

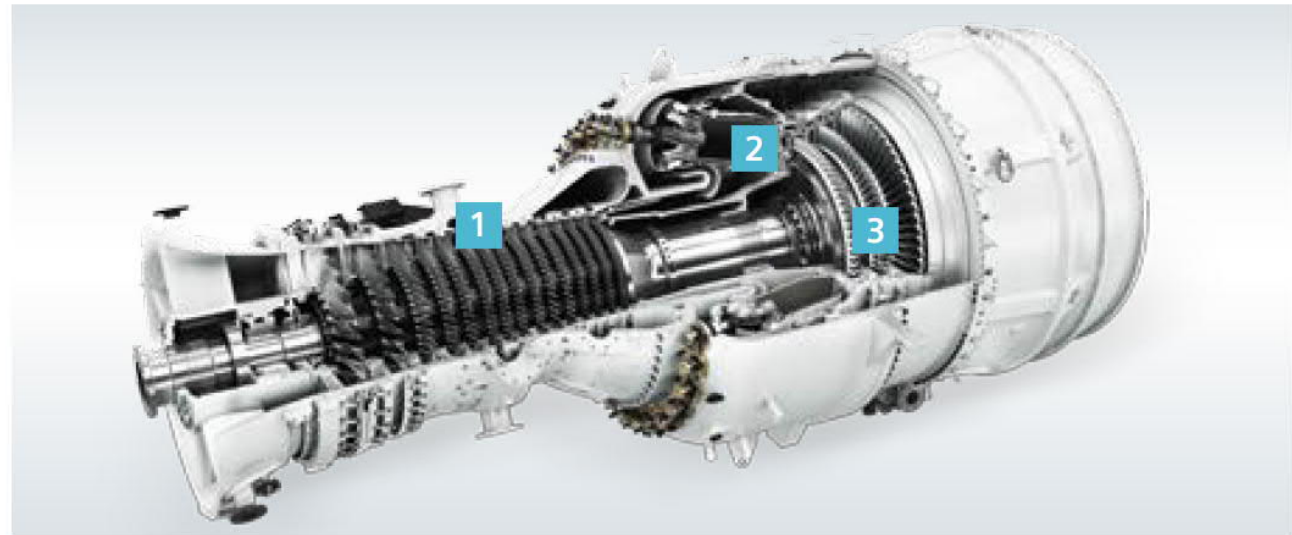
Process Compensated Resonance Testing of industrial gas turbine AM heat shields

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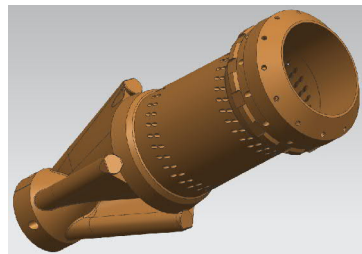
Siemens Industrial Turbomachinery

- Industrial gas turbines 5-60 MW
- Aero-derivative gas turbines
 - Core part manufacturing
 - Packaging



Additive Manufacturing at Siemens Industrial Turbomachinery

- Burner tip repair
- Orifice plates
- Burner fronts
- Workshop for prototypes and burner tip repair
- New workshop with 5 PBF- laser units for serial production



