Review of the Geometry Factors in the CHECWORKS 4.0 Steam Feedwater Application

Non-Proprietary Version

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EPRI Project Manager

D. Smith

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

Worley Parsons Polestar

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

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The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Worley Parsons Polestar
601 Williams Blvd., Suite 3a
Richland, WA 99354

Principal Investigator
J. Horowitz

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PRODUCT DESCRIPTION

Flow-accelerated corrosion (FAC) continues to be a significant issue for nuclear power plants. The Electric Power Research Institute's (EPRI's) CHECWORKS™ software is the primary analysis tool used by FAC engineers to deal with the problem. A multipurpose computer program, CHECWORKS™ predicts the rate of FAC based on the Chexal-Horowitz correlation. This correlation uses component geometry factors to account for the influence of the added turbulence caused by piping components, such as elbows. This report presents the results of a study to update the geometry factors used in CHECWORKS™. The new factors will be used in future releases of the program and should provide more accurate predictions of the rates of FAC.

Background

For the past 25 years, EPRI computer programs have been used by engineers to predict the rates of FAC. These predictions assist utility engineers in selecting a sample of components to be inspected for wall thinning. Central to these predictions are geometry factors derived from plant data. The geometry factors are defined as the ratio of the wear rate found in a piping fitting (for example, an elbow) to the wear rate in a straight pipe with the same conditions. Geometry factors allow us to develop correlations suitable for plant components from laboratory data, which is invariably taken on straight pipes or tubes. Because CHECWORKS™' geometry factors were last reviewed in the mid-nineties, the CHECWORKS™ Users Group recommended that a study be performed to re-evaluate them.

Objectives

The main objective of this work was to review the geometry factors used in CHECWORKS™ and to recommend improved ones if necessary. A secondary objective was to examine the data and determine if there was an effect of component separation on the geometry factor of elbows. This effect has been observed in laboratory testing.

Approach

Twenty-four CHECWORKS™ databases were obtained and analyzed using a purpose-built version of CHECWORKS™ Version 4.0, a postprocessor, and a FORTRAN data analysis program.

Results

The research results are presented in this two-tier report, with the revised geometry factors included in the proprietary version. Examination of the data showed that no upstream geometry effect was obvious in the data.

Applications, Value, and Use

This report should be valuable to program developers because the revised geometry factors are expected to provide more accurate predictions. Further, the report illustrates to the user community the process used to develop geometry factors.

Keywords

CHECWORKS™
Flow-accelerated corrosion (FAC)
Geometry factors
Mass transfer

ABSTRACT

Flow-accelerated corrosion (FAC) is a degradation mechanism that continues to be a significant issue for nuclear power plants. The Electric Power Research Institute's (EPRI's) CHECWORKS™ software is the principal analysis tool used by FAC program owners to deal with the problem. A multipurpose computer program, CHECWORKS™ predicts the rate of FAC based on the Chexal-Horowitz correlation. This correlation uses component geometry factors to account for the influence of the added turbulence caused by piping components, such as elbows.

This report presents the results of a detailed study that was performed using years of actual plant inspection data to review the geometry factors currently built into CHECWORKS™. New factors will be considered in future releases of the program and should provide more accurate predictions of the rates of FAC.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Flow-Accelerated Corrosion

Flow-accelerated corrosion (FAC) is a degradation mechanism that attacks carbon steel piping and components. Typically, FAC occurs under the water chemistry and operating conditions found in the high-pressure portions of nuclear and fossil power plants. FAC is a general (i.e., widespread) attack that left uncorrected will result in piping or equipment failures. EPRI has published a comprehensive reference book on FAC [1].

Degradation caused by FAC has resulted in numerous instances of wall thinning and failures. Some of the significant historic failures in piping systems have been:

- Catastrophic failure of a condensate elbow at the Surry Unit 2 nuclear plant in December 1986. This failure resulted in four fatalities and caused nuclear units in the U.S. to develop programs to protect against single-phase (i.e., water only) FAC.
- Simultaneous failure of two drains lines from the moisture separator drain tank at the Millstone Unit 3 in December 1990. This and a failure the following year at Millstone Unit 2 lead to the publication of set of EPRI recommendations, NSAC-202L [2].
- Failure of a feedwater line at the Pleasant Prairie Power Plant (fossil-fired) in February 1995 resulted in two fatalities. This lead to increase awareness of FAC in fossil-fired power plants.
- Failure of a pipe downstream of a flow measurement orifice in the condensate system at the Mihama (Japan) Unit 3 in August 2004. This failure resulted in five fatalities and spurred renewed interest in FAC programs, particularly internationally.

More information about these failures can be found in [1] and [2].

CHECWORKS™ Steam Feedwater Application

In response to the accident at Surry Unit 2, mentioned above, the Electric Power Research Institute (EPRI) developed a family of computer program designed to assist utility engineers in conducting programs to guard against FAC. CHECWORKS™ Version 4.0 is the latest program in this series [3]. For the purposes of this document, the only feature of CHECWORKS™ that will be considered is the wear rate analysis portion that uses the Chexal-Horowitz model to predict the rate of FAC in piping components [1].

Chexal-Horowitz FAC Model

The Chexal-Horowitz FAC model was originally developed to predict the rate of FAC under single-phase conditions. It was incorporated into the program CHEC© [4]. It was later extended to cover two-phase (i.e., steam-water) flows, in addition to single-phase flows, and incorporated into CHECMATE™ [5] and later into CHECWORKS™ [3]. Although the details of the model have been modified, the form of the model has remained essentially the same over the years.

Single-Phase Formulation

As described in [1], the rate of FAC for single-phase conditions predicted by the Chexal-Horowitz correlation is given by:

$$Rate_{1-\varphi} = F_{Temp} * F_{Mass\ Transfer} * F_{Geometry} * F_{Alloy} * F_{pH} * F_{Oxygen} \qquad \textbf{Eq. 1-1}$$

Where:

$Rate_{1\text{-}\varphi}$	= Rate of single-phase FAC
F_{Temp}	= Factor to account for the temperature
$F_{Mass\ Transfer}$	= Factor to account for mass transfer from the steel to the fluid
$F_{Geometry}$	= Factor to account for the geometry of the pipe or fitting
F_{Alloy}	= Factor to account for the alloy content of the steel
F_{pH}	= Factor to account for the pH of the water
F_{Oxygen}	= Factor to account for temperature

Two-Phase Formulation

As described in [1], the rate of FAC for two-phase conditions predicted by the Chexal-Horowitz correlation is given by:

$$Rate_{2-\varphi} = F_{Temp} * F_{Mass\ Transfer} * F_{Geometry} * F_{Alloy} * F_{pH} * F_{Oxygen} * F_{Void\ Fraction} \qquad \textbf{Eq. 1-2}$$

Where:

$Rate_{2\text{-}\varphi}$	= Rate of two-phase FAC
$F_{Void\ Fraction}$	= Factor to account for the void fraction of the flow.

