Least Squares Methods for Evaluating Inspection Data

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PRODUCT DESCRIPTION

Inspections to detect damage from flow-accelerated corrosion (FAC) are routinely performed in nuclear power plants. These inspections are normally performed using the ultrasonic technique (UT) on a predefined grid. The evaluation of the data obtained is one of the most important and challenging functions of FAC engineers.

Previous Electric Power Research Institute (EPRI) guidance has been directed at evaluating data from one or two inspections. Recently, EPRI became aware of a method used in Japan for evaluating data from three or more sets of inspection data. This Japanese method uses a "least squares approach" and has been named the least squares point to point (LSPTP) method. Because no comparable methodology was available to EPRI members, a study of the suitability of this method was performed. During the course of this work, another related method, the least squares slope (LSS) method, was developed and added to the scope of this work. This report presents the results of this study.

Results and Findings

Inspection data sets from six nuclear units were examined, and data sets from multiple inspections were selected and evaluated using the LSPTP method and the LSS method. A purpose-built FORTRAN program was used to calculate the wear rates using these methods. Comparisons were made using ad hoc methods. The results of these comparisons showed that the agreement was, in general, quite good. However, there were some outliers which were investigated and explained. Differences between the two least squares methods were highlighted.

With some reservations, it is recommended that these methods be considered for incorporation into a future release of the CHECWORKS™ Steam/Feedwater Application (SFA).

Challenges and Objectives

This report should be of value to FAC engineers because it describes new methods of evaluating data from multiple inspections. To date, such data have been evaluated using time-consuming, ad hoc methods rather than the automated approach available using the least squares methods. Therefore, FAC engineers should be able to perform a usually time-consuming portion of their job more efficiently.

Applications, Value, and Use

With modifications necessary to ensure accurate results, least squares methods should be a valuable addition to the suite of inspection evaluation tools available in CHECWORKS™ SFA. These methods would satisfy the need of FAC engineers for a standard methodology to handle multiple sets of inspection results.

EPRI Perspective

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

Approach

The primary goal of this report was to examine the suitability of the least squares methods for evaluating sets of multiple inspection data. Plant data from several plants were used to make this evaluation. The work performed demonstrates good agreement between commonly used ad hoc methods and the two least squares methods investigated. Outliers, when they occurred, were examined and resolved. In addition, numerical experiments were performed to gain an understanding of these methods.

Keywords

Data evaluation
FAC
Flow-accelerated corrosion
Ultrasonic technique
UT

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INTRODUCTION

1.1 Background

Interpreting NDE inspection data is one of the most important tasks performed in a flow-accelerated corrosion (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 too conservative then unnecessary inspections will be performed. If the analyst is too non-conservative, then dangerous situations may occur as the re-inspection intervals will be too long. In the extreme example of this, failures would result due to the lack of re-inspection.

In general the task involves reviewing a matrix of inspection points, often several hundred 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, then the tasks 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 non-uniform 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 three or more sets of data taken using an identical grid arrangement. Currently the CHECWORKS™ Steam Feedwater Application (SFA) provides four methods for analyzing this data. 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, i.e., loss of material, experienced by the component measured. These four methods are the maximum delta method, the average delta method, the cutoff delta method and the fast delta method. A brief description of these methods will be presented below. Note that these methods are also known collectively as “point to point” methods.

Finally, it should be understood that all of the point to point 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. The analyst must be aware of this assumption, and if necessary account for the change of conditions.

1.2.1 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.

1.2.2 Average Delta Method

In the average delta method, all of the values produced by the difference matrix are averaged. The averaged value is taken as the wear. This results in an overly non-conservative (i.e., 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.

1.2.3 Cutoff Delta Method

The cutoff delta method was developed to attempt to overcome the shortcoming of the maximum delta method 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 minimum thickness of the component is determined.
- A cutoff thickness is calculated by multiplying this thickness by the cutoff ratio input by the user. This value is often taken as 112%.
- The two sets of inspection data are subtracted to obtain the matrix of the thickness differences at each grid point.
- Only those areas of the component 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.

1.2.4 Fast Delta Method

The fast delta method was also designed to overcome the problem of the wear being determined in the non-life-limiting portion of the component. At the same time, this method avoids the use of a user defined input value, e.g., cutoff thickness. The steps that are performed in using the fast delta method are:

- 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.

- At each point the time to reach minimum thickness is calculated using an extrapolation of the linear wear rate.
- The negative of the slope of the line with the minimum time is taken as the component wear rate.

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.

This method will be discussed in more detail in Section 3.

1.3 Japanese or 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 the identical grid pattern (1). In January 2008, the CHECWORKS™ Users Group (CHUG) recommended to EPRI that an assessment be made of this method. This report is an evaluation of this method. Note that in this report the method will be called the least squares point to point method (LSPTP).

In performing this work a variation of the LSPTP method was developed for convenience, this method will be called the LSS – for least squares slope method.

All of the comparisons in this report were done using the maximum delta method as a standard. This was done because the maximum delta method is the most commonly used way of evaluating multiple outage inspection data.

1.4 Report Overview

The report is organized as follows:

- Section 2 presents the objectives of this work.
- Section 3 presents a description of the LSPTP method and the LSS method used in this work and a discussion of the issues involved using PTP methods.
- Section 4 presents a comparison of the results of the LSPTP method and the LSS method with the maximum delta method using plant data.
- Section 5 presents recommendations and conclusions.
- Several appendices provide additional information.

2

OBJECTIVES

The objectives of this work are:

- To describe the least squares point to point method and the least squares slope method.
- To evaluate the suitability of the LSPTP method and the LSS method by comparing results obtained using these methods with results of the maximum delta method. Both plant data and hypothetical data are to be used.
- To recommend, if desirable, inclusion of this method, or a variant of this method, into a future version of CHECWORKS™ SFA.

3

LEAST SQUARES APPROACHES

This section will discuss in more detail the point to point methods and introduce the least squares methods. In general, PTP methods are considered to be more accurate than single-inspection data evaluations methods. However, there are still concerns with using PTP methods.

3.1 Issues with PTP Methods

Other than the change of conditions, the two main issues with PTP methods are the influence of inspection uncertainties and the determination of the wear in a “thick” part of the fitting.

3.1.1 Inspection Uncertainties

Typically FAC inspection data is taken by the ultrasonic technique (UT). The accuracy of this method is normally considered to be about ±5% of the thickness being measured (2). Using a PTP method involves subtracting thickness readings which mean that the magnitude of the inspection error is comparable and often exceeds the degradation being measured. This feature shows up as negative PTP readings for some of the grid points considered. As it is physically impossible that the component has added material, the explanation is that this is caused by measurement uncertainty.

The most practical matter to avoid this problem is to put more time (actually more material loss) between inspections. As the time between inspections is often dictated by other considerations (e.g., outage frequencies), the FAC engineer must live with these negative readings.

Alternately, another PTP method such as the averaged PTP method may be used. This method has been shown to remove the influence of some of these uncertainties (3). Finally, in extreme cases, single-inspection evaluation methods could be used in place of PTP methods.

3.1.2 Critical Location on the Component

When using the maximum delta method, for example, the area of the fitting that is wearing most rapidly will be determined. However, this method does not provide any information about whether or not the thinning is occurring on a thin area of the component or a thick area of the component.

The analyst must consider the wear rate and its location before estimating the life of the component and the re-inspection interval. The fast delta method and the cutoff method were designed to overcome this problem.

As the LSPTP method can be considered a logical extension of the fast delta method, the fast delta method will be described in detail before introducing the LSPTP method.

3.2 Fast Delta Method

Consider a component that has two inspections using an identical grid. Further consider Figure 3-1 which schematically shows thickness readings at a grid point. Now, at each grid point with two valid inspection points, the linear wear rate for this location[1] is given by:

$$WR = \frac{(T_1 - T_2)}{\Delta time} \tag{3-1}$$

Where:

T_1 = Thickness at first measurement

T_2 = Thickness at second measurement

Δ *time* = Operating time between inspections

WR = Wear rate

Now, the fast delta method considers the wear rate at each grid point and defines the determinant point (i.e., the grid point that establishes the component wear) as the one with the smallest time from the second inspection until the critical thickness for the fitting is reached. Note that the wear rate is assumed to be constant with time. Note also that one critical thickness is assumed to be appropriate for the entire fitting. With these assumptions, the time to reach critical thickness for each grid point is written as:

$$TT_{crit} = \frac{T_2 - T_{crit}}{WR} \tag{3-2}$$

Where:

$TTcrit$ = Time to reach critical thickness

$Tcrit$ = Critical thickness

By solving Equation 3-2 for the wear rate and equating it with Equation 3-1, the wear rate may be eliminated.

$$WR = \frac{T_1 - T_2}{\Delta time} = \frac{T_2 - T_{crit}}{TT_{crit}} \tag{3-3}$$

Rearranging:

$$TT_{crit} = \frac{(T_2 - T_{crit})}{(T_1 - T_2)} \cdot \Delta time \tag{3-4}$$

---

[1] The assumption of a linear wear rate between inspection points implies that the operating conditions and the water conditions are unchanged during this time.

As the time between the first and second inspections is the same for all points on the component, the determinant location is where the minimum of the first part of the above equation (the ratio of the thicknesses) is found.

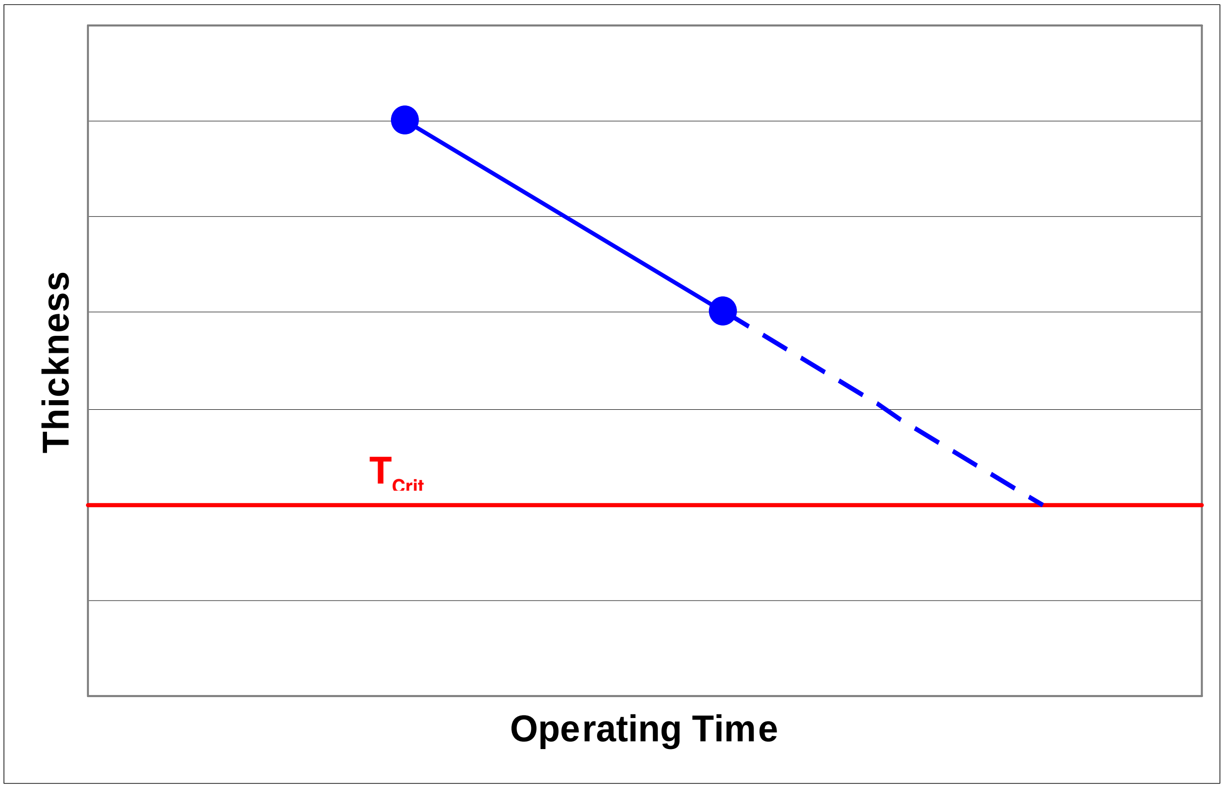

Figure 3-1
Schematic of the Fast Delta Method

3.3 Least Squares Point to Point Method

The LSPTP method is the logical extension of the fast delta method to any number of sets of inspection data. Consider Figure 3-2. This is similar to Figure 3-1 except that four sets of thickness measurements are shown for the grid point in question.

Through these points a linear least squares curve fit is made. This is shown as the broken line on the figure. As the equation of the straight line is known, and *Tcrit* is known, the time to *Tcrit* can be determined for every grid point. The grid location with the minimum time to *Tcrit* is the determinant location.

The mathematics of the least squares curve fit and the determination of the time to *Tcrit* are presented in Appendix A.

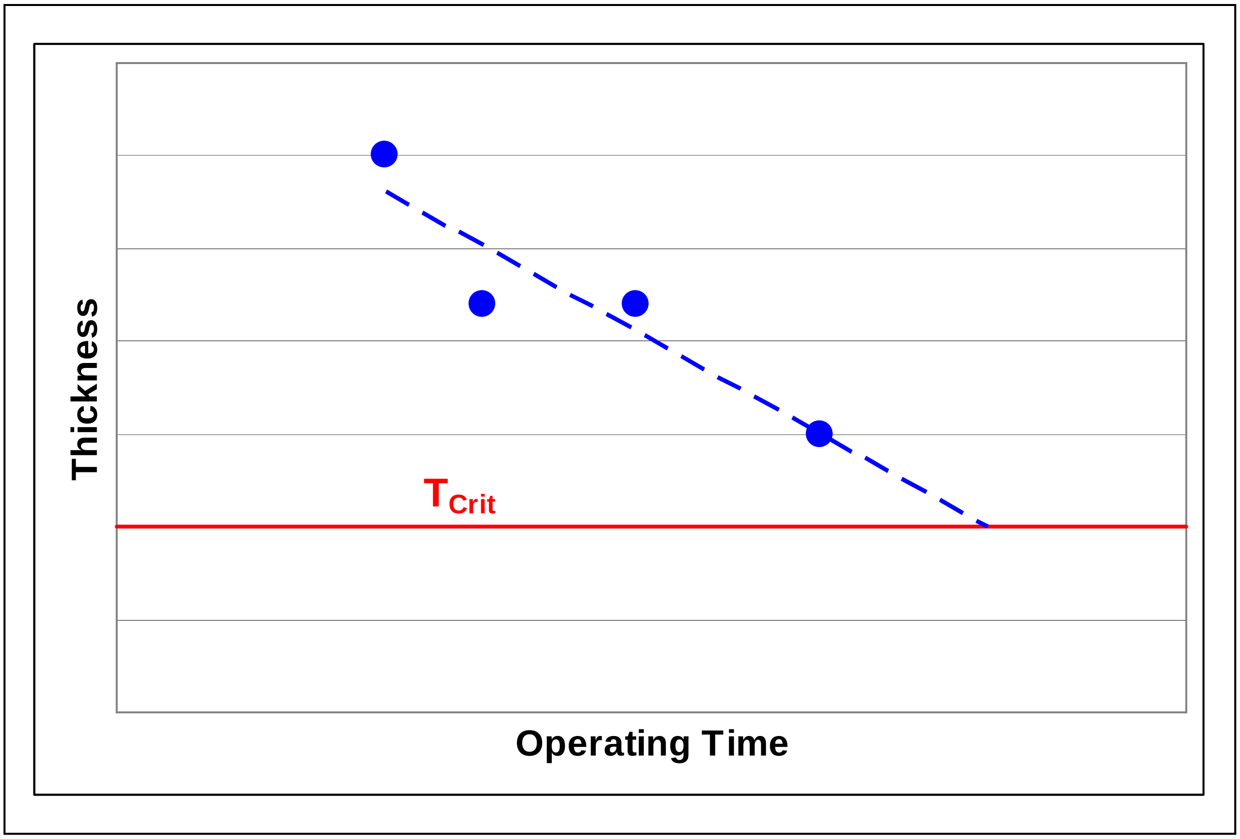

Figure 3-2
Schematic of the Least Squares Point to Point Method

From the above description of the LSPTP method, several characteristics should be mentioned:

- The method will work for any number of inspections greater than 2.
- With two inspections, the method reduces to the fast delta method.[2]
- The method is automatic in that the wear rate is calculated without any input or interaction with the operator.
- The method will give an estimate of the initial thickness. This is because the intercept of the linear curve fit is the initial thickness. This is shown in Figure 3-3.

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[2] When a linear least squares fit is made using two points, the result is a straight line fit between the two points which is exactly what the fast delta method does.

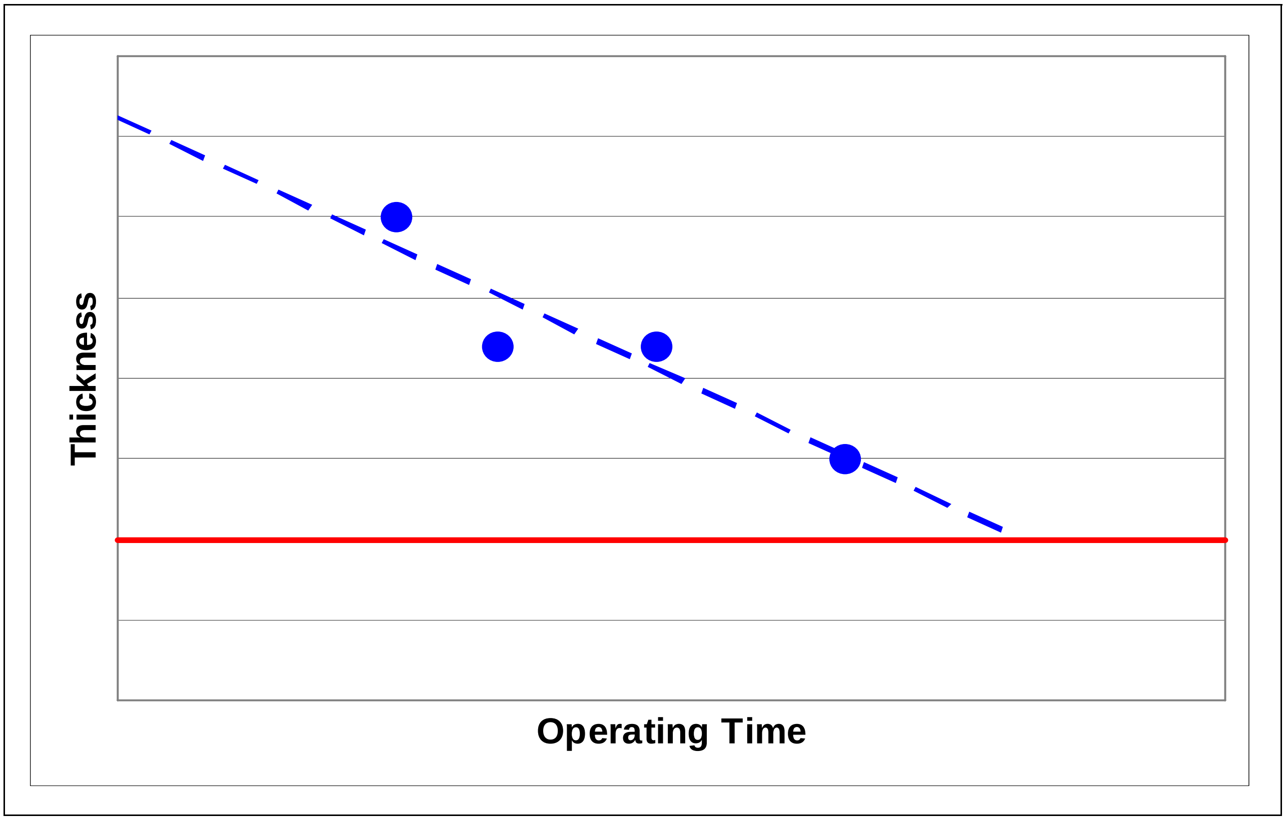

Figure 3-3
Back Extrapolation to Obtain the Initial Thickness

3.4 Least Squares Slope Method

Although not originally planned for inclusion in this work, the least squares slope method is a variant of the LSPTP approach. Rather than fitting a straight line through the data and extrapolating, the wear rate for a component is defined as the maximum value of the slope of fit lines through a component's grid points.

