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Guide to Optimized Nuclear Low-Pressure Turbine Rotor Inspection

Prepared by
EPRI NDE Center, Charlotte, North Carolina

(continued on back cover)

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Guide to Optimized Nuclear Low-Pressure Turbine Rotor Inspection

In the past few years, the nuclear utility industry has reduced downtime for refueling outages to trim costs and improve overall unit performance. Consequently, this has also reduced the time available for other routine outage work and has often placed turbine maintenance and inspection tasks on the critical path. This report provides a review of the strategies several nuclear utilities have employed at their plants to reduce the time required to perform low-pressure turbine inspections. Included is a review of the most common inspection methods used by turbine manufacturers and inspection service providers.

INTEREST CATEGORIES

Non-destructive evaluation techniques
Nuclear plant operations

KEYWORDS

Inservice inspection
Steam turbines
Stress corrosion cracking
Nondestructive evaluation
Nondestructive inspection

BACKGROUND Nondestructive examination of low-pressure turbine disk blade attachments and shrunk-on disk keyways is a timely process that often places low-pressure turbine rotor work on the critical path during refueling outages. The performance of these inspections is crucial to ensure safe and reliable uninterrupted service of power generation equipment. The results of these inspections impact recommended reinspection intervals based on initial flaw sizes, material properties, and equipment operation. As rotor inspection schedules approach the technical limit for minimum examination times, continued opportunities for reducing outage duration and cost are being sought.

OBJECTIVES To provide a review of the strategies several nuclear utilities have employed at their plants to reduce the time required to perform low-pressure turbine inspections.

APPROACH The results of successful efforts of various utilities to optimize their nuclear low pressure turbine rotor inspections were compiled into a guide.

RESULTS This report provides a review of the most common inspection methods used by turbine manufacturers and inspection service providers and describes techniques to reduce the time required to perform these inspections.

EPRI PERSPECTIVE By applying the strategies outlined in this guide, utilities should be better able to plan for the most probable low-pressure turbine rotor inspection results prior to the beginning of an outage by involving all the necessary decision makers and reaching agreement on key issues ahead of time.

PROJECT

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Energy Conversion Group

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Guide to Optimized Nuclear Low-Pressure Turbine Rotor Inspection

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ABSTRACT

Service-induced cracks in keyways and bores of shrunk-on turbine disks have been found in many low-pressure turbine designs. Cracking of these disks, regardless of the location, has generally been attributed to an intergranular stress corrosion mechanism. The performance of inspections is crucial to ensure safe and reliable uninterrupted service of power-generating equipment. The results of these inspections affect recommended reinspection intervals based on initial flaw sizes, material properties, and equipment operation. In the past few years, the industry has reduced downtime for refueling outages to trim costs and improve overall unit performance. This has also reduced the time available for other routine outage work and has often placed turbine maintenance and inspection tasks on the critical path. This report provides a review of the strategies that several nuclear utilities have employed at their plants to reduce the time required to perform low-pressure turbine inspections. Included is a review of the most common inspection methods used by turbine manufacturers and inspection service providers.

ACKNOWLEDGMENTS

In 1994, PECO Energy assembled a team to address turbine inspection issues during the fifth refueling outage for Limerick Generating Station Unit 1. The strategies developed by this team proved valuable in reducing the time for performing turbine inspections and have been documented in this report. The authors acknowledge several of the individuals and organizations involved at that time: Dave Helwig of PECO Energy and Ellen Smith of General Electric Company for their sponsorship of the project; Don Warfel, Ron Hess, Paul Weymuller, and Tim Moore of PECO Energy for their engineering, management, and execution of the outage plan; and Dr. Ron Placek, Tom Wagner, Bob Scott, and Curtis Rose of General Electric Company for their responsiveness in developing innovative inspection and analysis options to ensure a maximum safe reinspection interval for the unit.

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1

INTRODUCTION

It has been over 25 years since the first shrunk-on turbine disk rupture attributable to intergranular stress corrosion cracking occurred [1]. In the interim, the problem has been found to be widespread, and many initiatives have been taken to mitigate the situation. Improved disk designs, which concentrated mainly on reducing stresses, were quickly prepared and made available to the industry to retrofit onto existing rotors. Inservice inspections were introduced by the rotor manufacturers to identify any cracking before a dangerous condition could be reached. Massive forgings capable of producing single piece (monobloc) rotors with integral disks eventually reached the market as a more permanent fix, and welded rotors have also been used as a replacement option to eliminate the bore and keyway. For the turbines still operating with the original shrunk-on disks, nondestructive evaluation (NDE) procedures and appropriate life assessment methodologies are used to track the progress of any crack initiation or propagation and to determine safe operating lifetimes. Studies have also produced recommendations for steam chemistry improvements to minimize corrosion attack. However, disk stress corrosion cracking still remains an issue [2].

Stress corrosion cracking in turbine disks is neither a new problem nor one that is restricted to the United States or to domestic turbine manufacturers. Even though this problem has been recognized for many years, it remains an important maintenance issue in the power industry. In 1969, the first major turbine disk rupture occurred on a low-pressure (LP) turbine at the Hinkley Point A power station in Great Britain [1]. The shrunk-on disk on the Hinkley Point rotor failed catastrophically because of stress corrosion cracking in the keyway. This major event was followed by the discovery of similar cracking on other LP disks around the world and eventually in the U. S. These events led directly to numerous studies in the U. S. and abroad aimed at determining the root cause of failures, contributing factors, potential consequences, interim inspection and remedial action requirements, and long-term fixes [3].

Following the Hinkley Point failure, emphasis in the U. S. quickly centered on 1,800 revolutions per minute (rpm), nuclear LP rotors, and keyway cracking was identified as the primary issue of concern. The operative crack initiation and growth mechanism was found to be intergranular stress corrosion cracking (IGSCC). Eventually, other areas of the disks, including the bores, web faces, and rim / blade attachments, were also found to be susceptible to cracking, although the preponderance of cracking was found in the keyways.

Over the years, much has been learned about turbine disk cracking. Crack initiation and growth mechanisms have been identified, and the susceptibility of particular disks and specific areas on disks to cracking have been determined and categorized based on machine design and stresses, material characteristics, the location of the Wilson line, steam chemistry, and other less significant variables. Inspection methods and techniques have been developed primarily by the original equipment manufacturers (OEMs) and other inspection vendors to enable detection and sizing of the relatively large cracks that are of interest in nuclear LP rotors. Material behavior has been characterized, at least to the degree necessary for conservative analyses, and this information has been used in the life assessment process. Life assessment techniques have evolved and been accepted throughout most of the industry, and these techniques have been used to establish reinspection intervals and as the basis for eventual retirement of a disk or the entire rotor [4]. In addition, interim and long-term fixes have been designed and implemented to reduce inspection and evaluation requirements and improve the overall reliability of turbine rotors.

