contains the scaled data.

<table>
<thead>
<tr>
<th>Table 8B-Fusion #1-(4-in)</th>
<th>Dia=</th>
<th>0.343</th>
<th>ft.</th>
<th>k=</th>
<th>0.108</th>
<th>in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
<td>F</td>
<td>G</td>
<td>H</td>
<td>I</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1</td>
<td>Q_{model}</td>
<td>1.41</td>
<td>1.39</td>
<td>1.18</td>
<td>1.10</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>d_{model}</td>
<td>0.343</td>
<td>0.343</td>
<td>0.343</td>
<td>0.343</td>
<td>0.343</td>
</tr>
<tr>
<td>3</td>
<td>V_{model}</td>
<td>15.32</td>
<td>15.10</td>
<td>12.86</td>
<td>11.90</td>
<td>10.55</td>
</tr>
<tr>
<td>4</td>
<td>dia</td>
<td>h_{model}</td>
<td>0.023</td>
<td>0.019</td>
<td>0.035</td>
<td>0.042</td>
</tr>
<tr>
<td>5</td>
<td>8&quot;</td>
<td>V_{abs}</td>
<td>9.98</td>
<td>9.93</td>
<td>9.38</td>
<td>7.75</td>
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<tr>
<td>6</td>
<td>6.57&quot;</td>
<td>h_{abs}</td>
<td>0.005</td>
<td>0.004</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>7</td>
<td>12&quot;</td>
<td>V_{abs}</td>
<td>6.69</td>
<td>6.56</td>
<td>5.69</td>
<td>5.17</td>
</tr>
<tr>
<td>8</td>
<td>1.0&quot;</td>
<td>h_{abs}</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.003</td>
</tr>
</tbody>
</table>

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Table 8B Observations

As previously done, the scaled prototype velocities \( V_{\text{proto}} \) are presented in Table 8B above, in lines 5 and 7. These values were obtained by scaling from the model velocities \( V_{\text{model}} \) (line 3) using equation 11.

Next, the corresponding prototype head losses, \( h_{\text{proto}} \), were obtained by scaling the model head losses \( h_{\text{model}} \) (line 4) and listing them in lines 6 and 8. Here, equation 12a was used.

The head loss data are presented to the third decimal place to indicate there might be a slight head loss at these velocities (and pipe diameters), which were caused by the indentions. However, considering the lack of accuracy to this degree, it is proper to state that the values should only be used as a guide to potential head loss.
Section 9 Fusion Test #2 Results

Introduction
The second fusion test series was conducted in a nominal 6-inch HDPE pipe. Figure 24 shows the 6-inch fusion section in its test condition. The fusion procedure is discussed in the introductory portion of this section. The protrusion depth, k, shown in Figure 25 was approximately 4 mm (≈ 0.15 inch).

Hydraulic Considerations
The formed melt bead creates a small obstruction to flow on the inside wall of the pipe. Many of the fused pipe systems are made of 20- or 30-feet lengths and can be thousands of feet long. Therefore, it can be assumed that a summation of the losses created by the melt bead might be significant. The purpose of this portion of the research program was to attempt to define the hydraulic head loss, h, created by these melt beads.

Research Considerations
When one “scales” from one pipe diameter to a usually larger one, all other cross-section dimensions are held constant. Thus, one must assume the melt bead diameter remains constant while the pipe diameter is increased (or decreased). From the research conducted on a limited number of pipes, the protrusion increased with increasing diameter. Nevertheless, some scaling is carried out to give a general idea of the melt bead effect on changing pipe diameters. Additional difficulty in predicting a fixed protrusion, k, is the likely difference in personnel application of fusion pressure, pressure application time, and the degree of heat applied.
Figure 25 presents the cross-section of a pipe section containing a fusion joint. For the tested “4-inch” pipe, the protrusion of the bead melt was about 3mm. For the “6-inch” pipe the protrusion was about 4mm.

