Evaluation of Multiple-Inspection Flow-Accelerated Corrosion Data on Unequal Grids

1020527

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Technical Update, April 2010

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Work to develop this product was completed under the EPRI Nuclear Quality Assurance Program in compliance with 10 CFR 50, Appendix B and 10 CFR Part 21,

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This document describes research sponsored by the Electric Power Research Institute (EPRI).

This publication is a corporate document that should be cited in the literature in the following manner:

Evaluation of Multiple-Inspection Flow-Accelerated Corrosion Data on Unequal Grids. EPRI, Palo Alto, CA: 2010. 1020527.

PRODUCT DESCRIPTION

Inspections to detect damage from flow-accelerated corrosion (FAC) in large-bore piping components are routinely performed in nuclear power plants. These inspections are normally performed using ultrasonic testing (UT) on a predefined grid. Evaluation of the data obtained to determine the amount of degradation that has occurred is one of the important and challenging functions of FAC engineers.

Previous EPRI guidance has been primarily directed at evaluating data from single inspections or multiple inspections with identical grids. However, there is no generally accepted way of evaluating data from two or more inspections when the measurement grids or inspection methodologies are different (for example, ultrasonic versus radiographic inspection). Because this is a not an uncommon occurrence, the membership of the CHECWORKS™ Users Group (CHUG) recommended that EPRI perform a study examining and evaluating methods to handle unequal grids or differing inspection methodologies. Three methods were selected and evaluated, and this report presents the results of this study.

Results and Findings

Inspection data evaluation methods were reviewed, and three methods for estimating the amount of degradation that had occurred were selected. Inspection data sets from several nuclear units were examined, and data sets from multiple inspections were selected, modified as necessary, and evaluated. Purpose-built FORTRAN programs were used as far as possible to estimate the wear using these methods.

With some reservations, it is recommended that the slope of the minima method be used to evaluate this situation of multiple inspections using unequal grids. Serious consideration should be given to incorporating this method into the next release of the CHECWORKS™ Steam Feedwater Application (SFA).

Challenges and Objectives

This report should be of value to FAC engineers because it describes and evaluates methods of evaluating data from multiple inspections with unequal grids. Differing inspection methodologies (for example, UT, RT, etc.) can be accommodated, assuming that the data resulting from these inspections are presented in a grid format that can be imported into CHECWORKS™ SFA. To date, such data have been evaluated using time-consuming *ad hoc* methods. As such, FAC engineers should be able to perform this portion of their job more efficiently. Additionally, more accurate evaluations should be possible, which could lead to the elimination of unnecessary reinspections.

Applications, Value, and Use

The use of the slope of the minima method for evaluating unequal grids should be a valuable addition to the suite of inspection evaluation tools available in CHECWORKS™ SFA. This method would satisfy the need of FAC engineers to have a standard methodology to handle multiple sets of inspection results taken on unequal grids.

EPRI Perspective

CHECWORKS™ SFA is the most widely used FAC evaluation program in the world. The continued addition of new evaluation approaches has helped it maintain its competitive position.

Approach

The primary goal of this report was to examine the suitability of methods to evaluate multiple sets of inspection data with differing grids. Three potential methods were identified and examined. Plant data from several plants were used to make this evaluation.

Keywords

Data evaluation
FAC
Flow-accelerated corrosion
Radiography
RT
UT

ACKNOWLEDGMENTS

The author wishes to acknowledge the utility engineers who provided the data used in this work. The contributions to this work of Harold Crockett, David Ha, and Stacey Burnett of EPRI are also acknowledged.

The helpful suggestions of several utility engineers who reviewed this work are also acknowledged.

CONTENTS

1
INTRODUCTION

1.1 Background

Flow-accelerated corrosion (FAC) is a degradation mechanism that attacks carbon steels under specific operating conditions. Unfortunately, these conditions are often found in power plants. Consequently, loss of pipe wall material due to FAC has caused numerous leaks and ruptures resulting in fatalities, costly outages, and replacement of piping and equipment. Some of the experience is described in the EPRI report *Flow-Accelerated Corrosion in Power Plants* (TR-106611-R1) [1].

Because of the potential damage possible from FAC, utilities have initiated programs to protect their plants from degradation caused by FAC. Interpreting nondestructive evaluation (NDE) inspection data is one of the most important tasks performed as part of a FAC program. The task is to evaluate the inspection data and to determine in a realistic manner the amount of degradation or wear that each component is experiencing. If the analyst is overly conservative, unnecessary inspections will be performed. If the analyst is nonconservative, dangerous situations may occur because the reinspection intervals will be longer. In the extreme example of this, failures could result due to the lack of reinspection.

In general, evaluating NDE data involves reviewing one or more matrices of inspection points, often several hundred individual data points, and determining a single value that represents the amount of wear experienced in a given time period. If there is more than one set of data available or if the data were obtained using differing inspection methodologies resulting in different grid sizes, then the task involves analyzing and interpreting all of this information, again to determine a single value of the measured wear for a given time period.

The task of accurately interpreting inspection data is made much more difficult when only one set of inspection data is available. The major difficulty is the fact that even brand new components will have a nonuniform wall thickness distribution. Unfortunately, the interpretation of data from multiple inspections presents difficulties of its own.

1.2 Interpreting Multiple-Inspection Data

For the purpose of this work, *multiple-inspection data* will be defined as two or more sets of data taken using any grid arrangement. Currently, the CHECWORKS™ Steam Feedwater Application (SFA) [2] provides four methods for analyzing data from components with **identical** grid arrangements. These methods may be used automatically when there are only two sets of data. When there are more than two sets of data, the user must choose which pair of inspections will be used. As currently configured, the program can handle only a pair of data sets at a time.

It is important to realize that the objectives of these methods are to estimate accurately the location and the extent of the maximum wear, that is, the loss of material experienced by the component measured. The four methods that are available in the SFA are as follows:

- The maximum delta method
- The average delta method
- The cutoff delta method
- The fast delta method

These methods are also known collectively as “point-to-point” (PTP) methods and are described later in this report.

Finally, it should be understood that all of the PTP methods tacitly assume that the wear rate is constant during the period of measurements. This implies that the water chemistry and operating conditions are unchanged throughout the period. The analyst must be aware of this assumption and, if necessary, account for any changes of conditions.

The subject of the importance of data accuracy in PTP evaluations has been the subject of recent work sponsored by the CHECWORKS™ Users Group (CHUG) [3, 4]. These investigations have shown that FAC engineers must be careful when using PTP methods to evaluate small amounts of wear.

It should be stressed at this time that there are no generally accepted methods for evaluating data from multiple inspections if the grids are not identical (that is, not suitable for analysis using PTP methods).

1.3 Why Unequal Grids?

It is certainly a legitimate question to wonder why there are grids that do not match other grid arrangements because it seems obvious that grids, once established, should remain unchanged. There are two main reasons for this to occur:

- **Change of procedure:** Often utilities have changed their gridding procedure. For example, the process may have changed from scanning the area between grid lines to recording the values at the grid intersections. Another example would be modifying the grid size to account for a new governing procedure. This has occurred when a plant has been absorbed by another utility or when gridding was not standardized (in early years).
- **Errors:** Occasionally, when re-gridding a component, an error will be made, and there will be, for example, an extra row of data. If this error is not caught during an outage, this dataset will not match the previously taken data.

1.4 Report Overview

The report is organized as follows:

- Section 2 presents the objective of this work.
- Section 3 presents a description of the methods available for evaluating inspection data for single-inspection data sets and for multiple-inspection sets with equal grids.
- Section 4 presents a description and evaluation of the three methods selected for evaluating inspection data with multiple sets of inspection data with unequal grids
- Section 5 presents recommendations and conclusions.
- Section 6 contains relevant references.
- Several appendices provide additional information.

2
OBJECTIVE

The objective of this work was to identify and examine available methods for evaluating multiple sets of inspection data taken on unequal grids and making recommendations for their use.

3
AVAILABLE INSPECTION DATA EVALUATION METHODS

This section will present some of the available methods for evaluating inspection data. It will be broken down into three areas: Single-inspection data, data from two inspections with identical grids, and data from more than two inspections with identical grids.

