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# Hard Spots NDE- Validation and Verification

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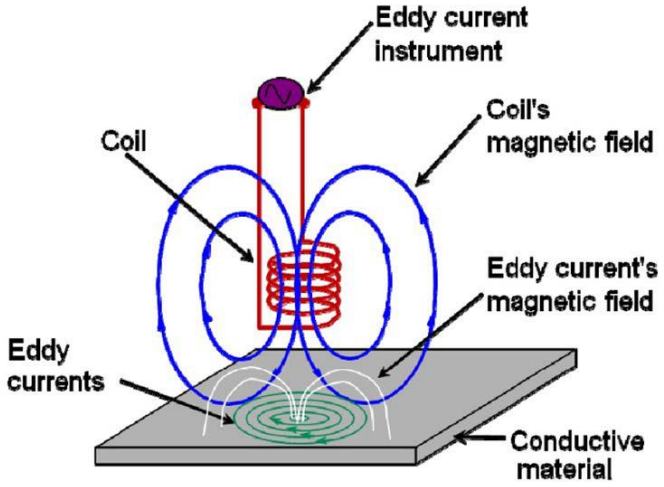
# Phase I (March 2017)



**HARD SPOT: Localized regions of increased hardness in high strength Thermo-mechanically Controlled Processed (TMCP) line pipe grades**

- Shallow small region of increased hardness (>248 $HV_{10}$)

- Review of existing and emerging technologies for hard spot detection
- Five different providers were identified
  - *ExxonMobil*
  - *Innospection*
  - *Voestalpine-Fortec*
  - *Rosen*
  - *Rohmann*
- All the technologies were based on eddy current and electromagnetic principles (permeability , retentivity and coercivity), but with unique ways of hard spot identification



# NDE 4-11 : Phase II (Aug 2018) – Focus of this Presentation



- **Technologies were relatively new with no publicly available data**
- **Detection and Discrimination data were not publicly available**
- **Objective**
  - ***Evaluate and assess the performance of the hard spot detection technologies***
  - ***Conducted in two stages***
    - ***Calibration testing***
    - ***Blind trials testing***
  - ***Finally, statistical evaluation of obtained results from the providers***

# Outline



- Calibration Phase
- Blind Trials Phase
- Statistical Evaluation
- Summary

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## Calibration Phase

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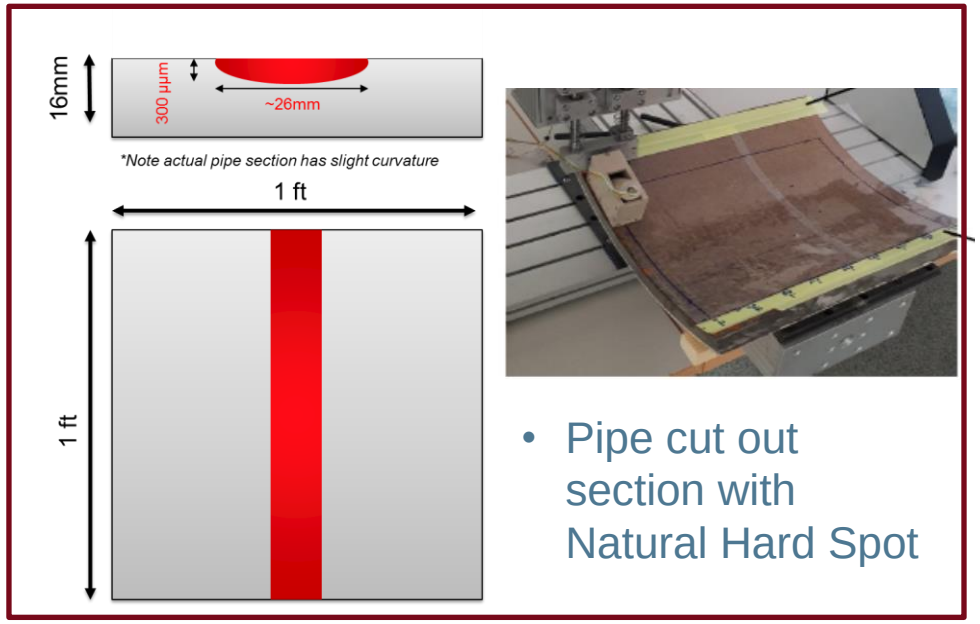
# Calibration



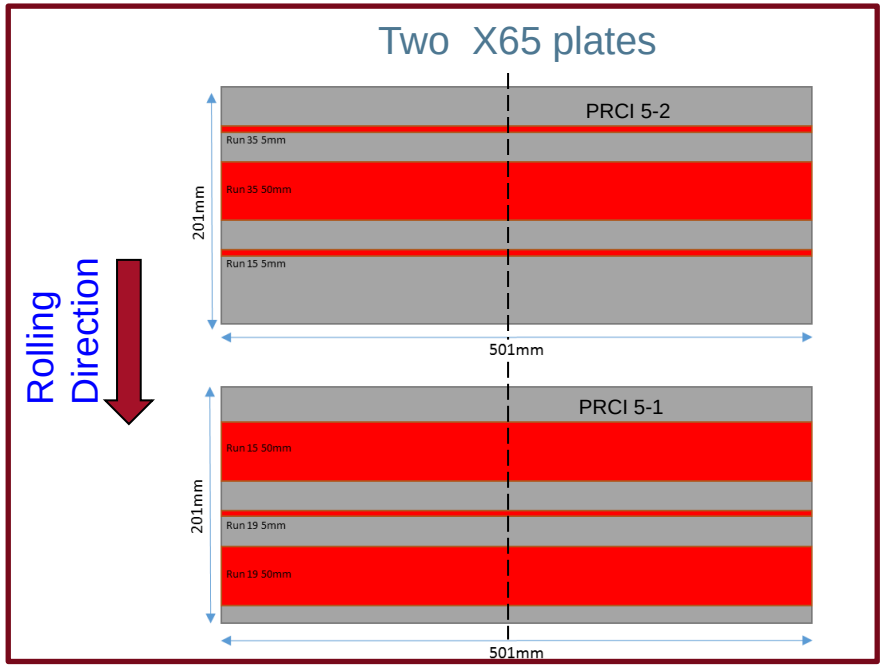
- **Electromagnetic Principles distinguish hardened zones from base**
  - Material specific
- **Assess the technologies on artificially laser-hardened zones**
  - Compare with natural hard zones
- **Define the laser parameters appropriate for the blind trials**




