Early Experience Applying PCRT to Turbine Blade Quality Assurance

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Gas Turbine Quality

Complex International Supply Chain

6 Sigma Quality Standards

Low Production

Increasing Supplier Deviation Reports

TRUST

New and Innovative Quality?

Quality standards for custom single crystal alloys and additively manufactured parts are trailing

Service/Parts Agreements

Widely Spread and Growing

Risk vs. Quality Balance

BUT…

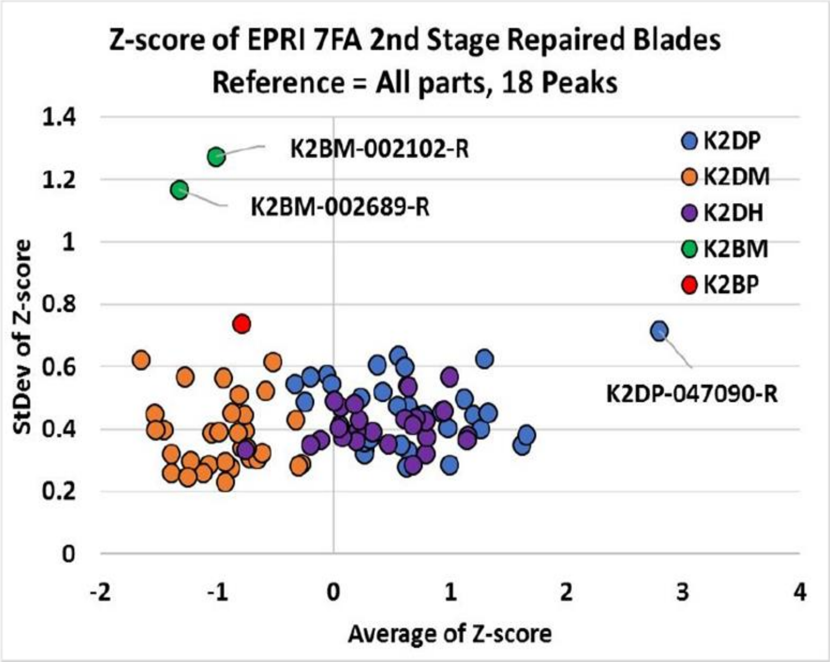
VERIFY

Process Compensated Resonance Testing (PCRT)

Rapid Component Quality Screening

Adopting Quality Verification from Other Industry

- General new and refurbished component quality concerns
- Adapt Process Compensated Resonant Testing used on aircraft engines to industrial gas turbine components
- Test sets of components and material specimens with controlled defects



Turbine Blade Over-Temperature Evaluation

DELTA TechOps

- **Delta Technical Operations**
  - P&W JT8D-219 commercial engines prone to over-temperature incidents
  - PCRT offers increased sensitivity to defects, less engine down time and reduced waste
  - PCRT was added in 2009 for prescreening over-temperature blades
  - FAA approved PCRT in 2010
  - Reduced Engine Inspection Costs by Nearly $2M Annually

Delta Airlines facility manager spoke at EPRI meeting in 2017

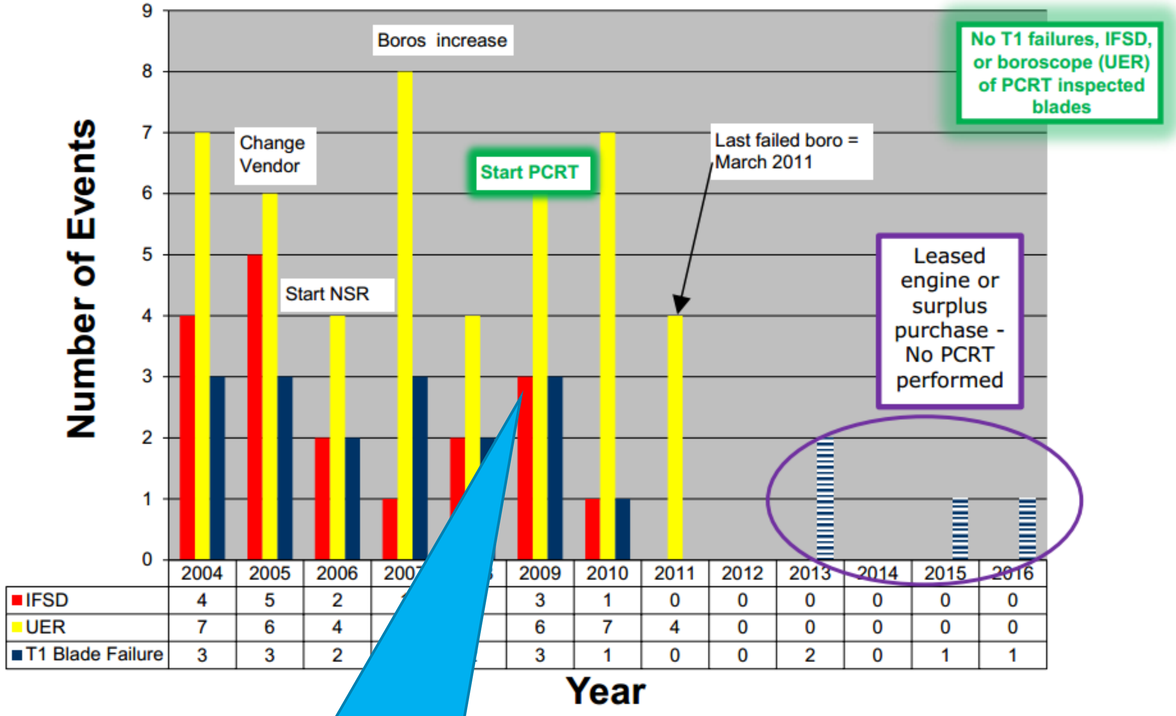
Detecting Aircraft Gas Turbine Blade Anomalies with PCRT

- Targeted anomaly detection trained for:
  - Over temperature
  - Thin Wall
  - Inter-Granular Attack
  - Cracking
- Replaced destructive sample cut-up
- Allowed salvage of previously rejected blades
- Reduced inspection bottleneck

Operational results w/PCRT - Stellar

DELTA TechOps

JT8D T1 Blade Pareto



	2004	2005	2006	2007	[illegible]	2009	2010	2011	2012	2013	2014	2015	2016
IFSD	4	5	2	[illegible]	[illegible]	3	1	0	0	0	0	0	0
UER	7	6	4	[illegible]	[illegible]	6	7	4	0	0	0	0	0
T1 Blade Failure	3	3	2	[illegible]	[illegible]	3	1	0	0	2	0	1	1

PCRT Targeted Defect Sort implemented

Feb 2009

Standards and Approvals for PCRT

ASTM Standard Guide E2001-18 **–** Outlines capabilities and applications of several resonant inspection methods

ASTM Standard Practice E2534-15 **–** Describes auditable method for application of PCRT Targeted Defect Detection inspection

ASTM Standard Practice E3081-16 **–** Describes auditable method for application of PCRT Outlier Screening inspection

