DOT Contract: DTRS 56-04-T-001
PRCI Contract: GRI 8715

Nonlinear Harmonic-Based Mechanical Damage Severity Criteria for Delayed Failures in Pipelines

Teleconference Presentation by Graham Chell and Alfred Crouch
Southwest Research Institute
San Antonio, Texas

Final Project Review Meeting

April 19, 2007
Teleconference

Overview

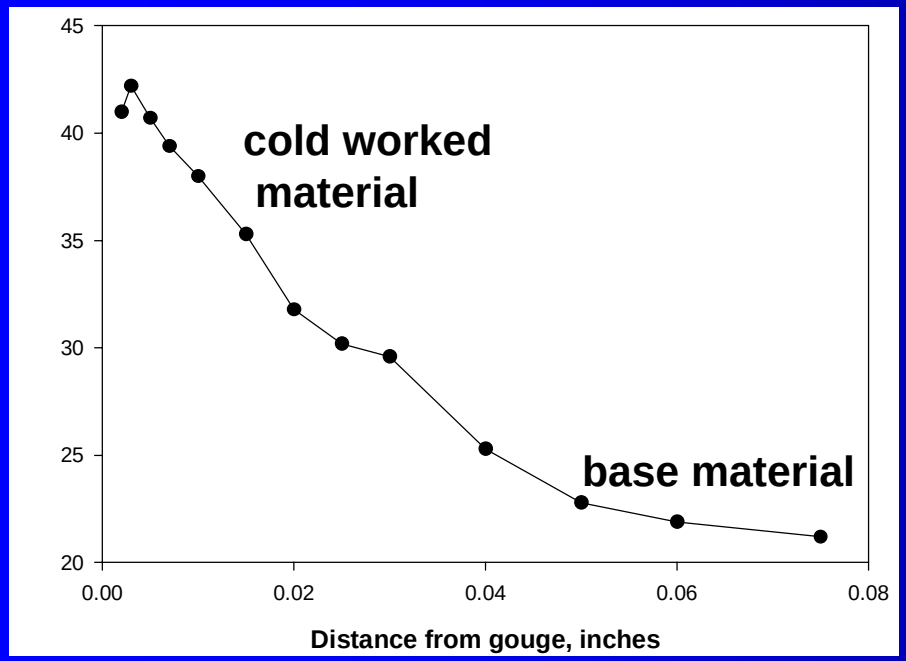
- Background: General and Non-Linear Harmonic (NLH) Inspection Method
- Introduction to Current Project, Objectives and Tasks
- Task Descriptions, Technical Accomplishments, and Conclusions
- Technology Transfer (Task 8)
- Project Summary and Conclusions
- Recommendations

Background

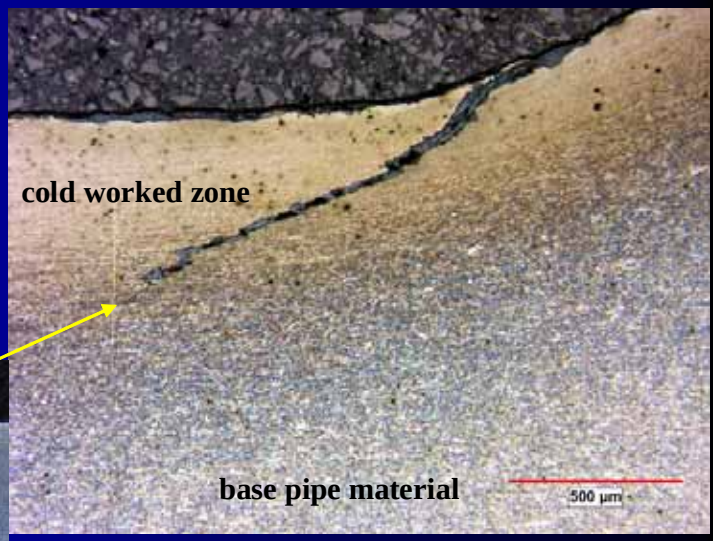
Delayed failures due to mechanical damage are a small fraction of total pipeline incidents, but can have tragic consequences.

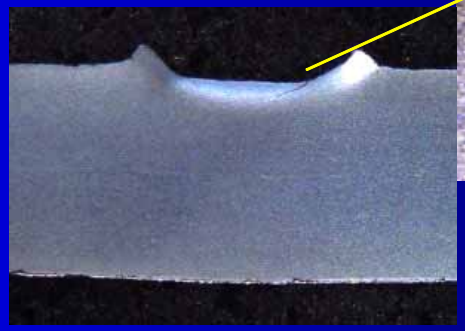
Scenes from the Bellingham Pipeline failure.

Background



Gouging creates a cold worked zone: a brittle region where the original microstructure is destroyed.





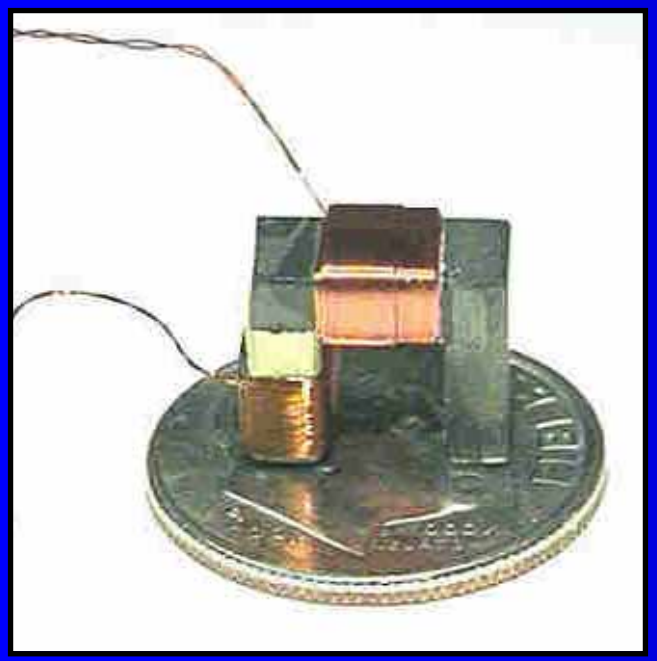
Hardness measurements over the cold worked zone show how the material properties have changed over a distance of around 1mm (0.04in).