- Pipe cut out section with Natural Hard Spot

# Artificial Hard Spots






| Run# | Power, kW | Speed, m/min | Focal Position, mm | Spot Diameter, mm | Heat Input J/mm | Case Depth, µm |
|---|---|---|---|---|---|---|
| Run 35 | 3 | 20 | 60 | 4.8 | 0.493 | 75-90 |
| Run 15 | 3 | 5 | 100 | 8.0 | 0.714 | 160-205 |
| Run 19 | 3 | 20 | 40 | 3.25 | 1.09 | 125-127 |

- One half was circulated amongst technology providers to calibrate and evaluate their sensors
- Can they distinguish the natural hard spot and their comparison

# CALIBRATION



| | Run 35 (Tn) ~208 HV | Run 35 (Tk) ~219 HV | Run 15 (Tn) ~234 HV | Run 15 (Tk) ~279 HV | Run 19 (Tn) ~254 HV | Run 19 (Tk) ~ 306 HV | Natural Hardspots ~275 HV | Speed | Repeat'ty | Lift-off | Foot-print (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Voestalpine | | | | | | | | S | R | ~2mm | 40x20; 20x10 |
| Rohmann | | | | | | | | S | R | ~2mm | 10x10 |
| Rosen | | | | Detected | | | Detected | - | R | ~2mm | 20x20 |
| Innospection | | | | | | | | - | R | ~1mm | 2x2* |
| Exxon-Mobil | | | | | | | | S | R | ~2mm | 20x40 |

*Probes used; actual sensor footprint is 10 x10 mm

## Calibration Phase Conclusions

- Thin streaks (~5mm) hard spots were difficult to detect
- NDE response from Run 19 parameters are similar to the responses from natural hard spots
- Run 19 parameters produced hardness varying from 250-310 $HV_{0.1}$ comparable to natural hard spot;
- Run 19 had a smallest spot diameter, which can be leveraged to create defects of varying sizes

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## Blind Trials Phase

**Creating artificial hard spots**
**Verification / Validating defects**
**Execution and Assessment of Technologies**

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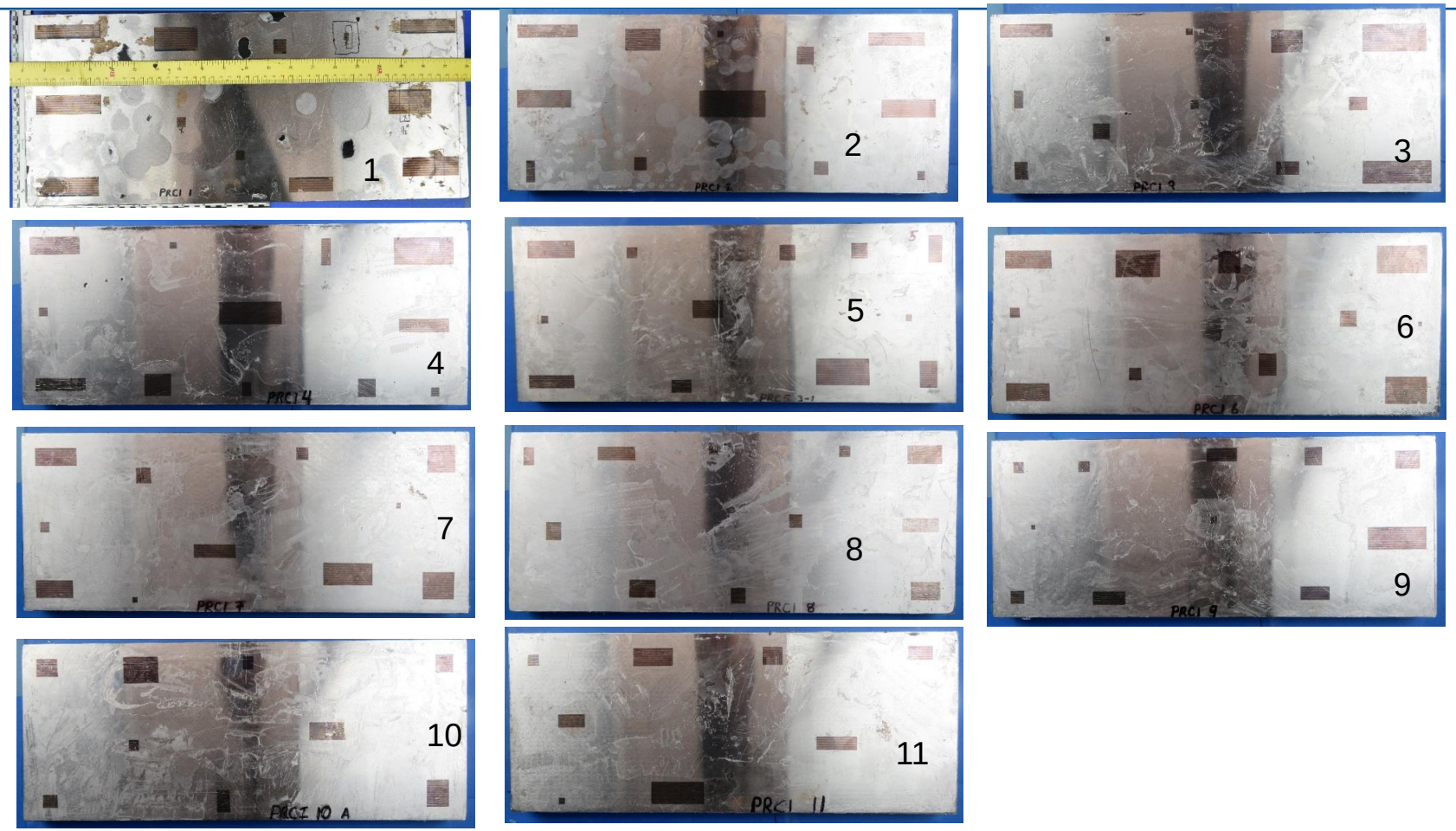
# Test Plates

