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Boresonic Inspection Primer

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REPORT SUMMARY

Boresonic inspection systems provide flaw data that are essential inputs for rotor life assessment programs. Boresonic system technology has evolved from early manual inspection units using broad-beam inspection probes to computer-controlled systems with variable-focus probes and automated data collection. Boresonic inspection systems can identify inherent forging defects as well as flaws that have propagated in service. Evaluation of boresonic inspection systems identifies the flaw detection, sizing performance, and repeatability of these systems.

Background

The catastrophic failure of the Gallatin rotor in 1974 prompted U.S. utilities to conduct boresonic inspections of their rotor fleets to detect near-bore flaws in order to avoid future catastrophic failures. Early rotors were typically bored to remove the segregates and nonmetallic inclusions that congregated along the center axis as a result of the forging process. After a rotor is bored, the tangential stress resulting from centrifugal force is the greatest at its bore surface. Because of the stress concentration at the bore surface, it is essential to identify significant near-bore flaws in the forging. Inclusions can potentially link by a creep mechanism to form subsurface cracks lying near the bore. The cracks can propagate by a combined creep and fatigue mechanism until they reach critical size, and they can then lead to catastrophic rotor failure. A boresonic inspection is critical for detection of near-bore inclusions and cracks.

Objective

- To provide information about the background, preparation, purpose, function, and evaluation of boresonic inspection systems that will be useful to personnel responsible for managing boresonic inspections

Approach

This report addresses various aspects of boresonic inspection, including the following:

- Industry events that led to increased rotor bore inspections
- Rotor failure mechanisms and their correlation with rotor bore flaws
- Inspection systems and their primary components
- Data analysis
- Inspection system evaluation program
- System evaluation history

Results

This report provides an overview of the key aspects of boresonic inspection and a list of references for further investigation.

EPRI Perspective

This report provides key information about boresonic inspection systems as they relate to rotor life assessment and avoidance of catastrophic failure. The catastrophic failure of the Gallatin rotor was an impetus to inspect the fleet of bored rotors. The evolution of boresonic inspection systems and rotor life assessment software programs has contributed to effective management of the rotor fleet.

Keywords

Boresonic inspection
Boresonic system performance
Nondestructive examination
Rotors
Ultrasonic inspection

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Steam turbine rotor reliability and remaining-life prediction are subjects of interest to electric utilities. The importance of rotor reliability and the need for rotor inspection and evaluation methods were graphically illustrated by the catastrophic failure of the Gallatin rotor in 1974. Early nondestructive inspection of utility steam turbine and generator rotors—especially the ultrasonic inspection of the central bore, or *boresonic inspection*—was performed almost exclusively by original equipment manufacturers (OEMs) to determine a rotor's operability. The OEMs also provided rotor life assessment and recommended operational changes or rotor retirement for suspect reports. Some utilities, however, thought that the OEMs might have been too conservative in their rotor inspection and analysis methods, possibly causing premature retirement of some rotors. This belief spawned the use of independent commercial testing organizations or in-house utility personnel and resources for boresonic inspection of rotors and subsequent rotor analysis.

A rotor fleet strategy incorporating life extension, rather than replacement, emphasizes the use of the maximum safe operating life. This strategy usually involves extending operating life well beyond the original design life. To remove conservatism and improve the accuracy and reliability of remaining-life prediction, boresonic equipment and procedures must detect the significant flaws in a rotor and accurately define their locations and sizes. These requirements have provided the impetus for improvements in existing test equipment and procedures as well as the development of new boresonic inspection systems. In addition, these requirements have led directly to the implementation of boresonic system demonstration and evaluation standards.

The Gallatin rotor failure started from a near-bore flaw and resulted in a catastrophic rotor burst, generating missiles that exited the casing and, in some cases, the turbine building. This failure prompted U.S. utilities to conduct boresonic inspections of their rotor fleets to detect near-bore flaws in order to avoid future catastrophic failures. This event was also the impetus for the Electric Power Research Institute (EPRI) to fund development of the original Stress and Fracture Evaluation of Rotors (SAFER) code as a tool for assessing remaining rotor operating life. The current version, SAFER-PC, uses boresonic inspection data as inputs for assessing remaining rotor life. Accurate, repeatable boresonic data are essential for the rotor assessment process and the decision to run or retire a rotor.

2 BACKGROUND

Catastrophic failures of forged turbine and generator rotors are rare events. The consequences of a catastrophic failure or other unscheduled outage can be costly in terms of repair, collateral damage, and lost electric generation revenue. The catastrophic failure of the Tennessee Valley Authority's Gallatin 2 intermediate pressure-low pressure rotor in 1974 emphasized the need for boresonic inspection of all large, bored rotor forgings (see Figure 2-1). Ultimately, the Gallatin rotor failure was the genesis of boresonic inspection and rotor analysis for the power generation industry.

Figure 2-1
Segment of Gallatin rotor from catastrophic failure

The Gallatin rotor was forged from an air-melted ingot in the 1950s. Rotors produced in this manner were typically bored to remove nonmetallic inclusions and segregates that congregated along the center axis as a result of the forging process. After a rotor is bored, the tangential stress resulting from centrifugal force is the greatest at its bore surface. Because of the stress concentration at the bore surface, it is essential to identify significant near-bore flaws in the forging. A boresonic inspection is critical for detection of near-bore inclusions and cracks.

Modern forging techniques enable the production of extremely high-quality rotor forgings. The absence of nonmetallic inclusions and segregates along the center axis eliminates the need for a central bore and the stresses associated with the central bore surface. For a solid (nonbored) rotor, the maximum tangential stress is in the center of the rotor, and it is considerably less than that of a bored rotor (a typical example would indicate half the stress value) [1].

The failure of the Gallatin rotor started in an area of manganese sulfide inclusions that linked by a creep mechanism to form subsurface cracks lying near the bore. The cracks then propagated by a combined creep and fatigue mechanism until they reached critical size. Brittle cleavage propagation occurred in large steps. The failure occurred during a cold start of the unit [2]. The unit had been in operation for approximately 100,000 hours before failure. The rotor was a chromium-molybdenum-vanadium rotor steel that is similar to the American Society for Testing and Materials (ASTM) A470, Class 8, an alloy commonly used for rotors operating at high temperatures (>900°F [>482°C]). Unfortunately, at the time of manufacture, a preservice boresonic inspection was not required for this class of rotor. The lack of boresonic inspection eliminated any possibility of identifying the large cluster of manganese sulfides near the bore and possible avoidance of the catastrophic failure.

