Enhancing Reliability with Process Compensated Resonance Testing (PCRT) at Delta TechOps

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OUTLINE

- **PCRT Updates**
  - JT8D T1 Blade
  - JT8D T2 Blade for Overtemp
  - JT8D T4 Blade
  - PW2000 T1 Blade weld micro-crack
  - PW2000 T2 Blade for Overtemp
- **PMA vs OEM**
  - OEM scatter
  - AC non-compliance
- **'Lifing' program CFM56-7B T1**
  - New blades
  - Metallurgical anomalies

To date: Over $25M in savings, plus a phenomenal increase in reliability, simultaneously

JT8D T1 History at Delta

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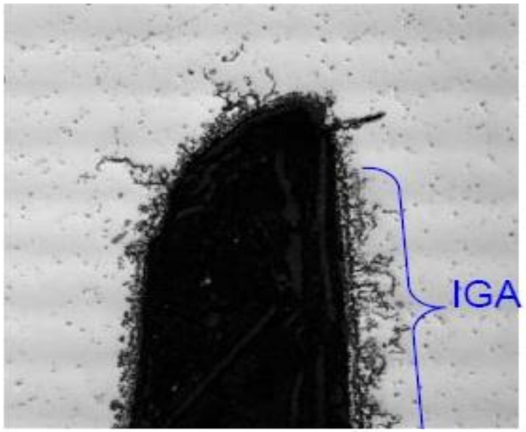
- JT8D-219 historically plagued by T1 failures; Each failure cost about $700K, plus additional work for shop
- Changed repair vendor 2005/6, yet failures persisted
- In 2007 bore scope interval reduced from 3,500 hours to 2,000, surplus and high time blades eliminated, yet failures persisted
- Trial program began in mid-2008 = eye opening
- PCRT added as a 'supplemental' inspection Jan. 2009
- Multiple defects with targeted sort algorithm
- FAA Approval of JT8D-219 T1 OT testing 7/2010 (P&W '1 out of 64' destructive sampling replaced with 100% PCRT)
- Delta & Vibrant win FAA *"Better Way"* Award 9/2010
- 70,000+ blades tested to date; Fleet "turned over"
  - 325+ Blades destructively examined in Lab
- T1 failures and in-flight shutdowns have *virtually* been eliminated

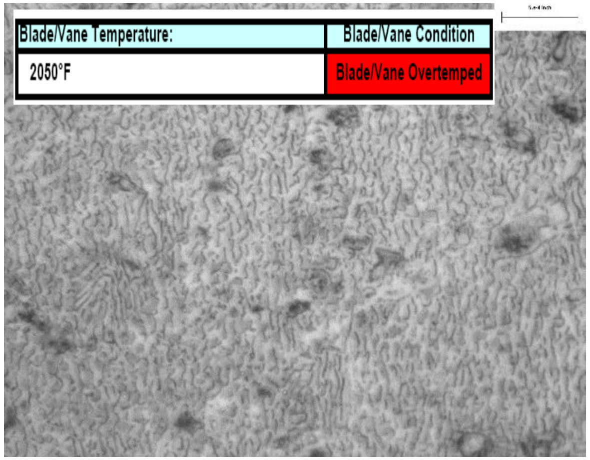
Increased reliability simultaneous with cost savings

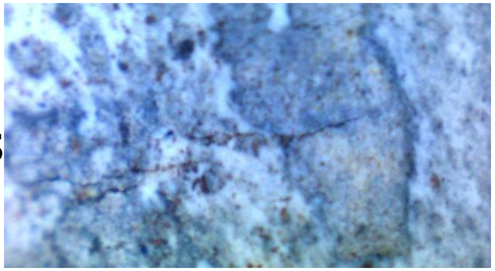
JT8D T1 Defects – 50% Inspection



Inter-granular attack

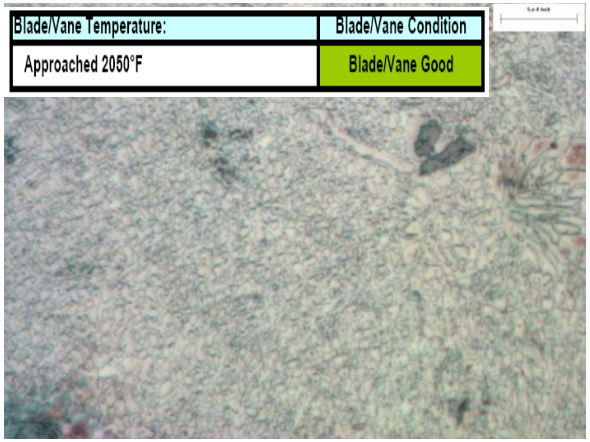
Thin wall





Cracks

- ✓ Heat treatment errors
- ✓ Solutioning errors
- ✓ Core shift & integrity
- ✓ Material loss
- ✓ Hidden discontinuities
- ✓ Material property variation



Over-temp = 1/64

Manual only inspected for ½ of defects known to cause failure

Operational results w/PCRT - Stellar

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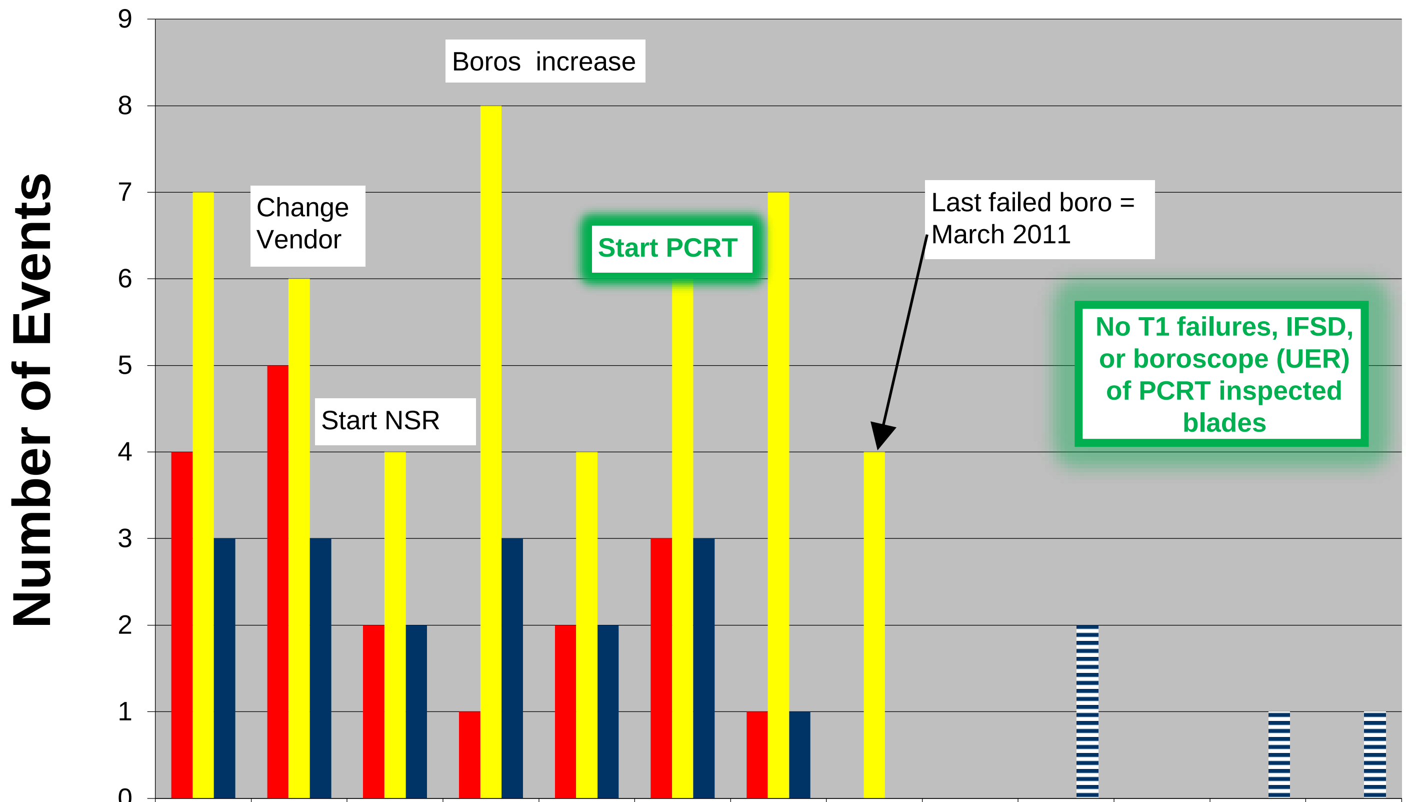
JT8D T1 Blade Pareto



	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
IFSD	4	5	2	1	2	3	1	0	0	0	0	0	0
UER	7	6	4	8	4	6	7	4	0	0	0	0	0
T1 Blade Failure	3	3	2	3	2	3	1	0	0	2	0	1	1

Year

Operational results w/PCRT - Stellar

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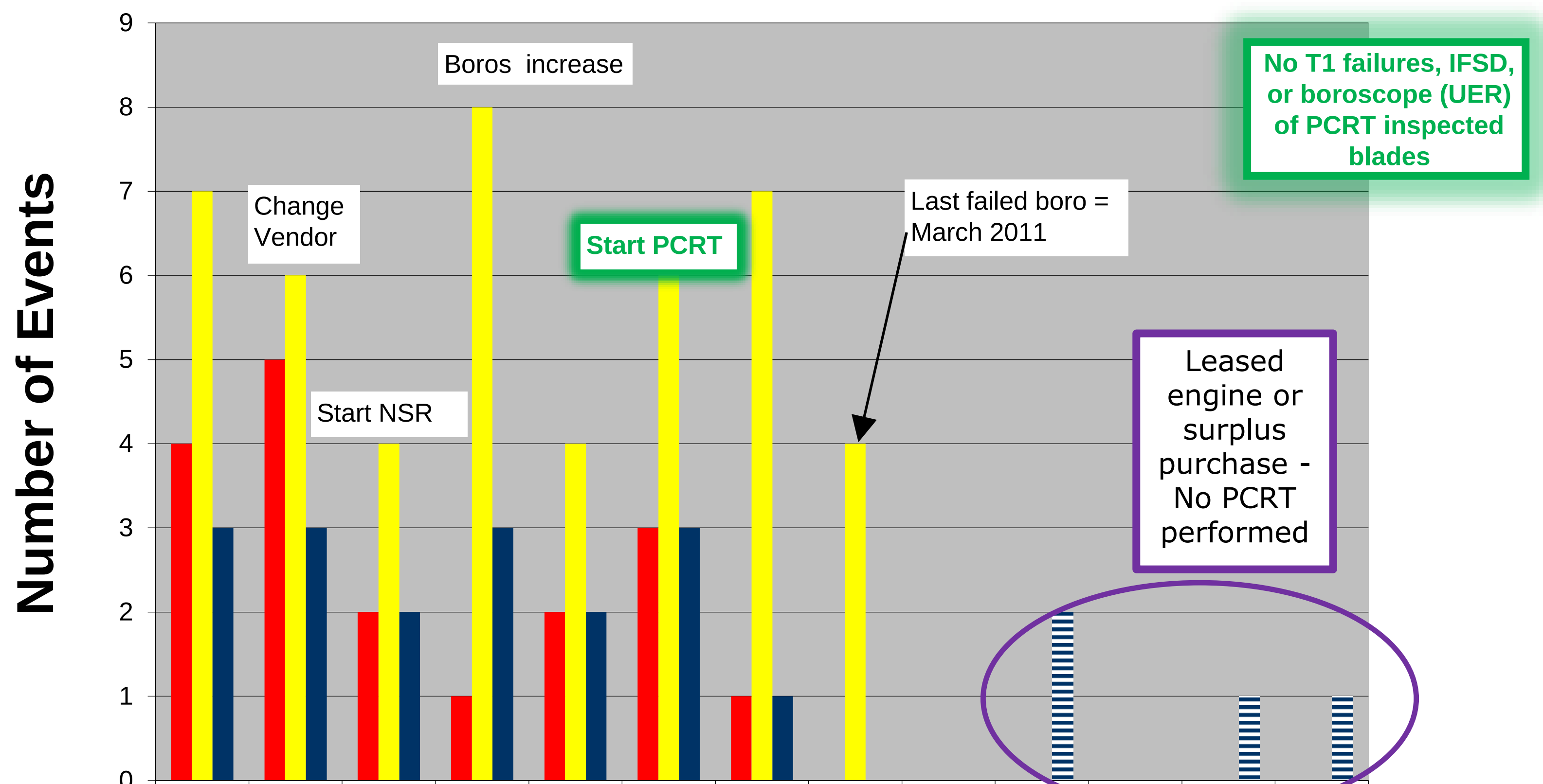
JT8D T1 Blade Pareto



	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
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UER	7	6	4	8	4	6	7	4	0	0	0	0	0
T1 Blade Failure	3	3	2	3	2	3	1	0	0	2	0	1	1