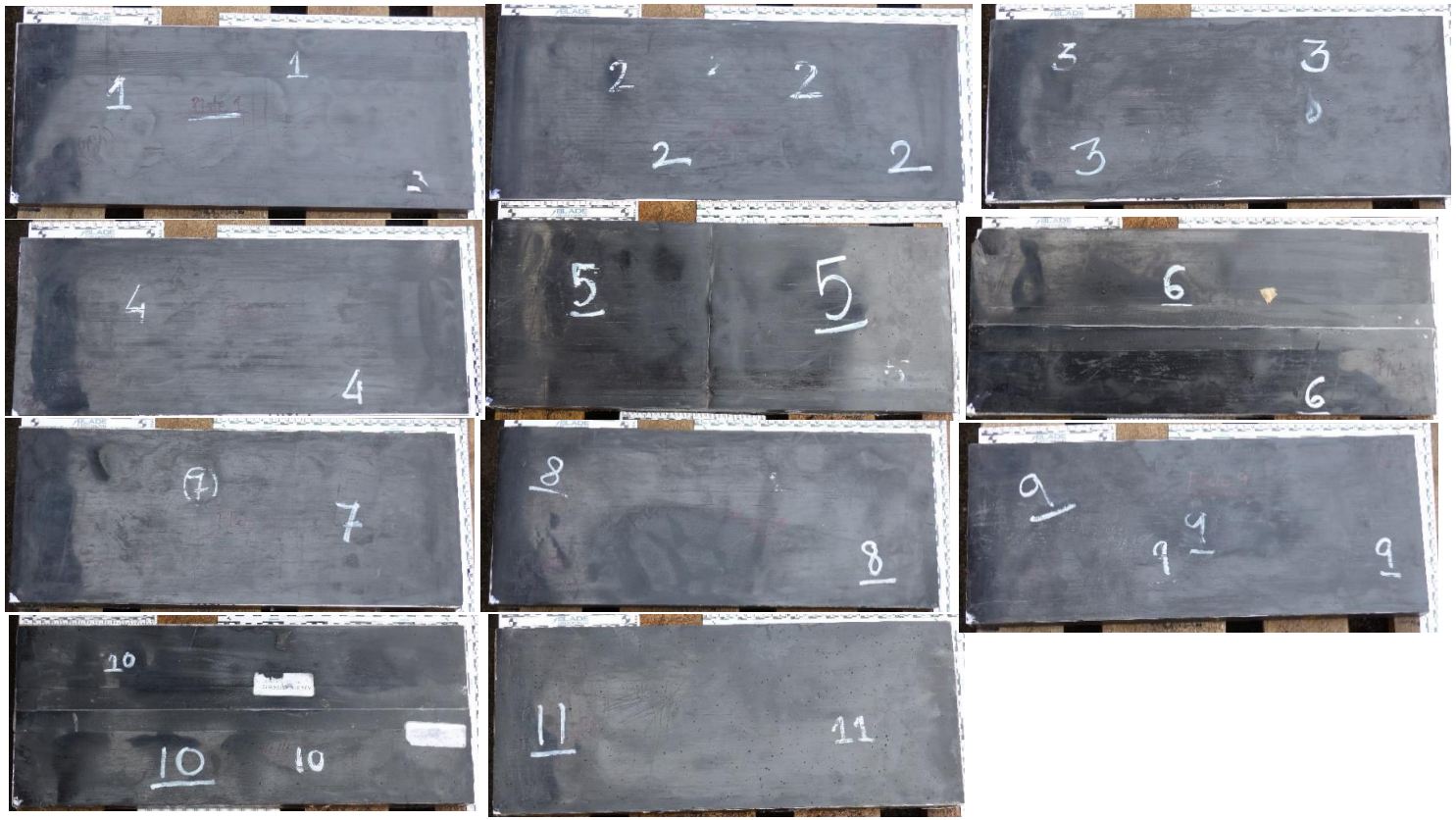





X65 Plates (500 mm × 200 mm) with 121 hard spots with sizes varying from 5 to 75 mm. Length was verified before and after the trials.