Utbyta brännare från gasturbin



Bearbetning för att få slät yta

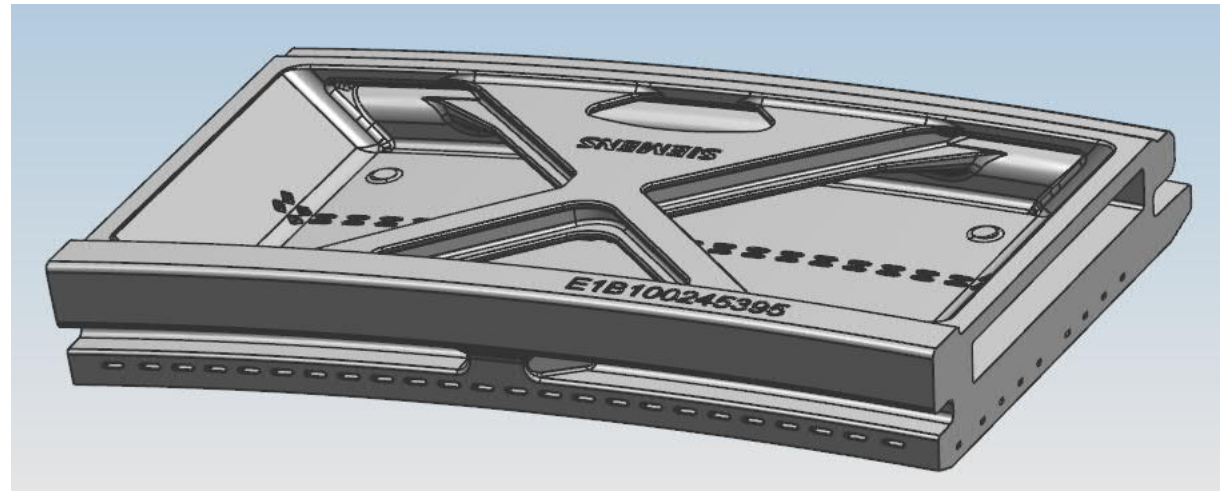


Efter reparation genom SLM



Additive Manufacturing of heat shields

- Powder Bed Fusion - Laser
- Oxidation resistant material
- Evaluation of different cooling channel configurations
- Printed parts to be installed in SGT-800 unit for evaluation
- Potential serial production part



AM validation heat shield were tested using immersion UT

- Testing carried out before machining, coating, and heat treatment
- 15 MHz-0,5" diameter, 2" focus
- High resolution scanning, long testing times





Designation: X XXXX-XX

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Standard Guide for Post-Process Nondestructive Testing of Metal Additively Manufactured Parts Used in Aerospace Applications¹

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NDT of AM products

- Red dye penetrant used for testing of production parts in Finspång
- PCRT included in ASTM standard for AM NDT

TABLE 5.2 Application of NDT during the Life Cycle of Additive Manufactured Parts^A

METHOD	Product and Process Design and Optimization	In-Process Monitoring	Post-Process Inspection	In-Service Remove and Inspect	Health Monitoring	Structural Health Monitoring	<i>in-situ</i>
CT	X	...	X^C	X	...	...	...
MET ^B	...	...	X	X	...	...	...
PCRT	X	...	X^C	X	...	...	...
PT	...	...	X	X	...	...	...
RT	...	...	X	X	...	...	...
TT	...	...	X	X	...	...	...
UT	...	...	X	X	...	...	...

^A Abbreviations used: ... = not applicable, CT = Computed Tomography, MET = Metrology, PCRT = Process Compensated Resonance Testing, PT = Penetrant Testing, RT = Radiographic Testing, TT = Thermographic Testing, UT = Ultrasonic Testing.

^B Includes post-process methods using visible light, structured light, and lasers.

^C Suitable for Design Complexity Group 5 parts.

TABLE 5.1 General Inspection Capabilities for Selected Conventional Post-Process NDT Techniques for Additive Manufactured Parts^A


METHOD	Material and Flaw Types Detected	Surface or Interior Defect Sensitivity	Global Screening or Detect Location
CT	In any solid material, any condition and/or defect affecting X-ray absorption	Surface and subsurface	Detects and images location
CT, microfocus	In any solid material, any condition and/or defect affecting X-ray absorption	Surface and subsurface	Detects and images location
MET	In any solid material, any condition and/or defect affecting visible, structured and laser light reflection	Surface	Detects and images location
PT	Any solid material. Discontinuities - cracks, pores, nicks, others	Surface breaking	Detects and images location
PCRT	Any solid material. Any defect or condition	Surface and subsurface	Global screening
RT	In any solid material, any condition and/or defect affecting X-ray absorption	Surface and subsurface	Detects and images location
TT	In any solid material, any condition and/or defect affecting heat conduction	Surface and subsurface	Detects and images location
UT	In any solid material, any condition and/or defect affecting sound attenuation, propagation, acoustic velocity and/or sensor-part juxtaposition	Surface and subsurface	Detects location

^A Abbreviations used: ... = not applicable, CT = Computed Tomography, ECT = eddy current testing, IR = Infrared, PCRT = Process Compensated Resonance Testing, PT = Penetrant Testing, RT = Radiographic Testing, TT = Thermographic Testing, UT = Ultrasonic Testing.