Year

PCRT of JT8D T1 Blades - Benefits

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- Enabled the **salvage** of blade previously 'trapped' as part of JT8D T1 OT sets.
  - ~3200 blades were salvaged, and were allowed back into service.
  - **Savings exceeded $9.2M**
- **Refined process** - Enabled cost savings by not having to scrap all the blades as part of OT sets, just the ones that fail PCRT.
  - **Annual, recurring savings of about $900K.**
- 3Q 2010 **Surplus blades** allowed, if they passed PCRT screening.
  - **Annual, recurring savings of about $1M.**
  - Even more important today with ‘surplus blade’, ‘surplus engine’, and ‘surplus aircraft purchase’
- ‘Rejuventation’ project underway – blades that are confirmed OT
- PCRT now performed at Engine Leasing company to ensure similar reliability as blades going through ATL Shop

Increased scope with Engine Leases, surplus materials

PCRT of JT8D T2 Blades - Benefits

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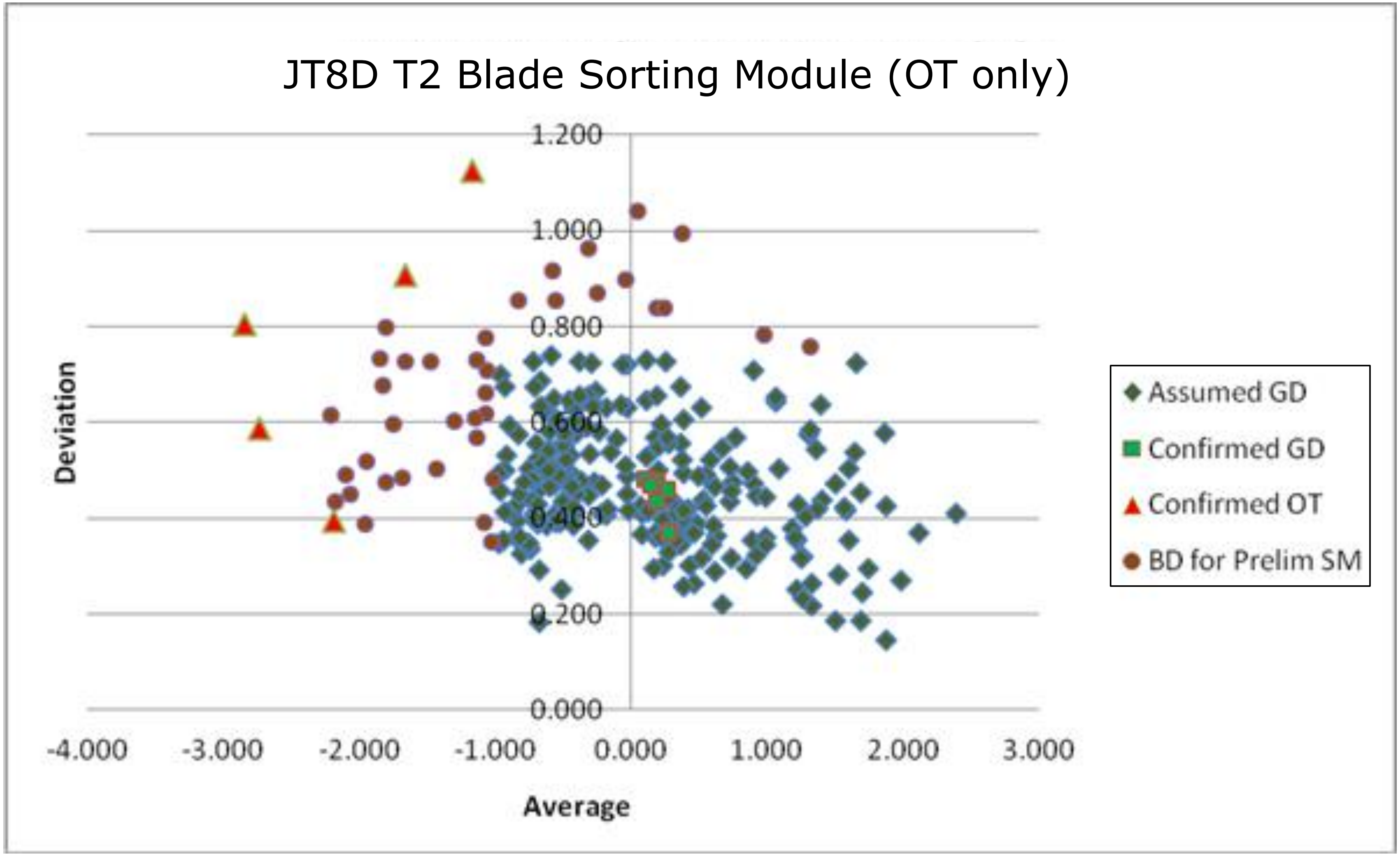

91% yield = Blades saved from scrap; $2.2M benefit
Inspection has been running for 22 months with no issues!

JT8D T4 blades – Overview

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The issue:

- ~40 failures of JT8D-219 T4 blades 2007-2013: Cost = $400K each failure
- 7 failures on 'new, first-run' blades, some before 1st torque check (AD 2011-07-02)

SUMMARY: We are superseding an existing airworthiness directive (AD) for the products listed above. That AD currently requires initial and repetitive torque inspections of the 3rd stage and 4th stage low-pressure turbine (LPT) blades for shroud notch wear and replacement of the blade if wear limits are exceeded. That AD also requires replacing LPT-to-exhaust case bolts and nuts with bolts

Solution - What:

- Solution was blade replacement due to HCF (one-and-done)
- New solution is PCRT Inspection on new, service-run, and repaired blades

Solution - Why:

- Reliability improvement (reduce/eliminate failures)
- Significant cost savings (avoiding material purchase), cost avoidance (reducing failures, UERs) = Can we use some blades again?
- Repair QA – Current vendor is 'outsourcing' repair
- Surplus blade purchases using PCRT as screen (similar to T1)

Solution - How:

- PCRT 'outlier' supplemental inspection – Piece part level for new blades, & service-run blades before & after Outside Service Repair

PCRT inspection on JT8D LPT T4 blades supplemented replacement

Why PCRT on Service Run JT8D T4 Blades?

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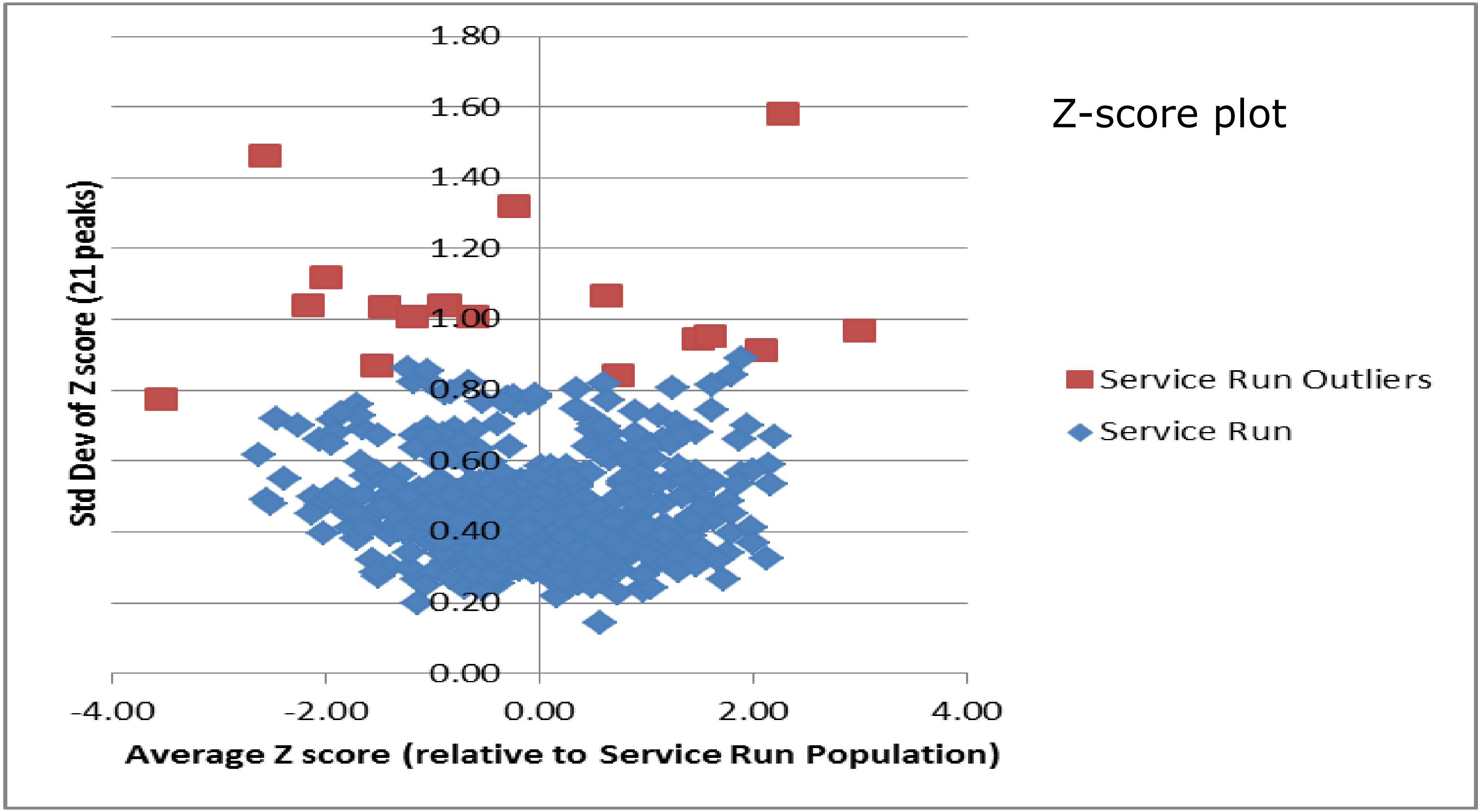
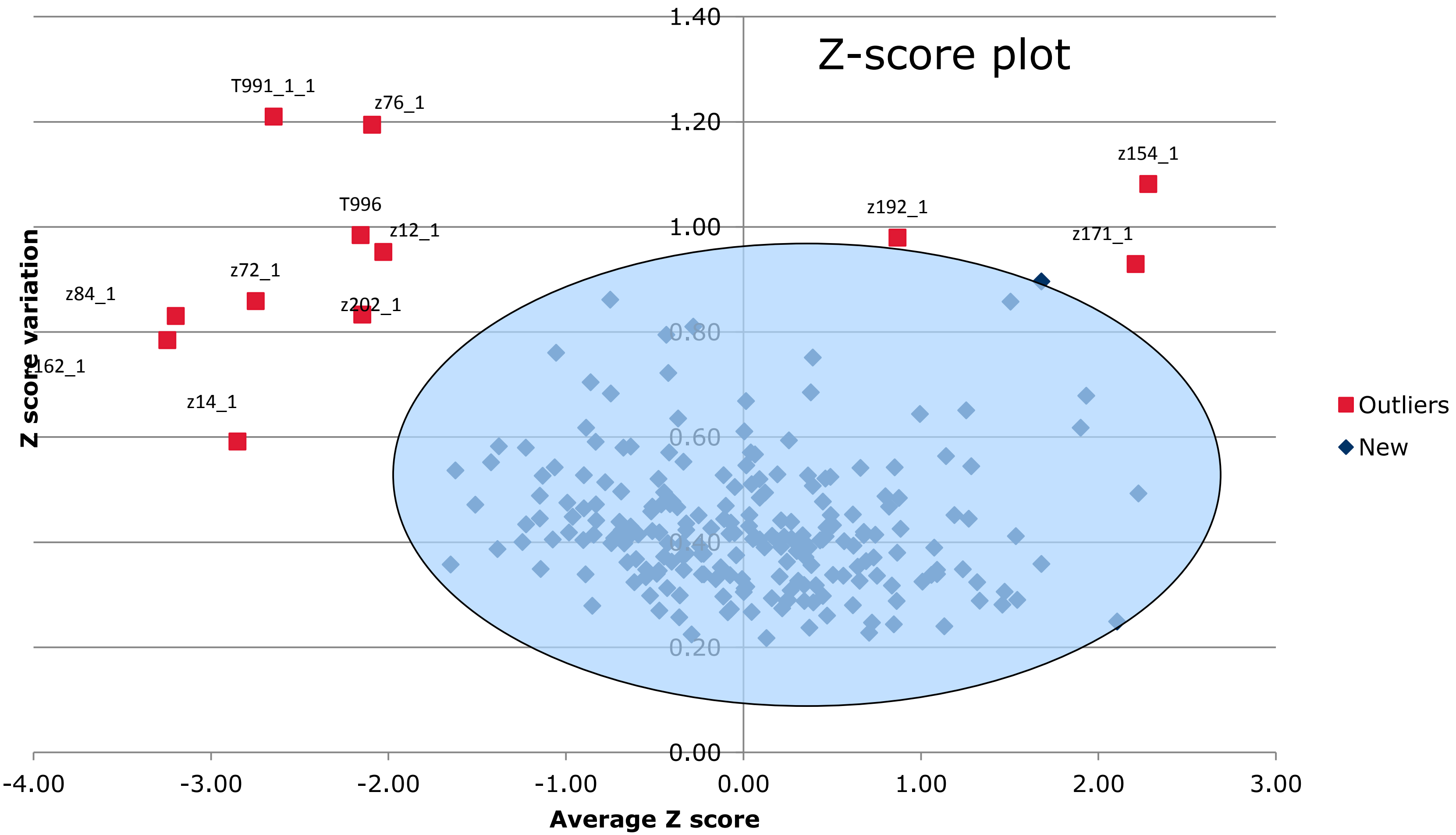
- ~40 in-service failures



PCRT can easily distinguish service-run and outliers

Why PCRT on new JT8D T4 Blades?