**Model Data, Table 9A**

The resulting model data for the nominal 6-inch pipe are given in Table 9A, *Model Fusion #2-(6-inch).* The definition of the data in this table are the same as those described for Table 1A, *Data Measured and Computed.*

**Table 9A Model Fusion #2**

<table>
<thead>
<tr>
<th>DATA</th>
<th>COMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>Temp</td>
</tr>
<tr>
<td>900</td>
<td>71</td>
</tr>
<tr>
<td>901</td>
<td>71</td>
</tr>
<tr>
<td>902</td>
<td>71</td>
</tr>
<tr>
<td>903</td>
<td>71</td>
</tr>
<tr>
<td>904</td>
<td>71</td>
</tr>
</tbody>
</table>

**Table 9B, Fusion #2, Scaled Data**

As in previous sections, the model data from Table 9A are listed in Table 9B, *Scaled Data, Fusion #2 (6-in).* In this table the diameter (dia.) is the inside diameter of the pipe itself and “k” is the depth of the fusion bead into the pipe. The outer portion of this fusion is shown in Figure 24.

As stated previously, data can be scaled in one parameter only. In this case that parameter is the diameter, D, of the pipe. The k value must be held constant. This restriction is not usually the case, as k apparently grows with increasing D. However, for a rough comparison, the scaling was carried out.
With this deviation in mind, the model data, as before, were entered into the scaling table (Table 9B). The discussion of the table, model entries and prototype scaling computations are the same as those discussed in the section headed, Table 1B, “4x4x4 tee scaled data.” The shaded area of Table 9B contains the scaled data.

**Table 9B Scaled Data, Fusion #2**

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>M</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Q_{model}</td>
<td>1.41</td>
<td>1.40</td>
<td>1.21</td>
<td>1.14</td>
<td>1.03</td>
<td>\text{kin vis}_{in}</td>
<td>1.047E-05</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>d_{model}</td>
<td>0.497</td>
<td>0.497</td>
<td>0.497</td>
<td>0.497</td>
<td>0.497</td>
<td>\text{Temp}_{m}</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>V_{model}</td>
<td>7.24</td>
<td>7.20</td>
<td>6.21</td>
<td>5.87</td>
<td>5.27</td>
<td>\text{abs vis}_{m}</td>
<td>2.04E-05</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>dia</td>
<td>0.012</td>
<td>0.010</td>
<td>0.012</td>
<td>0.010</td>
<td>0.007</td>
<td>\text{den}_{m}</td>
<td>1.94</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>8&quot;</td>
<td>V_{model}</td>
<td>6.75</td>
<td>6.72</td>
<td>5.79</td>
<td>5.43</td>
<td>4.01</td>
<td>\text{kin vis}_{p}</td>
<td>1.308E-05</td>
</tr>
<tr>
<td>6</td>
<td>6.7&quot;</td>
<td>h_{model}</td>
<td>0.007</td>
<td>0.006</td>
<td>0.007</td>
<td>0.006</td>
<td>0.005</td>
<td>\text{Temp}_{p}</td>
<td>55</td>
</tr>
<tr>
<td>7</td>
<td>12&quot;</td>
<td>V_{model}</td>
<td>4.50</td>
<td>4.48</td>
<td>3.66</td>
<td>3.55</td>
<td>3.27</td>
<td>\text{abs vis}_{p}</td>
<td>1.31E-05</td>
</tr>
<tr>
<td>8</td>
<td>1.0&quot;</td>
<td>h_{model}</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.001</td>
<td>\text{den}_{p}</td>
<td>1.94</td>
</tr>
</tbody>
</table>

**Table 9B Observations**

As previously done, the scaled prototype velocities ($V_{\text{proto}}$) are presented in Table 9B above, in lines 5 and 7. These values were obtained by scaling from the model velocities ($V_{\text{model}}$, line 3) using equation 11.

Next, the corresponding prototype head losses, ($h_{\text{proto}}$), were obtained by scaling the model head losses ($h_{\text{model}}$, line 4) and listing them in lines 6 and 8. Here, equation 12a was used.