^B Includes in-process and post-process methods using visible light, structured light, lasers, and non-visible wavelengths (IR and near-IR).

Process Compensated Resonance Testing, PCRT

- Based on two ASTM standards
- Vibrant NDT is the main (only?) supplier of equipment and services
- Not to be confused with Impulse testing

ASTM E2534 - 15 

Standard Practice for Process Compensated Resonance Testing Via Swept Sine Input for Metallic and Non-Metallic Parts

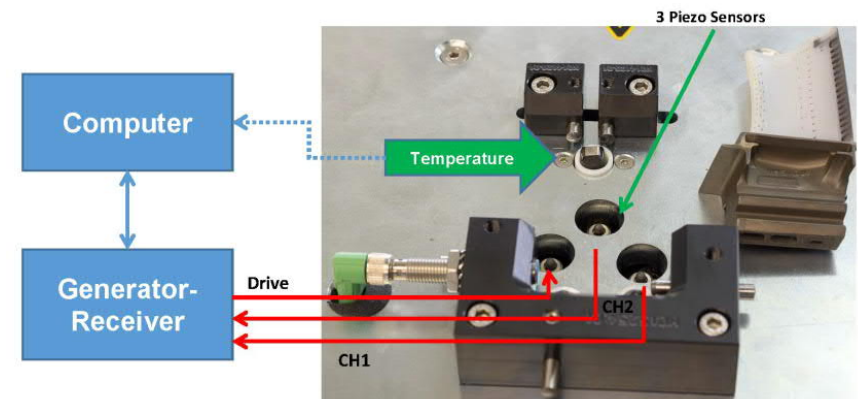
ASTM E3081 - 16 

Standard Practice for Outlier Screening Using Process Compensated Resonance Testing via Swept Sine Input for Metallic and Non-Metallic Parts



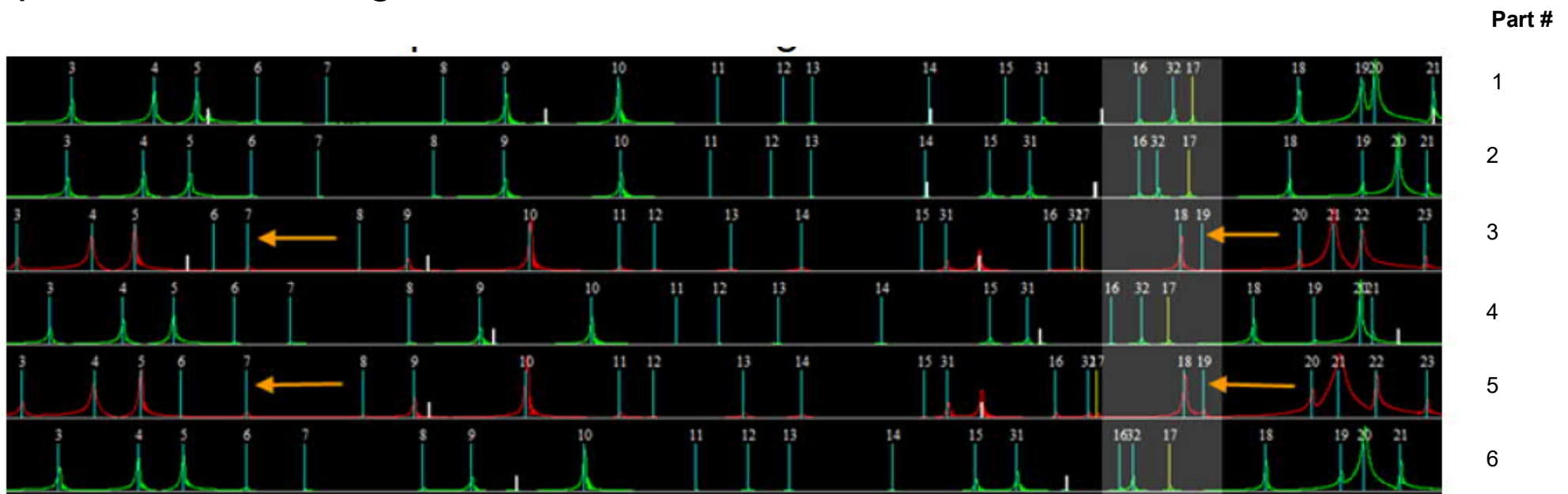
Process Compensated Resonance Testing, PCRT