- 5 failures of first-run blades



~2% of brand new blade population resonates differently

Outlier blade analysis:

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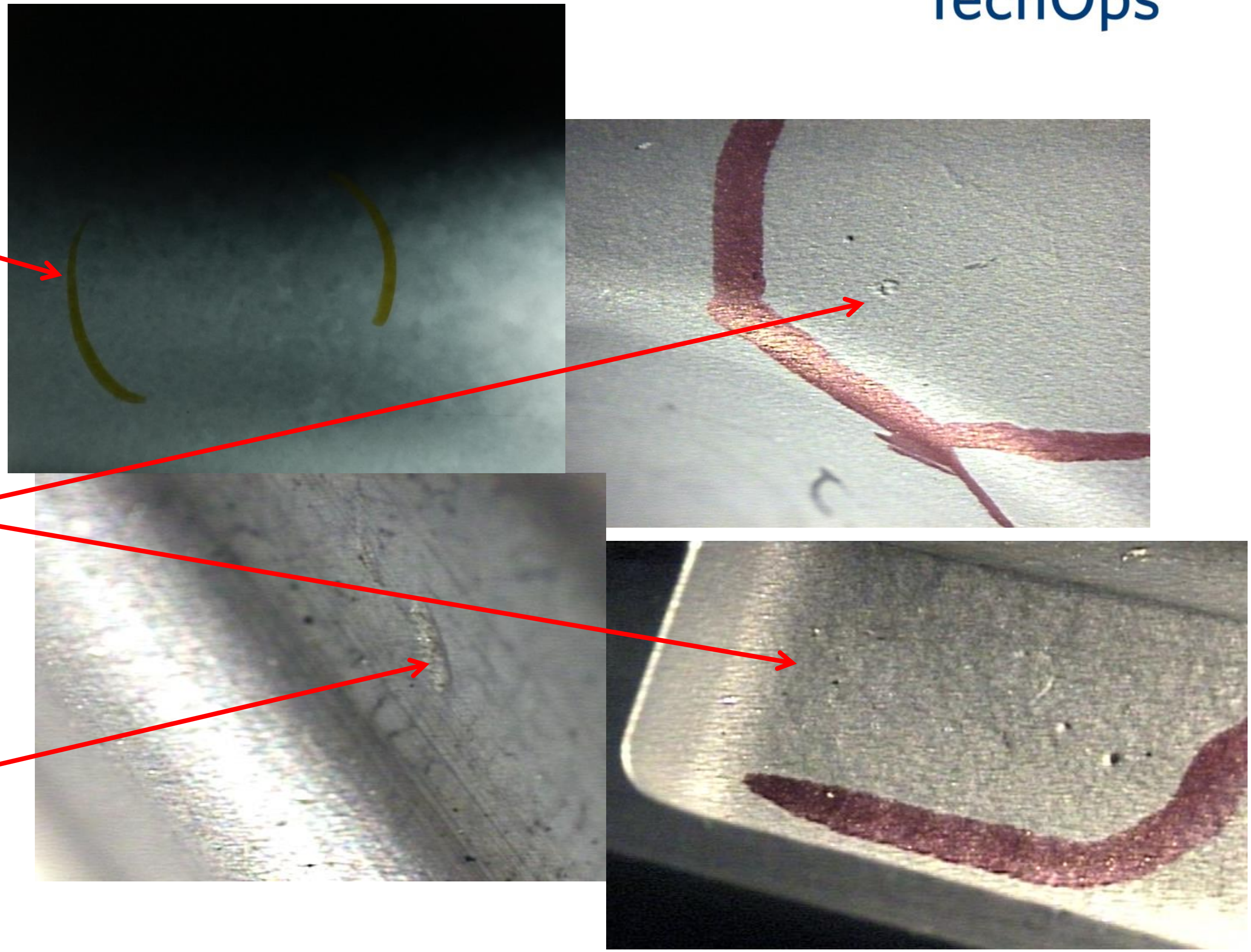
X-ray shows Shrink in airfoil, 1-2” from shroud.

Several different surface indications that are typically related to shrinkage

Shrink void open to the surface inside the root serrations?



Brand new blades with defects!

JT8D T4 Outlier blade analysis:

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- Shrink or 'porosity clustering' 1-2" below shroud causes the blade to 'dance' in a way that causes the root mean stress to activate and HCF cracking occurs
    - In a similar manner as if the shroud was worn
    - No access to casting house QA parameters on porosity
        - Some blades as much as 7-sigma different = WHY WOULD WE FLY THEM?
    - Outlier blades with shrink had acceptable shroud dimensions
    - Explains the early failures!

    Testing the hypothesis:

    - Expensive, time-consuming

- NPV = $29.6
- Benefits: Reduce failures; Material purchase reduction

Early failures being prevented with PCRT

Operational results w/PCRT - Stellar

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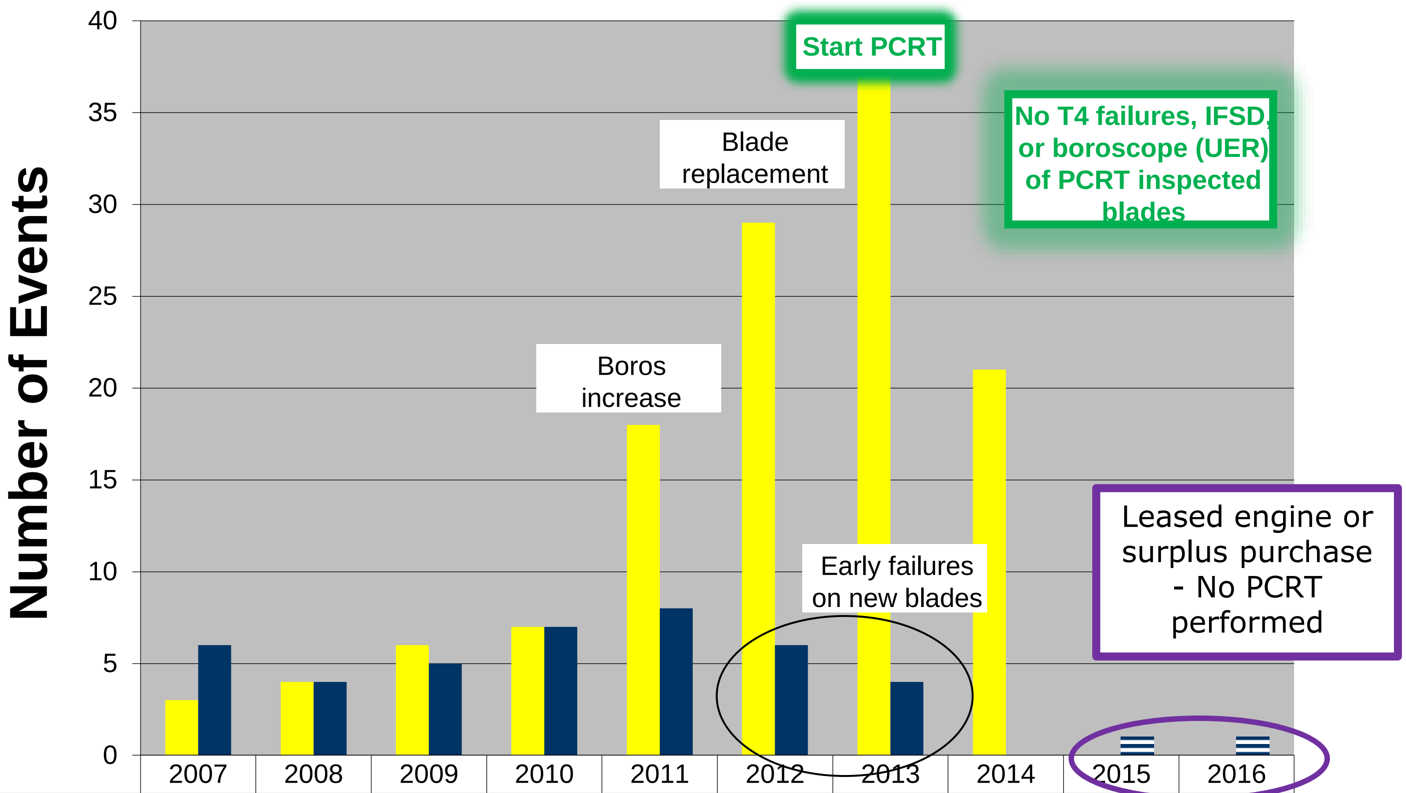
JT8D T4 Blade Pareto



	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
UER	3	4	6	7	18	29	37	21	0	0
T4 Blade Failure	6	4	5	7	8	6	4	0	1	1

Year

Simultaneous increase in reliability with cost savings

PW2000 T1 Blade

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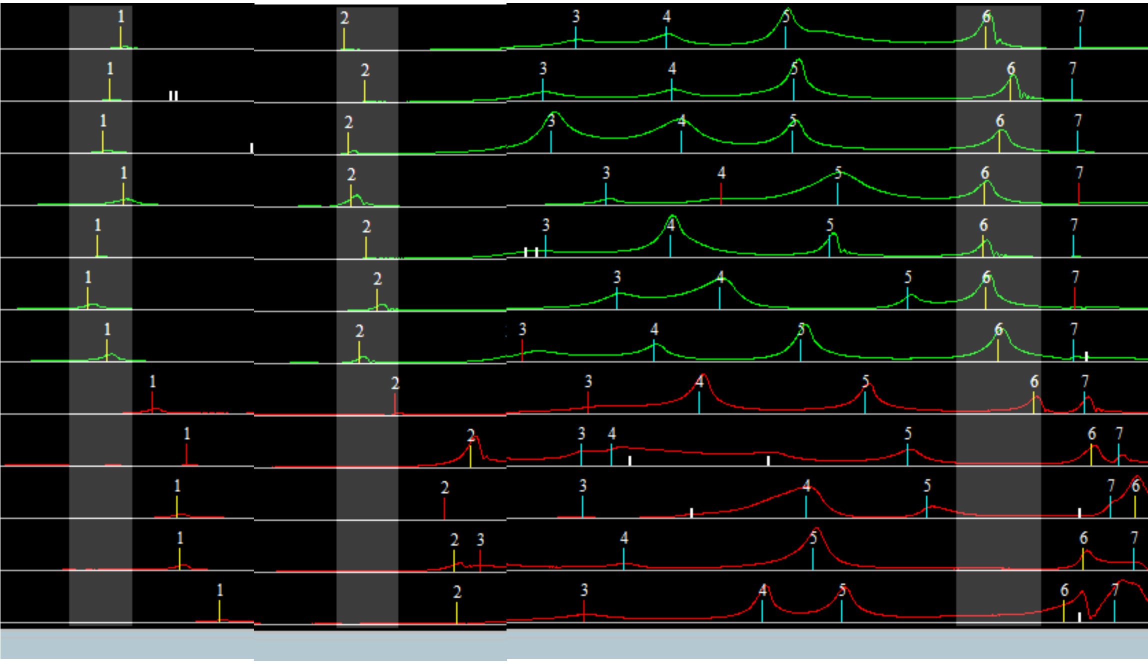
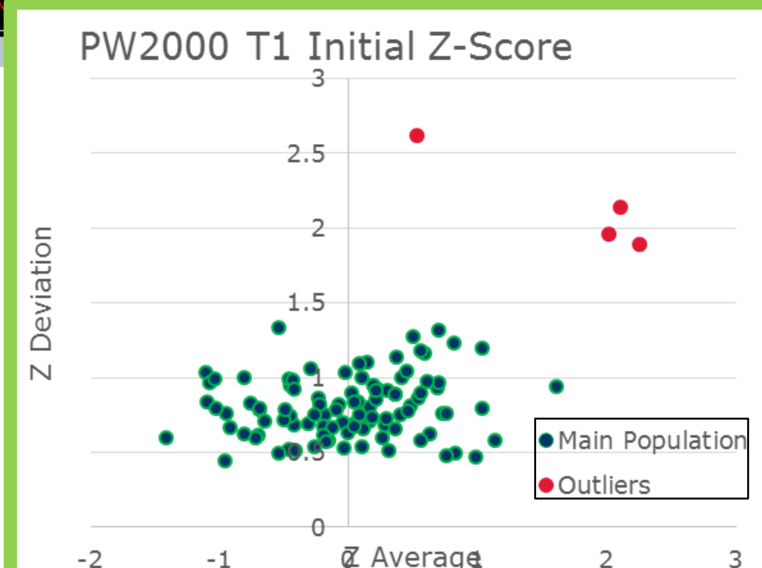


- Weld cracking on repaired blades
- Bad weld material – ODA/DER working final 'fix'
- PCRT to determine if blades can be used
- Validation complete
- Supplemental

- Easy detection of weld cracks
- Verified in Lab



Ready for implementation – Which T1 blades to use for another run?