Federal Aviation Administration Approved **–** Since July of 2010 for the detection of micro-structural changes indicating over-temp of turbine blades (JT8D-219 HPT)

AS9100D & ISO9001:2015 **–** Certificate #10928 issued by PRI Registrar

PCRT Solutions

- **<u>P</u>**rocess **<u>C</u>**ompensated **<u>R</u>**esonance **<u>T</u>**esting = Using resonance frequency measurements to:
  - Compare a part to a target (qualification) population, assure part consistency
  - Screen for outliers and/or specific defect conditions
  - Correlate to processing variables and/or material properties
  - Evaluate changes in a part, due to critical process operations (HT, HIP, repair, service, etc.) or over the part's life time

Recommended Areas of PCRT Testing for IGT

- Blade types of Advanced F class and above
- Blades undergoing novel repairs
- Blades undergoing extensive/heavy repairs
- Blades undergoing rejuvenation heat treatments
- Blade groups of mixed or unknown prior service histories
- Qualification of new repair service vendor or otherwise inexperienced with the specific component repair

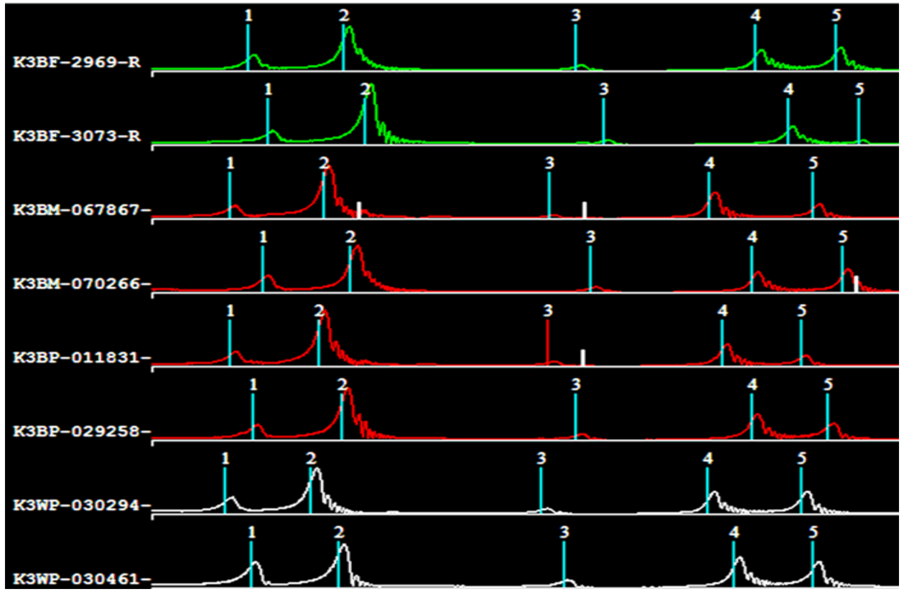
Building an EPRI GT Component Quality Database

- **Building a database**
  - Collect resonance spectrum for each part
  - Group by part type
    - Identify consistent resonance modes
    - Store N frequencies (f) for each part
- **Using the database**
  - Use stored frequencies in statistical analyses
    - Disk characterization
    - Population characterization
  - Collect future part spectra for comparison
    - <u>Part-to-Itself (PTI)</u> analysis to characterize a process such as repair

Example Frequency Database

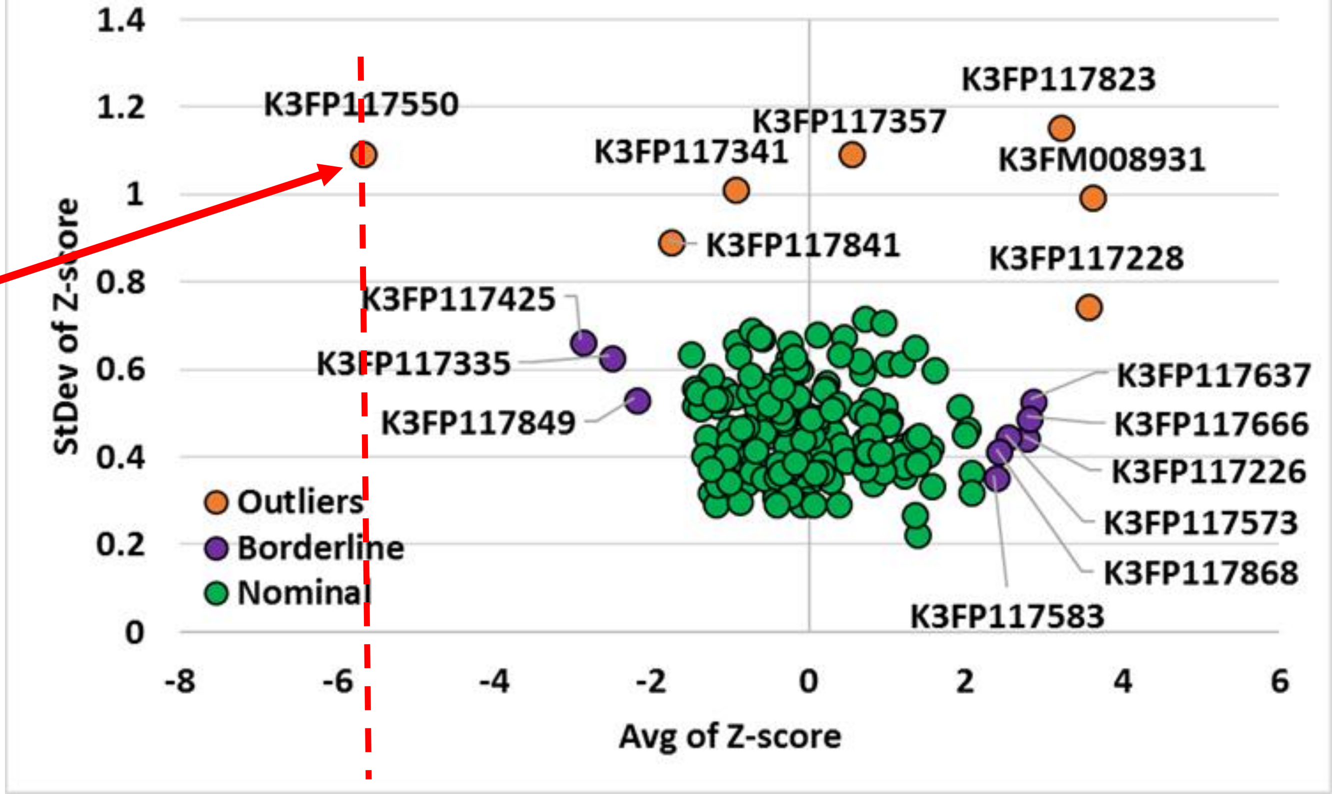
	Mode 1	Mode 2	Mode 3	...	Mode N
Part 1	$f_{1,1}$	$f_{1,2}$	$f_{1,3}$	...	$f_{1,N}$
Part 2	$f_{2,1}$	$f_{2,2}$	$f_{2,3}$	...	$f_{2,N}$
Part 3	$f_{3,1}$	$f_{3,2}$	$f_{3,3}$	...	$f_{3,N}$
⋮	⋮	⋮	⋮	⋱	⋮
Part M	$f_{M,1}$	$f_{M,2}$	$f_{M,3}$	...	$f_{M,N}$