This approach has the advantage of simplicity in that only the slope of the least squares line need be determined. However, it loses the advantage shared by the fast delta method and the LSPTP method of taking into consideration the local thickness.

4

COMPARISON OF LEAST SQUARES METHODS WITH PLANT DATA

In order to evaluate the LSPTP and the LSS methods, several trials were made using data from several operating plants. The data sets were evaluated using a custom built FORTRAN program. Sample results of the FORTRAN program were checked using a MS EXCEL spreadsheet written for that purpose. Numerical experiments, designed to better understand the operation of the methods, are presented in Appendix B.

Plant data will be discussed individually by site. A summary of all of the plant data will be presented at the end of this section. A discussion of the relative advantages of the two least squares methods will be presented in the next section. Note that only components with three or more sets of inspection data will be examined in this section.

4.1 Diablo Canyon

Diablo Canyon is a station containing two pressurized water reactors (PWRs). It is owned and operated by Pacific Gas & Electric and is located on the central coast of California. Historically, there have been a large number of repeat inspections made in the feedwater system of both units. Table 4-1 presents a summary of the data considered in this work. The components examined were 90° and 45° elbows.

Table 4-1
Summary of the Diablo Canyon Data

Unit	Number of Components	Number of Repeat Inspections						
		3	4	5	6	7	8	9
1	13	2	4	3	0	2	2	0
2	13	0	8	3	1	0	0	1

4.1.1 LSPTP Method

4.1.1.1 Overall Comparison

For each of the components considered, the following steps were performed:

- The wear rate using the maximum delta for the first and last inspection was calculated.
- The wear rate using the LSPTP method was calculated. Note that data from every inspection was considered in this calculation.
- The two results were cross-plotted on a unit basis and on a combined basis.
- Figures 4-1 and 4-2 show the results on a unit basis while Figure 4-3 shows all of the results.

Considering Unit 1, as shown in Figure 4-1, the results for both methods agree fairly well. In general, the results for the maximum delta method are slightly higher particularly at low values of wear rate than for the LSPTPT method. For reasons that will be discussed later in this section, two components are considered outliers and are indicated by the open (red) symbols.

Considering Unit 2, as shown in Figure 4-2, the results are similar, but once again the disagreement becomes larger at low values of wear rate. This is seen more clearly in Figure 4-3 where the comparisons from both units are presented together.

Another feature of these data sets is the fact that there are few points below the 45° line and only one point outside the scatter band. This is shown in Table 4-2 where the numbers of components with a lower wear rate by each method is tabulated.

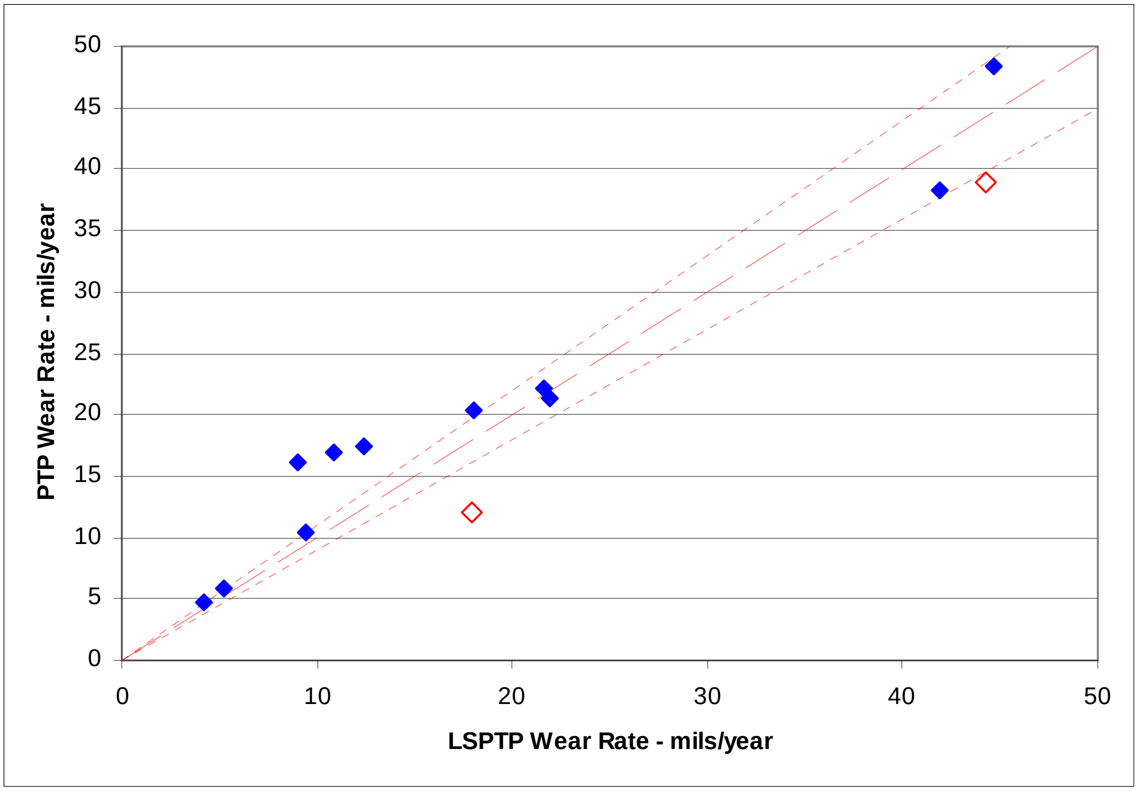

Figure 4-1
Diablo Canyon Unit 1 Results of the LSPTP Method

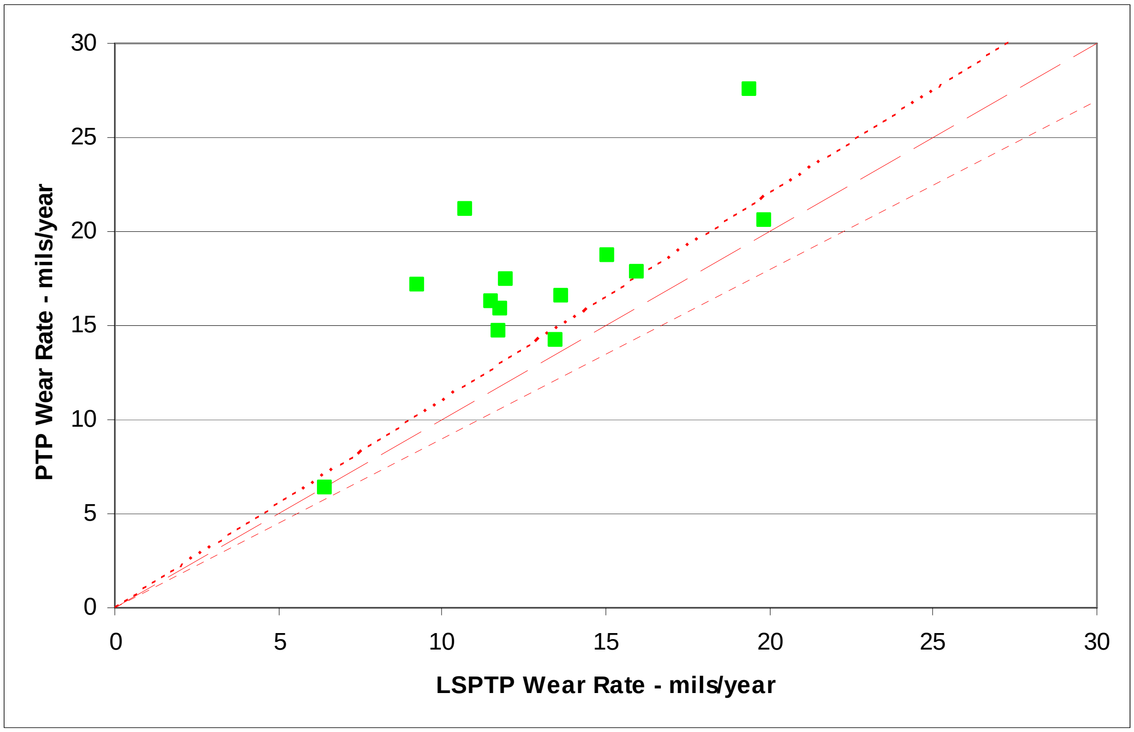

Figure 4-2
Diablo Canyon Unit 2 Results of the LSPTP Method

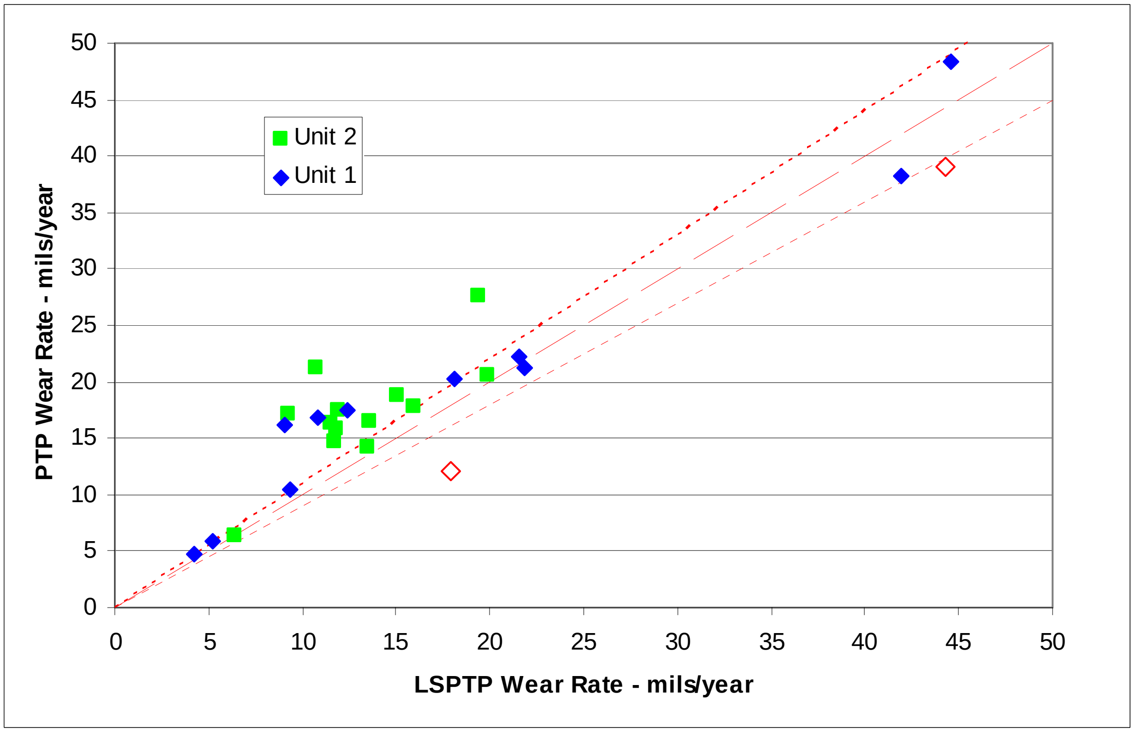

Figure 4-3
Diablo Canyon Results of the LSPTP Method for Both Units

Table 4-2
Diablo Canyon Overall Results – Least Squares Point to Point Method

	Number of Components	Number Where PTP Is Greater Than LSPTP	Number Where LSPTP Is Greater Than PTP
Unit 1	13	9	4
Unit 2	13	12	1
Total	26	21	5

To examine this feature of the results, a more detailed comparison was made.

4.1.1.2 Detailed Comparison

In the comparison above, the results of the LSPTP were compared with the maximum delta between the first and last inspection. To look at the results in more detail, another set of comparisons were made. In these comparisons, the LSPTP results for each component were compared with all possible wear rates calculated using the maximum delta method for that component.

To clarify this concept a simple example will be worked out in detail. Let us consider a component with 4 sets of inspection data taken on an identical grid. If we denote these inspections as #1 (oldest) through #4 (newest), we have a total of six possible PTP comparisons. These combinations are shown in Table 4-3.

Table 4-3
Possible PTP Results with Four Sets of Inspection Data

Number	Possible PTP Combinations
1	1-2
2	1-3
3	1-4
4	2-3
5	2-4
6	3-4

Before going further to discuss more general results, Figure 4-4 presents the results from a sample component with four sets of inspection data. Consider this figure. Plotted in column fashion are the six wear rates obtained with the maximum delta method. Plotted as a horizontal line is the wear rate determined using the LSPTP method. As can be seen, for this component, all of the conventional PTP results are above the LSPTP result.

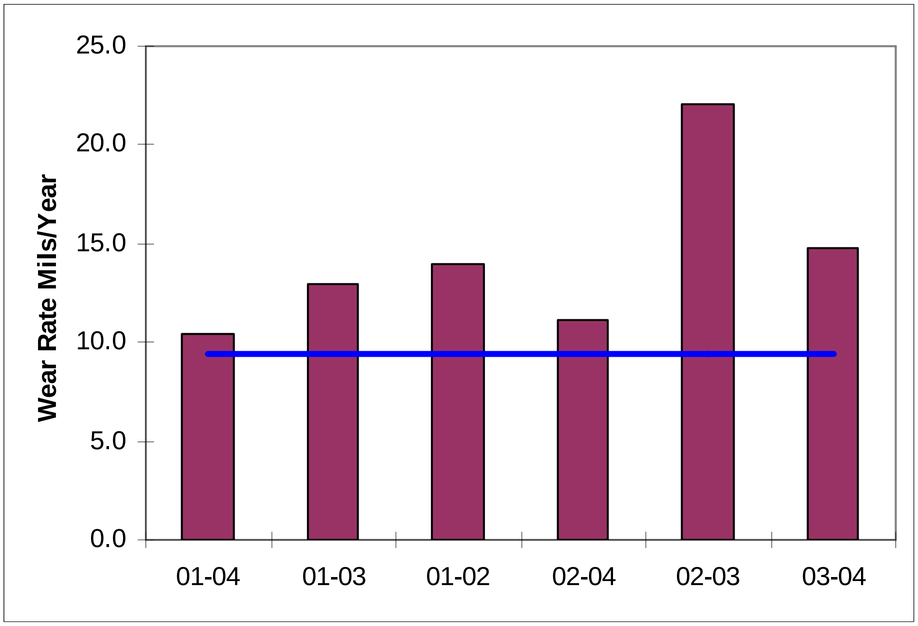

Figure 4-4
Sample Results of a Detailed Evaluation

Rather than plotting figures for each and every component, a summary table was prepared, see Table 4-4. In this table, the number of individual PTP determinations is presented in the second column. The third and fourth columns present the counts of which method resulted in a higher wear rate. As can easily be seen in over 92% of the cases, the LSPTP yielded a lower wear rate than the conventional, maximum delta PTP method.

Table 4-4
Diablo Canyon – Detailed Results – LSPTP Method

	Total PTP Calculations	Number Where PTP IS Greater Than LSPTP	Number Where LSPTP Is Greater Than PTP
Unit 1	158	142	16
Unit 2	129	123	6

4.1.1.3 Outliers

Based on the results, it seems apparent that outliers may be defined as:

- Components which have a higher LSPTP wear rate than PTP wear rate. For convenience, a 10% difference will be used to define a component as being an outlier. For Unit 1, the two open (red) points shown on Figure 4-1 fall into this category.
- Components which have a much higher PTP wear rate than LSPTP wear rate. For convenience, a 100% difference will be used to define a component as being an outlier.

The two outliers will be discussed in detail.

Considering the two Unit 1 outliers, examination showed that for both components, the same grid location was determinate (i.e., established the wear rate) for both methods. Thus, it is illustrative to examine the plots of the thickness measurements versus time for these components.

For convenience, these components will be denoted - the lower component (i.e., at coordinates ~ 18, 12 on Figure 4-1) as Component DCU1-A, and the upper component (i.e., at coordinates ~ 44, 40) as Component DCU1-B.

Figure 4-5 presents a plot of thickness versus operating time for Component DCU1-A. Note the four measured thickness are shown as diamonds (blue). Also note the solid (blue) line which is the least squares fit through the points. Note that one, apparently high point, pulls the curve above the other three points. Now, note the broken (red) line. This is the maximum delta wear between the extreme points. Note that the slope of the solid (blue) line is steeper than the broken (red) line, indicating a higher wear rate. Further note, that the third data point (i.e., at ~ 14 years and 0.855) was not fit, but falls on the line between the extreme points.

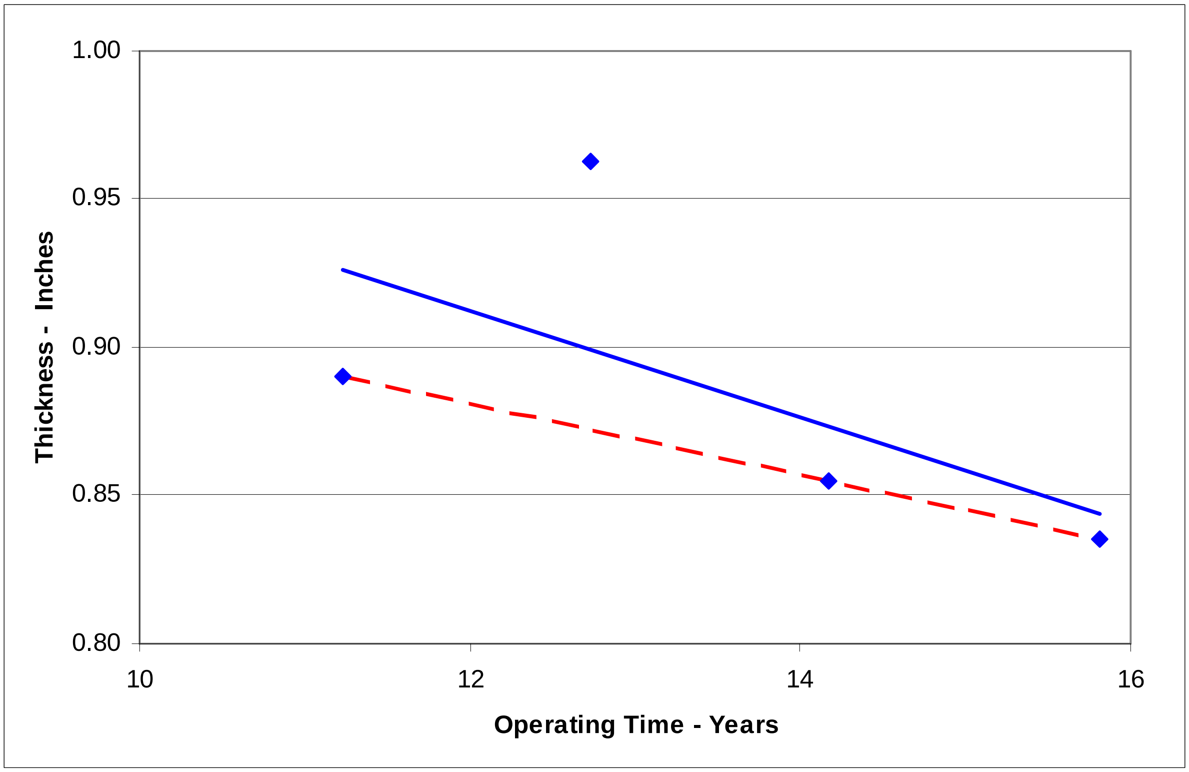

Figure 4-5
Thickness Plot for DCU1-A

Figure 4-6 presents a plot of thickness versus operating time for Component DCU1-B. Note the five measured thickness shown by the diamonds (blue). Also note the solid (blue) line which is the least squares fit through the points. Note that the impact that data scatter has on this line. Now, note the broken (red) line. This is the maximum delta wear between the extreme points. Note that the slope of the solid (blue) line is steeper than the broken (red) line, indicating a higher wear rate.