PW2000 T2 Blade – Background/Proposal

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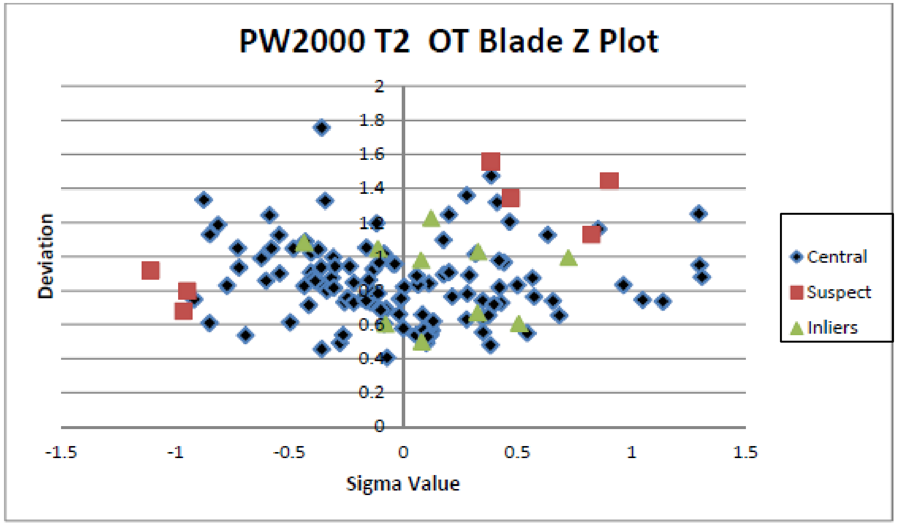
- Due to supply problems, desire to have PCRT approved for OT (instead of destructive Lab cut-up)
  - 1 out of 64 philosophy – identical to JT8D T1, T2
  - Lab reject rate has increased (to 75%) – scrapping more "sets"
- PW2000 Engine Manual revision requires FAA approval
  - ODA process to obtain approval, modify Engine Manual
- PW2K T2 has no service issues – only a supply problem
- Financial
  - Only 11 blade sets avg. per year
  - =~250 mhrs D572 (Lab) avoided
  - Annual material savings for not
  - having to scrap entire "set"
  - $9175/blade
  - **$2.1M avoidance & counting!**
  - **Estimate $4.5M annually**



Expensive blade means large savings, even with low volume

JT8D T4 Blades - OEM vs PMA

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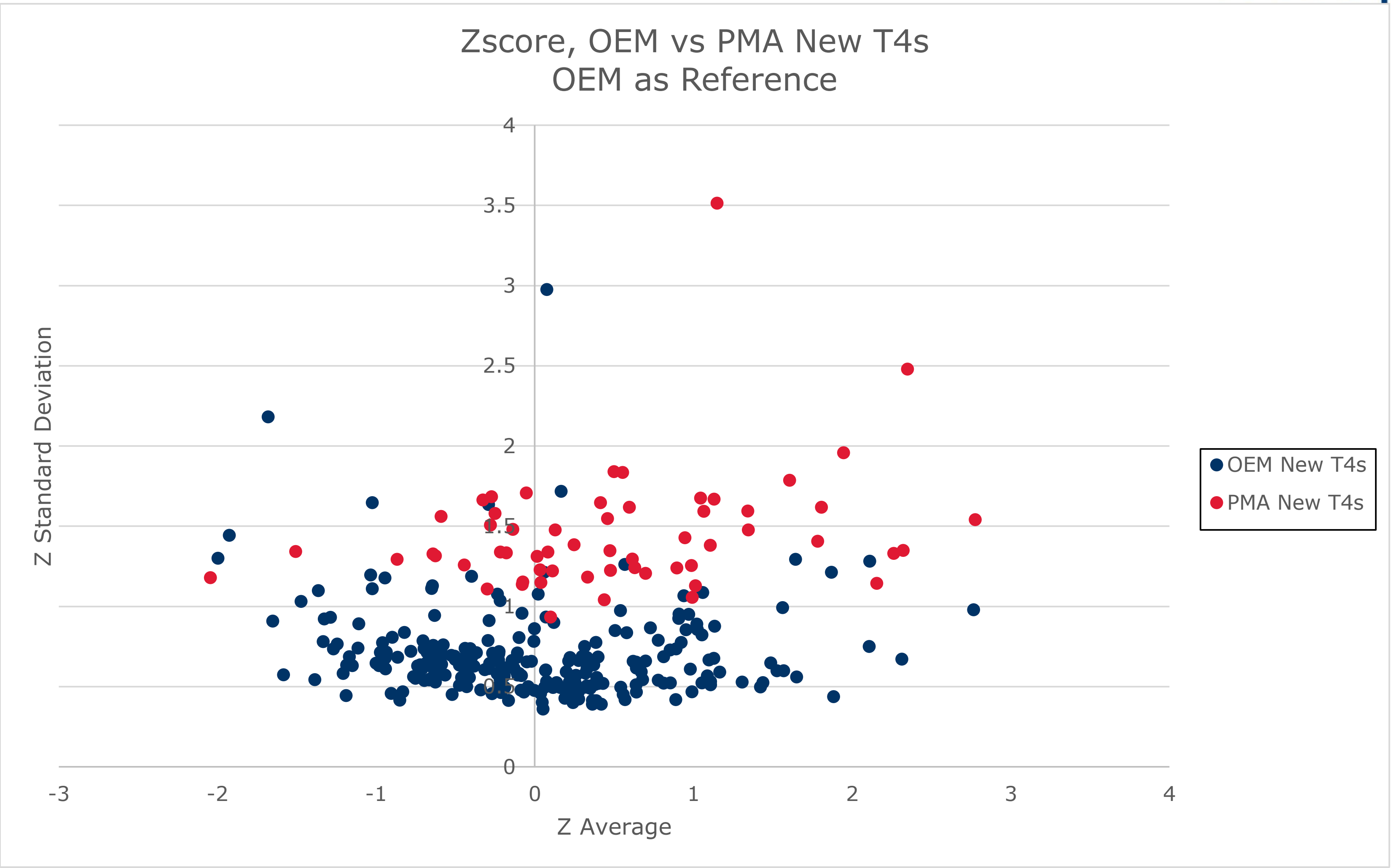

Vast resonance differences between OEM and PMA

JT8D T4 Blades - OEM vs PMA

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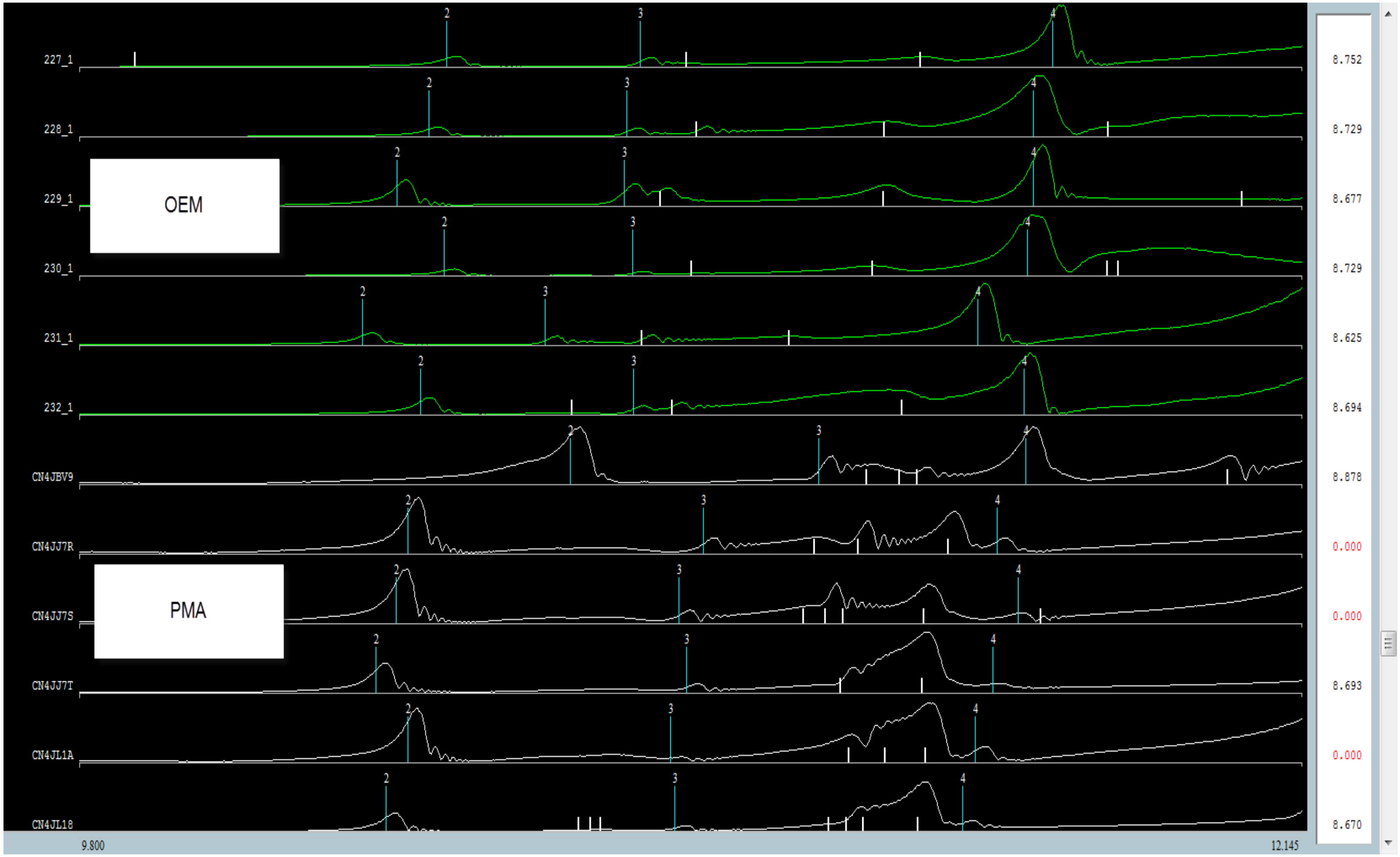
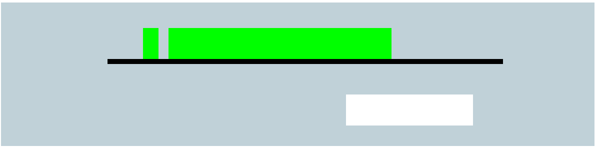


Vast resonance differences between OEM and PMA

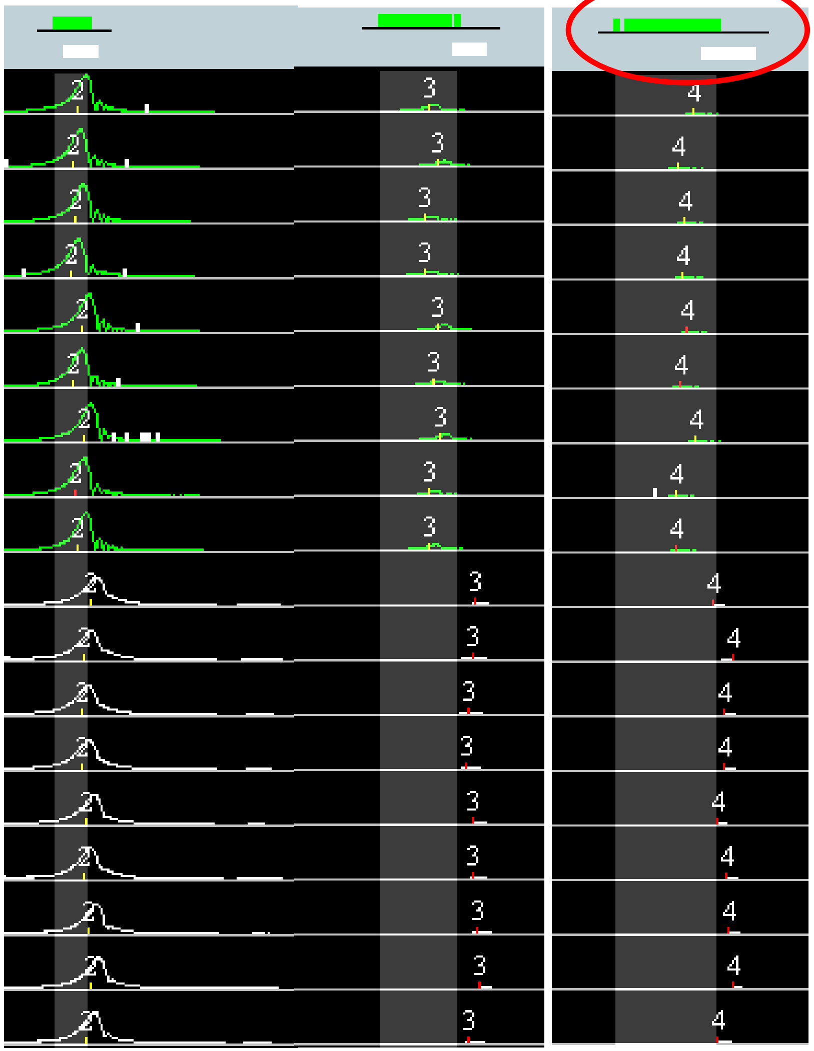
New OEM vs New PMA blades

- **New OEM vs. New PMA**
- Random Samples of OEM and PMA
- Distribution derived from **89** OEM and **98** PMA blades
- PMA blades are “different”