In the U. S., utilities have followed a variety of paths in addressing their turbine disk cracking concerns. In nuclear plants, some have identified cracks and continue to periodically measure the progress of crack extension and to reassess remaining life. Some disks have been replaced in like kind because crack extension became excessive before improved designs had been completed. Others have been replaced and continue to operate with disks having interim design improvements, for example the key plate design on Westinghouse rotors and the radial key design on General Electric machines [5]. Others have been replaced with rotors having partially integral or fully integral disks. Blade attachment cracking has not necessarily been addressed in the retrofit designs, which were primarily concerned with bore and keyway cracking; consequently, even the new rotors and disks may be susceptible to attachment cracking. Life-limiting stress corrosion cracking in blade attachments of fully integral rotors would require extensive machining or perhaps even rotor replacement because individual disks could not be removed to allow continued service.

In the past few years, the industry has reduced downtime for refueling outages to trim costs and improve overall unit performance. It has been estimated that every day a nuclear unit is off-line it can cost approximately $300,000 in direct costs, and this does not include replacement power costs that could easily equal that amount. It is likely that every day trimmed from an outage schedule means about $1 million in deferred costs and associated risk [6]. Consequently, this has also reduced the time available for other routine outage work and has often placed turbine maintenance and inspection tasks on the critical path. This report provides a review of the strategies that several nuclear utilities have employed at their plants to reduce the time required to perform low-pressure turbine inspections. Included is a review of the most common inspection methods used by turbine manufacturers and inspection service providers.

2

INSPECTION SUMMARY

Disk Inspection

Disk inspection is a term commonly used to describe the techniques applied to ultrasonic inspection of the keyway, bore, and hub face region of shrunk-on disks. Cracks 1, 2, and 5 (see Figure 2-1) are of the type the inspection is designed to detect. Indication 3 represents cracking in the blade attachment region and will be discussed later in this section. Indication 4 in Figure 2-1 is a crack on the surface of the web and is detected by surface-sensitive techniques, such as magnetic particle testing (MT) or penetrant testing (PT), which are not part of the disk ultrasonic inspection procedure.

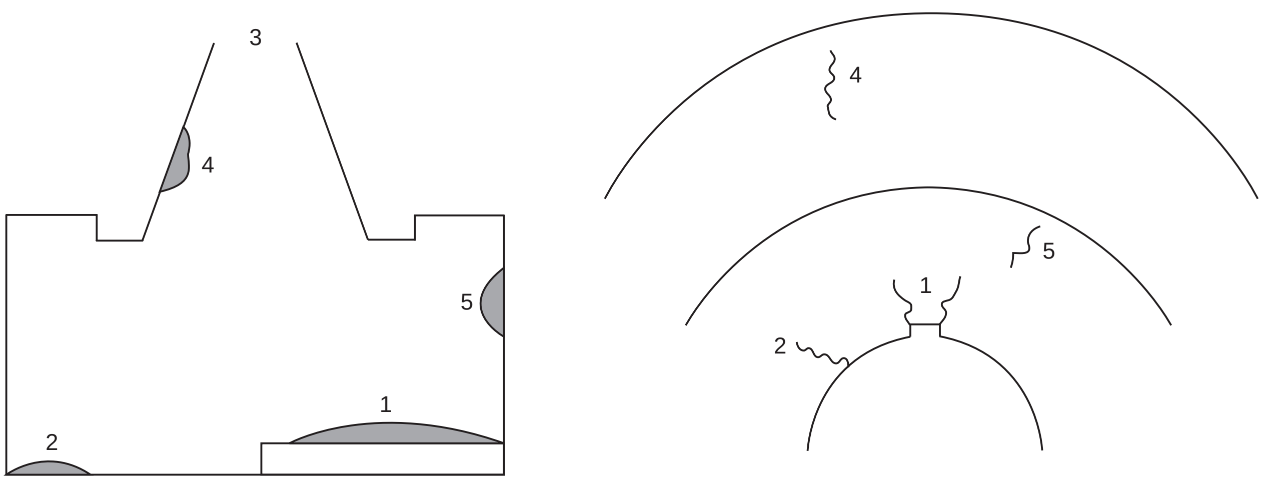

Figure 2-1
Primary Locations for Stress Corrosion Cracking

Most vendor inspection routines require two separate scans: detection scans and defect sizing scans. During detection scans, the ultrasonic transducers are placed on the wheel, as shown in Figure 2-2. The ultrasonic beam is introduced in a tangential direction toward the bore and keyway region, approaching the expected flaw as shown. Best detection occurs when the beam direction is perpendicular to the flaw face or when a corner reflector is formed by the flaw and the disk surface. To maximize the coverage area at the keyway and bore during the web inspection, the pitch-catch transducers are moved radially inward and outward on opposite sides of the disk.

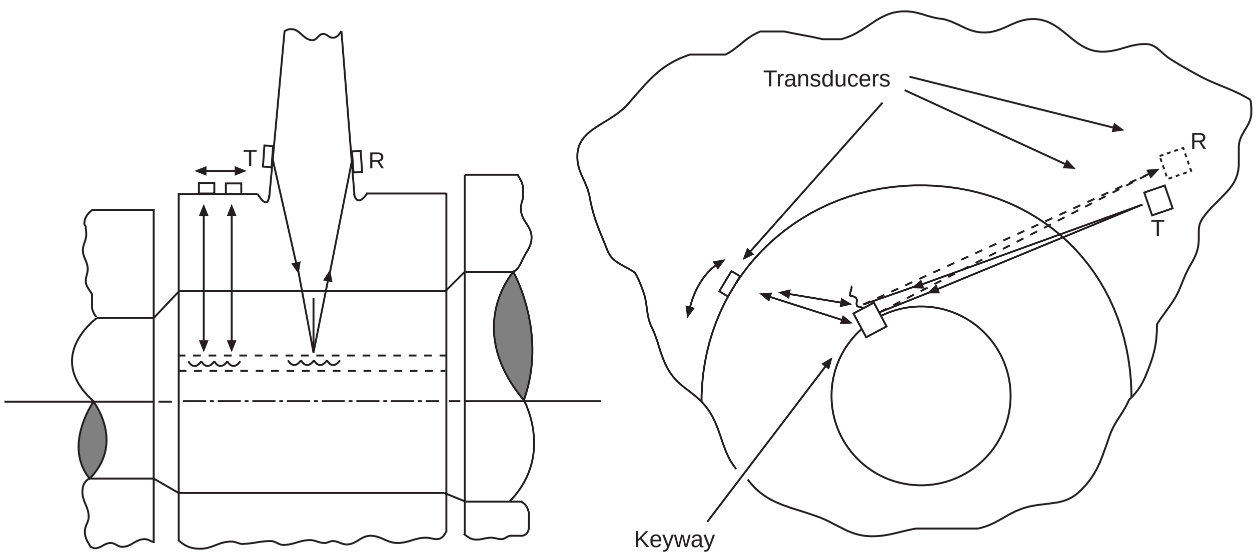

Figure 2-2
Ultrasonic Transducer Placement for Crack Detection

In the second step, sizing of indications found during the detection scans is typically performed using a zero-degree tip diffraction technique, directing the ultrasonic beam radially inward, as shown in Figure 2-3. Pitch-catch techniques are again used to size flaws under the web and pulse-echo techniques are used under the hub. Often during an inspection, flaws will be identified during the detection scan that cannot be verified with the sizing scan because they are too small or unfavorably oriented. When this occurs, the vendor usually assigns a default size that is based on historical data of such experiences.