Note that some of the factors have different values for single- and two-phase conditions. Also note that some prior versions of the above equations included a factor to account for hydrazine concentration. This term was removed based on the most recent laboratory results.

As geometry factors are the focus of this work, they will be discussed in detail.

Geometry Factors

As used in CHECWORKS™, the geometry factor is defined as the ratio of the maximum wear rate in a fitting divided by the wear rate in a straight pipe under the same conditions. The use of geometry factors in FAC analysis dates back to the work done by Keller in the early 1970s [1]. The concept of geometry factors is useful as it enables laboratory data on FAC rates – almost always taken in straight pipes – to be related to plant data. Basically, the prediction is made on an idealized straight pipe and then converted, through the use of the appropriate geometry factor, into a prediction for a fitting.

Keller was concerned with FAC in steam turbines. Due to the complicated geometries present in such machines, he developed the concept of geometry factors as defined above. The geometry factors he developed were for two-phase (i.e. steam-water conditions) and are presented in [1] as well as many technical papers.

Conceptually, the process is similar to the use of equivalent length of pipe fittings in pressure drop calculations. In that case, the pressure drop of a fitting (e.g., a gate valve) is related to the pressure drop in straight pipe of the same size with the same flowing conditions.

It is believed that Keller used pressure drop data to relate FAC rates for conditions that were not experimentally measured. However, it should be noted that the analogy of geometry factors and equivalent length is not perfect because the geometry factor relates to the maximum rate of FAC (i.e., a local parameter) while the equivalent length relates to pressure drop which is an average parameter for the fitting.

Methods Used to Estimate Geometry Factors

Investigators have developed several ways to estimate the geometry factors used in FAC analysis. In most of these methods, it is assumed that FAC is controlled by the local mass transfer rates so that an analogous degradation mechanism or mathematical model can be used to represent FAC. These methods will be briefly discussed.

- **Analogy with pressure drop –** this approach was used by Keller and used in the development of some of the original geometry factors used in CHEC®. Essentially, this approach is to argue that since the pressure drop of a 90° elbow is twice the pressure drop of a 45° elbow then the geometry factor of a 90° elbow should be twice the geometry factor of a 45° elbow.
- **Computational Fluid Dynamics (CFD) –** various researchers have used CFD to calculate the velocity fields for typical operating and boundary conditions. From the velocity fields, the investigators deduced the local mass transfer rates and hence the geometry factors for specific geometries, e.g. [6].
- **Copper Modeling Tests –** Poulson and Robinson [7] developed a modeling test using copper test sections containing a flowing acid solution. With this approach the copper corroded in a way analogous to steel degrading by FAC, but roughly a thousand times faster. Compared to scale-model tests using water and carbon steel, this approach allows rapid, economical testing of various geometries.
- **Plaster of Paris Tests –** Similar in concept to the copper tests, a ‘dissolving wall’ of plaster is a commonly used technique for measuring mass transfer. In this approach, hot water flowing through a plaster of Paris model dissolves the surface. Post test measurements reveal the wear pattern and from this pattern the local mass transfer and the geometry factors could be found. Examples of FAC related works using this technique are [8] and [9].
- **Limiting Current Density –** this is an electrochemical approach that is not commonly used for complicated geometries. In this approach, an electrochemical cell is established in model geometry in such a way that the current flow is limited by mass transfer. Electrical measurements establish the local mass transfer rates. See [7] for a discussion of the method and its drawbacks.
- **Use of Plant Data –** perhaps the most straightforward way to determine the geometry factors is the use of measurements made on fittings from a power plant. This approach has the advantages of using plant conditions in developing the geometry factors. However, the fact that in general the conditions, particularly the initial thickness of the component being studied, are not well defined can compromise the accuracy of this approach.

History of Geometry Factors in EPRI FAC Programs

CHEC® [4] was the first EPRI computer program to predict FAC. The correlation used in it covered only single-phase (i.e., water only) conditions. When it was developed in the late 1980s, the main sources used for the geometry factors were:

- Very limited amounts of plant data
- The Keller factors
- Analogy with pressure drop

User feedback from Version 1.0 of CHEC® indicated that some of the predictions using the Keller factors did not agree well with plant experience. Consequently, plant data was used to modify some of these geometry factors. Additionally, experiments were performed in the United Kingdom using the acid-copper modeling approach to better understand the geometry factors. (See [7]). Although the results of these tests were useful, they were not used to establish the geometry factors used in the program.

In 1989, EPRI released CHECMATE™ [5]. This program added two-phase capabilities to CHEC®. As such, it was necessary to use the limited amount of two-phase plant data available at that time to develop two-phase geometry factors.

The geometry factors used in CHECMATE™ were also used in the early versions of CHECWORKS™. All of these geometry factors were revisited and revised using plant data in the mid-1990s. At that time, all of the geometry factors used were derived from plant data. The geometry factors have been unchanged since that time.

CHECWORKS™ Analysis

In order to understand how the Chexal-Horowitz model is used in the CHECWORKS™ wear rate analysis, it must be recognized that there are two types of analysis performed – Pass 1 Analysis and Pass 2 Analysis.

Pass 1 Analysis

The Pass 1 analysis consists of predictions made without using inspection data. That is, CHECWORKS™ uses the operating conditions, the water chemistry values, input by the user, and the Chexal-Horowitz correlation to predict the rate of FAC for every component being analyzed. Any available inspection data is not considered in this analysis.

Pass 1 analysis is generally used before inspection data are available or in the case of lines with low rates of FAC wear in which case the inspection data is likely to contain a great deal of statistical scatter.

Pass 2 Analysis

Pass 2 analysis is Pass 1 analysis refined with a statistically determined line correction factor (LCF) for a given analysis line [3, 10]. The LCF is used to multiply the Pass 1 predictions as follows:

$$WR_{Pass\ 2} = WR_{Pass\ 1} * LCF \qquad \textbf{Eq. 1-3}$$

Where:

$WR_{Pass\ 2}$ = Pass 2 wear rate
$WR_{Pass\ 2}$ = Pass 2 wear rate
LCF = Line Correction Factor

A detailed discussion of the line correction factor can be found in [10].

Generally, Pass 2 analyses are used for the bulk of calculations made with CHECWORKS™.