Example Spectra Stack



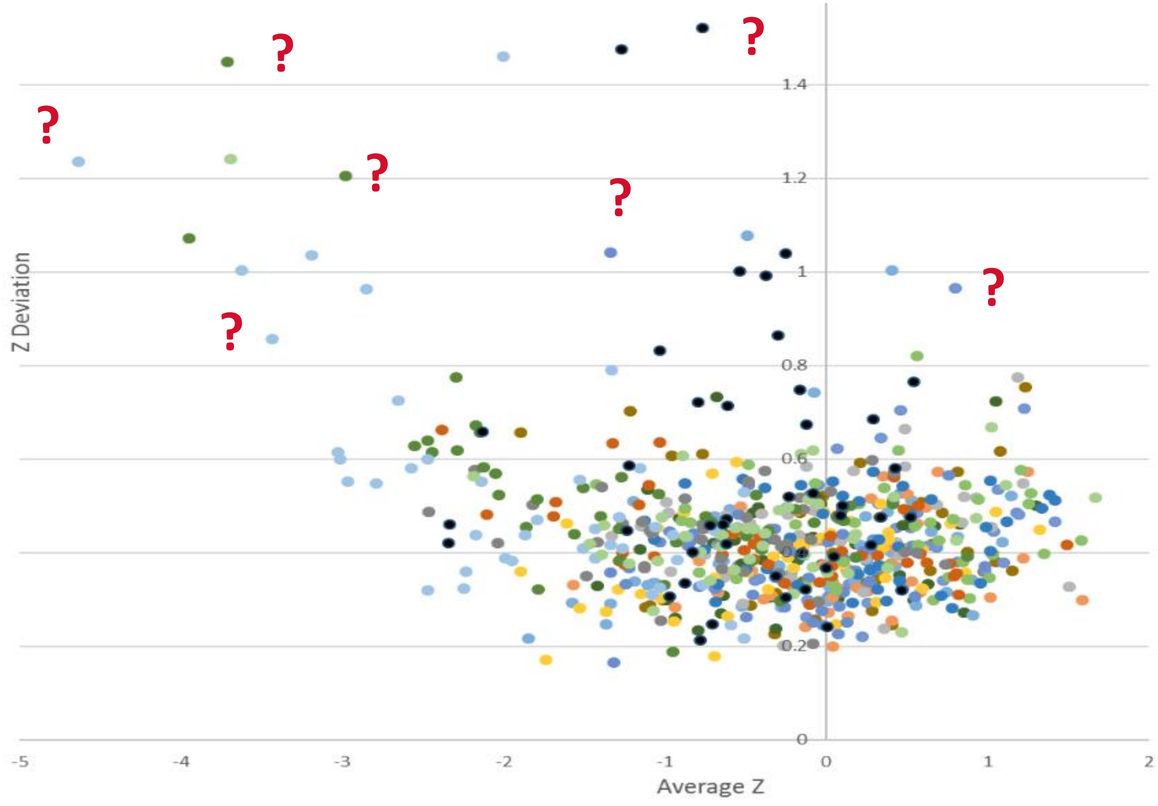
Example: Analysis of New 3rd Stage 7FA.04 Blades

- 184 total blades examined
- 168 nominal parts
  - Cluster exhibits moderate spread → multiple clusters with overlap.
- 7 obvious outliers
  - Part K3FP117550 is a drastic outlier and exhibits a Z-score difference larger than the vast majority of outliers.
- 9 borderline parts

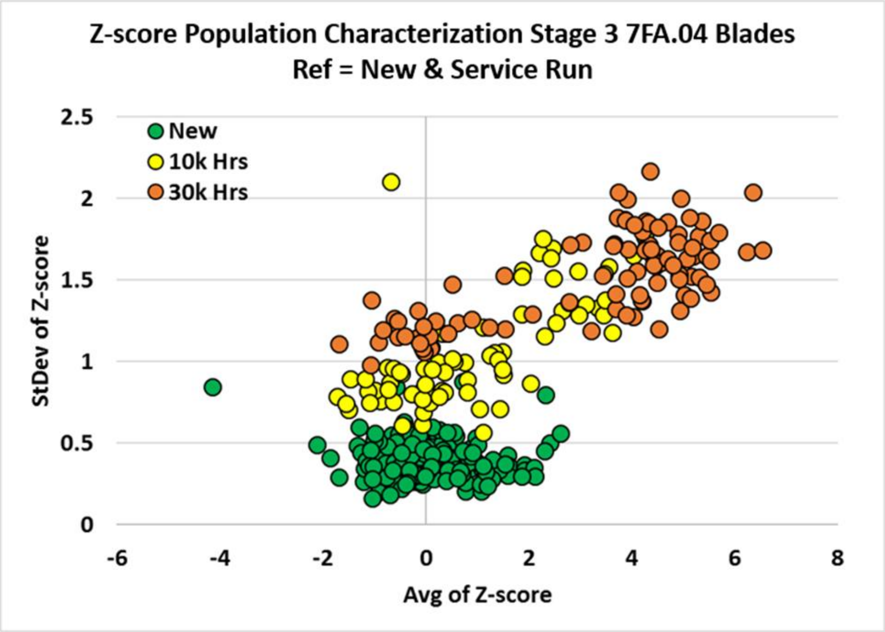


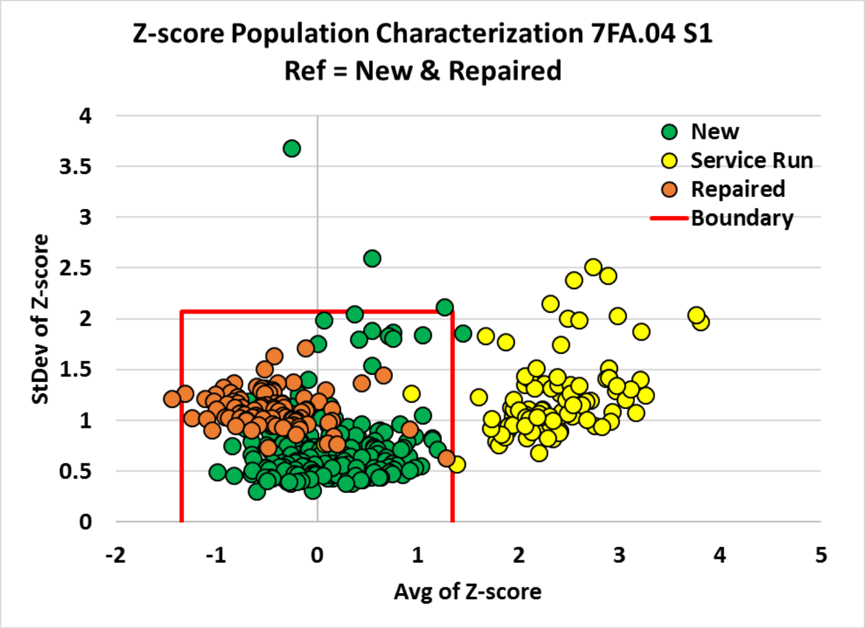
Why is a Part an Outlier?