The head loss data are presented to the third decimal place to indicate there might be a slight head loss at these velocities (and pipe diameters), which were caused by the indentions. However, considering the lack of accuracy to this degree, it is proper to state that the values should only be used as a guide to potential head loss.
CHAPTER 7

SUMMARY AND CONCLUSIONS

Introduction

The traditional approach of pipeline rehabilitation by digging up the pipe and replacing with a new pipe has been used for as long as underground sewers have been in existence. Rehabilitation of sanitary sewers using “trenchless” methods has grown in popularity in recent years [13]. “It is essential that a thorough evaluation of the sewer system include the assessment of……and the hydraulic conditions be conducted prior to the design and selection of a rehabilitation process” [11]. The Trenchless Technology (TT) processes are now becoming more generally accepted as viable forms of rehabilitation and owners and engineers are becoming more familiar and confident with the methods. However, there are still certain issues that need further study. One of the areas of concern includes the appropriateness of current design methodologies and the availability of the necessary design data to cover all the appropriate application conditions.

Because changes to the pipe flow characteristics are inherent in rehabilitation, an evaluation of the impact on the overall system should be performed. Of the many factors affecting the hydraulic flow in a pipe, pipeline rehabilitation systems usually change the flow cross-sectional area, internal pipe roughness, and the pipe shape. The change in pipe size typically reduces the flow cross-sectional area and hydraulic radius components of pipe flow calculations. The flow cross-sectional area reduction can be substantial where circular pipe
sections are rehabilitated using a slip-liner system, due to the annulus formed between the host pipe and the liner [12].

Tight-fit linings such as cured-in-place pipe (CIPP), fold-and-formed pipe (FFP) and deform-reform pipe (DRP) result in a smaller loss of cross-sectional area that is offset by a smoother pipe wall.

**General**

The study looked at three distinct areas of sewer pipe flow considerations. All three parts of the study were concerned with head loss through a pipe fitting or obstruction.

The first was the head loss created by flow through smooth, “injection molded” wye and tee fittings. The second study looked at losses caused by liner folds and the third looked at losses in fusion joints created by fusing pipe ends together. The coverage of each of the fittings are presented as follows:

- Wyes and tees Chapter 4
- Liner folds Chapter 5
- Fusion joints Chapter 6

The diameter of the fittings of Chapter 4 were restricted to a maximum diameter of 12-inches (305 mm) for reasons discussed elsewhere. The objective here was to derive head losses across these fittings and compute the resultant head loss coefficients, K.

The second study involved measurements of head losses created by liner folds inside the host pipe. These folds are normally created by failure to stretch the liner properly and also due to problems encountered at bends in the host pipe. Again, the maximum diameter was restricted to 12-inches. Larger diameters required higher velocities than available in the test system. However, higher velocities in sewer systems are not realistic and, therefore, were not considered.
The third study looked at a special obstruction created in the pipe interior in the “fusion process” (also discussed elsewhere). These small protrusions into the flow were studied to be able to predict an overall head loss due to small, cumulative head losses in a long, “fused” pipe system.

**Importance of Study**

While many of the typical head losses to be found in piping systems were established decades ago, it proved difficult to find the data necessary to estimate the head losses for the fittings, defects and fused joint conditions considered in this research. Documenting the head losses for these three conditions through a careful experimental study provides the necessary data to be able to determine more closely the impact of relining a pipe when fittings, folds or joint fusion beads are present. Also, the planned creation of a new test facility will allow further study of other defect conditions to be undertaken.

**Summary of Modeling Approach**

Model tests were first conducted on piping and fixtures which represented the smallest units of interest. For instance, for measuring the losses through the wye or tee fitting, the smallest host pipe of interest is the 4-inch (102 mm) diameter pipe. The range of discharge through the model pipe, whether it be a 4- or 6-inch (152 mm) pipe was about 0.30 to 1.40 cfs (0.008 to 0.04 mps). This discharge range corresponded to the following velocities:

<table>
<thead>
<tr>
<th>Q-cfs</th>
<th>V_{4-in-fps}</th>
<th>V_{6-in-fps}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30</td>
<td>3.40</td>
<td>1.50</td>
</tr>
<tr>
<td>1.40</td>
<td>16.20</td>
<td>7.10</td>
</tr>
</tbody>
</table>

These values restricted the diameter to which the data could be scaled. In addition to the reasoning given above, it is noted that for the “injection molded fittings,” the largest diameter known to be presently fabricated is 12 inches.
The “liner folds”, as well as the “fusion protrusions” occur in diameters of PVC pipe greater than one foot. However, as stated before, higher velocities necessary to keep the larger pipes flowing full are not justifiable in sewer flow. One of the objectives of the study was to provide useful data based upon flow conditions which, as closely as possible, matched actual field conditions.