- Measurement of patterns of multiple resonance frequencies in 1kHz – 20MHz range
- Resonant frequencies are determined by the dimensions and material properties of the whole component
- PCRT is not a focused inspection but is instead a full body inspection
- “Black box” testing: No operator interpretation, test is Go/No-go



Process Compensated Resonance Testing, PCRT

- The multi-frequency pattern can be used for defect detection and/or process monitoring

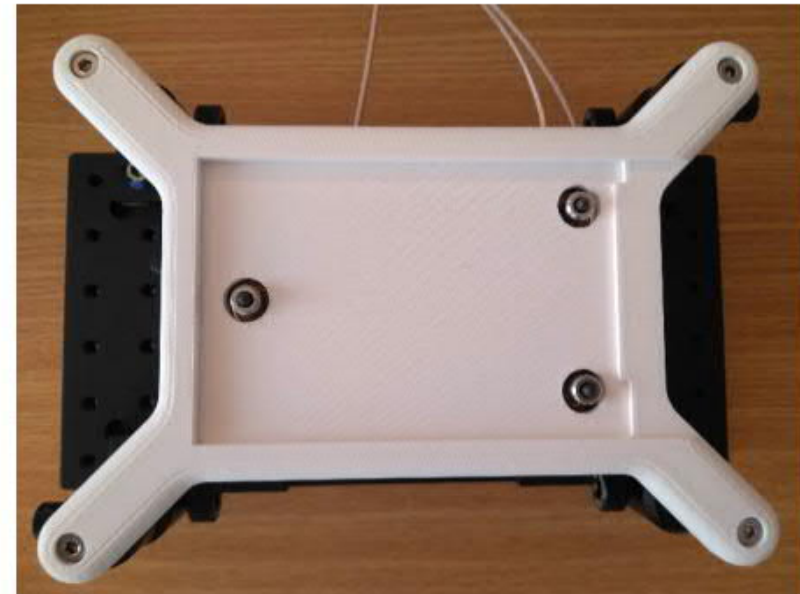
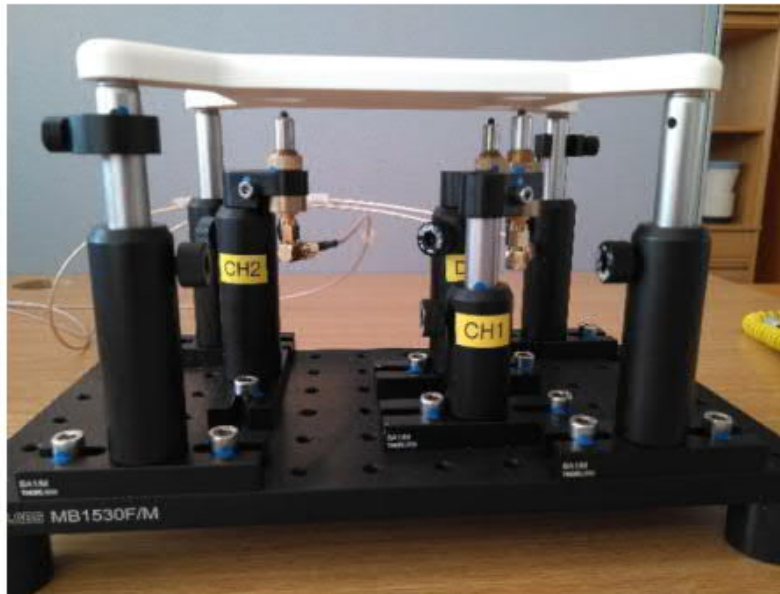


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- h
- MTS Fail** – part looks unlike good parts
- Bias limit**
- Bads**
- Goods**
- MTS limit**
- Pass**
- Pass**
- BIAS Fail** – part looks more like other bad parts