Counterbores

When butt welding pipes or fittings, welders must ensure that there is proper fit-up between the mating pieces. If one piece is thicker than then the other, the piping code requires that the thicker one is machined to match the thickness of the thinner one. The machining is tapered to avoid a stress concentration. This machined end is known as a counterbore.

In the late 1980s, when EPRI staff was analyzing the feedwater inspection data from the Trojan Nuclear Power Plant, it was noted that the large counterbores present in some of the joints increased the degradation due to FAC. The feedwater piping at Trojan was 14-Inch Schedule 60 piping which has a nominal thickness of 0.594 inch. Elbows in the system were found to have nominal thickness of 2 or 3 inches. This significant mismatch of sizes required the use of large counterbores to properly weld the thinner pipe to the much thicker elbows. These large counterbores contributed to the rate of FAC seen. Because of this observation, an effort was made to examine the influence of counterbores on the geometry factor.

From the data available at that time, it was concluded that large counterbores only influenced the geometry factors for elbows. Thus, at user option, counterbores as an additional factor could be added to CHECWORKS™ Geometry Codes 1 through 4. However, the enhancements to these geometry codes have not been examined since the late 1980s.

Outline of This Report

This report is broken down as follows:

- Section 2 defines the objectives of this work.
- Section 3 explains the technical approach used.
- Section 4 describes the results of Stage 1 of this project.
- Section 5 describes the results of Stage 2 of this project.
- Section 6 presents the recommendations and conclusions of this project.

2 OBJECTIVES

The objectives for this project are to examine the geometry factors used in CHECWORKS™ Version 4.0 and to recommend revised geometry factors, if necessary. The geometry factors developed in this work will be derived from plant data.

These tasks will be performed by:

- Using existing CHECWORKS™ databases as a source, review the accuracy of the geometry factors used in CHECWORKS™ Version 4.0. This portion of the project will be called Stage 1.
  - As part of the Stage 1 work, examine the factors used to account for counterbores.
- Using the same databases, investigate whether or not incorporating an upstream geometry effect for elbows would be desirable. This portion of the project will be called Stage 2.
  - As part of the Stage 2 work, consider whether the incorporation of the modeling work done by AECL on the impact of elbow geometry on geometry factors (see, for example [9]) would be beneficial.
- Using the result of the above studies, recommend geometry factors for future versions of CHECWORKS™.

3
TECHNICAL APPROACH

This section will present the technical approach used in this project. Some of the mathematical background will also be provided.

Since the basic approach to this work was to use plant data contained in CHECWORKS™, the first step was to select the databases to be used.

Database Selection Considerations

The databases used in this work were selected using the considerations described in Table 3-1.

Table 3-1
Database Selection Criteria

Feature	Comment
Large amounts of degradation	The larger the wear the better the estimate of the measured wear.
Large number of re-inspections with the same grids	Although this is somewhat contradicts the comment above, certainly at least two inspections are desirable.
Good coverage of geometries	Obviously, there will be some geometry codes with a very small number of inspected components.
Few if any chemistry changes	More accurate correlation of measured with predicted wear values.
Few if any power changes	More accurate correlation of measured with predicted wear values.
Consistent analysis of inspection data	Different analysts and analytical approaches would likely result in larger data scatter.

Databases

Databases Used First Go-Round

Using the considerations described above, several knowledgeable FAC engineers were surveyed to locate candidate databases. From their recommendations, a number of databases were selected. The utility engineers were asked for permission to use their databases. The eleven databases used consisted of seven PWRs and four BWRs. These databases contain 3,785 individual components with inspection data.

Databases Used – Second Go-Round

For reasons that will be further discussed in the next chapter, the eleven databases described above did not contain sufficient number of components to cover all of the geometry factors in CHECWORKS™. In an attempt to deal with this problem, thirteen additional databases were obtained.

As all of the results that will be discussed used all of the twenty four databases, these databases will now be described in some details.

The breakdown by reactor type of the twenty four databases is presented in Table 3-2.

Table 3-2
CHECWORKS™ Databases Used

Reactor Type	Number of Databases	Number of Components with Inspection Data	Number of Downstream Pipes with Inspection Data
Boiling Water Reactor	10	2,043	1,113
Pressurized Water Reactor	14	4,007	1,628
Total	24	6,050	2,741

The component breakdown is shown in Table 3-3 for fittings, and for pipes downstream of fittings. The ten fitting that occur most often are presented in Table 3-4. Not surprisingly, the most common fitting types are elbows and pipes downstream of elbows.

Additional breakdowns of the available data are presented in Table 3-5. Note that the data in this table includes sub-components (i.e., all portions of partitioned components – e.g., the branch of a tee).

Note that it was not possible to obtain the number of times a component was inspected from the databases; rather the post-processer output included the inspection data evaluation method (e.g., the band method). From the evaluation method, the components were binned in three classes:

- Components evaluated using a single-inspection method (e.g., moving blanket method).
- Components evaluated using a method for two or more inspections (e.g., maximum delta, point-to-point method).
- Components evaluated using a user defined method. In this case, it was impossible to determine the number of inspections.

Reviewing the information in the databases, it is surprising that the majority of the fittings were evaluated using single-inspection methods. Table 3-6 presents a breakdown of the inspection methods used for these databases.

Table 3-3
Breakdown of Fittings Considered by CHECWORKS™ Geometry Code

Geometry Code	Description	Number	Geometry Code for Downstream Pipe	Number
1	45° Elbow	386	51	167
2	90° Elbow	2,168	52	1,027
3	45° Elbow with Close Upstream Fitting	253	53	78
4	90° Elbow with Close Upstream Fitting	1,269	54	478
5	180° Return	68	55	16
6	Orifice	28	56	192
7	Reducer with Close Upstream Fitting	301	57	98
8	Valve	0	58	311
9	Straight Pipe	66	59	0
10	Tee – Branch to Runs	43	60	5
11	Tee – Runs to Branch	32	61	68
12	Tee – Run and Branch to Run	282	62	95
13	Tee – Run to Branch and Run	27	63	22
14	Reducing Tee – Run to Branch and Run	110	64	45
15	Tee – Run to Run (No Branch Flow)	174	65	42
16	Reducing Elbow	23	66	13
17	Reducer	50	67	11
18	Expander	227	68	62
19	Expanding Elbow	43	69	8
20	Angle Valve	1	70	3
21	Globe Valve	0	*	
22	Gate Valve	22	*	
23	Butterfly Valve	0	*	
24	Control Valve	4	*	
25	Check Valve	10	*	
30	Inlet Nozzle	263	Not applicable	
31	Exit Nozzle	200	†	

Notes:
* Downstream pipe code covered by Geometry Code 58
† Downstream pipe code covered by Geometry Code 61