The Gallatin rotor failure spurred requirements for boresonic inspections and analysis for all rotors. EPRI undertook an extensive R&D program, known as the Steam Turbine Rotor Reliability program, on behalf of the electric power industry to address rotor inspection and life-prediction methodologies. The program included tasks to develop a lifetime prediction analysis code, investigate effectiveness of nondestructive inspection methodologies for rotors, correlate destructive analysis of rotor segments with inspection results, and evaluate material mechanical properties measurement.

After the R&D program, the EPRI Nondestructive Evaluation (NDE) Center began a boresonic system evaluation plan to identify the flaw detection, sizing, and repeatability performance of boresonic inspection systems. The evaluations were based on several examinations of a set of bore blocks that were fabricated during the R&D program. The blocks contain a variety of flaw targets close to the bore. The boresonic system evaluation program is described in Section 6.

3
DAMAGE MECHANISMS

Bore holes were originally machined in rotor forgings as a means of removing segregates, inclusions, and other undesirable flaws that accumulated along the rotor axial centerline as a result of the forging process. Boresonic inspection evolved as a method to detect and size any remnant undesirable flaws in the near-bore volume and to monitor crack initiation and growth resulting from material deficiencies in early forged rotors. The initial inspection findings increased concern for other rotors, even those that were deemed to have suitable material properties, and the practice of boresonic inspection was expanded to include most rotors. Refer to the EPRI report *NDE Guidelines for Fossil Power Plants* (TR-108450) for more information [3].

Rotor damage can occur through various combinations of mechanisms including low-cycle fatigue, thermal fatigue, and creep (in high-temperature rotors), resulting in a linkup of preexisting flaws over time. High-temperature rotors can also be susceptible to degradation of material properties by temper embrittlement, resulting in decreased tolerance for cracks with increased operational time.

In the case of older rotors that are used in load-following or peaking duty, there is increased exposure to more start-stop and thermal cycles that are normally associated with low-cycle and thermal fatigue. Creep is a time-dependent, thermally assisted deformation that occurs under constant load. Creep can also produce dimensional changes and microcracking. Local creep processes at inherent flaw locations can accelerate crack initiation and flaw growth, leading to premature failure. For rotors operating at low temperatures (<900°F [<482°C]), creep is not a consideration. Rotors operating at elevated temperatures, such as high-pressure and intermediate-pressure rotors, are susceptible to creep and can potentially fail at constant load as a result of creep damage. Refer to the EPRI report *Rotor Boresonic Inspection Guidelines* (NP-6742-L) for more information [4].

Detecting crack initiation and growth in the radial-axial plane is of primary concern because of the potential for rotor rupture resulting from operative stresses at the rotor bore surface. Failure of a massive rotor operating at relatively high speed results in massive collateral damage because a failed rotor cannot be contained by the internal stationary components and the rotor casing. Detecting radial-circumferential cracking is also important. Typically, this type of cracking begins at the outer body of the rotor and is more likely detected with nondestructive inspection techniques performed on the outer surface. If it is not detected by nondestructive means, this type of cracking can present itself as increased vibration of the rotor during operation, resulting in the unit being shut down for operational reasons before catastrophic failure can occur [3].

4
BORESONIC INSPECTION SYSTEMS

The purpose of a boresonic inspection is to detect, locate, and size near-bore and bore-connected flaws. The flaws can be either inherent from the forging process or service-induced flaws in the rotor material. Examinations are performed to detect radial-axial or radial-circumferential crack-like reflectors originating at or near the rotor bore surface as well as forging defects distributed radially through the first 4–6 in. (10.2–15.2 cm) of the forging. Flaws are detected using a combination of ultrasonic inspection probes that are mounted together in an inspection head and inserted in the rotor bore for scanning.

The two primary types of boresonic inspection systems are the contact and immersion types. The contact system features contact inspection probes that ride on the bore surface and use a couplant to transmit sound from the probe into the rotor. The immersion system requires flooding the bore with conditioned water. Immersion probes are positioned precisely above the bore surface (noncontacting), and the ultrasonic energy is transmitted from the probe through the conditioned water (acting as a couplant) and into the rotor. Both systems have advantages and disadvantages.

Contact Systems

The most common commercial boresonic inspection systems are contact systems. For contact systems, the inspection head maintains contact with the inspection probes on the bore surface; the assembly is rotated circumferentially in the bore and indexed axially along the bore to facilitate complete inspection of the near-bore and bore surface. The head is typically rotated slightly more than 360° in one direction so that there is sufficient scanning overlap of all the probes as the head is indexed and the head rotation is reversed. Reversing the head rotation is necessary to keep the probe cables and couplant lines from becoming twisted to the breaking point.

Some systems use a helical (spiral-shaped) scan pattern. In this mode, the inspection head is rotated in one direction for the entire inspection scan and incrementally indexed during the rotation. Special slip rings for electrical connections and special couplant delivery schemes are necessary to effect a helical scan. A helical scan mode eliminates inspection probe positional errors that potentially exist with scanning in a reversing mode. The helical scan mode is more difficult to implement than the reversing mode, and thus it is less common in commercial boresonic equipment.

The inspection head typically has expandable arms to position the probes against the bore surface. In addition to inspection probes, the head can also accommodate ultrasonic couplant delivery lines. Ultrasonic couplant is necessary to couple (transmit) the sound from the inspection probe into the rotor material. Turbine oil is a typical couplant; other light oils and kerosene are also used. Figure 4-1 shows an example of an inspection head with inspection probes mounted and ultrasonic couplant delivery lines attached.

Figure 4-1
Boresonic system inspection head with contact inspection probes and couplant lines mounted and probe arms expanded to simulate configuration inside the rotor bore

A computer-driven scanner-controller moves the boresonic inspection head through the bore in a predetermined pattern and speed. The rotational speed of the scanning head depends on the diameter of the bore and the pulse repetition rate of the ultrasonic system. Rotational speeds generally range from 0.5 to 10 revolutions per minute, depending on the rotor bore diameter. Larger-diameter bores require more bore surface area to be scanned per revolution. This requires the rotational speed to be decreased to maintain an optimal surface scanning speed for acquisition of data in predetermined intervals along the bore surface. A typical interval could be 0.020–0.030 in. (0.051–0.076 cm); an ultrasonic signal is acquired at each interval. The pulse repetition rate of the system is adjusted to provide ample time between consecutive pulses for the round-trip propagation of the sound wave from the farthest target of interest at the desired scanning rate and data acquisition interval.