PCRT of AM heat shields, overview

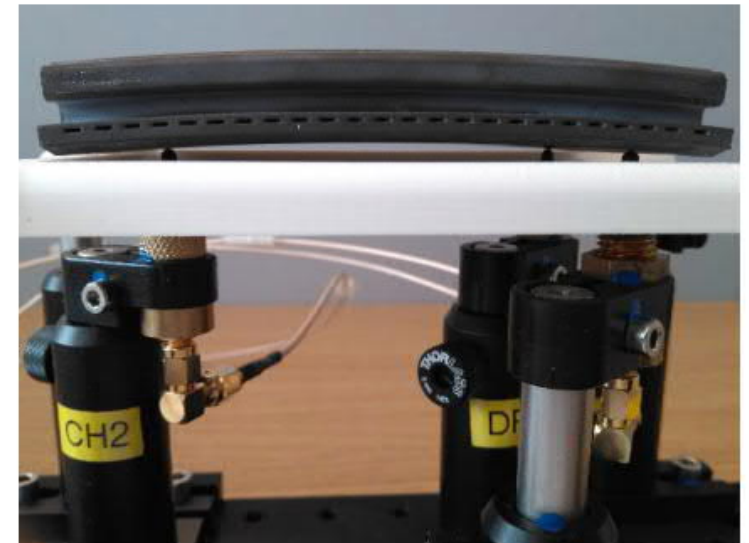
- Two heatshields were sent to Vibrant in Germany for design and testing of PCRT fixture



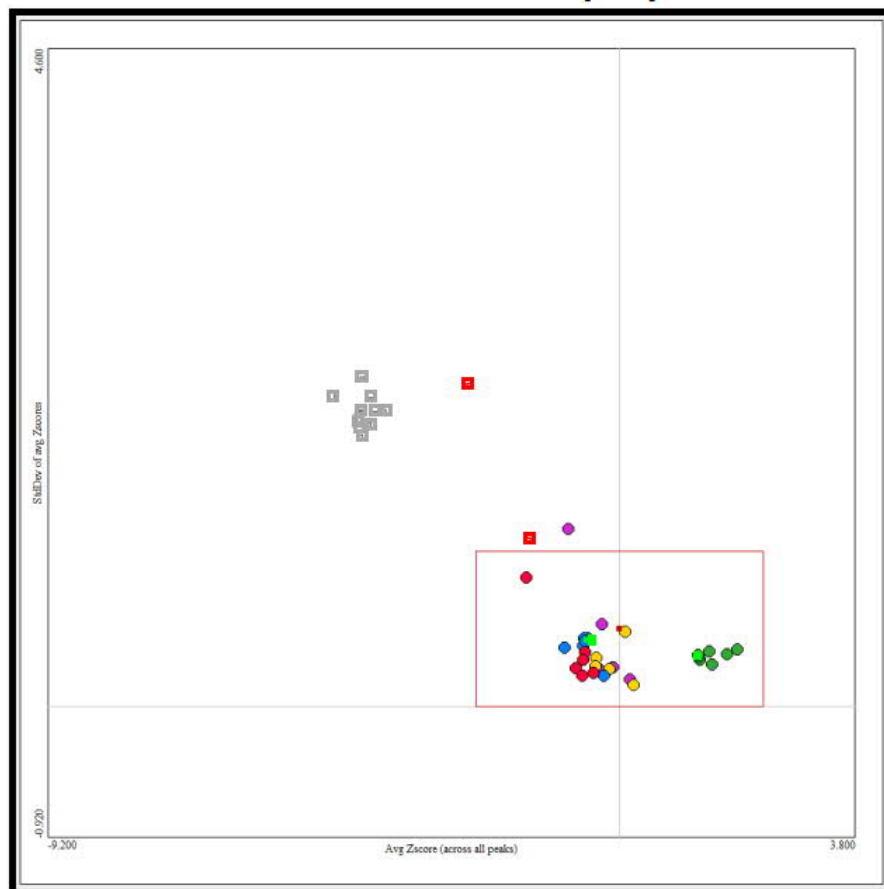
- PCRT equipment sent to Finspång for data collection on printed parts

