ELECTRIC POWER RESEARCH INSTITUTE

2011 TECHNICAL REPORT

Steam Generator Management Program: Foreign Object Wear Scar Sizing Prototype Development

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EPRI Project Manager
R. Guill

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue
Palo Alto, CA 94304-1338
USA

PO Box 10412
Palo Alto, CA 94303-0813
USA

800.313.3774
650.855.2121

askepri@epri.com

www.epri.com

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

R. Brooks Associates

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Acknowledgments

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

R. Brooks Associates
6546 Pound Road
Williamson, NY 14589

Principal Investigators
J. Blank
B. DeLaCroix
J. Welker

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Product Description

Steam generator tubes are susceptible to scratches or wear scars on their secondary (steam/water) side surfaces. Currently, the standard method used to gather data for analysis of the scar is to characterize wear scars using eddy current technology from the primary side.

As allowed by plant Technical Specifications, some utilities do not open the primary side of their steam generators during every refueling outage; instead, they open only the secondary side for sludge lancing, visual inspection, and foreign object search and retrieval. The data gathered from the secondary-side inspections provide critical information for deciding whether to mobilize a primary-side service team and equipment. Emergency mobilization of such a team and equipment is time consuming and costly, and it is unlikely that a team will be available when needed during a refueling outage season.Therefore, during refueling outages when the primary side is not opened, a method that allows characterization of wear scars from the secondary side is desirable.

This report describes the research and development of an optical-based solution to characterize a tube wear scar from the secondary side of a steam generator. A custom lens solution was manufactured and tested for this initial prototype development phase. Testing was performed to provide proof of concept and to provide data that can be used in future development of a field-ready, secondary-side wear scar measurement system.

Results and Findings

An optical measurement approach proved to be effective at measuring the depth of wear scars in a benchtop setting. With adequate development time, it would be possible to design a field-ready system for measuring wear scar depth. Initial prototype testing and prototype development proved the concept of optical measurement and identified several challenges and factors that must be considered with future development.

Challenges and Objectives

During an operating cycle objects may find their way to the steam generator where there is a high probability they may become lodged in-between tubes. The operating conditions of a steam generator can cause these objects to vibrate, burnish, or wear against the surface of the tubes. Because of the extremely high primary side internal tube pressures and the thin tube wall design, small wear areas are of interest and concern for utilities and require further analysis. The challenge is to design a system to deliver the measurement tooling to the affected tube. Key information regarding the tubes and gaps that a tool must navigate in a steam generator are as follows:

- Tube diameters, 0.625–0.875 in. (15.87–22.23 mm)
- Tube gap (row spacing)
  - Square pitch, 0.292–0.406 in. (7.42–10.31 mm)
  - Triangular pitch, 0.116–0.180 in. (2.95–4.57 mm)
- Tube wall thickness, 0.036–0.050 in. (0.91–1.27 mm)

Application, Value, and Use

Many secondary-side foreign object search and retrieval inspections are performed every year. The tooling needed to determine a tube's wear scar depth could be added to the foreign object search and retrieval tooling.

Approach

This report presents the findings of an optical micrometer approach that has been designed to determine wear scar depth measurements from the secondary side of steam generators.

Keywords

Optical micrometer
Steam generator tube depth measurements
Steam generator tube wear scars
Steam generator tubing

Abstract

This report was created for nuclear utility personnel who are interested in measuring the depth of a tube's wear scar from the secondary side of a steam generator. This method and tool would be deployed during secondary-side visual inspections of steam generators to determine whether a tube in question has (or shortly will) become compromised and require plugging. During an operating cycle, foreign objects can find their way to the tube sheet, where there is a likelihood for them to become lodged between tubes. The operating conditions associated with a steam generator can cause these objects to vibrate and, in some cases, burnish or wear the surface of the tubes. Due to the internal tube pressures and the thin wall design, small wear areas become extremely important points of interest and concern for further analysis.

It has been determined that an optical micrometer could be tailored and designed to determine wear scar depth measurements from the secondary side of steam generators. Currently, eddy current examinations are performed from the primary side of steam generators and provide an accurate characterization of tube defects; however, industry trends based on advanced tubing materials show that fewer eddy current examinations are being performed during refueling outages to save time and money. Therefore, an industry method is needed to assess wear scars from the secondary side.

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Section 1: Introduction

1.1 Product Description

Steam generator tube surfaces can become scratched or scarred due to wear. Currently, wear scars are characterized from the primary side using eddy current technology, which is a time consuming and costly process. In this technology study, an optical micrometer measurement approach was chosen to characterize wear scars from the steam generator's secondary side.

1.2 Results and Findings

The optical micrometer approach is being studied to determine the optimal system configuration for efficiently and accurately characterizing wear scars. This report presents the findings of benchtop, pre-prototype testing using an optical micrometer approach. Ultimately, this process and tooling must be designed and matured to determine wear scar depth measurements from the secondary side of steam generators.

1.3 Background

This report was created for nuclear utility personnel who are interested in measuring the depth of tube wear scars from the secondary side of a steam generator. This method and tool would be deployed during secondary-side visual inspections of steam generators to determine whether a tube has become (or shortly will become) compromised and require plugging. During an operating cycle, foreign objects can find their way to the tube sheet, where they are likely to become lodged between tubes. Operating conditions can cause these objects to vibrate and, in some cases, burnish or wear the surface of the tubes. Due to the internal tube pressures and the thin wall design, small wear areas become points of interest and concern for further analysis.

The current method for characterizing wear scars uses eddy current examination from the primary side of the steam generator. Although eddy current examinations provide highly accurate and recognized characterization of tube defects, industry trends based on advanced tubing materials are to perform fewer eddy current examinations during refueling outages to reduce cost and outage cycle duration. Because secondary-side foreign object search and retrieval can be performed in a steam generator where eddy current is not deployed, developing a method to differentiate between a burnished and a worn surface is highly desired.

Although eddy current testing provides characterization of tube defects, a direct measurement could be more accurate. Another method of measurement would be to take a mold of a wear scar, which could possibly be more accurate than eddy current testing, but this method would be difficult to deliver and achieve in all locations within the secondary-side tube bundle.

Developing an optical solution with the characteristics required to obtain images for wear scar measurement within the geometry constraints of a steam generator proved to be a challenging task. Several other factors also contributed to the challenges. The consistency of recorded measurements can be influenced by human interpretation—that is, the features or the perceived deepest portion of a scar can be viewed differently from one person to another. Physical characteristics—field of view, depth of field, and magnification—must also be considered when designing a lens system because these attributes affect the ability to measure a scar, as well as image resolution and quality.

The testing conducted in this study has provided an improved understanding of how these attributes will influence the performance and functionality of a lens system, and the results will provide a basis for future development of wear scar characterization. Continued development—including the design of an improved lens assembly, additional testing, and conceptual assembly modeling—is required for a more accurate and consistent characterization of wear scars. Results of this study indicate that optical measurement, although showing some inconsistencies, can produce a certain level of accuracy. Continued development efforts might require several attempts to achieve the final result of a field-ready system that can accurately characterize the depths of tube wear scars within the secondary side of a steam generator.

Section 2: Pre-Prototype Testing

2.1 Introduction

2.1.1 Preliminary Design Decisions

A feasibility study conducted in February 2010 provided recommendations for future development of a system for characterizing wear scars from the secondary side [1]. Several methods of wear scar characterization were investigated, including ultrasonic testing, polymer molding, optical micrometers, and laser measurement. The feasibility study produced a decision matrix outlining criteria that should be considered in the development of solutions for wear scar characterization. The Electric Power Research Institute (EPRI) selected the optical solution as the desired approach for wear scar characterization.

2.1.2 Different Methods

Based on current, leading-edge measurement technology, as well as technology from toolmakers' microscopes and in-house testing of optical depth measurement, it has been determined that two methods of optical depth measurement are successful.

The first method uses a fixed-focus lens, and the measurement is a direct result of the change in distance between the probe tip and the outer surface of the tube. The second method is accomplished by keeping a probe at a steady standoff distance from the outer surface of the tube and adjusting the offset distance between the lens and probe. The pros and cons of these methods were factored into the design decision, along with considerations and results from this initial phase of testing using an optical measurement system.