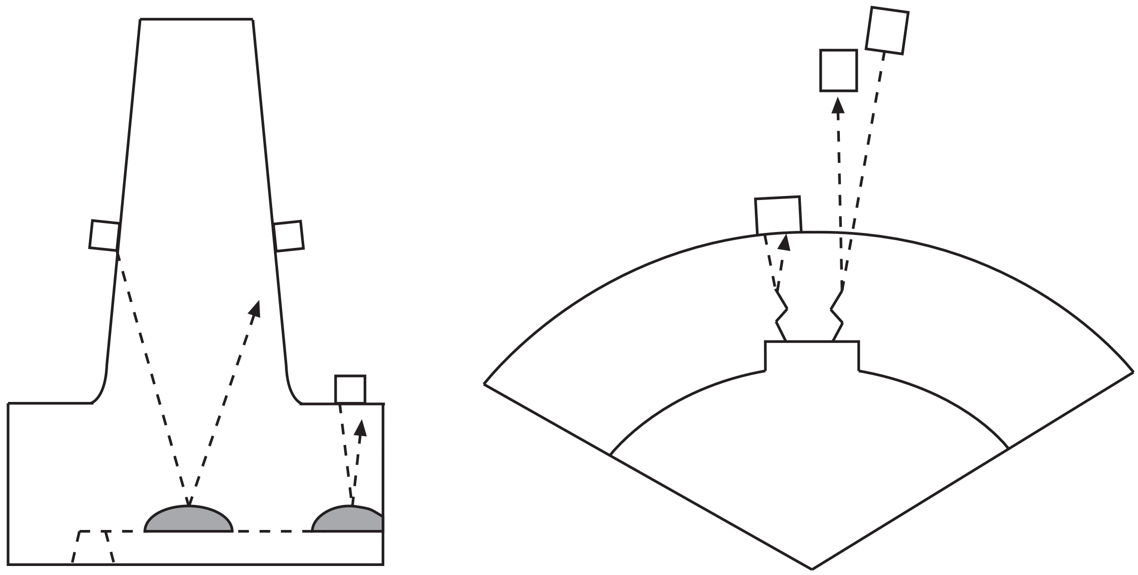

Figure 2-3
Ultrasonic Transducer Placement for Crack Sizing

Hub Face Inspection

To detect flaws that are aligned on the hub face, shown as crack-type 5 in Figure 2-1, a refracted ultrasonic beam from the hub outside diameter (OD) is used. The transducer is placed on the hub OD and pitched slightly toward the face of the hub to obtain the best results.

Blade Attachment Inspection

The purpose of the blade attachment inspection is to detect cracks in the dovetails of the disk rim where the blades are installed, shown as Indication 3 in Figure 2-1. EPRI has published technical report TR-104026, *Inspection of Turbine Disk Blade Attachment Guide*: *Volume 1, Background and Inspection Principles* that provides more detailed descriptions of these inspections [7]. Depending on the design, the dovetails can be circumferential or axial. Figure 2-4 shows a typical circumferential dovetail design with cracks in the expected locations. It is important to know certain features about the dovetail geometry to enable proper inspection. The manufacturers have machine drawings of the dovetails. Other vendors must rely on alternative methods to determine the geometry prior to the inspection.

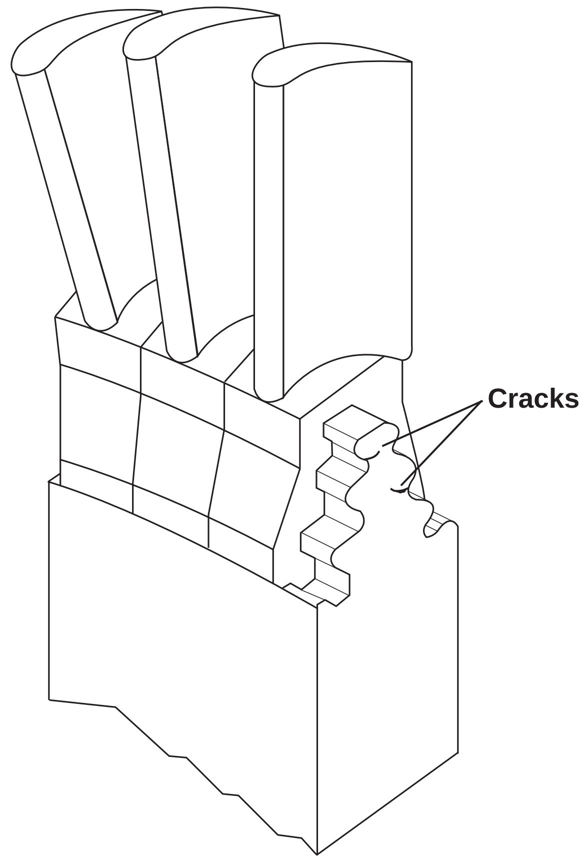

Figure 2-4
Typical Crack Location in Turbine Blade Attachments

After the geometry is determined, a scan plan is developed. The scan plan provides details about transducer positions and refracted angles of the ultrasonic beam. The inspection is typically performed by fixing the transducer at the indicated location and rotating the turbine while the data collection process is performed.

Additional Inspections

In addition to the inspections described above, a periphery visual and magnetic particle exam is performed primarily to look for defects in the blade foils. Also, many monobloc design rotors have a central bore that is examined with automated ultrasonic inspection equipment [8].

3

APPROACHES FOR OPTIMIZING LP ROTOR INSPECTIONS

The single most important element in reducing outage time and cost is advanced planning. The goal is to determine the most probable inspection results to be encountered during an upcoming outage, develop decision trees to map out courses of action based on the actual inspection results, develop contingency plans for unexpected results, and develop a detailed schedule for the inspections to be performed during the outage. To achieve this goal, typical planning schedules require that work-scope identification be completed ten to twelve months ahead of the outage with an executable outage plan issued three months before the start of the outage [6]. Ideally, outage planning should also involve the selected inspection vendor and other consultants early in the process to ensure that critical tasks are not overlooked.

Advanced Planning

A preliminary engineering evaluation of rotor material properties, past inspection results, and industry experience would allow inspections to be prioritized such that the highest risk components are inspected first, permitting more time to evaluate the inspection results and implement corrective actions, if necessary. For example, calculations for turbine missile generation will reveal which shrunk-on disk has the highest contribution to the overall missile generation probability for the unit. Likewise, an evaluation of previous blade attachment inspection results will indicate which stage should be examined first. In the absence of previous inspection results, industry data from inspections on similar turbines can be reviewed to determine the relative risk of finding indications. This is also a good time to perform a review of the technical basis for performing other recommended inspections, such as periphery magnetic particle, visual, and penetrant exams to determine whether these tests are really necessary for your specific design. Conversely, involving the inspection vendor and manufacturer early in the planning process reduces the likelihood of omitting critical tests that might be required for safety or reliability.

Decision Trees

Once the preliminary engineering analysis is complete, decision trees or flowcharts can be developed. The goal is to gather the key engineering and management decision makers together, review the most probable "what if" scenarios, and map out the actions to be taken based on the actual inspection results. The decision trees permit significant decisions to be made prior to the beginning of the outage based on the quantity and size of indications found during the actual inspection. Then, if problems arise with one or more of the most life limiting rotor components during the exam, the appropriate alternative inspection, analysis, or repair options will have already been considered and a course of action can be chosen quickly. A sample decision tree is shown in Figure 3-1.