# Defect Concealment



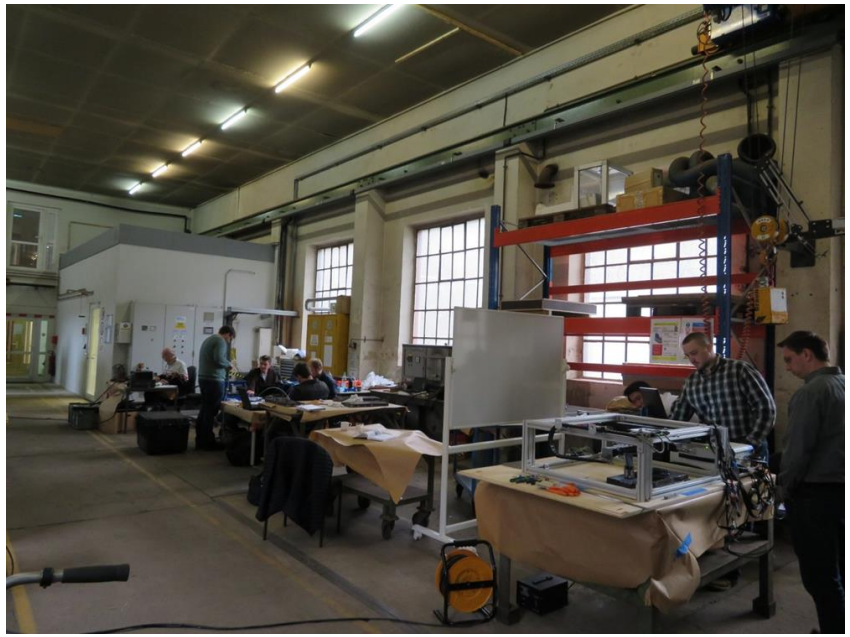



Plates surfaces were glued with  1mm thick black opaque ABS sheets

# Blind Trials Phase



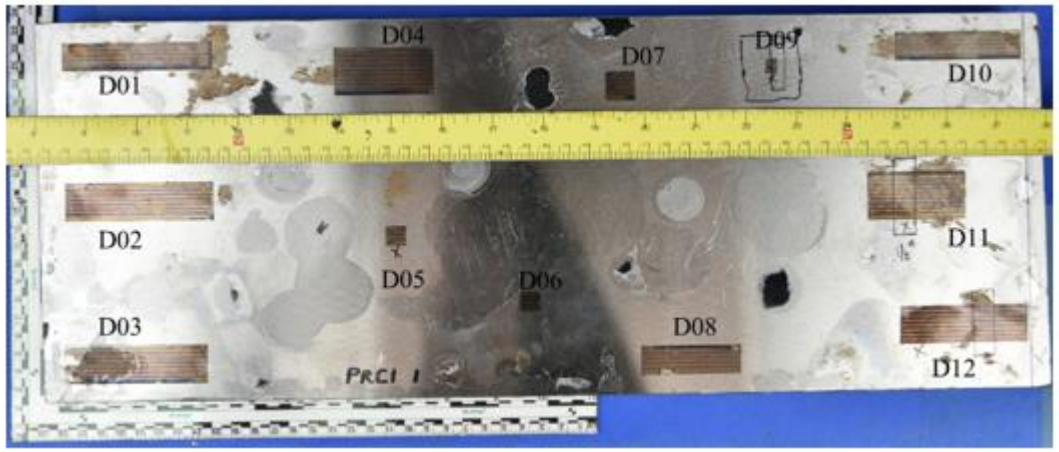
- Conducted at Dillinger Facility in Germany from 1st -12th April, 2019
- 121 hard spots with sizes varying from 5 – 75 mm were fabricated (i.e., Run-19 parameters)
- Technology providers came to the facility and participated in turn to assess their technologies
- A detailed blind trials protocol was followed by all the providers. All the providers had 3 days to scan 11 surfaces and evaluate their technologies.

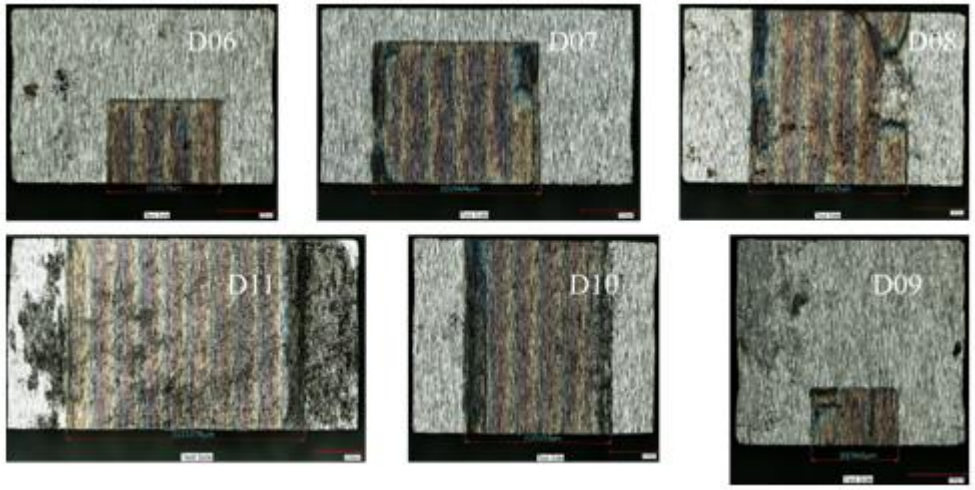


Dillinger Hutte Facility, showing an overview of blind trials testing

# Hard Spot Validation






| Sectioned Defect | Defect Dimensions | Average | Maximum | Minimum | Top 5 | Top 10 |
|---|---|---|---|---|---|---|
| B01 | Base Material | 199 | 226 | 182 | 219 | 214 |
| B02 | | 199 | 229 | 185 | 217 | 214 |
| D1 | 15 x 75 | 215 | 251 | 191 | 243 | 239 |
| D2 | 20 x75 | 225 | 291 | 188 | 288 | 283 |
| D3 | 20 x 70 | 221 | 266 | 190 | 254 | 250 |
| D4 | 25 x 50 | 228 | 293 | 173 | 288 | 283 |
| D5 | 10 x 10 | 209 | 255 | 190 | 249 | 240 |
| D6 | 10 x 10 | 208 | 269 | 178 | 262 | 253 |
| D7 | 15 x 15 | 209 | 281 | 185 | 268 | 259 |
| D8 | 15 x 50 | 206 | 267 | 181 | 261 | 251 |
| D9 | 6 x 6 | 208 | 246 | 187 | 244 | 241 |
| D10 | 15 x 65 | 210 | 288 | 179 | 272 | 266 |
| D11 | 25 x 50 | 209 | 251 | 176 | 244 | 241 |
| D12 | 20 x 65 | 222 | 299 | 181 | 285 | 279 |