- Shrink
- Crack
- Dimensions
- Core Shift
- Inclusion
- Lack-of-fusion
- Heat treatment
- Boiling porosity
- Creep
- Grain Angle
- Twist
- Material
- Inconsistent build parameters
- Material oxidation



Life-cycle of Gas Turbine Blades

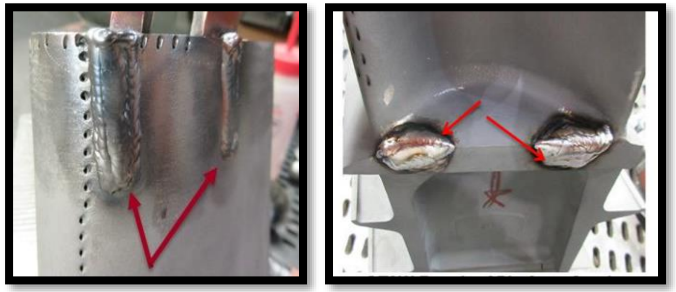




New Blades – Use PCRT to identify outliers

Service-run Blades – Use PCRT to identify candidates to repair or replace

Repaired Blades – Use PCRT to monitor repair process



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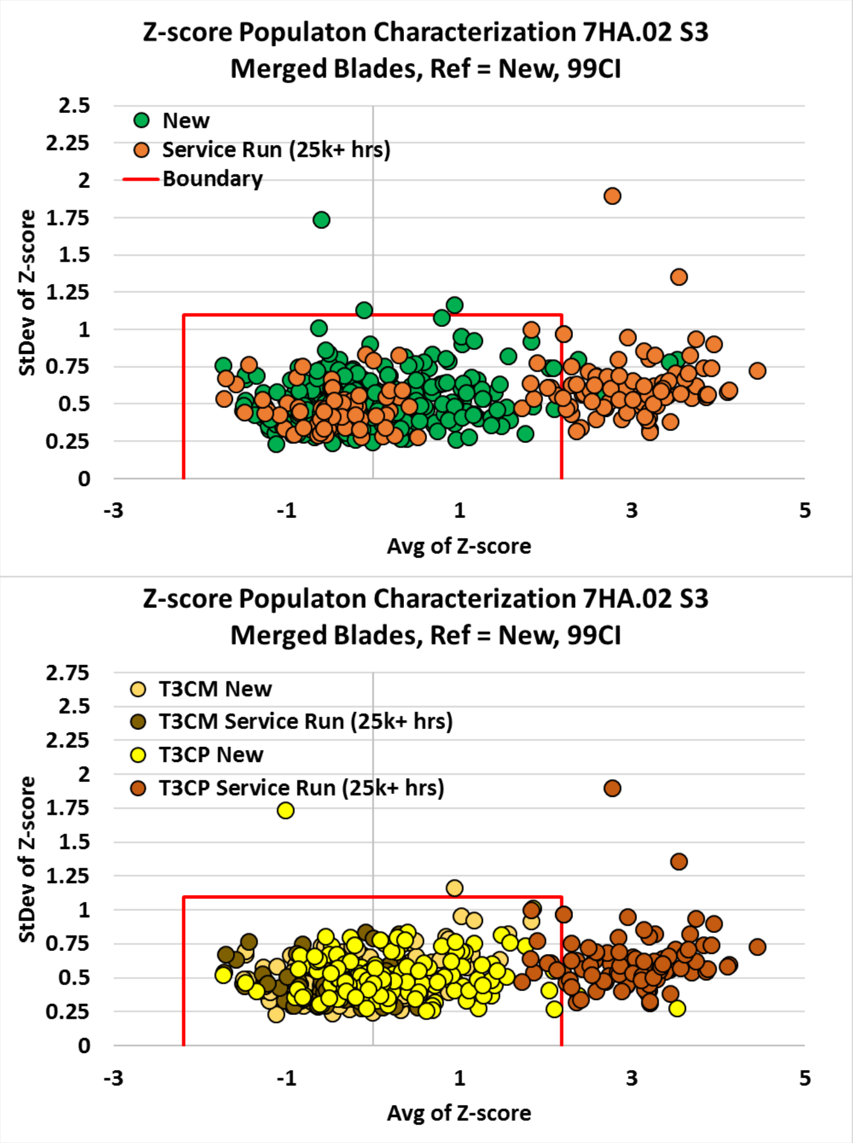
Analysis of 7HA.02 Stage 3 Population – Merged

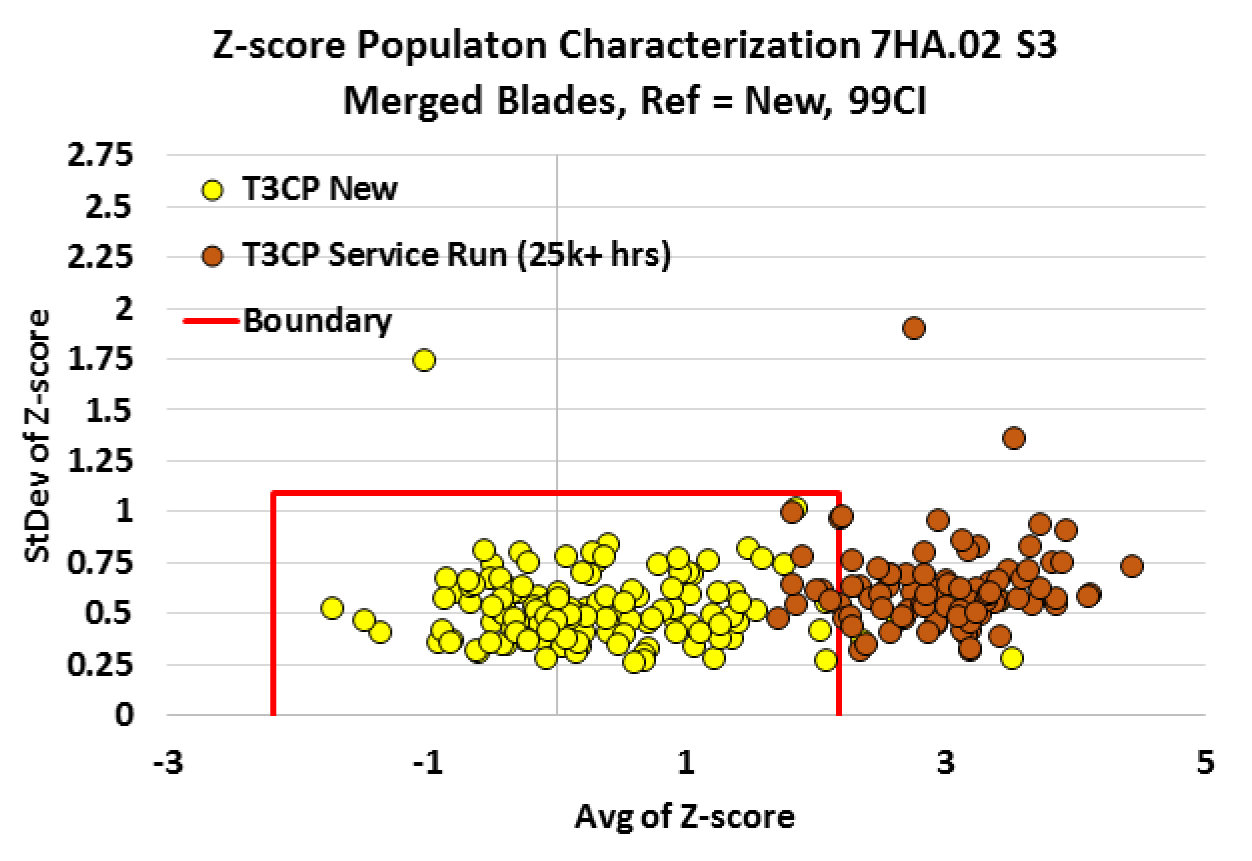
- Parts examined
  - Current Parts
    - 2 disk sets, 160 blades total
    - Service Run condition
  - Previous Parts
    - 4 disk sets, 320 blades total
    - New Condition