PCRT of AM heat shields, setup and scope

- Temperature and mass of each heatshield was recorded
- 78 useable resonance frequencies in the range 1kHz to 66 kHz were identified
- Time required for complete sweep: <5 min
- 47 production parts from 8 batches were tested
- Two parts with visual cracking were also tested



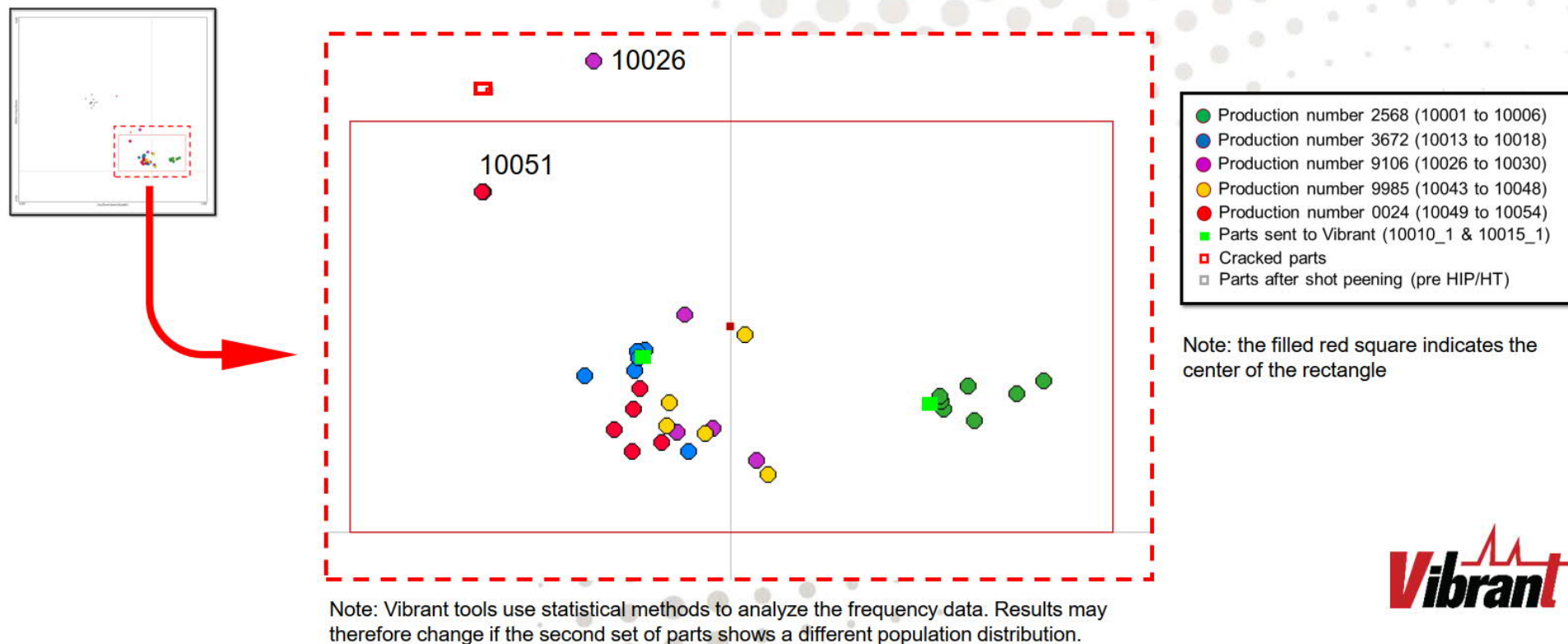
PCRT of AM heat shields, initial Z-score results



- Production number 2568 (10001 to 10006)
- Production number 3672 (10013 to 10018)
- Production number 9106 (10026 to 10030)
- Production number 9985 (10043 to 10048)
- Production number 0024 (10049 to 10054)
- Parts sent to Vibrant (10010_1 & 10015_1)
- Cracked parts
- Parts after shot peening (pre HIP/HT)