# Blind Trials Summary

- **A detailed blind trials protocol followed by all the providers. Following runs from all technology providers:**
  - Eleven plate surfaces inspected at an optimum speed
  - One plate surface inspected at three different speed
  - One plate surface inspected thrice at their optimum speed
- **Results (including the defect maps and the defect dimensions) were provided to Blade for statistical analysis**

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# Statistical Evaluation

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# Statistical Evaluation



- Defect map indicating the defect position were compared with the original defect layout
- Centroid position and defect dimensions (length, width) were compared with the original defects.
- Defects dimensions were divided into eight different size groups (5-10, 10-15, …, 50+ etc.) and assessments were conducted for eight groups

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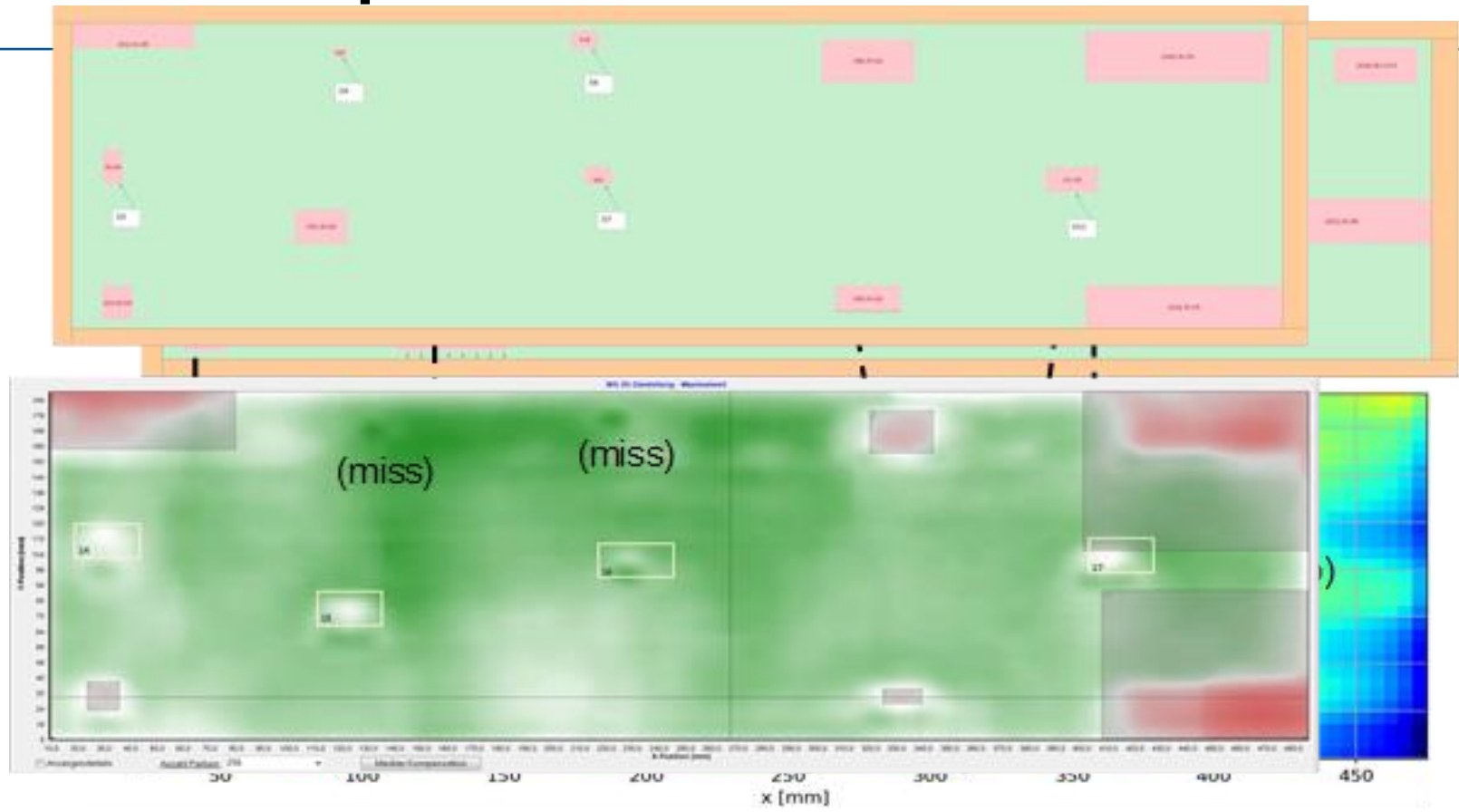
# Visual Comparison




Reporting a defect either larger or smaller compared to original defect was considered a success
Reporting a defect at a location with no original defect was considered a false call

# Statistical Methods



- **Probability of Detection**
  - Success Rate
    - *Detected compared with actual number of defects*
  - Binomial Probability, $P(x)$), distribution Method
    - *Used to determine the probability of finding "x" cases out of "n" measurements*

$$P(x) = C_x^n p^x (1-p)^{n-x}$$

n = total number of measurements, x = number of "success,"

- **POFC ( Probability of False Calls), frequency that tool falsely reports an anomaly**

# Statistical Methods



- **Sizing Accuracy**
  - Measure of a NDE tool's ability to predict an anomaly's dimension (width and length)
  - Tolerance in the measured dimension was calculated by mean size error and standard deviation

$$Tol_i = \mu + t_{\alpha/2} {}^{\sigma}/_{\sqrt{N_i}}$$

  - Unity Graph and Regression Analysis
- **Position Accuracy**
  - Measure of tool's ability to locate a hard spot and the relative error in reporting a defect location