3.1 Single-Inspection Methods

Historically, single-inspections methods were used originally to evaluate inspection data (that is, there were no baseline inspections since secondary piping was not typically inspected at the time of installation). In time, most engineers have preferred to use, when possible, the multiple-inspection methods discussed below. Note, however, that there are times when the use of single-inspection methods is necessary. EPRI report *Determining Piping Wear Caused by Flow-Accelerated Corrosion from Single-Outage Inspection Data* (1013012) [5] is a recent work that evaluates some of the newer single-inspection methods.

3.1.1 Band Method

The band method is the oldest and simplest method available in CHECWORKS™ SFA [2]. The band method assumes that the component initially had uniform cross sections along its length. With this implicit assumption, the method used to calculate the wear from the band method is as follows:

1. The component is divided into bands (that is, circumferential rings) that are one inspection point wide.
2. The maximum and the minimum measured thicknesses in each band are determined.
3. The band maximum thickness is defined as the larger of the maximum measured thickness or the nominal thickness.
4. The band wear for that band is taken as the maximum thickness less the minimum measured thickness.
5. The band wear for the component is taken as the maximum of the individual band wears.

As might be expected, the band method works well with components that initially have nearly uniform cross sections, such as straight pipes and concentric reducers. It produces overly conservative results for components such as elbows or other components that do not have a uniform cross section.

The band method is available in the Wear Calculation module of CHECWORKS™ SFA.

3.1.2 Average Band Method

The average band method is an improvement to the band method [5]. The wear calculation is similar to the band method and is performed as follows:

1. The component is divided into bands (that is, circumferential rings) one inspection point wide.
2. The mean (that is, arithmetic average) and the minimum measured thicknesses in each band are determined.
3. The band maximum thickness is defined as the larger of the mean measured thickness or the nominal thickness.
4. The wear for that band is taken as the mean thickness less the minimum measured thickness.
5. The average band wear for the component is taken as the maximum of the band wears.

This method has been shown to perform well for straight pipes, elbows, and reducers.

The average band method is available in the Wear Calculation module of CHECWORKS™ SFA.

3.1.3 Moving Blanket Method

The moving blanket method (MBM) was developed in the mid-1990s to overcome the shortcomings of the band method, particularly when applied to elbows [6].

The concept of the MBM is to compare the thickness readings in a rectangular portion of a component called a *blanket.* The following process is used to calculate the wear using the MBM:

1. The component is divided into blankets. The blanket size that yields the best results has been found to be one that spans both of the following:
   - Three grids in the longitudinal direction
   - One-third of the diameter of the component in the circumferential direction. (Note that this is the default blanket size in CHECWORKS™ SFA.)
2. In each blanket, the upper value is the larger of the average of two highest readings or the nominal thickness. The lower value is the average of the two lowest readings. The difference between the upper and lower values is taken as the blanket wear.
3. All possible blanket locations are considered.
4. The maximum blanket wear in the component is taken as the wear.

The MBM works well for elbows and straight pipes, but not for reducers. Note that it has been reported that the MBM does not work well for elbows that are Schedule 100 and above, probably due to the likely presence of counterbores.

The MBM is available in the Wear Calculation module of CHECWORKS™ SFA.

3.1.4 Area Method

The area method is a variation on the above methods with the area being defined by the user. Thus in a given area, the component wear is taken as the difference between the high or nominal (whichever is greater) and the low point. Clearly, this method should be used with care. The Wear Calculation module of CHECWORKS™ SFA allows the user to select any rectangular area in the component data for evaluation using this method.

3.1.5 Strip and Other Methods

The above methods do not exhaust the possibilities for determining the wear from single-inspection data. For example, the strip method is similar to the band method, except longitudinal strips are used rather than circumferential bands. This method is described along with numerous other possibilities in a recent EPRI report (1013012) [5].

3.2 Two Inspections with Identical Grids

The following methods are available for evaluating data from two inspections with identical grids. These methods are all accessed by selecting both inspection periods and then entering the Wear Calculation module of CHECWORKS™ SFA.

3.2.1 Maximum Delta Method

The maximum delta method is the simplest and most commonly used method for interpreting multiple-inspection data. Thickness readings from identical grid points are subtracted. The largest difference is taken as the wear for the component. This wear value divided by the operating time between inspections is taken as the wear rate. In spite of its inherent simplicity, the method has two main disadvantages:

- The result is dependent on the accuracy of two specific readings. If either the first or second reading is in error, the result will be directly impacted.
- The result may be accurate, but the location of the wear may be occurring in a thick portion of the fitting that is not life limiting.

3.2.2 Average Delta Method

In the average delta method, all of the differences between the thicknesses are averaged. The average value is taken as the wear. This results in an overly nonconservative (that is, the wear obtained is less than the maximum) value of the component wear. That is, this method understates the wear compared to other methods since, on average, the fitting is wearing less than the maximum location. Consequently, this method is not normally used.

3.2.3 Cutoff Delta Method

The cutoff delta method was developed to attempt to overcome the shortcoming of the maximum delta method, namely that the wear may be occurring in a non-life-limiting location within the component. The steps that are performed in using the cutoff delta method are the following:

1. The minimum thickness of the component is determined.
2. A cutoff thickness is calculated by multiplying this thickness by the cutoff ratio input by the user. This value is often taken as 112%.
3. The two sets of inspection data are subtracted to obtain the matrix of the thickness differences at each grid point.
4. Only those areas of the component that are thinner than the cutoff thickness are considered. The maximum difference between the thickness matrices from this area is taken as the component wear.

This method has been in the release version of CHECWORKS™ SFA for several years, and only a small amount of user feedback has been received concerning the usefulness of this approach.

3.2.4 Fast Delta Method

The fast delta method was also designed to overcome the problem of the maximum delta method (that is, that the wear could be determined in the non-life-limiting portion of the component). At the same time, this method avoids the necessity of a user-defined input value, that is, a cutoff thickness. The steps that are performed in using the fast delta method are the following:

1. At each point where there is a pair of valid inspection points, the wear rate is calculated by dividing the difference in readings by the operating time between inspections. This calculation defines the linear wear rate.
2. At each point, the time to reach minimum thickness is calculated using an extrapolation of the linear wear rate.
3. The negative of the slope of the line with the minimum time is taken as the component wear rate.
4. The wear rate is then multiplied by the operating time at the last inspection to yield the wear at that inspection.

This method has been in the release version of CHECWORKS™ SFA for several years, and only a small amount of user feedback has been received concerning the usefulness of this approach.

3.3 Data from More Than Two Inspections with Identical Grids

Note that at the present time, none of the following evaluation methodologies are available within CHECWORKS™ SFA.

3.3.1 Least Squares Point-to-Point Method

Recently, EPRI has become aware of the method used by Japanese utilities to evaluate inspection data from three or more outages with identical grid patterns [7]. In January 2008, the CHUG recommended to EPRI that an assessment be made of this method. The EPRI report *Least Squares Methods for Evaluating Inspection Data* (1018456) [8] is an evaluation of this method.

Note that in this report, the method is called the least squares point-to-point (LSPTP) method. The following steps are performed to determine the wear using the LSPTP method:

1. At each point where there are at least two valid inspection points, a linear, least-squares straight line is fit through the measured thickness versus the operating time.
2. The straight lines are extrapolated to the minimum specified thickness for the fitting.
3. The measurement location with the least time to the minimum thickness is the determinate location.
4. The negative of the slope of the straight line in the determinate location is taken as the wear rate.
5. The wear rate is then multiplied by the operating time at the last inspection to yield the wear at that inspection.

Note that this method is an extension of the fast delta method for more than two inspection locations. Note also that for two inspection locations, it reduces to the fast delta method.

In the course of developing EPRI report 1018456 [8], a variation of the LSPTP method was developed. This method is referred to below as the LSS—for least squares slope method.

3.3.2 Least Squares Slope Method

The least squares slope method was an outgrowth of the examination of the LSPTP method [8]. As is the case with the LSPTP method, a least squares straight line is fit through the thickness data at each grid point. The wear rate is taken as largest negative slope of the grid points evaluated. The wear at the time of the last inspection is the product of the wear rate (just determined above) by the operating time.

As demonstrated in the cited report, both the LSPTP and the LSS methods generally give wear rates as low as or lower than the corresponding wear rates determined by the maximum delta PTP method. This is discussed at length in EPRI report 1018456 [8].

Although, there is limited experience in the United States with the two methods described above, they seem preferable to other approaches for this situation.