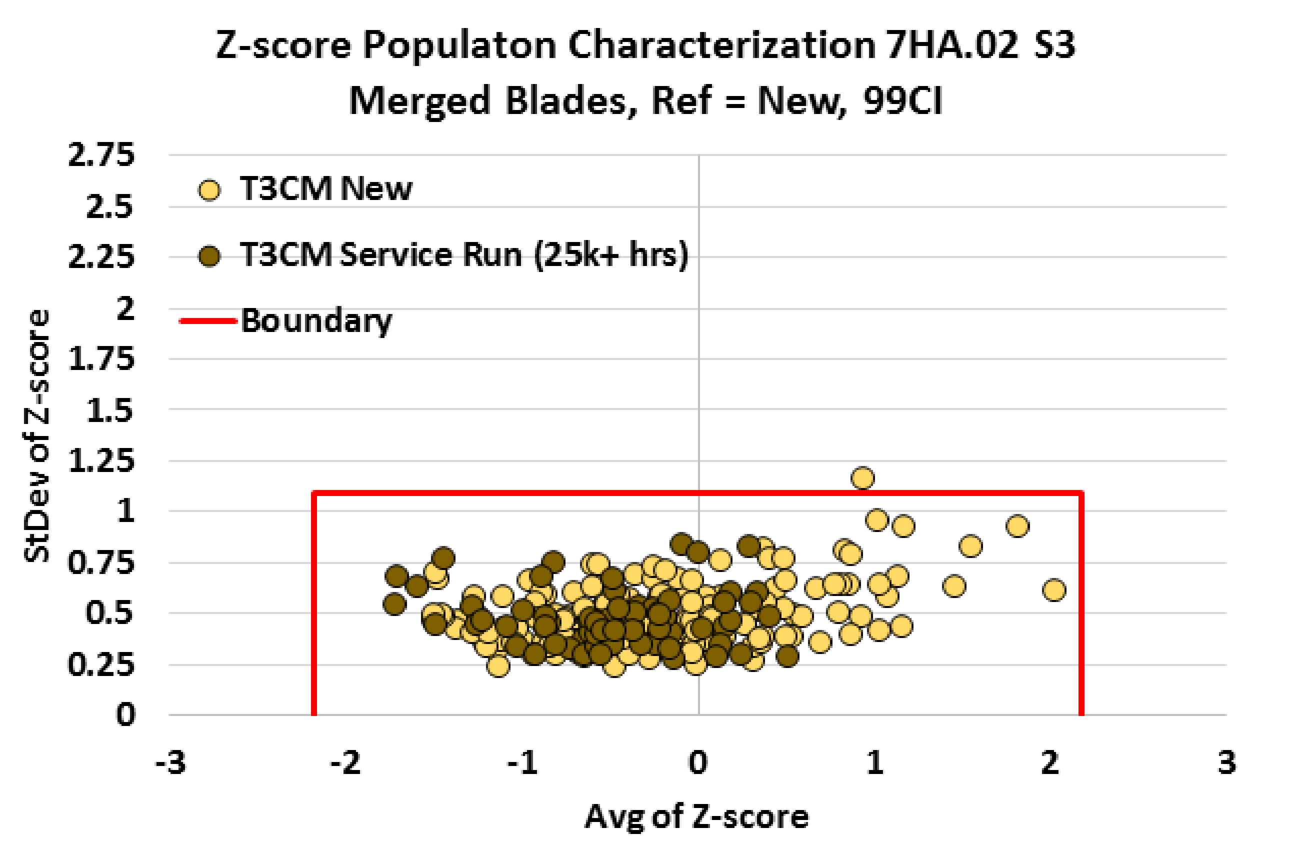
- Population characterization
  - New blades are the reference set
  - Service Run blades in casting lot T3CP drift significantly higher in Average Z
  - Casting lot T3CM does not significantly change

- Interpretation
  - T3CP and T3CM casting lots come from different suppliers
  - Casting lot T3CP shows a larger aging effect than casting lot T3CM
    - Consistent with T1CP and T2CP casting lots
      - Continues trend with 'CP' supplier
  - Casting lot T3CM shows minimal change
  - It is possible that the materials from the separate suppliers react differently to operational loading



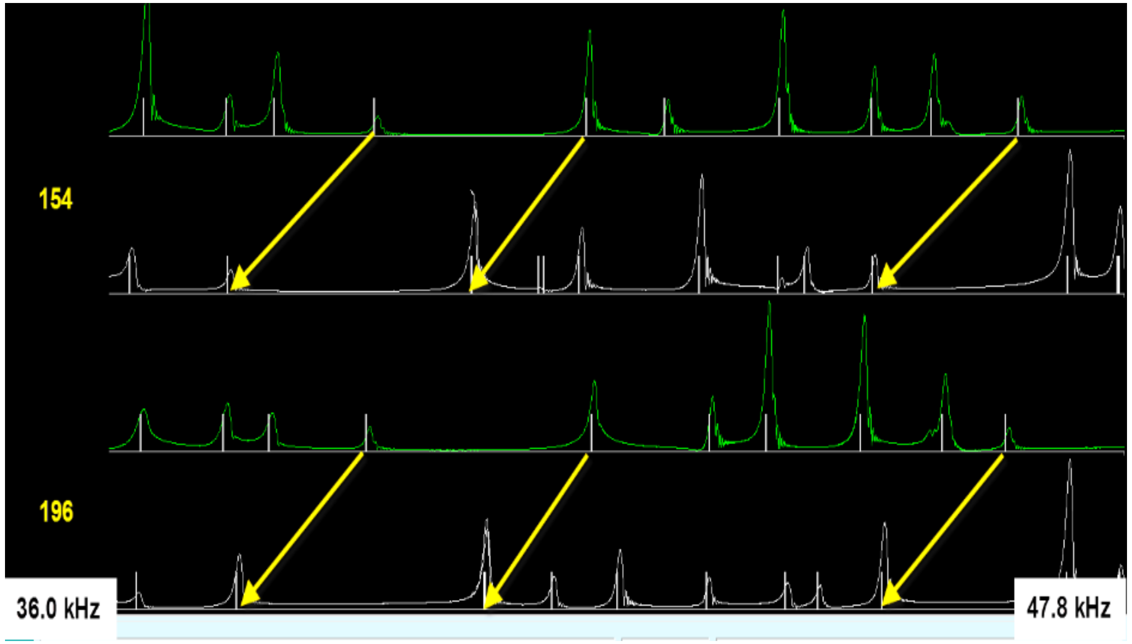
Analysis of 7HA.02 Stage 3 Population – Merged