# POD (Success Rate )



- **Defects were categorized in terms of sizes and the success rate of all the providers were evaluated.**

| Size Range | Provider "A" | Provider "B" | Provider "C" | Provider "D" | Provider "E" | Provider "F" |
|---|---|---|---|---|---|---|
| 5<=x<=10 | 96% | 83% | 70% | 43% | 61% | 96% |
| 10<x<=15 | 100% | 84% | 100% | 47% | 68% | 100% |
| 15<x<=20 | 100% | 100% | 94% | 71% | 76% | 100% |
| 20<x<=25 | 100% | 83% | 100% | 100% | 100% | 100% |
| 25<x<=30 | 100% | 100% | 100% | 83% | 83% | 100% |
| 30<x<=40 | 100% | 100% | 100% | 92% | 100% | 100% |
| 40<x<=50 | 100% | 100% | 100% | 100% | 100% | 100% |
| 50<x<=75 | 100% | 100% | 100% | 88% | 88% | 100% |
| Total | **99%** | **93%** | **93%** | **73%** | **81%** | **99%** |

All the providers showed an overall success rate of 70% or higher. Provider "A" and "B" technologies have showed 99% success rate.

# POFC (Probability for False Calls)



| Technology | Total Defects (n) | False Calls (x) | POFC (x/n) |
|---|---|---|---|
| Provider 'A' | 121 | 0 | 0% |
| Provider 'B' | 121 | 2 | 1.7% |
| Provider 'C' | 121 | 3 | 2.5% |
| Provider 'D' | 121 | 38 | 31.4% |
| Provider 'E' | 121 | 25 | 20.7% |
| Provider 'F' | 121 | 1 | 0.8% |

**Generally low POFC**

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## Provider “A”

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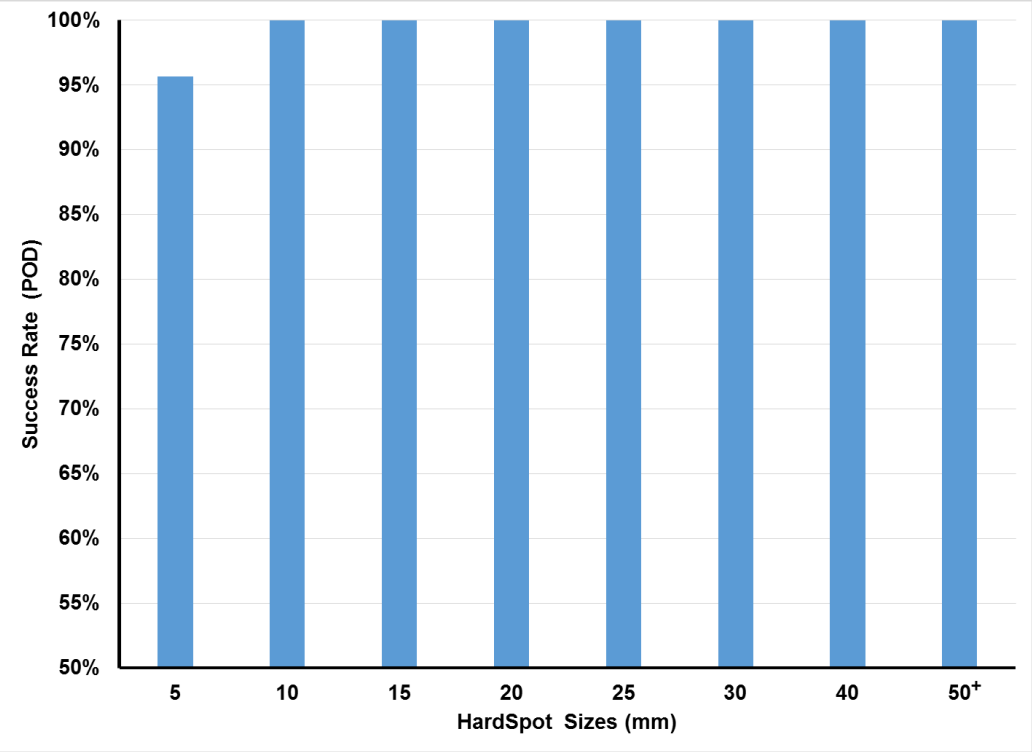
# Probability of Detection (POD)