3.3.3 Slope of the Minima Method

This method was formally described in the EPRI report *Optimization of FAC Inspections: BWR Feedwater Systems* (1018466) [3], although it had been used informally by a number of FAC engineers previously. As compared to the various methods previously discussed, this methodology uses an entirely different approach:

1. The minimum thickness on the entire component is determined for each inspection.
2. With these values and the knowledge of the operating time at each inspection, a least squares straight line is fit through these thicknesses versus time.

3. The negative slope of this line is the wear rate.
4. The wear at the time of the last inspection is the product of the wear rate (determined above) by the operating time.

This method is discussed and demonstrated in the EPRI report *Statistical Methods for the Analysis of Multiple-Inspection FAC Data* (1019175) [4].

3.3.4 Use of Conventional PTP Methods

Of course, the FAC engineer may elect to use any of the PTP methods used for two inspections to evaluate the degradation between any two inspection locations. Normally, the first and last inspection locations are chosen for this determination.

4
EVALUATION METHODS CONSIDERED

4.1 Introduction

In considering the problem of correcting for the presence of differing grids, there seemed to be three separate approaches to the problem:

- Basing the determination of the wear on each grid independently from the other measurements
- Correcting for the misplaced points by mathematically correcting the position of the data
- Ignoring the grids entirely

In considering these categories of approaches available to evaluate data from multiple inspections with unequal grids, three methods were selected for evaluation—using single-inspection methods, interpolation to match grids, and the slope of the minima method. These methods will now be described and evaluated.

4.2 Using Single-Inspection Methods

4.2.1 Description

As apparent from the name, single-inspection methods use information from only one set of inspection data. Consequently, it is always possible to employ a single-inspection method (or methods) multiple times (one for each data set), and from the combined results, deduce the wear and wear rate that has been experienced.

If a single-inspection method operates in an ideal fashion, the wear predicted by the method should increase with operating time in a monotonic (that is, always increasing) fashion. Note that the slope of the curve would be the wear rate. Realistically, the behavior could be expected to be a roughly monotonic increase with a curve fit through the data producing a reasonable estimate of the wear rate. A sample of such a data plot is shown in Figure 4-1.

Consider Figure 4-1. Note the data scatter, but with the trend upward of the points. Note also the equation of the straight line through the data. The slope is positive at about 12 mils per year (a reasonable value of the wear rate). Note also that the intercept is around 30 mils. This indicates that the method is not perfect, but again should be considered reasonable.

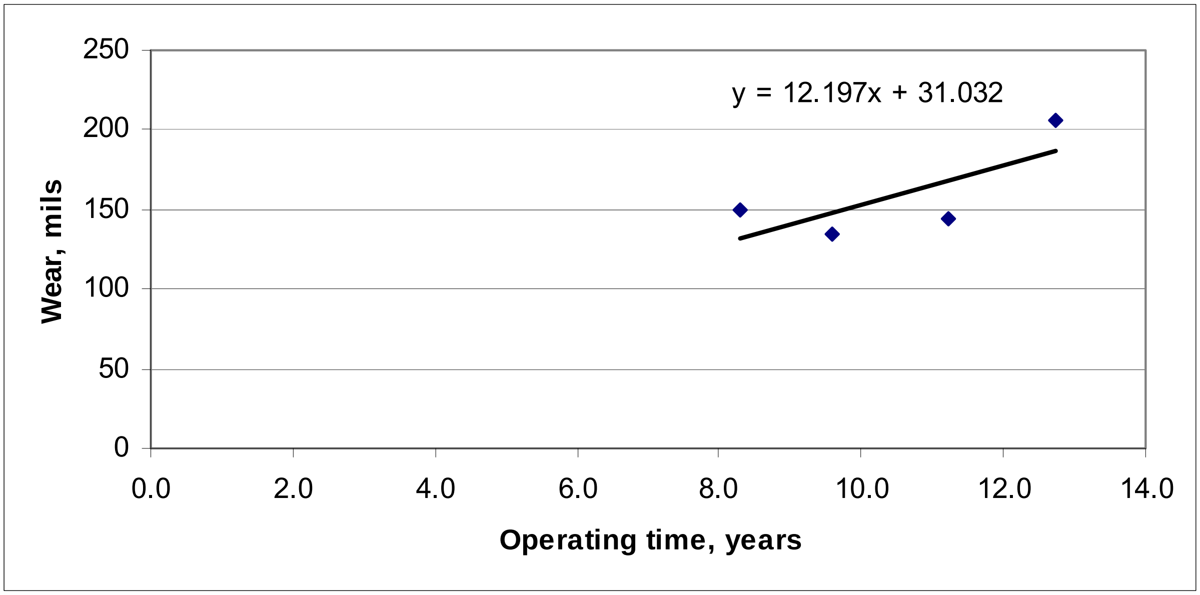

Figure 4-1
Sample of Data Plot with a Positive Slope

Now, consider Figure 4-2, which shows a commonly seen appearance of this type of plot. Note that the slope is negative, and the wear, estimated by the single-inspection method, is not changing much with time. This is a situation where one could not expect reasonable answers from this approach.

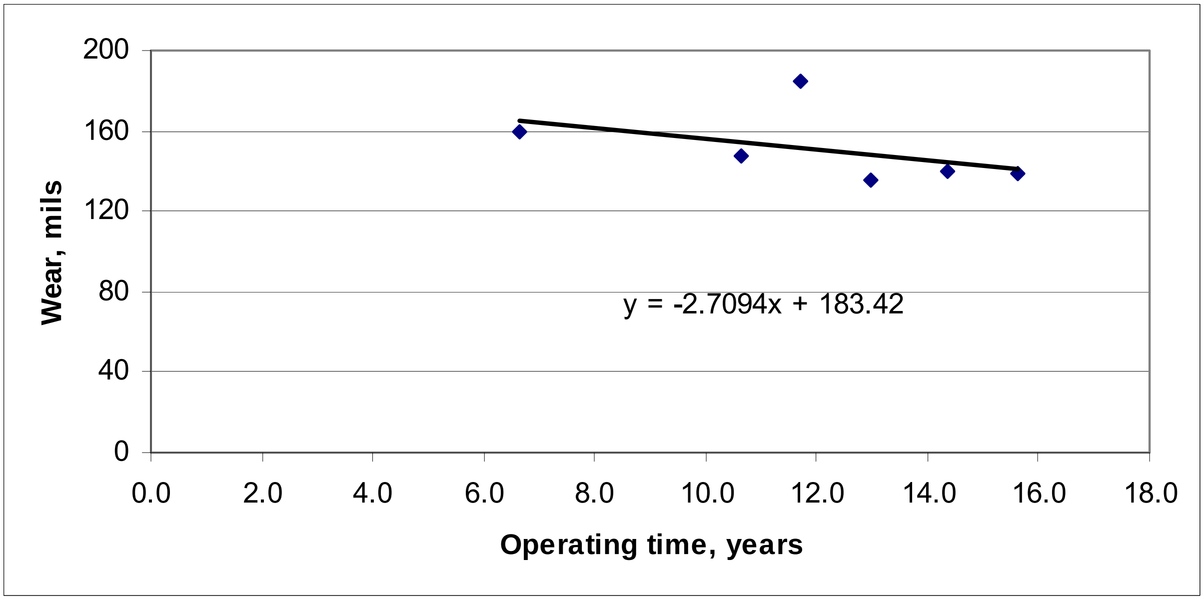

Figure 4-2
Sample of Data Plot with a Negative Slope

4.2.2 Evaluation

A large database of 227 components with multiple-inspection plant data was used in this evaluation. This database has been used in other reports. A summary of the data used is presented in Table 4-1.

Table 4-1
Plant Data Used to Evaluate the Single-Inspection Method Approach

Number of Inspections	Number of Components
2	29
3	117
4	46
5	14
6	12
>6	8
	227

The components were examined using a purpose-built FORTRAN program that evaluated for each inspection period the amount of wear as predicted by the average band method and the moving blanket method. After the data were calculated, a least-squares straight line was fit through the wear versus operating time, and the slope and intercept recorded.

Both the moving blanket method and the average band method were studied. As a first step to examine the characteristics of this approach, the number of negative and zero slopes for each method was counted. Recall that a negative or zero slope would indicate that the method was not providing useful results. (This assumes, of course, that the component was actually wearing.[1]) A summary of these results, expressed as percentages, is presented in Table 4-2.