Table 3-4
Ten Most Commonly Occurring Fittings

Rank	Geometry Code	Description	Number
1	2	90° Elbow	2,168
2	4	90° Elbow with Close Upstream Fitting	1,269
3	52	Pipe Downstream of a 90° Elbow	1,027
4	54	Pipe Downstream of a 90° Elbow with Close Upstream Fitting	476
5	1	45° Elbow	386
6	58	Pipe Downstream of a Valve	311
7	7	Reducer with Close Upstream Fitting	301
8	12	Tee – Run and Branch to Run	282
9	30	Inlet Nozzle	263
10	3	45° Elbow with Close Upstream Fitting	253

Table 3-5
Additional Breakdowns of the Available Data

Attribute	Parameter	Number[1]	Percentage[1]
Phase of Fluid	Single-Phase Components	8,096	80.8%
	Two-Phase Components	1,923	19.2%
Number of Inspections	One Inspection	6,792	67.8%
	More than One Inspections	1,291	12.9%
	User Defined	1,939	19.3%
Pipe Nominal Diameter	0 – 4 Inch NPS	980	9.8%
	6 -12 Inch NPS	2,961	29.5%
	>12 Inch NPS	6,078	60.7%
Counterbore	Components with Counterbores	19	0.19%

[1] Figures include sub-partitioned components.

Table 3-6
Breakdown of the Data Evaluation Methods Used by Sub-Components

Method	Frequency	%
User Defined	1,939	19.3
Band	3,201	31.9
Area	7	0.1
Blanket	3,083	30.8
Maximum Point to Point - Lifetime	458	4.6
Average Point to Point - Lifetime	198	2.0
Baseline	0	0
Maximum Point to Point	472	4.7
Average Point to Point	1	0.0
User Defined Point to Point	159	1.6
Cutoff Point to Point	2	0
Fast Delta Point to Point	0	0
Cutoff Point to Point - Lifetime	1	0
Fast Delta Point to Point - Lifetime	0	0
Band Average	496	4.9
Strip	5	0
	10,022	

Mathematical Basis

With the databases defined, the next step was to develop the mathematical basis for the analysis. The method selected was to use the Pass 2 predicted wear (i.e., the degradation) results from every component together with the measured wear to extract what the ‘correct’ geometry factor would be. Note that this geometry factor is correct only if the LCF is also correct for the analysis line involved. Once the correct geometry factors were obtained, they would be binned by geometry code and then analyzed further. This process will be discussed below.

Single-Phase

For single-phase components, by assuming that the measured wear and the LCF are accurate, it can easily be shown that the 'correct' geometry factor is given by:

$$F_C = \frac{MW}{PW_{Pass\ 2}} * F_{Geometry} \qquad \textbf{Eq. 3-1}$$

Where:

F_C = 'Correct' geometry factor
MW = Measured wear
$PW_{Pass\ 2}$ = Pass 2 predicted wear
$F_{Geometry}$ = Single-phase geometry factor used in CHECWORKS™

Two-Phase

For two-phase conditions, the form of the two-phase geometry factor is EPRI proprietary. Nevertheless, the form of the 'correct' geometry factor for two-phase conditions is similar to Equation 3-1.

Data Analysis

Conceptually, the data analysis task was to apply the appropriate equation (i.e., Equation 3-1 for single-phase conditions and the equations for two-phase conditions) to calculate the correct geometry factor and record the information by geometry type. In practice, this process took part in several steps using different tools developed for this work.

The data analysis tools used will be introduced in the order of use.

Data Analysis Tools – Stage 1

Post-Processor

The first step in the process was to use a post-processor[2] to read CHECWORKS™ databases and produce an output containing the information needed for further analysis. Note that a special version of CHECWORKS™ was used for this analysis. The post-processor files were read into MS EXCEL where some formatting was done. MS EXCEL was then used to generate input files which were read by a purpose-built FORTRAN program.

FORTRAN Data Analysis Program

The bulk of the data analysis was performed in a FORTRAN program. This program read in the re-formatted post-processor information, and for each component with measured wear:

- Calculated the 'correct' geometry factor.
- Stored the result with other components with the same geometry code and with the same phase.
- Performed statistical analysis for each component geometry code at each phase.

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[2] The post-processor was written by David Ha of EPRI.

- Generated output files containing the processed data as well as the results of the statistical analyses.
- A separate file was produced containing information for each component with a counterbore.

Further Processing with MS EXCEL

The final step of the data evaluation process was to import the FORTRAN generated files into MS EXCEL and carefully examine each set of results. In doing this the flexibility of MS EXCEL to plot results, generate histograms and perform statistical calculations were all used on a case by case basis.

Data Analysis Tools – Stage 2

The data analysis stream used for Stage 2 was identical to Stage 1 with the following exceptions:

- The FORTRAN data analysis program also generated an output file for CHECWORKS™ geometry codes 1 through 5 (i.e., 45° elbows {2 types}, 90° elbows {2 types}, and returns) for single-phase and two-phase conditions. This file contained the geometry code, the correct geometry factor, and the distance to the upstream component.
- MS EXCEL was used to read in the FORTRAN generated output, performed statistical analyses and produced plots of the correct geometry factor versus distance to the upstream component.

Other Considerations

In addition to the ‘normal’ components (i.e., components with one geometry factor – e.g., an elbow), there are two classes of components that have to be treated differently:

- Sub-partitioned components – tees (Geometry Codes 10-15) and reducer-like components have more than one geometry factor, thus the data analysis tools had to account for the differences.
- Components with counterbores – the small percentage of components with counterbores were also treated separately to evaluate the impact of counterbores.

4
STAGE 1 RESULTS

This section will present a discussion of the results of the Stage 1 portion of this project.

General Approach to Data Analysis

There was a large spread in the ’correct’ geometry factors calculated for each geometry type. This was expected due to several facts including the different sources of the data, the inherent scatter present in inspection results including the measurement uncertainties and error propagation in the interpretation of the data. (See, for example [11].) In order to deal with the inherent scatter present, two principles were used:

- To be considered, there had to be 10 or more components included in the sample, and
- The median[3] of the corrected geometry factors was used to select the recommended value

First Go-Round

Upon examining the results of the eleven databases originally used, it was apparent that this work would benefit from having a larger sample of inspection data. This was apparent from the number of geometry types that had fewer than 10 components. Therefore, the additional databases were obtained.

The results presented below are for all of the data analyzed in the course of this work.