2.1.3 Design Considerations

The first method, using a fixed-focus lens, could potentially provide a simpler approach, which pairs a video probe and a solid-mounted lens. After the probe is positioned at a focused distance from the tube surface, the probe is pushed closer, until the bottom of the wear scar is in focus. Although the probe and lens configuration might be simpler in design, the movement of the probe would still require positional locating to determine the distance moved to calculate wear scar depth. Also, years of experience using video probes for foreign object search and retrieval activities have shown that the ease of navigation and articulation of probes within a tube bundle depends on the location and the amount of sludge on the tube sheet. This experience has also proven that the precise movement and repositioning of a video probe to achieve an accurate measurement in this configuration would be extremely difficult.

A design concept reviewed during this project incorporated locating features to position the delivery mechanism and distal (closest to the probe) end of the probe at a desired location within the tube bundle. A motorized lead screw would then be activated to move the probe and solid-mounted lens, while the delivery mechanism remained stationary. This movement in relation to the tube would be encoded, and when a person focused from the tube surface to the wear scar depth, a measurement could be calculated from the total distance moved. This concept seems relatively simple in theory, but several factors related to the operating environment and small design envelope created difficulties with this type of design. Operating a delivery system such as this remotely within a tube bundle does not allow for a straightforward method of ensuring that the probe is properly seated. The small scale of the mechanical system required to position the probe would be extremely complex in design to incorporate motion components with the probe. The team also considered the necessary features for retrieval in a power-loss scenario, in which the probe can be extended from the delivery system. In normal foreign object search and retrieval activities, processes and procedures are in place to retrieve tooling in certain scenarios without causing damage to tubing within the tube bundle and to retrieve the tooling intact. The small scale of this mechanical packaging would not allow a fail-safe design with wire strain-relief for retrieval in a power-loss scenario.

The second method would use an adjustable-focus lens assembly in conjunction with a probe. The adjustable-focus lens assembly is a complex design, both mechanically and in terms of software control requirements for moving the lens and encoding the focal change. However, this design would allow the probe to be moved into location for viewing the wear scar, and all subsequent movement for focusing would be achieved through the adjustable-focus assembly. This design would allow for increased accuracy in measuring wear scar depth, and it could potentially eliminate errors that could be noticed with repositioning of a fixed-focus probe assembly. The following sections describe the challenges involved in determining proper lens configurations for an adjustable-focus assembly. The upfront testing performed in this study has achieved varied results in image quality, resolution, and magnification, all which can ultimately affect the accuracy of wear scar measurement.

At the conclusion of the preliminary prototype testing, the second method, using an adjustable-focus lens assembly, was chosen. It was determined that keeping a probe at a set or steady distance away from the tube or wear scar would be more practical than moving the entire probe and accurately tracking its movement.

2.1.4 Types of Scopes

Several methods of video inspection using probes exist; each of them has benefits and drawbacks. The various probes that have been reviewed include videoscopes and flexible borescopes or fiberscopes.

Videoscopes are the most suitable in a wear scar measurement application. Videoscopes are rugged and durable and can last in the harshest environments, unlike fiberscopes, which are not as robust and can easily break or degrade with use. Videoscopes are flexible, and some are designed with a four-way articulating tip that makes maneuvering in a steam generator's tube bundle simpler. This type of probe also presents approximately five times the definition of fiberscopes. The charge-coupled device (CCD) or complementary metal oxide semiconductor sensor in a video probe configuration is placed at the distal end of the probe to prevent the loss of resolution through a relay such as fibers.

Fiberscopes are less durable, and image resolution is inherently poor because the image is transmitted through an image bundle.This image bundle is a group of coherent fibers made of high-quality glass. Image resolution is a direct relation to the number of fibers and their diameter. In these scope configurations, each fiber forms a pixel in the final image; under high magnification, these individual pixels are seen, which would not clearly represent the object of interest.

2.1.5 Focusing Techniques

It was discovered that the focusing adjustment must take place at the distal end of any probe, which is the end that is closest to the tube. The lens and the system that moves the lens must be at the distal end; however, that system can be controlled and adjusted at the user end of the probe. The limitation of focus assembly placement results from the object being converted into an image at the face of the fiber bundle or relay, having no depth. You cannot focus (move the focal plane) on an image with no depth; therefore, the focusing must take place before the image goes through the objective lensing that forms the image at the distal end of the probe. These limitations with focusing an image could be compared to viewing an image that was recorded on a video camera; when the image is played back and projected on a monitor, any portions of the projected image that were out of focus during the initial recording on the video camera remain out of focus. Similarly, after an image is passed through the lens of a probe and converted to an image projected onto the fiber bundle, it resembles a recorded image that remains out of focus.

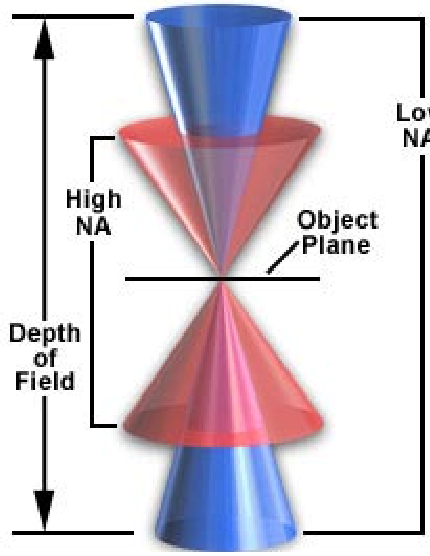

Figure 2-1
Diagram Showing Depth of Field

2.2 Objective Lens Options

To make depth measurements with an optical approach, you must first determine the required lens properties for an optical solution. This measurement will essentially require a lens with the same characteristics as a microscope to be placed on the tip of a video probe. The following subsections describe some properties and the desired outcomes from the optical element. The correct balance between these properties is required for precise optical measurement.

2.2.1 Depth of Field

As seen through a microscope lens, the geometric image plane or object plane represents an infinitely thin section of the object. Realistically, each image point you see extends both above and below the center of the intermediate object plane, as shown in Figure 2-1. The distance between these points is the depth of field where the image is known to be in focus.

The size of your depth of field in optical measurement must be small. The less distance you have between the nearest object plane in focus and the farthest object plane simultaneously in focus, the more accurate the measurement will be when captured.

Depth of field varies with numerical aperture and magnification of the optical element. Numerical aperture is a property of microscope lens systems that can be thought to affect depth of field, much as the inverse of the focal ratio does for traditional camera lenses. The higher the numerical aperture (or lower the focal ratio), generally, the shallower the depth of field.

2.2.2 Working Distance

Microscopes are generally designed for laboratory environments in which a specimen is on a slide. However, in the secondary side of a steam generator, the working distance is not specifically known, and a set distance is not always obtainable. The *working distance* is the linear distance measured from the objective front lens to the object in sharp focus. In general, the working distance decreases as the magnification and numerical aperture increase, or, in other words, when the depth of field produced from the lens becomes smaller.

There are two conflicting parameters—object distance and depth of field. To provide a lens capable of optical measurement in a steam generator, one must compromise between these two parameters. If the standoff distance is increased, the depth of field is larger; therefore, the accuracy within the measurement capabilities will decrease. Likewise, if the standoff distance is decreased, the number of tubes and the area on each tube that can successfully be measured will decrease; however, the accuracy of the wear scars that can be measured will increase.

2.2.3 Other Specifications

Field of view and angle of view are properties that are determined after the depth of field and working distance specifications are determined. The field of view and angle of view must be sized to encompass the area of interest. They are determined from the standoff distance and the average wear scar size. Compromises might be required in the design of a lens to provide an optimal depth of field at the applicable working distance, while still allowing a sufficient field of view for capturing adequate detail of a wear scar within the image view. A larger field of view that would encompass a larger area of interest would also potentially create a barrel distortion or fisheye effect on the image. This distortion also produces vignetting of the image, in which lighting falls off in the corners of the image. These issues can be deemed acceptable if the outer portions of the image are not viewing features used in an actual measurement.

Magnification of the object should also be considered. Total magnification ideally should fall between 5X and 10X the actual object size; however, for measuring wear scars, this is impractical. A magnification this large would render a field of view that is much too small to allow positioning of the probe system. Therefore, a compromise must be made with the actual magnification value. One thing to consider is that when a change in focus takes place, the magnification will also change. This change can usually be neglected due to its small value, but the user must be aware of it.

These specifications should be considered when looking into an objective element design solution for wear scar measurement; they are limited due to the physical constraints in the lens design and the available lens manufacturing technologies.

