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COLLABORATIVE RESEARCH IN GAS TURBINE COMPONENT RELIABILITY AND QUALITY CHARACTERIZATION

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Abstract

The asset value of natural-gas-fired gas turbines (GT), especially in combined-cycle (CC) plants, is on the rise. But cycling and high-temperature operations can adversely affect GT component life. Life-cycle costs, premature wear, failure risks, and environmental performance are critical issues affecting plant performance, reliability, and cost. Improved operational flexibility can help plants address load demands. At the same time, GT and CC technologies continue to evolve, providing significant efficiency gains and relative improvements in installed cost. Informed decisions about technologies and plant designs are especially important because efficiency, emissions, availability, maintainability, and durability are all key selection factors. The Electric Power Research Institute (EPRI) Combined Cycle Turbomachinery program (Program 79) provides resources to address all aspects of the life management and the operational and maintenance (O&M) improvements of conventional and advanced GTs.

To address growing concerns in the area of quality control, some leading GT owners are implementing more routine part inspections to independently verify adequate quality. Visual, full component dimensional scanning, flow testing, and other advanced techniques such as Process Compensated Resonant Testing (PCRT) can rapidly identify many anomalies, or at least identify outliers prompting a more in-depth review of the serial numbered part quality record. EPRI is consolidating quality inspection results into an EPRI Component Quality Database to cover a broad range of GT models and component design variations.

This paper will summarize three past examples of collaboration between EPRI and electric power utilities. It will also highlight one ongoing activity that addresses assisting GT owners/operators with implementing the use of PCRT to support quality assurance which may reduce the probability of failure and performance degradation.

EPRI Introduction

The objective of the EPRI is to ensure that the institute's research and development programs advance the clean, affordable, safe and reliable production and delivery of electricity for the public benefit. Complex issues require leadership that employs high standards of honesty and integrity. EPRI's Board, Officers and employees are committed to sound principles of corporate governance that continue to support our public benefit mission. To help facilitate the development of the work, EPRI relies on a comprehensive advisory structure. The portfolio of research programs is defined and guided by advisors from both industry and public stakeholders. More than 1,400 leaders and technical experts from the worldwide electricity sector, academia and government help EPRI develop and conduct its research, deliver results, and provide for technology transfer and the application of research findings.

The EPRI Mission and Values are:

- Integrity, we interact and transact with honesty, transparency, fairness and respect. Every action we take is conducted ethically and beyond reproach.
- Objectivity**,** we conduct every aspect of our business free from favoritism, self-interest and bias in judgment.
- Public Benefit, our actions and decisions demonstrate corporate responsibility and ultimately benefit

EPRI Gas Turbine Research Area

Users of natural-gas-powered simple-cycle (SC) and combined-cycle (CC) plants for power generation continue to benefit from the increased worldwide supply of natural gas fuel, the availability of these fuels at lower and stable prices, and the continued environmental pressure to limit the use of coal-based power plants. They will also continue to benefit from the expected limited growth of new nuclear power generation and the ability of natural-gas-powered plants to operate in cycling duty to accommodate the growing deployments of wind and solar power sources in some areas of the grid.

The asset value of natural-gas-fired GT, especially in CC plants, is on the rise. But cycling and high-temperature operations can adversely affect GT component life. Life-cycle costs, premature wear, failure risks, and environmental performance are critical issues affecting plant performance, reliability, and cost. Improved operational flexibility can help plants address load demands. At the same time, GT and CC technologies continue to evolve, providing significant efficiency gains and relative improvements in installed cost. Informed decisions about technologies and plant designs are especially important because efficiency, emissions, availability, maintainability, and durability are all key selection factors.

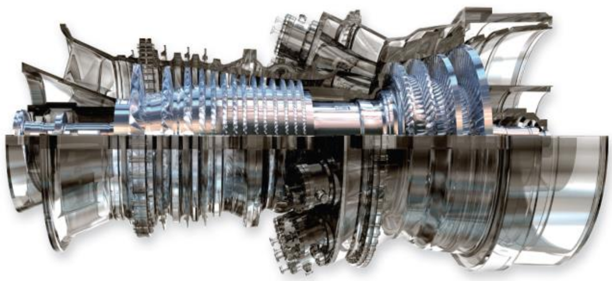


Figure #1: Large Frame GE 7FA.05

EPRI's Combined Cycle Turbomachinery program (Program 79) provides resources to address all aspects of the life management and the operational and maintenance (O&M) improvements of conventional and advanced GTs. It also addresses all aspects of CC plant-wide integration, including specific issues relating to the steam turbine (ST) and generator for CC applications.