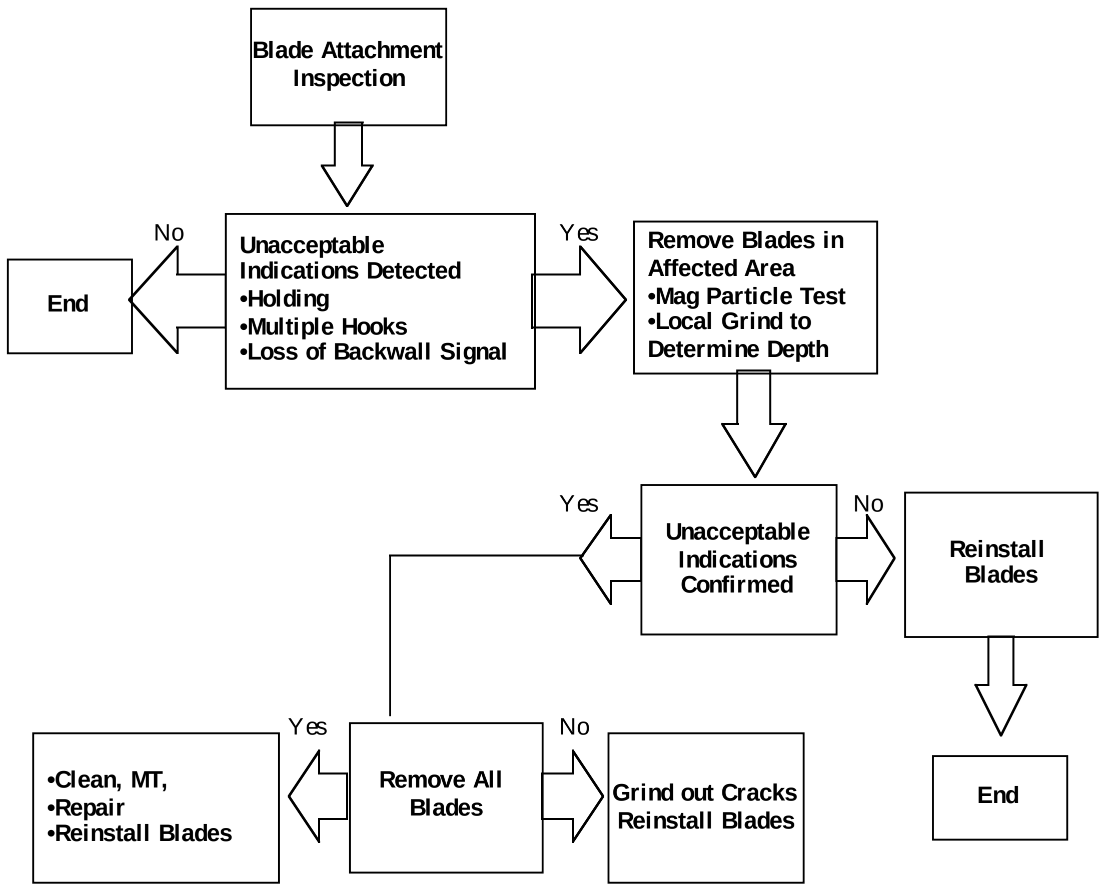

Figure 3-1
Sample Decision Tree for Blade Attachment Inspection

Contingency Plans

While improvements in analytical techniques and inspection methodology might reduce the risk of a major repair, that possibility should not be overlooked. A risk assessment can be performed for the rotor to identify the potential repair scenarios. For each scenario, materials and labor requirements should be identified, schedule impact determined, and cost impact of the repair and potential lost generation capability developed. Contingency plans can then be developed for the most likely scenarios. These may include removing a disk and installing a pressure plate because of keyway cracking, and / or removing a blade or group of blades to confirm the presence and extent of attachment cracking. Pressure plates are stationary discs with drilled holes in the steam path that replace the stationary blading upstream of the removed disk or row of blades. Placement of the pressure plate in the area of the removed disk / blades provides the required stage pressure and temperature reductions and redirection of steam flow so that the downstream stages are not adversely affected by the removal of a row of blades.

Depending on the results of the risk assessment, engineering drawings can be prepared for machining a pressure plate, pressure plate material can be procured, materials to support blade removal and reinstallation can be obtained and special tooling and craft arranged to be on standby. A detailed plan and schedule should also be developed to guide work during the outage. This type of preparation can save several days of outage time if a repair becomes inevitable.

Inspection Scheduling

An optimized schedule should be developed to complete the inspections in the shortest time practical. The priority should be to inspect the highest risk components first. Also, opportunities for performing tasks in parallel should be taken advantage of. For example, with the LP turbine it is usually possible to perform the disk keyway exams from a raised platform at the same time blade attachment exams are being performed from the floor on the opposite side of the rotor. Further time savings can be realized by having inspection systems set up on both the turbine end and generator end of the rotor. Multiple systems and inspection crews would obviously increase the cost of the exam, but if turbine inspection work is truly on the critical path, the payback can justify the extra cost.

The use of automated inspection equipment and UT imaging allow the inspection data to be efficiently collected and immediately transmitted to the analysis vendor for evaluation. Enhanced imaging also provides for on-the-spot preliminary assessment of inspection results. Communication links between the inspection vendor, analysis vendor, and the plant can provide around-the-clock technical support for the inspection team. Additionally, some utilities have requested that consultants be available on-site to provide third-party reviews of the inspection procedures and results. Furthermore, if the stress and fracture mechanics analysis is performed ahead of time up to the point of inputting inspection results, it is often possible to get a final recommendation within 24 hours once the inspections are complete.

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SUMMARY

Nondestructive examination of low pressure turbine disk blade attachments and shrunk-on disk keyways is a timely process that often places LP rotor work on the critical path during refueling outages. The performance of these inspections is crucial to ensure safe and reliable uninterrupted service of power generation equipment. The results of these inspections impact recommended reinspection intervals based on initial flaw sizes, material properties, and equipment operation.

Previous work at the EPRI NDE Center has focused on improving turbine inspection technology. However, experience has shown that outage delays that arise as a result of evaluating indications found during the inspection and deciding what, if any, additional work may be required can have a significant financial impact as well. Effective outage planning, including development of decision trees, can allow significant decisions to be made prior to the beginning of the outage based on realistic assumptions about the type and severity of the most probable indications, thereby reducing the delays caused by attempts to gather necessary technical information under the time constraints imposed during outage conditions. By applying the strategies outlined in this guide, utilities should be better able to plan for the most probable LP turbine rotor NDE results prior to the beginning of an outage by involving all the necessary decision makers and reaching agreement on key issues ahead of time.

A technical paper describing a team effort between PECO Energy, General Electric, and EPRI for improving rotor inspection performance during a 1994 outage at Limerick Unit 1 is provided in Appendix A [9]. This was PECO Energy's first effort at significantly reducing the time for reactor refueling and placed turbine inspection tasks in a potential critical path scenario. The success of this outage provided the impetus for turbine manufacturers and inspection vendors to offer rapid turbine rotor inspections as an option industry-wide. Since then, record-breaking outages approaching 20-day schedules have become routine [6].