Section 3: Initial Prototype Testing: Simple Testing of Probe and Lens Components

3.1 Lensing Options

After determining that the optical measurement of wear scars was possible, off-the-shelf lensing options were pursued. Unless a new custom probe and lens configuration is desired, the solution is limited by the current optical arrangement within the already manufactured probe. Lensing can be added to the tip of the probe, and focus can be adjusted with movement of the additional lens. The results of adding any such lens to the tip of different probes could give variable results; therefore, working with the probe manufacturer is critical in finding an appropriate configuration to pair with a lensing solution used in prototype development.

Two optical elements from a probe manufacturer were used with a probe that would provide the needed results. The first configuration was a single lens configuration with a depth of field of approximately 0.005 in. (0.127 mm), and the other was a double lens configuration with a depth of field near 0.002 in. (0.051 mm).

3.2 Optical Micrometer Validation Procedure

Optical measurement is a simple, yet sensitive process. The process requires the operator to focus on two separate surfaces (highest and lowest depths) within the same field of view. The operator focuses on the base material and sets the measurement to zero on the micrometer. The lens is then moved in relation to the CCD imager to adjust focus on the second target. This adjustment is tracked and saved as a value to be converted into an actual measurement. The distance that the lens is adjusted to focus the image is related to the depth or height of the second focus target. This method is depicted in Figure 3-1.

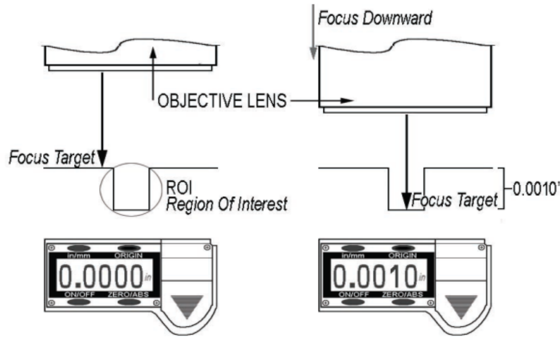

Figure 3-1
Detailed Diagram of How the Optical Micrometer Works

This step creates a certain level of difficulty in obtaining measurements when deployed in a tube bundle, especially when one cannot easily determine one point or feature of a wear scar that has a greater depth than others. This scenario requires several measurements to be taken, if possible, to effectively determine the deepest portion of the scar.

The setup for this laboratory environment test is shown in Figure 3-2. During setup, the probe is adjusted to be perpendicular to the wear scar surface.

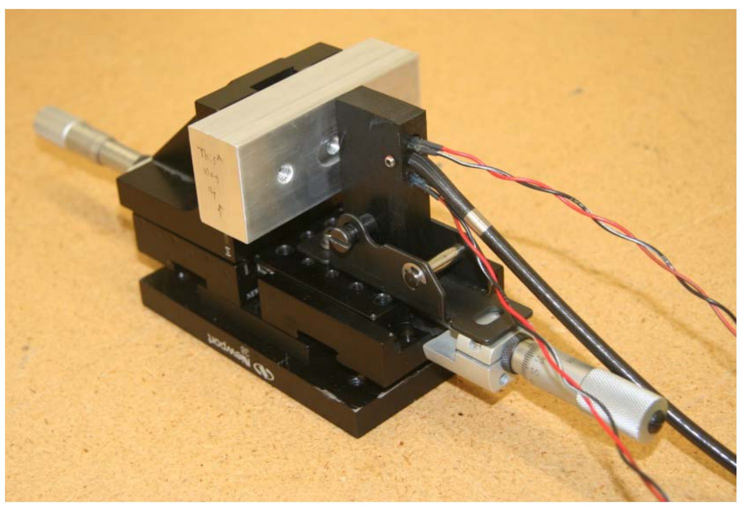

Figure 3-2
Laboratory Focus Testing Fixture

The step-by-step procedure is as follows:

1. Place the desired lens atop the probe. Use a small drop of lens-matching refractive index oil to adhere the lens to the probe tip.
2. Zero the right stage (used to adjust the fine focus) to set a starting value for obtaining a measurement.
3. Move the left stage to adjust the coarse focus until the bottom of the wear scar is in focus.

4. Take the image, and record the image number and description.
5. Move the right stage to adjust the fine focus until the top surface of the wear scar is in focus.
6. Record the measurement (shown on the right micrometer).
7. Take the image, and record the image number and description with the measurement.

Figure 3-3 was taken during testing with a single lens to determine whether the setup is realistic and practical for the application.

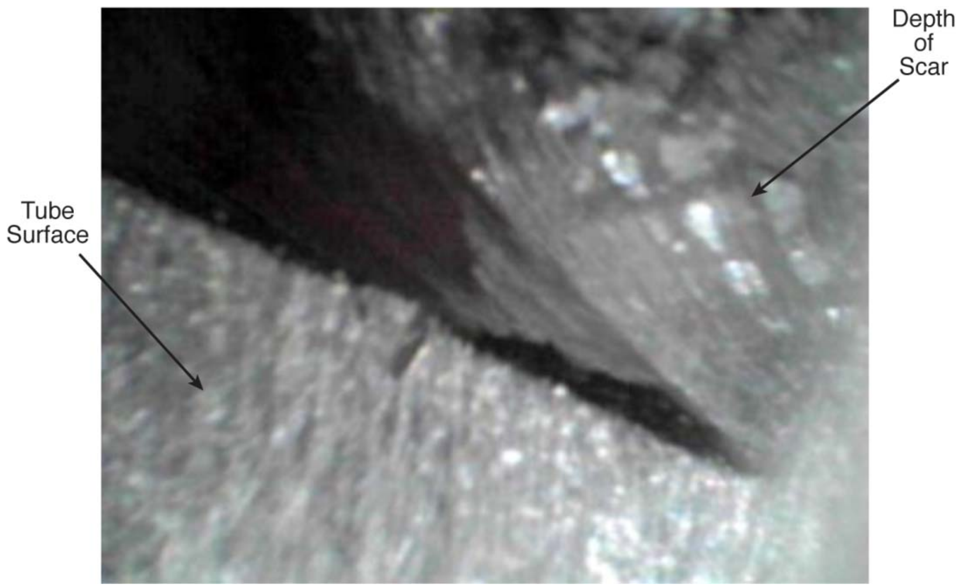

Figure 3-3
Single Lens Image

Figure 3-4 was taken during testing with a double lens configuration to determine whether this setup is realistic and practical for the planned application.

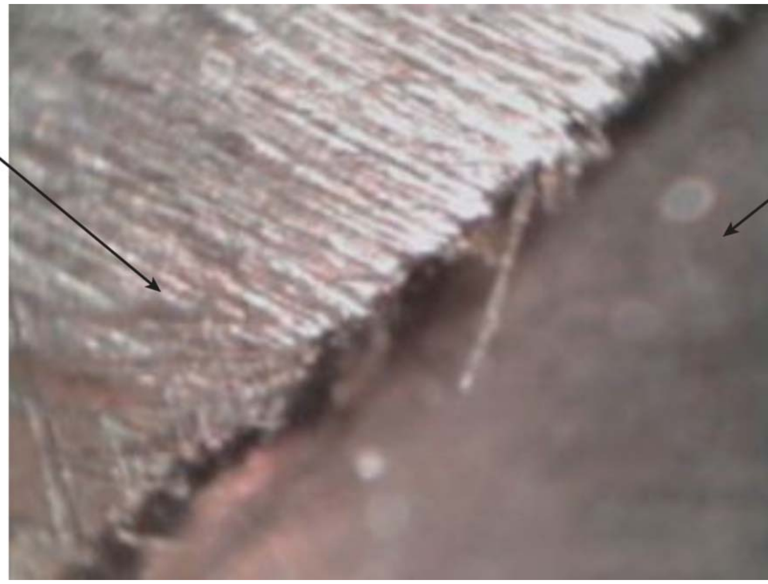

Figure 3-4
Double Lens Tube Surface Image

Several differences are noticeable between Figures 3-3 and 3-4. Testing with a single lens provided an image with acceptable resolution that clearly shows the outer tube surface and the bottom edge of the scar. However, both the tube surface and the scar surface are in focus at the same time.

The image taken with the double lens configuration provided an image that is significantly higher in magnification, and only the tube surface is clearly in focus. By changing the object distance, the lower edge of the scar surface would come into focus, and the outer tube surface would not be visible (see Figure 3-5). This better demonstrates the desired depth of field for optical measurement.