Single-Phase Results

In order to compare the exiting geometry factors with the ones determined in this work, the following figure of merit was defined:

$$\Delta = \frac{GF_{new} - GF_{old}}{GF_{old}} \quad \textbf{Eq. 4-1}$$

Where:

Δ	Figure of merit for the change of geometry factors
GF_{new}	Median of the geometry factors from this work
GF_{old}	Geometry factor from CHECWORKS™

[3] The median is a statistical measure of the midpoint of a frequency distribution of values such that there are an equal number of values falling above or below it. Medians are useful because they are less affected by the presence of outliers than other central measures such as the arithmetic mean (i.e., the simple average).

The single-phase results are presented, qualitatively using the symbols shown in Table 4-1. The results for components are presented in Table 4-2 and for the pipes downstream of the components Table 4-3. Note that in general, most of the geometry factors, especially the more common ones, had only small changes.

Table 4-1
Key to Tables 4-2 through 4-4

Symbol	Definition
🡅	$\Delta > +0.30$
⇧	$0.15 < \Delta < 0.30$
↔	$-0.15 < \Delta < 0.15$
⇩	$-0.30 < \Delta < -0.15$
🡇	$-0.30 < \Delta$
0	Fewer than 10 components

Note that Δ is defined as the difference between the new value and the old value divided by the old value. (See Equation 3-1) Thus an “up arrow” indicates that the new factor is larger than the old value.

Table 4-2
Qualitative Single-Phase Results for Fittings

Geometry Code	Description	Δ
1	45° Elbow	↔
2	90° Elbow	↔
3	45° Elbow with Close Upstream Fitting	↔
4	90° Elbow with Close Upstream Fitting	↔
5	180° Return	🡅
6	Orifice	🡅
7	Reducer with Close Upstream Fitting (Small End)	⇧
*	Reducer with Close Upstream Fitting (Large End)	↔
8	Valve	**0**
9	Straight Pipe	🡇
10	Tee – Branch to Runs (Runs)	↔
*	Tee – Branch to Runs (Branch)	↔
11	Tee – Runs to Branch (Runs)	⇩
*	Tee – Runs to Branch (Branch)	⇩
12	Tee – Run and Branch to Run (Runs)	↔
*	Tee – Run and Branch to Run (Main)	↔
13	Tee – Run to Branch and Run	↔
*	Tee – Run and Branch to Run (Main)	↔
*	Tee – Run and Branch to Run (Branch)	↔
14	Reducing Tee – Run to Branch and Run	🡅
*	Tee – Run and Branch to Run (Main)	↔
15	Tee – Run to Run (No Branch Flow)	↔
16	Reducing Elbow (Small End)	⇧
*	Reducing Elbow (Large End)	↔
17	Reducer (Small End)	↔
*	Reducer (Large End)	⇩
18	Expander (Small End)	⇧
*	Expander (Large End)	↔
19	Expanding Elbow (Small End)	↔
*	Expanding Elbow (Large End)	↔
20	Angle Valve	**0**
21	Globe Valve	**0**

Table 4-2 (continued)
Qualitative Single-Phase Results for Fittings

Geometry Code	Description	Δ
22	Gate Valve	⬆
23	Butterfly Valve	**0**
24	Control Valve	**0**
25	Check Valve	**0**
30	Inlet Nozzle	↔
31	Exit Nozzle	⇧

Note that an asterisk (*) in the Geometry Code Field indicates a sub-component associated with the component listed above.

Table 4-3
Qualitative Single-Phase Results for Pipes Downstream of Fittings

Geometry Code	Description – Pipe Downstream of	Δ
51	45° Elbow	↔
52	90° Elbow	↔
53	45° Elbow with Close Upstream Fitting	↔
54	90° Elbow with Close Upstream Fitting	⇧
55	180° Return	⬆
56	Orifice	⬇
57	Reducer with Close Upstream Fitting	↔
58	Valve	↔
59	Straight Pipe	**0**
60	Tee – Branch to Runs	**0**
61	Tee – Runs to Branch	↔
62	Tee – Run and Branch to Run	⇩
63	Tee – Run to Branch and Run	⬇
64	Reducing Tee – Run to Branch and Run	⬇
65	Tee – Run to Run (No Branch Flow)	⇩
66	Reducing Elbow	↔
67	Reducer	↔
68	Expander	⬇
69	Expanding Elbow	**0**
70	Angle Valve	**0**

It is interesting to view the above results in terms of the most common fittings. Table 4-4 summarizes the above results for the ten most common single-phase fittings. It also contains the number of components of each type considered. Note that these ten components make up approximately 70% of the total single-phase components evaluated.

Table 4-4
Qualitative Single-Phase Results for the Ten Most Common Geometry Codes

Geometry Code	Description	Number	Δ
2	90° Elbow	1,696	↔
4	90° Elbow with Close Upstream Fitting	1,041	↔
52	Pipe Downstream of a 90° Elbow	890	↔
54	Pipe Downstream of a 90° Elbow with Close Upstream Fitting	409	⇧
1	45° Elbow	305	↔
†	Reducer with Close Upstream Fitting (Large End)	283	↔
7	Reducer with Close Upstream Fitting (Small End)	261	⇧
58	Pipe Downstream of a Valve	260	↔
12	Tee – Run and Branch to Run (Runs)	226	↔
3	45° Elbow with Close Upstream Fitting	206	↔

† Component is a subcomponent of Type 7 Reducer.

Sensitivity Study of Component Diameter

In order to determine whether there was any sensitivity in the above results to the diameter to the fitting or pipe, additional analyses were performed. Depending on the number of components available:

- The median of each diameter was plotted against the diameter. This was done when there were more than 100 components available. A normalized version of a sample plot is presented as Figure 4-1 for Geometry Code 58. Note that the ordinate of this plot is the median for the diameter versus the median for the entire geometry code. Further note the presence of one outlier at 2 inch. It turns out that there was only one component of this size.
- When fewer components, but still more than about 50, were available, the median was taken for three bins of diameters – 0 through 5 inch, 6 through 12 inch, and greater than 14 inch pipe size.

After carefully considering these results, it was concluded that there was no apparent bias caused by the fitting or pipe diameter. In other words, the geometry factor is not a function of the diameter.