**Observations**

A number of parameters have been investigated in this study. Primarily, they consist of:

(a) **Head Losses Generated by Fittings.**

The loss in this case is created by the lateral section joining the trunk line. Loss magnitudes are subject to:

(a) the diameter of the pipe and lateral,

(b) the lateral angle of entrance (45° or 90°),

(c) the roundness of the joining surfaces of the lateral and the trunk pipes.

The fittings tested, with the exception of the 4x4x4 tee, were rounded and smooth at the connection corners.

Of the two fittings tested, (4x4x4 and 6x6x6) the larger diameter of each grouping created the smaller head losses. The reasons for this were:

(a) velocities, for a given discharge, were higher in the smaller diameter fittings.

(b) in the case of the tees, the 4-inch tee did not possess the corner smoothness of the larger diameter tee.

In all cases of the fittings:

(a) the largest head loss occurred at the highest velocity:
It can be seen that for approximately the same velocities the 4x4 tee and the 4x4 wye give relatively close maximum head losses (0.67 vs. 0.51, respectively). Again, for the same velocities, the tee $K_m$ values are relatively close also (0.17 vs. 0.13, respectively).

In the case of the 6x6 tee and 6x6 wye (for common velocities), the maximum head loss values are approximately the same (0.09 vs. 0.10, respectively). Likewise, at common velocities, the loss coefficients, $K_m$, are close in value (0.12 vs. 0.13, respectively). Though not uniformly true, these findings are in general true for the range of velocities.

Note also, in the preceding table the 4-inch fittings have head losses many times greater than the 6-inch counterparts. The 4-inch velocities are about twice as large. Since $K$ is a ratio of the two ($h/V^2/2g$) the net result is that the range of the $K$ values is small (0.05). It should also be noted that the test conditions had no flow entering the main pipe from the lateral. In the field, with a substantial flow entering from the lateral, the disruption to flow in the main pipe could be expected to be greater in the case of the tee.

(b) **Head Losses Generated by Liner Folds**

The loss in this case is created by the "fold" extending from the pipe wall into the pipe flow. This intrusion into the flow passage creates a head loss accompanied by a reduction in flow capacity. Loss magnitudes are subject to:

(a) the intrusion depth, $k$, into the pipe flow,

(b) the orientation of the fold to the pipe direction.
In the case of this study, one fold was considered which was perpendicular to the flow. Three protrusion depths were studied. These depths are given in Chapter 5.

A table is presented which compares the fold protrusion diameter to that of the pipe diameter, i.e., d/D. Also listed are the largest head losses $h_m$ and the largest loss coefficients $K$ with their accompanying velocities.

<table>
<thead>
<tr>
<th>Fold#</th>
<th>d/D</th>
<th>$h_m$, ft</th>
<th>vel, fps</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.94</td>
<td>0.15</td>
<td>6.12</td>
<td>0.26</td>
</tr>
<tr>
<td>2</td>
<td>0.85</td>
<td>0.25</td>
<td>6.12</td>
<td>0.44</td>
</tr>
<tr>
<td>3</td>
<td>0.78</td>
<td>0.30</td>
<td>6.11</td>
<td>0.52</td>
</tr>
</tbody>
</table>

For common velocities, it can be seen that both the head loss, $h$, and loss coefficient $K$, increase as the ratio $d/D$ decreases. That is to say, as the protrusion into the flow increases it causes the head loss and the loss coefficient to increase, signifying a greater resistance to flow with the increasing obstruction. This is true at other common pipe velocities.

(c) Flow Obstructions Due to Pipe End Fusion

Losses in energy occur at points where the ends of the pipes are “fused” together. The protrusion into the flow, created by this method is usually small. However, when a great number of pipes are fused together in a long pipe length, significant losses can accrue.

The method of fusing PVC and HDPE pipe is described in Chapter 6. From the description, it can be acknowledged that a “human factor” is involved and there is no assurance the created protrusion depth, $k$, will be the same in a particular diameter pipe. From limited observations, it is postulated that an increased protrusion exists with increasing pipe diameter.