The scanner-controller also controls the axial increment of the scanning head as it moves down the bore. The axial increment is typically in the range of 0.030–0.250 in. (0.076–0.635 cm). The axial increment is influenced by several factors, including inspection probe size and customer requirements. The axial increment must allow for sufficient overlap of successive scans to ensure 100% coverage of the inspection area of interest. The scan increment must be smaller than the probe diameter to allow suitable coverage and overlap. A small axial increment provides multiple chances to detect and size near-bore flaws but also significantly increases the number of scans and the time needed to complete the boresonic inspection.

Commercial providers of boresonic inspection services select a scan increment value that provides sufficient overlap to ensure 100% coverage of the near-bore area of interest and allows the boresonic inspection to be completed in a reasonable period. They might also rescan some areas of interest using a smaller scan increment to better evaluate the flaw morphology or verify flaw sizing. Some utility purchasers of commercial boresonic inspection services require that the vendor use a smaller scan increment to allow multiple opportunities to detect and size near-bore flaws. The trade-off is that the inspection can take more time and be more expensive.

Contact systems are highly portable, compact, and easily deployed in the field. Contact systems use focused or unfocused probes for data collection, depending on the service provider. Modern contact inspection probes have good flaw detection and sizing performance.

Immersion Systems

Immersion boresonic inspection systems that use array probes, rather than conventional probes, offer dynamic focusing and the potential for improved flaw detection and sizing performance. Setup of an immersion system is more complicated than that of a contact system. Use of the immersion probes requires flooding the bore with a couplant such as water or oil to provide a sound path to the bore surface.

Couplant water is conditioned to remove bubbles, increase wetting, and mitigate formation of rust on the bore surface. Formation of bubbles in a water or oil couplant will interfere with propagation of the ultrasonic energy and adversely affect the inspection. The couplant level in the bore is maintained by using seals at the bore opening or by plugging one end of the bore and attaching a trough at the entry end of the bore. The level of couplant in the trough is maintained at a level higher than the largest bore diameter to mitigate introduction of air.

The immersion probes are noncontacting. The scanning head precisely positions the probes at a fixed distance from the bore surface. The scanning head incorporates spacers or rollers that ride on the bore surface and maintain a fixed position of the immersion probes from the bore surface.

Figure 4-2—from the EPRI report *Duke Power Compact PHOCUS Boresonic System Evaluation* (TR-103342)—shows the configuration of an inspection probe head that was used on an early immersion boresonic inspection system [5].

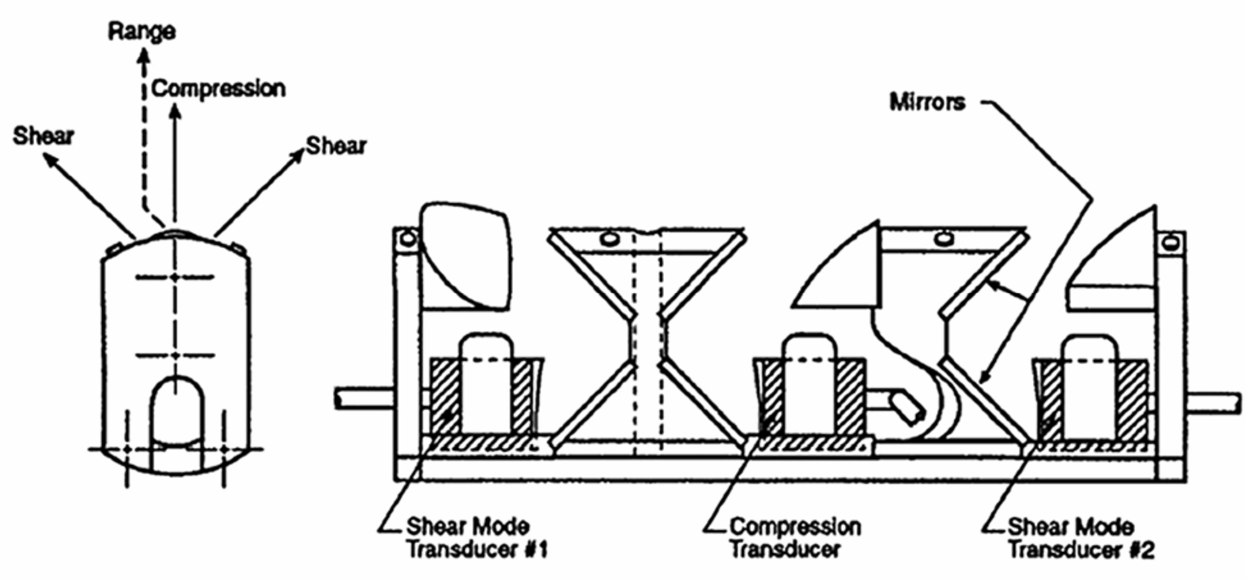

Figure 4-2
Configuration of inspection probe head used on an early immersion boresonic inspection system

The immersion inspection probe head is moved down the bore in a similar fashion as the conventional contact system. Probe head rotational speed, data collection intervals, and axial index values for the immersion system are determined based on inspection requirements and system capabilities.

The inspection head in Figure 4-2 uses annular array probes that are dynamically focused through several depth zones to cover the first 4 in. (10.2 cm) of the near-bore material. The pulse repetition is set at a constant rate to allow data acquisition for multiple focal-depth zones. The rotational speed of the inspection head is varied, depending on bore size, to maintain a constant surface scanning speed.

For this system, the rotational speed varies from 3 to 15 revolutions per minute, and data are collected every 0.020 in. (0.051 cm) of circumferential travel. The axial index is approximately 0.025 in. (0.0635 cm) to allow for overlap of the finely focused probe beam. Typically, immersion inspections take longer than contact inspections because of the additional setup complexity and the small scan increment that must be used with the small, focused beam of the immersion probes.

Inspection Probes

Boresonic inspections concentrate on the volumetric area from the bore surface to a depth of typically 4 in. (10.2 cm), or 6 in. (15.2 cm) in some systems, measured in the radial direction. The primary stresses are concentrated on the bore surface and decrease with increasing distance from the bore surface. Consequently, the near-bore volume of material is of primary interest.