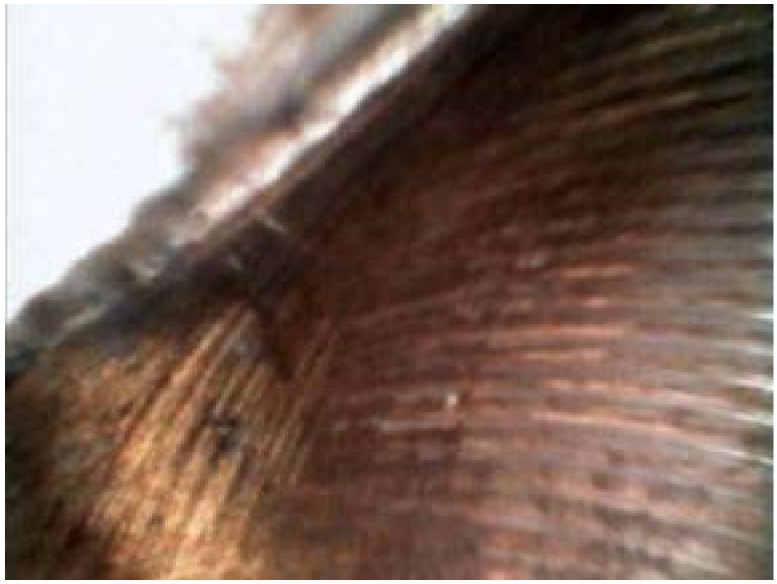

Figure 3-5
Double Lens Scar Depth Image

3.3 Initial Prototype Testing Results

The result of initial prototype testing found that it would be impossible to source an off-the-shelf optical solution for depth measurement and wear scar sizing inside a steam generator. The current lenses used for single and double lens configuration testing were less capable and were used only to prove the concept. Ultimately, they did not provide the desired measurement resolution.

A custom solution is possible with additional research, a specialized optical design for an attachment on the end of the probe with specialized lighting, a lens assembly, and position tracking software. Working with optics manufacturers, it is possible to source an appropriate lens and probe configuration that provides the desired balance between field of view, magnification, and depth of field to attain the appropriate working distance from the tube surface.

Section 4: Prototype Testing: Custom Lens Assembly Benchtop Testing

During initial prototype testing, we used a video probe and simple, off-the-shelf lens components to provide a basis for better determining the needs for wear scar measurement. Results of this testing proved that a custom solution is required for depth measurement and that continued research is necessary.

JML Optical Industries, Inc., an optical vendor specializing in the manufacture of custom lens solutions, designed a lens assembly (part number 92200-2) suitable for the wear scar measurement project based on several criteria provided by the research team. Some of these requirements were anticipated object distance, desired field of view, and specifications required to appropriately pair the lens with a specific-sized video probe CCD imager.

4.1 Prototype Fixture

For the properties of this lens to be characterized, each variable must be controlled independently. This has been done by using a fixture with built-in adjustments of critical parameters. This fixture controls the distance from the vertex of the front lens to the surface of the tube; this distance is known as the *standoff distance* or *object distance*. The fixture also controls the offset between the CCD and the back vertex of the lens, which is known as the *back focus adjustment*. These two variables are shown in Figure 4-1. Two configurations of this fixture are used—one to measure the depth of wear scars on a tube surface (using EPRI wear sample X30370) and the other to characterize the system using a Ronchi plate.

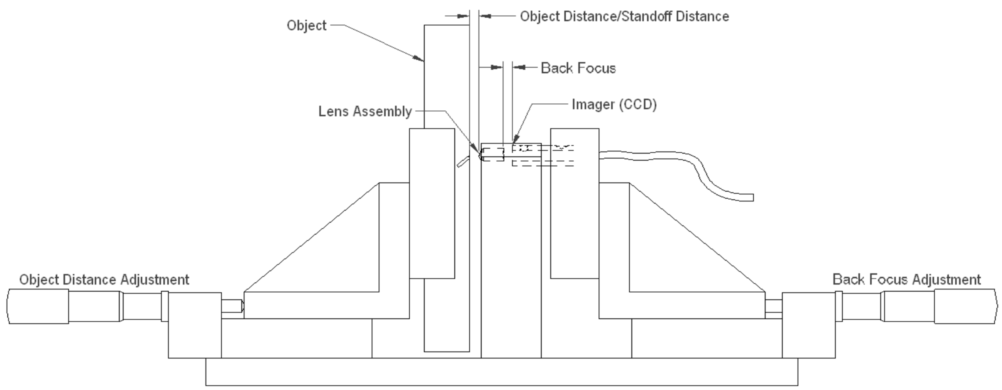

Figure 4-1
Laboratory Test Fixture with Tube Attachment

The second configuration of this fixture was designed for the characterization of the lens assembly, using Ronchi scale rulings as a substitute for a tube with a scar. A *Ronchi scale* is a specific type of target that consists of a straight line pattern etched on a glass plate, with the line width equal to the line spacing. When the Ronchi plate is placed on a determined angle, these lines can be used to simulate a known and accurate depth.

This configuration of the fixture is shown in Figure 4-2, with the view through the lens displayed on the monitor in the background. Each cycle of lines below the center of the image is 0.002 in. (0.051 mm) from the front of the lens assembly.

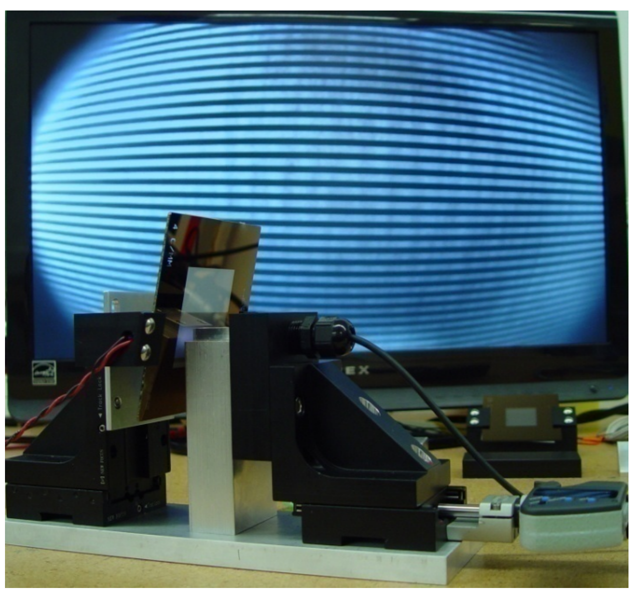

Figure 4-2
Laboratory Test Fixture with Ronchi Plate Attachment

4.2 Lens Characterization

Accurate lens characterization is critical to the accuracy and performance of the final system. These data are acquired from testing under ideal conditions in a laboratory environment and correlated to a depth value when measuring wear scars on a tube surface.

4.2.1 Standoff Distance

The first variable to understand is standoff distance, also known as object distance. Recognizing the influence of this variable is quite simple, and it was found that the closer the lens is positioned to the outer surface of the tube, the higher the resolution and the more easily the fine surface details are viewed. This gives the technician the ability to view and focus on a sharper image, thus providing a depth measurement of greater accuracy. The optimal standoff distance was found by measuring the number of lines on the Ronchi plate that are in focus at given standoff distances. These data points are plotted in Figure 4-3.