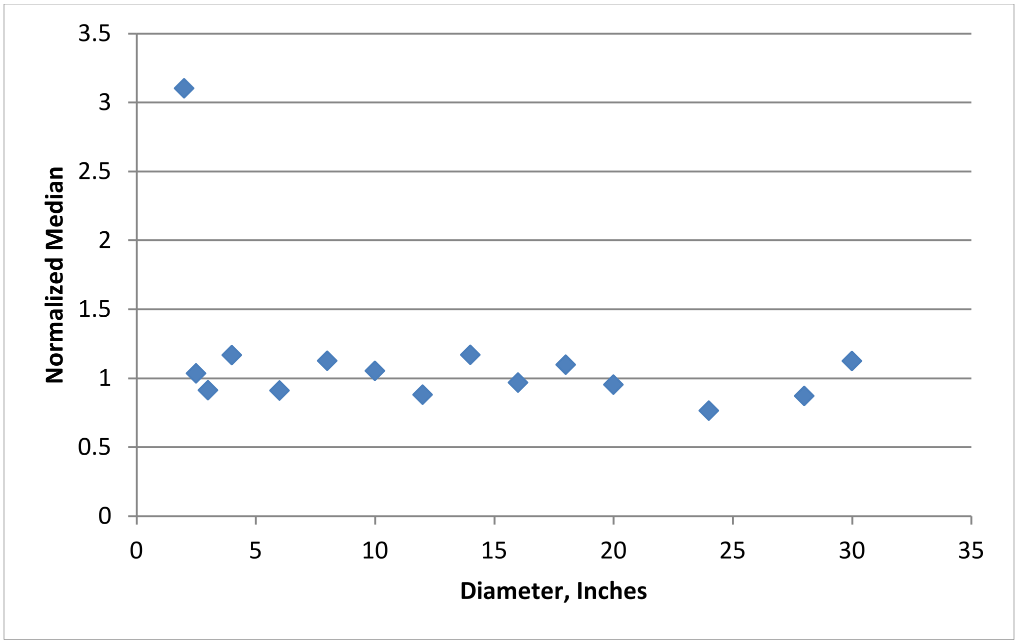

Figure 4-1
Diameter Sensitivity of Geometry Code 58

Counterbores

As shown in Table 4-5 there were only 19 elbows with counterbores. These components are broken down by geometry code in Table 4-4. In light of the small number of components with counterbores and the small percentage of the total components with counterbores, it is recommended that the treatment of counterbores be unchanged in future versions of CHECWORKS™.

Table 4-5
Counterbore Data

Geometry Code	Total Number of Fittings	Number of Components with Counterbores	Percentage of Components with Counterbores
1	305	0	0.00%
2	1,696	7	0.41%
3	206	9	4.37%
4	1,041	3	0.29%

Elbow R/D

An investigation was performed to determine the influence of elbow curvature (i.e., the R/D) on the single-phase geometry factor. The results of this study have shown that high R/D bends (e.g., 5 diameter bends) should have a higher geometry factor than standard elbows. These conclusions are already reflected in Table 4-2. It is recommended that elbows and sweeps have separate geometry factors.

Two-Phase Results

Before discussing the two-phase results, it should be mentioned that there was considerably less two-phase data than single-phase data. Not only that, there were many more component codes with fewer than ten components and in fact a number of components with no data. Note that, as mentioned in Table 3-5, the number of subcomponents decreased from 8,096 for single-phase to 1,923 for two-phase.

With that in mind, the results for the two-phase results are presented, qualitatively, in Table 4-6 for the fittings and Table 4-7 for the pipes downstream of the fittings. Again, the symbols defined in Table 4-1 were used to define the change in geometry factors.

Note that in general, most of the geometry factors for the fitting, especially the more common ones, had only small changes. An exception to this rule was both types of nozzles (i.e., Geometry Codes 30 and 31). Also note that all of the changes were either within the ±15% range or outside the ±30% band.

The results for the pipes downstream of fittings were less orderly although the most common type (i.e., Geometry Code 52) showed little change.

Table 4-6
Qualitative Two-Phase Results for Fittings

Geometry Code	Description	Number	Δ
1	45° Elbow	81	↔
2	90° Elbow	472	↔
3	45° Elbow with Close Upstream Fitting	47	↔
4	90° Elbow with Close Upstream Fitting	228	↔
5	180° Return	6	0
6	Orifice	6	0
7	Reducer with Close Upstream Fitting (Small End)	40	↔
*	Reducer with Close Upstream Fitting (Large End)	40	↓
8	Valve	0	0
9	Straight Pipe	8	0
10	Tee – Branch to Runs (Runs)	21	↔
*	Tee – Branch to Runs (Branch)	14	↑
11	Tee – Runs to Branch (Runs)	6	↔
*	Tee – Runs to Branch (Branch)	3	↔
12	Tee – Run and Branch to Run (Runs)	56	↑
*	Tee – Run and Branch to Run (Main)	33	↔
13	Tee – Run to Branch and Run	8	0
*	Tee – Run and Branch to Run (Main)	5	0
*	Tee – Run and Branch to Run (Branch)	5	0
14	Reducing Tee – Run to Branch and Run	29	↑
*	Tee – Run and Branch to Run (Main)	26	↑
15	Tee – Run to Run (No Branch Flow)	28	↔
16	Reducing Elbow (Small End)	0	**0**
*	Reducing Elbow (Large End)	0	**0**
17	Reducer (Small End)	6	**0**
*	Reducer (Large End)	6	**0**
18	Expander (Small End)	65	↔
*	Expander (Large End)	65	↓
19	Expanding Elbow (Small End)	0	↔
*	Expanding Elbow (Large End)	0	↔
20	Angle Valve	0	↔

Table 4-6 (continued)
Qualitative Two-Phase Results for Fittings

Geometry Code	Description	Number	Δ
21	Globe Valve	0	↔
22	Gate Valve	2	↔
23	Butterfly Valve	0	↔
24	Control Valve	0	↔
25	Check Valve	1	↔
30	Inlet Nozzle	145	🡅
31	Exit Nozzle	54	🡅

Note that an asterisk (*) in the Geometry Code Field indicates a sub-component associated with the component listed above.

Table 4-7
Qualitative Two-Phase Results for Pipes Downstream of Fittings

Geometry Code	Description – Pipe Downstream of	Number	Δ
51	45° Elbow	9	0
52	90° Elbow	137	↔
53	45° Elbow with Close Upstream Fitting	10	⇧
54	90° Elbow with Close Upstream Fitting	69	⇧
55	180° Return	0	0
56	Orifice	6	0
57	Reducer with Close Upstream Fitting	17	⇧
58	Valve	51	🡇
59	Straight Pipe	0	0
60	Tee – Branch to Runs	3	0
61	Tee – Runs to Branch	10	⇩
62	Tee – Run and Branch to Run	18	0
63	Tee – Run to Branch and Run	7	0
64	Reducing Tee – Run to Branch and Run	8	0
65	Tee – Run to Run (No Branch Flow)	7	0
66	Reducing Elbow	0	0
67	Reducer	0	0
68	Expander	17	⇩
69	Expanding Elbow	0	0
70	Angle Valve	0	0

Sensitivity Study of Component Diameters

To evaluate the possibility of a change in two-phase geometry factor with diameter, the three most common geometry factors (i.e., Geometry Factor = 2, 4 and 30) were examined. Plots similar to Figure 4-1 were made. These showed the expected scatter, but no trend.