OEM

PMA



PMA has less variance, but vastly different than OEM

FAA AC 33.83 PMA Natural Freq Reqt's

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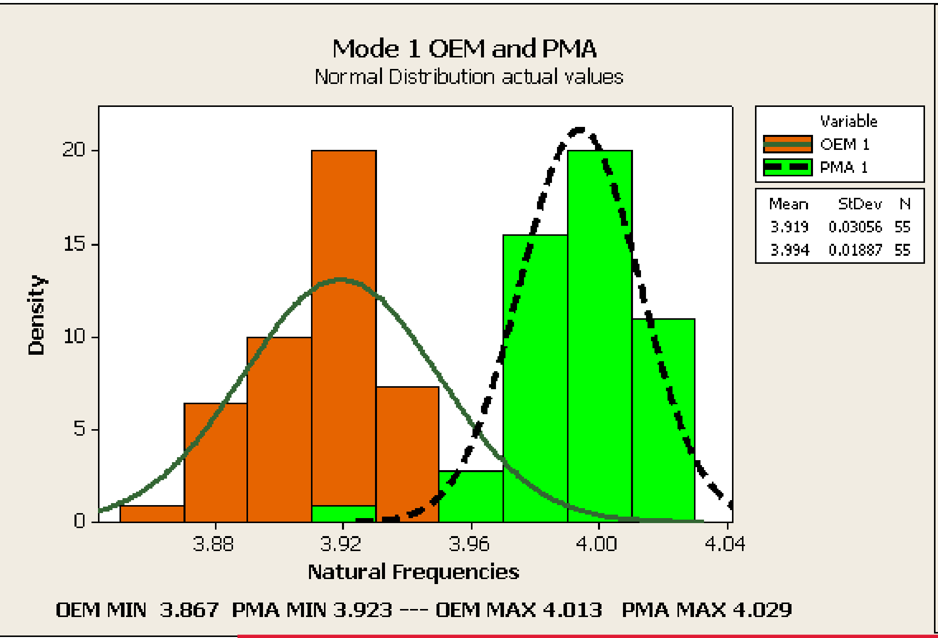
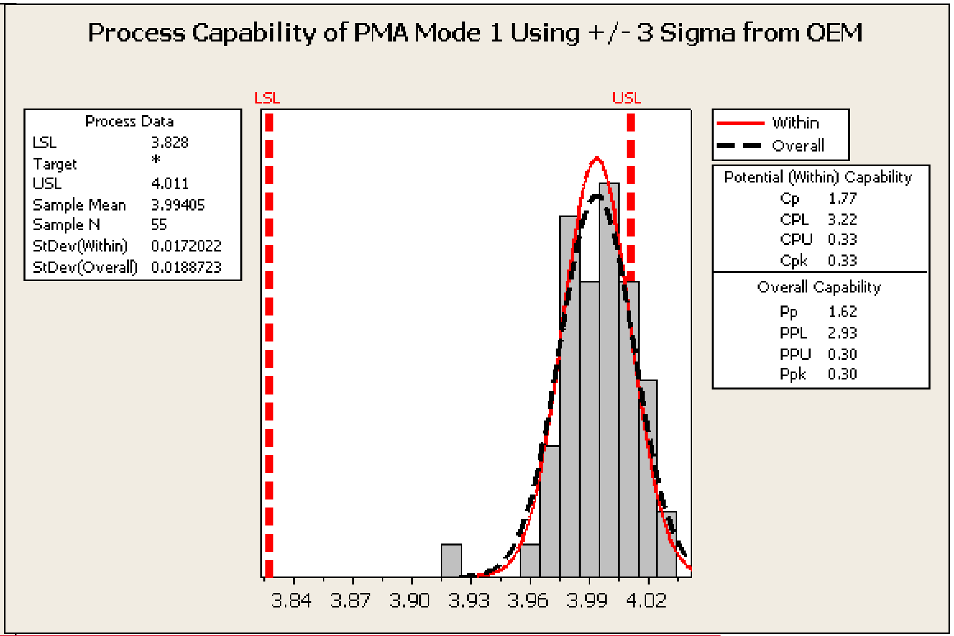
(2) Pass/fail criteria. **The blade natural frequencies are considered equivalent if the PMA frequency scatter band for each mode is equal to or less than the scatter band of the type design parts.** The frequency scatter band for each mode is computed using the measured frequencies by determining the mean frequency and the standard deviation. The scatter band lower bound frequency is defined as the mean minus three (-3) standard deviations. The upper bound frequency is defined as the mean plus three (+3) standard deviations.





PMA samples do not meet FAA requirements

FAA AC 33.83 PMA Natural Freq Reqt's

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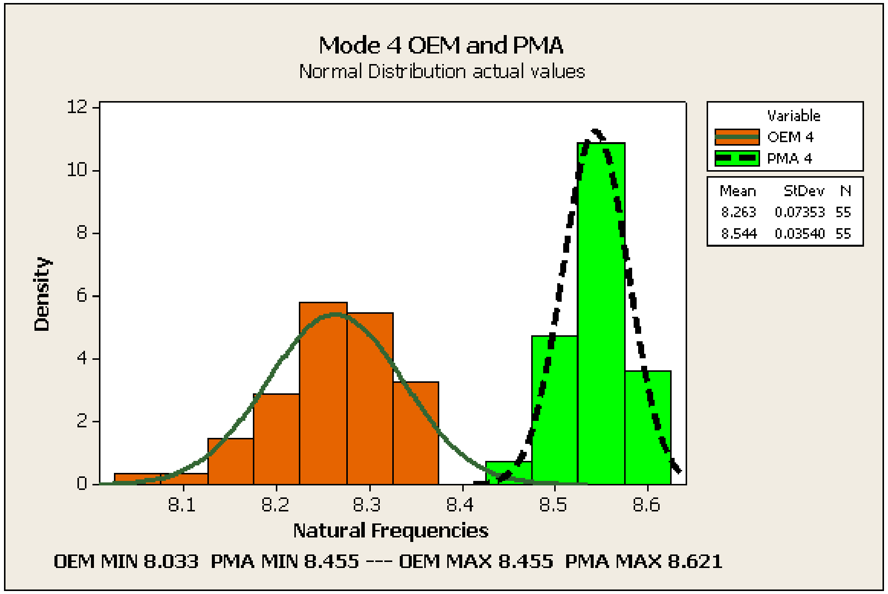
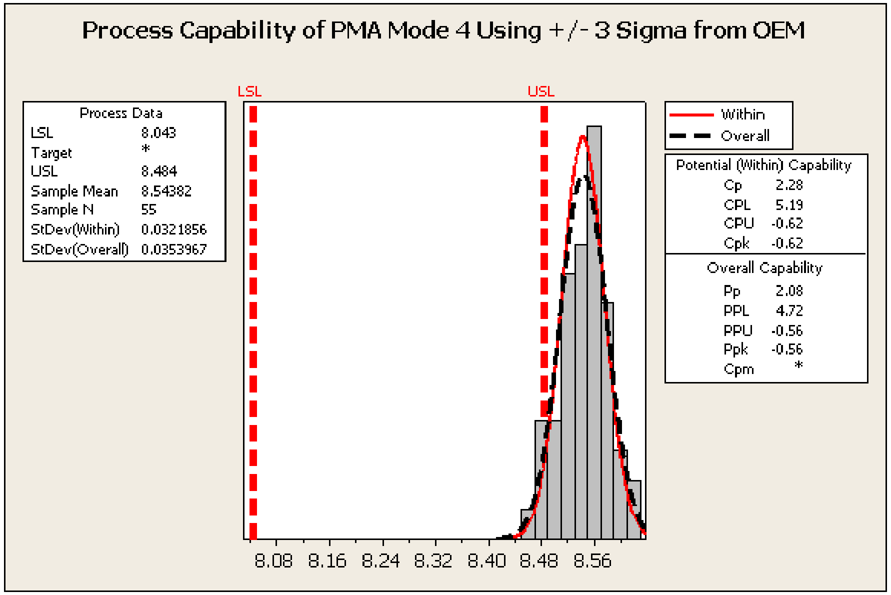
(a) The following pass/fail criteria must be met for each natural frequency:
1 The PMA parts' lower bound frequency must be equal to or greater than the lower bound frequency established by the type design parts.

2 **The PMA parts' upper bound frequency must be equal to or less than the upper bound frequency established by the type design parts.**

3 **The difference between the means of the PMA and type design samples must meet an 80% confidence test for means**





PMA samples do not meet FAA requirements

CFM56-7 T1 Blade – "Lifing" Program

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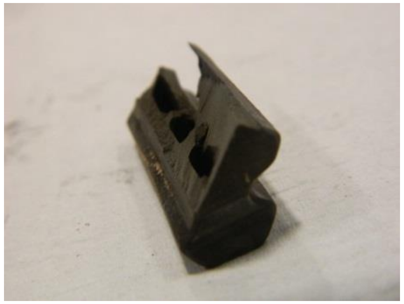
•"Cradle to grave" PCRT to maximize life of parts safely = Life cycle monitoring

•Proactive approach = better reliability, total life-cycle cost

8 Failures in ~6 years of older PNs ($3.5M cost per failure = $28M)



- Multiple part numbers
- Multiple failure modes
- No confidence in GE (9th part redesign); Historic pain
  - Hard time (20,000 FH) vs Soft time (10,000 FH)
- Implemented PCRT on new blades in 2013
  - ~1% fallout (55 blades of ~10,000 since 9/13)
  - Working to implement 'outlier sort' on in-service (avoid scrap costs at OSR) and repaired blades (repair QA)
- Further examination of new blades reveals metallurgical issues

CFM56-7 T1 blade is using PCRT as a "lifing" (pro-active) program

CFM56 T1 Blade = Multiple areas of cracking

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Types of Blade Distress

Trailing Edge Corner Loss (AMM) →

Root Trailing Edge Cracks →

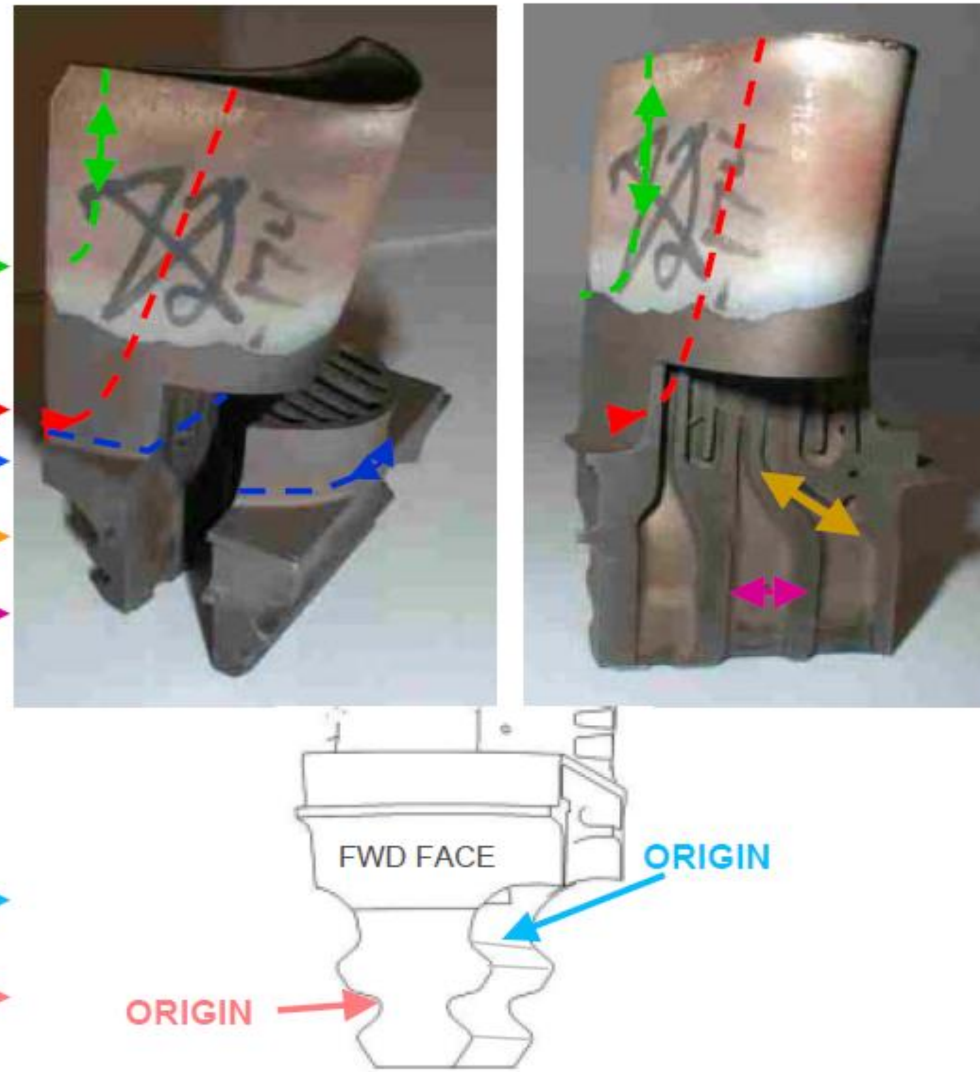
Airfoil Liberation (last Oct. 2002) →

Transition Zone Cracks →

Type 1 separations →

Edge of Contact →

Min-Neck →



Problems, problems, problems!