Power utility companies that participate in this EPRI program can use the research and development (R&D) to respond to the issues, challenges, and opportunities in integrating and operating CC assets in a rapidly expanding and changing power generation environment; implement specific and detailed engineering analyses in the areas of CC turbomachinery life assessment, risk management, and improved operation and maintenance of current assets; and gain a thorough understanding of the technologies incorporated in the latest GT and ST offerings for improved decision-making in CC project development.

The Program 79 portfolio has two primary technical objectives:

- Provide a holistic approach and perspective on all R&D elements related to integrating all the equipment and systems of a CC plant.
- Address all aspects of managing CC turbomachinery assets, including life assessment, risk management, O&M improvements, and technology advancements.

Recent Gas Turbine R&D Highlights

Potential projects for each subsequent year's R&D are discussed and prioritized with the Program 79 utility member advisors within the third-quarter each year. These potential projects are typically identified during the year by EPRI staff, program members, user group discussions, and at industry events. The number of projects completed each year is based on yearly funding levels, coupled with project prioritization.

The following three (3) projects are recent examples of collaboration between EPRI and an electric power producing utility company. Each project is based on a different section in the GT and/or CC plant.

1. Southern Company Evaluates New Techniques for Diagnostic Monitoring of Gas Turbine Compressors

Southern Company and EPRI teamed together to install and evaluate the effectiveness of new technologies for tracking and quantifying GT compressor damage. The results of this research will assist the utility's GT operators in potentially avoiding or mitigating in-service turbine failures and improving operational flexibility [1-3].

Finding the Sources of Compressor Damage and Failure

EPRI has been investigating the sources of dependability loss in GT compressors, particularly those associated with the widely used 7FA model. Of particular concern to engine owners has been the occurrence of cracks, clashes, rubs, and related damage in rotating blades and stationary vanes. Root cause investigations have often do not identify a single, clear-cut explanation, but rather to a set of probable complex interactive mechanisms that require further investigation.

Figure #2: Damage to compressor section can be very severe

Aerodynamic anomalies such as rotating stall, flutter or incipient surge-flow reversals may manifest themselves at various levels of severity during transients or part-load conditions under certain ambient conditions. Standard compressor instrumentation may be insufficient to adequately detect the onset of such conditions. A number of newer technologies are available for turbomachinery condition monitoring but are unproven for GT compressor application.

Field Testing Advanced Instrumentation and Diagnostics

EPRI initiated a two-year project with Southern Company, the parent company of four electric utilities, to demonstrate the effectiveness of advanced instrumentation and associated diagnostic techniques to detect the onset of adverse compressor operating conditions and early damage indications. The project team installed instrumentation, data acquisition systems and related software on a Southern Company combined-cycle unit.

Advanced monitoring technologies studied in the project included vibration, tip deflection, dynamic pressure and acoustic emissions.

Vibration Monitoring: Bearing vibration measurements have been used on industrial gas turbines for years to aid in overall gas turbine health monitoring. These sensors have been proven to detect issues with the bearings as well as identify mistuned rotors. Recent literature indicates that vibration measurements may be useful for detection of precursors to compressor blade failures in gas turbines.

Tip Deflection: Tip deflection measurement systems have been used to capture the vibration of the blades for different modes of interest as well as monitor the actual displacement over time. Very precise arrival times are measured for each blade-passing event on each sensor. From the measured blade positions, zero values are established, and the deflection is calculated relative to each blade’s measured zero or equilibrium position. For the combined-cycle application, tip deflection sensors were installed circumferentially around the R0 (first stage) of the gas turbine. In all, eight sensors were used, spaced throughout the top half of the case.

Dynamic Pressure: Piezoelectric pressure probes were installed in existing compressor casing access ports used for inspection. The fluctuating pressure spikes that are detected with these probes may be associated with the onset of flow instability. Pockets of low-pressure transients potentially could create conditions in which downstream air foils deflect into upstream components, causing clashing and severe fatigue damage.

Figure #3: PCB probes mounted on outside of compressor casing

Acoustic Emissions: Specialized acoustic emissions (AE) monitoring techniques have been developed for monitoring the initiation and growth of cracks in other power plant components such as piping systems. In this case, AE monitoring was applied to detect vane damage events and progressive damage (crack growth) in an operating compressor. Transducers were located on the outside of the casings to monitor for structure-borne acoustic events associated with internal clashing, rubbing and foreign-object damage.