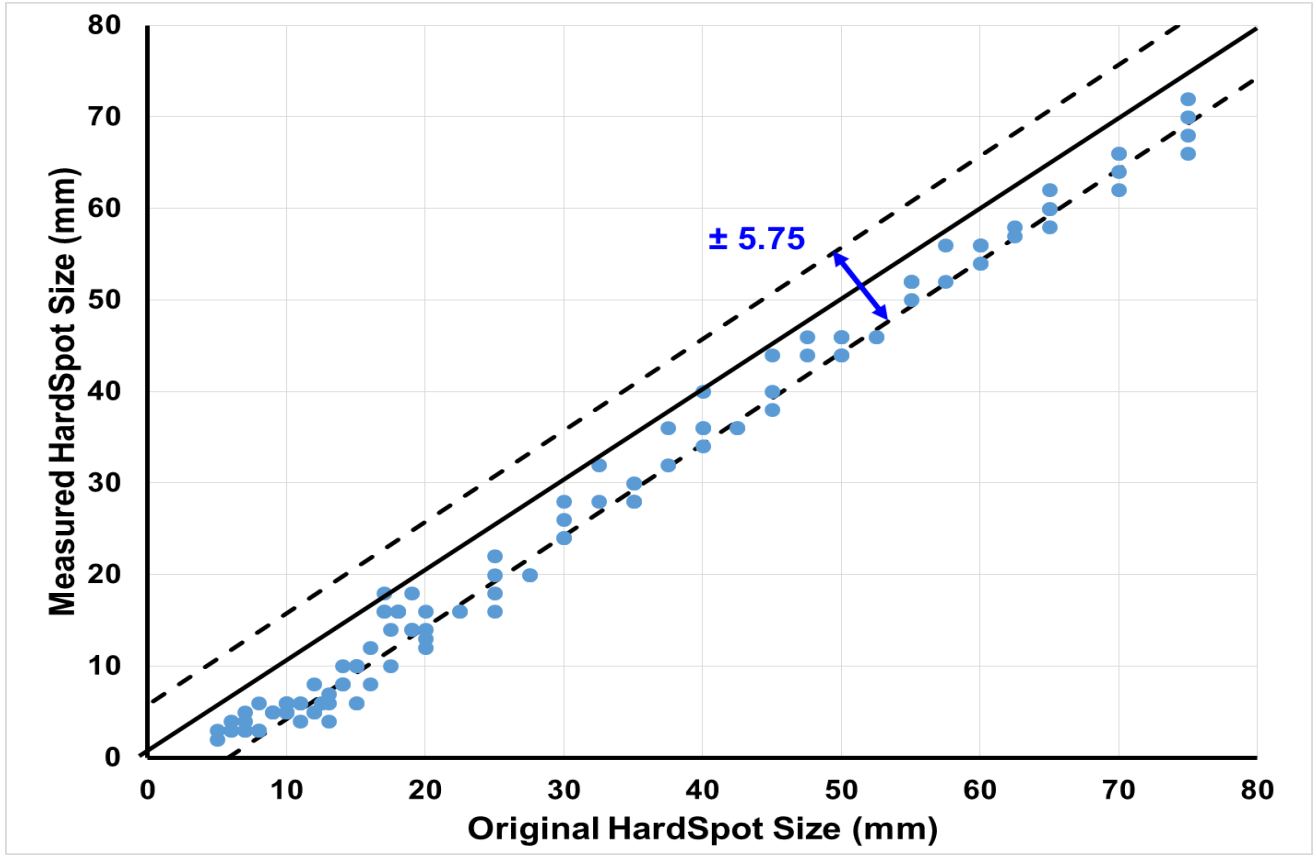



| | Observations | Success | Binomial Probability | Binomial Confidence | C-P Lower | C-P Upper |
|---|---|---|---|---|---|---|
| 5<=x<=10 | 23 | 22 | 88% | 95% | 81% | 100% |
| 10<x<=15 | 19 | 19 | 85% | 95% | 85% | 100% |
| 15<x<=30 | 29 | 29 | 90% | 95% | 90% | 100% |
| 30<x<=50 | 24 | 24 | 88% | 95% | 88% | 100% |
| 50<x<=75 | 26 | 26 | 89% | 95% | 89% | 100% |
| Total | 121 | 120 | 98% | 95% | 96% | 100% |

Provider “A” can detect $5^{+}$ mm hard spots with a certainty of 80% and with 95% confidence

# Sizing Accuracy – Unity Plot






- Original versus Measured Hard spot size

# Sizing Accuracy



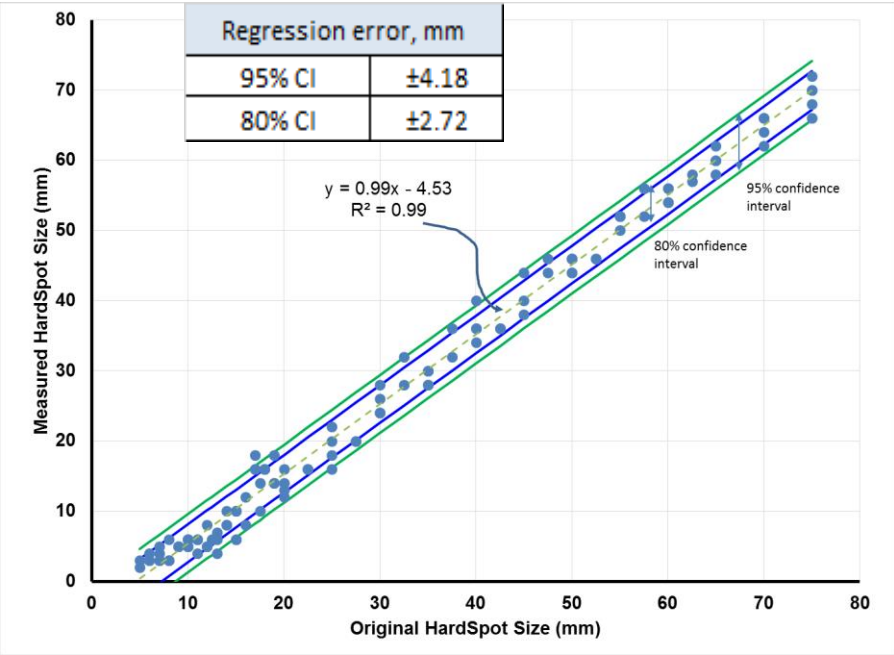
Tolerance: $\mu \pm t_{\alpha/2}\, \sigma/\sqrt{n}$

| Size (mm) | Mean size (mm) | Detected size (mm) | Mean Size Error (mm) | Std. Dev | Tolerance (mm) |
|---|---|---|---|---|---|
| 5<=x<=10 | 7.9 | 4.4 | 3.7 | 1.0 | 4.13 |
| 10<x<=15 | 13.2 | 6.9 | 6.3 | 1.5 | 6.99 |
| 15<x<=20 | 18.2 | 14.3 | 4.0 | 2.5 | 5.29 |
| 20<x<=25 | 24.2 | 18.0 | 6.2 | 1.8 | 8.01 |
| 25<x<=30 | 29.2 | 23.7 | 5.5 | 2.0 | 7.46 |
| 30<x<=40 | 36.7 | 32.5 | 4.2 | 2.2 | 5.58 |
| 40<x<=50 | 47.1 | 42.5 | 4.6 | 1.9 | 5.76 |
| 50<x<=75 | 63.3 | 58.3 | 5.0 | 1.7 | 5.70 |
| Total | 30.7 | 26.1 | 4.8 | 2.0 | 5.75 |