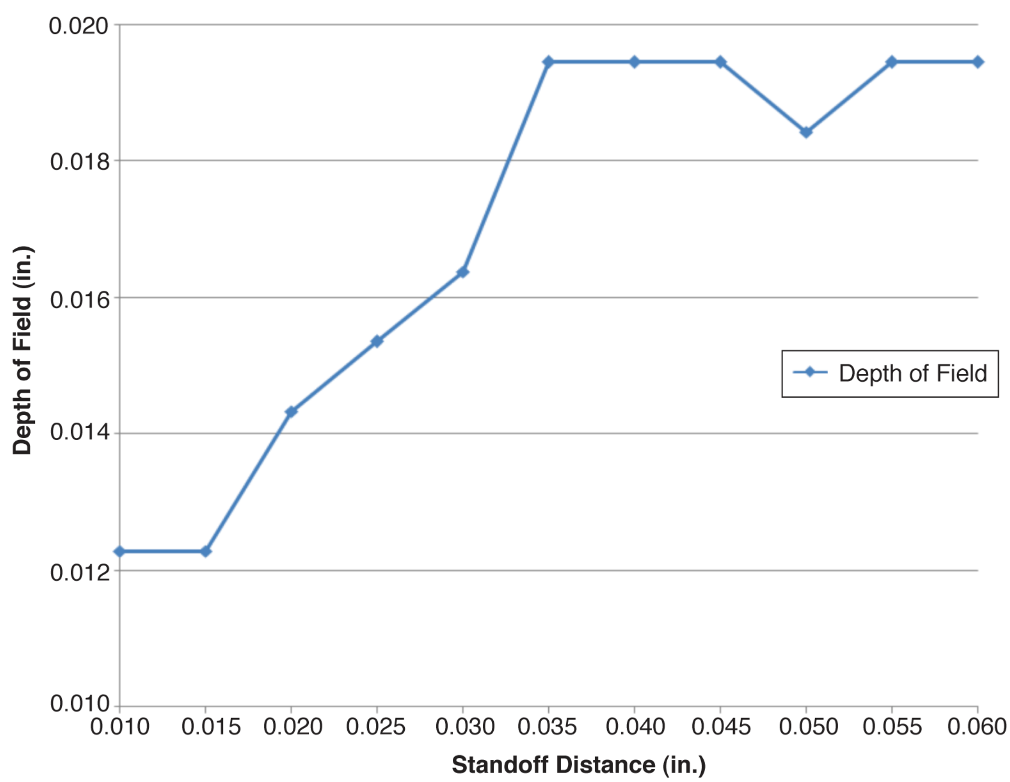

Figure 4-3
Optimal Standoff Distance Plot

When analyzing the graph in Figure 4-3, one might conclude that the depth of field appears to be slightly narrower at closer standoff distances; however, this is not the case. Depth of field is a constant for the lens assembly and only appears to be shallower at close standoff distances. This is due to an increased image resolution from a slight magnification of details in the field of view, giving a more accurate judgment of what the human eye sees as in focus and out of focus. The human eye can see a certain level of detail at less than a 0.035-in. (0.89-mm) standoff distance through the custom lens. This shows that, if possible, measurements should be taken from this distance or closer to provide maximum accuracy.

Another characteristic observed was that, at a set standoff distance, the outer surface of the tube is in focus when the back focus adjustment is at a particular value. A second value can be determined for each standoff distance, showing the value at which a 0.043-in. (1.09-mm) through-wall depth can be perceived as in focus. These two values create a focal range that must be characterized for each standoff distance, where the back focus of a wear scar measurement could lie. A typical representation is shown in Figure 4-4.

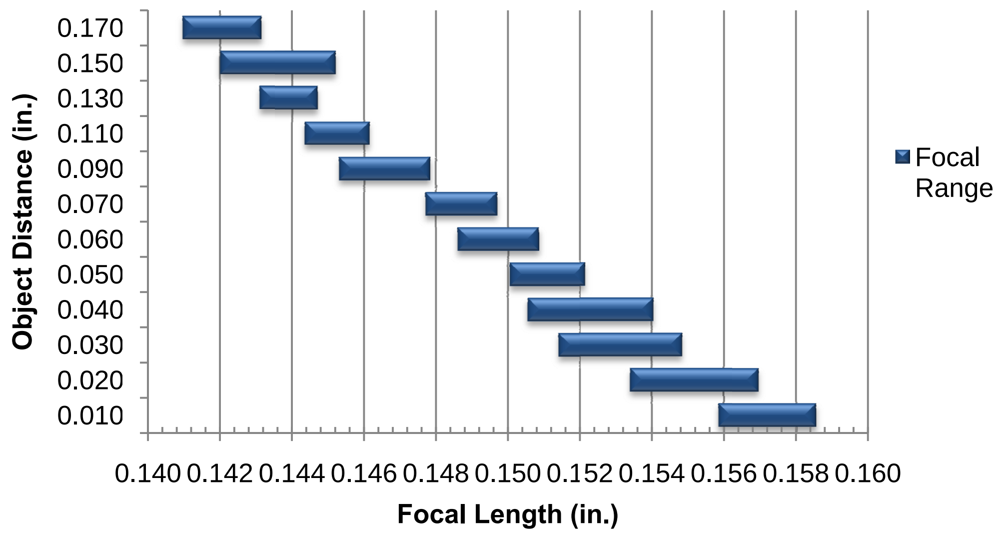

Figure 4-4
Back Focus Range Graph

This chart would primarily be used to verify the approximate object distance at which the measurement would be taken. It can also aid in better approximating the depth of wear scars at unknown object distances, thus assisting the technician in obtaining a more accurate measurement.

4.2.2 Software Characterization

Software methods of characterizing the lens assembly were attempted in the study to minimize human error. National Instruments LabVIEW Vision Assistant, a technology that has been successfully implemented in the past, was used to help determine when each line was in the sharpest focus. Figure 4-5 shows the luminescence plane of two lines that were individually focused, representing a depth of 0.014 in. (0.36 mm).

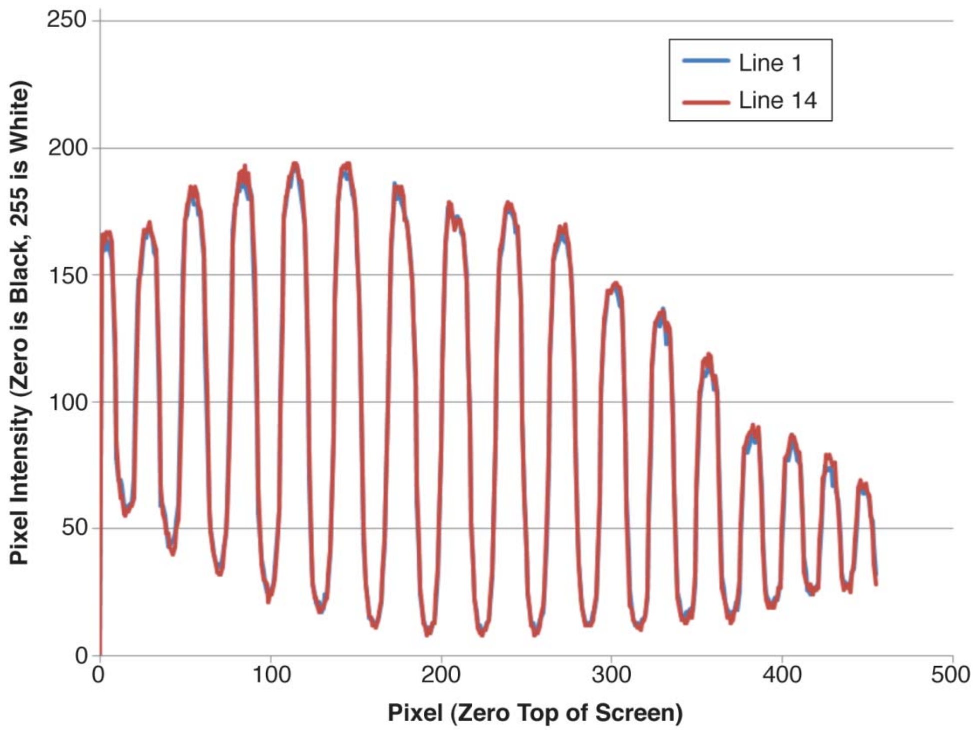

Figure 4-5
Luminescence Plane for Software Characterization

A single wave length shown in Figure 4-5 represents a cycle on the Ronchi ruling plate. At a depth of only 0.014 in. (0.36 mm), the change in focus is small enough that the difference cannot be determined by computer software. The line deemed in focus by the software would go from black to white at the fastest rate; in other words, the slope between the minimum and maximum values should be the steepest compared to that of any subsequent line that is in focus.

This method failed to deliver the results required, due to the size of the CCD imager that is required for the system and the geometry constraints of the narrow tube gap. The two curves shown are almost identical because the imager lacks the resolution necessary for the software to recognize the small change. This shows that the human eye is more capable than the currently available computer software of seeing the difference in pixels at high magnification and low resolution, due to interpolation at a sub-pixel level. This sub-pixel accuracy would require software investment or higher-quality (larger) images for a successful implementation.