5 STAGE 2 RESULTS

The results of the Stage 2 section of this project will be presented in this section.

Background

The concept of an "upstream geometry effect" has been around for years. Briefly, this effect presumes that the location of the component upstream influences the geometry factor of the downstream component. Thus, the geometry factor of, say, an elbow would be higher when there is an upstream fitting in close proximity as opposed to an elbow with a long, straight pipe upstream.

In fact the earliest versions of the EPRI programs recognized, for example, the differences between a Type #2 elbow and a Type #4 elbow.[4] Also, both the Electricité de France program, BRT-CICERO™ [12], and the AREVA program, COMSY [13], have used this concept as well. The methodology used in BRT-CICERO™ is discussed in [1]. Finally, some recent laboratory work in Canada seems to endorse this approach. The applicability of the Canadian work, particularly [9], to this project will be discussed later in this section.

Data Used

From the databases described earlier, components with the following attributes were selected for consideration in this stage of the project:

- Geometry Codes 1 through 5 – that is elbow-like components.
- Had measured wear
- Had a listed distance to the nearest upstream component.

There were a total of 1,542 components available with these characteristics. They are broken down in Table 5-1. Note that most of these components are single-phase.

[4] It is also still present in that there are two types of reducers – Geometry Code 7 and Geometry Code 17. The difference being that the Geometry Code 7 reducers have an upstream component within one pipe diameter.

Table 5-1
Breakdown of Components Used for Stage 2

Geometry Code	Description	Number Single-Phase	Number Two-Phase	Total	Outside Diameter Range - Inch
1	45° Elbow	131	13	144	3.5 – 30
2	90° Elbow	848	184	1,032	3.5 – 36
3	45° Elbow with Close Upstream Fitting	39	1	40	4.5 – 30
4	90° Elbow with Close Upstream Fitting	282	35	317	3.5 – 36
5	180° Return	9	0	9	3.5 – 10.75
	Total	1,309	233	1,542	- - -

Data Analysis

The following approach was used to analyze the data:

- The FORTRAN program read the input files and produced an output file containing data for each selected fittings, the correct geometry factor and the ratio of the upstream distance to the inside diameter (i.e., x/ID).
- The FORTRAN output file was read by MS EXCEL and EXCEL was used to produce a plot of the correct geometry factor versus the distance to diameter ratio. If data were available, plots were also made of the single-phase components as well as for the two-phase components.
- To aid in the analysis, EXCEL was then used to fit a linear trend line through the data. A typical plot, in normalized fashion, is presented as Figure 5-1.
- For the geometry codes with large number of data points, i.e., geometry codes 2 and 4, additional plots were made to examine possible parametric influences, including:
  - Producing individual plots for the single-phase and two-phase data.
  - Producing plots for four diameter ranges using the single-phase data.
  - Producing plots with varying maximum distance to inside diameter ratios using the single-phase data.
  - Some of the above plots were re-plotted with obvious outliers removed.

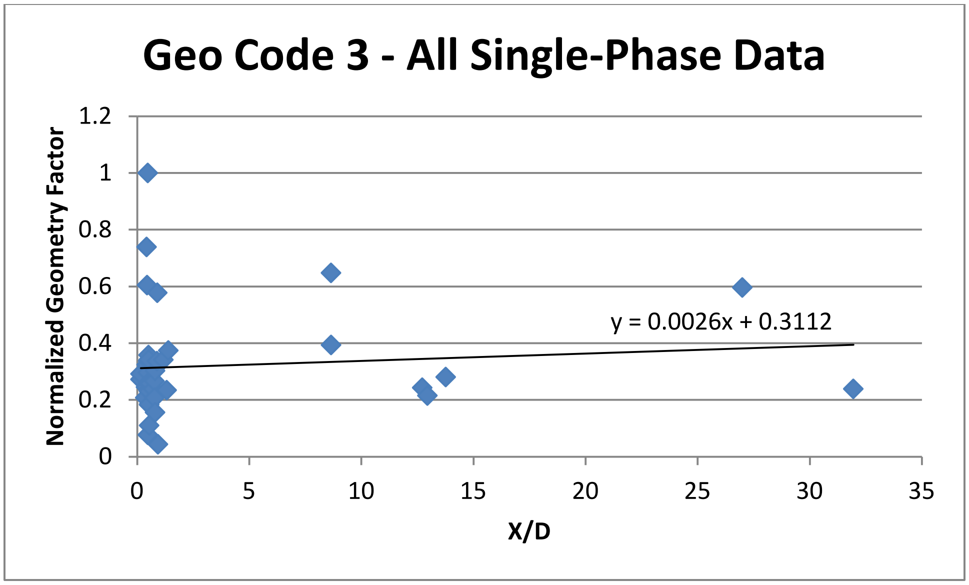

Figure 5-1
Stage 2 Results for CHECWORKS™ Geometry Code 3

Discussion of Results

Overall View of Data

The first step in analyzing the results was to review the five plots produced showing all the data for each geometry code. In every case, there was no decrease apparent of the geometry factor as the upstream distance increased. In fact, for every case, the trend line showed a positive slope, i.e., the geometry factor increased with increasing upstream distance. This is opposite of what would be expected from the upstream geometry effect.

Detailed View of the Data

After the first look at the data, a detailed review was performed for the two components with the most data – geometry codes 2 and 4 – i.e., the 90° elbows. This detailed look consisted of plotting subsets of the overall dataset as described above.

Observations

Based on consideration of all the plots made, there was no obvious tendency for the correct geometry factor to decrease with distance as would be expected with an upstream effect. While it is true that the data plots all had considerable scatter, there was no downward trend that appeared to be more than random scatter.

Applicability of the Canadian Work

Background

For the past several years, the CANDU® Owners Group has sponsored research at McMaster University, Hamilton, Ontario. This research has been focused on using the plaster of Paris dissolution method studying the influence of various geometrical parameters on the wear patterns seen in modeled elbows. From these wear patterns, the geometry factors were deduced.

The most recent laboratory work available [9], concentrated on the behavior of combinations of bends of various bend radius to diameter ratio in an out of plane configurations. Their previous work (e.g., [14]) had studied two other configurations called: "C-shaped" and "S-shaped." These configurations are shown schematically in Figure 5-2.

This work demonstrated that there was an upstream effect, i.e. the geometry factor decreased as the distance between the pair of bends increased. See, for example, Figure 5-3 from [9]. Note that the results indicate a considerable decrease (~33%) in the geometry factor going from back to back configuration (i.e., L/D=0) to a 5 diameter separation.