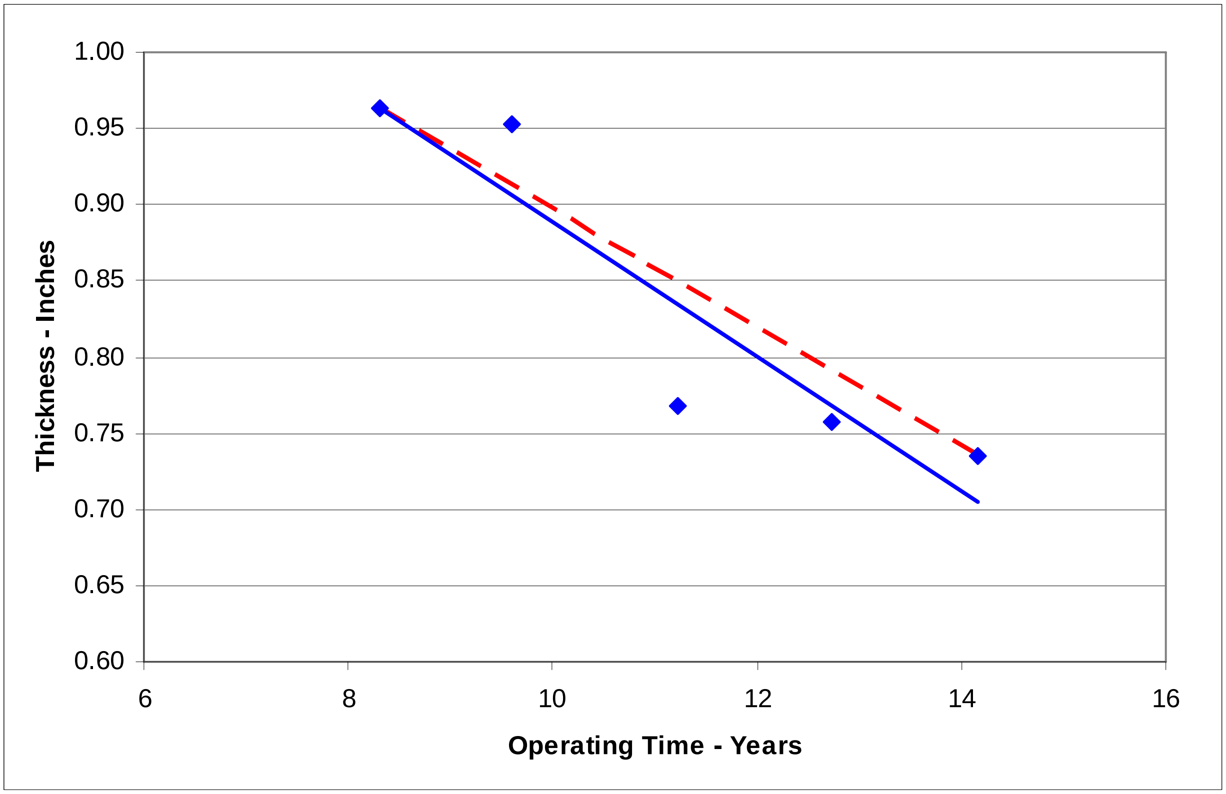

Figure 4-6
Thickness Plot for DCU1-B.

4.1.2 Least Squares Slope Method

The same data sets from Diablo Canyon were examined using the LSS method using much the same methodology as for the LSPTP method.

4.1.2.1 Overall Comparison

Figure 4-7 presents the comparison of the LSS method with the maximum delta method for Diablo Canyon Unit 1. This figure is quite similar to Figure 4-1 with two exceptions.

- The data is generally closer to the 45° line
- There is a third outlier, close to the upper one. It is shown as an open (red) symbol. Note that two of the three outliers are the same points as previously discussed. The new outlier is designated as DCU1-C and will be discussed later in this section.

Figure 4-8 presents the comparison of the LSS method with the maximum delta method for Diablo Canyon Unit 2. This figure is similar to Figure 4-2 again with the data points generally much closer to the 45° line.

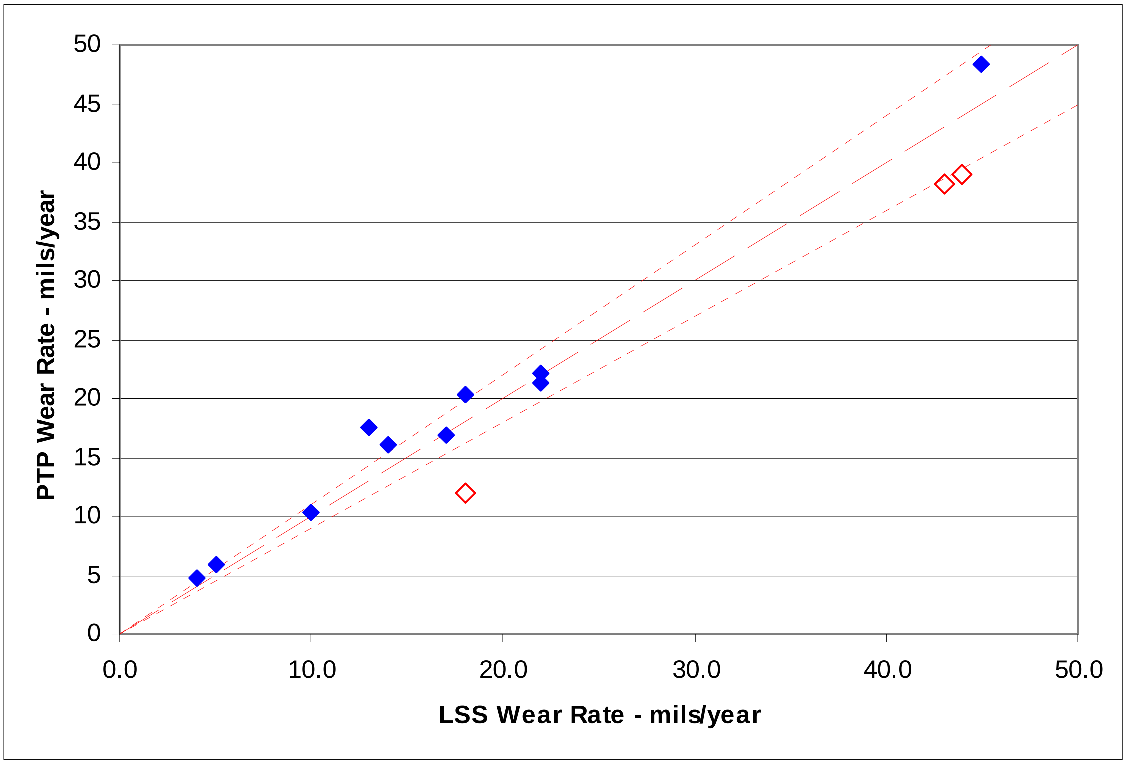

Figure 4-7
Diablo Canyon Unit 1 Results of the LSS Method

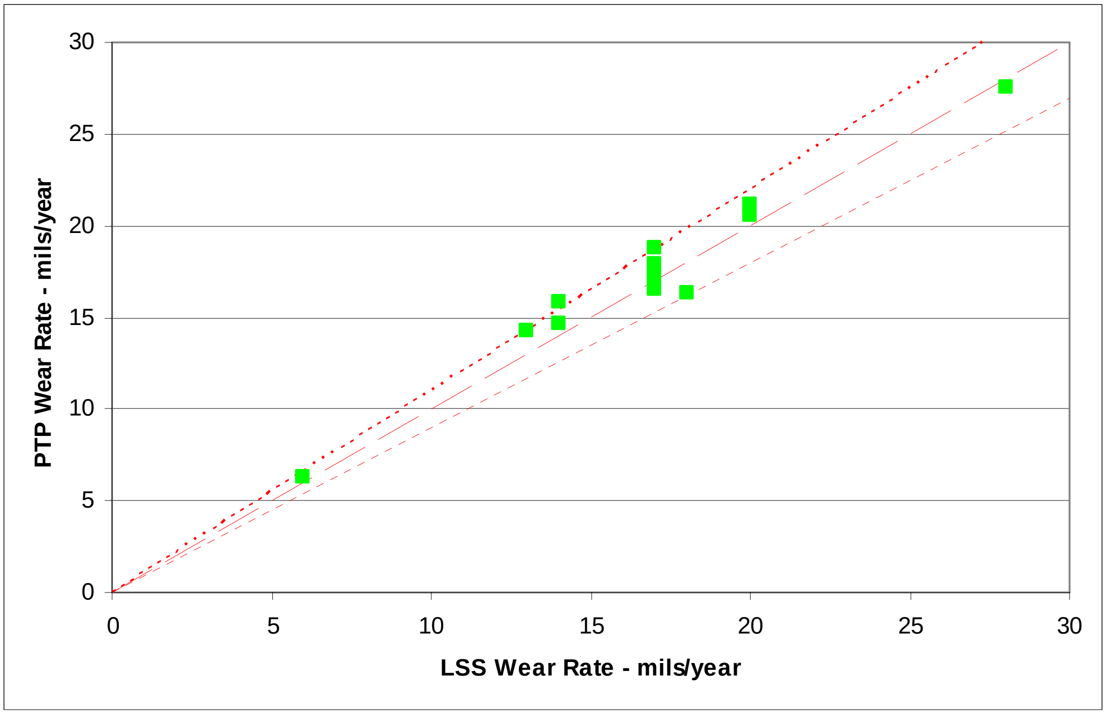

Figure 4-8
Diablo Canyon Unit 2 Results of the LSS Method

As mentioned, one feature of use of the LSS method compared to the LSPTP method is that the data seems closer to the 45° lines. Similar to Table 4-2, Table 4-5 presents the number of components which have a lower wear rate compared to the PTP method. Comparing these results with the earlier table, it is apparent that the LSS method provides a less biased result than the LSPTP method.

Table 4-5
Diablo Canyon Overall Results – Least Squares Slope Method

	Number of Components	Number Where PTP Is Greater Than LSS	Number Where LSS Is Greater Than PTP
Unit 1	13	8	5
Unit 2	13	10	3
Total	26	18	8

4.1.2.2 Detailed Comparison

A detailed comparison was made of the results of the LSS method using the Diablo Canyon datasets. These results are summarized in Table 4-6. As expected, the results indicate that the LSS method was less biased than the LSPTP method. In fact the percentage of PTP determinations greater than LSS determinations fell slightly from 92% to 90%.

Table 4-6
Detailed Comparison of Diablo Canyon – Least Squares Slope Method

	Total PTP Calculations	Number Where PTP IS Greater Than LSS	Number Where LSS Is Greater Than PTP
Unit 1	158	140	18
Unit 2	129	117	12

4.1.2.3 Outliers

There were three outliers identified in this subsection all in Unit 1. The first two, DCU1-A and DCU1-B were previously discussed and the same explanation holds for the LSS as well as the LSPTP. Let us now consider DCU1-C. This point is located in Figure 4-7 near DCU1-B at approximately, 43, 38. For DCU1-C, the determinate location for the PTP and the LSS methods were not the same, therefore, we must consider two different grid locations.

Figure 4-9 presents the thickness data for the two grid locations of interest. The diamonds (blue) represent the thickness readings for the determinate location for the PTP wear rate. The slope of the dashed (blue) line drawn between the two end points represents the PTP wear rate. Consider now the square (red) points. The three symbols represent the determinate location for the LSS method, and the solid (red) line is the least squares fit through these points. Although, it is not obvious, the slope of the solid line is steeper, by about 10% than the other line. Therefore, it appears that while this component is classified as an outlier, no significance to this classification should be made.

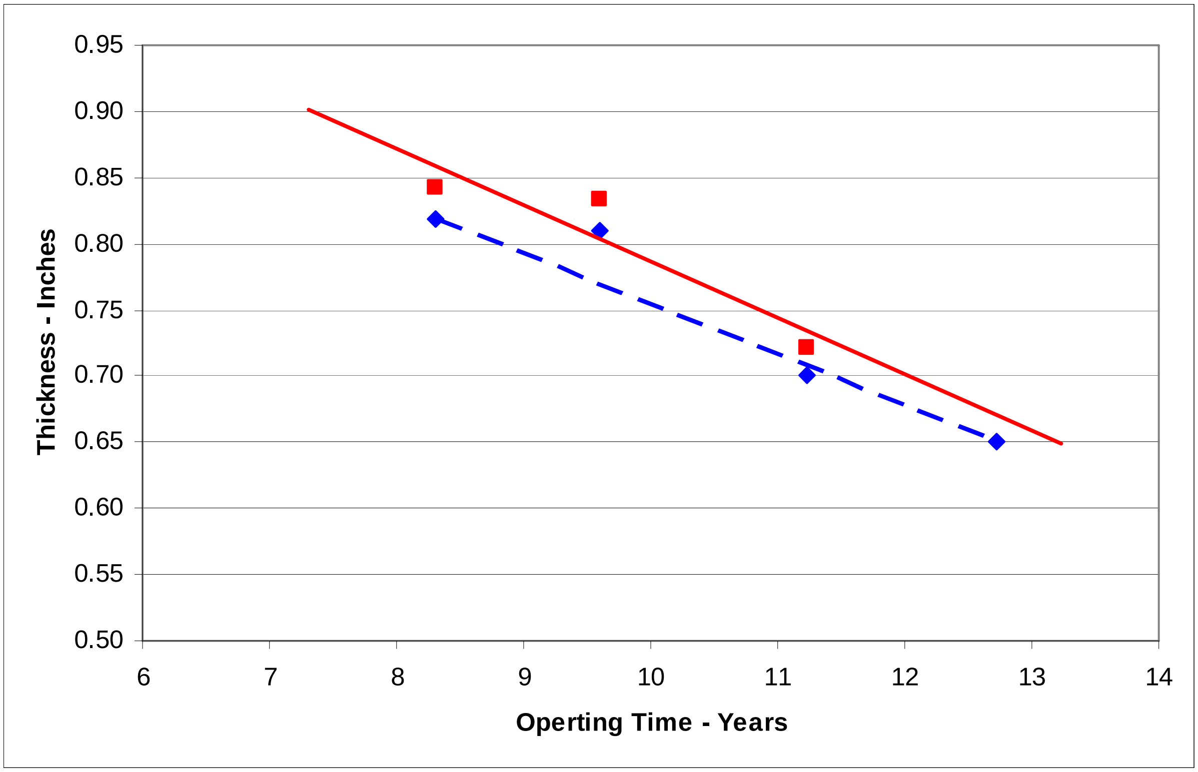

Figure 4-9
Thickness Plot for DCU1-C

4.2 Dresden

The Dresden Generating Station is composed of two operating BWRs – Units 2 and 3. It is owned and operated by Exelon Nuclear and is located in northeastern Illinois.

Inspection data from the two Dresden units were examined and a number of components with multiple inspection data were selected. The selected components were from a number of systems with feedwater being the predominant system. Table 4-7 presents a summary of the selected components.

The data from Dresden was analyzed in the same manner as the Diablo Canyon data. As such, little narrative will be provided.

Table 4-7
Selected Components from Dresden Units 2 and 3

Unit	Number of Components	Number from Feedwater	Number of Repeat Inspections		
			3	4	5
2	9	5	6	3	0
3	4	3	3	0	1

Due to the small number of points, the two Dresden units will be discussed together.

4.2.1 LSPTP Method

4.2.1.1 Overall Comparison

Figure 4-10 presents an overall comparison of the LSPTP method and the data from the two Dresden Units. Note that the units are differentiated by the shape (and color) of the points. One outlier is shown as an open (red) symbol, it will be denoted as D3-A, and be discussed later in this section.

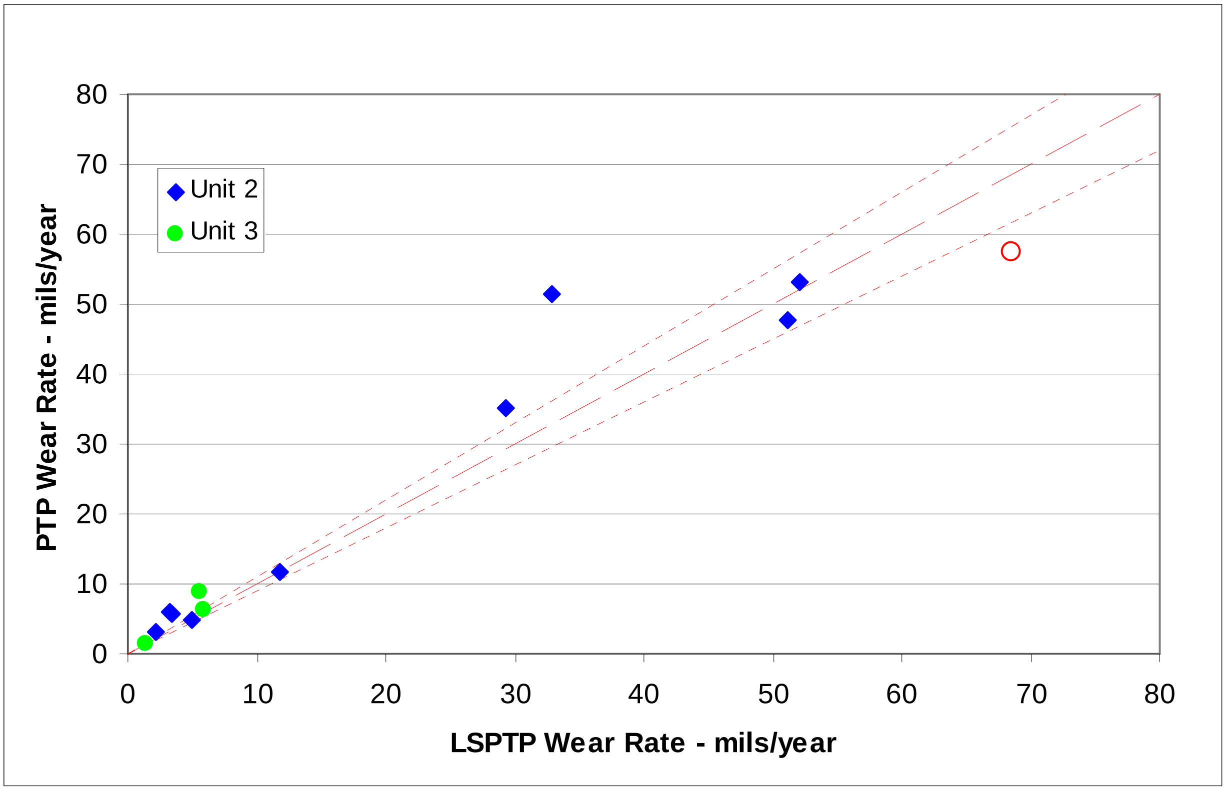

Figure 4-10
Overall Results from Dresden Units 2 and 3 using the LSPTP Method

Examining these results, 9 of the 13 PTP wear rates were greater than the LSPTP wear rates.

4.2.1.2 Detailed Comparison

A detailed comparison of the results for the Dresden Units, broken down by units is presented in Table 4-8. As before there was a large majority of determinations in which the PTP had a higher wear rate than the LSPTP. However, for these results, the percentage was 76% - less than for Diablo Canyon.

Table 4-8
Detailed Results from Dresden Units 2 and 3 Using the LSPTP Method

	Total PTP Calculations	Number Where PTP IS Greater Than LSPTP	Number Where LSPTP Is Greater Than PTP
Unit 2	36	27	9
Unit 3	22	17	5

4.2.1.3 Outlier

As shown in Figure 4-10, there was one component significantly below the 45° line. As the same grid location was the determinate location for both the LSPTP and the PTP method, a plot of thickness versus time is presented as Figure 4-11. As can easily be seen, the scatter in the data causes the least squares fit line, the solid (blue) line, to have a steeper slope than the dashed (red) line that represents the PTP wear rate.