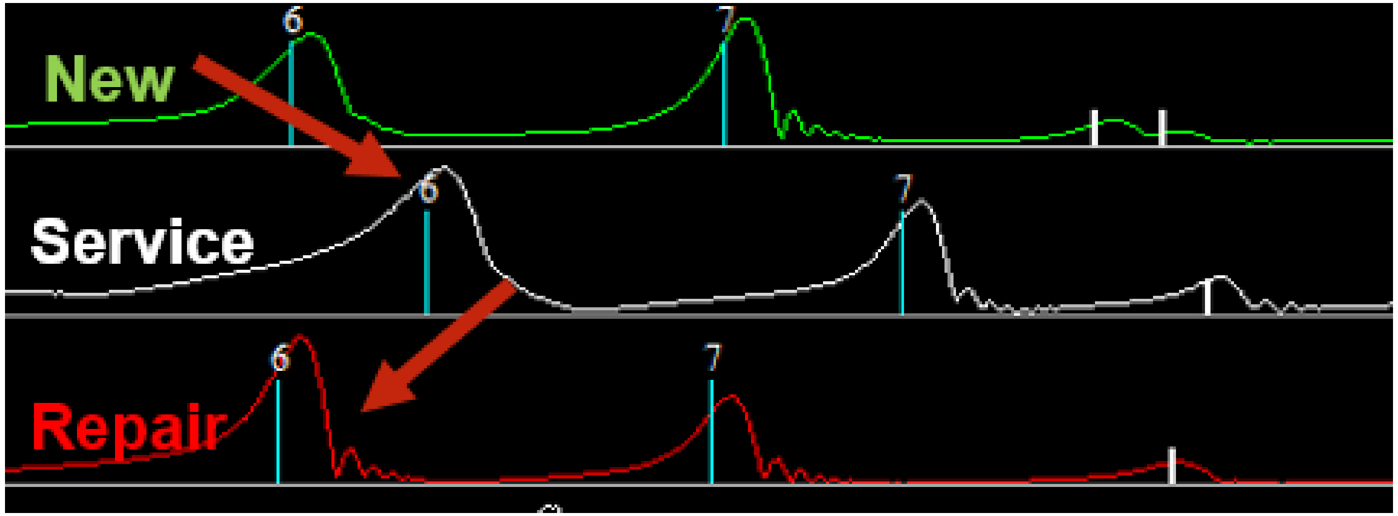




PTI = Part-to-Itself

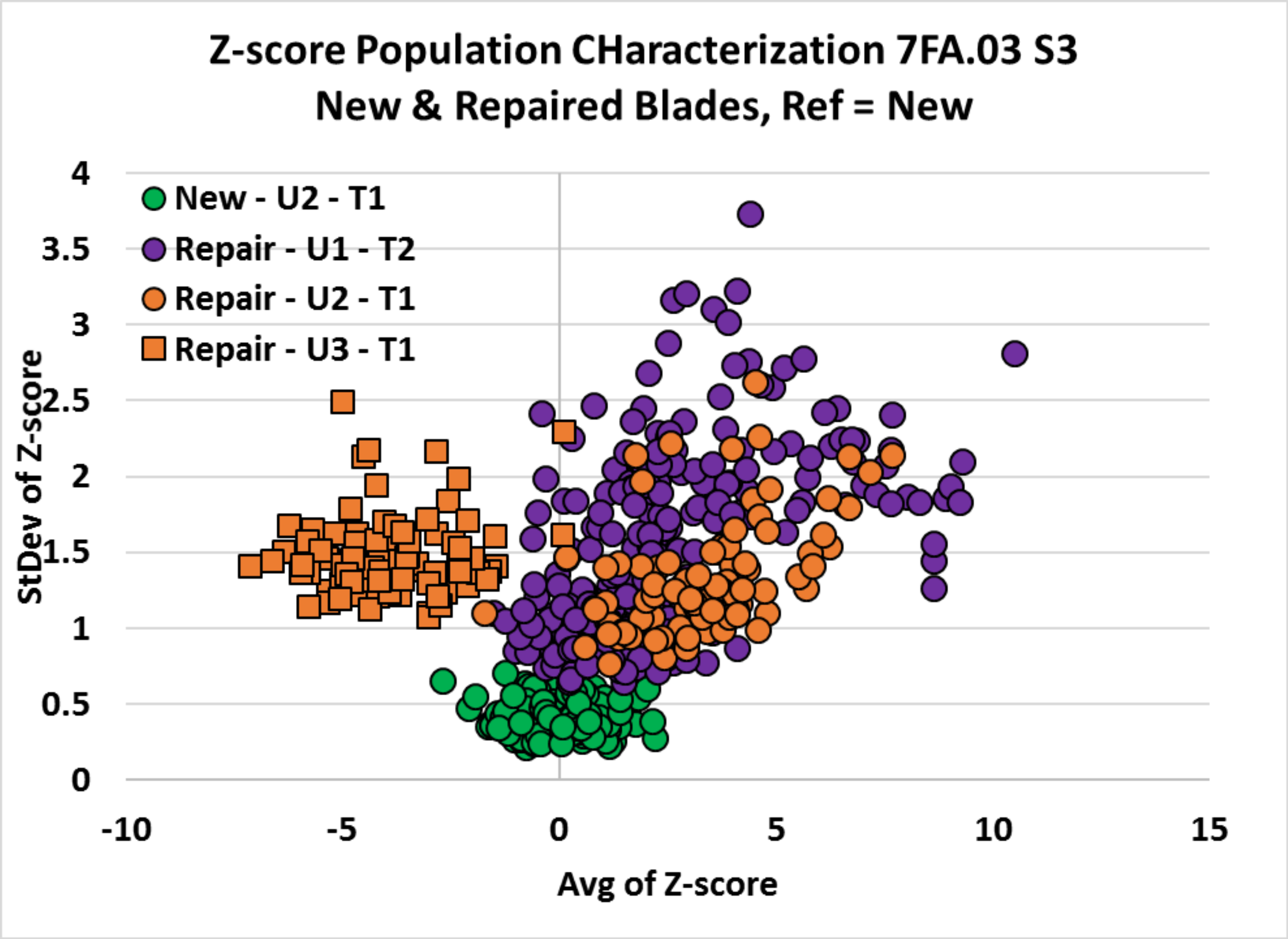
- Measure a part before and after an event
  - Service Cycle
  - Repair
  - Critical Processing Operation
    - HT
    - Coating
    - Hardening
    - HIP
    - Rejuvenation
- Evaluate the change
- Compare to expectations