Inspection probes used in contact systems are fitted with a shoe or wedge that passes the ultrasonic energy at the prescribed inspection angle. To detect a radial-axial flaw, the ultrasonic beam is directed at the major dimension of the radial-axial target. This requires an ultrasonic beam that is subsurface and tangent to the bore. For radial-axial planar flaws, much of the ultrasonic energy is reflected away from the transmitting probe. However, energy reflected from facets of the planar flaw is generally sufficient for detection and sizing purposes. The probe wedge is also contoured to fit the curvature of the bore surface.

The inspection probes are most often operated in a pulse-echo mode in which the ultrasonic wave is transmitted and received by the same probe. The boresonic inspection head can carry several inspection probes to examine the area of interest. A typical configuration is designed to detect radial-axial, radial-circumferential, and volumetric flaws. Clockwise and counterclockwise tangential shear wave probes detect radial-axial oriented flaws. A typical inspection angle is 45°; some systems also include 60° probes. Axial forward- and reverse-looking shear wave probes detect radial-circumferential flaws using an inspection angle of 45°. Radial-aim longitudinal wave (0°) probes are used to detect volumetric flaws.

Contact systems use either conventional ultrasonic probes or array probes. Conventional ultrasonic probes have a single element transducer and a fixed focal zone. As the ultrasonic wave travels through the rotor material beyond the focal zone, the wave becomes divergent and less intense with increasing distance. Deeper flaws become more difficult to detect and size.

Array probes contain several independent transducer elements (arrays), and each element is driven by its own pulser. The pulsers for the various array elements are sequentially fired at precise intervals so that the ultrasonic waves from each element arrive in phase at a given point in the material being examined. This point can be steered to different depths within the material by selectively varying the elements used, the pulse sequence, or the phasing intervals.

Array probes used in contact systems can be controlled to provide depth focusing in the radial direction. Focusing optimizes the ultrasonic beam for a finite range of depth. The array probe can provide multiple focal zones, thus eliminating the need for multiple fixed-focus probes to cover the same area of interest. Because inherent flaws can grow and link, the ability to distinguish between active and benign flaws is desirable. The ability to resolve small reflectors lying in close proximity to one another, as opposed to identifying the cluster as a single large flaw, is also desirable. Focusing can improve flaw detection and sizing as well as resolution of multiple flaws in close proximity.

Immersion probes enable the implementation of fairly simple focusing techniques using acoustic lenses and mirrors to redirect the ultrasonic beam and correct for bore curvature. Immersion array probes have multiple elements that can be electronically controlled to vary the focal depth and provide multiple focal zones. Focusing can improve flaw detection and sizing as well as resolution of multiple flaws in close proximity.

The immersion inspection head in Figure 4-2 contains three probes: a radial-aim longitudinal wave probe, a clockwise shear wave probe, and a counterclockwise shear wave probe. The longitudinal wave probe is used for detection of deep-seated flaws. The shear wave probes are used for detection of radial-axial flaws in the near-bore region [5]. Array probes used in immersion systems provide the same advantages as those used in contact systems.

Calibration

Calibration of a boresonic inspection system is necessary to set system sensitivity and to verify that the system can accurately measure the distance to targets of interest (flaw depth) over a set range. A calibration block is used to check these functions. Artificial targets in the calibration block are scanned with the ultrasonic probes to set the system sensitivity. The sensitivity is optimized to detect targets of interest over a predetermined range of depth. The distance calibration allows accurate depth location and sizing of detected flaws.

Calibration blocks are fabricated from material that is similar to rotor material in metallurgical structure and composition. Calibration blocks are built to match a certain rotor bore size or a range of bore sizes. A calibration block has a central bore hole of a similar diameter as the rotor bore to be inspected. Side-drilled or flat-bottomed holes (or both) are located around the perimeter of the bore hole at various radial depths from the bore hole (see Figure 4-3). The boresonic system inspection head is inserted into the bore of the calibration block. Each inspection probe is rotated and positioned until an optimized reflection from each calibration hole is obtained, and the system sensitivity is set to a predetermined level. An automated scan of the calibration block is made. The resultant data are evaluated to verify the accuracy of depth measurements to the calibration holes and to verify system sensitivity.

Figure 4-3
Boresonic calibration block with side-drilled holes at varying distances from the bore surface

Boresonic inspection procedures require periodic calibration checks to verify the inspection system performance. As a minimum, the system calibration must be verified at the conclusion of the boresonic inspection to determine that the sensitivity and depth measurement values are within allowable tolerances. Procedures might also require rechecking the calibration at the beginning of each work shift, with a change of boresonic system operator, or when inspection probes or probe wedges (in a contact system) are changed. If the calibration values are found to be out of tolerance, all the data collected after the most recent calibration check are discarded. The boresonic inspection system is then recalibrated and the appropriate areas are reinspected. The calibration of the inspection system is checked again after those activities.

Boresonic inspection is an effective method to detect and size flaws in the near-bore region. Other surface inspection techniques are used to better characterize flaws on the bore surface. These techniques include visual inspection, magnetic particle inspection, and eddy current inspection. Visual inspection precedes the boresonic inspection and uses borescopic equipment to look along the entire length of the bore surface. This inspection is conducted before surface preparation of the bore to record the as-found condition of the bore. Typical findings include oxide, pits, scale, scratches, and more serious flaws such as cracks. Record is also made of the locations of bottle bores and any grind-out areas where surface connected flaws have been removed. This inspection is repeated after the bore surface preparation to record any additional flaws that were exposed and to confirm adequacy of the surface preparations.

A magnetic particle inspection or eddy current inspection of the bore is performed to identify surface flaws along the bore. Bore magnetic particle inspection is performed using a central conductor running the full length of the bore. In the case of a blind bore, the central conductor is in contact with the end of the bore. Bore magnetic particle inspection is conducted using the wet, visible method with the particles in a suspension of kerosene or another suitable carrier. The magnetic particle suspension is applied during application of the magnetizing current. The magnetizing current is turned off, the central conductor is removed, and a borescope is inserted into the bore. The residual magnetic field is sufficient to hold the magnetic particles to surface flaws for viewing with the borescope. The location and size of surface flaws are recorded.

The application of the magnetic particle suspension results in a puddle being formed in the bottom of the bore, masking indications in that area. To view that area, the rotor is rolled 180° and the test is repeated. The recorded magnetic particle inspection flaws are combined with the boresonic inspection data to determine associations of indications that should be linked because of their proximity. The principal limitation of the magnetic particle inspection of the bore is in the lack of precision that can be achieved in reporting flaw locations. Comparisons with boresonic data are sometimes limited as a result of the imprecision of the magnetic particle inspection data. This can result in associations from the two inspections being overstated or understated [6].