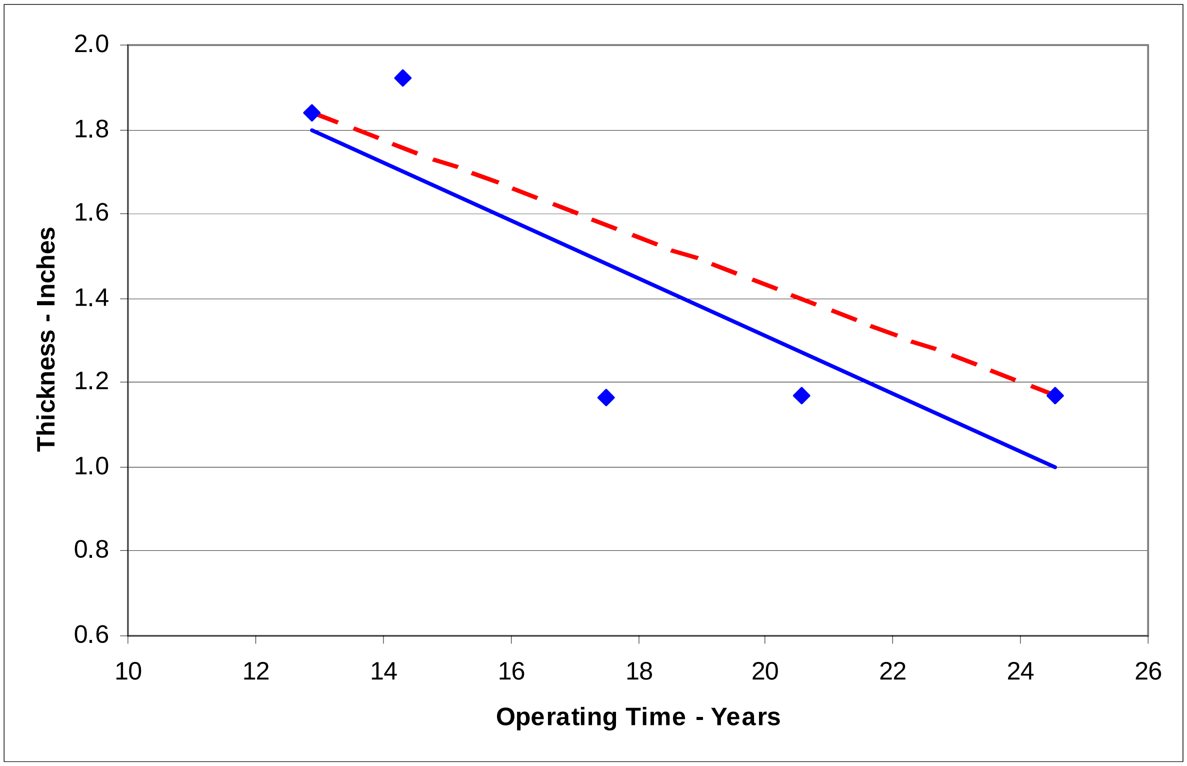

Figure 4-11
Thickness Plot for D3-A

4.2.2 Least Squares Slope Method

4.2.2.1 Overall Comparison

Figure 4-12 presents the overall results for Dresden Units 2 and 3 using the least squares slope method. This figure is quite similar to Figure 4-12. Once again the same outlier is present and is shown as an open (red) symbol. In general, the data points seem slightly closer to the 45° line. Examining these results, 9 of the 13 PTP wear rates were greater than the LSPTP wear rates. This is exactly the same result as with the LSPTP method.

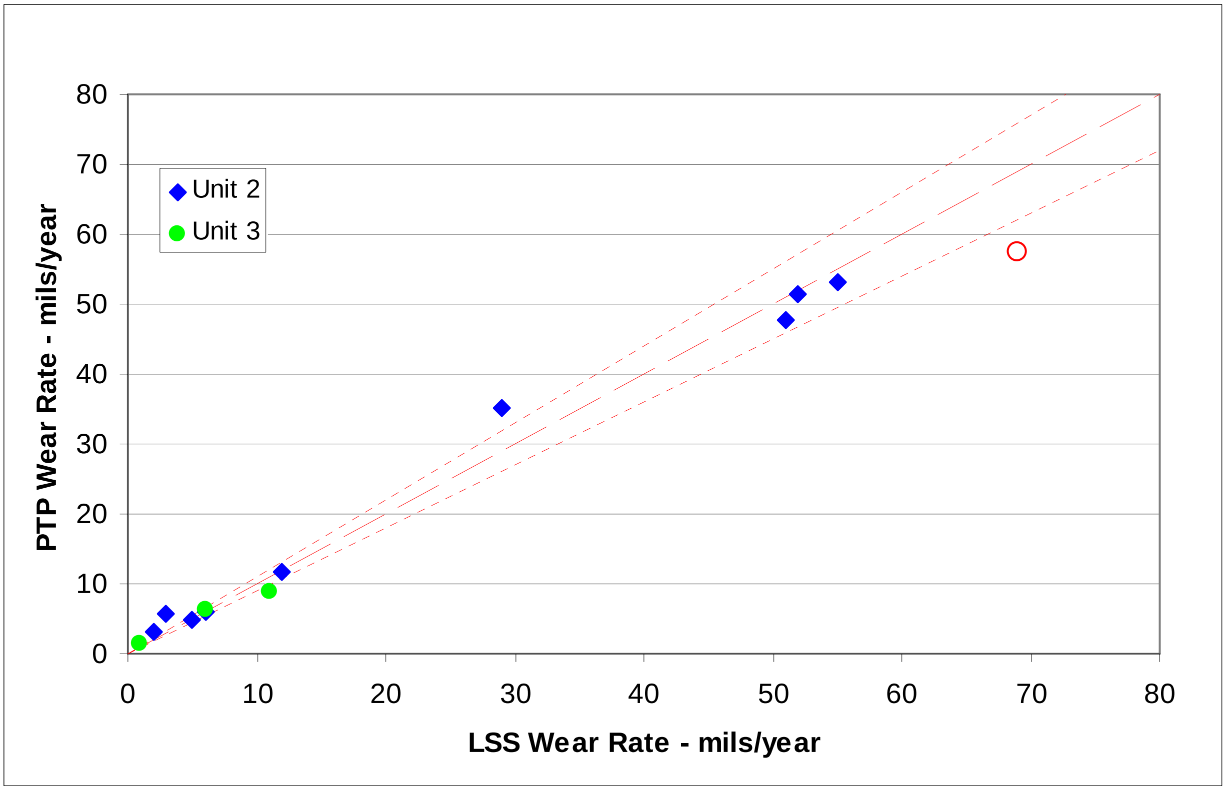

Figure 4-12
Overall Results for Dresden Using the Least Squares Slope Method

4.2.2.2 Detailed Comparison

Table 4-9 presents the results of the detailed comparison for the Dresden units using the LSS method. Comparing the tabulated values with Table 4-8, it can be easily seen that the use of the LSS results in less bias (i.e., there is closer to an even number of points on the sides of the 45° line).

Table 4-9
Detailed Results from Dresden Units 2 and 3 Using the LSS Method

	Total PTP Calculations	Number Where PTP IS Greater Than LSS	Number Where LSS Is Greater Than PTP
Unit 2	36[3]	21	14
Unit 3	22	16	6

---

[3] One of the determinations had equal wear rates calculated by the LSS method and the PTP method.

4.2.2.3 Outlier

For outlier D3-A, the determinate location for the LSS method was the same for the other two methods. As the thickness plot was previously presented and discussed, no further discussion of the outlier D3-A is necessary.

4.3 Hope Creek

The Hope Creek Generating Station is a single unit BWR. It is located in southwestern New Jersey and is owned and operated by PSEG Nuclear

Inspection data from Hope Creek was examined and 73 components with multiple inspection data were selected. Of these components, over one-quarter are from the feedwater system with the other components from several other systems including condensate, extraction steam, heater drain, moisture separator drain, reactor water cleanup, seal steam and cross-under.

The selected components are summarized in Table 4-10.

Table 4-10
Summary of Hope Creek Inspection Data

Number of Components	Number from Feedwater	Number of Repeat Inspections			
		3	4	5	6
73	21	57	9	3	4

4.3.1 LSPTP Method

4.3.1.1 Overall Comparison

The overall comparison of the LSPTP method with the PTP method is presented in Figure 4-13. The agreement is generally good with some outliers present. Three outliers were selected for further examination. They are shown in the large, open (red) symbols and are designated as follows:

- HC-A is the point closest to the origin at about coordinates - 11, 3.
- HC-B is the next point, below the line, at about coordinates - 42, 18.
- HC-C is the last point below the line at about coordinates – 64, 16.

These outliers will be discussed later in this section.

Examining these results, of the 73 components considered, 41 of the components had higher wear rates as determined by the PTP method, 31 had higher wear rates as determined by the LSPTP method, and one component had the same wear rate.

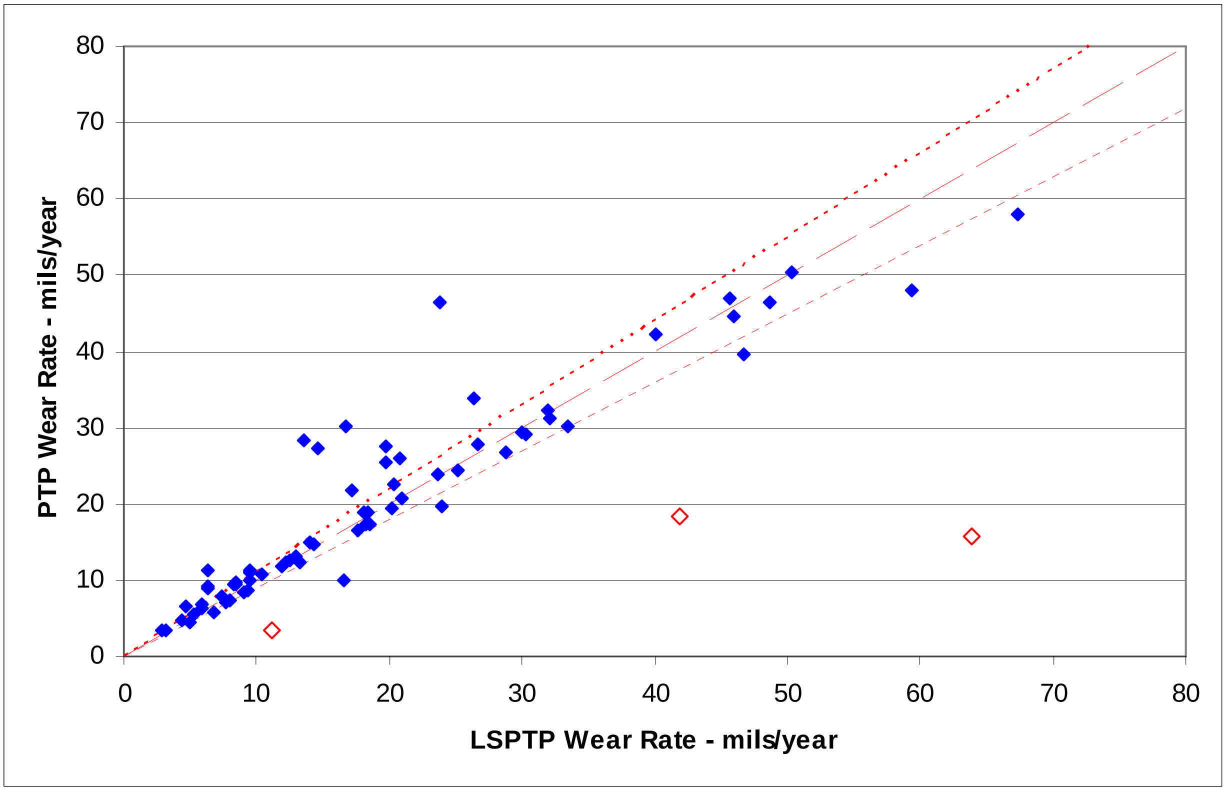

Figure 4-13
Overall Comparison of Hope Creek Using LSPTP Method

4.3.1.2 Detailed Comparison

A detailed comparison of the results for Hope Creek was performed. As before there was a large majority of determinations in which the PTP had a higher wear rate than the LSPTP. In fact 83% of the wear rate determinations (i.e., 261 out of 316) showed a larger value for the PTP method.

4.3.1.3 Outliers

The three outliers identified were examined. In each case, there were different determinate grid locations for the LSPTP and the PTP methods.

Figure 4-14 through 4-16 present thickness plots of the three components. The diamonds (blue) represent the thickness readings at the PTP determinate location, and the dashed (blue) lines represent the PTP wear rates. The squares (red) represent the thickness readings at the LSPTP determinate location, and the solid (red) line is the least squares fit through these points. As can easily be seen, the slopes of the solid (red) line are greater than the slopes of the respective dashed (blue) lines. Note also, for the first two components, there were only two measurements for the determinate LSPTP location.

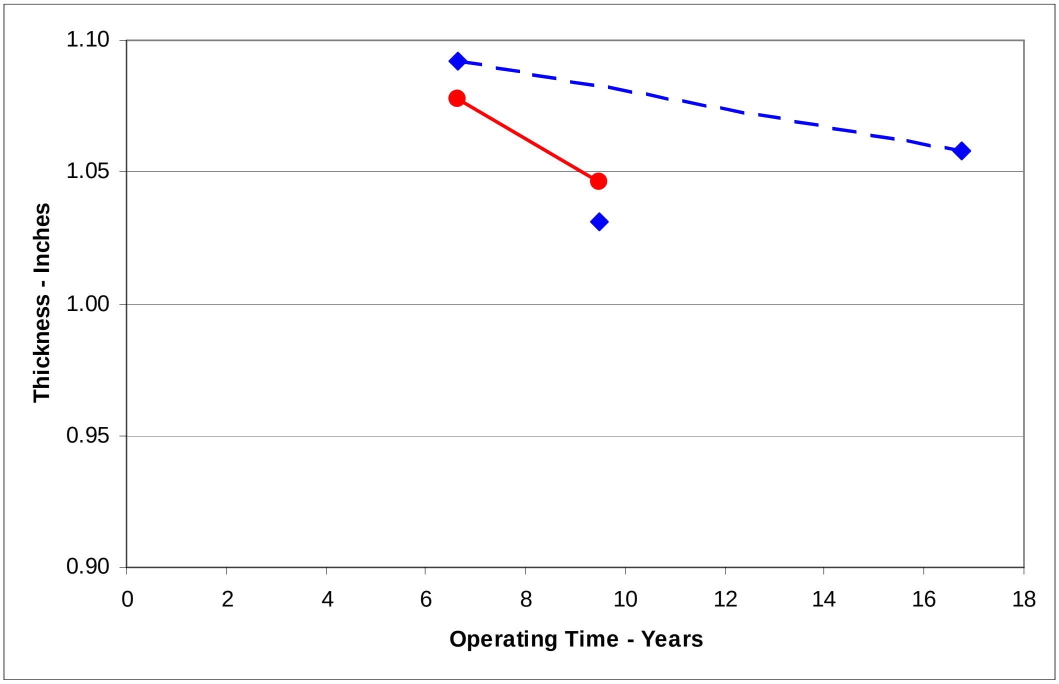

Figure 4-14
Thickness Plot for Component HC-A-LSPTP

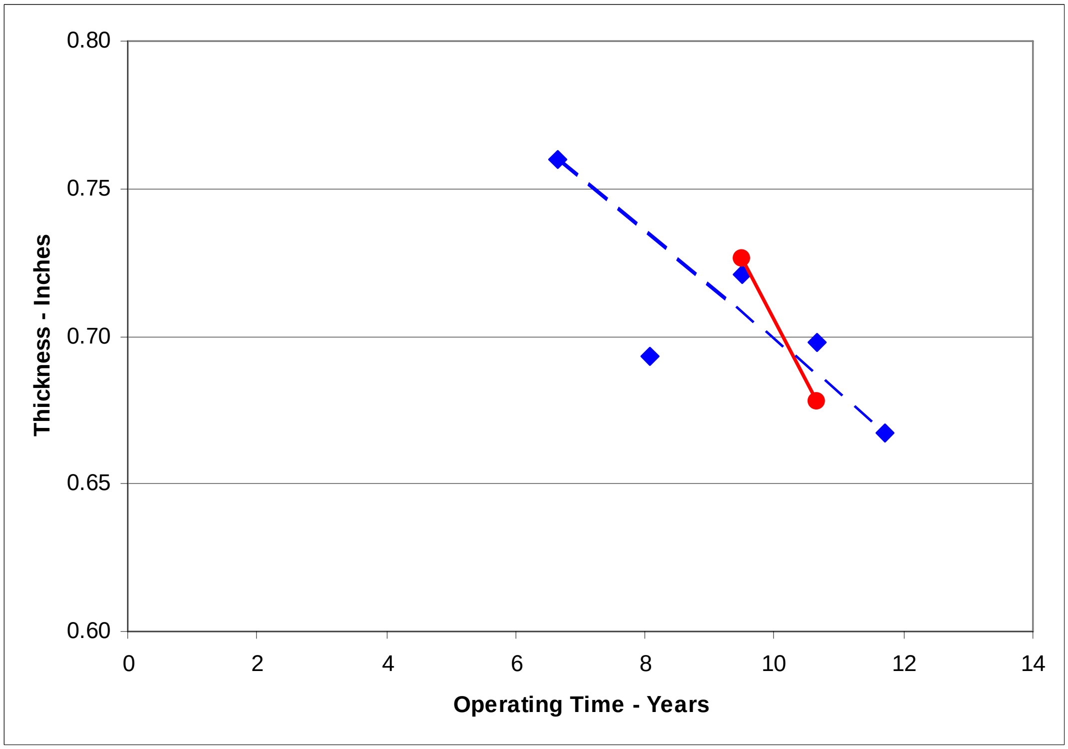

Figure 4-15
Thickness Plot for HC-B-LSPTP

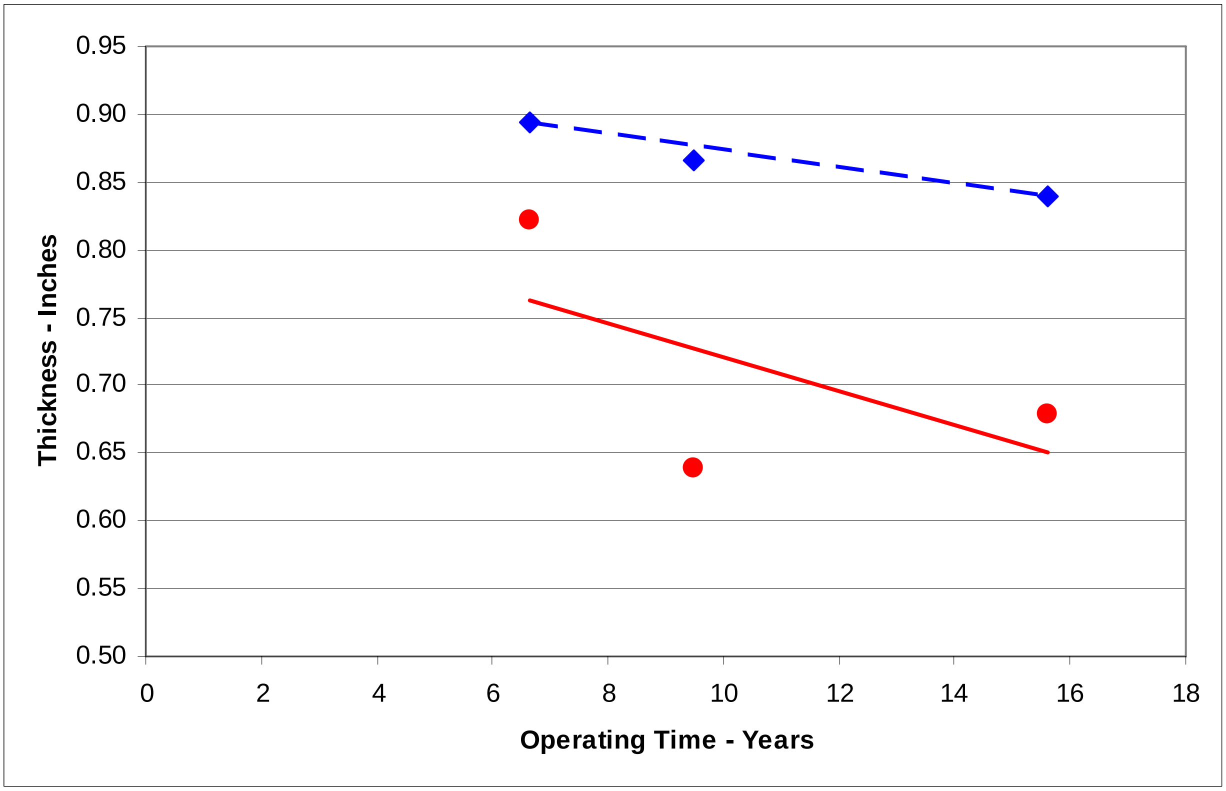

Figure 4-16
Thickness Plot for HC-C-LSPTP

4.3.2 Least Squares Slope Method

4.3.2.1 Overall Comparison

Figure 4-17 presents the overall results for Hope Creek using the least squares slope method. Once again, the figure is quite similar to the corresponding figure, Figure 4-13. Again, the points appear to be somewhat closer to the 45° line. The same outliers are shown as open (red) symbols.