The following table looks at the difference in the head loss and $K$ values created by the two tested pipe diameters with their corresponding $k$ ( intrusion) values. The recorded data were small in value and therefore difficult to measure accurately.
Using the closest comparable velocities (6.21 and 6.35 fps), of the two pipes, and acknowledging the protrusions, k, are approximately the same, the following conclusions are made:

(a) at common velocities, the head loss, h, and the loss coefficient, K, increase with decreasing pipe diameters.

These findings are common where the pipe roughness and velocity are approximately the same.

Conclusions

Based on the findings of the study the following conclusions are presented:

Methodology

1. Using the smallest diameter pipe as the model and scaling to larger diameters is a cost effective method to determine head loss, h, and loss coefficients, K across fittings and obstructions to flow.

Head Loss Trends With Respect to Fittings and Defects

2. For the example presented, and for similar velocities, the 4-inch tee creates a slightly higher head loss, h, than the 4-inch wye.

3. For the example presented and for the same velocity, the 4-inch tee loss coefficient, K, is slightly larger than that of the 4-inch wye.

4. For the example presented and at similar velocities, the 6-inch wye registers a slightly higher head loss than the 6-inch tee. The same is true in the case of the K value at similar velocities.
5. As would be expected, as the fold diameter ratio d/D, decreased, at common velocities, the head loss, h, increased, as did the loss coefficient, K..

6. For pipes with similar surface roughness (such as the studied protrusion depth, k) and velocity, the larger head loss h, and loss coefficient K, occurred in the smaller diameter pipe (4-inch).

Data For Flow Studies

The principal contribution of this research is in the experimental values measured for head loss and their extrapolation to larger pipe sizes. This allows the changes in pipe flow conditions before and after rehabilitation to be estimated more accurately. To illustrate the applications of the research data, a prototypical section of sewer pipe has been evaluated for flow conditions under 10 different scenarios before and after rehabilitation. The results of the flow calculations for each scenario are shown in Table 10.
## Table 10. Pipe Lining Discharge Comparisons, 8 Inch Pipe

<table>
<thead>
<tr>
<th>Row</th>
<th>Pipe Liner Type</th>
<th>L-ft</th>
<th>d-ft</th>
<th>n</th>
<th>f</th>
<th>Δh = 10.0</th>
<th>Laterals</th>
<th>Liner Folds</th>
<th>Fusion Beads</th>
<th>Vel</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Conc-rough (1)</td>
<td>300</td>
<td>0.667</td>
<td>0.0165</td>
<td>0.0576</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>CIPP lined only</td>
<td>300</td>
<td>0.643</td>
<td>0.0090</td>
<td>0.0174</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>Sliplined only</td>
<td>300</td>
<td>0.534</td>
<td>0.0090</td>
<td>0.0185</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>Conc-rough(10-4&quot; T's) (1)</td>
<td>300</td>
<td>0.667</td>
<td>0.0165</td>
<td>0.0576</td>
<td>10</td>
<td>0.080</td>
<td>0.800</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>CIPP lined(10-4&quot;T's)</td>
<td>300</td>
<td>0.643</td>
<td>0.0090</td>
<td>0.0174</td>
<td>10</td>
<td>0.080</td>
<td>0.800</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>6</td>
<td>Sliplined(10-4&quot;T's)</td>
<td>300</td>
<td>0.534</td>
<td>0.0090</td>
<td>0.0185</td>
<td>10</td>
<td>0.080</td>
<td>0.800</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>7</td>
<td>CIPP-(3 folds)</td>
<td>300</td>
<td>0.643</td>
<td>0.0090</td>
<td>0.0174</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>CIPP(3 folds,10-T's)</td>
<td>300</td>
<td>0.643</td>
<td>0.0090</td>
<td>0.0174</td>
<td>10</td>
<td>0.080</td>
<td>0.800</td>
<td>3</td>
<td>0.277</td>
<td>0.831</td>
</tr>
<tr>
<td>9</td>
<td>Sliplined(beads@20')</td>
<td>300</td>
<td>0.534</td>
<td>0.0090</td>
<td>0.0185</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>10</td>
<td>Sliplined(beads@20'+10-T's)</td>
<td>300</td>
<td>0.534</td>
<td>0.0090</td>
<td>0.0185</td>
<td>10</td>
<td>0.080</td>
<td>0.800</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>11</td>
<td>Colum n 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Notes:
1. Unlined
2. Water temp - 55°F
Table 10 Development