Cracking can occur in the brittle zone during re-rounding.

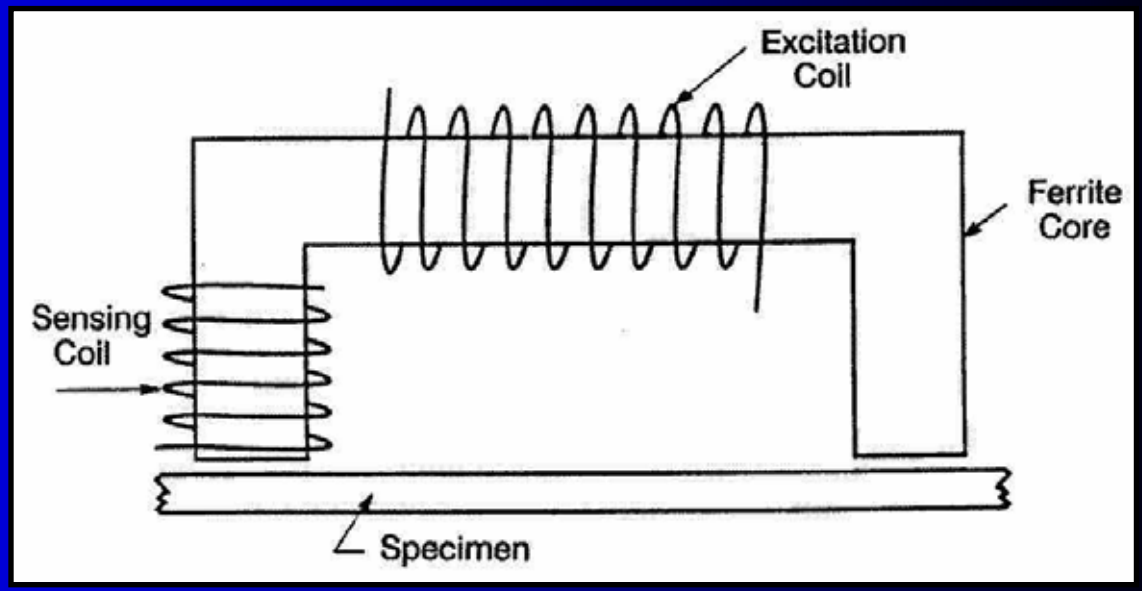
Background: Nonlinear Harmonics (NLH)

- An electronic method for detecting surface strain patterns
- Developed and refined at SwRI on rails, pipes, other steel products
- Uses an alternating magnetic field (10kHz), making it sensitive to surface strain changes
- Examines only a small area, requiring multiple sensors for complete coverage of pipe surface
- Senses magnetic field in very thin surface layer (compare Magnetic Flux Leakage (MFL) that detects magnetic field leaking from surface)

Background: NLH Sensor

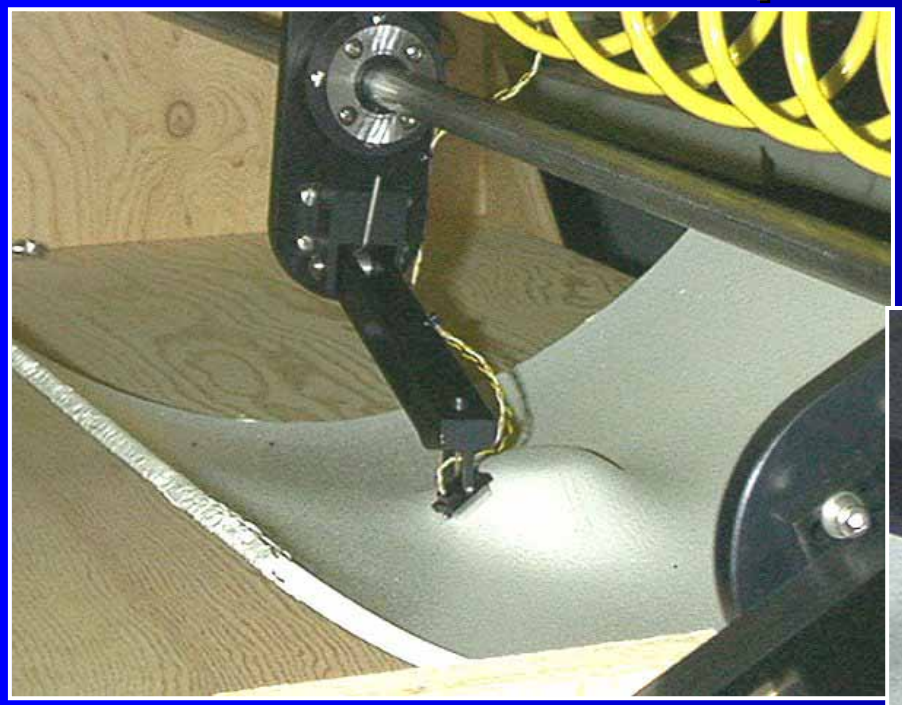


NLH probe is a transformer wound on a small C-shaped ferrite core.