Examining these results, 39 of the 73 PTP wear rates were greater than the LSS method wear rates. This result is slightly less biased than the LSPTP method.

4.3.2.2 Detailed Comparison

A detailed comparison of the results for Hope Creek was performed. As before there was a large majority of determinations in which the PTP had a higher wear rate than the LSS method. In fact 83% of the wear rate determinations (i.e., 261 out of 316) showed a larger value for the PTP method. This was very slightly less than the comparison with the LSPTP method.

4.3.2.3 Outliers

As the same outliers were identified, and the determinate locations for these locations were the same with both the LSPTP method on the LSS method, no further discussion is needed.

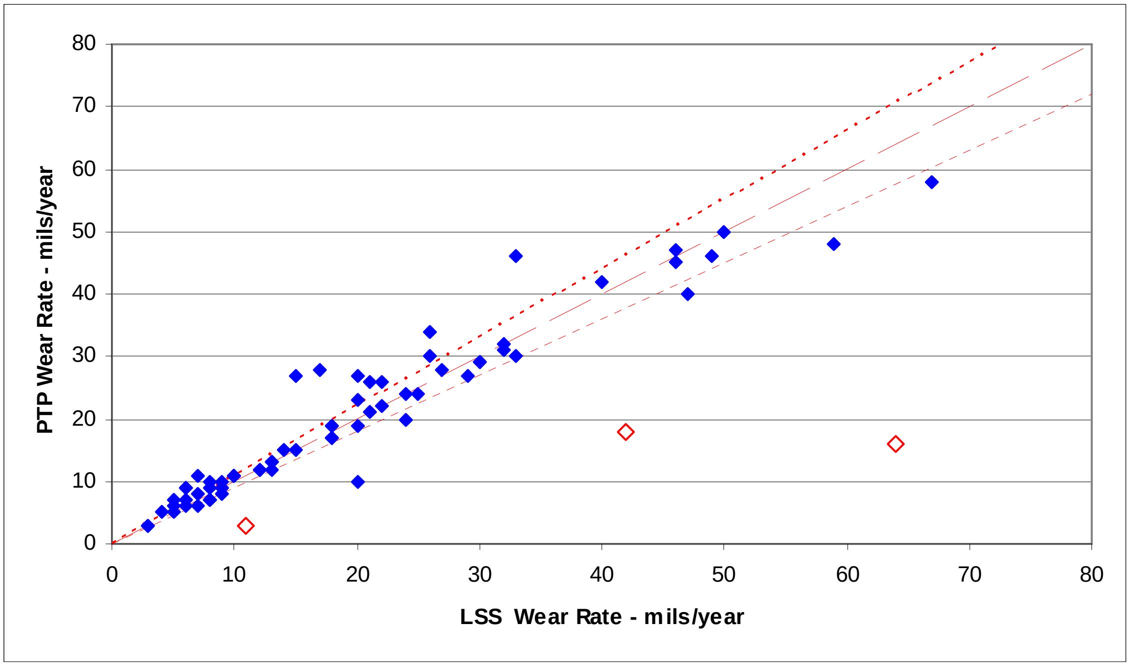

Figure 4-17
Overall Results for Hope Creek Using the Least Squares Slope Method

4.4 Vogtle

The Vogtle Electric Generating Plant is a two-unit PWR located in eastern Georgia. It is operated by Southern Nuclear.

Inspection data from Unit 1 at Vogtle was examined and 13 components were selected. All but one of these components was from the feedwater system. The other component was from the condensate system.

The selected components are summarized in Table 4-11.

Table 4-11
Summary of Vogtle Unit 1 Inspection Data

Number of Components	Number from Feedwater	Number of Repeat Inspections			
		3	4	5	6
13	12	9	2	1	1

4.4.1 LSTPTP

4.4.1.1 Overall Comparison

Figure 4-18 presents the overall comparison of the Vogtle Unit 1 data with the LSPTP method. As can be seen, the agreement is quite good except for one outlier identified as an open (red) symbol. This outlier will be examined later in this section.

Of the 13 component considered, 9 components had higher PTP wear rates than LSPTP wear rates.

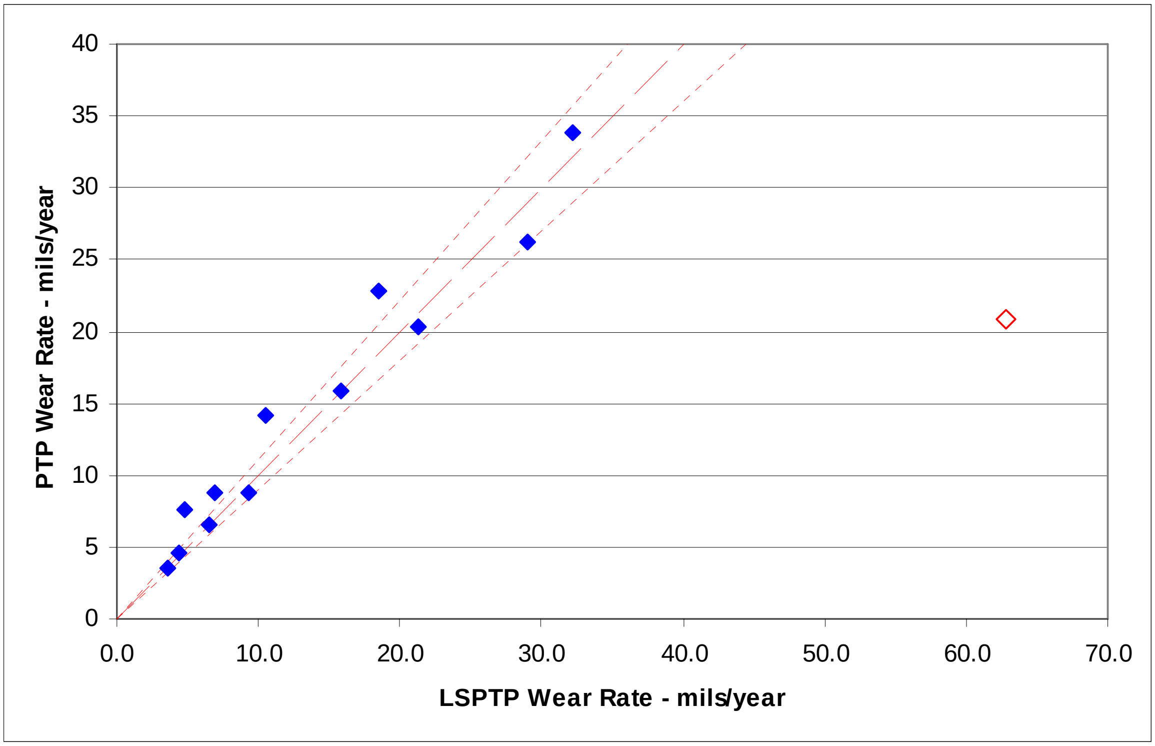

Figure 4-18
Overall Results for Vogtle Unit 1 Using the LSPTP Method

4.4.1.2 Detailed Comparison

A detailed comparison of all of the possible determinations showed that 89% (57 out of 64) PTP determinations had higher wear rates than the LSPTP method.

4.4.1.3 Outlier

Figure 4-19 presents a thickness plot of the outlier, V1-A. As before, the diamonds (blue) represent the thickness measurements for the determinate PTP location, the dashed (blue) line represents the PTP wear rate, the starred (red) points represent the thickness measurements at the determinate LSPTP location, and the solid (red) line is the least squares slope. Note that as before, the solid (red) line is much steeper than the dashed (blue) line. Further note, that once again, the determinate LSPTP location had only two valid data points.

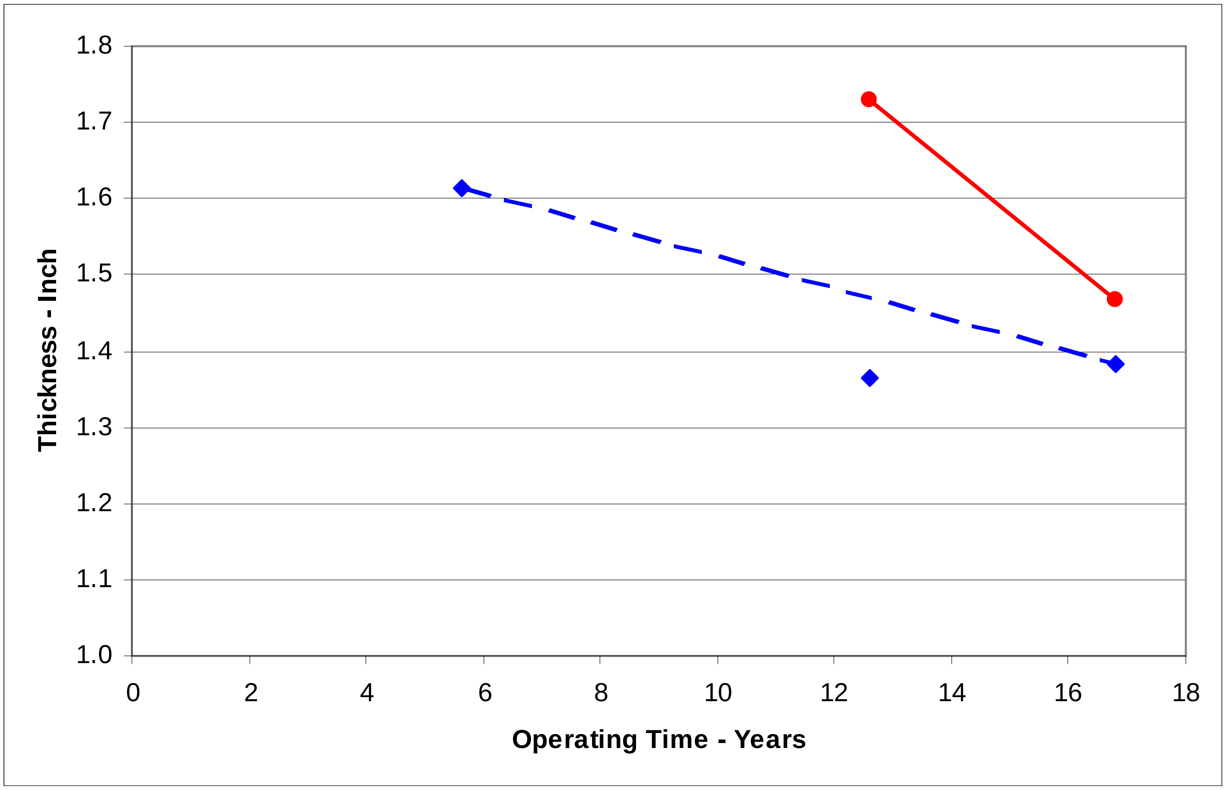

Figure 4-19
Thickness Plot of V1-A

4.4.2 Least Squares Slope Method

4.4.2.1 Overall Comparison

Figure 4-20 presents the overall comparison of the Vogtle Unit 1 data with the LSS method. This plot is quite similar to the corresponding plot using the LSPTP method, Figure 4-18. The same outlier is shown in the same location. Of the 13 components considered, 9 components had higher PTP wear rates than LSS method wear rates. This is the same outcome as seen with the LSPTP method.

4.4.2.2 Overall Comparison

An overall comparison of the Vogtle Unit 1 data using the LSS method showed that 87% of the determinations made with the PTP method were larger than the determinations made with the LSS method. This figure is just slightly below the LSPTP figure of 89%.

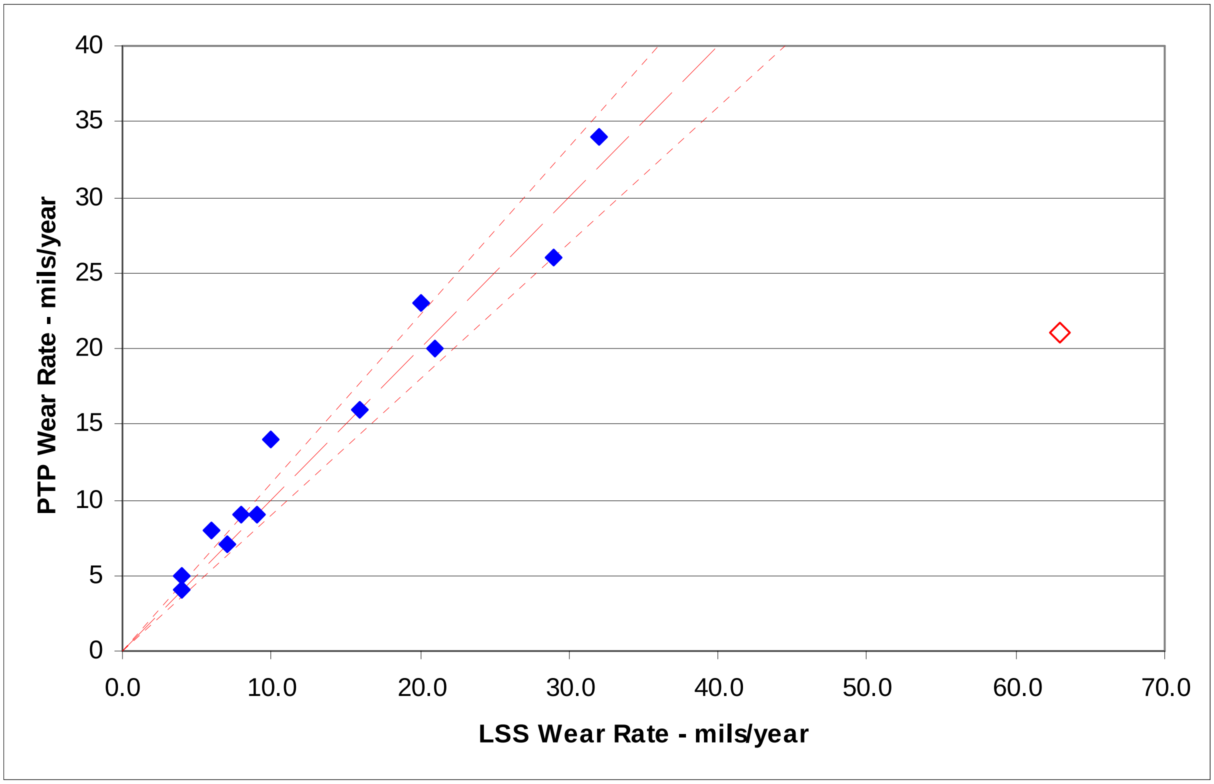

Figure 4-20
Overall Comparison of Vogtle Unit 1 Using the Least Squares Slope Method

4.4.2.3 Outlier

As the came component was an outlier with both the LSPTP and the LSS methods, and the determinate location was the same, no further discussion of V1-A is needed.

4.5 Summary

Multiple inspection data sets from six nuclear plans were examined using the LSPTP method. A composite plot showing all of the comparisons (on an overall basis) is presented in Figure 4-21. This comparison shows a total of 125 components on this figure.

Similarly, Figure 4-22 presents the results of a comparison using the LSS method. Comparing these two figures, it should be apparent that the points of the LSS method are somewhat closer to the 45° than the LSPTP method. This observation is confirmed by statistical analysis that shows that the correlation coefficient, a measure of the strength and direction of a linear relation, is slightly higher for the LSS method compared to the LSPTP method (i.e., 0.893 vs. 0.862). Note that closer the value of the correlation coefficient to unity the better the fit.

Throughout this report the assumption has been made that the actual wear rates are constant with time. In actuality, this is not normally a good assumption because of changes in water chemistry and power levels. The implications of this assumption are examined by means of numerical experiments presented in Appendix C.