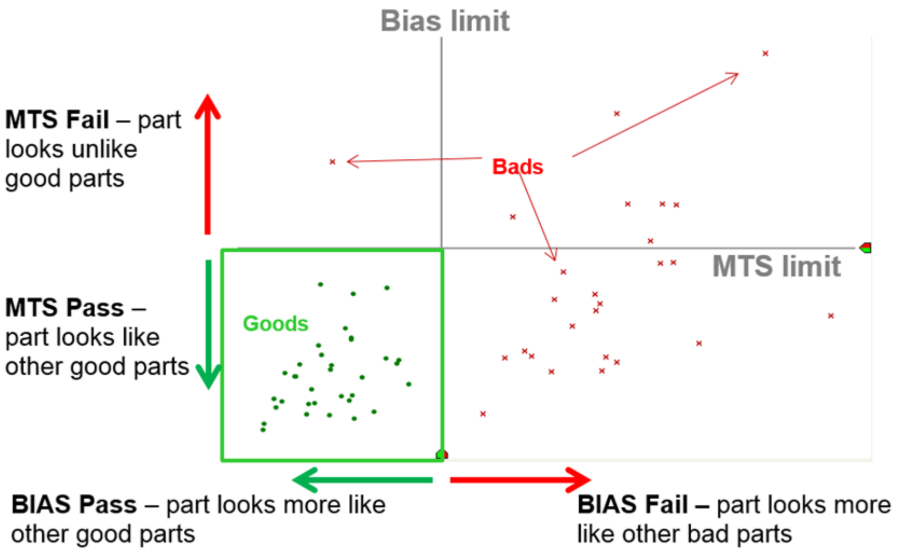
7FA Changes in OEM Rejuvenation Heat Treatment

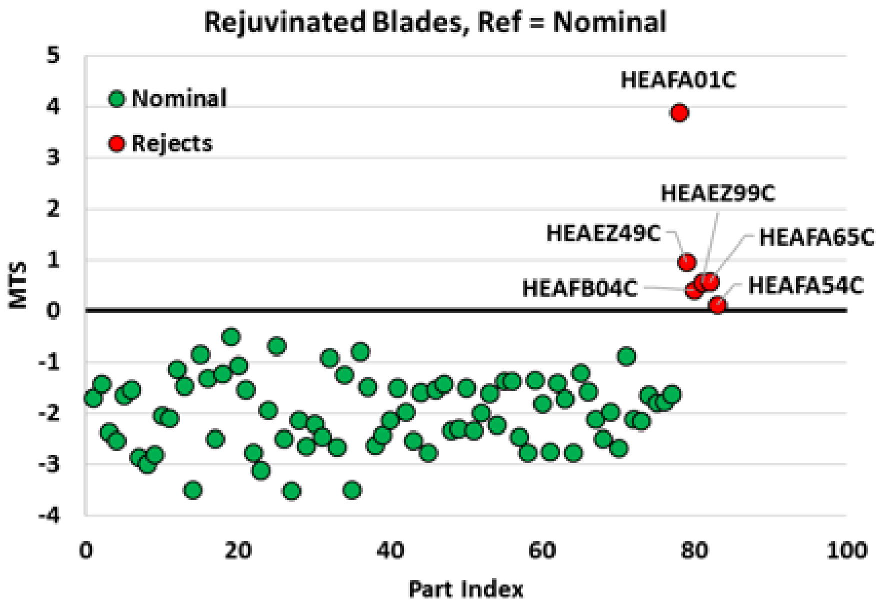
- OEM changed rejuvenation heat treatments on S3B
- Member had experienced several S3B failures and needed to validated the rejuvenation
- PCRT validated the microstructural changed in effective stiffness with new HT process



Introduction to Targeted Defect Sort

- Vibrational Pattern Recognition (VIPR, Vibrant Corp.)
  - Proprietary pattern recognition algorithm
  - Developed to target specific defects and determine the combination of resonance frequencies that are most diagnostic of the defect
  - Based on the Mahalanobis-Taguchi System (MTS)
- This is a machine learning algorithm and must be trained
  - Needs statistically significant populations
- A typical VIPR solution provides a scatter plot of x-y ordered pairs (Bias, MTS) for each part
  - Passing parts will have negative values in both Bias and MTS (quadrant III)
  - Failing parts will have a positive value in the Bias, MTS, or both
- Interpretation
  - MTS – dissimilarity from the good population
  - Bias – similarity to the bad population