The Manning equation roughness value, $n$, (Table 10, column 4) for pipe flow was taken from ‘The Handbook of Hydraulics’ [15] and private correspondence [16]. To simplify the table computations the Darcy-Weisbach (D-W) equation [2] was used. In order to do this the Manning $n$ values were converted to D-W friction loss values, $f$ (column 5), using the $n$-to-$f$ conversion equation [15]:

$$f = \frac{185n^2}{D^{1/3}}$$

In equation 13 the value of $f$ is inversely proportional to cube root of the pipe diameter, $D$. As the diameter decreases (column 3) the D-W value of $f$ increases (see column 5, Table 10 for “CIPP lined only” and “Sliplined only”). Note that the smaller diameter, sliplined pipe ($D = 0.534$, column 3) has a greater $f$ value than the CIPP pipe ($D = 0.643$).

The columns titled, “Laterals,” “Liner Folds,” and “Fusion Beads” allow the entrance of

(a) the number of flow obstructions,

(b) their $K$ values (taken from the appropriate sections or estimated from available data) and,

(c) the product of (a) times (b).

These minor loss values are summed and added to the computed pipe friction loss to obtain the total head loss. With this information, the final two columns (15 and 16) compute the resulting pipe velocity and discharge.

A comparison of the unlined and different linings combined with different minor losses follows.

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Liner Type Comparisons (Table 10)

Table 10 lists different types of pipes, lined and unlined, for comparison of their discharge efficiencies. The host pipe is an 8-inch, rough, concrete pipe. As can be seen in the sketch accompanying Table 10 a total head of 11.5 feet drives water through the pipe of length 300 feet. Naturally, the specific changes in flow capacity will depend on the pipe diameter, gradient, number of fittings and/or defects, etc. The following observations are made relative to each pipe, with or without linings or fusion joints. The pipes are listed in the vertical order of the table.

1. Concrete-rough, unlined: A bare pipe with a friction factor (f) of 0.0576 yields 1.83 cfs of flow.

2. CIPP only: The liner reduces the diameter of the host pipe (case 1) by approximately 3.6 % but reduces f by a factor of 70% which causes a discharge increase to 2.92 cfs, an increase in efficiency of approximately 37%. This combination of wall smoothness and minimum diameter reduction produces the largest discharge of the ten pipe conditions considered.

3. Sliplined only: Though f is almost as small as the CIPP liner it has a smaller diameter. The combination of smallest diameter and a resulting slightly larger f, results in a discharge of 1.81 cfs which is very near the unlined pipe value.

4. Concrete-rough, with 10 4-in tees: The 10 tees cause a slight lowering of the pipe discharge compared to the concrete-rough pipe above (case 1). In this case, computed Q = 1.80 cfs.

5. CIPP with 10-4-in tees: The 10 4-in tee laterals reduce the most efficient liner (CIPP only) from 2.92 cfs to 2.80 cfs, a decrease of about 4%.
6. **Sliplined with 10-4-in tees:** Adding the ten tees to the sliplined only pipe reduced the discharge from 1.81 cfs to 1.75 cfs. This is a reduction, due to the tees, of about 3%.

7. **CIPP with 3 folds:** The three folds (fold #3, chapter 6) resulted in a discharge of 2.80 cfs. This is a slight decrease of about 4% relative to the CIPP lined only. This condition is approximately the same in efficiency as the CIPP lined with 10 4-in tees (2.80 cfs also).

8. **CIPP-3 folds-10 4-in tees:** This combination of tees and folds results, as would be expected, in the lowest discharge efficiency of CIPP conditions studied (2.69 cfs). The reductions from the other CIPP considerations were:
   (a) 8% less than lined only,
   (b) 4% less than three folds,
   (c) 4% less than 10 4-in tees.

9. **Sliplined with beads @ 20 feet:** A 300 feet length of 20 feet sections of pipe would result in 14 beads. This condition would result in a discharge of 1.78 cfs. This is about 2% less efficient than the sliplined only and about 2% more efficient than sliplined with tees.