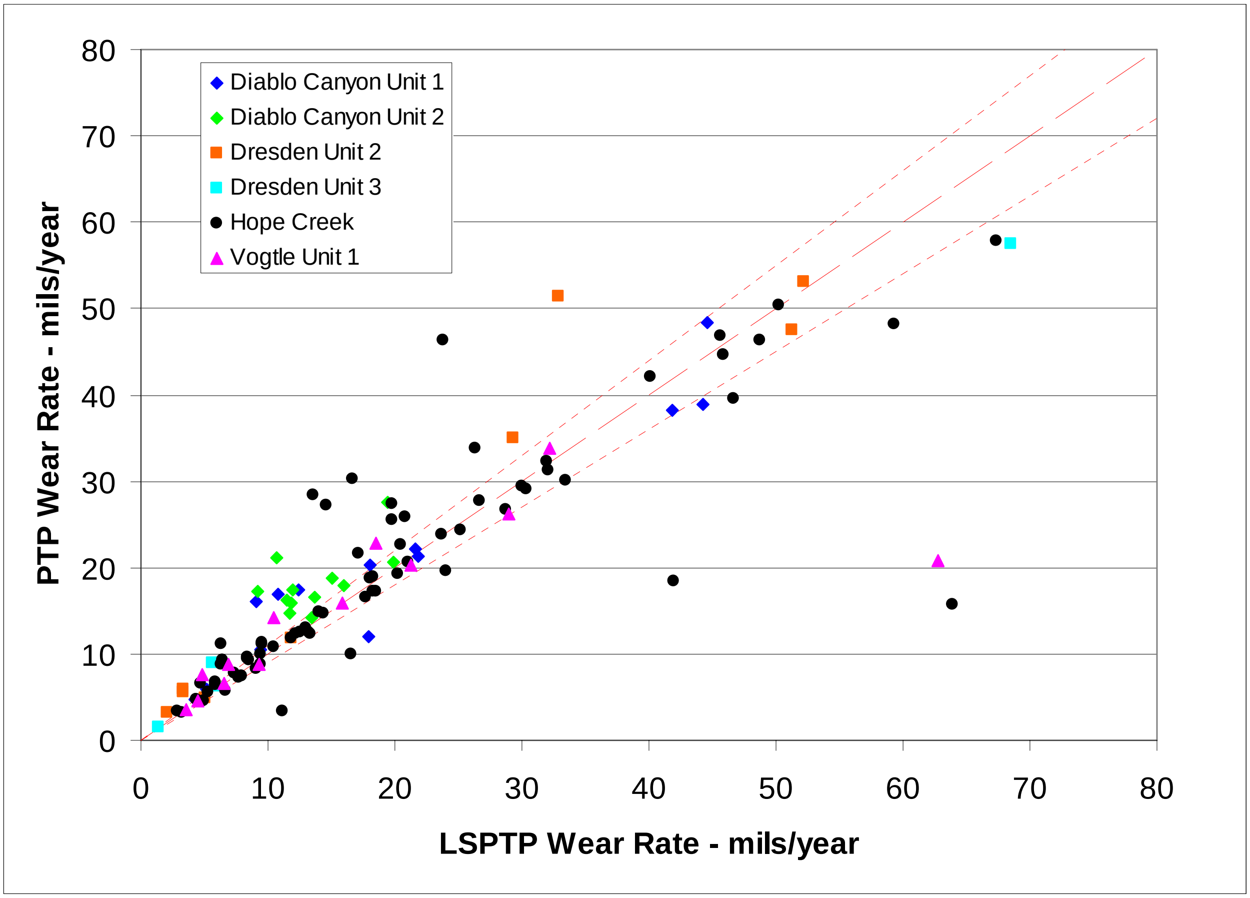

Figure 4-21
Composite Plot of the LSPTP Results

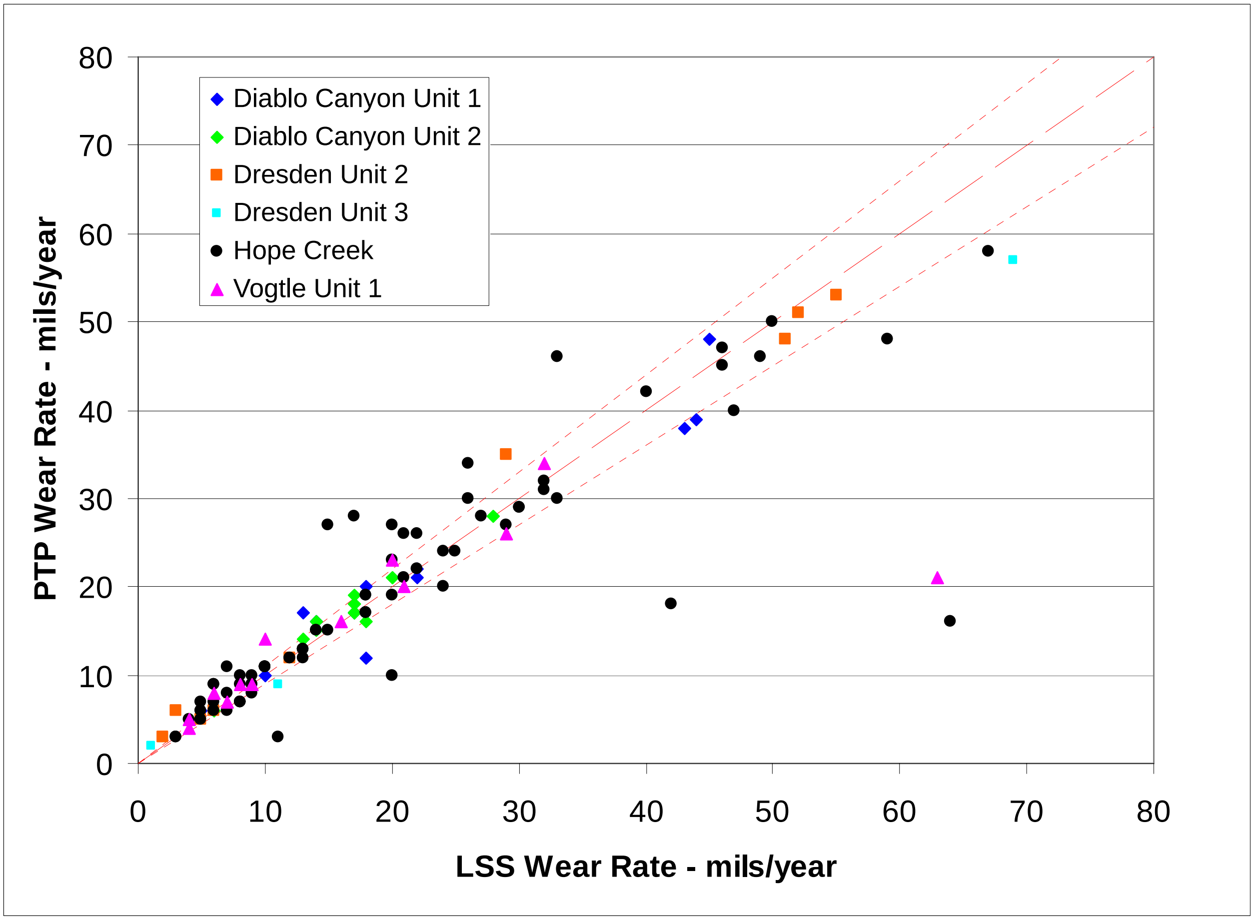

Figure 4-22
Composite Plot of the LSS Method Results

5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the plant comparisons and the numerical experiments performed in Appendix B, the following conclusions can be made:

- Both the least squares point to point method and the least squares slope method produce results that are comparable to the maximum delta point to point method between extreme points. In general, the least squares methods produce equal or slightly lower wear rates than the PTP method.
- Comparing the results from 125 components, there were several components that could be considered outliers. These outliers seemed to have several common features, namely: limited number of fit points, and or excessive data scatter.

5.2 Recommendations

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

- The least squares slope method should be incorporated into the next version of the CHECWORKS™ Steam Feedwater Application.
- The least squares slope method is recommended over the least squares point to point method for two reasons:
  - There was slightly better agreement with the PTP data
  - The method does not need user input *Tcrit*. As such, the user does not have to have specified values in the data base. The use of *Tcrit* also opens up the possibility of erroneous results caused by *Tcrit* being close to the *Tinitial* determined by the least squares curve fit. An example of a component that poses this problem is presented in Appendix D.
- If the LSS method is implemented in the CHECWORKS™ Steam Feedwater Application, it is recommended that the user have optional displays of the thickness plots of the determinate locations (similar to the outlier plots presented in the previous section). Additionally, a warning should be given or prohibition enacted if only two points are used to make the curve fit.

6
REFERENCES

1. “Secondary Piping Rupture Accident at Mihama Power Station, Unit 3 of the Kansai Electric Power Co, Inc. (Final Report)”, Nuclear and Industrial Safety Agency (Japan), March 30, 2005. Available on the Internet at: http://www2.jnes.go.jp/atom-db/en/trouble/mihama_final.pdf.
2. Bridgeman, J. & Shankar, R. *“Erosion/Corrosion Data Handling for Reliable NDE,”* presented at the post-SmiRT post-conference, Monterey, CA, 1989.
3. *Development of an Averaged Point-to-Point Method for Inspection Data.* EPRI, Palo Alto, CA, unpublished report.

A

MATHEMATICAL BACKGROUND OF THE LSPTP METHOD

As stated in the body of this report, the LSPTP method calculates for each grid point the time to reach the critical thickness of the fitting. This thickness is assumed to constant for the entire fitting being considered. To determine this time, a linear least squares curve fit is used.

In a similar manner, the slope of the negative of least squares slope is used as the wear rate in the LSS method.

Least Squares Curve Fitting

In either method, the first step is to write the equation of the straight line being fit, noting that the thickness at operating time equal zero is the initial thickness of the component. Therefore:

$$T = T_{initial} - WR \cdot time \qquad \text{(A-1)}$$

Where:

T = thickness

T_{inital} = initial thickness of the component

WR = wear rate

$Time$ = operating time

Now in this situation, the only known quantities are a table of measured thickness at each grid versus operating time. The wear rate and the initial thickness are unknown.

For convenience, the wear rate will be taken as positive in equation A-1, so A-1 will be rewritten below. Note that it is fully expected that the wear rate will be determined as a negative (i.e., physically correct) number.

$$T = T_{initial} + WR \cdot time \qquad \text{(A-2)}$$

Now, Equation A-2 is in the standard form of a linear equation, namely:

$$Y = B + M \cdot X \qquad \text{(A-3)}$$

Where:

Y = dependent variable

B = intercept (i.e., the value at X=0)

M = the slope of the straight line

X = independent variable

To solve the problem of fitting a least squares, the input must be a table of at least two pairs of thickness and times. Denoting the time (the independent variable) as X and the thickness (the dependent variable) as Y, and the number of observations as n, the least squares slope and intercept can be obtained using the set of equations presented below[4]. Note that the symbol Σ (i.e., the capital Greek letter sigma) is a mathematical operator that indicates that there is a summation of the variables following the operator.

Let:

$$S_X = \sum_1^n X_i \tag{A-4}$$

$$S_Y = \sum_1^n Y_i \tag{A-5}$$

$$S_{X2} = \sum_1^n X_i^2 \tag{A-6}$$

$$S_{XY} = \sum_1^n X_i \cdot Y_i \tag{A-7}$$

$$D = n \cdot S_{X2} - (S_x)^2 \tag{A-8}$$

With these definitions, equations for the slope and intercept may be written as:

$$b = T_{Initial} = \frac{S_{X2} \cdot S_Y - S_X \cdot S_{XY}}{D} \tag{A-9}$$

$$m = WR = \frac{M \cdot S_{XY} - S_X \cdot S_Y}{D} \tag{A-10}$$

Thus, knowing the values of the operating time and the thickness, the least squares parameters may be determined.

Coefficient of Determination

How well the straight line fits the data set, (called by statisticians "the goodness of fit") is normally expressed as a term known as the coefficient of determination. This term is better known by its symbol R^2. The coefficient of determination varies from unity (a perfect fit) to zero (no fit at all).

---

[4] See any mathematical handbook for more details.

The coefficient of determination is found by computing the variance of the dependent value and the variance of the fit and then comparing them. Operationally, these parameters may be found by:

$$\bar{y} = \frac{1}{n}\sum_{1}^{n} Y_i \tag{A-11}$$

Where:

n = number of points

Y = dependent variable

$\bar{y}$ = average value

$$Vy = \frac{1}{n}\sum_{1}^{n} (Y_i - \bar{y})^2 \tag{A-12}$$

Where:

Vy = variance of the dependent value

$$Ve = \frac{1}{n}\sum_{1}^{n} (Y_i - (m \cdot X_i + b))^2 \tag{A-13}$$

Where:

Ve = variance of the estimate

$$R^2 = 1 - \frac{Ve}{Vy} \tag{A-14}$$

Where:

R^2 = coefficient of determination

Description of the Least Squares Methods

Least Squares PTP Method

Consider now Figure A-1 (which is identical to Figure 3-2). Using the methodology described above, the least squares straight line through the data points can be determined. In conventional form, the equation of the fit line for the variables of interest was given by Equation A-2.

$$T = T_{initial} + WR \cdot time \tag{A-2}$$

As the *Tinitial* and the wear rate are known form the curve fit, the time to any value including *Tcrit* is easily found.

$$T_{crit} = T_{initial} + WR \cdot time_{to\,Tcrit} \tag{A-15}$$

Rearranging Equation A-15:

$$time_{to\ Tcrit} = \frac{(T_{crit} - T_{initial})}{WR} \tag{A-16}$$

As the curve fit parameters, and the critical thickness are known, the minimum time to reach the critical thickness can be determined. Note that in Equation A-16 both the numerator and the denominator should be negative so that the *time to Tcrit* is positive. The numerator is negative because *Tcrit* should be less than *Tinital* while the denominator is negative as the wear rate, i.e. the slope of the curve) is negative.

The location with the smallest time to *Tcrit* in the fitting is the determinate location, and the wear rate for that point is taken as the component wear rate.

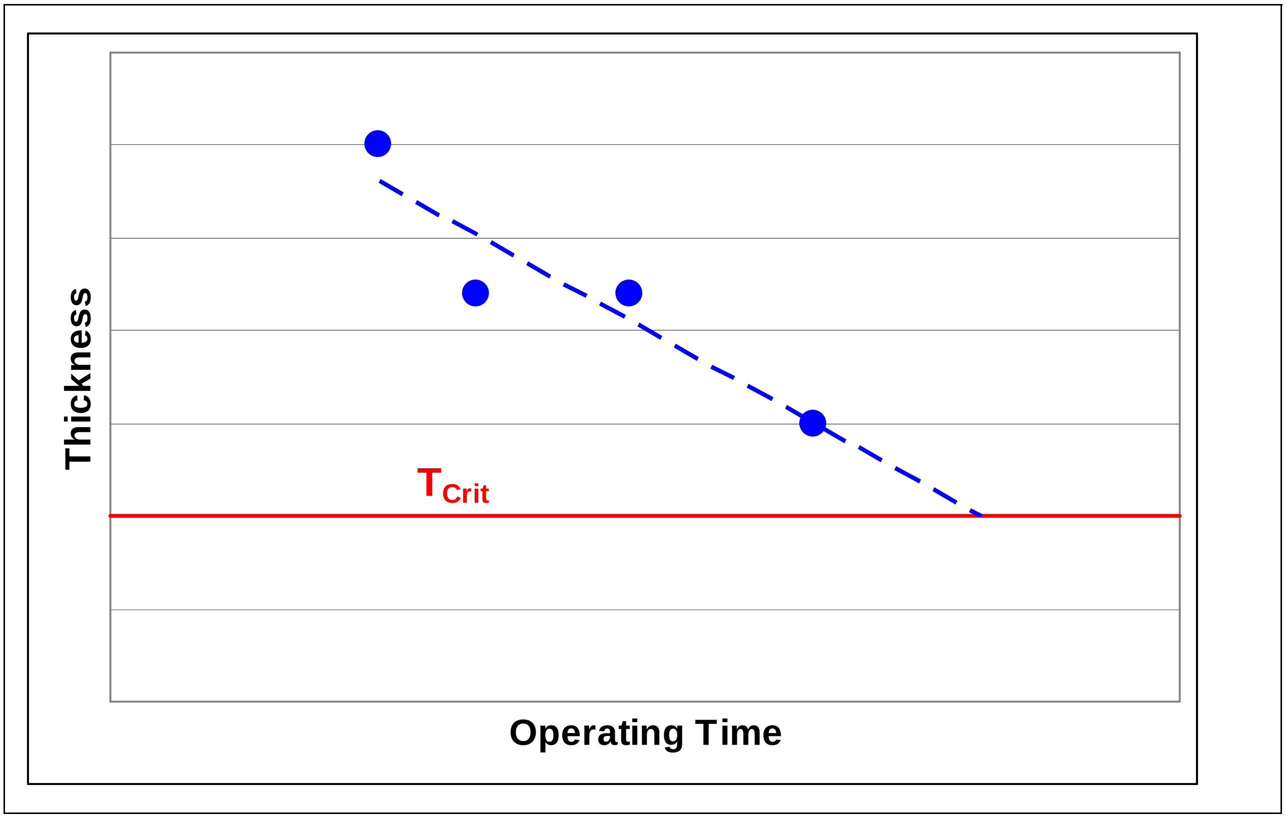

Figure A-1
Schematic of Least Squares Methods

Description of the Least Squares Slope Method

The linear least squares slope method uses the same methodology as the LSPTP method up until the point that all of the slopes of the curve fits are calculated. At that point, the maximum of the negative slopes is found. This slope is the wear rate b the LSS method.

B

NUMERICAL EXPERIMENTS

During the course of this work, several sets of numerical experiments were performed. In all of these cases, the data used was hypothetical and was produced using a random number generator.

Tests Using Hypothetical Data Containing Imposed Wear

To further explore the behavior of the least squares method, four hypothetical data sets were constructed using a custom built FORTRAN programs to generate input files. These data sets are named and described in Table B-1.

Table B-1
Hypothetical Data Sets

Name	Description
Uniform	Constant initial thickness
Hot-Spot	A 5 x 5 area in the center of the grid had twice the random variation of the bordering area
Local	A 3 x 3 area in the center of the grid has three times the random variation of the bordering area
Point	The central point had four times the random variation of the remainder of the grid

Each set consisted of an 11 x 11 grid with initially uniform thickness. The following procedure was used to generate the hypothetical data sets.

- To the initial grids, a fixed wear rate was imposed for five cycles.
- Random errors were then superimposed on every grid location for each of the five cycles as defined in Table B-1.
- The random errors used were based on four values of the standard deviation. Thus the random error varied from a small percentage of the initial component thickness to a large fraction of the component thickness.
- To the cases other than the “uniform case” additional errors were added at the specified locations (see Table B-1).
- After the data sets were generated, the wear rates using the LSPTP and the LSS methods together with the wear rate using the conventional maximum delta PTP wear rate were calculated. As before the maximum delta wear rate was based on the first and last “inspection.” All combinations in between were also calculated.
- To get a representative result, the results of 10 separate, randomly generated sets of input were averaged.

In contrast with the plant data (discussed in the body of this report), these results were examined using only an overall approach.

Overall Results

Least Squares Point to Point

Figure B-1 presents the results of an overall comparison of the results of the two methods evaluating the hypothetical data sets. As mentioned above, the plotted data represents the average of ten randomly generated cases. Plotted are the ratios of the PTP wear to the LSPTP wear. Note that the maximum delta method wear was found using the first and last “inspections.” Four different standard deviations of the applied randomness were used. It is important to note that the addition of random errors seems only to increase the apparent wear rate, at least in these hypothetical cases.

Note that the wear rates calculated using the LSPTP were always less than the results of the maximum delta method.

In order to examine the influence of the number of “inspections” on these results, similar tests were made using different numbers of inspections. The results are presented and discussed later in this appendix.

Least Squares Slope Method

In a manner similar to above, the above tests were repeated with the LSS method. The results of these comparisons are presented in Figure B-2. Note that fairly consistently, the ratios plotted in this figure are closer to unity than on the previous figure. Thus the LSS method appears to give results more consistent with the PTP method than the LSPTP method. This conclusion appears true for both these hypothetical cases and the plant cases considered in the body of the report.

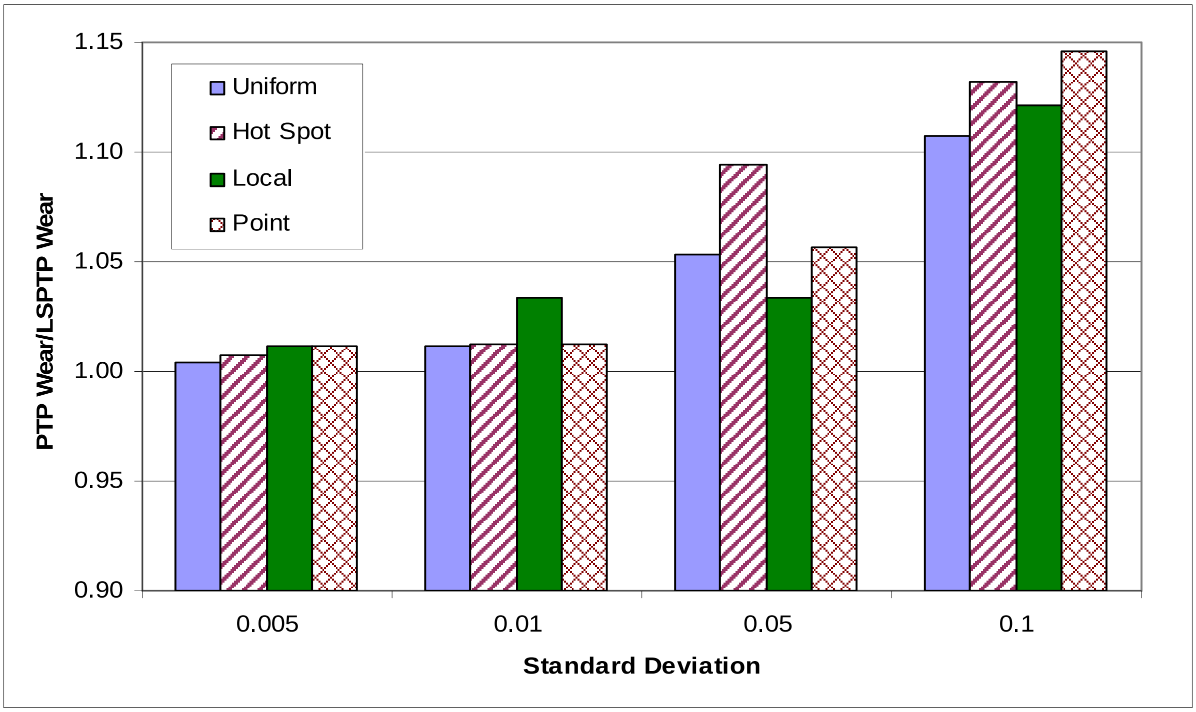

Figure B-1
Overall Results of LSPTP Method for Hypothetical Tests with Imposed Wear

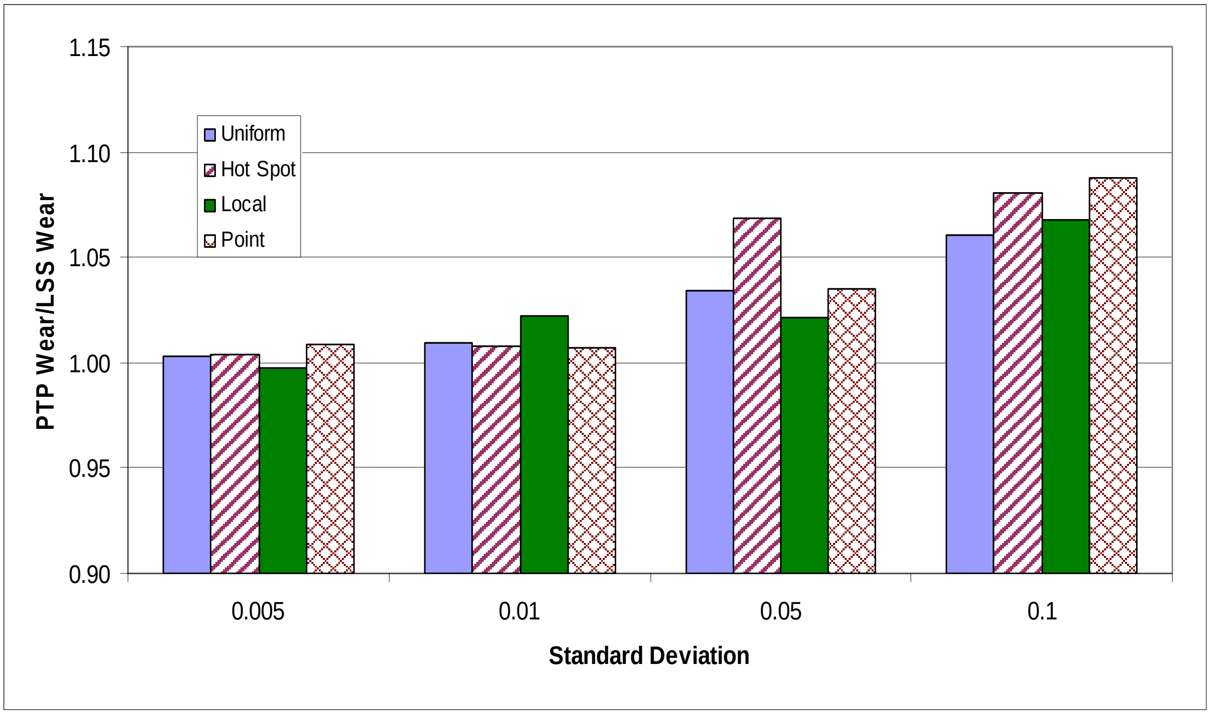

Figure B-2
Overall Results of the LSS Method for Hypothetical Tests with Imposed Wear

Tests Using Hypothetical Data Containing No Imposed Wear

In addition to the tests described above using data with imposed wear, additional tests were performed with no applied wear only a random error designed to model measurement error. In order to get a statistical picture of how the methods compare for the randomly generated data sets, the ensemble approach was used.[5] In this approach, a large number of copies of the same physical case are considered simultaneously and the results are compared.