As rotor inspection schedules approach the technical limit for minimum examination times, continued opportunities for outage cost reduction are being investigated. Current EPRI initiatives underway include projects to develop guidelines for extending the time between turbine-generator overhauls, strategies to reduce turbine-generator outage time and cost, and *in situ* inspection techniques to assess turbine-generator condition without disassembling the unit.

5

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APPENDIX A:
IMPROVED NUCLEAR LP TURBINE INSPECTION STRATEGY — A TEAM APPROACH

(PWR-Vol. 28, Proceedings of the ASME International Joint Power Generation Conference, Book No. G00983 - 1995)

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Abstract

This paper describes the impact of nondestructive examination (NDE) of turbine wheel dovetails and shrunk on wheel interfaces to the power generation provider. The performance of these inspections is crucial to ensure safe and reliable uninterrupted service of power generating equipment. The results of these inspections impact recommended reinspection intervals based on initial flaw sizes, material properties and equipment operation. Current technology in inspection practices has provided for new solutions that support optimization of recommended planned outage intervals.

A case study is provided which details the combined team effort of customer, consultant, and original equipment manufacturer (OEM) to improve the process of inspection and data evaluation in order to provide appropriate resolution of the test results. Advances in ultrasonic test imaging and flaw sizing techniques were used to evaluate standard flaw default values assigned to turbine wheel keyways. Structural assessment of the corrected flaw default sizes and consideration of equipment operation, including turbine preheating, served to extend the reinspect cycle to 6 years.

Background

Stress corrosion cracking in turbine wheels is neither a new problem nor one that is restricted to the United States or to domestic turbine manufacturers. Even though this problem has been recognized for many years, it remains an important maintenance issue in the power industry. In 1969, the first major turbine wheel rupture occurred on a low pressure (LP) turbine at the Hinkley Point A power station in Great Britain [1]. The shrunk-on wheel on the Hinkley Point rotor failed catastrophically because of stress corrosion cracking in the keyway. This major event was followed by the discovery of similar cracking on other LP wheels around the world and eventually in the U.S.

Following the Hinkley Point failure, emphasis in the U.S. quickly centered on 1800 rpm nuclear LP rotors, and keyway cracking was identified as the primary issue of concern. The operative crack initiation and growth mechanism was found to be intergranular stress corrosion cracking (IGSCC). Eventually, other areas of the wheels, including the bores, web faces and blade attachment dovetails, were also found to be susceptible to cracking, although the preponderance of cracking was found in the keyways.

PECO Energy Assembles Team

PECO Energy Company owns and operates Limerick Generating Station, Units 1 and 2, which are boiling water reactors with a nominal capacity of 1,100 MWe. The turbines are supplied by General Electric Company (GE) and have shrunk-on wheels with axial keyways which are susceptible to cracking.

The Limerick #1 LPA rotor went into service in April of 1985 and the first in-service rotor inspection was performed in February of 1989. During the 1989 rotor inspection, several wheel keyway indications were revealed on the 2nd, 3rd and 6th stage wheels.

The 2nd and 6th stage wheel indications were non-measurable indications (i.e., indications were detected but could not be sized) while the 3rd stage wheels had measured indications of up to 0.37" in depth. GE's missile probability analysis resulted in a recommendation to reinspect the rotor within 6 years of additional service provided the wheels are prewarmed to 100°F prior to start-up and maintained during all operating modes. The limiting wheel driving the prewarm recommendation was the 6th stage.

In 1993, a parametric study by GE of wheel keyway indications identified during the previous exam of the Unit 1 A low pressure rotor in 1989, combined with recent industry experience with cracking in the wheel dovetails, generated concerns at PECO Energy that some type of extensive repairs might be necessary to return the turbine to service following the Unit 1 winter 1994 refueling outage. The outage was planned to last no more than 42 days and expectations were that the outage could actually be completed in a shorter time.

PECO Energy's concern with keyway and dovetail cracking, and the risk of major repairs during refueling outages, led to the formation of a team of PECO Energy, General Electric and Electric Power Research Institute (EPRI) personnel to accomplish the following vision:

> To maintain a six year inspection interval for the Limerick low pressure turbine rotors while ensuring the safe operation of the unit and complying with all NRC regulations. In addition, eliminate the need to remove any of the rotor wheels during the refueling outage on Unit 1. This was to be accomplished without any adverse impact on the outage schedule, since turbine activities were on the outage critical path.

In a joint effort with GE, the EPRI NDE Center was asked to assist in developing a basis for returning to a six-year inspection interval. A review of GE's probabilistic analysis procedure and inspection methods followed. GE evaluated the feasibility of additional prewarming and demonstrated more effective flaw sizing methods. An improved inspection procedure was used to provide smaller default flaw sizes for non-measurable indications and smaller correction factors for measurable indications.

Review Of GE's Probabilistic Analysis

The Nuclear Regulatory Commission (NRC) has established reliability criteria for nuclear turbine operation that are based on the probability of missile generation [2]. The reliability criteria differ in value depending on the favorable or unfavorable orientations of the turbine with respect to the reactor. A favorable orientation exists when the reactor and the turbine centerline are in line, thereby making a turbine missile less likely to strike and damage the reactor than in other orientations. PECO Energy's Limerick #1 Unit is unfavorably oriented. General Electric's interpretation of the NRC criteria is listed in Table A-1 for both turbine orientations. In order to satisfy the NRC requirements and also to assure the integrity of the unit, GE has established guidelines for safe operation of its nuclear turbines which has been approved by the NRC. When the annual probability of missile generation for any LP rotor exceeds the NRC limit divided by the number of LP rotors in the unit, the wheels on that rotor are recommended to be ultrasonically examined for stress corrosion cracks at the keyways and bores. This action ensures that the annual probability of missile generation for the unit will not exceed the NRC limit during operation. GE's recommendation for shrunk-on wheels of nuclear rotors is to conduct a sonic test of the wheels at no more than six (6) year intervals. The many uncertainties which are associated with life predictions of a component and the need to ascertain the condition of the entire turbine rotor assembly, including wheels, make this recommendation prudent. Thus, a maximum of six (6) years is given as a recommendation of reinspection for nuclear shrunk-on wheels.

EPRI NDE Center staff reviewed the probabilistic analysis procedure and concluded that it was an appropriate methodology for calculating missile generation probabilities. The rotor material property database is based on a statistical distribution of both laboratory results and field experience and not worst case values. Some conservatism was found in the procedure in that every indication is assumed to be a crack, i.e., the probability that an indication is not a crack is not factored into the calculation. Also, the IGSCC crack growth rate data is based largely on field experience. The apparent crack growth rate is determined by comparing indication sizes from one inspection to another. Due to uncertainty in the NDE techniques, cases arise where the reported indication size may be smaller than in the previous inspection. These data points are not factored into the database, with the effect that the average growth rate may be skewed marginally higher than if these points were considered for statistical purposes.