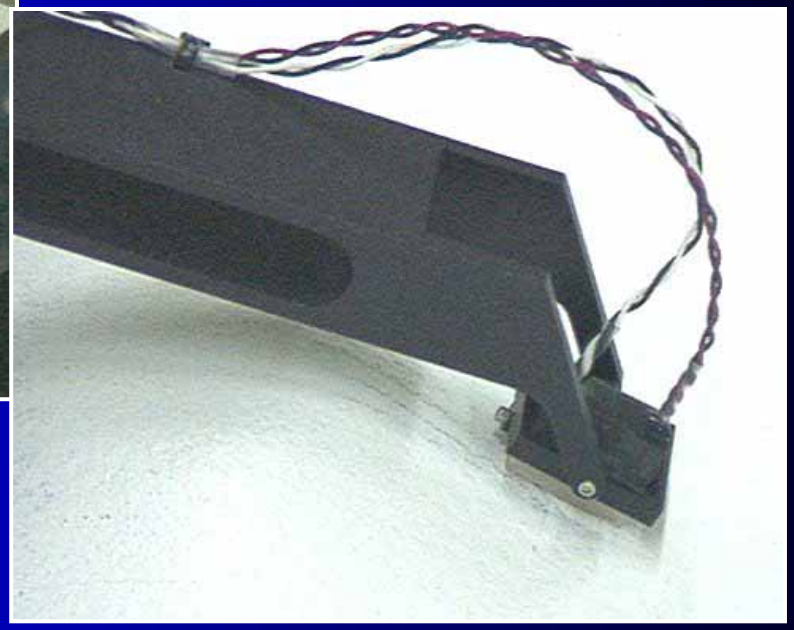


Background: NLH Sensor:

Gimbal mounting facilitates scan over defect imprint on inner surface



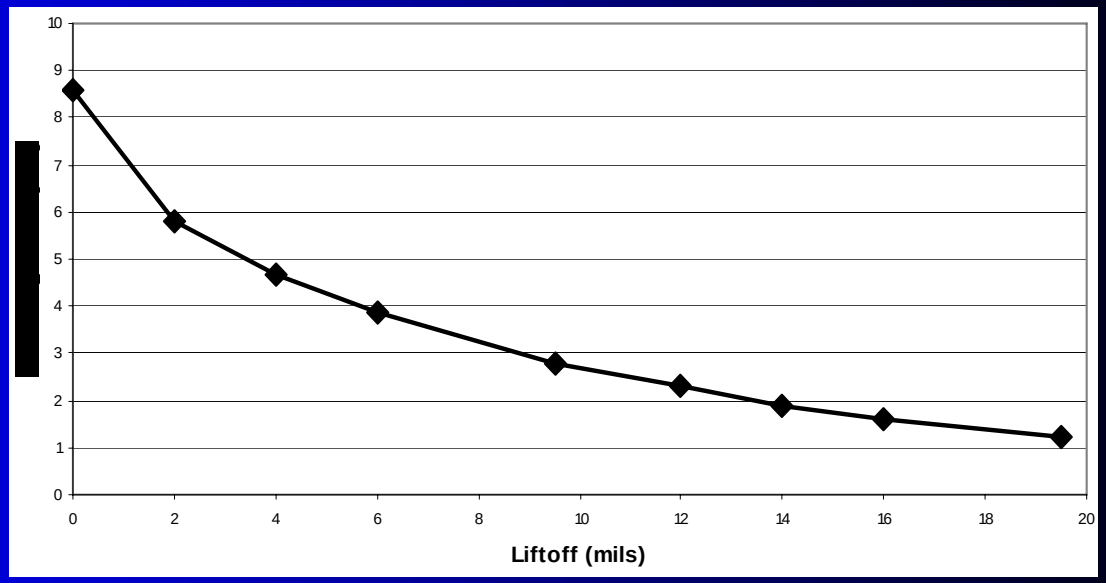
AC magnetic field causes production of odd-numbered harmonic frequencies in pipe surface by magnetic induction



NLH measures amplitude of third harmonic frequency

Strains produced by gouging change magnetic properties and hence NLH signal amplitude

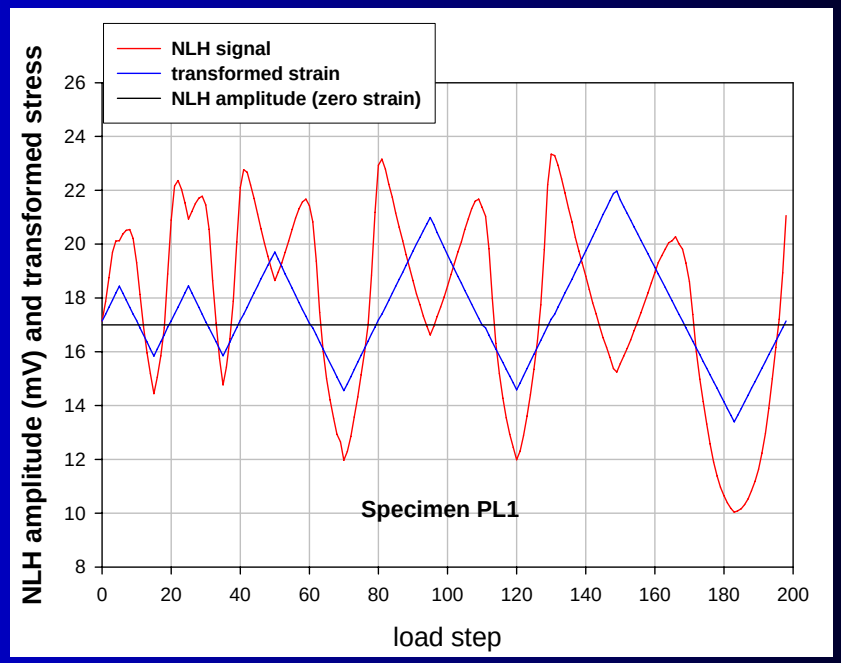
Background: NLH Sensor:
Lift-off Effects



- NLH sensor response is sensitive to distance probe is from scanned surface (lift-off).
- NLH scanning over gouge imprints that produce severe curvatures in a pipe inner surface can result in changes in signal response due to variations in lift-off.