Why PCRT on new CFM56-7B T1 Blades?

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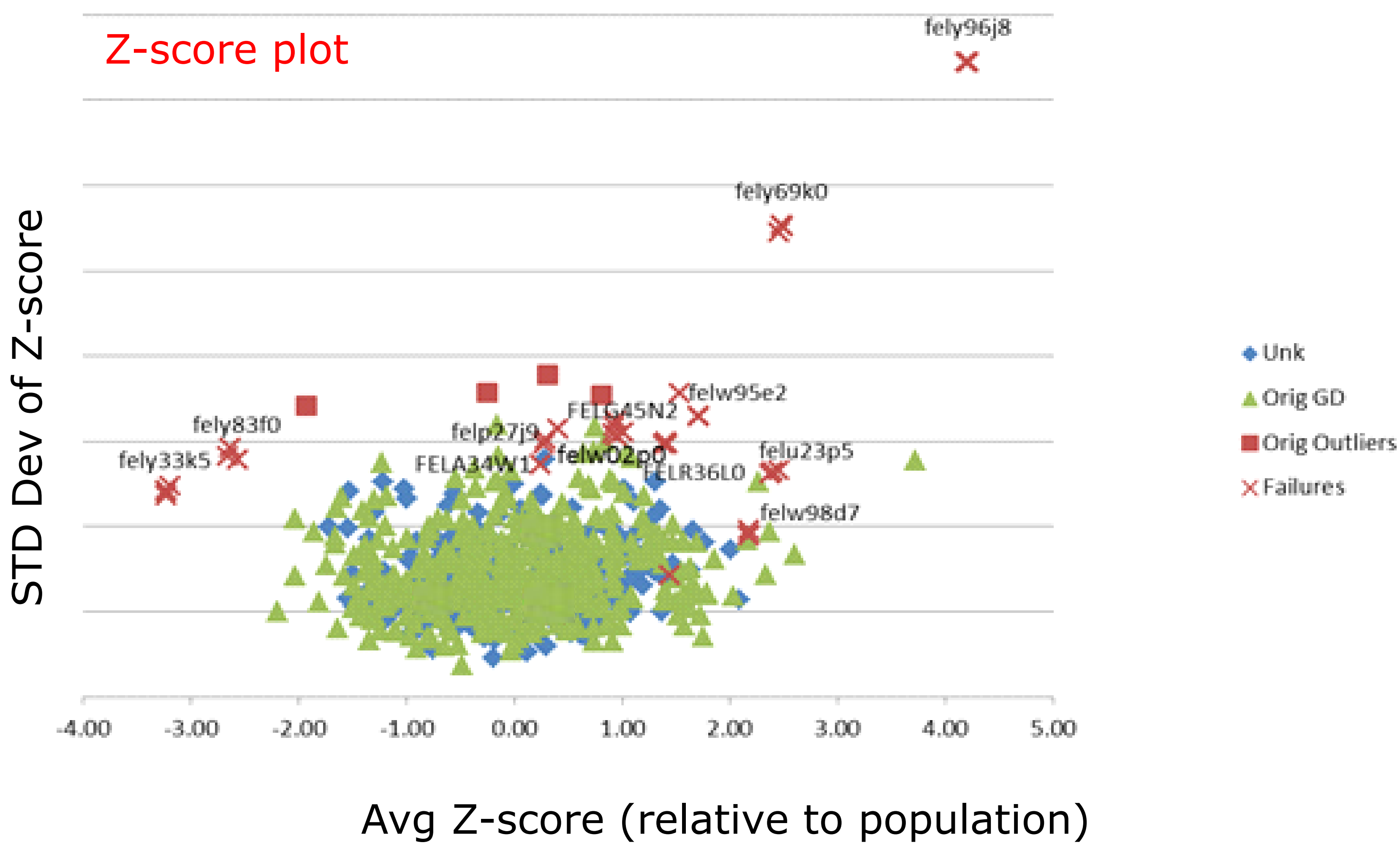


~0.7 % of brand new blade population resonates differently

Investigation reveals metallurgical issues

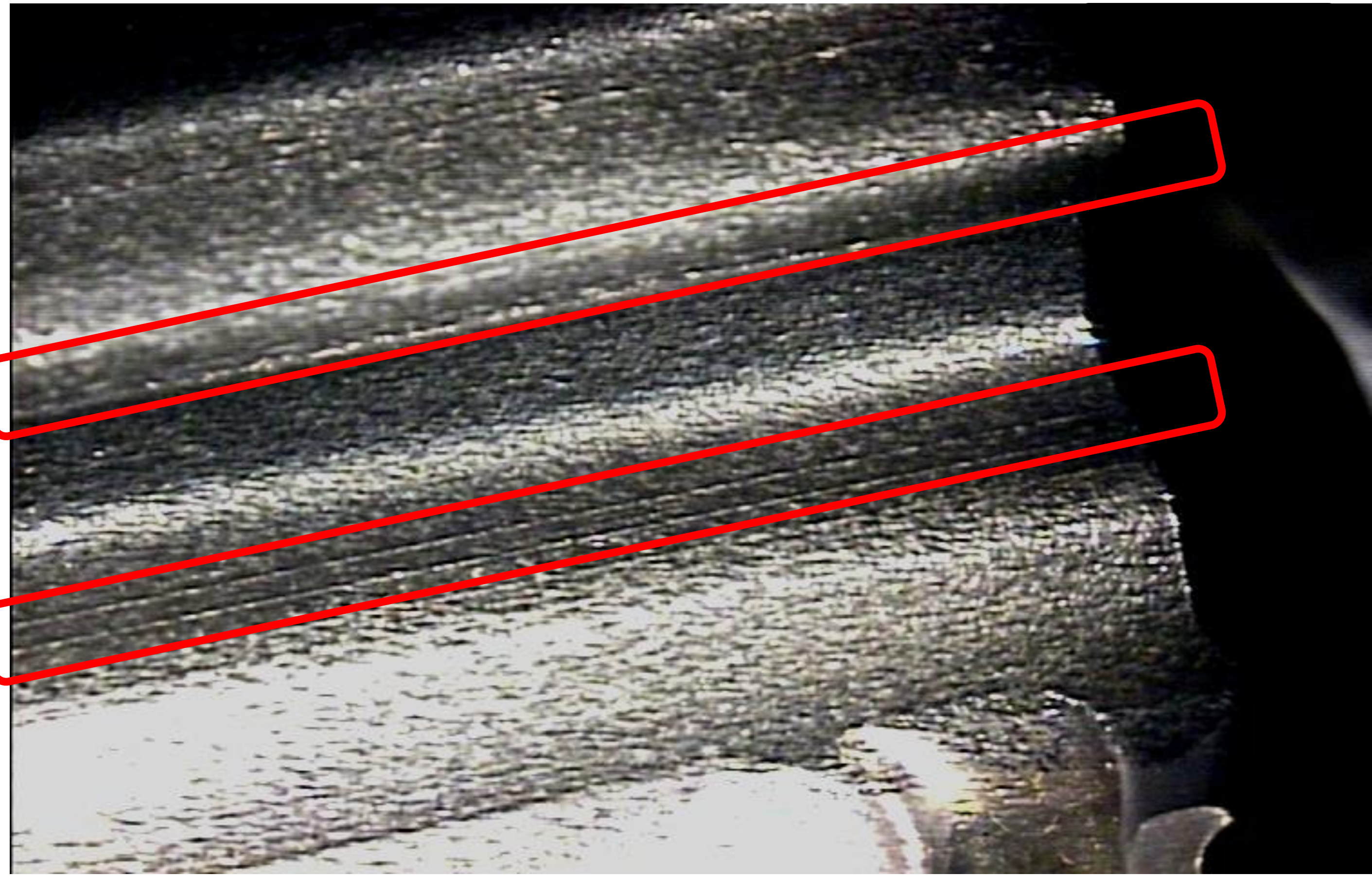
- Various NDT methods used to identify anomalies = Visual, Dimensional, X-ray, Eddy Current, Computed Tomography, Destructive Cut-ups
  - **Believe that PCRT is identifying metallurgical issues most likely formed during the solidification process during casting.** There is also the possibility that we are detecting some residual stresses in the fir tree due to aggressive machining.
  - For the casting issue, **the trailing edges have suspect areas that can be seen even visually.** Confirmed these issues with CT and DR.
  - **Eddy Current 'Edge of Contact' indications in known failure area**

Metallurgical issues noted on outlier 'new' blades

Rough Machining? Edge of Contact

Many Blades have rough machining right in the area where EOC issues occur and blades show slight indications using GE's EOC Eddy Current inspection = **'Starter notch'**

Many more areas in fir tree, but not in EOC inspection area



Starter notches in new blades? = Not in Delta engines!

Investigation reveals solidification issues

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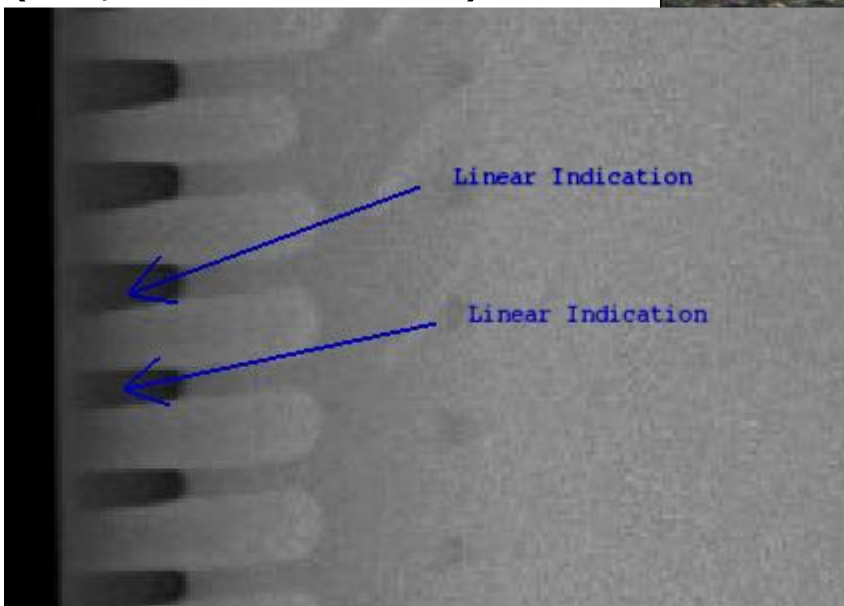
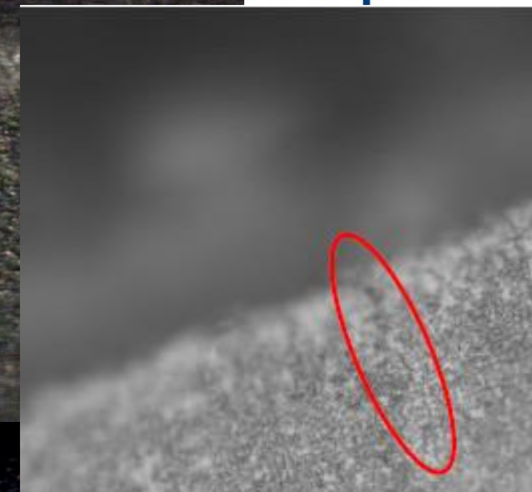
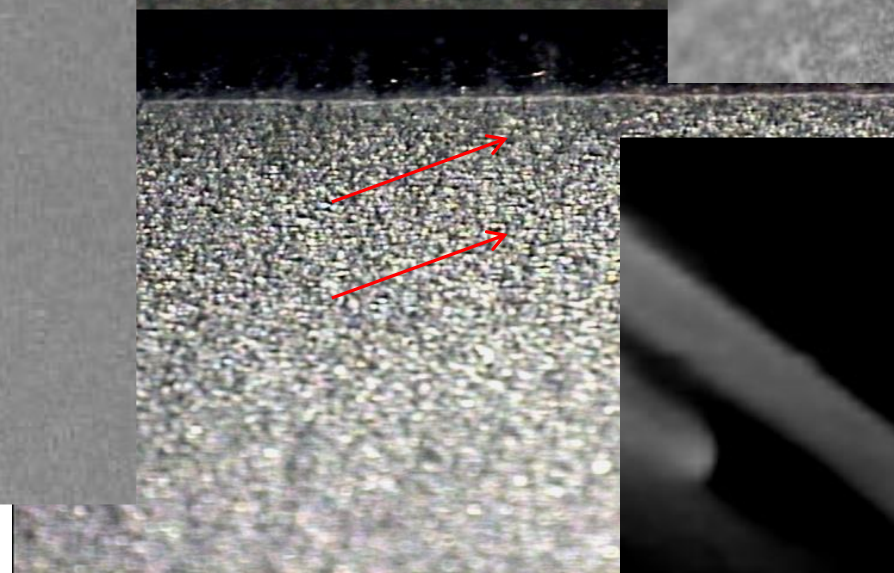
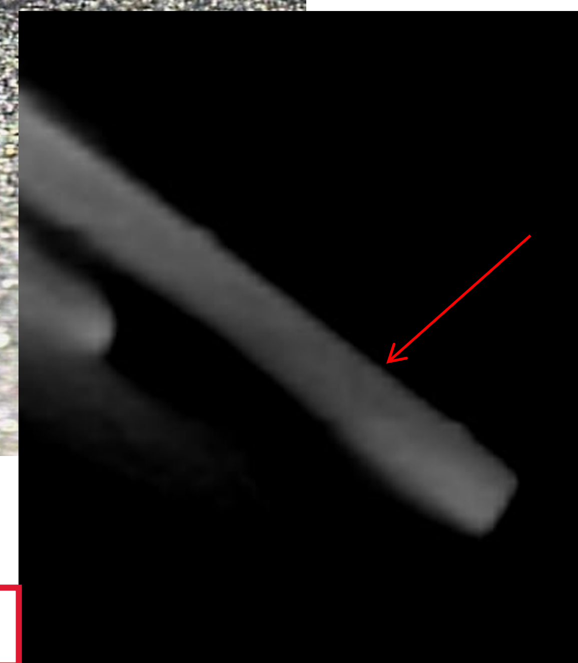
Numerous flow/solidification issues on the TE and possible micro-cracking (DR, CT and Visual)