Options Considered To Achieve Vision

In preparation for the February 1994 LPA rotor in-service inspection, PECO Energy, EPRI and GE worked closely, reviewing several possible scenarios of wheel keyway and wheel dovetail indications which could impact the refueling outage schedule. One scenario evaluated was finding non-measurable indications in both of the most limiting 6th stage wheels. The result was that the reinspection interval would decrease significantly from the current 6.0 years. Since the reinspection interval for this case was greater than zero (0) years, PECO Energy would have the option to operate at least one refueling outage. However, if other indications were observed in other wheels, the LPA missile probability could have exceeded the NRC probability limit for returning the rotor to service.

Based on the above keyway cracking scenarios which could reduce the rotor reinspection cycle or delay the outage significantly, GE worked closely with PECO Energy and EPRI to evaluate what could possibly be done to maintain the 6 year rotor reinspection cycle and decrease the possibility of outage delays due to wheel keyway and dovetail indications. One variable evaluated was the impact of higher rotor prewarming temperatures on reinspection cycles. The benefit of increasing rotor prewarming temperatures is discussed in detail below. GE also expedited the development of improved NDE UT imaging procedures and equipment in an effort to reduce indication default sizes for both measurable and non-measurable keyway indications. Incorporation of the keyway imaging system and the resulting decrease in indication default sizes is discussed in detail in the NDE section of this paper. Another area discussed in an effort to reduce the possibility of outage delays was prioritizing the sequence of wheel inspections. A decision was made to inspect the most limiting wheels first in order to expedite NDE test result dispositions. The wheel inspection priorities are also discussed below.

Additional Rotor Prewarming

Wheel warming involves prewarming the wheel prior to turbine-generator unit start-up and maintaining this warming throughout all operating modes. The objective is to maintain wheel bore metal temperatures of at least 100°F for turbine operation above 100 RPM. The advantage of wheel warming is that it increases the toughness of most wheels and usually extends the rotor reinspection intervals. Increasing the rotor prewarming temperature above the normal 100°F prewarm can sometimes result in further extending the rotor reinspection interval.

NDE Technology Improvements

Improvements in technology have been applied to the technique and tools of the inspection utilizing the imaging system. The imaging system has the capability of capturing, displaying and storing RF or video waveform data. This information is useful for further interpretation of the data to define ultrasonic anomalies, transducer misalignment and general surface conditions. It also allows for further comparison and refinement of data. Performance tests demonstrate detection / sizing with a signal to noise ratio of 3:1 compared to 2:1 using the wheel bore detection system solely.

The wheel bore radial examination has also been enhanced through application of an advanced transducer positioning algorithm. This algorithm is applied through use of the transducer positioning software, GEODRAW, which calculates optimum transducer beam angles and positioning to focus the ultrasonic energy at the desired target location.

Additionally, a more effective pulser has been linked to the imaging system in order to provide an increase in the signal to noise ratio. The pulser outputs a square wave pulse which is adjusted to closely match the frequency response of the transducers and consequently allows more efficient transfer of ultrasonic energy. These items have combined to provide a refined flaw detection and sizing system.

Re-evaluation Of Default Flaw Sizes

Low pressure turbines of built-up construction, those which the turbine wheels are shrunk onto the shaft, require a variety of nondestructive tests to ensure safe and uninterrupted system operation. Ultrasonic tests are critical to this type turbine design for interrogation of areas known to be susceptible to intergranular stress corrosion cracking. In particular, the shaft and wheel interfaces, especially in the keyway region and the wheel dovetail areas, require nondestructive examination.

After the parametric study, it was determined that a defect in the wheel keyway region would be considered extremely limiting with regard to the reinspection cycle goal, after applying the conventional default defect measurement criteria used in the evaluation of turbine wheels. An ongoing GE plan was identified which provided improvements to the flaw default criteria for sizing of keyway defects. A class of defect indications which can be detected but not sized due to wheel geometry are considered non-measurable, and as a matter of course assigned a flaw size based on historical information from nondestructive test measurements and destructive test data. These values are rather conservative, especially when considering improvements in test technique and tools since these values were derived. Testing was initiated to establish more accurate sizing of wheel keyway defects. Ultrasonic imaging system results and the most recent correlation of destructive test data were used to justify a revision to the indication default criteria.

Test Data Gathered

Data gathering was accomplished using a test system routinely used to collect, record and image wheel keyway and dovetail ultrasonic data. The keyway imaging system is used primarily when flaws have been detected with the conventional turbine wheel bore inspection system and serves to provide a higher detail of flaw orientation, which also aids in flaw sizing. Proven scanning techniques applied in the wheel bore test have been adapted to the imaging system with automated data capture.

GE conducted reviews of imaging test performance on a reference test wheel representative of those found in service. Examinations were performed in order to ascertain the resolution of the imaging test system compared with the conventional wheel bore arrangement. The results indicate that the system with data capture and imaging capability performs reliably for detection, with an enhanced capacity to size indications.

The reference test wheel contains five keyways, four of which are flawed. In addition, several bore indications are located in this sample. The test wheel is absent of wheel dovetails and allows a 0° examination of the bore surfaces to be performed as an alternative to the normal pitch-catch setup used on wheels in service. This affords a more detailed analysis to be performed and also serves as a referee to the pitch-catch examinations; i.e., scans utilizing the 0° angle provide the most accurate means for detection and sizing in this test case.

Test Results

The tests were conducted using procedures established and accepted for wheel bore examinations. The experiments were intended to provide information to optimize analog-to-digital (A-D) data processing rates and discern differences in results at various test frequencies. Optimum test frequency and A-D rates were established during these tests. Comparison of the imaging and standard wheel bore tests revealed that flaw sizing performed with 0° transducer correlated more closely with the imaging system test results. In addition, material discontinuities were imaged that had not been detected previously. Illustrative pitch-catch images extracted from this test data show

(Figure A-1a) a keyway without cracking, (Figure A-1b) a keyway with a crack, and (Figure A-1c) a bore crack.

These tests demonstrate the imaging test capability of compiling data intact with no loss or degradation of data compared to the manual results. In addition to the inspection of laboratory specimens, GE NDE Services has examined in-service wheels by both manual and automated testing means. The data again demonstrated accurate detection correlation with the standard wheel bore test data. Detailed surface examination following ultrasonic examination proved the existence of defects at the indicated flaw sites. Flaw detection is achievable below 0.030" depths and verification of radial depth is achievable to approximately 0.060" in the hub and 0.125" in the web areas.

Revised Default Flaw Size

The qualification and field tests were responsible for establishing new defect default sizing guidelines for wheel keyways. The Limerick turbine was re-evaluated to determine the impact of various size defects on the reinspect cycle given the new default criteria. The lower limits placed on the default values positively impacted the reinspection schedule, and the six year cycle sought by the customer appeared achievable, given that no other more critical flaws existed in the rotor.

The efforts to increase the detection sensitivity and sizing capability of wheel keyway anomalies added the possibility of identifying flaws in the turbine that may have otherwise gone undetected. Also, detected flaws might possibly be sized larger with the imaging system, driving them to critical size. These scenarios were discussed in detail prior to the inspection and the decision to proceed using the most up to date equipment and methods was made.