Background: Task 6: SwRI IR&D Report R9449

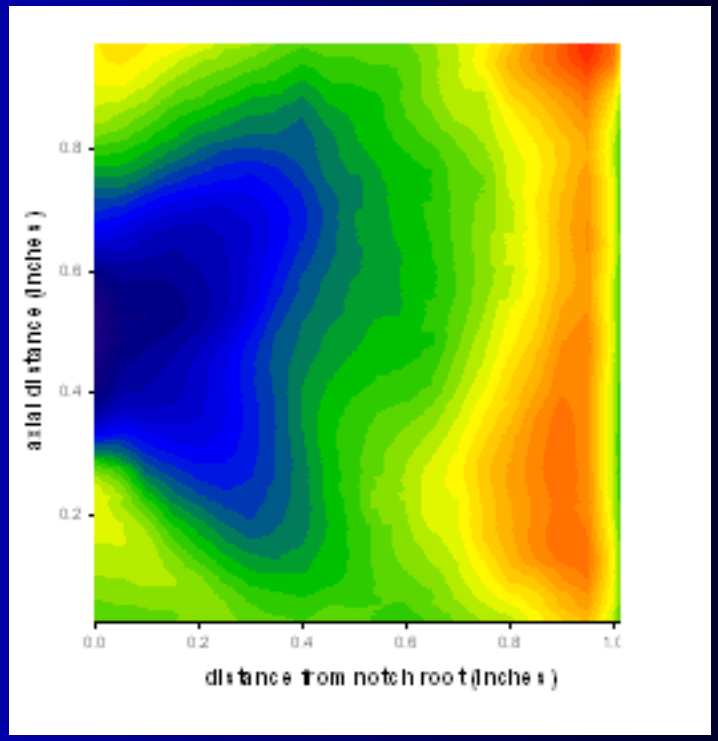
Plane specimen tensile and biaxial stressing



CONCLUSIONS:

- NLH signals respond predominantly to strain: Poisson changes in stain in y-direction detected due to tensile stressing in x-direction with zero stress in the y-direction.
- NLH measurements can detect and monitor complex changes in strain.
- Relationship of NLH signal to strain is nonlinear and goes through a maximum as strain increases.

Background: Task 6: SwRI IR&D Report R9449



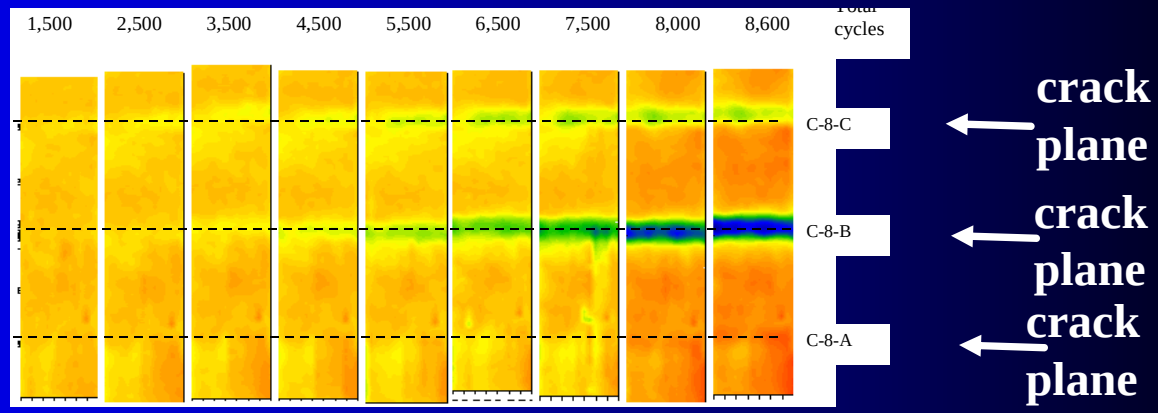
Notched specimen tensile stressing

CONCLUSION:

- **NLH signals detect strain gradients at stress concentration features.**

Background: Task 6: SwRI IR&D Report R9449

Fatigue of surface cracked tensile specimens

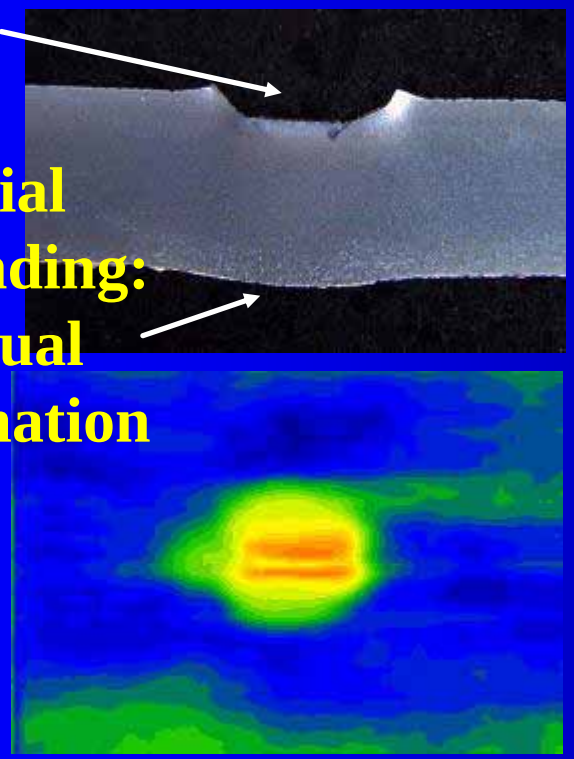


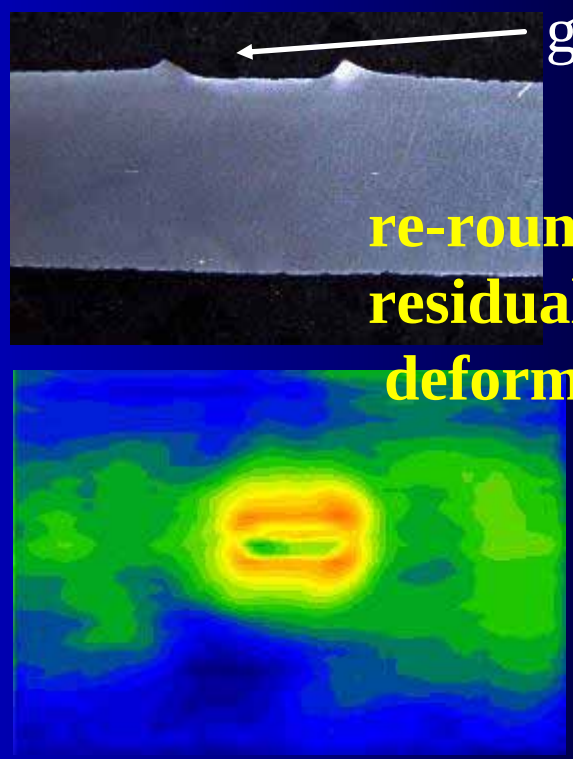
increasing fatigue cycles

CONCLUSION:

- **NLH signals detected changes in strain anomalies due to fatigue crack growth leading to failure.**

Background: Typical NLH Scan Results: NLH signals detect strain anomalies even after re-rounding (GRI 8076)





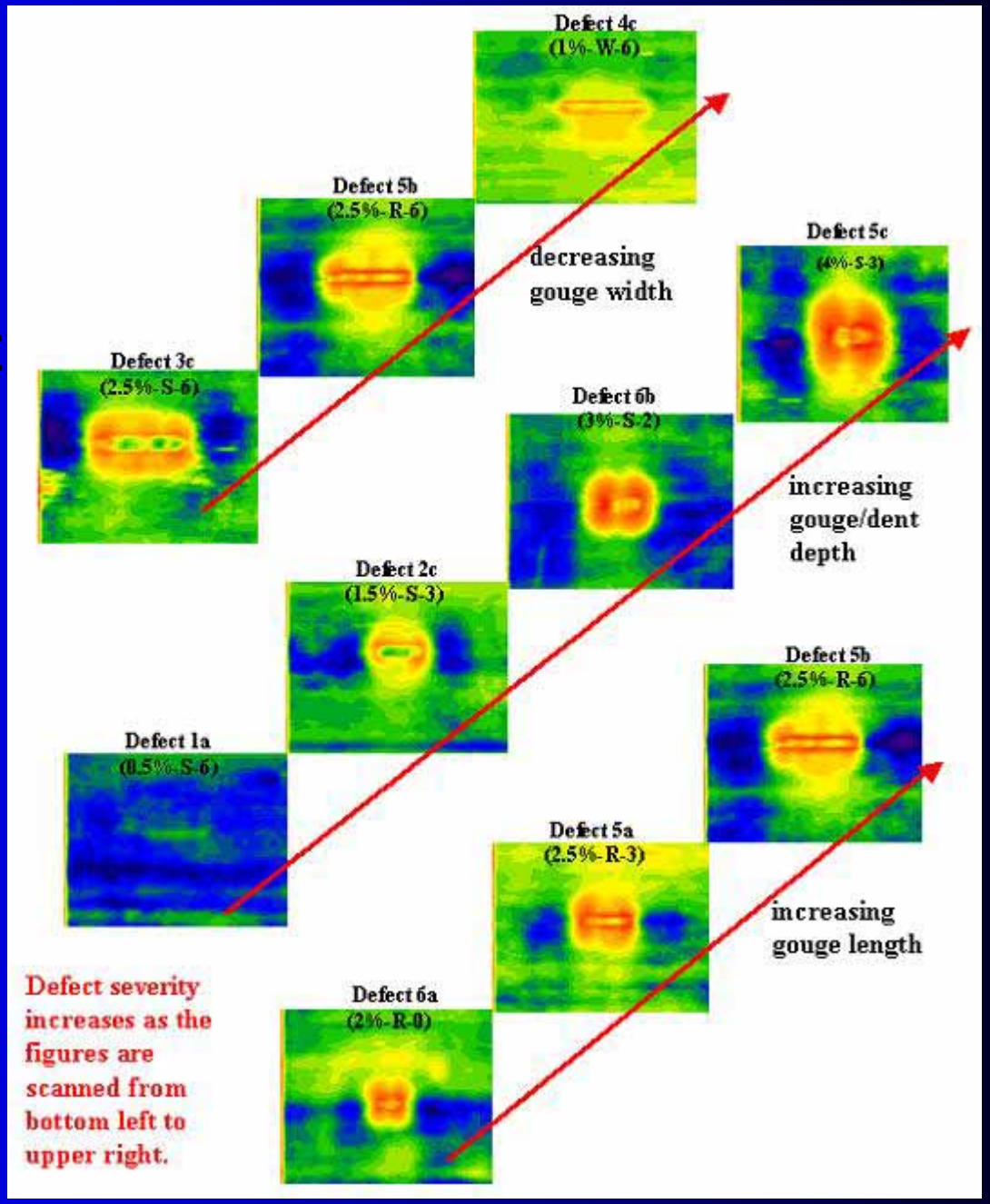
NLH scans on inside surfaces of pipes detect strain anomalies due to defects on outside surfaces <u>even if residual deformation is absent.</u> Re-rounded defects can not be detected with calipers.

Background: NLH-Based defect severity criteria (GRI 8076)

Conclusions:

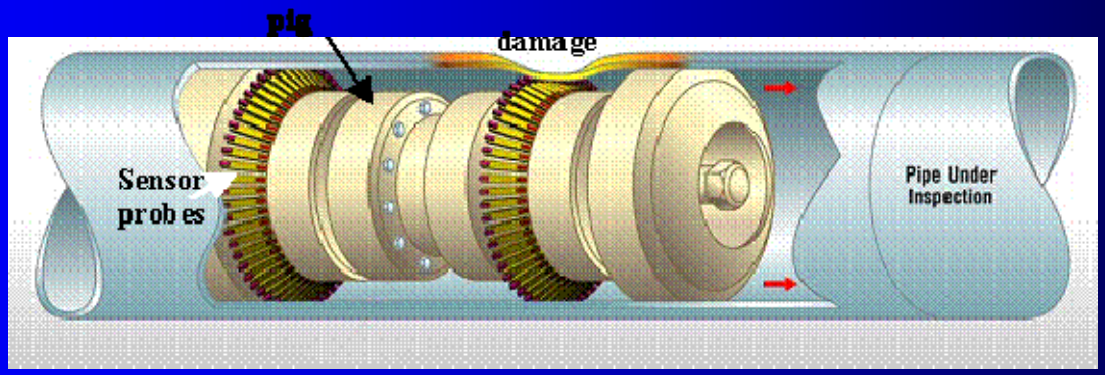
NLH signals qualitatively indicate:

- length of gouge
- width of gouge
- depth of gouge
- severity relative to rupture



Introduction to Current Program

- Addresses delayed failures from fatigue crack initiation and propagation at gouges.
- Current ILI systems detect mechanical damage but cannot determine its severity with respect to remaining life



- Nonlinear harmonic method offers a promising alternative ILI tool for detecting and characterizing severity of defects

Introduction to Current Program: Funding Sources

- PRCI/GTI (cash): $200,000
  -
- Tuboscope (in-kind): $50,000
  [Software/Design developments for ILI equipment]
- SwRI (in-kind): $90,000
  [SwRI IR&D project report R9449]
- DOT (cash): $333,230

Introduction to Current Program: Schedule

Preliminary PRCI/GTI contract with Kiefner Associates:

- **Started: August, 2004**
- **Completed: September, 2004**

DOT Contract

- **Started: October 2004**
- **Completed: March 2007**

Objectives and Technical Approach of Current DOT/PRCI Program

- **Characterize change in strain anomalies due to mechanical damage in terms of NLH signals and derive NLH-based defect severity criteria related to remaining fatigue life (delayed failure).**

  Approach: Measure NLH signals as a function of pressure cycles on full-scale pipe segments containing realistic gouged dents.

- **Transfer the developed NLH-based technology to ILI companies.**

  Approach: Cooperate with Tuboscope Pipeline Services to develop methods for implementing NLH severity criteria on ILI tools.

Program Tasks

Task 1: Procure Pipe, Fabricate Defects, Characterize Material

Task 2: Fabricate NLH probes and pressure test facilities

Task 3: NLH Capabilities for Detecting Cracks in Pipes

Task 4: NLH Measurements on Cyclically and Statically Pressurized Damaged Pipes

Task 6: NLH Measurements and Delayed Failures: SwRI R&D Report R9449

Task 5 Process NLH Signals

Task 7: Develop NLH-based Defect Severity Criterion

Task 8: Technology Transfer and Tuboscope Software Development

Task 9: Project Reviews

Task 10: PRCI Oversight

Task 11: Management/Reporting

Task 1: Pipe Procurement and Fabrication of Defects for Cyclic Pressure Tests

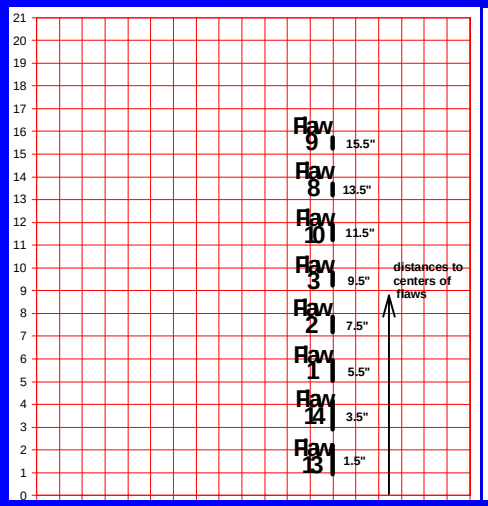
Pipe Material:
X60
Pipe Dimensions:
OD 12 inches
Thickness 0.25 inches

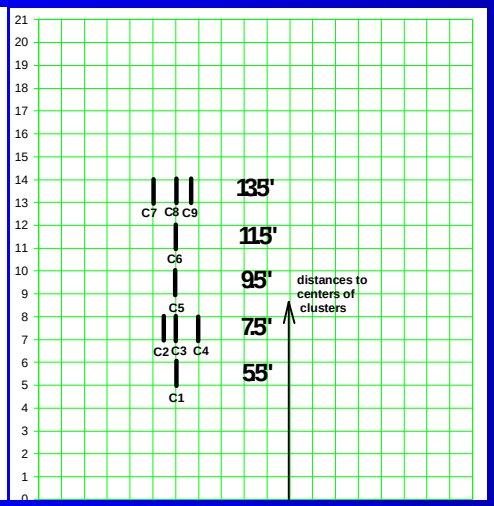
Five 6-foot pipe samples

Six gouging defects in each of four samples manufactured at Stress Engineering Services, Houston

Measuring residual gouge depth.