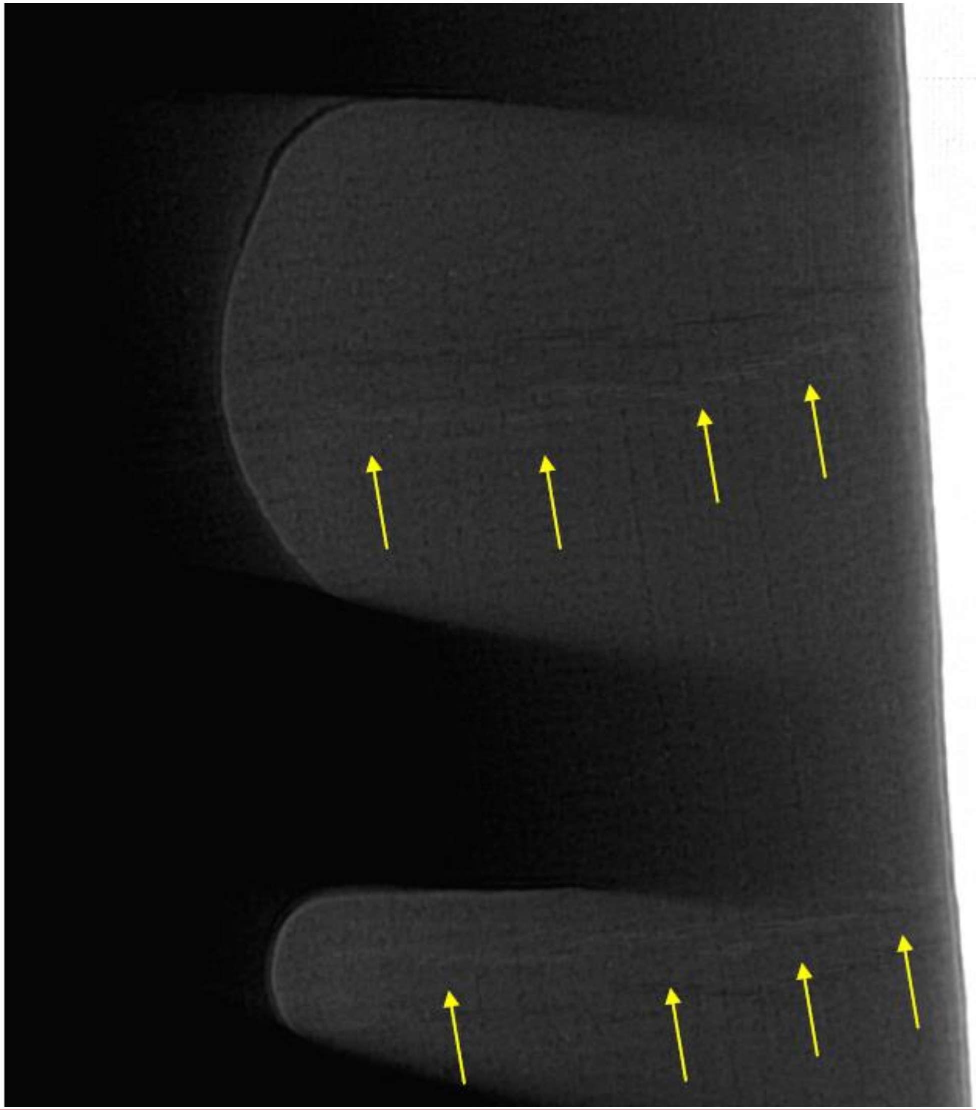




PCRT flagging parts for metallurgical issues

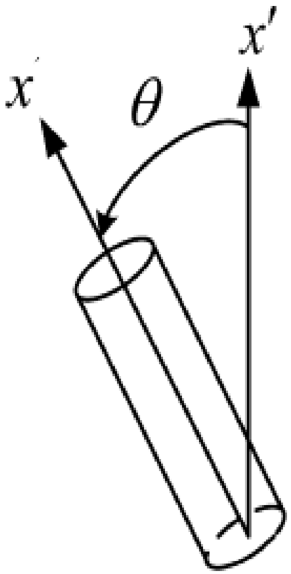
Indications perpendicular to grain angle…

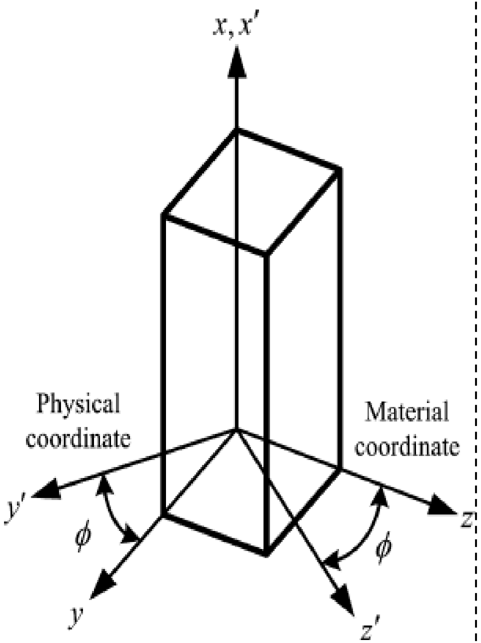
Indications along the TE cooling slots that run perpendicular to the primary grain angle