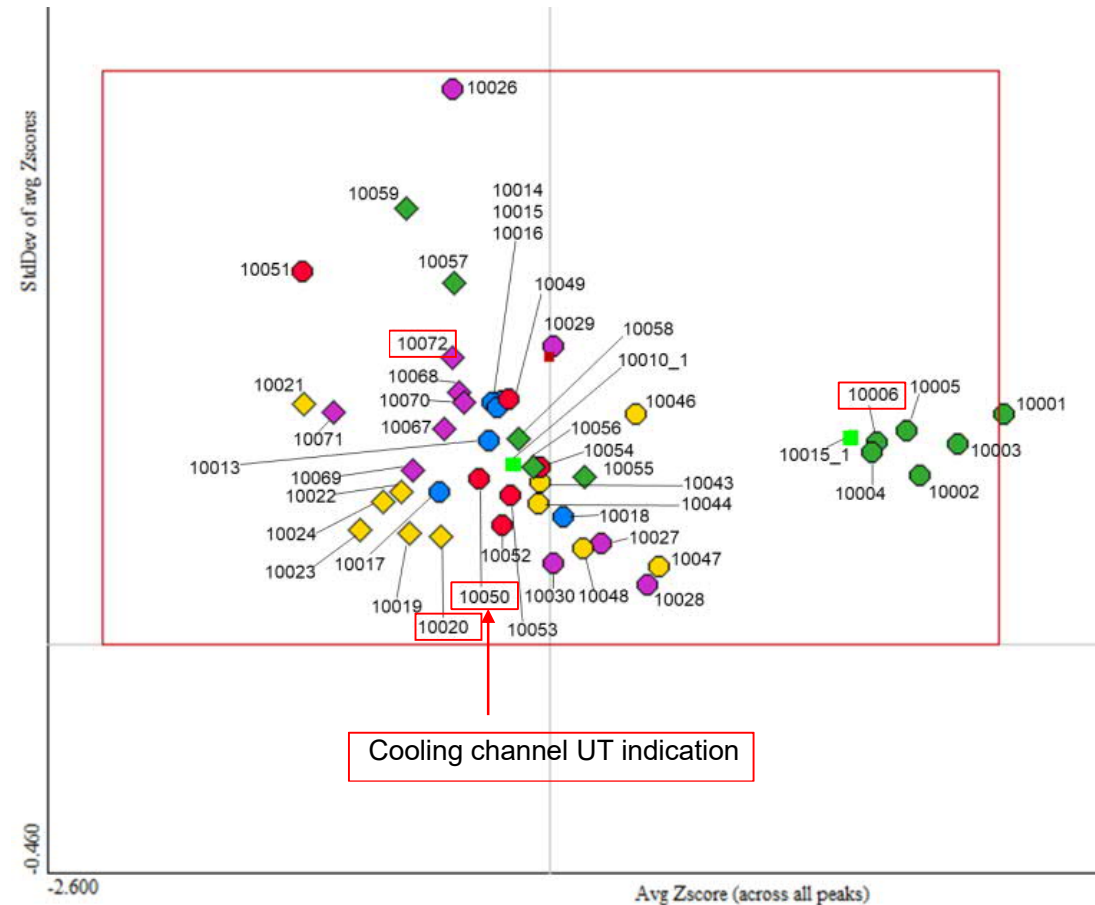
* Note: the red rectangle represents a 99% confidence interval

PCRT of AM heat shields, initial Z-score results

**Vibrant**

PCRT of AM heat shields, final Z-score results

- Data from 22 frequencies
- Cracked and pre-HT parts not included
- The red rectangle represents a confidence interval of 99%
- Several batches are tightly grouped
- Parts in batch 2568 were 2,4% heavier