In this test, an 11 x 11 grid was used. To the grid random wear variations were applied. These random variations were based an input standard deviation. The above procedure was repeated 1,000 times and the results evaluated as before. There were three trials performed with five different standard deviations for the two least squares methods considered

Table B-2 presents the integrated comparison of the two least squares methods against the maximum delta PTP method. The tabulated values are the percentage of runs (out of the 1,000 trials) that the PTP method had a higher value of the predicted wear.

Table B-2
Hypothetical Results with No Imposed Wear

---

[5] See http://en.wikipedia.org/wiki/Statistical_ensemble_%28mathematical_physics%29 for some background material concerning the ensemble approach.

Standard Deviation	PTP Wear Rate Greater than LSPTP Wear Rate	PTP Wear Rate Greater than LSS Wear Rate
0.005	79.2	79.2
0.010	78.5	78.5
0.05	79.2	79.2
0.10	79.3	79.2
0.25	81.4	79.3

Considering the table, two conclusions seem apparent. As the standard deviation increases, the percentage of members with a higher PTP wear rate than a LSPTP wear rate seems to increase. While the percentage for the LSS method wear rate remains relatively constant at about 79%. Whatever the dependence on standard deviation, it is apparent that the least squares methods do a better job of reducing the impact of random errors than the maximum delta PTP method.

Influence of the Number of Inspections

In order to examine the influence of the number of inspections on the LSPTP method, a series of numerical experiments were performed. These experiments were an extension of those discussed in earlier in this appendix. Recall that Table B-1 presents the cases performed.

In the earlier subsection, the comparisons between the LSPTP and the PTP results were compared using 5 hypothetical "inspections." In this subsection the comparisons were made using 3, 5, 7 and 9 inspections. Note that these comparisons were only done with the LSPTP method.

Figure B-3 through B-6 present the results of these experiments. Plotted is the ratio of the wear rates found by the two methods versus the standard deviation of the imposed random variation. As before, the ratios plotted were the average of ten randomly generated trials.

As can be seen, although there is still scatter present, the larger the number of inspections considered, the greater the difference between the LSPTP and the PTP results.

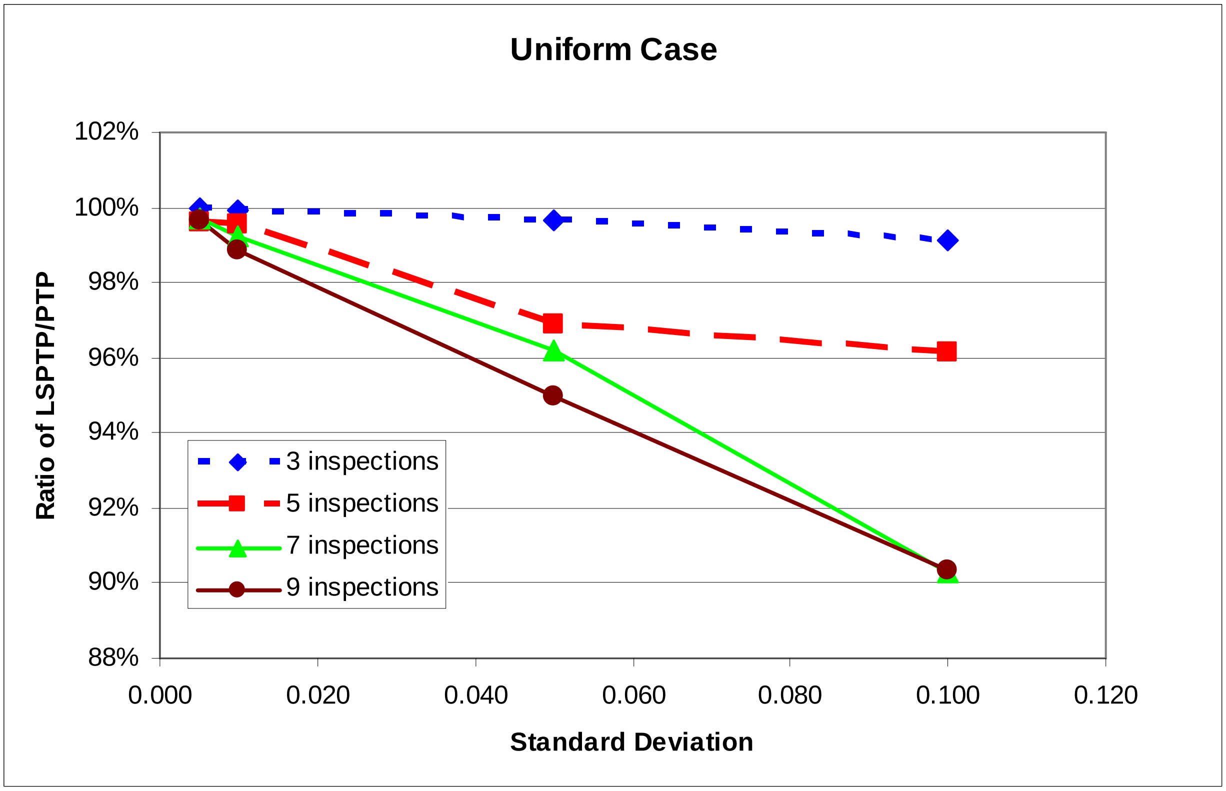

Figure B-3
Results of the Uniform Case

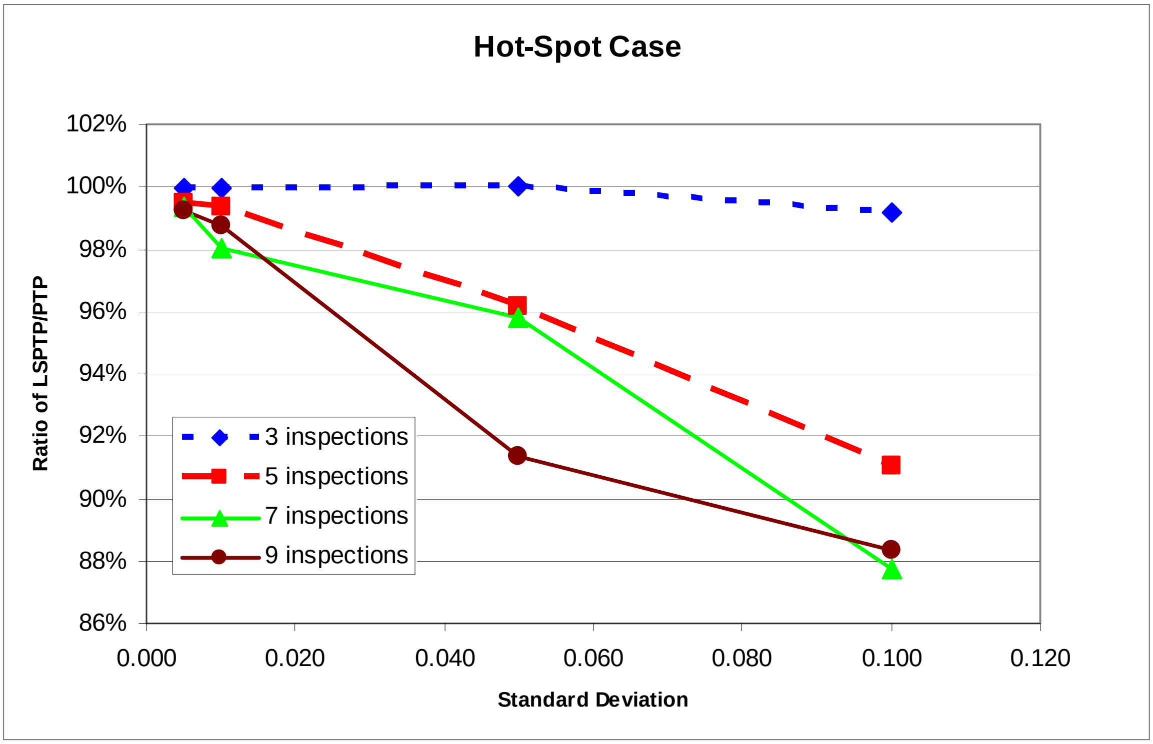

Figure B-4
Results of the Hot-Spot Case

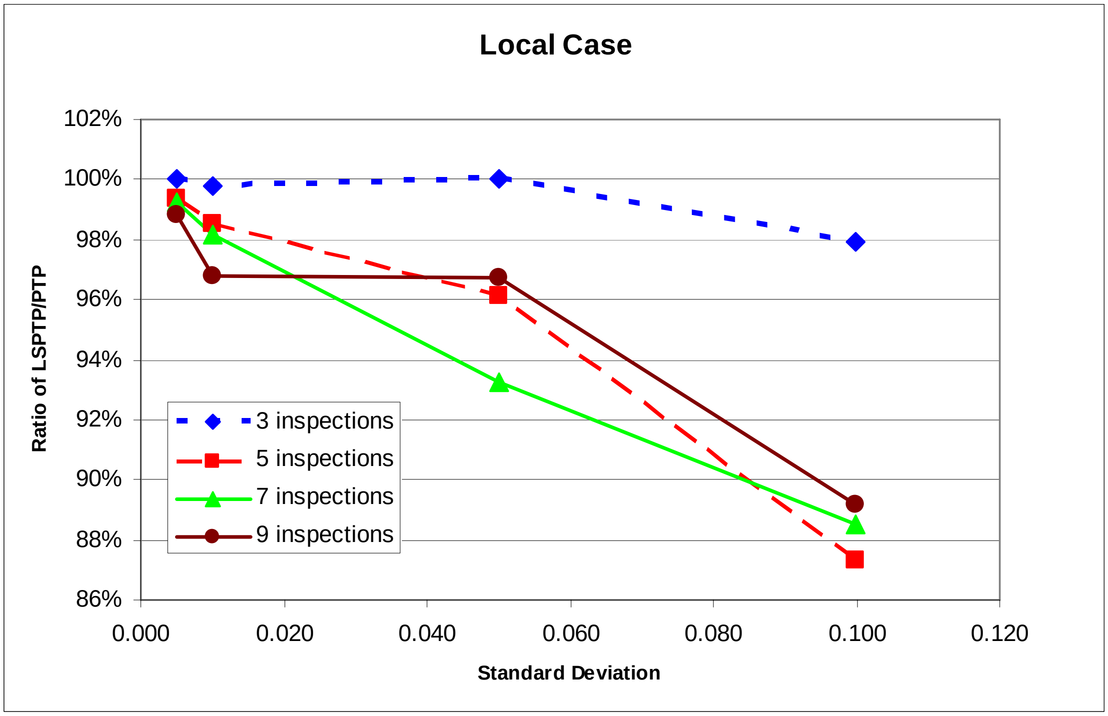

Figure B-5
Results of the Local Case

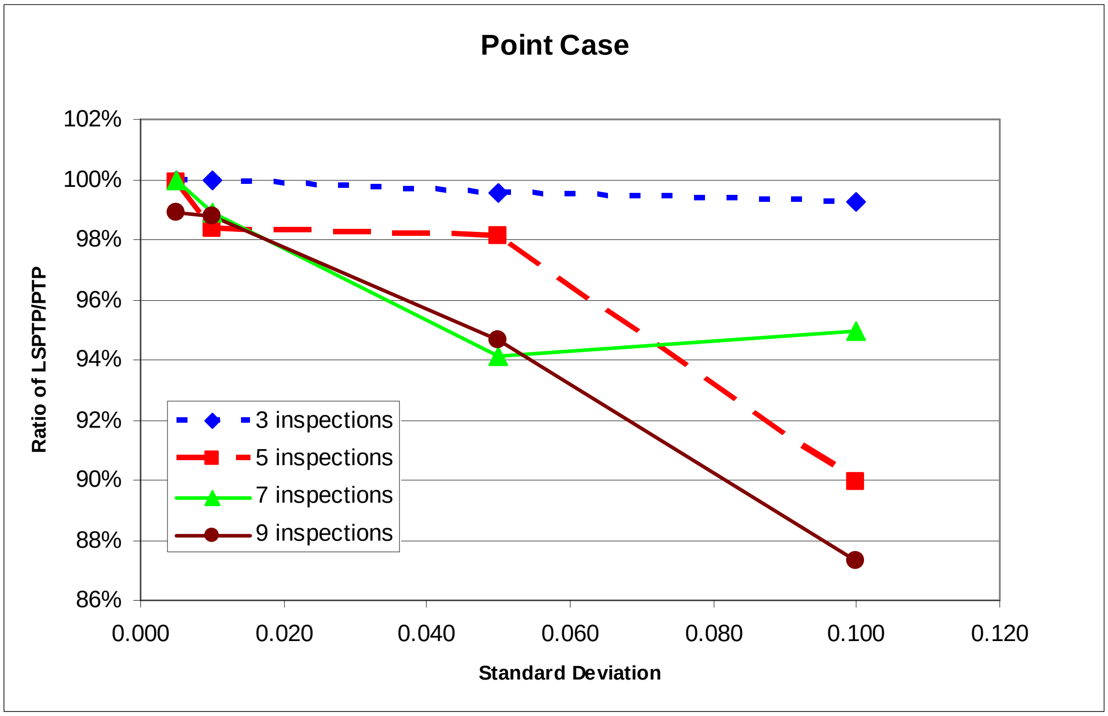

Figure B-6
Results of the Point Case

C

EXAMINATION OF VARIABLE WEAR RATES

During the course of this work the tacit assumption was made that the wear rates actually experienced by the measured components were constant with time. In general, for most nuclear plants in the United States, this is not a very good assumption for two reasons:

- Water Chemistry – changes in water chemistry have been made over time. These changes directly impact the rate of FAC experienced.
- Power Level – a number of operating plants have increased their power levels – in some case by 20% or more.

In order to examine the impact of variable wear rates on predictions made using point-to-point methods, three sample cases were developed. These will be discussed in a simplified manner first, and then with consideration of measurement uncertainty.

Simplified Analysis

This section will present and examine three sample wear rate variations on a “one-point” basis. That is the component will be represented by a single grid point. The wear rates calculated by the maximum delta method and the two least squares methods will be calculated and compared to the actual wear rate.

Before proceeding, the term “current wear rate” as used in CHECWORKS™ SFA will be defined. Current wear rate is the wear rate being experienced by a component at the conditions at the time of the analysis – often the time of the latest inspection. On the following figures it is equal to the negative slope of the last segment of the thickness versus time plot.

Case 1

This case assumes a constant wear rate for one inspection, and then the wear rate is halved for an equal period of time. Figure C-1 presents a plot of the values assumed to represent this case. This behavior is shown by the broad gray line. The dotted line connecting the end points represents the point-to-point wear rate, and the dashed line slightly offset from the dotted line is the linear least squares fit through the three points. The calculated wear rates together with the current wear rate (at 5 years) are presented in Table C-1.

Table C-1
Wear Rates for Case 1

Value	Wear Rate – mils/year
PTP Wear Rate	150
LSPTP & LSS	150
Current	100

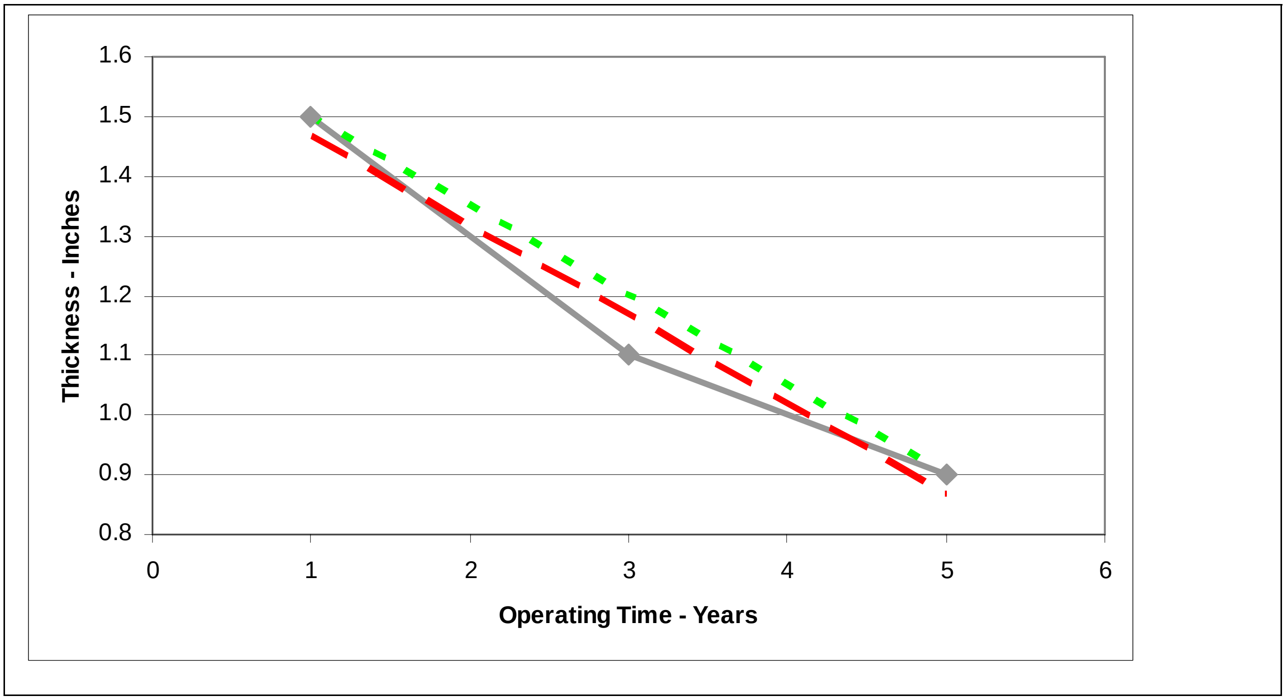

Figure C-1
Presentation of Case 1 and Its Wear Rates

Considering Table C-1, the wear rates for the three PTP methods are the same and higher than the current rate. Note that the dotted and dashed lines on Figure C-1 are parallel because of the symmetry of the assumed values. Also note that the current value is 2/3rds of the PTP methods. Finally note that the values for the LSPTP and the LSS methods are identical as there is only one least squares fit and thus only one slope.