4.2.3 Lens Characterization Data

The last step that must be taken in prototype testing is to better understand the focal range at each object distance. This is the most critical element in taking an accurate depth measurement. For every standoff distance, there is an individual relationship for focal change versus depth measurement. This relationship is gathered from testing, using the test fixture coupled with the Ronchi ruling plate attachment.

Data are collected by focusing on a line within the Ronchi plate that is nearest to the lens assembly, then focusing on a subsequent line, and noting the change in focus. Doing this would give you a known value of depth from the Ronchi rulings, as well as a determined change in focus.

Every trial is plotted; the measured variables—change in focus and the given depth—are used to determine a line of best fit for each standoff distance. This line of best fit, as shown in Figure 4-6, would be used to correlate the change in focus to a depth value for a wear scar.

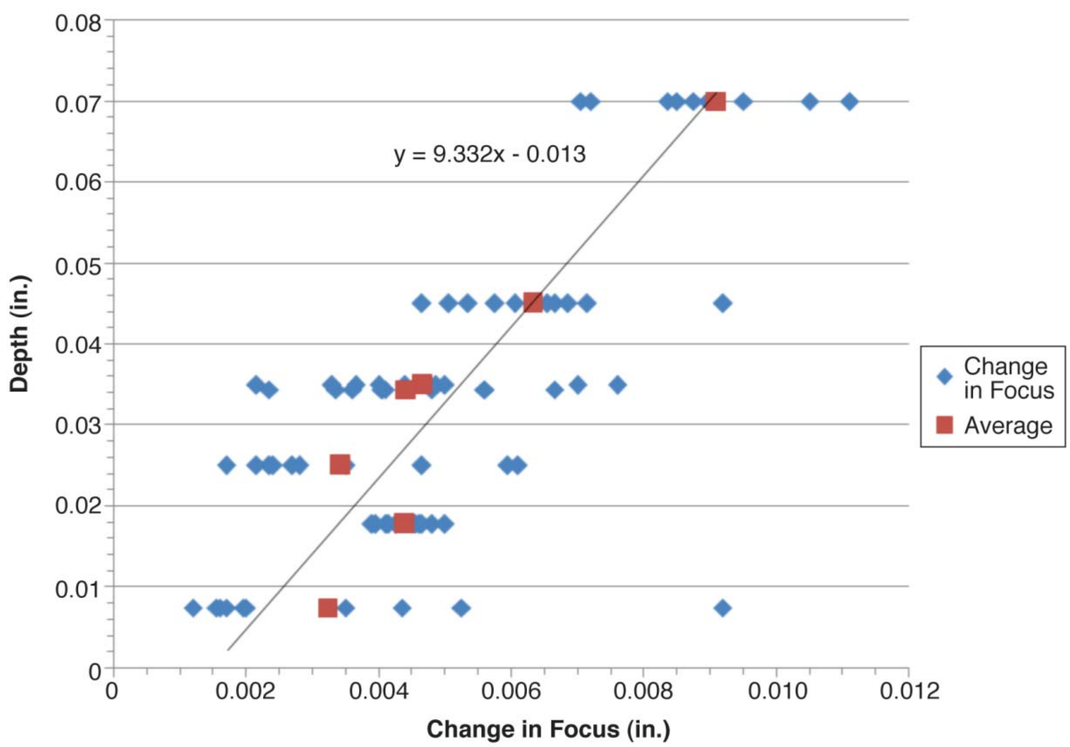

Figure 4-6
Lens Characterization Data at 0.30 in. Using the Ronchi Plate

Additional data were taken using scars of a known depth, giving a larger range of data. This larger range gives increased accuracy and validates data taken from testing with the Ronchi rulings.

4.3 Wear Scar Measurement on Alloy 690 Tube

After lens characterization data were taken at a single standoff distance, actual scars with known depths were measured to verify the data and determine the accuracy of the benchtop optical measurement system. Two technicians collected the measured data in Table 4-1 at a standoff distance of 0.070 in. (1.778 mm) from EPRI loose part wear sample X30370, with a wall thickness of 0.043 in. (1.09 mm).

In Table 4-1, user 1 is a person with depth measurement experience gained by having previously taken part in data collection for this project. User 2 has no experience in depth measurement and was briefly trained to use the measurement fixture for depth measurement. For each depth, 10 measurements were taken; the averages of those values are given in Table 4-1. With two users taking a series of measurements of a single wear scar, the collected data points can be used to calculate a standard deviation for the particular standoff and depth. This will provide a level of confidence that the actual measurement will be within a given tolerance range.

Table 4-1
Test Measurement Results

User	Percent Through Wall	Actual Depth (in.)	Average Measured Depth (in.)	Error
1	28.60%	0.0123	0.0026	0.00965
2	28.60%	0.0123	0.0220	-0.00968
1	34.42%	0.0148	0.0113	0.00348
2	34.42%	0.0148	0.0131	0.00166
1	41.40%	0.0178	0.0170	0.00081
2	41.40%	0.0178	0.0219	-0.00411
1	53.49%	0.0230	0.0216	0.00143
2	53.49%	0.0230	0.0382	-0.01517
1	63.72%	0.0274	0.0231	0.00433
2	63.72%	0.0274	0.0321	-0.00469
1	89.30%	0.0384	0.0366	0.00181
2	89.30%	0.0384	0.0314	0.00700

1 in. = 25.4 mm

The average absolute error was 0.0053 in. (1.346 mm; 12% wall thickness), and the largest observed error was 0.01517 in. (0.385 mm; 35% wall thickness). These values give an idea of the accuracy of the measurement tool; however, these measurements were taken under ideal conditions on EPRI loose part wear sample X30370, in which the scar was perpendicular to the lens and the standoff distance was precisely known.

4.4 Statistical Analysis

Understanding the accuracy of the system is imperative in taking reliable measurements. A large majority of the error within the system is due to the large depth of field (≈0.015 in. [≈0.38 mm]). This large depth of field makes characterization of wear scars difficult due to their typically small size—the wear scar could be shallower than the depth of field. This causes inconsistency in measurements of wear scars, specifically those of shallow depths. Statistical analysis was conducted to quantify the uncertainty that exists within the system at each standoff distance.

For each depth measured at a given standoff distance, 10 measurements were taken, and the change in back focus adjustment was averaged. The average values for the 10 measurements are presented in column 2 of Tables 4-2 and 4-3.

Table 4-2
Statistical Analysis of 0.030-in. Standoff Distance (in.)

Depth Measured	Average Change in Focus	Standard Deviation of ΔFocus	99% Confidence Tolerance (ΔFocus)	99% Confidence Interval for Focus Adjustment		99% Confidence Interval for Depth Measurement Range		Tolerance on Depth Measurement (±)
				Lower Confidence Limit	Upper Confidence Limit	Lower Confidence Limit Measurement	Upper Confidence Limit Measurement	
0.0178	0.0016	0.0005	0.0004	0.0011	0.0020	0.0000	0.0060	0.0042
0.0250	0.0016	0.0009	0.0007	0.0027	0.0042	0.0126	0.0263	0.0069
0.0344	0.0035	0.0011	0.0009	0.0030	0.0049	0.0154	0.0327	0.0086
0.0148	0.0040	0.0008	0.0006	0.0012	0.0025	0.0000	0.0099	0.0058
0.0274	0.0018	0.0014	0.0011	0.0021	0.0043	0.0068	0.0274	0.0103
0.0384	0.0032	0.0010	0.0008	0.0034	0.0049	0.0184	0.0331	0.0073
0.0123	0.0040	0.0010	0.0008	0.0010	0.0027	0.0000	0.0120	0.0079
0.0230	0.0018	0.0014	0.0012	0.0023	0.0046	0.0081	0.0299	0.0109
0.0292	0.0034	0.0007	0.0006	0.0025	0.0037	0.0102	0.0214	0.0056

1 in. = 25.4 mm

Table 4-3
Statistical Analysis of 0.070-in. Standoff Distance (in.)