10. **Sliplined with 14 beads and 10 4-in tees:** This, of course, is the least efficient of the sliplined conditions since it combines two flow resistors (1.73 cfs). It is:
    (a) 4% less efficient than sliplined only,
    (b) 3% less efficient than sliplined with beads,
    (c) 1% less efficient than sliplined with 10 tees.
Liner Ranking

Table 11 was developed to illustrate the efficiency ranking of each lined or unlined pipe. Flow efficiency is relative to the allowed quantity of discharge. The maximum discharge (2.92 cfs) was assigned the value of unity. All others were calculated by dividing their discharge by the maximum value.

Table 11. Pipe Discharge Efficiency

<table>
<thead>
<tr>
<th>Rank</th>
<th>Pipe Type</th>
<th>Q-cfs</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CIPP lined only</td>
<td>2.92</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>CIPP lined-3 folds</td>
<td>2.80</td>
<td>0.959</td>
</tr>
<tr>
<td>3</td>
<td>CIPP lined-10 4 inch tees</td>
<td>2.80</td>
<td>0.959</td>
</tr>
<tr>
<td>4</td>
<td>CIPP lined-3 folds, 10 4 inch tees</td>
<td>2.69</td>
<td>0.921</td>
</tr>
<tr>
<td>5</td>
<td>Concrete, rough-unlined</td>
<td>1.83</td>
<td>0.627</td>
</tr>
<tr>
<td>6</td>
<td>Sliplined only</td>
<td>1.81</td>
<td>0.620</td>
</tr>
<tr>
<td>7</td>
<td>Concrete, rough-10 4 inch tees</td>
<td>1.80</td>
<td>0.616</td>
</tr>
<tr>
<td>8</td>
<td>Sliplined-fusion beads @ 20 feet</td>
<td>1.78</td>
<td>0.610</td>
</tr>
<tr>
<td>9</td>
<td>Sliplined-10 4 inch tees</td>
<td>1.75</td>
<td>0.599</td>
</tr>
<tr>
<td>10</td>
<td>Sliplined-fusion beads @ 20 feet, 10 4 inch tees</td>
<td>1.73</td>
<td>0.592</td>
</tr>
</tbody>
</table>

Table 11 Comments

The most efficient pipe, in terms of flow capacity is the “CIPP lined-only pipe.” The reason for this is the combination of having the second largest area (0.32 ft²) and the smallest friction factor ($f = 0.0174$). Because of the same factors, all CIPP lined pipes are by far more efficient than the other types. As shown in Table 10 the four CIPP lined pipes are the most efficient in terms of flow capacity. In all cases, regardless of number of fittings, their flow efficiency is greater than 90%.

After the CIPP lined pipes the next most efficient is a rate of 63% (rough unlined pipe). This is a fraction greater than the “sliplined only” (62%). This means the rough, unlined concrete pipe is approximately as efficient as the sliplined pipe if only discharge capacity is considered. This is the result of the reduced area of the slipline pipe even though it has an $f$ factor of 0.0185 (second smallest). Problems such as leakage would
offset this apparent similarity.

The final three pipes, all sliplined with fittings, are about the same, being between 59% and 61%.

The listed pipe flow and ratios present examples of flow based upon specific conditions. These conditions include the pipe diameter, smoothness, gradient, number and type of fittings and/or defects, etc. Except for losses due to pipe fusion, such changes can be evaluated using the data contained in this dissertation.

**Suggestions for Further Study**

A clearer understanding in the area of fused pipe endings is needed. Some of the questions needing answers before further research is undertaken are:

1. Does the standard fusion procedure result in a consistent size of bead at different diameters?

2. Can an acceptable protrusion depth growth with diameter be established? If yes, it would be possible to conduct measurements on a few diameters and perhaps extrapolate to other (especially larger) diameters.
APPENDIX A

CALCULATION OF VISCOSITY

Certain secondary variables characterize specific fluid mechanical behavior. The most important of these is viscosity, which relates the local stresses in moving fluid to the strain rate of the fluid element, [2]. Viscosity is a quantitative measure of a fluid's resistance to flow. An object can move through air much easier than it can move through water, which is 50 times more viscous. Thus viscosity is a very important characteristic in the study of fluid flow in confined quarters, such as pipes, as well as other situations.