Case 2

This case assumes that the initial wear rate is halved and then halved again. This is shown in Figure C-2 in a manner similar to the previous figure. The wear rates for this case are presented in Table C-2. Note that the PTP method and the least squares give some what different although comparable results while the current rate is less than half of the PTP methods.

Table C-2
Wear Rates for Case 2

Value	Wear Rate – mils/year
PTP Wear Rate	116.7
LSPTP & LSS	115
Current	50

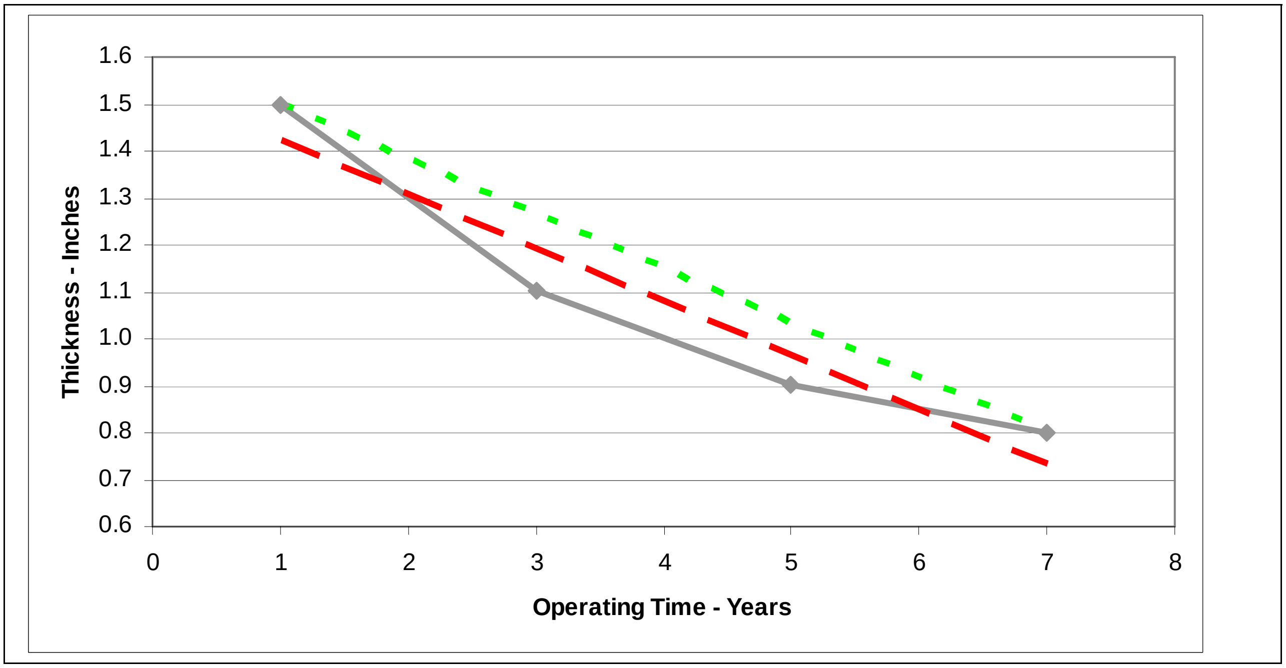

Figure C-2
Presentation of Case 2 and Its Wear Rates

Case 3

This is a more complicated case in which the wear rate decreases twice, and then increases. As before, this case is presented in Figure C-3 and the wear rates tabulated in Table C-3.

In this case the wear rate for PTP is equal to the current wear rate. Clearly, the wear rate pattern could be chosen in such a way as to achieve any desired result.

Table C-3
Wear Rates for Case 3

Value	Wear Rate – mils/year
PTP Wear Rate	100
LSPTP & LSS	90.5
Current	100

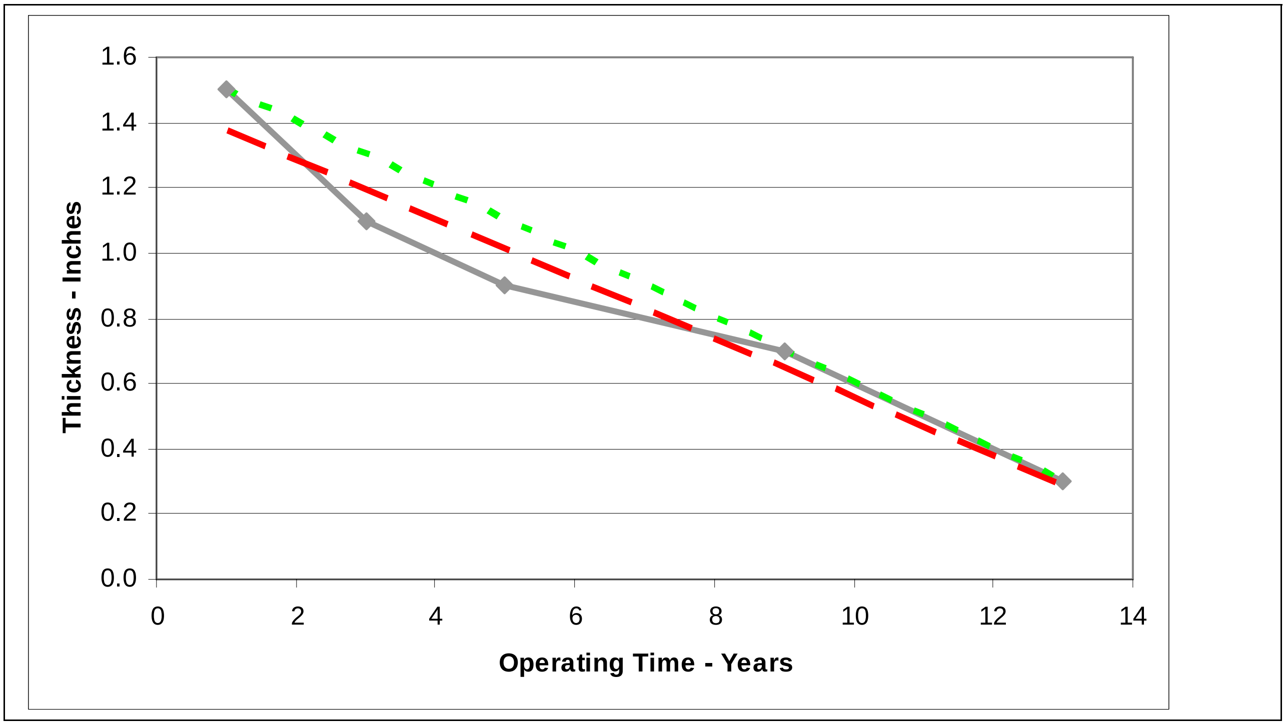

Figure C-3
Presentation of Case 3 and Its Wear Rates

Realistic Analysis

The same three cases were considered in a manner similar to the experiments presented in Appendix B. That is the wear rates for each case were imposed on an eleven by eleven grid. At each "inspection time" a random error was imposed at one of four standard deviations. The average of ten trials was computed for each of the three methods and compared with the current wear rate.

The results of these calculations for the three cases are presented in Figures C-4 through C-6. Considering these figures, the same trends as those seen in the numerical experiments previously presented are observed. The least squares methods show less of an impact of random errors than the PTP method. In general the LSS method is intermediate between the PTP and the LSPTP method.

Conclusions

The variable wear rates considered in this appendix show that while there are differences between the "current" wear rates and the PTP methods, the least squares methods tend to show less impact of random errors than the maximum delta method.

Users of these methods are cautioned to use point-to-point methods with care when there are variable wear rates. Of course there are situations where this practice cannot be avoided.

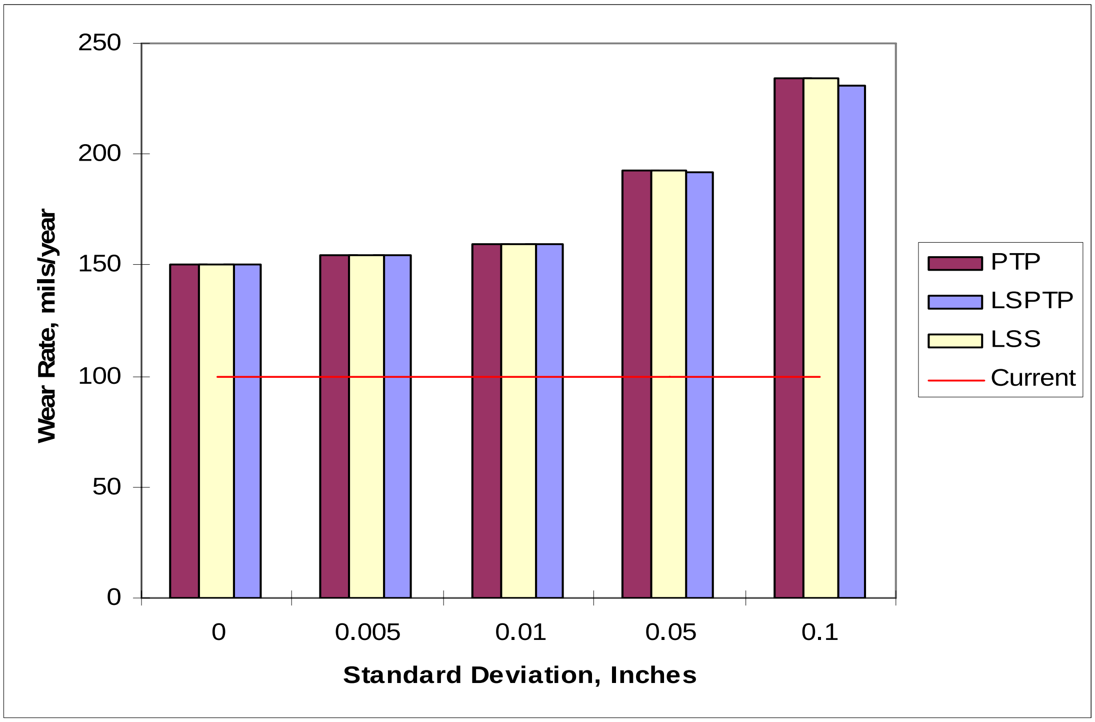

Figure C-4
Realistic Results for Case 1

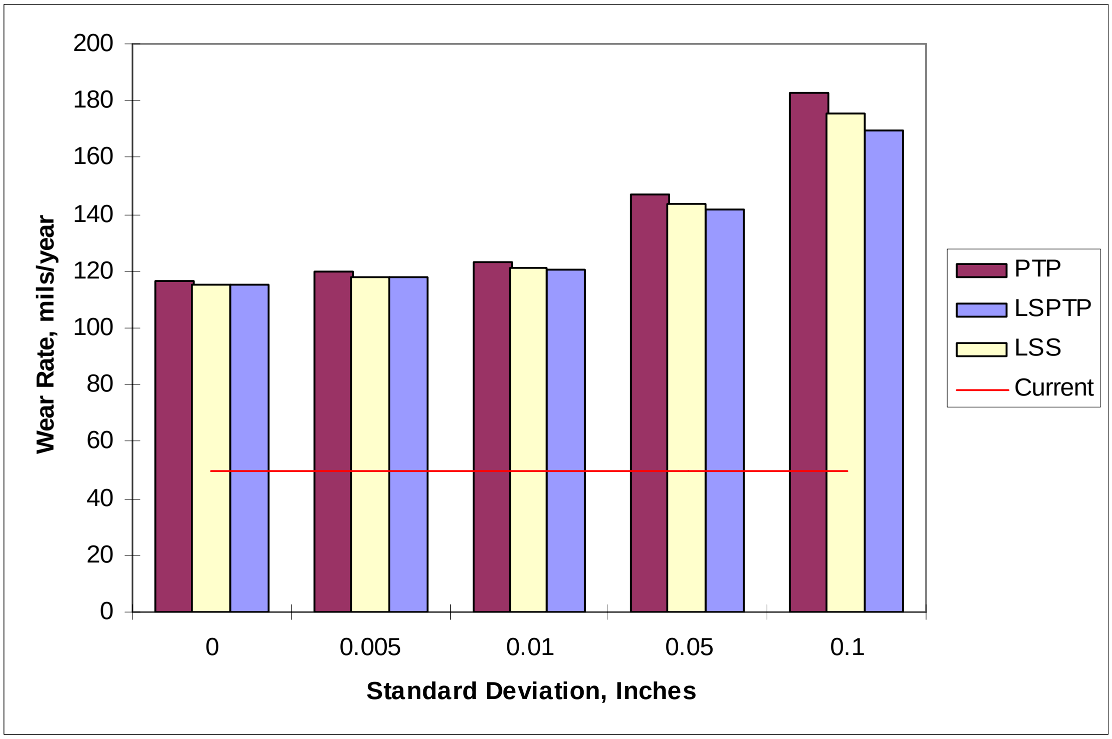

Figure C-5
Realistic Results for Case 2

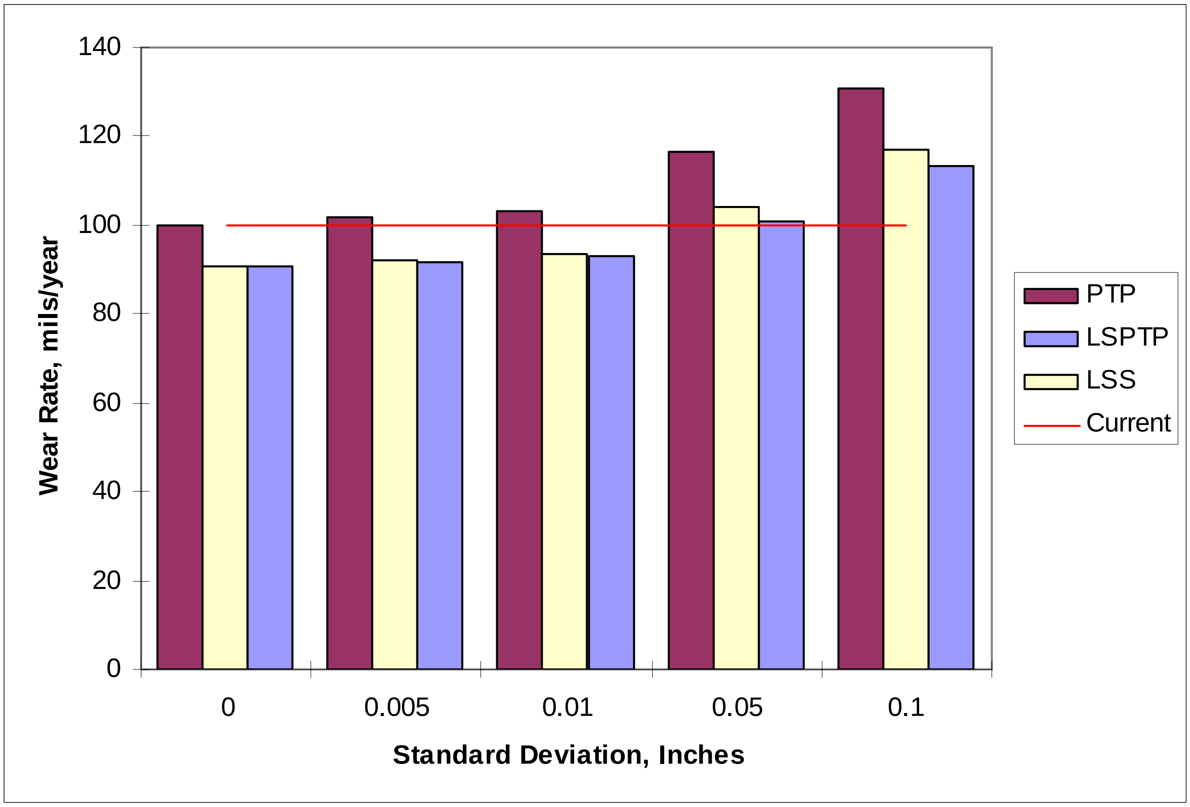

Figure C-6
Realistic Results for Case 3

D

ANOTHER EXAMPLE OF AN OUTLIER

During the course of this work, a component was discovered that had a negative wear rate when the LSPTP method was used. This was contrasted with a low wear rate with the maximum delta method. Although, not included in the components discussed in this report, is illustrates a possible problem with the LSPTP method and hence was included in this appendix.

Figure D-1 presents a thickness plot for this component at the determinate location of the LSPTP method. Considering this figure, there is a large amount of scatter present, but the least squares straight line shown as a solid line (blue) seems to have a reasonable slope corresponding to a wear rate of about 1 mil per year. However, the dashed (red) line on this figure corresponds to *Tcrit*. Thus, with *Tcrit* greater than the intercept of the least squares straight line[6], by Equation A-16, the time to *Tcrit* is negative and an erroneous result is obtained.

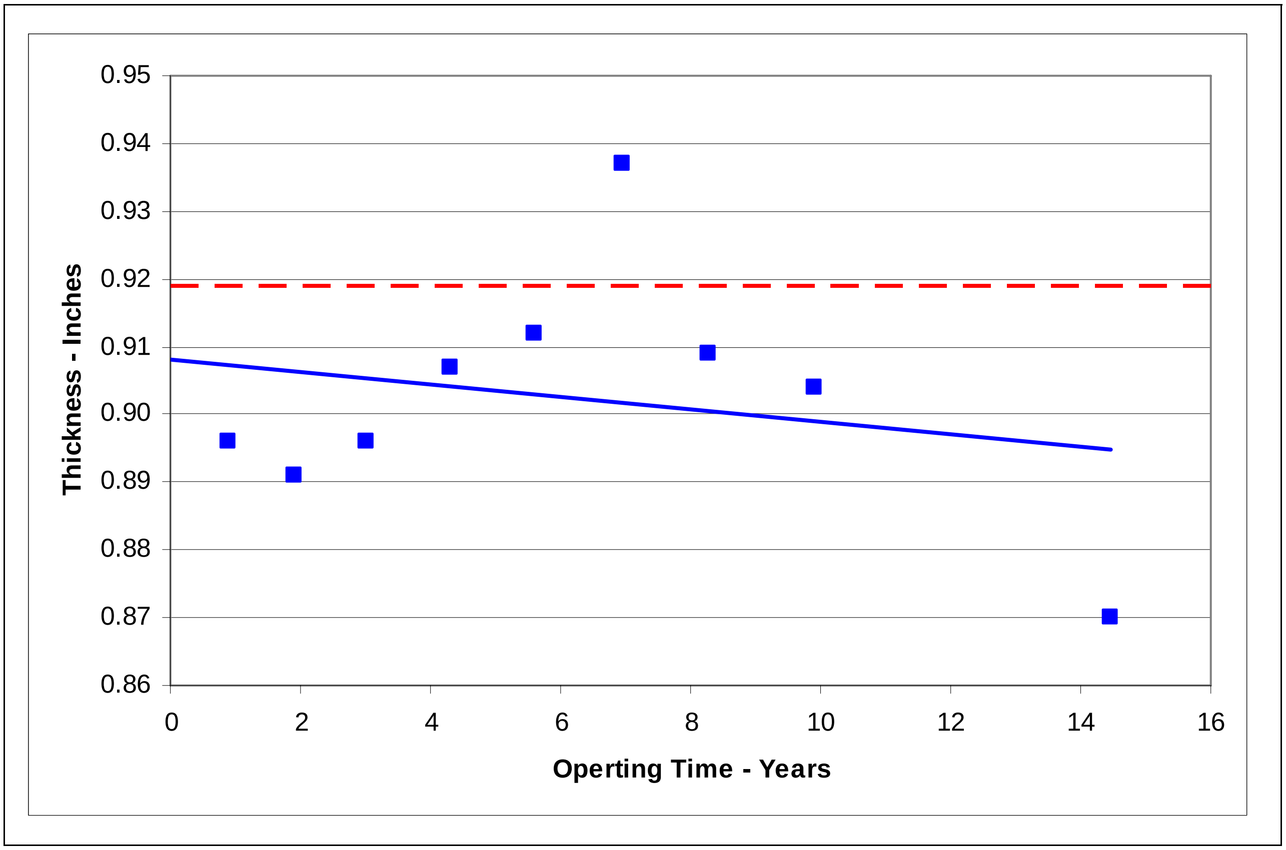

Figure D-1
Thickness Plot of Outlier

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[6] Recall that the intercept of the least squares fit corresponds to the initial thickness of the component.

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