Depth Measured	Average Change in Focus	Standard Deviation of ΔFocus	99% Confidence Tolerance (ΔFocus)	99% Confidence Interval for Focus Adjustment		99% Confidence Interval for Depth Measurement Range		Tolerance on Depth Measurement (±)
				Lower Confidence Limit	Upper Confidence Limit	Lower Confidence Limit Measurement	Upper Confidence Limit Measurement	
0.0178	0.0013	0.0005	0.0004	0.0010	0.0018	0.0082	0.0193	0.0055
0.0250	0.0014	0.0007	0.0006	0.0021	0.0033	0.0240	0.0398	0.0079
0.0344	0.0027	0.0006	0.0005	0.0025	0.0035	0.0289	0.0421	0.0066
0.0148	0.0030	0.0003	0.0003	0.0010	0.0016	0.0091	0.0166	0.0038
0.0274	0.0013	0.0006	0.0005	0.0020	0.0030	0.0221	0.0362	0.0071
0.0384	0.0025	0.0007	0.0005	0.0032	0.0043	0.0388	0.0534	0.0073
0.0123	0.0037	0.0006	0.0005	0.0007	0.0016	0.0048	0.0174	0.0063
0.0230	0.0012	0.0003	0.0003	0.0020	0.0025	0.0221	0.0297	0.0038
0.0292	0.0023	0.0008	0.0006	0.0018	0.0031	0.0200	0.0374	0.0087

1 in. = 25.4 mm

The standard deviation, which is the average variance from the mean change in back focus, was calculated from these measurements. This standard deviation with the sample size was then used to build a 99% confidence interval for focal change, within which the focal change for the actual depth of the scar should lie.

These upper and lower focal change confidence limits give a maximum and minimum focal change that is then directly correlated to a depth range of the measured scars. Based on the 10 test measurements taken, half the difference between the lower and upper 99% confidence depth measurements is the tolerance for that set of measurements. This confidence limit is made assuming that the data follow a normal Gaussian distribution.

After recording the measurements for the various known depths at both standoff distances, the average tolerance was determined to be less than ±0.007 in. (±0.18 mm), or 16% of the 0.043-in. (1.092-mm) wall thickness away from the measured value. This tolerance is approximately half the depth of field provided by the current lens assembly.

This type of measurement is not an absolute form of measurement. It is highly dependent on the characterization data of the lens, as well as the uncertainty that is introduced by the inconsistency of the user and his or her ability to accurately judge when the area of interest is in focus or out of focus. To provide greater accuracy with the current lens design, it is recommended that the user take an average of several measurements to determine the depth of a wear scar. The more measurements that are taken, the closer the average will be to the actual depth of the scar. Further development of a measurement system and the processes and techniques required for characterizing wear scars will, in all probability, increase overall measurement capacity.

Considering the results of this analysis, a new lens solution should be designed with a shallower depth of field. To further reduce the uncertainty in the measurement system, additional characterization of a subsequent lens could potentially be performed by the lens manufacturer. This might assist in providing greater accuracy within the characterization process, in turn reducing systematic error.

Section 5: Prototype Concepts

5.1 Mechanical Design

Based on initial test results, two design configurations are acceptable for use. One of them holds a standoff distance constant and moves only the CCD portion of the system, adjusting only the back focus. In the other design configuration, the lens moves, creating a change in back focus as well as a small change in standoff distance.

The movement in each design would be controlled by micro-piezoelectric motors that, when coupled with position trackers, can be encoded and used to precisely record the change in focus during each measurement. Both design configurations would be packaged in a small probe head capable of being delivered into the tube bundle of steam generators.

The configurations described in the following subsections are designed to couple with an existing ribbon-style probe that has been successfully delivered into tube bundles from the secondary side during other steam generator inspections.

5.1.1 Constant Standoff Configuration

Figure 5-1 shows a concept of the constant standoff configuration design. In this design, the head of the probe stays in a fixed position; the only adjustment that occurs is a back focal adjustment. This type of housing performs identically to the existing test fixture, in which each of the variables—standoff distance and back focus—is controlled separately.

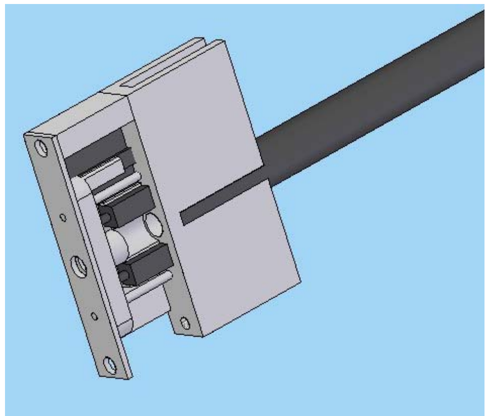

Figure 5-1
Constant Standoff Configuration

5.1.2 Moving Lens Configuration

Figure 5-2 shows a configuration that differs from that of the test fixture. The one major difference is that when the back focus of the lens is adjusted, the standoff distance also changes. The change in standoff distance, as large as 0.006 in. (0.15 mm) with this type of measurement, can introduce uncertainties in the measurement compared to that of the collected data. This type of configuration has not yet been attempted during this study; however, it is a feasible method that could be implemented, if necessary, with appropriate testing and development.

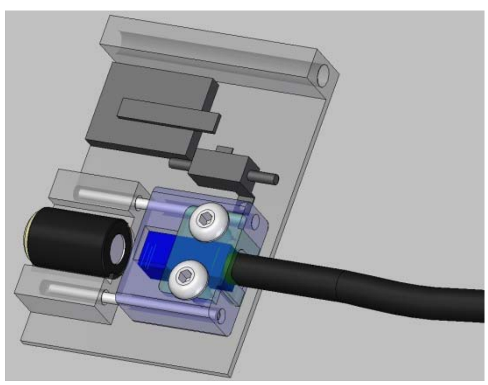

Figure 5-2
Moving Lens Configuration

5.2 Lighting Requirements

Lighting is an important and influential factor in optical measurement. The lighting supplied with a standard probe would be partially blocked by the lens assembly and inadequate for measurement scenarios, which would mean that external lighting must be provided. This lighting should be oblique lighting that gives illumination resulting in the image having a three-dimensional appearance and otherwise invisible features being highlighted. With too much lighting, the image becomes washed out, and details are not easily distinguished. The brightness of the light source must be controlled so that this can be prevented, but also so that an appropriate amount of light is maintained to help illuminate and bring out otherwise invisible features. This can be accomplished by controlling each individual light's intensity. One might also need to diffuse the light to help eliminate the glare within the image caused by the close proximity of the light sources and the lens assembly.

5.3 Software Interface

A software interface was designed to control the light sources and to allow the user to control the back focus adjustment from the software. The graphical user interface is shown in Figure 5-3.

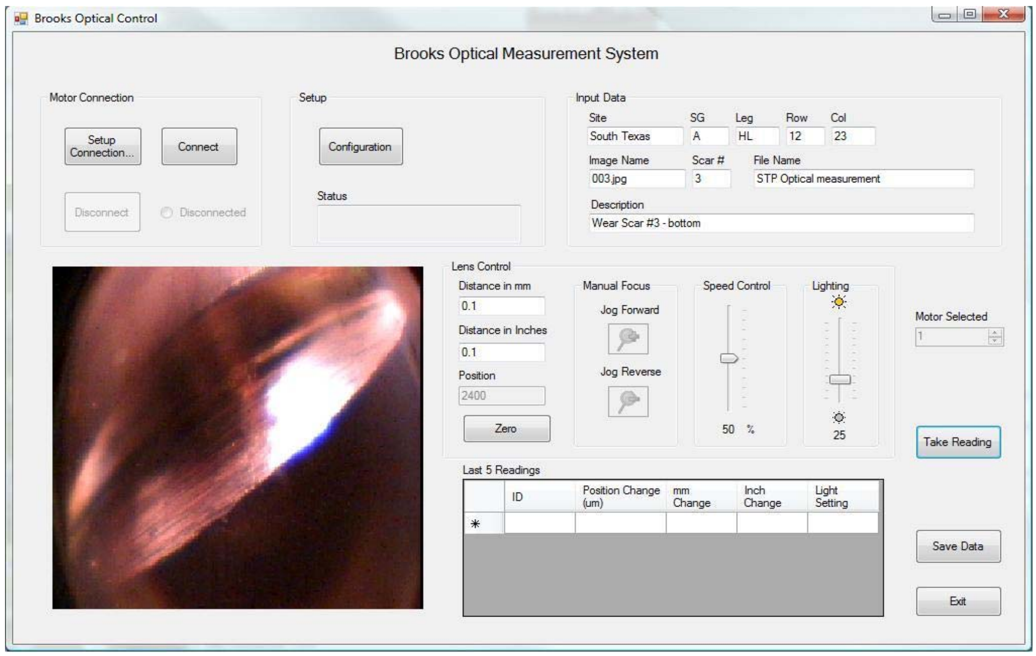

Figure 5-3
Brooks Sample User Interface

The software creates a log of the measurements taken, and this information can then be saved to a secure database specifically designed to access remotely through the Internet. These log files save not only the depth measured but also pictures, light settings, standoff distance, and site and location information within the tube bundle of the steam generator. These data are important to store for details of the measurements taken and for comparison with future inspection data of the wear scar, helping to judge whether the depth of the scar has increased or remained constant.