Performance and Process Analysis: This project also developed mechanisms for collecting GT process data and other performance indicators, because gradual performance degradation in compressors may increase the possible occurrence of aerodynamic anomalies such as stall or surge. IT security protocols were developed to capture the operating state of the engine and to correlate with dynamic pressure and acoustic emissions events.

The project team analysed early data to establish a baseline and set provisional thresholds. Then, over a 24-month period, the team reviewed the data collected from the monitoring instrumentation and the performance/process plant data in order to investigate data anomalies and identify potential or emerging problems.
The demonstration allowed the team to identify techniques to detect damaging compressor-flow instabilities in failure-prone front stages. The project also developed fleet-wide recommendations for specific monitoring instrumentation and related diagnostic techniques.

Information to Avoid Future Failures

Failure of an entry-stage blade and vane can result in equipment damages exceeding $10 million. The knowledge gained through by this project will provide GT operators with information to improve operational flexibility, potentially avoid further in-service failures, assess remedial/corrective actions currently offered, and identify alternative corrective solutions and strategies.

"With the elevated capacity factor of our natural gas combined cycle fleet, the reliability of these assets has become increasingly important," said Josh Barron, research engineer, research and environmental affairs at Southern Company. "Technologies like this will ensure we can maintain high reliability and will give plants an additional level of information needed to make critical decisions."

This knowledge will also assist in understanding operating conditions that contribute to GT compressor failures and maintenance improvements, and fine-tune the EPRI research specific to GT life-cycle cost reductions, failure avoidance and component reliability improvement. Analysis of the results will be incorporated in a series of EPRI design and O&M guidelines that address GT compressor dependability.

2. Duke Energy Increases Life and Reduces O&M Costs of F-Class Gas Turbine Hot-Section Components

Duke Energy has worked with EPRI over several years to conduct durability analysis studies of the hot-section components within the company's advanced high-temperature F-class gas turbine fleet. These studies included advanced computer simulation using aerothermal and structural analysis to better understand temperature and stresses within the hot-section components for different operating profiles. Extensive material testing of service-aged components was then performed to further validate life consumption estimates and establish criteria for safely extending operating intervals. The results of this research are assisting the utility in maximizing the useful life of F-class components, reducing operating and maintenance (O&M) costs, and managing risks [4-7].

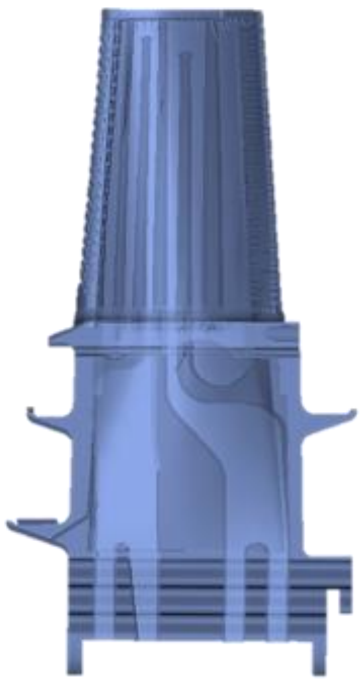


Figure #4: Advanced hot section blades have very sophisticated cooling

Reducing Life-Cycle Costs

Gas turbine hot-section components are complex designs, incorporating superalloys, advanced forced-air cooling schemes, and protective coating systems. Each model type has design-specific features that require specialized knowledge to effectively manage machine O&M. For instance, each turbine model has unique blade designs made of superalloy thin-walled castings requiring complex internal cooling, and oxidation and thermal barrier coatings to survive in a high-temperature environment.

Gas turbine owners routinely inspect, refurbish, and replace combustion parts and the downstream hot-section vanes and blades. The cost of extensive maintenance associated with the gas turbine life-cycle can exceed the initial equipment cost by as much as a factor of three.

Faced with such specialized hardware, gas turbine owners seek to reduce O&M expenses without increasing risk by optimizing all the activities and costs related to the inspect/repair/ replace life cycle. Model-specific, objective knowledge is needed of component design, repair, and degradation mechanisms experienced in the company's own units.

To meet this basic need, EPRI has developed core competencies in hot-section design analysis and repair procedures and applied them to different combustion turbine models. EPRI collaborative projects, supported by the owner/operators of 50- and 60-Hz models, have created an extensive knowledge-base, addressing widely used conventional and advanced engines.
The EPRI model-specific projects aim to optimize the hot-section economic life-cycle at the plant or fleet level according to how the parts inventory is managed. Tools are developed to manage critical aspects of the life cycle, including repair procedures, accumulated damage tracking, and replacement/upgrade procurement guidelines.