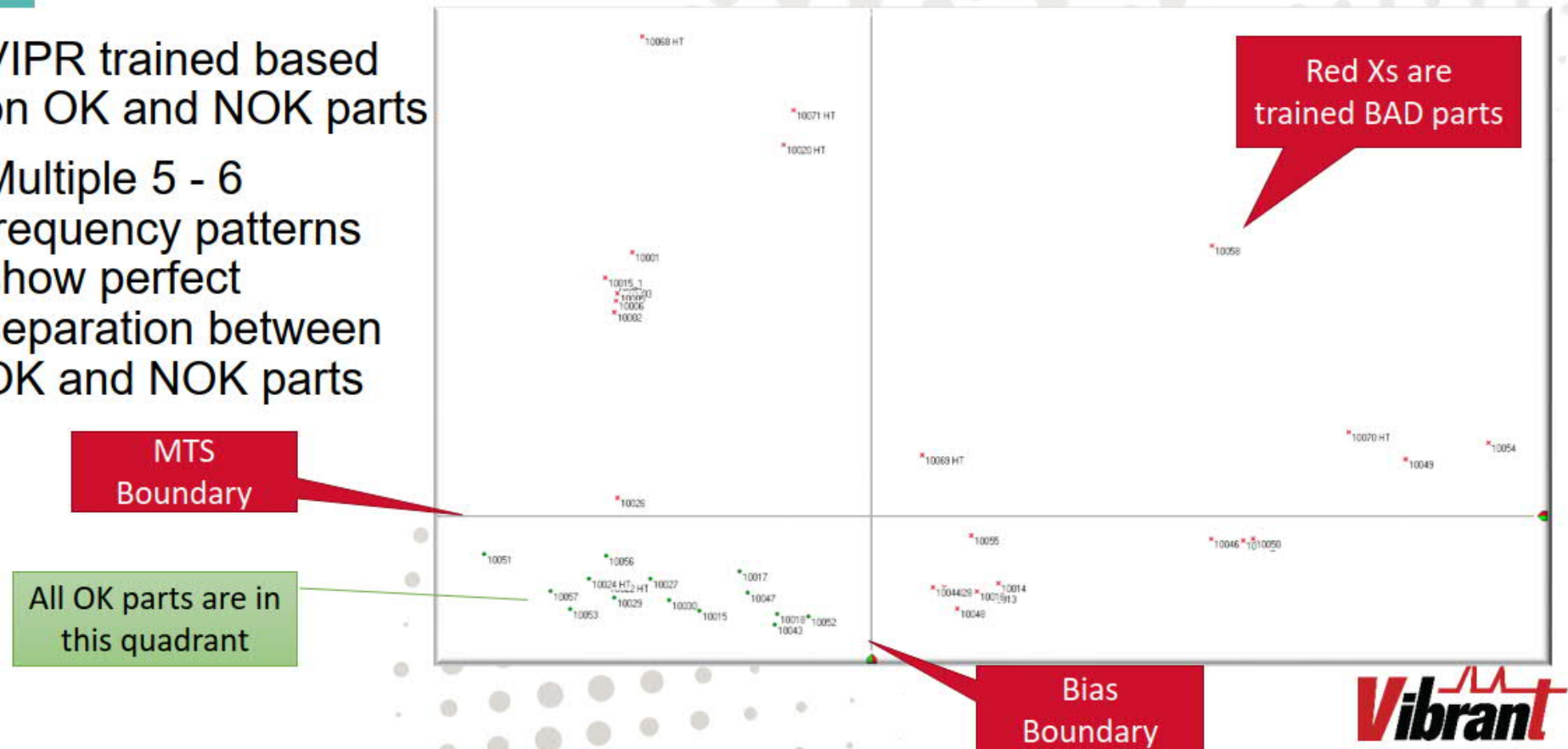
PCRT of AM heat shields, final Z-score results

- Parts with defect cooling channels could not be identified using Z-score
- Heat shield 10026 was sectioned for metallographic examination but no defects except the ~~cooling channel cracks~~ were found
- Vibrant requested information about good and bad parts for VIPR training
- Due to misunderstandings, all parts that were not used for the ~~engine test~~ were considered not OK for the VIPR training. Some of these did not pass the flow test, but this was due to machining debris introduced after PCRT...

PCRT of AM heat shields, VIPR score results. Heat shields chosen for turbine use=OK. All other heat shields NOK

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- VIPR trained based on OK and NOK parts
- Multiple 5 - 6 frequency patterns show perfect separation between OK and NOK parts



Conclusions

- Vibrant NDT were very cooperative and professional, providing equipment, expertise and experience for the PCRT technique
- The PCRT technique requires a statistically significant number of good and bad parts, which might be difficult to obtain if the AM process is stable
- It is essential to provide correct input regarding good and bad parts to the VIPR training!

Additional testing: Comparative Cooling Test Rig

- Predefined transient
- Response of the surface temperature
- Core displacement, blocked channels
- Long term comparison