Table 4-2
Summary of the Results of the Single-Inspection Method Approach

	Positives	Zeros	Negatives
Average Band Method	37%	21%	41%
Moving Blanket Method	48%	0%	52%

4.2.3 Conclusions

Based on the evaluations performed, the use of single-inspection methods will yield nonphysical results more than half the time. Thus, this approach is not recommended.

[1]This assumption that these components are showing wear is supported by the fact that all of the evaluation methods used indicate that they are wearing. However, the more fundamental question of whether the components are actually wearing is addressed using statistical methods in EPRI report 1019175 [4].

4.3 Curve Fitting or Data Interpolation

4.3.1 Description

Mathematically, the question of how to relate different grid arrangements has been widely studied in the mathematical areas of curve fitting and interpolation. The simplest method is linear interpolation with the next simplest being bilinear interpolation from one grid to another. Although there are other more complicated methods available, the two variants of interpolation will be used in this report. Mathematical treatments of these two types of interpolation are presented in Appendix A. Also, included in this appendix is an explanation of how these methods can be used to relate grids with different sizes.

4.3.2 Evaluation

The evaluation of interpolation methods posed problems in that if unequal grid data were used, there would be limited ways to verify the results. Also, there are clearly a number of different possibilities of unequal grids, and producing software to test them all would be very time consuming. To deal with these issues, a different approach was adopted.

A number of data sets were examined by selectively removing portions of data and reestablishing the data by use of linear interpolation. Different patterns were used to remove the individual data points. Some of these results are discussed in Appendix B. Unfortunately, no clear results could be drawn. Rather, the results depended on the data used and the particular data points removed.

4.3.3 Conclusions

Although these tests are difficult to summarize, the conclusion was that the success of the interpolation process, measured by how close the interpolated value was to the value removed, varied greatly with the component being examined and the grid points involved. Based on this, interpolation cannot be recommended as a general method for dealing with unequal grids.

Interpolation could be used with caution to evaluate simple situations—normally, cases where linear interpolation could be used.

4.4 Slope of the Minima Method

4.4.1 Description

The slope of the minima method was first defined in EPRI report 1018102 [3], although it was used previously in various forms by FAC engineers. This method is unique among the multiple-inspection evaluation methods, described in the previous section, in that its use is independent of grids. Thus, it seems a natural approach to use this method to evaluate multiple-inspection data on unequal grids.

4.4.2 Evaluation

The evaluation of the slope of the minima method was performed in two parts. The first phase looked directly at the equal grid data from Table 4-1. For each component, the wear rate using the slope of the minima method was calculated and compared to the wear rate determined by the maximum delta PTP method taken from the first and last inspection. Figure 4-3 presents a comparison of these two methods. As seen in earlier work, the wear rates determined by the slope of the minima method will always be below those determined by the maximum delta PTP method.

The second phase was to use the same data set and modify some of the inspection data so that some of the data points were missing. In this way, different grids were simulated. Because this method is completely independent of the inspection grid used, these modified component data sets were evaluated using the slope of the minima method. These evaluations were then compared to the evaluations using the full grids as described above. The evaluations performed are discussed in Appendix C.

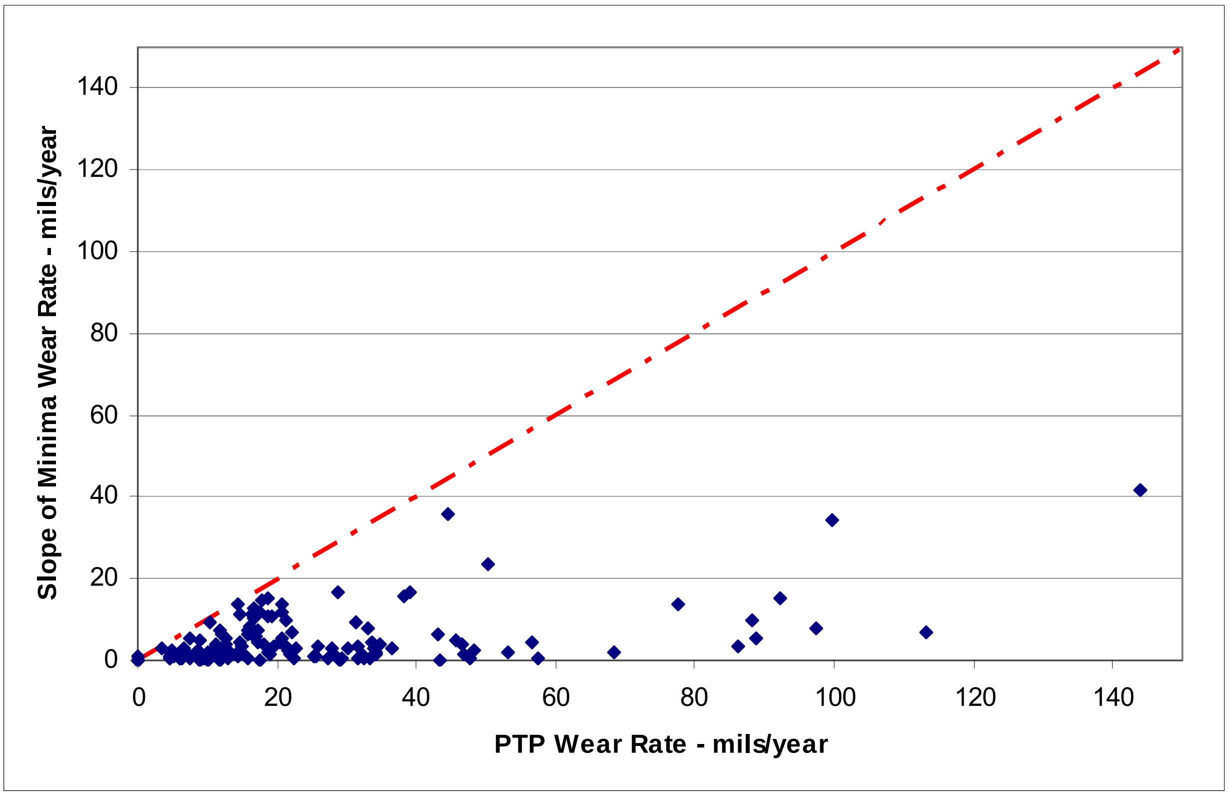

Figure 4-3
Comparison of Slope of the Minima and Point-to-Point Wear Rates

4.4.3 Conclusions

Based on the evaluations performed, it appears that the slope of the minima method should be the preferred method for performing evaluations on inspections with unequal grids. As shown in Appendix C, caution may be required if the unequal grid is the last one used.

5
RECOMMENDATIONS AND CONCLUSIONS

5.1 Conclusions

Based on the work performed, the following conclusions were reached:

- When used with multiple-inspection data, the use of single-inspection methods, as described in Section 4, may produce unreliable results and, therefore, are not generally recommended.
- Although it is possible that linear or bilinear interpolation may be appropriate for certain cases, they are not generally recommended.
- The slope of the minima method appears to be the method most suited to evaluate inspection data on unequal grids.

5.2 Recommendations

Based on the work performed, the following recommendations are offered:

- The slope of the minima method should be added to CHECWORKS™ SFA. This repeats the recommendation made in EPRI report 1018466 [3].
- When this method is used with unequal grids, the user should be warned of the fact that unequal grids are being used.

6
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A
INTERPOLATION

This appendix will describe linear and bilinear interpolation. The relevance of these methods to the issue of unequal grids will also be discussed.

A.1 Linear Interpolation

Prior to the days of the widespread availability of electronic calculators, linear interpolation was normally described to high school students when tables of logarithms or trigonometric functions were introduced. For example, Table A-1 presents a small portion of a table of sines. Assuming that the sine of 44.4° is desired and the only available information is the table shown, the interpolated value is calculated as follows.

$$\mathrm{Sin}(44.4) = \mathrm{Sin}(44) + 0.4 *(\mathrm{Sin}(45) - \mathrm{Sin}(44)/(45 - 44) \qquad \text{(Eq. A-1)}$$

Or

$$\mathrm{Sin}(44.4) = 0.69466 + 0.4*(0.70711 - 0.69466)/1.0$$

Or

$$\mathrm{Sin}(44.4) = 0.69964$$

Note that this value is quite close to the exact value of 0.69963.