An alternative to magnetic particle inspection is eddy current inspection. Eddy current inspection is normally conducted concurrently with the boresonic inspection. The eddy current probes can be mounted on the boresonic probe inspection head. This arrangement ensures that the eddy current data and boresonic data can be directly compared because they are using identical positional data. Eddy current inspection also provides a permanent digital record of the surface inspection results [6].

Bore Preparation

In preparation for bore inspection, the rotor is set in a horizontal or nearly horizontal position. Sufficient space at one end of the rotor is required to accommodate bore surface preparation equipment and bore inspection equipment. Bore plugs seal the bore and are installed with an interference fit. The bore plugs are removed to allow access to the bore for inspection.

After the bore plugs are removed, the bore is cleaned in preparation for the first visual inspection. The bore is honed to remove oxide, pits, scale, and scratches. Honing equipment varies in size and complexity. Small portable hones remove a minimal amount of rotor material and are usually sufficient for preparation of the rotor surface for boresonic inspection. Large power hones can remove material at a much faster rate, but they generally take longer to set up and are more costly to transport. After the bore surface is prepared, the bore inspection can begin. Bore diameter dimensional measurements are also made along the length of the bore. After the bore inspections, the bore is cleaned and new bore plugs are installed. Figure 4-4 shows the rotating head of the honing device, with honing stones attached, before it is inserted into the rotor bore [6].

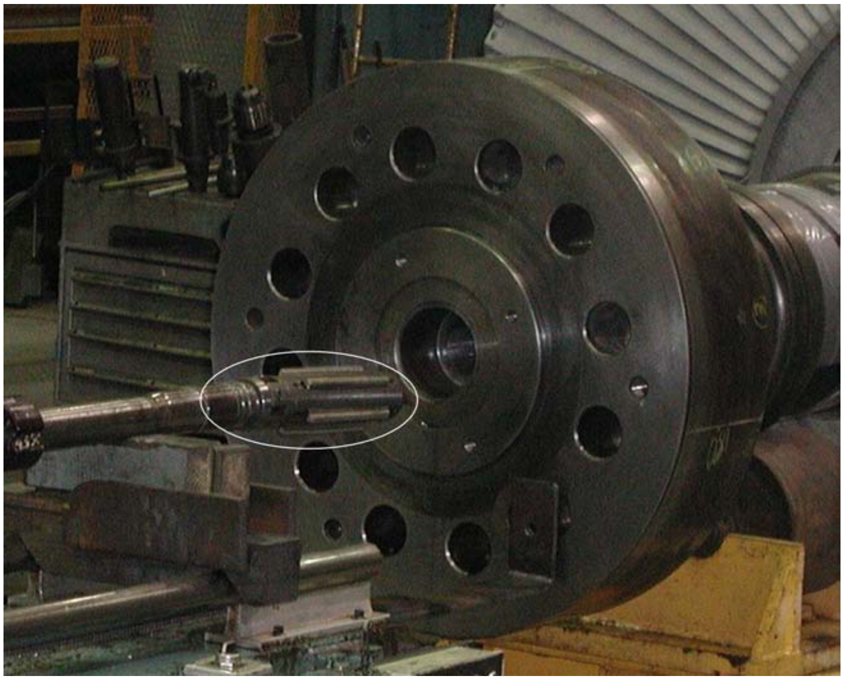

Figure 4-4
Rotating head of honing device with honing stones installed

5 BORESONIC DATA ANALYSIS

The purpose of boresonic inspections is to detect, locate, and size near-bore and bore-connected flaws. The flaws can be inherent forging defects or flaws that have propagated in service. The boresonic inspection data are used in the rotor analysis process to determine remaining rotor life. Rotor life assessment is a multidisciplinary process involving flaw characterization using inspection data, determination of material properties, analysis of mechanical and thermal stresses, consideration of duty cycle, and a fracture mechanics assessment. Permissible flaw size varies for different rotors, depending on the rotor design, size, operating speed, start-up conditions, operating temperature, and material properties. Permissible flaw size also varies for different locations along the rotor. Stresses vary dramatically with distance from the bore and axial location along the rotor. Age is also an influence because of accumulated stress cycles and potential material property degradation. Accuracy of the boresonic data can influence the rotor life assessment.

OEMs and commercial inspection vendors offer rotor analysis services to evaluate remaining rotor life. Typically, an analysis program processes the boresonic data and uses those data with other rotor data to provide a remaining life assessment.

The EPRI SAFER-PC software evaluates the remaining life of steam turbine and generator rotors as described in the EPRI report *SAFER-PC, Stress and Fracture Evaluation of Rotors—Personal Computer, Version 2.2* (1013044) [7]. The software combines thermal-elastic finite-element stress analysis, fracture mechanics, material property data, and the clustering and linking of surface defects identified by nondestructive examination data to assess remaining rotor life. SAFER-PC can also perform probabilistic analysis of remaining life and material creep, and it allows importing boresonic data in any format to generate a flaw file [7].

The flaw linkup algorithm analysis determines whether individual neighboring volumetric indications (flaws) should be considered as one larger defect for the purpose of calculating remaining life. The default setting of the procedure that performs this determination in SAFER-PC has been shown to provide conservative results—that is, it overestimates the size of linkup defects. The linkup evaluation depends on the quality of the boresonic data provided. A conservative linkup analysis is appropriate if there is low confidence in the boresonic data or if the performance of the boresonic system has not been evaluated. However, tools (parameter options) are provided that allow personnel to reduce the safety factor applied in any given calculation in order to reduce the conservatism of the analysis. SAFER-PC also allows personnel to define arbitrary flaws, independent of the boresonic data, as a way to parametrically assess remaining rotor life. Either spherical or nonspherical data can be linked. The data from boresonic systems that provide flaw sizing based on effective flat-bottom-hole diameter are referred to as *spherical data*. The data from boresonic systems that are provided in tabular form typically result in the flaws being characterized as elliptical; these data are referred to as *nonspherical data*. SAFER-PC linkup evaluations can be performed deterministically or probabilistically (spherical data only). In deterministic linking, the defect sizes, stress, and temperature conditions are treated as known, nonrandom variables. In probabilistic linkup calculations, defect size, stress, and temperature are treated as random variables in a Monte Carlo solution procedure with user-specified mean values and standard deviations [7].