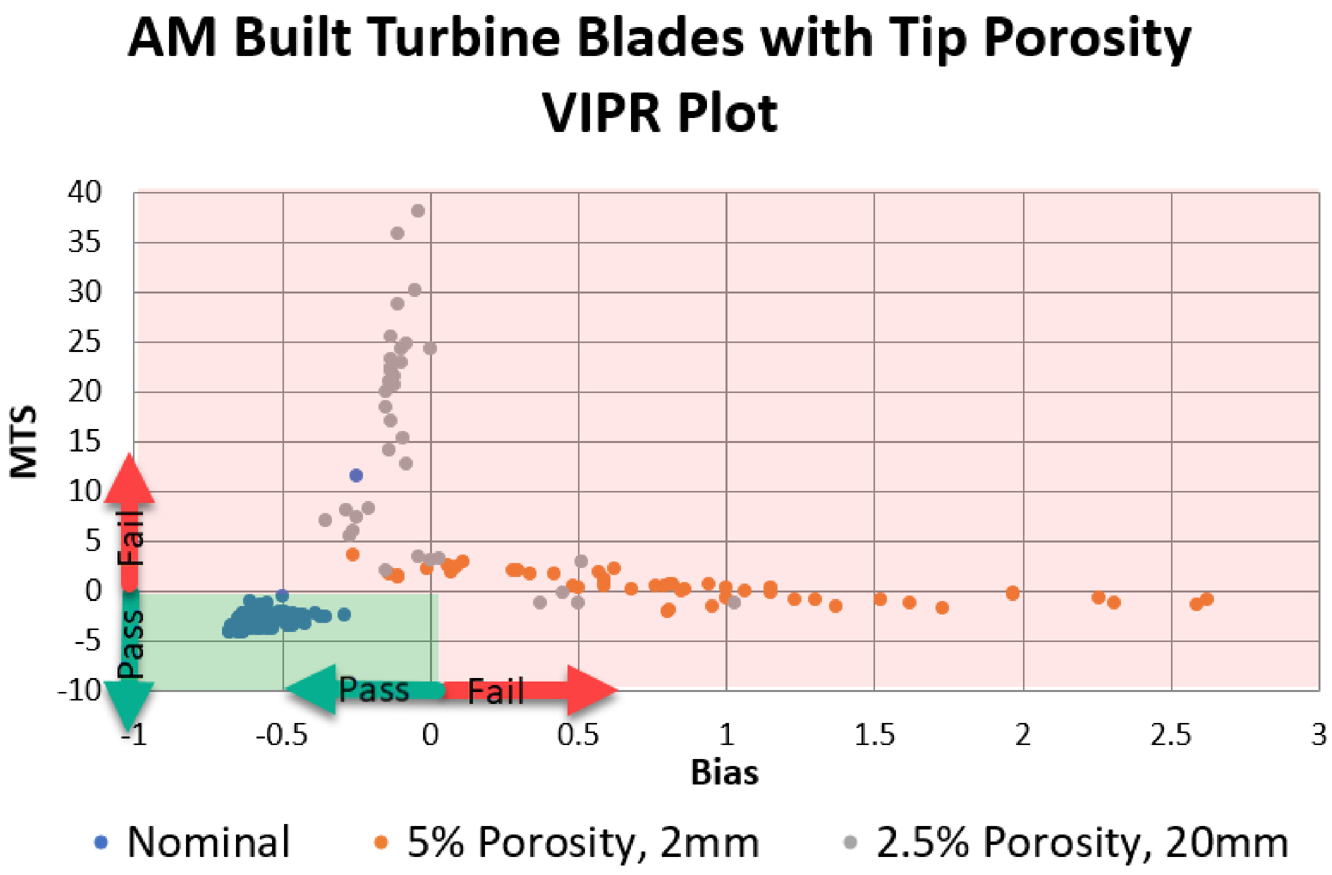
Targeted Defect Sort – AM Tip Repair

Fully Built AM Blades

- 5 Builds
- Builds 1-4 had 5% porosity in the top 2mm of the blade tip
- Build 5 was a ‘gross’ example with 2.5% porosity for the top 20mm of the blade tip

Using VIPR, the nominal and parts with porosity were 98% successfully separated

- 1 ‘Nominal’ part failed
  - Part was a ‘corner’ part on the build, may not have been robust



NDE Inspection Technique Toolbox

Comparison of NDE techniques for inspection of IGT components

Each method has areas of strength and weakness

No one method to replace all other methods

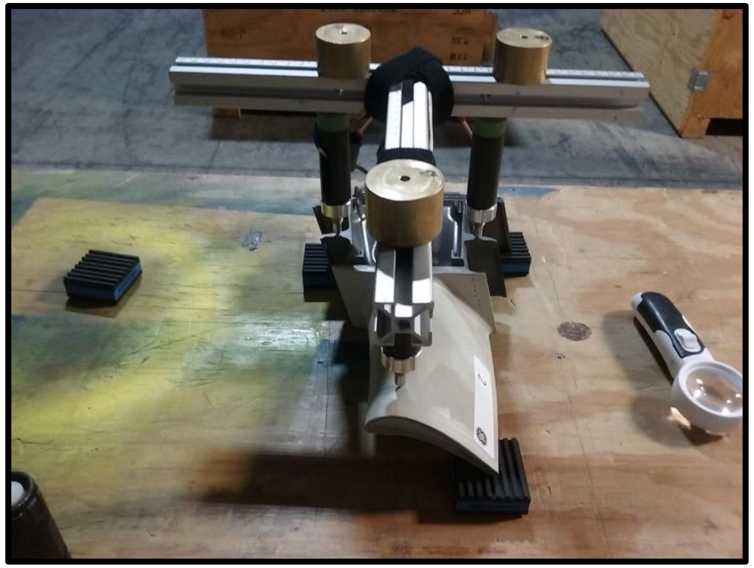
1 – Low applicability/capability
2 – Fair applicability/capability
3 – High applicability/capability

	UT	ET	MT/PT	RT	PCRT
Defect Types					
Material Property	1	1	1	1	3
Process Variation	2	2	1	2	3
Structural Defect	3	3	3	3	3
Crack Indications	3	3	3	2	2
Porosity/Voids	2	3	3	2	2
Defect Location					
External	3	3	3	1	3
Internal	3	1	1	3	3
Locating Defect	3	3	3	2	1
Economics					
Speed	3	2	2	1	3
Cost	1	2	2	1	3
Training	2	1	1	1	2

EPRI NDE and Dimensional Characterization

- Dimensional:
  - Laser scanning
  - Blue light scanning (new)
- Visual/Surface
  - Borescopes
  - Dye Penetrant
  - Eddy current & advanced electromagnetics
- Volumetric
  - Ultrasonics technologies
  - Process Compensated Resonance Testing (PCRT)
  - Microwave
- Dedicated laboratory space for NDE and configurable space for specific jobs

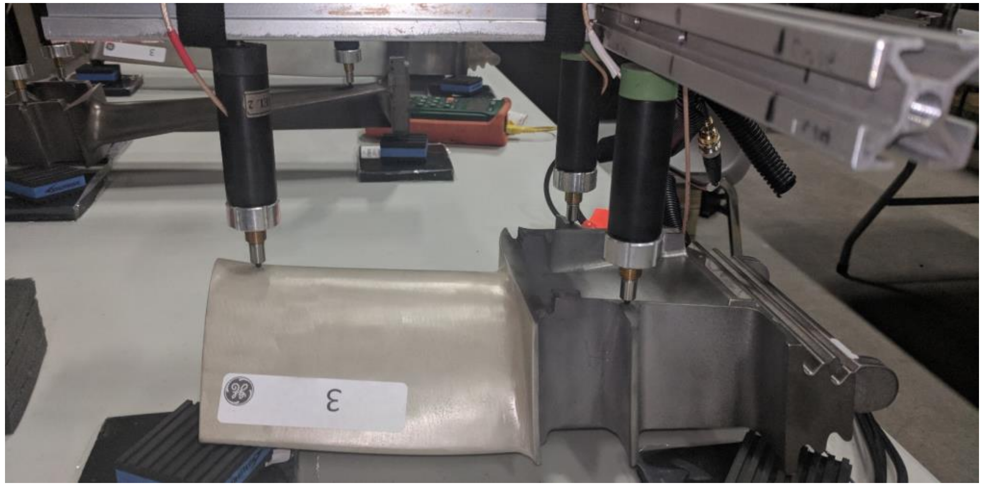
Most tools are field deployable



Gas Turbine Component Quality Characterization

Objectives and Scope

- Implement a simple component characterization process to augment quality assurance processes for gas turbine blades
  - Reduce probability of failure and maximize life cycle
- Conduct component inspections and enhance quality data analyses
- Develop a comprehensive data base of signatures for comparative analysis and trending
- Define process variables that may identify root causes of quality anomalies
- Track degradation and repair adequacy



Non-destructive evaluation of gas turbine hot section blade

Value

- Develop additional methods of screening parts to increase overall quality and assess repair methods
- Provide additional tools to assess the quality of new designs
- Increase life cycle without added risk
- Compare individual parts signature to an extensive data base

Details and Contact

- Cost and schedule dependent on number of parts to be evaluated

Project Manager: John Scheibel

- jscheibe@epri.com, 650.855.2446

Supplemental Project: SPN 3002015408

Characterize blade signatures to enhance quality and reduce risk of failure

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