Table A- 1
Portion of a Table of Sine Functions

Angle	Sine
42	0.66913
43	0.68200
44	0.69466
45	0.70711
46	0.71934
47	0.73135

What is not often apparent, especially to the student, is that there is a geometric explanation of this process (See Figure A-1). Plotted in this figure are the values of the sine shown in Table A-1 versus the angle. What Equation A-1 represents is a straight line fit between the angle below the value desired (that is, 44°) and the angle above the value desired (that is, 45°).

It should be obvious that the accuracy of this procedure depends on how closely the actual curve of the function matches with a straight line between the two points considered.

In addition to this method, there are other more complicated methods designed for the same task. Consult a textbook on numerical methods [A-1] for more information.

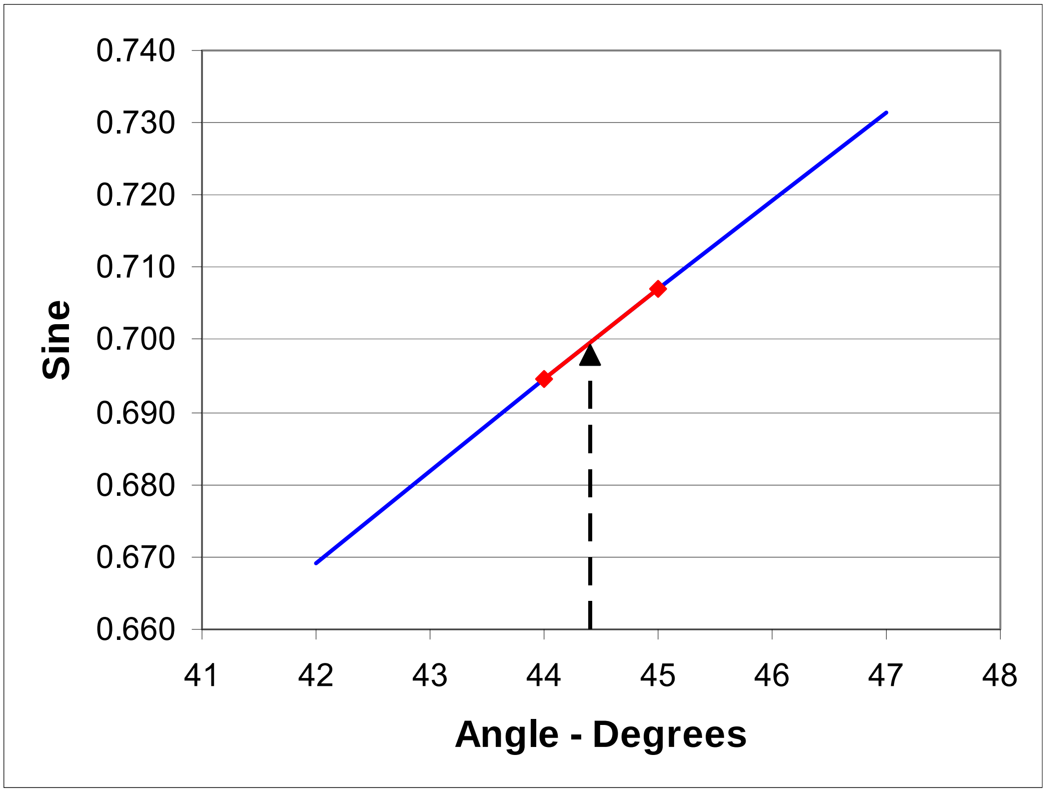

Figure A- 1
Example of Linear Interpolation

A.2 Bilinear Interpolation

Bilinear interpolation can be considered as the extension of linear interpolation to two dimensions—hence, the name. Wikipedia [A-2] defines and describes bilinear interpolations as the following:

> *In mathematics, bilinear interpolation is an extension of linear interpolation for interpolating functions of two variables on a regular grid. The key idea is to perform linear interpolation first in one direction, and then again in the other direction.*

To derive the basic equation for bilinear interpolation, consider Figure A-2. Shown is a portion of a rectangular grid in X-Y coordinates. Note that the values are known at the grid intersection points, and these values are denoted as $Q_{i,j}$. Given this information, the value of Q at the arbitrary point P is desired.

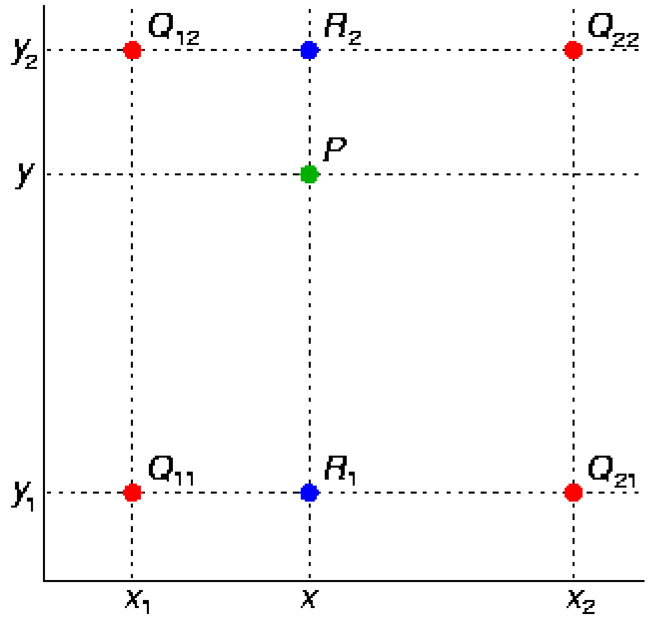

Figure A- 2
Schematic of Bilinear Interpolation [A-2]

The first step is to perform two linear interpolations in the x direction to determine values of Q at the intermediate values R_1 and R_2. Once these interpolations are performed, another interpolation is performed in the Y direction to determine the estimate of Q at point P.

The algebra to these steps is straightforward, but tedious. Skipping to the result (see Reference A-2 for details of the algebra), the final equation has four parts, representing the three different linear interpolations performed. Note also that the final result is independent of the order of the derivation.

$$P = \frac{Q_{11}}{XY} \cdot (x_2 - x)(y_2 - y) + \frac{Q_{21}}{XY} \cdot (x - x_1)(y_2 - y) + \frac{Q_{12}}{XY} \cdot (x_2 - x)(y - y_1) + \frac{Q_{22}}{XY} \cdot (x - x_1)(y - y_1)$$

Where:

$$XY = (x_2 - x_1)(y_2 - y_1) \qquad \text{(Eq. A-2)}$$

Finally, note that the nongeometric interpretation of this procedure is that Equation A-2 represents a weighted average of the surrounding points.

A.3 Application to the Problem of Unequal Grids

Depending on the situation, either linear or bilinear interpolation can be used to relate unequal grids. Note that at this point, we are assuming that the grids under consideration are rectangular when unwrapped (for example, from a straight pipe). To illustrate this point, two examples will be considered.

A.3.1 Example of the Use of Linear Interpolation

Consider the case of a pipe with six circumferential grid lines and 2-inch longitudinal spacing. Let us further assume that, in one inspection, seven circumferential grids were used with the correct grid origin and the correct longitudinal spacing. Let us consider one arbitrary band. A schematic view of this situation is presented in Figure A-3. In this figure, the red, broken line connecting the squares represents straight lines drawn between the measured thickness measurements. The blue diamonds represent the interpolated values between the thickness readings to match the previously used grid.

Note that, depending on the variation of the thickness reading with position, the accuracy of this approach will vary. Also note that, although possible, the procedure would be more involved for a more complex fitting, such as a reducer or elbow, but should be possible.