6
EPRI BORESONIC SYSTEM EVALUATION PROGRAM

Determining the structural integrity of a turbine or generator rotor is a crucial element in determining the remaining life of the component. Boresonic inspection has become a standard accepted by the utility industry to provide needed flaw information. The techniques, however, are not regulated, and there are no standard practices and procedures for obtaining the flaw information. EPRI recognized this problem in the early 1980s and developed a system evaluation program to assist utilities in making technical decisions concerning available boresonic practices. In addition to evaluating flaw information, the resulting performance statistics can be used to quantify flaw detection and sizing accuracy for probabilistic analysis. In the first series of evaluations, the inspection organization conducted multiple scans of the boresonic evaluation blocks and then provided the collected flaw data to EPRI staff to determine flaw detection and sizing performance.

In 1990, the procedure used for previous boresonic performance demonstrations was reviewed. This review was precipitated by two factors. First, a reduction of funding for such activities by EPRI transferred much of the financial burden to the participating vendors and made it extremely expensive for the inspection vendors to demonstrate their test system capabilities. Second, the reflector sizing procedures used by the EPRI NDE Center for earlier evaluations were considered inappropriate in some cases in which alternative evaluation procedures had been developed and implemented by various vendors.

The sizing approach used by the EPRI NDE Center was based on a hit envelope. Although this approach was applicable for evaluating earlier systems (because many early systems used this technique), it was not considered suitable for the newer systems that used echodynamics, statistical approaches, and other methods to estimate size.

Although these considerations were included in the reappraisal, it was obvious that the best way to factor the effects of system-specific sizing algorithms into the performance demonstration and to reduce the cost of an appraisal was to permit the vendors to do more of the costly data evaluation and sizing steps. With this in mind, a new performance demonstration plan was developed and implemented. Steps were included in the plan to ensure that vendor data evaluation and sizing were done in a manner that did not compromise the confidentiality of the blocks or the integrity of the results. The security of the blocks was accomplished through a system of strategically placed seals at locations where the fixture that houses the blocks is coupled together. When the test fixture was returned to EPRI, any sign that the seals had been tampered with or that supplemental bore examinations (for example, dye penetrant or magnetic particle inspections) had been conducted invalidated the examination.

Another major cost-reduction step involved the data reduction portion of an evaluation. The evaluation of the data to determine detection performance and flaw size locations, which was previously performed by EPRI staff, would now be performed by the vendor. This was a major change in procedure because it effectively made the vendor's data evaluation a determining parameter in the total evaluation of the system. This change was made not only to reduce cost but also for technical reasons. The adequacy of the size estimates made by the EPRI staff for earlier evaluations was demonstrated, but these size estimates were considered appropriate only for systems that used a hit envelope approach to sizing. As new testing and sizing philosophies emerged, it became increasingly difficult to provide identical analyses to those performed by the vendor. The logical choice was to transfer this function to the vendor because the sizing function would be performed in a rotor analysis.

To validate the sizing analysis performed by the vendor, the new evaluation plan required that a complete set of all raw data be sent to EPRI immediately at the conclusion of the data acquisition phase of an evaluation. In addition, the vendor was required to either describe the data reduction methodology or submit the algorithms. EPRI staff performed the following validation tasks:

- Coordinate the overall program for each vendor, including the following:
  - Identify the locations in the blocks where the vendor should perform evaluations
  - Perform the statistical analysis of the evaluation
  - Write the final report
- Determine case by case whether it was possible to reduce the total number of scans that a vendor must perform to complete a performance demonstration (the recommendation is 25 scans; however, as few as 15 scans have been performed during several evaluations)
- Spot-check the detection and sizing results for accuracy

The Bore Blocks

All the experimental measurements in the evaluation are performed using nine bore blocks that were fabricated at the Battelle Columbus Laboratory and the EPRI NDE Center. Blocks 1–8 were fabricated as part of the R&D program that began after the Gallatin rotor failure in 1974. Block 9 was fabricated at the NDE Center in 1988 as part of another project, and it was added to the original blocks for future evaluations. The blocks were made from chromium-molybdenum-vanadium material taken from a retired rotor. After flaws were fabricated in segments of the rotor material, the segments were bonded together using hot isostatic pressing and machined to form blocks with 4-in. (10.2-cm) diameter bore holes.

Blocks 1–8 contain surface-connected fatigue cracks, subsurface glass beads, and subsurface disk-shaped reflectors lying in radial-axial planes. Block 9 contains the same types of defects as those in blocks 1–8, except that it has no surface-connected fatigue cracks and the flaws are positioned more deeply (further from the bore surface) in the material. Tables 6-1 and 6-2 list the sizes and location ranges of the reflectors in blocks 1–8 and block 9, respectively.

Table 6-1
Flaw sizes and locations in blocks 1–8

Flaw Type	Size Range (in.)	Size Range (cm)	Distance from Bore (in.)	Distance from Bore (cm)
Surface-connected fatigue cracks	Radial depth ~0.060 to 0.300	Radial depth ~0.1524 to ~0.7620	Bore-connected	Bore-connected
	Axial length ~0.250 to ~1.250	Axial length ~0.6350 to ~3.175		
Embedded disks	Diameter 0.062 to 0.375	Diameter 0.1575 to 0.9525	0.0 to ~0.200	0.0 to ~0.508
Embedded beads	Diameter 0.062 to 0.212	Diameter 0.1575 to 0.5385	0.0 to ~0.200	0.0 to ~0.508

Table 6-2
Flaw sizes and locations in block 9

Flaw Type	Diameter (in.)	Diameter (cm)	Distance from Bore (in.)	Distance from Bore (cm)
Embedded disks	0.125	0.3175	1 to 2	2.54 to 5.08
Embedded beads	0.062 to 0.125	0.1575 to 0.3175	0.500 to 4	1.27 to 10.16

Together, the blocks contain approximately 70 intentional flaws and several naturally occurring defects in the parent rotor material and at the segment bond lines. In an evaluation, the participating vendor is asked to evaluate some of the naturally occurring flaws and some areas having no apparent flaws in order to protect the confidentiality of the blocks. However, only the intentional defects are used in the statistical analysis.

The nine blocks are clamped together in a fixture to form a continuous bore. The fixture (see Figure 6-1) was designed, fabricated, and donated to the EPRI NDE Center by Carolina Power & Light. A flange on the reference end of the fixture simulates the coupling of a rotor and provides an adapter as an interface between the mechanism and the fixture. With lead-in adapters in both ends of the blocks, the flange plate, and the blocks themselves, the fixture forms a test piece with a continuous bore that is approximately 45 in. (114 cm) long.