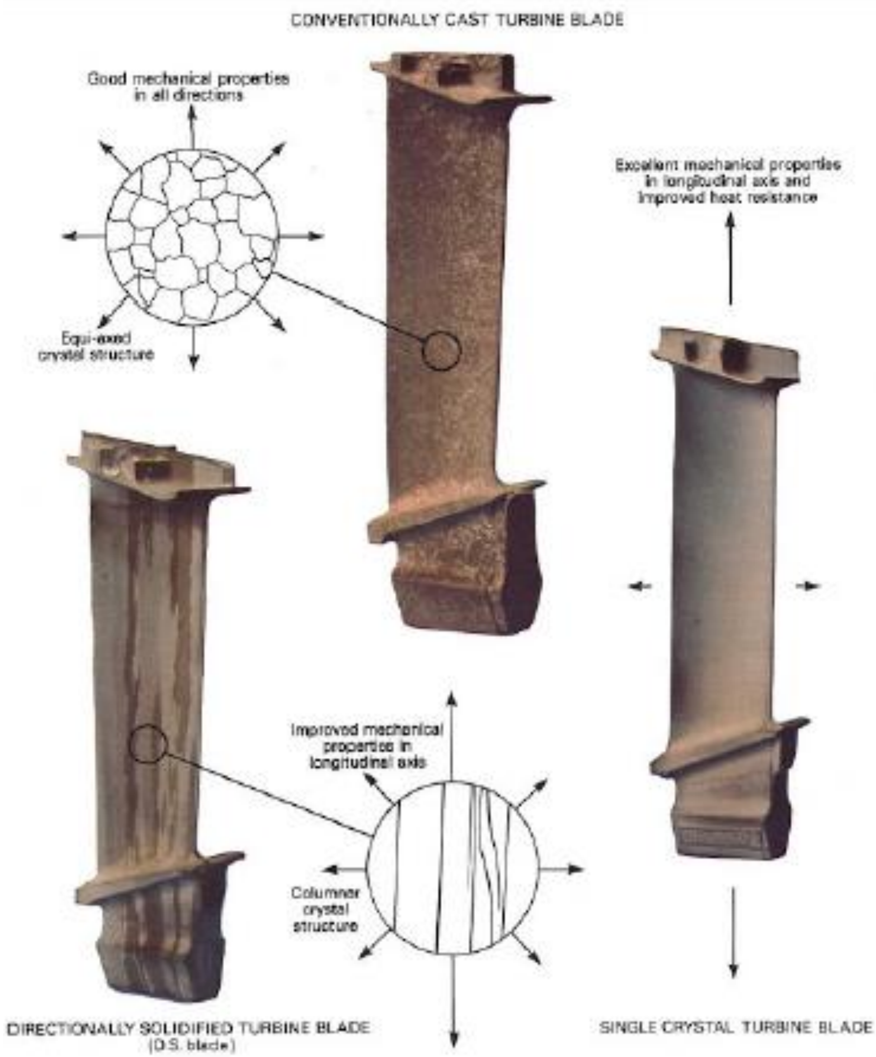


Perpendicular to grain angle = bad for mat'l properties

Affect material properties, life





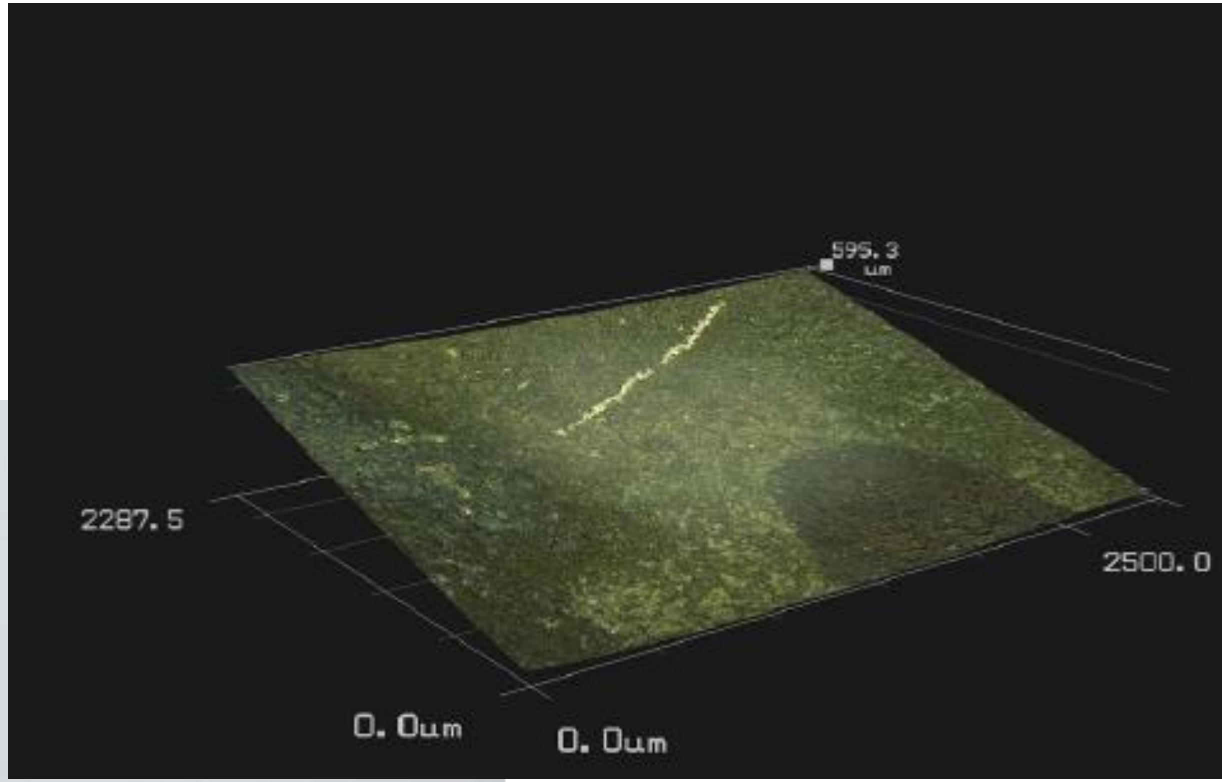


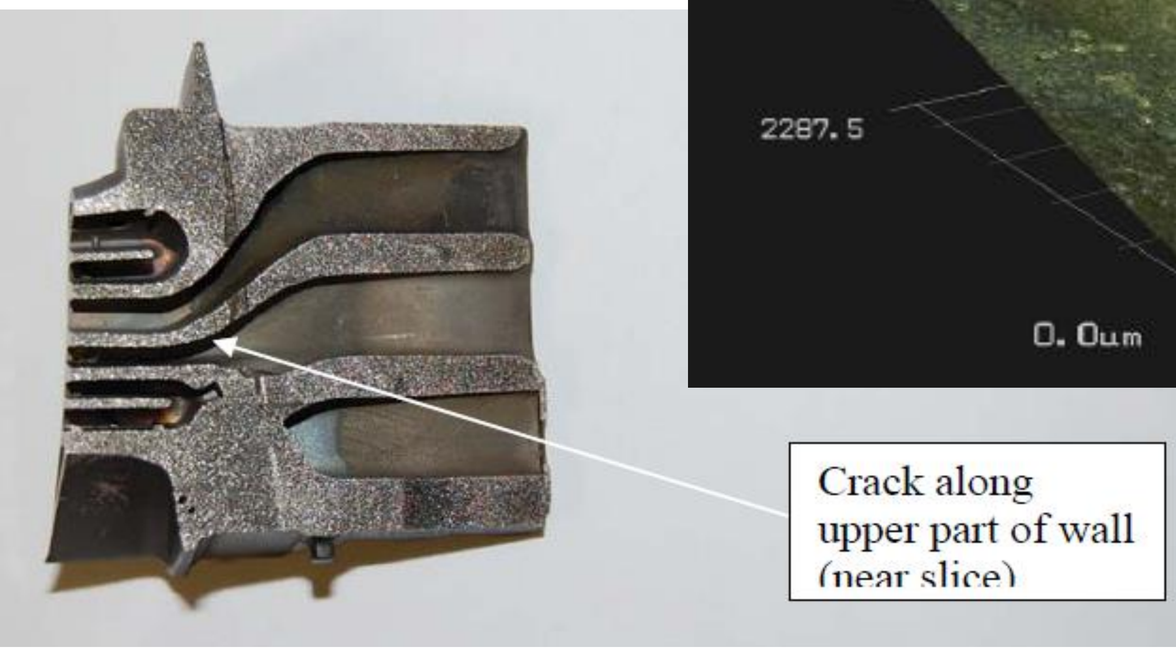
*C-M Kuo, "Effects of Disoriented Grains on the Elastic Constants of Directionally Solidified Superalloys", 2007

Ever changing 'soft-time' recommendations? 20K to 16K to 10K to…

Transition Zone cracking

Crack Length
= 0.060”





No current inspection for this crack

Even the newest Part Number!

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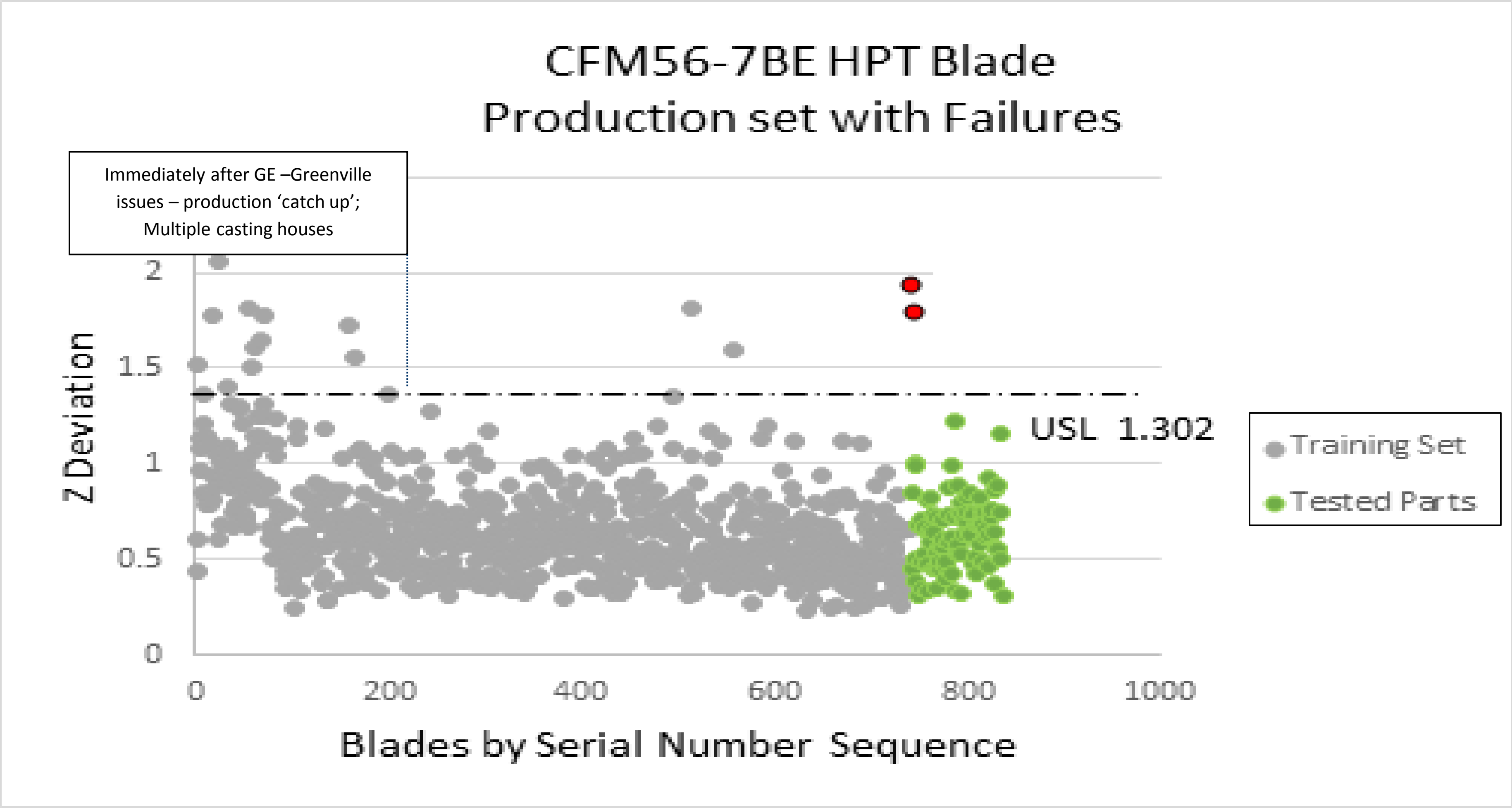

Larger variability with 'facility' issues

CFM56-7B T1 Blade – Newest blade

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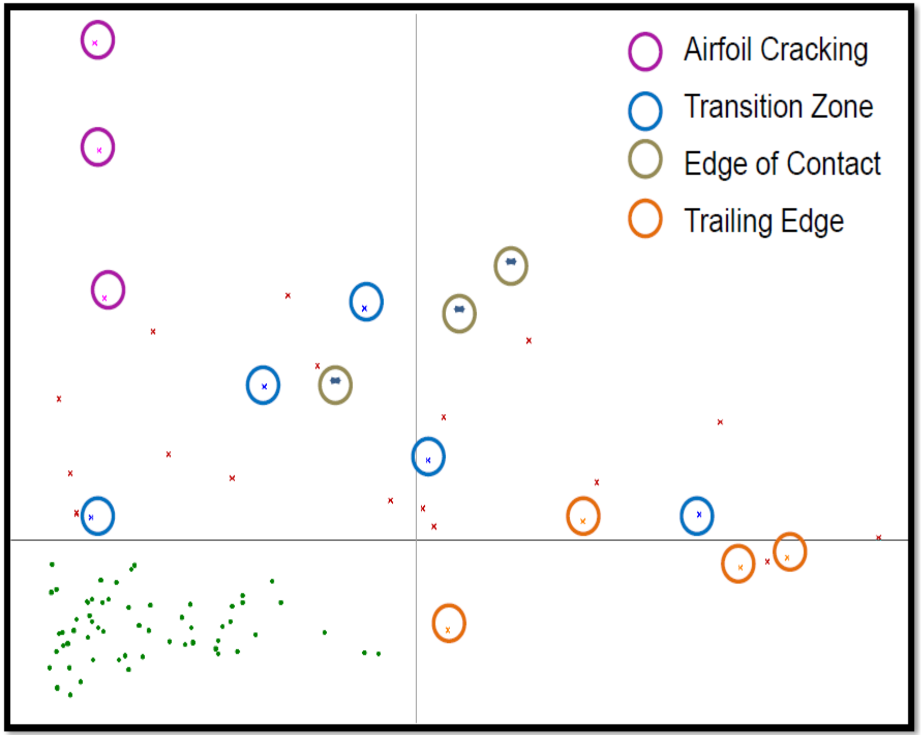
- Newest PN:
  - 99.5% confidence interval
  - 0.55% reject rate (after turning on accept/reject sort algorithm)
  - Blades noted with 'gouge' in EOC area
  - **Soft time reduced to 10K FH (1/2 of what we paid for!)**
  - **~20% scrap rate at 4K FH via Eddy Current EOC!**
  - All 'passed blueprint'

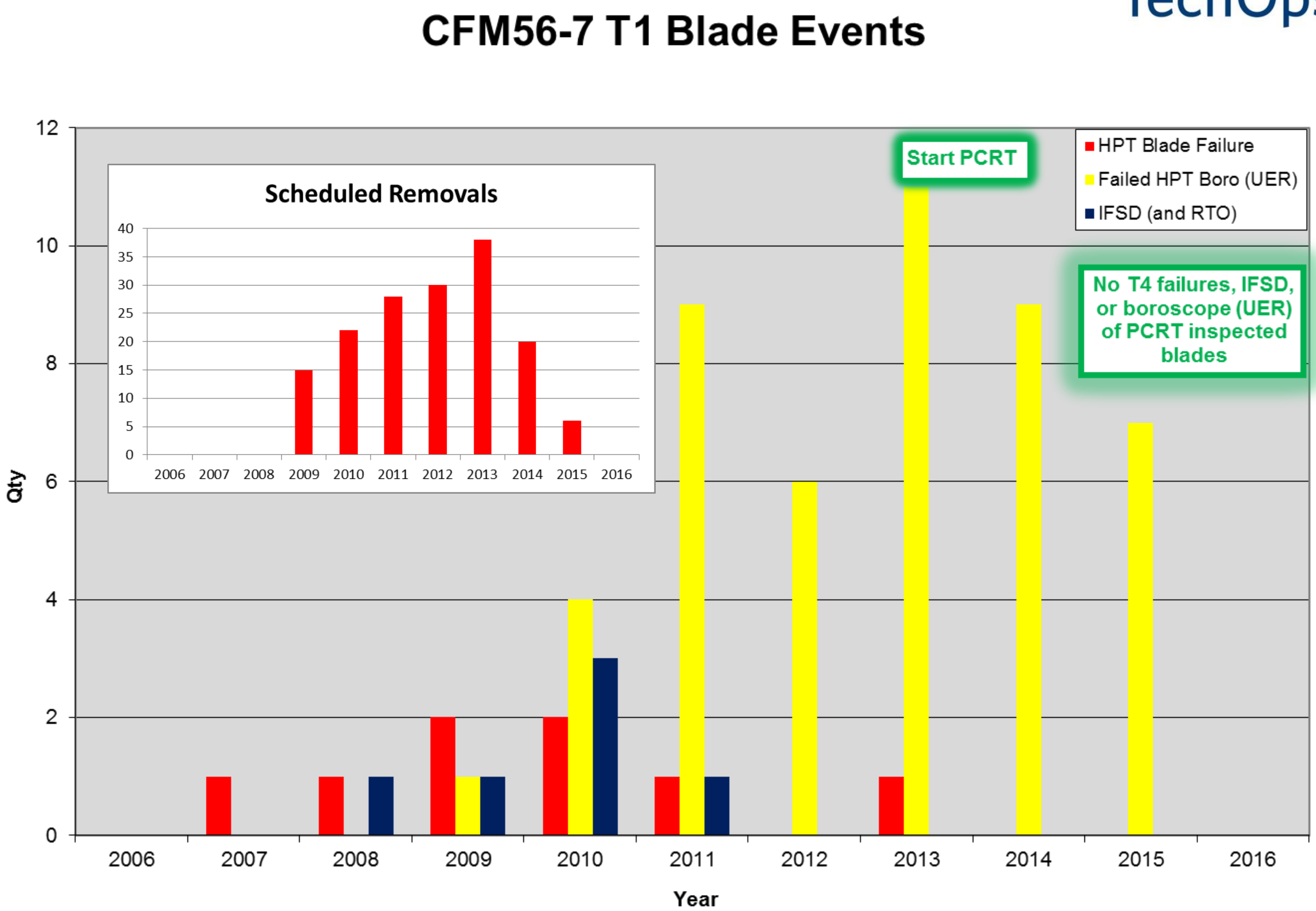
- No failures of PCRT inspected blades

- VIPR Plot for Serviced Blades
  - Lower left quadrant is pass
  - All others = fail
  - Metallographic correlation



High confidence of correlation of PCRT to defects

CFM56-7B T1 Pareto



Summary

- PCRT has been huge success at Delta, industry
  - Simultaneous increase in Fleet Reliability with decreased cost
  - Typically where no other NDT technique is applicable
    - Metallurgical defects
  - Proven with correlation to Lab destructive cut-up

- Mix of PCRT programs at Delta
  - Screening for Process Outliers
  - Targeted Defect Detection
  - Manufacturing/ repair Process Control (for existing and emerging processes)
  - PCRT Life Monitoring
  - Material Property Characterization