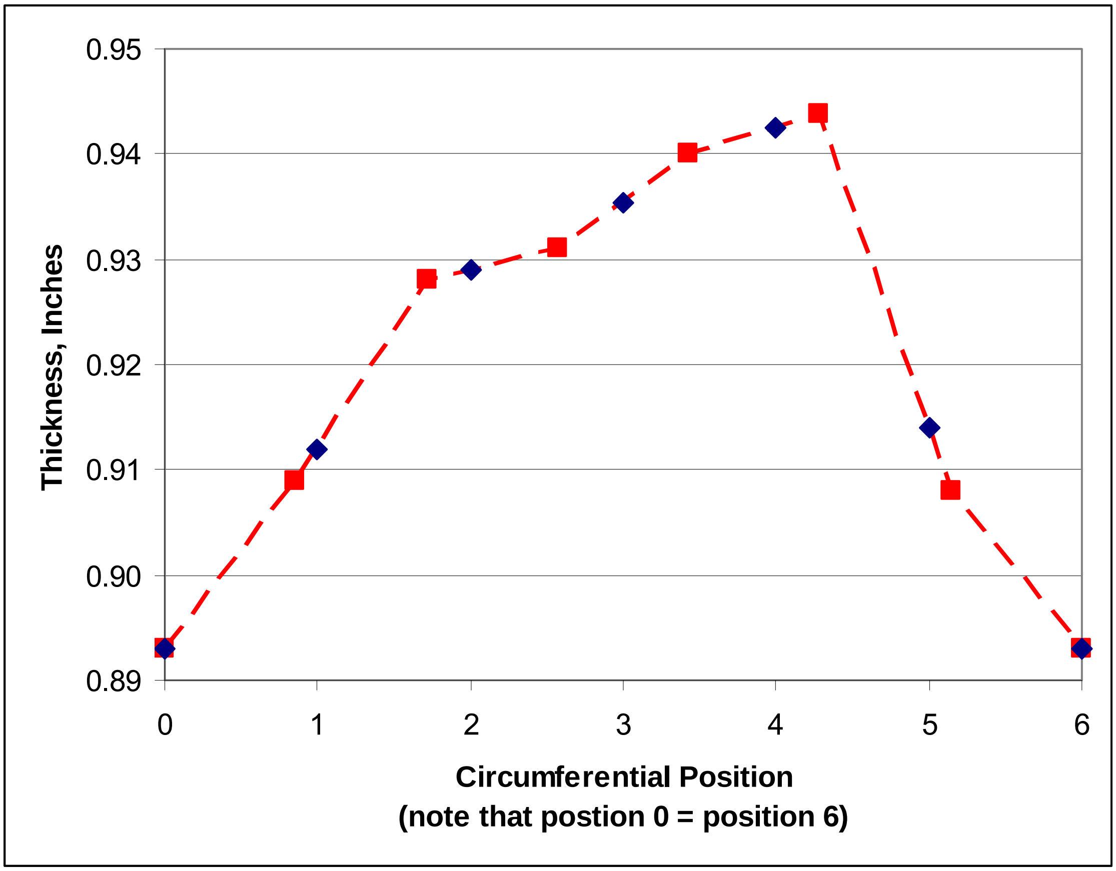

Figure A- 3
Schematic of an Application of Linear Interpolation

A.3.2 Example of the Use of Bilinear Interpolation

As might be expected, the use of bilinear interpolation is more complicated and perhaps more limited. Again, let us consider a straight pipe with six circumferential grid lines and 2-inch longitudinal spacing. Let us further assume that in one inspection, seven circumferential grids were used with the correct grid origin, but in this case the longitudinal spacing was 2.5 inches. In this situation, every grid point except for the grid origin would have to be determined by interpolation.

Figure A-4 presents a schematic of the first few rows of this situation. Note that the grid origin is at the 0,0 position. Considering this figure, two kinds of interpolation would be necessary:

- Linear interpolation. The first row (that is, the row containing the grid origin) would be performed as illustrated above. Also, the column of data through the grid origin would also be found with linear interpolation.

  In other words, the grid locations on the primary axes would be found with linear interpolation.

- Bilinear interpolation. The values for all other grid locations (that is, the ones not located on the primary axes) would have to be found by bilinear interpolation. For simple geometries (for example, a straight pipe), this procedure would be performed exactly as outlined in the section above. Consider again Figure A-2.

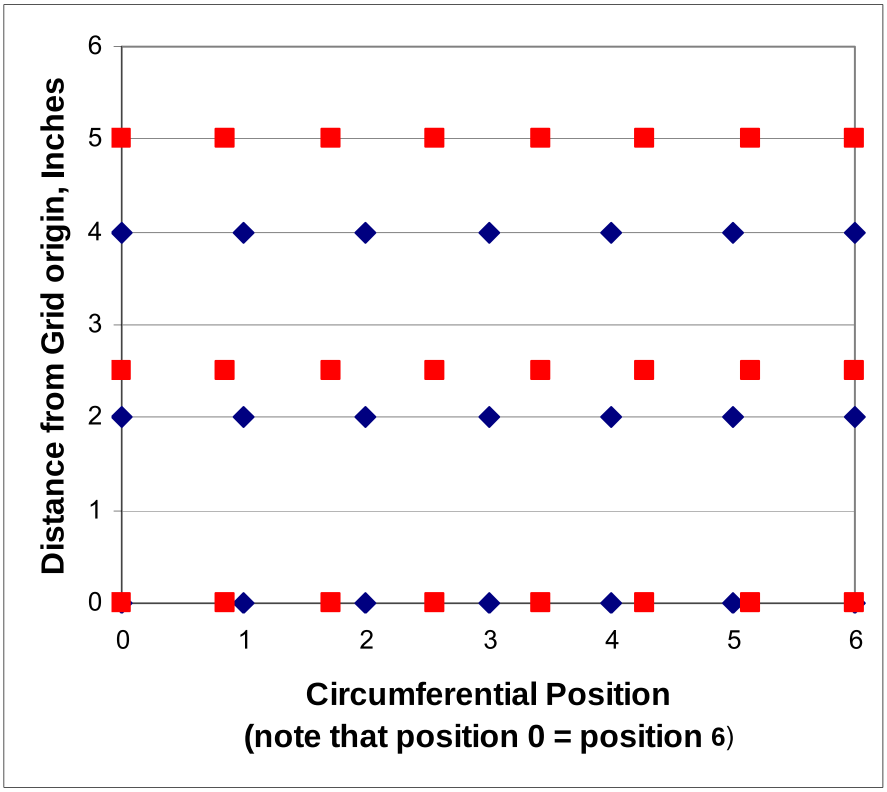

Figure A- 4
Example Showing Bilinear Interpolation

A.4 References

A-1 B. Carnahan, H. A. Luther, and J. O. Wilkes, *Applied Numerical Methods.* John Wiley, New York, 1969.

A-2 "Bilinear interpolation." *Wikipedia, The Free Encyclopedia*. 28 Aug 2009, 18:25 UTC. 28 Aug 2009 <http://en.wikipedia.org/w/index.php?title=Bilinear_interpolation&oldid=310582971>.

B
RESULTS OF INTERPOLATION TESTS

B.1 Approach

In order to study the sensitivity of linear and bilinear interpolation, some plant data were selected and examined. Two components were selected based on the following criteria:

- Pipe geometry to avoid geometric complications
- At least three sets of inspection data
- An odd number of bands of data
- An even number of data columns

The reasons for these seemingly arbitrary requirements should become clear in the following paragraphs as the geometries of the tests performed will be presented.

Figure B-1 presents a schematic of the unrolled grid arrangement. The use of a pipe geometry makes the unwrapping a straightforward process. The geometry shown in this figure is considered the base or nonperturbed case.

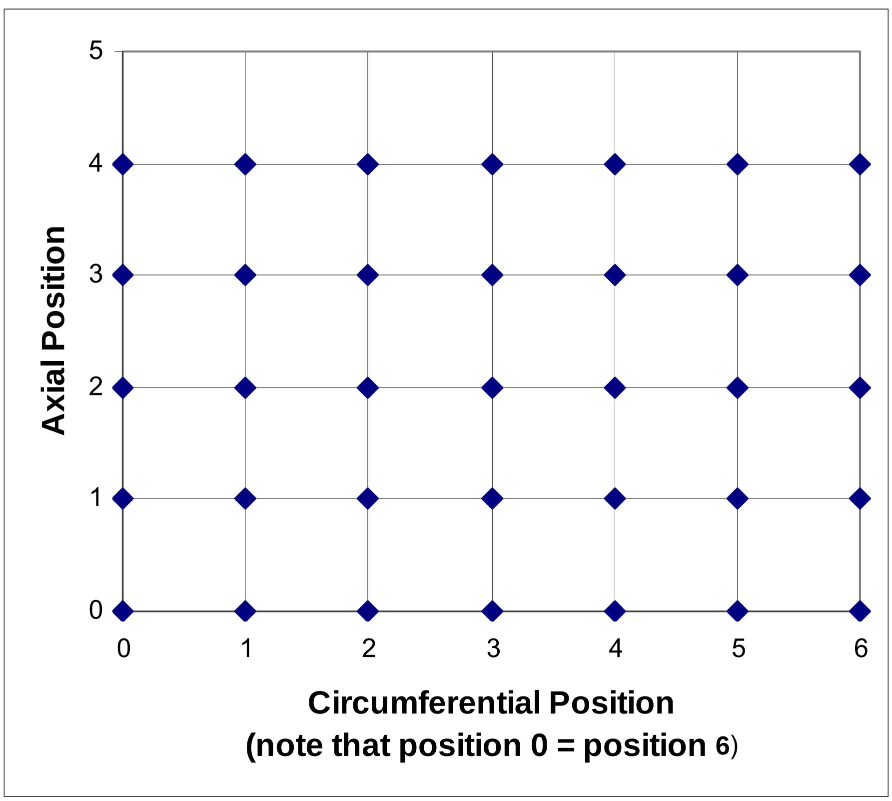

Figure B-1
Base Case for Interpolation Tests

B.2 Perturbation Geometries Used

Starting with the base case, four different perturbations were used. In each case the actual data were removed, and new values based on interpolations were added.