Task 1: Pipe Procurement and Fabrication of Defects for Crack Detection Studies

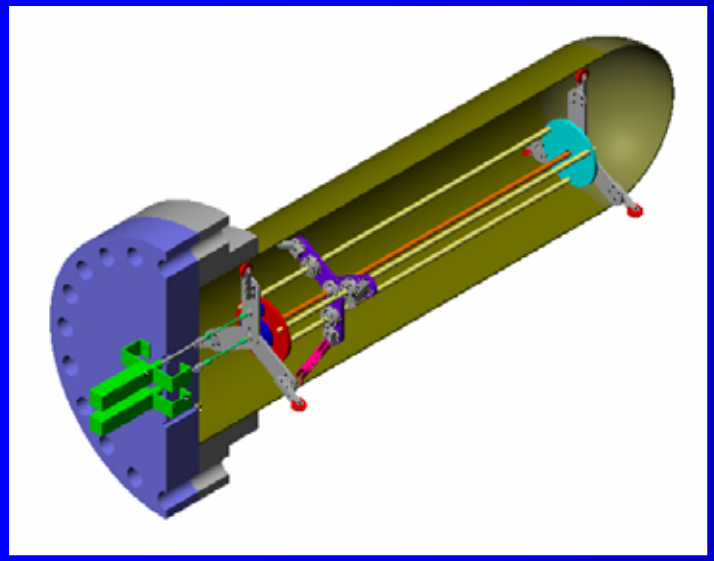


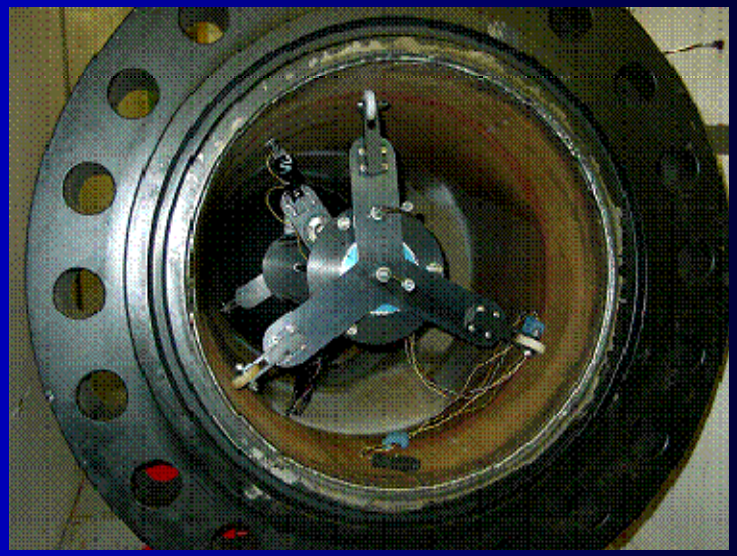


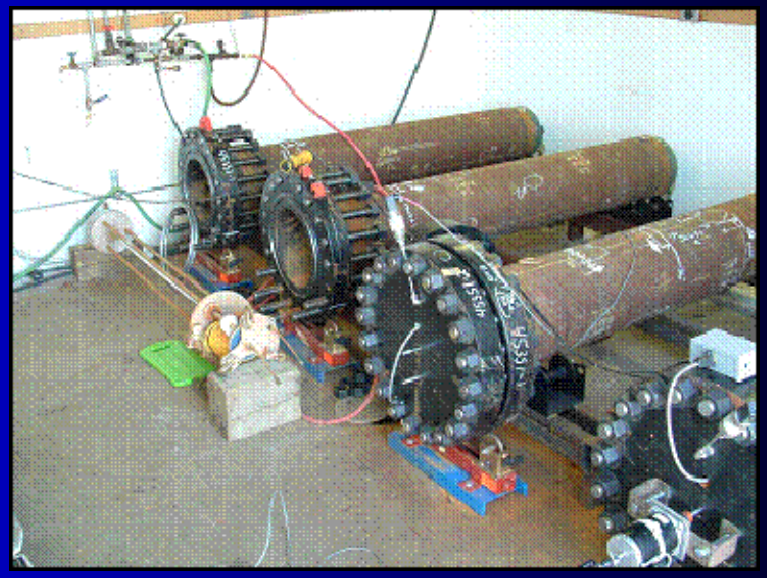
50 EDM notches in one pipe sample manufactured at Scan Systems, Houston