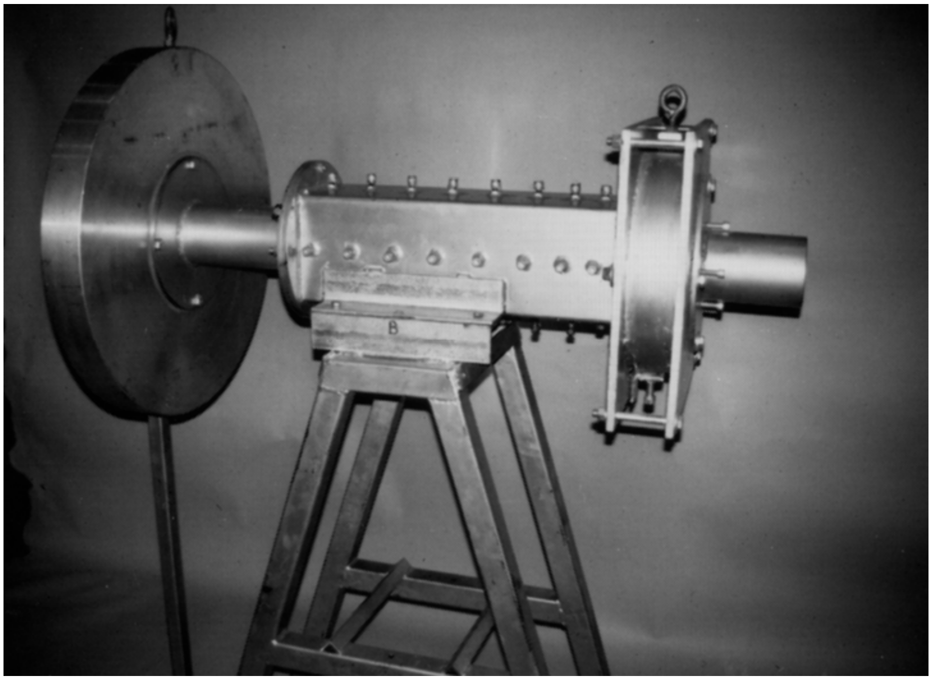

Figure 6-1
Continuous bore fixture for flaw blocks

The blocks and the fixture that houses them are transported to the inspection vendor's facilities for data collection using their boresonic system. A total of 25 scans are made through the blocks to provide a statistically significant amount of flaw detection and sizing data for analysis.

During the preliminary evaluation, the inspection vendor is permitted to practice on two of the blocks (a routine procedure that is provided to all participants). After the practice session is completed, the blocks are returned to EPRI for installation in the bore block fixture. The fixture is then shipped to the inspection vendor for collection of data over 25 data acquisition runs. When the data collection phase is completed, EPRI staff identifies approximately 70 locations in the nine blocks for evaluation. The inspection vendor's staff provides length and depth sizing data for each detected target. The inspection vendor also provides electronic files of the collected inspection data. The inspection vendor's personnel have no knowledge of the true flaw locations or sizes during the examination of the blocks.

Data Analysis Method

The inspection data provided by the inspection vendor are statistically analyzed. The mean value and standard deviation for all scans are computed for each dimension included in the study for approximately 70 flaws. A linear least squares fit of all the data for each measured dimension for each type is then used to determine the best fit of the measured values versus the true dimension.

The linear best fit is represented by the slope, intercept, correlation coefficient, and root-mean-square error. The slope and intercept are indications of systematic error. The correlation coefficient is a measure of the strength of the linear relationship between the true and indicated values. The standard deviation indicates the spread or dispersion associated with the measured data, and the rms error indicates the closeness of the experimental data to the estimated true values averaged over all measurements. Ideally, the fit line has a slope of 1 and an intercept of 0; the standard deviation and the root-mean-square error are 0, and the correlation coefficient is 1.

Even with perfect correlation, system errors might be present because the correlation is a measure of how well the fit line represents that data, not how well the data represent reality. Systematic errors, however, contribute to the rms error and yield a nonzero intercept or nonunity slope or both. The true size values for the flaws were determined by special nondestructive means; therefore, they might have an error associated with them. Even though the error is considered relatively small, the exact magnitude of the error is not known, and no correction for the error has been made in the calculations. Therefore, the calculated root-mean-square error can be slightly inaccurate because of the error associated with the true values. The formulas used for determining the various parameters are shown in Equations 6-1 through 6-6.

$$\rho = \frac{\sum (x-\bar{x})(y-\bar{y})}{\mathrm{N}\sigma_x \sigma_y}$$

Equation 6-1
Correlation coefficient

$$\bar{x} = \frac{\sum x}{\mathrm{N}}$$

Equation 6-2
Mean

$$m = \frac{\dfrac{\sum x \sum y}{\mathrm{N}} - \sum xy}{\dfrac{\left(\sum x\right)^2}{\mathrm{N}} - \sum x^2}$$

Equation 6-3
Slope

$$\sigma_y = \left[\frac{\sum (y-\bar{y})^2}{\mathrm{N}}\right]^{1/2}$$

Equation 6-4
Sample standard deviation

$$b = \bar{y} - m\bar{x}$$

Equation 6-5
Intercept

$$rms = \left[\frac{\sum (x - y)^2}{\mathrm{N}} \right]^{1/2}$$

Equation 6-6
Root-mean-square error

Where:

x	is the true size
N	is the total number of measurements
y	is the measured size
σ_x, σ_y	are the standard deviations
ρ	is the correlation coefficient
$\bar{x}$, $\bar{y}$	are the means

The resultant evaluation report provides flaw sizing and detection performance for surface-connected fatigue cracks, subsurface spherical flaws (beads), and simulated subsurface cracks (disks). A linear regression plot for sizing of each flaw type is included. Values for slope, intercept, correlation coefficient, and root-mean-square error are also provided.

7
EPRI BORESONIC SYSTEM EVALUATION HISTORY

EPRI has sponsored several projects related to improvements in inspection reliability and rotor analysis accuracy. The R&D program that began after the Gallatin rotor failure in 1974 resulted in development of the EPRI report *Steam Turbine Rotor Reliability* (NP-2736) and the initial version of the SAFER-PC life-prediction computer code, which allows utilities to perform their own rotor analyses [8, 7].

That same R&D program also supported the development of a boresonic inspection system called the Turbine Rotor Examination and Evaluation System (TREES), which incorporated focused-beam technology. The interest generated in this program led to a request in 1982 by Duke Power, Carolina Power & Light, and Virginia Power to demonstrate the capabilities of the TREES system. An evaluation of the TREES system was performed at the EPRI NDE Center, using a series of blocks fabricated at the Battelle Columbus Laboratory.