Outage Considerations

Turbine outage activities included the inspection of all shrunk-on wheels and all dovetails. An engineering evaluation of wheel material properties, past NDE results, and industry experience allowed the wheel keyway inspections to be prioritized such that the highest risk wheels were inspected first, permitting more time to evaluate the NDE results and implement corrective actions, if necessary. Based on calculations for missile generation probability, the 6th stage wheels had the highest contribution to missile generation and were inspected first. For the dovetails there was no prior Limerick NDE inspection data. Therefore, industry data from inspections on similar turbines was reviewed to determine the relative risk of finding indications. Based on this review, the 4th and 5th stages were determined to present the highest risk and were scheduled first for inspection.

Inspecting the most limiting wheels first allowed PECO Energy to get a feel for the rotor reinspection cycle before the complete rotor was inspected. Also, GE's dovetail UT data review criteria were discussed before the outage to assure that PECO Energy understood the various dovetail recommendation scenarios that could require bucket removal to investigate wheel dovetail UT indications detected during the outage.

An optimized inspection schedule was developed to complete the inspections in the shortest time practical. To inspect the wheel keyways, two teams worked concurrently, one on each end of the rotor. Two 12-hour shifts per day were scheduled. For the dovetails, one inspection team per shift completed the necessary inspections. The teams were comprised of four inspectors per shift to allow the wheel keyway and dovetail inspections to be performed in parallel. An evaluator was available at all times to receive the inspection data from the field site. Dovetail and keyway anomalies were transmitted via modem directly from the acquisition system computers to the data evaluator. The total inspection duration lasted only eighty-eight hours, almost a full shift under the time allotted.

The use of automated inspection equipment and UT enhanced imaging allowed the inspection data to be efficiently collected and immediately transmitted to GE in Schenectady for more detailed review. The enhanced imaging also allowed for an on-the-spot preliminary assessment of results by the EPRI NDE Center staff and PECO Energy personnel present during the inspections. Communication links were established between GE Schenectady and the Limerick site to keep all parties informed and to provide around-the-clock technical support for the inspection teams. This eliminated schedule delays in moving each inspection team from wheel to wheel, minimized reinspection, and expedited technical evaluation of NDE data. The technical assessment of data and recommendation to remove the inspection equipment and release the rotor for other work was completed within 24 hours of completing the last required inspection.

Contingency Plan

Planning was an integral component of the strategy team's success. It was recognized that improvements in analytical techniques and inspection methodology could reduce the risk of a major repair, but it could not be eliminated. A risk assessment was performed for the rotor to identify the potential repair scenarios. For each scenario, materials and labor requirements were identified, schedule impact was determined and cost impact of the repair and potential lost generation capability was developed. Contingency plans were developed for the most likely scenarios. These included removing a wheel and installing a pressure plate because of keyway cracking, and / or removing the bucket notch group and adjacent groups of buckets to confirm the presence and extent of dovetail cracking. Pressure plates are stationary discs with drilled holes in the steam path which replace the diaphragm upstream of the removed wheel or row of buckets. Placement of the pressure plate in the area of the removed wheel / buckets provides the required stage pressure and temperature reductions and redirection of steam flow so the downstream stages are not adversely affected by the removal of a row of buckets.

For these scenarios, engineering drawings were prepared for machining a pressure plate, pressure plate material was procured, materials to support bucket removal / reinstallation were obtained and special tooling (lathe) and craft were arranged to be on standby. A detailed plan and schedule was developed to guide work during the outage. The decision trees permitted significant decisions to be made prior to the beginning of the outage based on the inspection results rather than during the outage. As a result, had there been a problem with one or more of the most limiting wheels which required removing a wheel from service and installing a pressure plate due to keyway or dovetail cracking, there would have been a several day jump on initiating the pressure plate machining efforts. Fortunately, the pressure plate material was not needed during this outage.

NDE Results

During the February 1994 LPA rotor inspection, wheel keyway ultrasonic indications were detected in several wheels. A summary of the test results, including sizes and locations of the keyway indications, is provided in Table A-2. The 1989 keyway indications are also listed in Table A-2. In the probabilistic evaluation, it is conservatively assumed that all keyway indications are cracks. Experience has also shown that the possibility of not detecting an indication is real, although small. Therefore, where no indication is found in a wheel, an estimated probability of the failure to detect one is included in the probability analysis.

The ultrasonic examination of the tangential entry dovetails (stages 1 through 5) revealed several localized point source indications on the 2nd, 3rd, 4th and 5th stage wheels. Two of the 4GA wheel dovetail indications were circumferential holding indications up to 0.70" in length. These indications were detected during the higher primary test frequency but were only seen as point source indications when using the lower secondary test frequency. GE typically ultrasonically tests wheel dovetails first using a higher primary test frequency. If indications are revealed, a lower secondary test frequency is used to verify the indications. There was no further action recommended for these reported dovetail ultrasonic indications.

Reinspection Recommendation

GE’s rotor reinspection recommendation, based on the above noted NDE test results, resulted in a 6.0 year rotor reinspect recommendation provided that the wheels be prewarmed to 110°F prior to start-up and maintained throughout all operating modes. By increasing the rotor prewarming temperature from 100°F to 110°F and by incorporating the new UT imaging system indication default sizes, the rotor reinspection cycle was increased from 4.3 years to 6.0 years. Table A-3 provides a list of the variations in rotor reinspection intervals for rotor prewarming of 100°F versus 110°F and for the new default indications sizes versus the old default sizes.

Conclusions

With the combined team effort of General Electric and EPRI, PECO Energy was able to apply improved NDE, refinements in NDE data evaluation, and contingency planning during their recent low pressure (LP) turbine inspection at Limerick Generating Station.

The team successfully accomplished their vision of achieving a six-year inspection interval for the turbine and contributed to completing the shortest refueling outage (35 days) in PECO Energy's history, and one of the shortest outages ever completed by a nuclear plant in the United States. The team's efforts also helped control the Limerick outage costs and reduce the risk of a major outage extension.

References

1. J.L. Gray. "Investigation into the Consequences of the Failure of a Turbine-Generator at Hinckley Point A Power Station." Proceedings: Institute of Mechanical Engineers. 1972, pp. 379-390.
2. NUREG-1048 Supplement No. 6. "Safety Evaluation Report Related to the Operation of Hope Creek Generating Station." U.S. Nuclear Regulatory Commission. July 1986.

Table A-1
Turbine System Reliability Criteria
GE's Interpretation From NRC Information

	Annual Probability		
	Favorably Oriented Turbine	**Unfavorably Oriented Turbine**	**Required Licensee Action**
(A)	P1 < 1E -4	P1 < 1E-5	This is the general, minimum reliability requirement for loading the turbine and bringing the system on line.
(B)	1E -4 < P1< 1E-3	1E -5 < P1 < 1E-4	If this condition is reached during operation, the turbine may be kept in service until the next scheduled outage at which time the licensee is to take action to reduce P1 to meet the appropriate A criterion (above) before returning the turbine to service.
(C)	1E-3 < P1 <1E-2	1E-4 < P1 < 1E-3	If this condition is reached during operation, the turbine is to be isolated from the steam supply within 60 days, at which time the licensee is to take action to reduce P1 to meet the appropriate A criterion (above) before returning the turbine to service.
(D)	1E-2 < P1	1E-3< P1	If this condition is reached during operation, the turbine is to be isolated from the steam supply within 6 days, at which time the licensee is to take action to reduce P1 to meet the appropriate A criterion (above) before returning the turbine to service.