The geometries used were called the "row," the "odd column," the "even column," and the checkerboard. These arrangements are shown schematically for a smaller grid than was actually used in Figures B-2 through B-5. Note that in these figures, the open symbols represent locations where the actual data have been removed and were replaced with interpolated values.

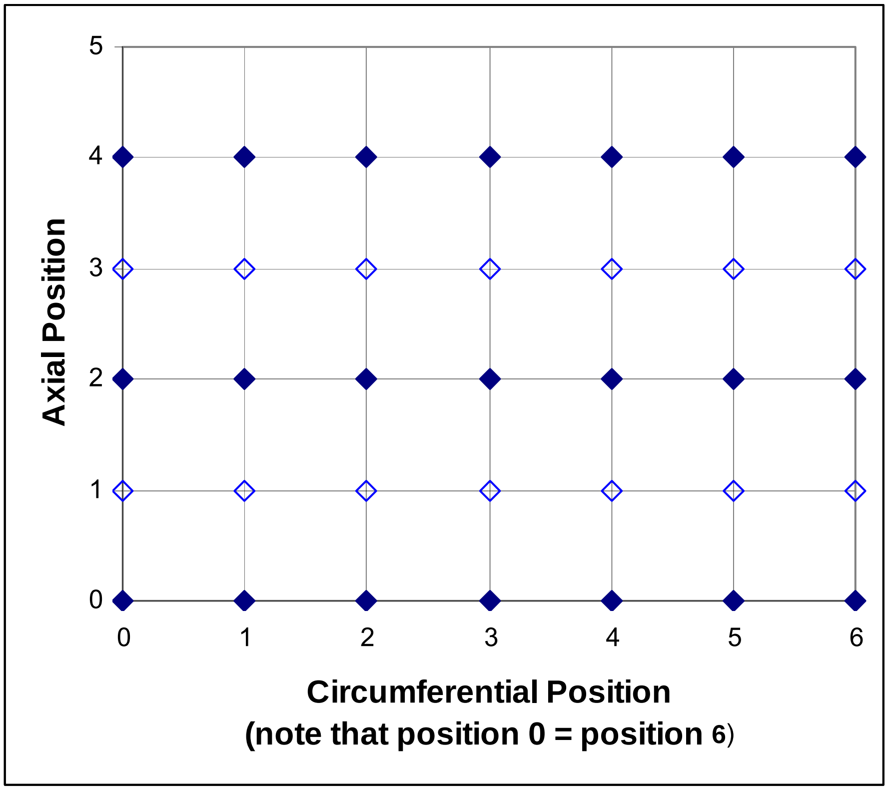

Figure B-2
The "Row" Perturbation

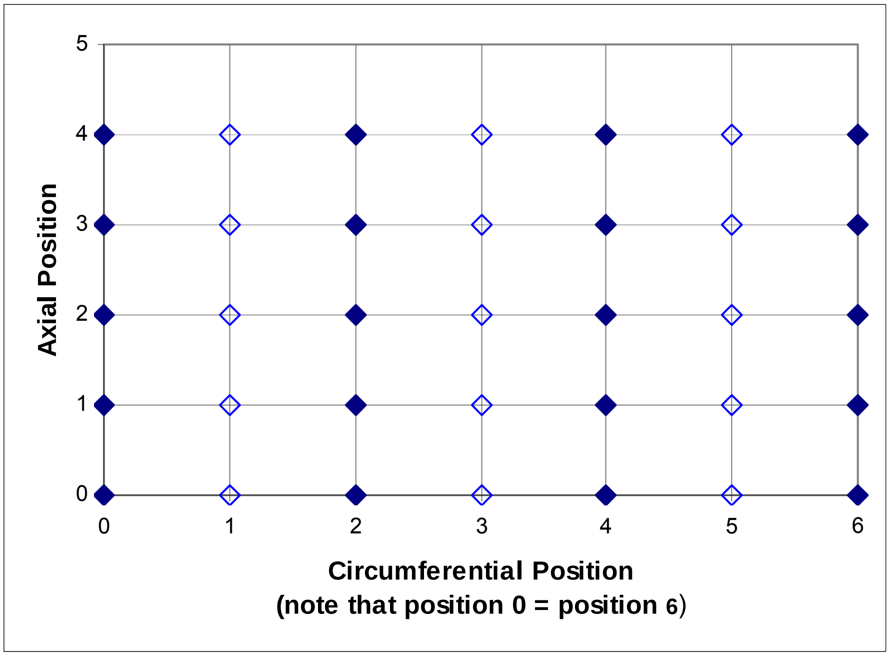

Figure B-3
The "Odd Column" Perturbation

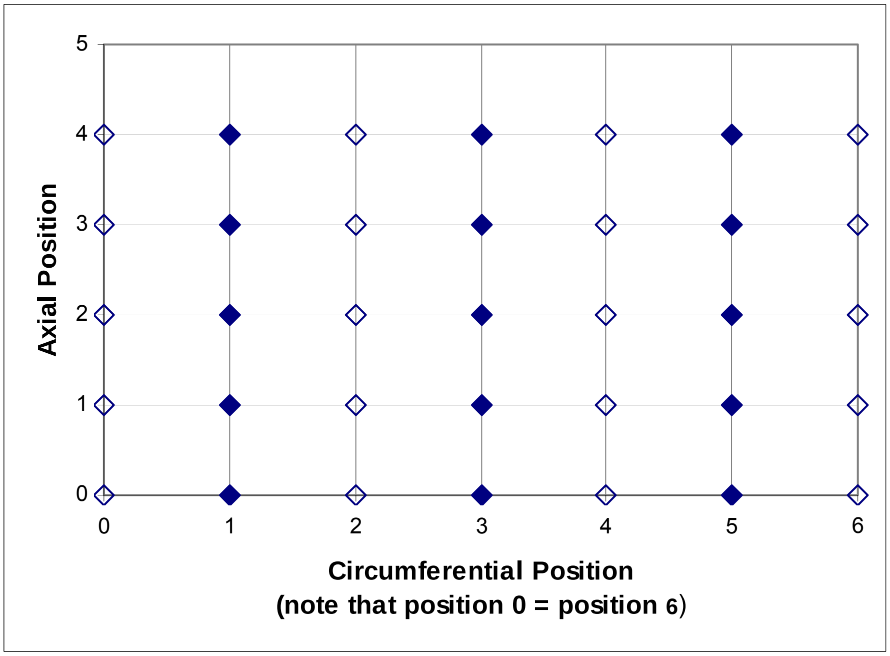

Figure B-4
The "Even Colum" Perturbation

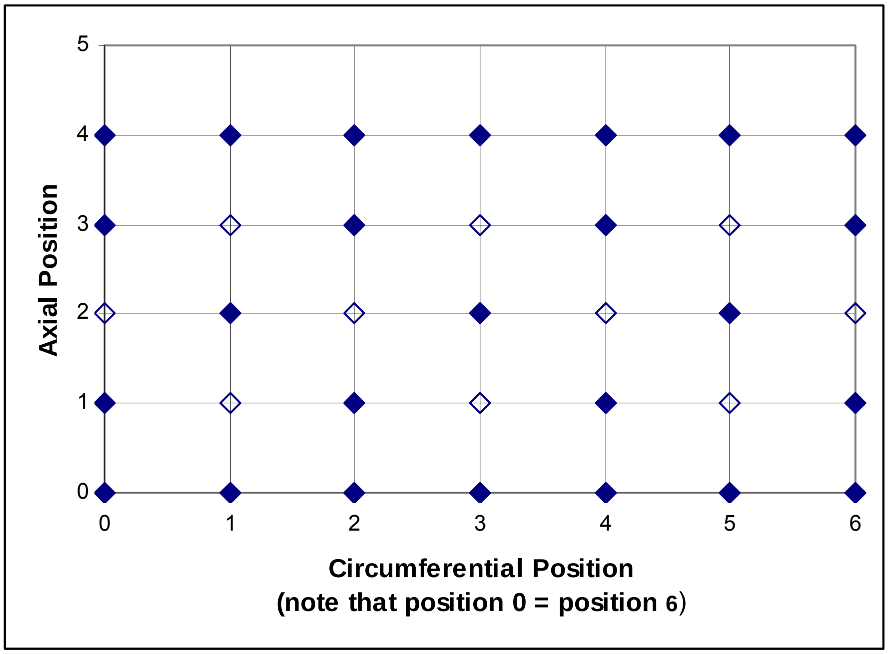

Figure B-5
The “Checkerboard” Perturbation

B.3 Tests Performed

Two components were selected for examination based on the criteria given above. They are described in Table B-1. For each component, two tests were conducted.

Table B- 1
Data Used in Interpolation Tests

	Component A	Component B
Number of Inspections	3	3
Number of Bands of Data	7	10
Number of Columns of Data	11	14

B.3.1 Average Test

The first test performed was to compare the interpolated values for each perturbation to the original data points. The results of these tests are summarized in Table B-2. With the exception of the checkerboard perturbation, linear interpolation was performed to establish the interpolated values. For the checkerboard pattern, a simple form of bilinear interpolation (that is, taking the arithmetic mean of the surrounding four points was used). In performing the bilinear interpolation, it was assumed that the circumferential distance between grid points was equal to the axial distance between grid points. If the actual distances were used, a small correction to the interpolations would be necessary.

Table B- 2
Results of the Averaging Test

	Component A		Component B	
	Mean, inch	**Standard Deviation, inch**	**Mean, inch**	**Standard Deviation, inch**
Row Perturbation	0.000	0.014	-0.003	0.042
Odd Column Perturbation	-0.007	0.020	0.004	0.023
Even Column Perturbation	0.000	0.017	0.000	0.019
Checkerboard Perturbation	0.000	0.008	0.000	0.024

In Table B-2, the tabulated values are the arithmetic means and standard deviations of the differences for that perturbation between the original data point and the interpolated value. Considering these results, it appears that on average, the interpolation works fairly well at recapturing the missing values. This is especially true as the average thickness for both components is over 1 inch.

To further examine the performance of interpolation, an additional test was performed.

B.3.2 Wear Test

To examine the performance of interpolation using the same set of plant data, an additional test was performed to see how the interpolations affected the calculated wear estimated. This test was done by performing the following steps:

1. The first two sets of inspection data were unchanged.
2. The third set of data was perturbed in the ways described above.