An evaluation of the Bore Ultrasonic Computerized System (BUCS), a contact system, was performed at the same time to enable a direct comparison of the results from an immersion system (TREES) to those acquired with a contact system (BUCS). Each evaluation was based on more than 1500 measurements of known flaws, all lying within 0.50 in. (1.27 cm) of the bore surface, in a series of simulation blocks that were fabricated by hot isostatic pressing. The results, which were published in the EPRI report *Repeatability of TREES Boresonic Inspection System* (NP-2640), document the repeatability and accuracy of detection and sizing of near-bore flaws with the TREES system [9].

In 1985, again at the request of several utilities, the EPRI NDE Center evaluated another boresonic inspection system, the Phased Optics Computerized Ultrasonic System (PHOCUS) developed by Westinghouse Electric Corporation. It also uses immersion focused-beam techniques. The system evaluation was based on measurements of the same block that was used in the TREES study. The results of the evaluation were published in the EPRI report *Evaluation of the Prototype Westinghouse PHOCUS Boresonic System* (NP-4167) [10].

Also in 1985, EPRI evaluated a system built and operated by Public Service Electric and Gas Company (PSE&G) for testing their own rotors. The scope of the evaluation procedure was modified to accommodate PSE&G's specific requirements, and no formal report was published by EPRI on this evaluation.

In 1988, EPRI conducted a performance evaluation of another TREES system, this one built by Southwest Research Institute for Taiwan Power. Taiwan Power included the system evaluation as part of the purchase specification under which the system was built. The results of the evaluation can be found in the EPRI report *Reliability of the Southwest Research Institute TREES Rotor Bore Inspection System* (NP-6513) [11].

The EPRI report *Evaluation of the Commercial Machine Works BorSonic System* (NP-5948) was published in 1988 [12]. It describes the evaluation of a contact boresonic system developed by Commercial Machine Works. The system, including technology, hardware, and patent rights, was later acquired by Westinghouse, and has since been retired. It was the last system to be evaluated before the boresonic evaluation plan was revised.

In the early 1990s, a new test block was added to the fixture. The original eight blocks were designed to evaluate test system capability in the near-bore surface region. The new block was designed to evaluate system capability in the region from 0.500 to 4 in. (1.27 to 10.2 cm). The new block was developed in much the same way that the original eight blocks were made [13]. To accommodate the ninth block, a new evaluation program was instituted. The first systems to be evaluated with the new procedure and test block were owned by Northeast Inspection Services, Inc., and NEI Parsons, Ltd. The Northeast Inspection Services system was the Automated Computer Controlled Ultrasonic Recording Apparatus (ACCURA), and the NEI Parsons system was the Parsons Rotor Inspection and Evaluation System (PRIES). Both systems were contact systems. The results of these evaluations were published in the EPRI reports *Northeast Inspection Services, Inc. Boresonic System Evaluation* (TR-102256) and *NEI Parsons, Ltd. Boresonic System Evaluation* (TR-102126) [14, 15].

In 1994, a second evaluation of the PHOCUS system was performed. This system, owned and operated by Duke Power Company, was an updated and improved version of the Westinghouse PHOCUS system that was evaluated in 1985. The results of the evaluation are described in the EPRI report *Duke Power Compact PHOCUS Boresonic System Evaluation* (TR-103342) [5]. The system has since been retired.

Also in 1994, the EPRI report *Boresonic System Performance Guide* (TR-104355) was published [16]. It provided a comparison of all systems evaluated before that date.

In 1996, the EPRI report *WesDyne International UDRPS Boresonic System Evaluation* (TR-106234) was published [17]. It contains the evaluation results of the Ultrasonic Data Recording and Processing System (UDRPS), which was developed by Dynacon Systems, Inc., and is owned and operated by WesDyne International, Inc.

In 1997, two system evaluations were completed. The EPRI reports *General Electric Company Boresonic Inspection System Evaluation* (TR-107174) and *Reinhart & Associates, Inc. Boresonic Inspection System Evaluation* (TR-108423) provide the evaluation results from the DATAQ RIII boresonic system and the B-SURE boresonic system, respectively [18, 19].

In 2000, Baltimore Gas & Electric evaluated a system they purchased to replace their UDRPS system. The evaluation was performed using an abbreviated format agreed to by both Baltimore Gas & Electric and EPRI. The results were for internal use only.

In 2002, an evaluation of the WesDyne International, Inc., PARAGON system was completed. The system is an updated version of the UDRPS system evaluated in 1996. The system retained the ultrasonic transducer assembly and drive mechanism but made changes to the hardware interface and computer to take advantage of newer technology. Some changes were also made to the processing software; as a result, WesDyne requested that the EPRI NDE Center evaluate the system. The results were published in the EPRI report *WesDyne International PARAGON Boresonic Inspection System Evaluation* (1003084) [20].

In 2006, EPRI evaluated another system and published the results in the EPRI report *Evaluation of the AEA Technology Engineering Services AIS Rotor Bore Ultrasonic Imaging System* (1013284) [21].

In 2008, evaluations of a Siemens and a Sonomatic system have been completed, and the results have been published in the EPRI reports *Siemens SIEBOR Boresonic System Evaluation* (1016306) and *Sonomatic Contact Boresonic Examination System Evaluation* (1016309) [22, 23].

8 CONCLUSIONS

Boresonic inspection systems provide flaw data that are essential inputs for rotor life assessment programs. Boresonic system technology has evolved from early manual inspection units using broad-beam inspection probes to computer-controlled systems with variable-focus probes and automated data collection. Boresonic inspection systems are capable of identifying inherent forging defects as well as flaws that have propagated in service. Evaluation of boresonic inspection systems identifies the flaw detection and sizing performance as well as repeatability of these systems.

The catastrophic failure of the Gallatin rotor in 1974 prompted U.S. utilities to conduct boresonic inspections of their rotor fleets to detect near-bore flaws in order to avoid future catastrophic failures. Because of the stress concentration at the bore surface, it is essential to identify significant near-bore flaws in the forging. This report provides key information regarding boresonic inspection systems as they related to rotor life assessment and avoidance of catastrophic failure. The catastrophic failure of the Gallatin rotor was the impetus to inspect the fleet of bored rotors. The evolution of boresonic inspection systems and rotor life assessment software programs have contributed to effective management of the rotor fleet.

9
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