Section 6: System Limitations

6.1 Measured Depths

During prototype testing, we noted that additional user training will be required to eliminate incorrectly positioning the back focus adjustment and improve results. Several measurements must be taken to ensure correct wear scar measurement results. An average of these measurements can give a close estimate of the depth of the scar, and it is necessary due to the possibility for human error when taking only one measurement.

6.2 Wear Scar Size, Shape, and Location

The capability of the system to accurately measure a scar depth also depends on the ability to see both the tube surface and the deepest portion of the scar in the field of view without shifting the head of the probe. At an object distance of 0.030 in. (0.76 mm), the tube surface and area of interest must be encompassed within a 0.125-in. (3.18-mm) circle. If a larger scar is found, the probe should be repositioned for multiple sets of measurements to be taken.

Another influence limiting the ability to take depth measurements of wear scars in a tube bundle is the location of the scar on the tube. Every tube potentially has a blind spot. The blind spot on each tube depends on the configuration of the steam generator (square versus triangular pitch) and where the tube is located in the bundle. Visual representations of these blind spots are shown in Figure 6-1.

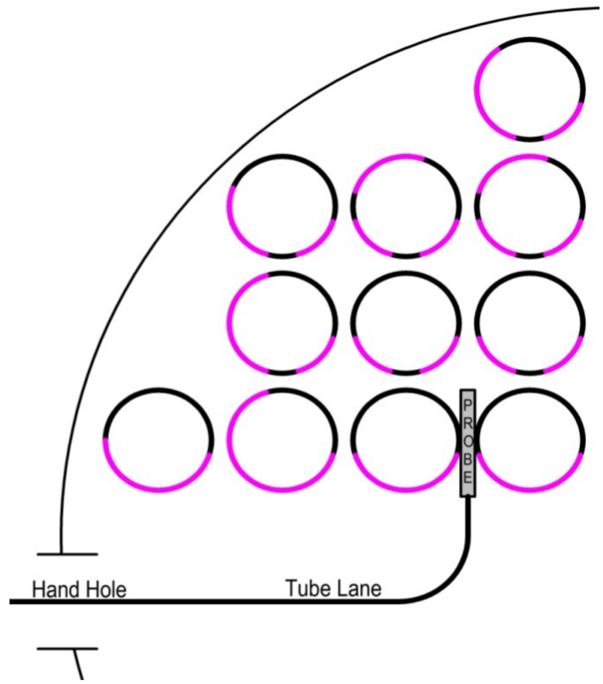

Figure 6-1
Visual Inspection Blind Spots

Measurements of the tube surface might be possible in the magenta portion of the tube wall. Tubes on the outer peripheral row and the first few rows adjacent to the tube lane are more susceptible to wear scar damage and are also more accessible than tubes in the bundle. Tubes located deep within the tube bundle or in areas with collaring or hard sludge deposits would likely be more challenging. Experience with in-bundle inspections indicate that delivery and use of a wear scar measurement tool would be possible if the wear scar is noticed during normal foreign object search and retrieval activities. However, if a foreign object is found elsewhere in the tube bundle, it might be possible to develop a method to approach the tube from alternative angles or locations to determine whether there is any wear damage to the tubes bounded by the foreign object.This approach would be more cost effective than mobilizing eddy current equipment. If a portion of a wear scar is visible on a tube surface and the remainder of the scar wraps around the tube or falls off the video image, future development and testing could define a method for obtaining oblique measurements, possibly with an articulating end-effector mounted on the probe.

6.3 Square Pitch Versus Triangular pitch

Another limitation to wear scar measurement is the spacing between tubes. The tube gap differs between models of steam generators, and sometimes spacing is not consistent within a single generator (sometimes due to drill run-out inconsistencies), resulting in slight variances between tube gaps.

Triangular pitch steam generators are the preferred tube bundle configuration currently being built. This configuration has small tube gaps compared to those of a square pitch steam generator, which creates additional challenges in designing a system to be used in bundles. The current prototype lens size will not fit these small gaps. A solution for a triangular pitch tube bundle would require a new lens to be designed and tested within the smaller geometry required for delivery into a triangular pitch steam generator.

Section 7: Conclusions

An optical measurement approach proved to be effective at measuring the depth of wear scars in a benchtop setting. With adequate development time, it would be possible to design a field-ready system for measuring wear scar depth. Initial prototype testing and prototype development proved the concept of optical measurement and identified several challenges and factors that must be considered with future development.

The current prototype solution is quite sensitive, and multiple measurements are required to ensure accuracy. Based on the functionality, sensitivity, and accuracy noticed with the prototype tool, further development of the current prototype into a field-ready prototype system might serve only as a go/no-go gage with the ability to approximate depths. A working prototype must be further researched and designed to provide a better understanding of the limitations and accuracy of the system within its working environment. Examples of various aspects that should be considered for future design include researching an improved lens design based on learned limitations with the current prototype lens, identifying potential locations within a tube bundle that will be viable for secondary-side measurement, realizing the percentage of nonmeasurable tube surface locations, and designing a mechanical packaging and delivery system that will allow for safe and controlled delivery within a tube bundle.

If a triangular pitch solution is desired, it is anticipated that significant research and testing would be required by a lens manufacturer to develop a functional lens set of a small enough scale to fit within the parameters of a narrow, triangular pitch tube gap. Challenges would also be presented in the design of small, precision packaging to contain the lens components together with micro-piezoelectric motion controls in a delivery system.

An optical approach has many benefits for wear scar measurement because the scar is viewable during examination. This allows for a visual characterization of the scar, identifying width, length, depth, sharp cut into the tube, and whether the scar is shallow with a flat or rounded bottom profile. This method would give a better understanding of the geometry of the scar than that provided by the current, nonvisual methods.

Before moving into a future phase to develop a field-ready system, we recommend further investigation into lens design for triangular pitch generators as well as for a more accurate square pitch design. We also suggest that a working prototype system be made for in-bundle measurements, to enable testing of micro-piezoelectric motors and controls, as well as software for tracking changes in focal length. Further characterization of this system should be performed at different standoff distances to make the system more universal and to reduce the uncertainties in the system's optical measuring capabilities.

The Gantt chart in Figure 7-1 shows a potential schedule for the development of a functional prototype that could be used for mock-up testing and eventually transitioned into a field-ready system. These estimates are presented merely as an example of what is anticipated in a future development phase; they should not be used for quotation or reference for outlining future development programs.

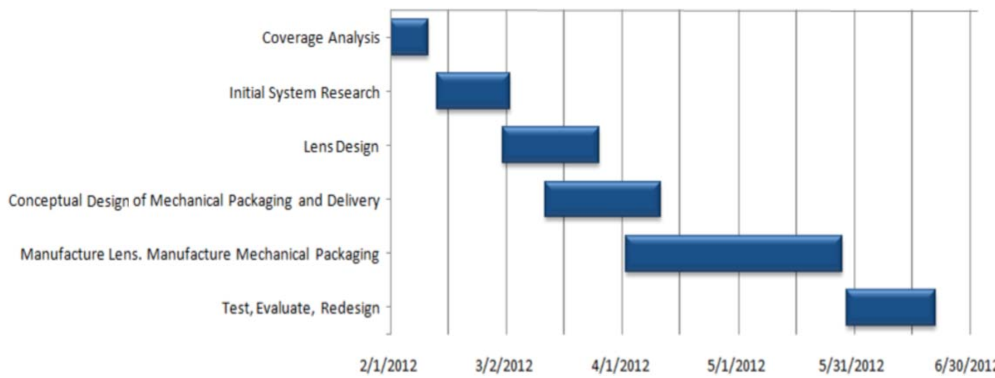

Figure 7-1
Example Prototype Development Schedule

Section 8: References

1. *Steam Generator Management Program: Foreign Object Wear Scar Sizing Feasibility Study*. EPRI, Palo Alto, CA: 2010. 1020629.

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