P1 - the probability of turbine missile generation external to the turbine casing.

Table A-2
Axial-Keyway Ultrasonic Indications

Philadelphia Electric Company Limerick #1: TB#170X463 LPA Rotor: Serial #: 5464V1					
		2/89: 1st Insp. (2.8 Years)**		2/94: 2nd Insp (6.5 Years)**	
Stage	**Keyway Location**	**Hub (Inches)**	**Web (Inches)**	**Hub (Inches)**	**Hub (Inches)**
2TA	MI		0.25 (NM)		
2GA	LE TE	0.08 (NM) 0.08 (NM)	0.24 (D2X) 0.25 (D2X)	0.08 (NM) 0.08 (NM)	0.17 (NM) * 0.20 (NM) *
3TA	LE TE	 0.08 (NM)	0.24 (D2X) 0.34 (M)	 0.19 (M)	0.16 (M) * 0.64 (M) *
3GA	LE TE	0.37 (M) 0.28 (M)	0.28 (M) 0.31 (M)	0.49 (M) 0.51 (M)	0.19 (M) * 0.22 (M) *
4TA	TE MI				0.17 (NM) * 0.19 (M) *
4GA	TE				0.24 (M) *
5TA	LE TE MI			0.21 (M) 0.16 (M)	 0.16 (NM) *
5GA	LE TE			0.21 (M)	0.20 (NM) * 0.18 (M) *
6TA	MI (0) TE (180)		 0.25 (NM)	0.08 (NM) 0.08 (NM)	 0.20 (NM) *
6GA	LE TE			0.08 (NM)	 0.20 (NM) *

LE: Leading Edge NM: The UT Ind. has no measurable Extent
MI: Middle D2X: Best Estimate
TE: Trailing Edge M: The UT Ind. has Measurable Extent
* Web indications include 0.20" adders for NM and 0.100" for M (Imaging Verification)
** Service Time (Total)

Table A-3
Reinspection Intervals

Philadelphia Electric Company: Limerick #1: 170X463 LPA Rotor: Serial #: 5464V1			
Case	**Prewarm**	**Web Adders**	**Recommendation**
1	110F	Old	5.8 Years
2	110F	New	6.0 Years *
3	100F	Old	4.3 Years
4	100F	New	4.5 Years *

* Using the new adders was contingent on performing the keyway imaging test.

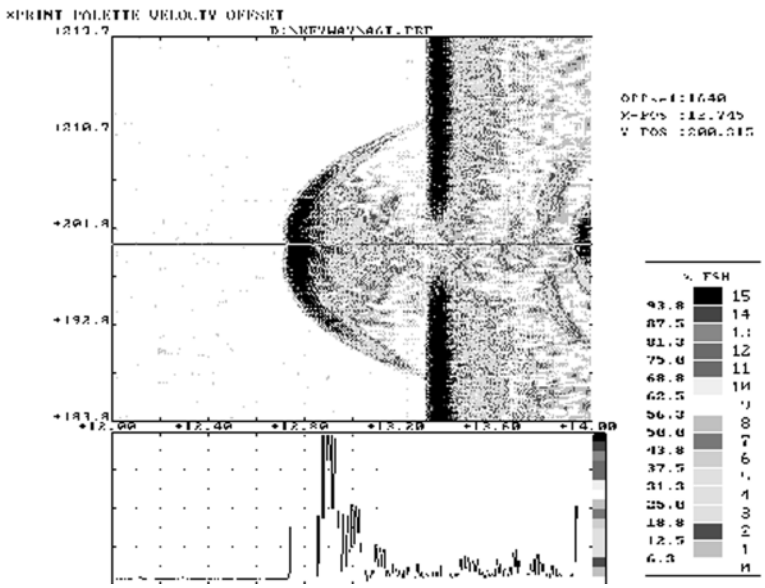

Figure A-1a
Keyway with No Indications

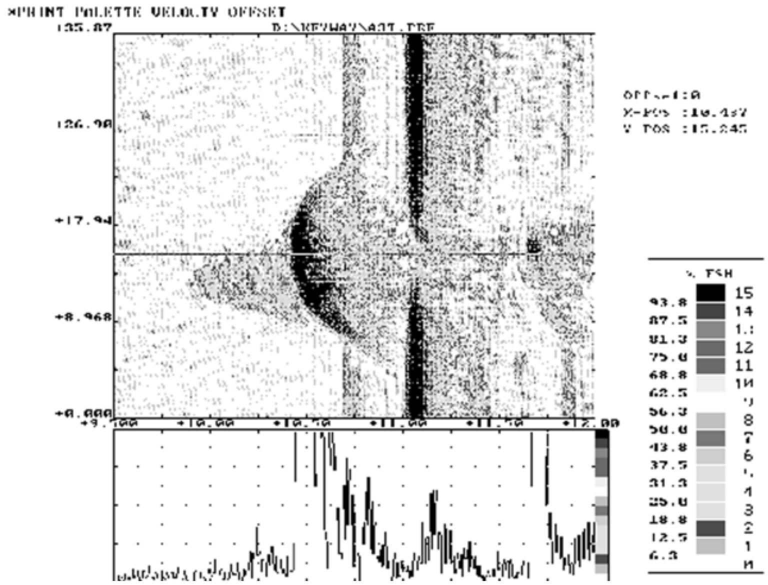

Figure A-1b
Keyway with Crack Indications

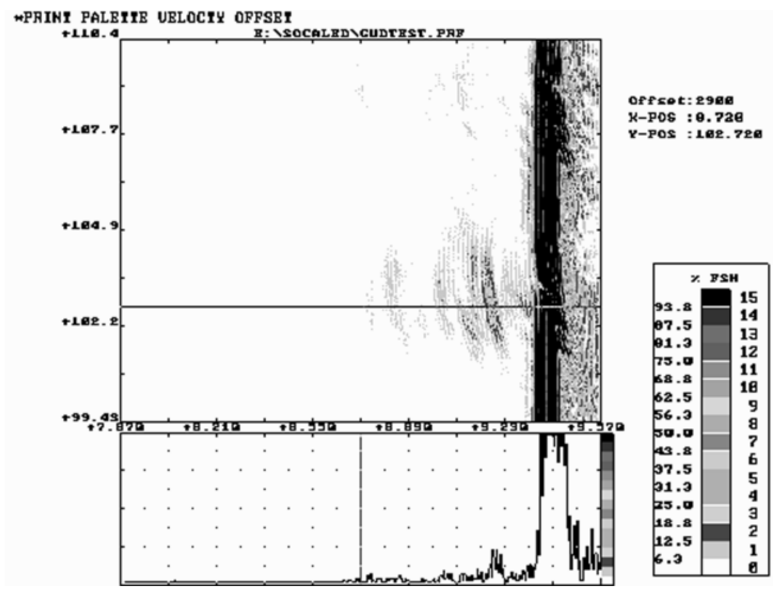

Figure A-1c
Bore Crack Indications

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