Targeted Studies for Duke Energy's Gas Turbine Fleet

Duke Energy maintains an extensive hot-section inventory with annual maintenance costs alone typically reaching several million dollars for its gas turbine fleet. (This does include the cost of new replacement parts, which is a significant part of the savings.) The utility teamed with EPRI to conduct targeted studies aimed developing criteria to maximize the useful life of critical hot-section components and thereby reduce maintenance costs.

Starting in 2009, the EPRI research initially focused on the rotating blades and then expanded to the stationary vanes. The research included analytical modelling of critical component designs, development of quantitative life predictions, and testing of service-aged components to better understand governing damage mechanisms and distress. This knowledge was applied to develop engineering-based life-cycle criteria based on specific machine operational profiles and component design features for the Duke fleet.

Benefits Realized by Duke Energy

Results that directly benefit Duke Energy include:

- Financial savings of tens of millions of dollars over the next 10-15 years

- Increased overall useful life for these components by as much as 50% (basis defined by original equipment manufacturer hot-section useable life criteria)

- Determination of optimal maintenance intervals for hours-based or starts-based engines

- Savings without sacrificing safety, future repairability, or operational reliability

- Path created towards other component extensions in the future (first-stage buckets are being refurbished for extended third interval of operation; second-stage buckets and first-stage nozzles to follow).

3. Endesa Develops Technical Basis for Extending Rotor Life of High-Cycle Gas Turbines

Endesa, the largest electric utility in Spain, organized and led a team, including EPRI and Spanish companies, to develop an independent, condition-based life management approach for the continued safe operation of Endesa's fleet of gas turbines beyond the original equipment manufacturer (OEM) nominal limit for turbine rotors of 5,000 starts.

Turbine manufacturers typically place design life limits on rotors based either on equivalent operating hours or start-stop cycles. While previous GT rotor life extension efforts have focused on hours-based operation, this project with Endesa was the first to challenge the more difficult cycle's limitation. Experience gained from this effort enabled Endesa to extend the useful life of its GTs and helped to further EPRI rotor developments in life analysis, non-destructive evaluation (NDE), and miniature material property testing [8-11].

Figure #5: Endesa GE 6B rotor

Gas Turbine Rotor Life

GT rotor materials are subject to degradation from prolonged hours and multiple start/stop cycles of operation. Only limited inspection of exposed rotor rim areas can be performed during hot gas path and major maintenance intervals when casing covers are removed. For rotor life assessment, a more thorough inspection is often required by the equipment manufacturer, entailing complete disassembly in an off-site shop to qualify the rotor for extended service. This involves disassembly of the compressor and turbine sections of the rotor system and inspection of the components for signs of creep, embrittlement, corrosion, thermal fatigue, and high- and low-cycle fatigue. OEMs typically assist in these inspections and judge whether the rotor is suitable for continued service.

Inspection and retirement practices vary widely among the major equipment suppliers. Sections of the rotor may be deemed non-serviceable after anywhere from 100,000 to 250,000 hours of operation or between 2,500 to 5,000 starts. For high-starts machines, the recommendation often is to retire them without inspection.

Replacement of the rotor or key sections of the rotor can cost from $3 million to $6 million, plus associated production downtime if a spare rotor is unavailable. The engineering basis for rotor operational extension or retirement is unclear, with little field experiential data to establish a quantifiable risk. Owners of GTs, therefore, need objective, model-specific criteria for determining rotor life to guide their inspection and retirement decisions.

EPRI's Rotor Life Project

EPRI's Gas Turbine Rotor Life Project provides GT owners with procedures and technical information to objectively evaluate the condition of their GT rotors. The overall work scope is structured around two major tasks: Rotor Life Inspection and Evaluation Guidelines, and Model-Specific Component Evaluation. Life prediction procedures are developed for the specific rotor design and material, with particular emphasis on rim-blade interface, bolt holes, and center-bores or alternatively welded rotors.

Over the years, the project has assessed a broad range of GT rotors that use a variety of materials and construction, including bolted, welded, and shrunk-fitted systems. This assessment includes component stress analysis and material testing to address cracking in rim attachments and the general structural integrity of engines subjected to high hours and high starts.