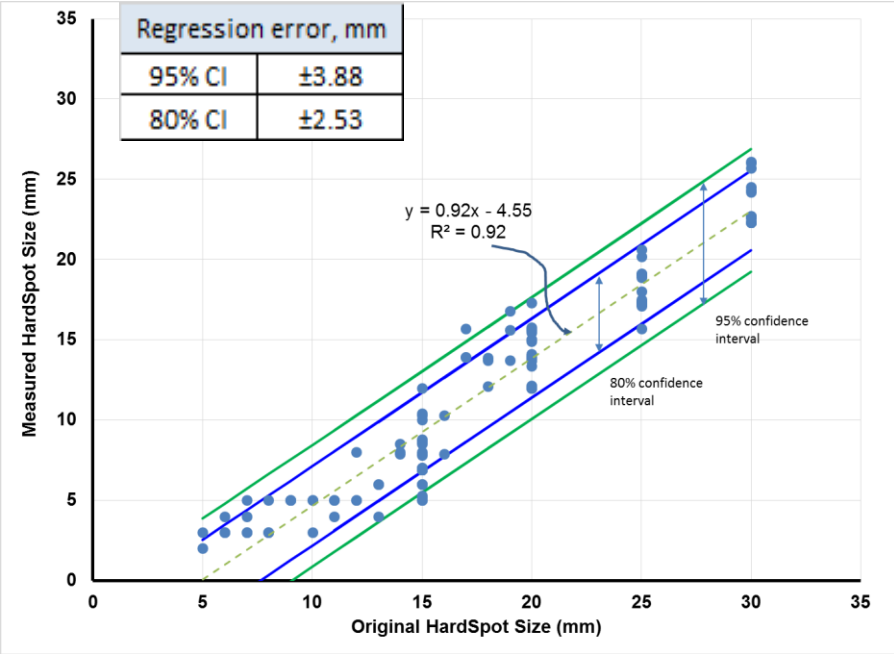
**Mean Tolerance 5.75 mm**

# Regression Analysis






Along the longitudinal orientation




Along the width orientation

1.) Can be used to estimate the size using the regression fit
2.) Deviation in the detected and original size at 95% confidence interval is ± 4.18 mm

# Statistical Summary



| Technologies | Overall Success rate | Binomial Probability | Tolerance (mm) | Size error for 80% CL (mm) | Mean Position Error (mm) | POFC |
|---|---|---|---|---|---|---|
| Provider "A" | 99% | 98% | 5.75 | 2.72 | 2.9 | 0% |
| Provider "B" | 93% | 89% | 5.89 | 6.35 | 1.9 | 1.7% |
| Provider "C" | 93% | 89% | 10.83 | 17.21 | 2.6 | 2.5% |
| Provider "D" | 73% | 66% | 26.56 | 21.47 | 14.7 | 31.4% |
| Provider "E" | 81% | 75% | 26.81 | 25.93 | 12.4 | 20.7% |
| Provider "F" | 99% | 98% | 9.28 | 10.62 | 3.3 | 0.8 % |

Success rate of all the technologies are above 70%
Tolerance in the measured size is approximately 11 mm or less for most of the technologies
Probability of false calls is below 2-3% for most of the technologies

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# Specifications Summary

| Technologies | Overall Success rate | Tolerance (mm) | Position Error (mm) | Optimal Speed (mm/s) | Sensor Pixel Size (mm) |
|---|---|---|---|---|---|
| Provider "A" | 99% | 5.75 | 2.9 | 10 | 20×10 |
| Provider "B" | 93% | 5.89 | 1.9 | -hand held | 2×2 |
| Provider "C" | 93% | 10.83 | 2.6 | 100 | 20×10 |
| Provider "D" | 73% | 26.56 | 14.7 | 10 | 30×10 |
| Provider "E" | 81% | 26.81 | 12.4 | 10 | 20×10 |
| Provider "F" | 99% | 9.28 | 3.3 | 100 | 10×10 |

1.) Provider "C" and "F" technologies are commercial; used a scanning speed of 100 mm/s
2.) Provider "A" "D" and "E" used an optimum scanning speed of 10 mm/s
3.) Provider "B" used a hand held probe to distinguish hard spots

# Variability in Speed



| Technology | Speeds Used (mm/s) | Mean Size Error with Speed Variation (mm) |
|---|---|---|
| Provider ‘A’ | 5,10,20 | 0.95 |
| Provider ‘B’ | -NA (handheld probe) | -NA |
| Provider ‘C’ | 50, 100, 200 | 0.54 |
| Provider ‘D’ | 5, 10, 20 | 2 |
| Provider ‘E’ | 5, 10, 20 | 1.9 |
| Provider ‘F’ | 100, 200, 300 | 2.1 |

**Limited Effect**

# Conclusions



- Currently two technologies (Provider “C” and “F”) capable of scan speeds over 100 mm/s with high POD and certainty - commercial
- One Technology (Provider “A”) had high POD and sizing accuracy; however at a lower speed of 10mm/s.
- Three laboratory scale technologies (Provider “B”, “D” and “E”) showing great promise

# Future Work



- **Further Assess the commerciality of viable NDE technologies and define operational limits**
  - All tools at predefined scanning speeds
  - Residual Magnetism
  - Lift off values reflective of plate reality
- **Hard spot impact on cracking in sour environment**
  - SSC susceptibility
  - Crack initiation

# Acknowledgment




- **Support of Dillinger Hütte ( especially Mr. Carmelo Collura) for providing the facility and helping in logistics.**
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  - Rosen ( Dr. Daniel Molenda)
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# QUESTIONS