3. The amounts of wear were estimated using the maximum delta point-to-point (PTP) method and the least squares slope (LSS) method for the baseline and the four perturbed cases.

The results of this test are presented in Table B-3.

Table B- 3
Results of the Wear Test

	Component A		Component B	
	PTP	**LSS**	**PTP**	**LSS**
	Wear, mils	**Wear, mils**	**Wear, mils**	**Wear, mils**
Baseline	36	43	169	177
Row Perturbation	32	35	111	110
Odd Column Perturbation	34	43	111	105
Even Column Perturbation	51	56	113	116
Checkerboard Perturbation	35	36	113	118

B.4 Discussion of Results

While the results in this appendix should not be viewed as conclusive, they indicate that interpolation will yield reasonable results. The results presented in Table B-3, show that the estimated wear may vary upward or downward, depending on the circumstances.

C
RESULTS OF SLOPE OF THE MINIMA TESTS

Several tests of the performance of the slope of the minima method simulating unequal grids were performed. These tests were difficult to design because of the grid-independent nature of this method. One of these tests will be described here.

C.1 Approach

Because the slope of the minima method is independent of the grid arrangement, arbitrarily removing grid locations as was done in the previous appendix would not have served the purpose. Rather, a different approach was taken.

A purpose-written FORTAN program was designed to study the behavior of the slope of the minima method under abnormal conditions. The final version performed the following calculations:

1. Inspection data from a component with multiple sets of data were input.
2. The slope of the minima wear rate was calculated.
3. The second lowest point for each inspection set was then determined.
4. For each set of inspection data, the second thinnest location was used in place of the thinnest location, and the wear rate was recalculated.
5. The above step was performed for each inspection, and the results were examined.

In reviewing the results obtained, there seemed to be no generalization that could be applied to them. However, it was noted that the last inspection location seemed to have the largest influence on the results. This is not surprising, considering the nature of the line fitting procedure.

Figure C-1 shows sample results for three components. Looking at this figure, it seems fair to say that the slope of the minima method should provide reasonable results even if some of the "lowest" points are missed through differences in grids. However, if there are more than two inspections, caution should be used if the different grid is used at the latest inspection and the lowest reading on the latest grid does not fall into line with the previous measurements. In this case, the wear rate may be significantly understated.

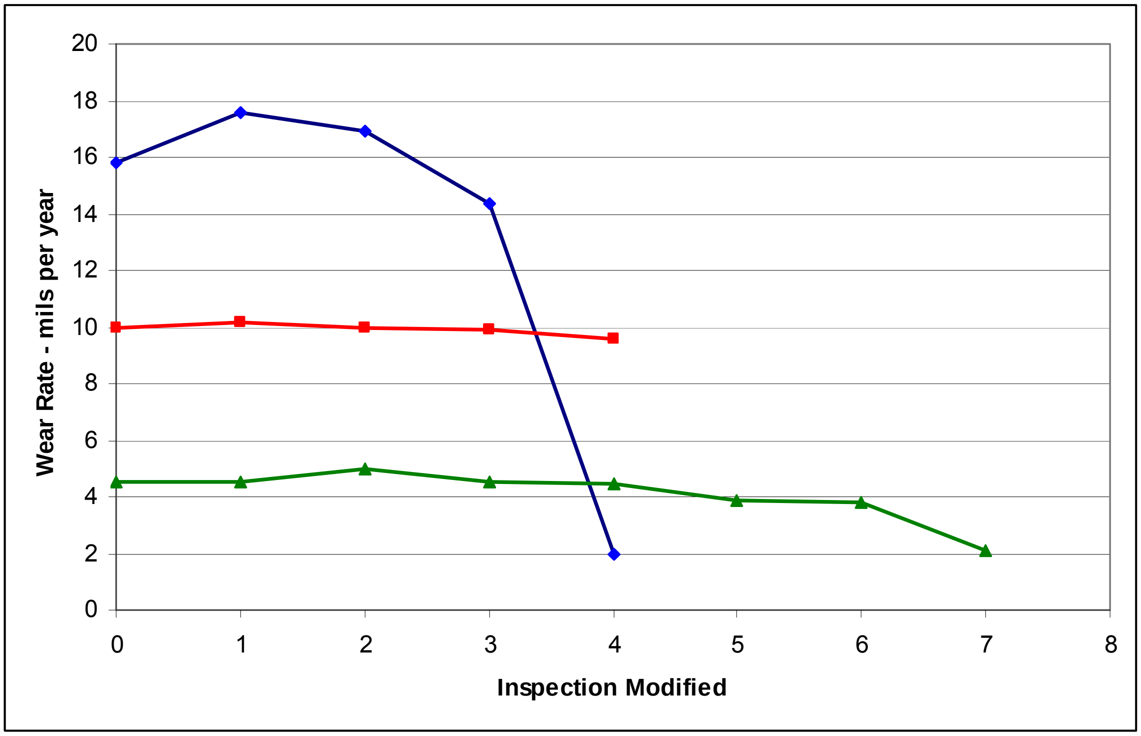

Figure C-1
Sample Results of Slope of the Minima Tests

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