The project's center-piece is the Gas Turbine Rotor Life Assessment Guideline, which provides a technical foundation for objectively evaluating the current condition of GT rotors and formulating a basis for timely replacement or continued safe operation. It includes sections on rotor design alloys and properties; rotor damage mechanisms with compressor and turbine section examples; end-of-life criteria and analysis methodologies; in-service material degradation mechanisms; non-destructive testing (NDT); and material sampling, testing, and property correlations.

The Guideline, coupled with the EPRI degraded rotor material database, provides a sound technical foundation which is being further refined in studies on specific models, including the General Electric FA, E/EA, 6B and Frame 5; Siemens V-engines, 501F, and 501B; and Alstom GT24/26. Retired rotor components are being tested to refine degraded material property correlations and qualify small sampling and NDT techniques.

Endesa's Gas Turbine Fleet

Endesa operates a fleet of 18 GE 6B heavy-duty GTs serving isolated islands. The duty of these GTs is cyclic and spinning reserve, which results in several starts per day and few operating hours.

For this joint project, Endesa provided the project team with access to disassembled compressor and turbine rotors, which were then dimensionally scanned and used to develop stress analysis models. A root cause analysis was performed of a turbine disc rabbet crack.

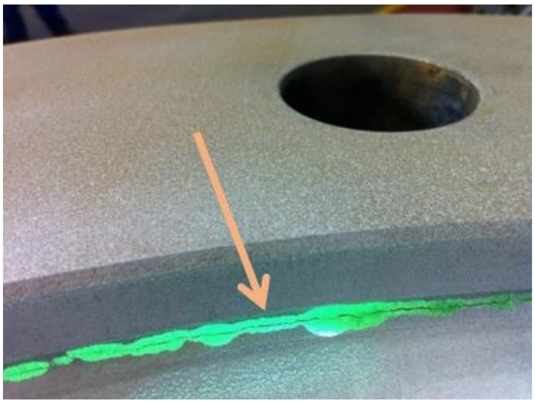


Figure #6: NDT required to detect crack in turbine disc rabbet region prior to de-stacking the rotor

An NDT method was developed to detect the early crack development without rotor de-stacking. This technique was validated with field experience. Material testing was also performed to establish baseline properties and life thresholds.

Application of Life Evaluation Procedures

The findings of this project were very valuable to Endesa, and the life management approach has been implemented across the utility's 6B fleet. Once a rotor exceeds 5,000 starts, NDT is performed at each hot gas- path inspection to ensure the disc rabbet integrity. As result of this evaluation, Endesa has implemented a rotor life extension program which has led to extensions of rotor life limits from 5,000 to 8,000 starts.

The replacement of the installed rotors are based on condition by means of an ultrasonic inspection performed in place without removing and de-stacking the rotor. This NDT is performed on those rotors which have exceeded the OEM limitation set at 5,000 starts. So far, four rotors have been replaced following this new approach, based on rotor condition and extending the rotor life to 8,000 starts.

Gas Turbine Component Quality Characterization

Key Research Question

The general quality of both new and repaired model-specific components has been a perennial concern of GT owners. This universal concern is shared across a range of models from vintage peaking simple cycle GTs to advanced combined cycle units. Consolidation and restructuring across the industry is further impacting GT aftermarket support. The diverse nature of the worldwide manufacturing and repair facility supply chain is contributing to a greater need for quality control and assurance. GT owners ultimately bear the risk of the quality of GT components.

Figure #7: Fully assembles large frame gas turbine rotor

Unlike enforced FAA design and repair quality standards and regulations used on aircraft engines, industrial GTs quality criteria are shrouded by OEM and alternative supplier proprietary standards and processes. Lack of quality standards

transparency and disclosure of part quality nonconformity is a common reality.

EPRI procurement and repair guidelines may help set a quality expectation, but alone are insufficient to address the many quality variants and overriding business dynamics.

To address this growing concern, some leading GT owners are implementing more routine part inspections to independently verify adequate quality. Visual, full component dimensional scanning, flow testing, and other advanced techniques such as Process Compensated Resonant Testing (PCRT) can rapidly identify many anomalous features, or at least, identify outliers prompting a more in-depth review of the serial-numbered part quality record [12-14]. *(For more information on PCRT: Vibrant Corporation, 8330 Washington Pl, NE, Albuquerque, NM)*

Fundamental Principles of PCRT

PCRT is a full body nondestructive evaluation (NDE) method that measures the resonance frequencies of a part and correlates them to the part's material state, structural integrity, or damage state. PCRT combines resonant ultrasound spectroscopy, pattern recognition analysis, and statistical scoring of frequency data to perform pass/fail NDE, process monitoring, life monitoring, and material characterization for commercial and scientific applications.