Another Canadian paper [15] states that CANDU® plant data has shown a large increase in the FAC rate in close-proximity bends (i.e. bends within one piping diameter).

Finally, it was recently determined that similar work is being done in Japan [16] studying the velocity profiles in the area downstream of various elbow configurations.

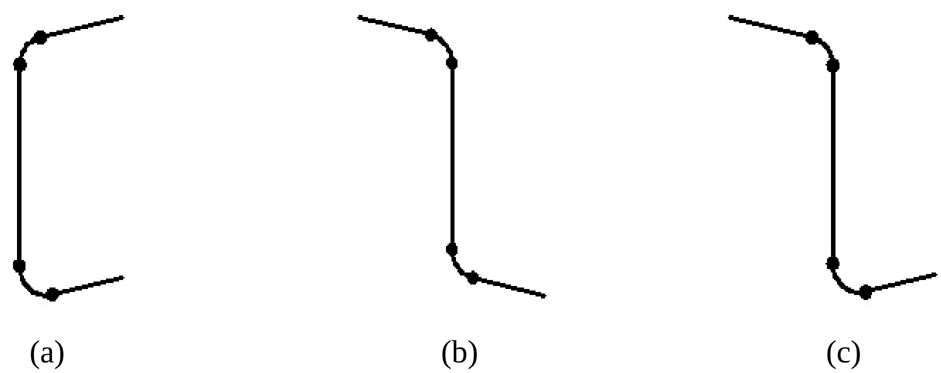

Figure 5-2
Test Geometries Used in the Canadian Work (a: C-shaped – in plane; b: S-Shaped – in plane; and c: Out of Plane)

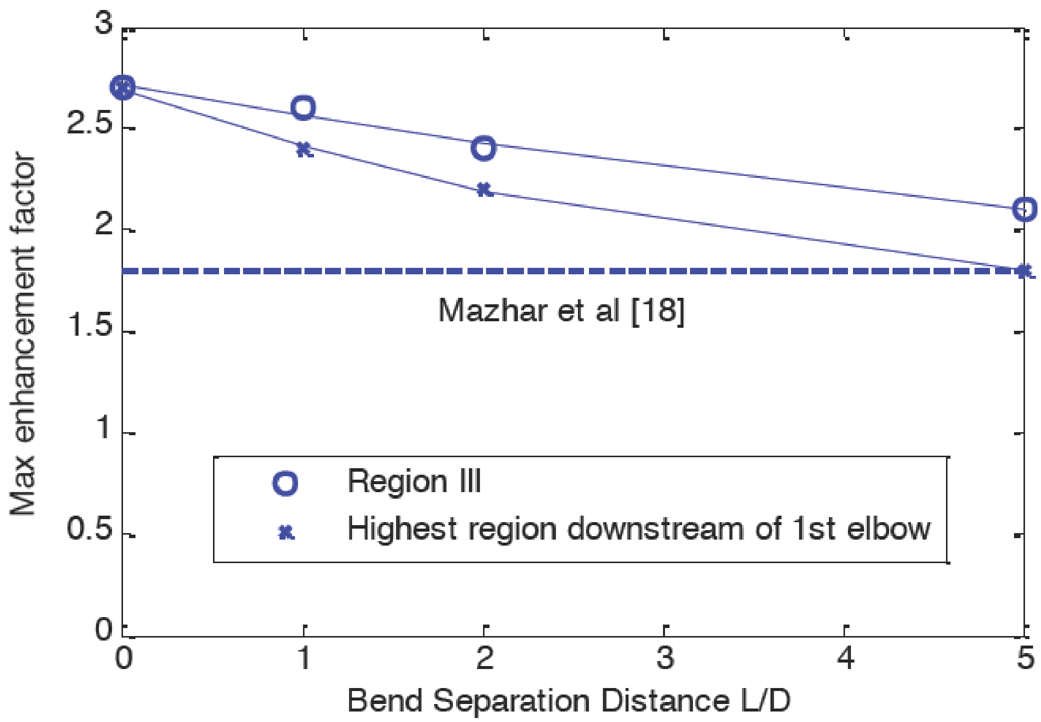

Figure 5-3
Results from the Out of Plane Configuration Tests [9]

Applicability to the Current Work

Although it is probably correct that there should be an upstream effect, the extensive dataset reviewed in this work did not reveal such an effect. There are at least two reasons why this may be so:

- The use of plant data is not an accurate enough to see the upstream effect. By the nature of what was done, all of the results were combined and it is possible that the effect was lost in the process of 'averaging' the results.
- The laboratory work done use an idealization of the geometry which does not match what the situation found in plants. For example, the details of the upstream flow and weld connections probably influence the geometry factor. The basis for this claim is that the geometry factors determined by computational fluid dynamics (CFD) tend to be smaller than the geometry factors determined by plant data.

As this project was designed to look at plant data, the proper conclusion is that no upstream effect was seen in this work.

6
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

From the work performed, the following conclusions for the two stages of this work are presented below.

Stage 1 Results

The recommended geometry factors for all of the geometry codes in CHECWORKS™ are presented qualitatively in Chapter 4. Generally, the recommended geometry factors for the most commonly used geometries had only small changes from their current values.

No change is recommended for the treatment of counterbores.

An investigation of the influence of elbow R/D on the geometry factor has shown that higher R/D ratios have higher geometry factors. It is recommended that elbows and sweeps be treated separately in the future versions of CHECWORKS™.

Stage 2 Results

No effect of upstream geometry was seen in the examination of data for Geometry Codes 1 through 5 (i.e., all of the elbows). The previous laboratory work showing this effect may well be correct, but the effect was not seen in plant data.

Recommendations

Based on the work performed here, with the exceptions of some detailed suggestions for related work presented below, it is recommended that no further work be performed in this area.

The following related work could be considered:

- **Adding Geometry Codes.** There has been user demand in the past to add some geometry codes. Among these are: downstream of a venturi, downstream of a flow nozzle, and a pipe cap. However, on at least one past occasion, the CHUG membership was solicited for data on such fittings, and insufficient data to develop geometry factors was available.
- **Elbow R/D Results.** As stated in Section 4, the plant data shows the anomalous results that the higher the R/D the greater the single-phase geometry factor. This result conflicts with both intuition, CFD, and laboratory results. An investigation could shed light on this issue.
- **Reconciliation of CFD results with Plant Data.** CFD seem to produce lower geometry factors than plant data. For example, the results of [6] show a geometry factor for a 90° elbow to be about half that of the geometry factor derived from plant data. This observation also holds with regard to the recent Canadian paper [15]. Clearly, explanations for this could be generated, but without more work, those explanations could not be verified.

7
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3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
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