Rather than look up, and record, each viscosity value (based on its temperature), a program was developed which computes the viscosity when given the liquid temperature. The results of the application of “Microsoft Excel” in this development are shown below.

The temperature data were taken from a published table [5]. Note in Figure 26 the defining equation for kinematic viscosity, $v$, has been taken to the third degree. The fit is excellent, i.e., the “coefficient of determination, $R^2$,” equals unity. This value of unity implies a perfect fit, with the model passing through every data point. The developed equation was placed in all “A” tables presented in the dissertation. Because of margin space requirements, the kinematic viscosity in these data tables has been “hidden.” However, in the “B” tables, the value of the kinematic viscosity, $v$, is presented for the model and prototype temperatures.
Figure 26. Graph - kinematic viscosity, \( \nu \), vs. temperature, °F.
To control discharges for the various tests, the gate control valve, whose location in the line is shown in Figure 1, was calibrated. The valve was opened fully and orientation marks painted on the valve handle and the valve body. The marks are shown.
in Figure 27. Starting from the fully open position, the valve was closed in segments and the corresponding discharges recorded. Following these measurements, the data were reduced and plotted. A curve of Valve Turns vs. Discharge was then developed, using procedures described in Appendix A, and is presented in Figure 28.

![Valve Opening vs. Discharge](image)

**Figure 28. Valve opening vs. discharge curve and equation**

For example, a discharge of 1.2 cfs (0.03 cms) requires approximately 8.8 closing turns of the gate control valve.
APPENDIX C

PVC FITTING SPECIFICATIONS

General

A large variety of smooth PVC pipe and pipe fittings are available to the designer or contractor. Fitting sizes generally vary from \( \frac{1}{2} \) to 12 inches in diameter. Examples of types and sizes of PVC fittings include:

(a) \( \frac{1}{2} \) to 12 inch diameter tees,

(b) bends of \( \frac{1}{4}, \frac{1}{6}, \frac{1}{8}, \) and \( \frac{1}{16} \) bends, with or without, side hubs,

(c) tees and wyes with many joining lateral sizes.

PVC pipe systems should be engineered and installed in accordance with established standards and procedures. Suitability for the intended service application should be determined prior to installation. Some manufacturers have consultants to assist the designer and installer in requirements.

The installer may consult the manufacturer to determine what NSF and ASTM specifications must be satisfied in the installation of their product. Some of these specifications follow.

PVC Fitting Specifications

PVC pipe has many properties that make it ideal for sewer flow containment. Some of the advantages of the material, which were provided by a major manufacturer, are:
The material is resilient, tough, and durable and has high tensile and impact strength. The material is self-extinguishing and will not support combustion. In some cases the pipe material has an ASTM E-84 flame spread rate of 25 or less. The walls provide chemical attack resistance within certain limits of temperature and pressure. When surface abrasions occur they do not provide points which corrosive elements can attack. The smooth surfaces of PVC pipe assure low friction loss and high flow rates. The given Manning roughness factor, $n$ varies from 0.08 to 0.012.

The type connectors studied (smooth surface wyes and tees) are limited to diameters of 12-inches (305 mm). The pipe fitting, molding machine, combines state-of-the-art tooling to produce consistent fittings. The fittings are checked for dimensional accuracy and chemical composition, as well as hydrostatic burst, crunch and impact strength. These tests and measurements insure the products meet or exceed ASTM standards. The fittings come in all standard geometries, in diameters from 1/2-inch through 12 inches (13mm to 305mm).

A rigid PVC (polyvinyl chloride) compound is used in the manufacture of Schedule 40 fittings. The compound is Type 1, Grade 1, PVC1120 (cell class 124-54-B) which is identified in ASTM D1784. The compound must contain the specified amount of pigment, stabilizers and other additives approved by NSF (National Sanitary Foundation) for conveyance of potable water.

**Joint Epoxy Curing**

Specifications suggest that an epoxied PVC joint should not be disturbed until it has initially set. The recommended set time specifications are:

Fitting diameter range: 4-inch through 8-inch
Temperature range: 60°F to 100°F

Set time: 2 hours

More details on the process of fusing PVC pipes are given in Chapter 6, Fusion Joint Protrusions into Pipe Flow.
BIBLIOGRAPHY