One of the most critical applications is the evaluation of GT hot section airfoils (buckets/blades) made from nickel-based super-alloys. Prior work on nickel-based super-alloy GT airfoils has shown PCRT capable of measuring shifts in resonance frequency peaks which are correlated with high temperature exposure. Additionally, the NDE potential gained from coupling forward finite element method models of incrementally crept “dog bone” samples to the PCRT measured changes in resonance resulting from creep strain was explored for polycrystalline nickel-based super-alloy dog bones.

Objective

The objective of this project is to assist GT owners and operators with implementing a component characterization process to support quality assurance to help mitigate probability of failure and performance degradation. In support of the objective, EPRI is consolidating quality inspection results into a proprietary component quality database that is unique resource for comparative analyses and trending of a broad range of GT models and component design variations.

Picture #8: PCRT equipment setup in the field

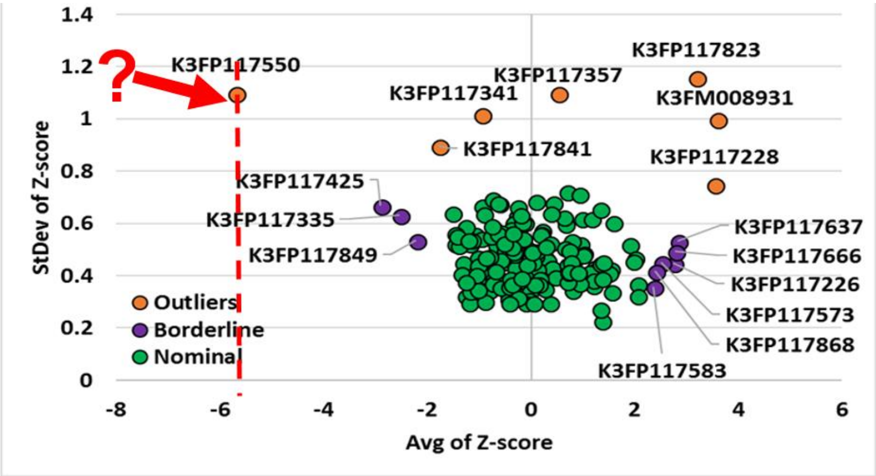
Approach

The work will be conducted in three tasks to support GT component quality characterization. The first task establishes explicit part counts by serial number, critical to quality measurements, and a general implementation plan. A review of critical parts factors will be conducted in engine-specific operational and maintenance histories, unique design features, repair techniques, inventories, and planned outages.

The second task comprises performing GT component inspection and data analyses of the critical parts identified in the first task. Visual and PCRT are typically used as the primary inspection techniques. Component anomalies are further tested to confirm results and narrow down possible causes. Where applicable, established quality standards such dimensional fit tolerances may be used. Additional analysis may be performed to compare inspected parts with similar parts in the EPRI Component Quality Database. A detailed analysis may be performed for specific parts with repeated PCRT inspections to track degradation and repair adequacy.

Picture #9: PCRT scanning device sitting on a hot section blade

The final task comprises the root cause and remedial actions of the PCRT outliers and parts with anomalies that were identified in the second task. For new and repaired parts, the inspection records produced during the manufacturing and refurbishment processes are required for this task, as well as any nonconforming quality reports. The new learning from this task may provide feedback to further the understanding of controlling and improving quality of GT components. The new learning may also improve the EPRI GT procurement and repair guidelines.



Picture #10: Example of PCRT data plot showing extreme outlier part K3FP117550

Research Value

The benefits of this project include early identification of quality issues in new and repaired components before installation into an operating GT, where access is dictated by maintenance intervals from four to ten years depending on duty cycle. Improving component quality provides a general societal benefit by helping to reduce equipment failure risks, and increase the overall reliability.

Additional benefits of this project may include assisting GT owners and operators with implementing a component characterization process to support quality assurance which may reduce the probability of failure and performance degradation.

Summary

The asset value of natural-gas-fired GT, especially in CC plants, is on the rise. But cycling and high-temperature operations can adversely affect GT component life. Life-cycle costs, premature wear, failure risks, and environmental performance are critical issues affecting plant performance, reliability, and cost. Improved operational flexibility can help plants address load demands.

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