- **Arranged in linear arrays and clusters (simulated SCC)**

Task 2: NLH Scanner and Pressure Test Facilities

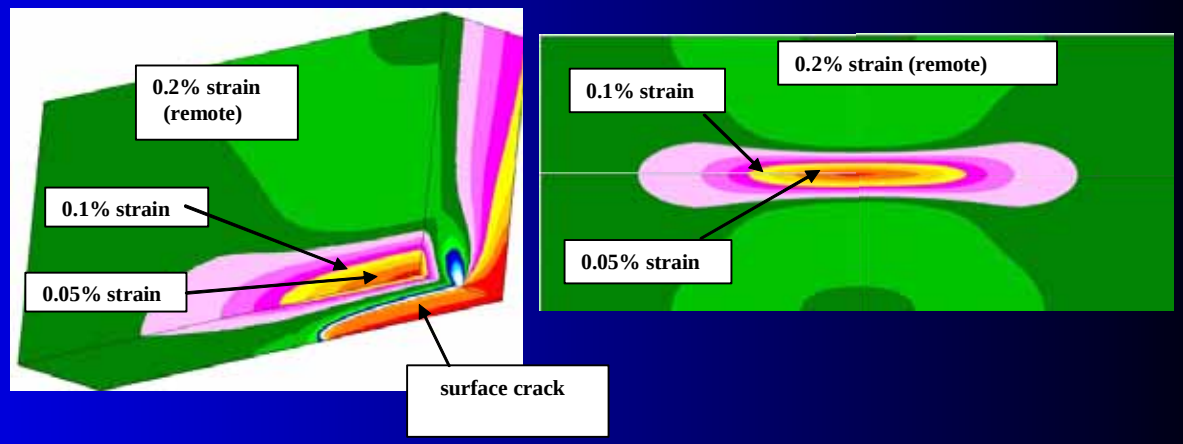




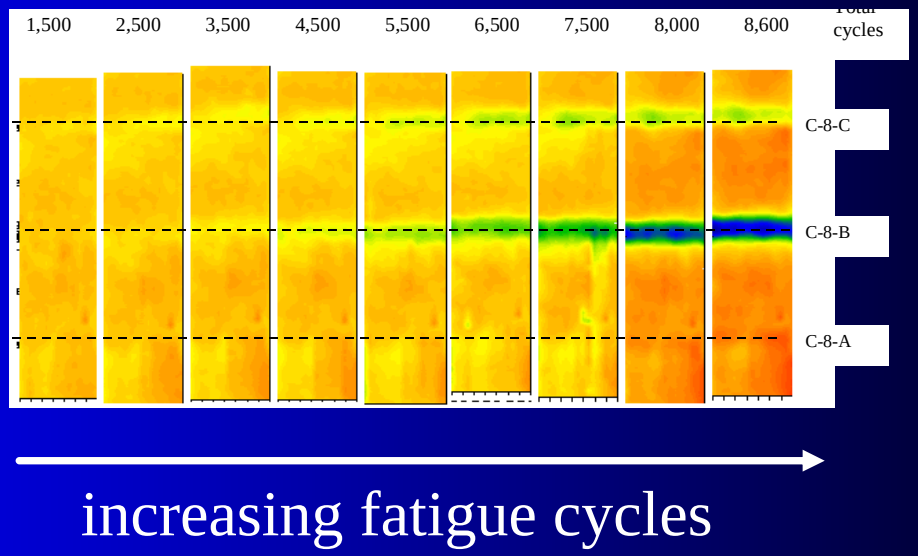


Task 3: NLH Capabilities for Detecting Cracks

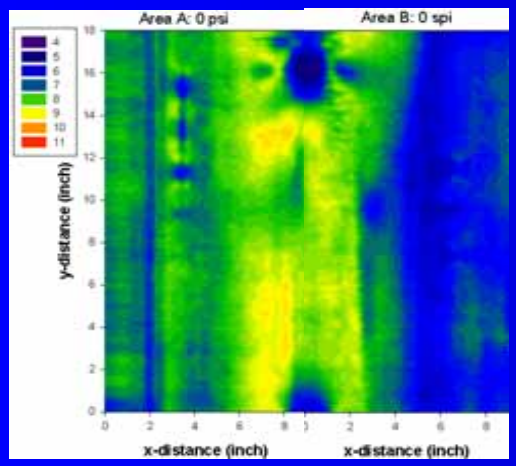
Finite element analysis predicts strain anomalies due to cracks.

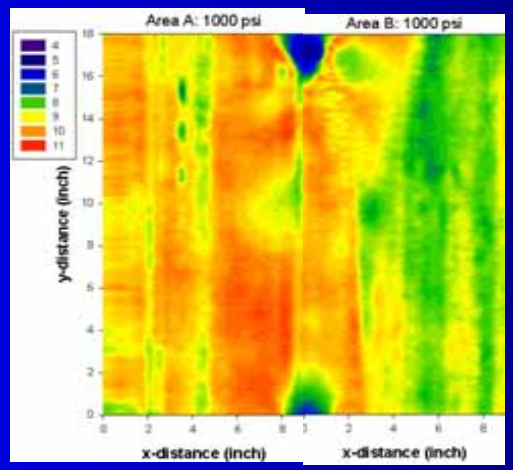


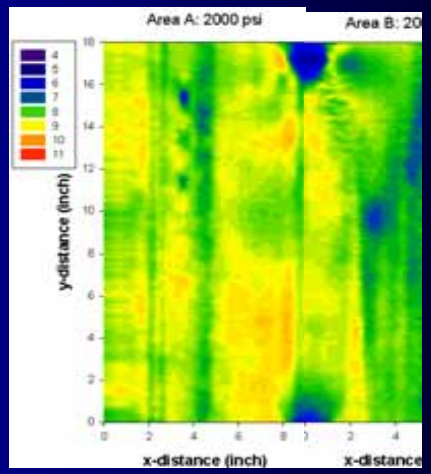
Results reported in SwRI R9449 indicate NLH can detect strain anomalies due to severe cracking

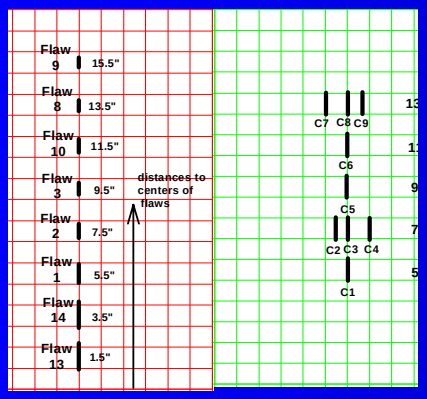


Task 3: NLH Capabilities for Detecting Cracks

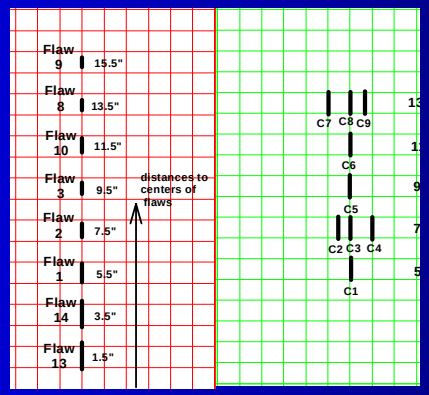




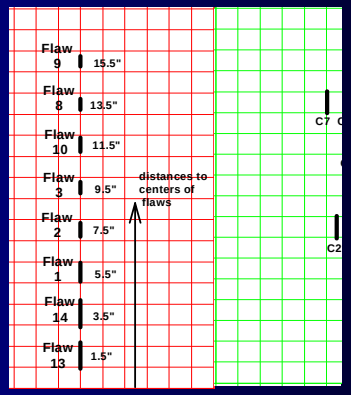




0 psi



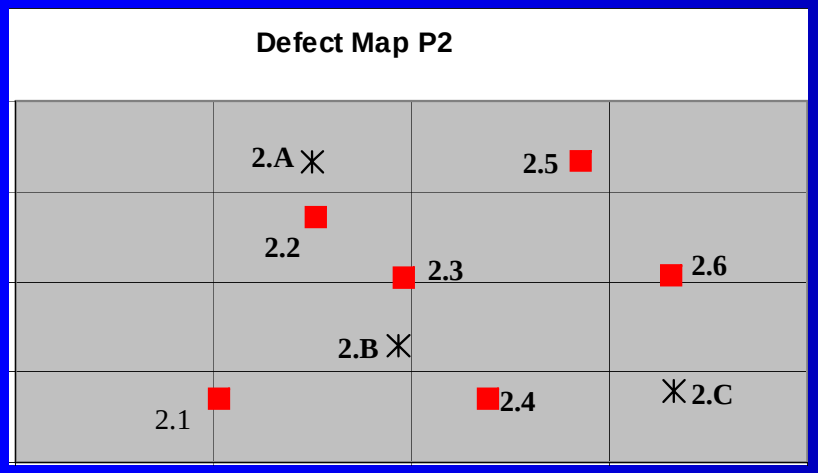
1000 psi

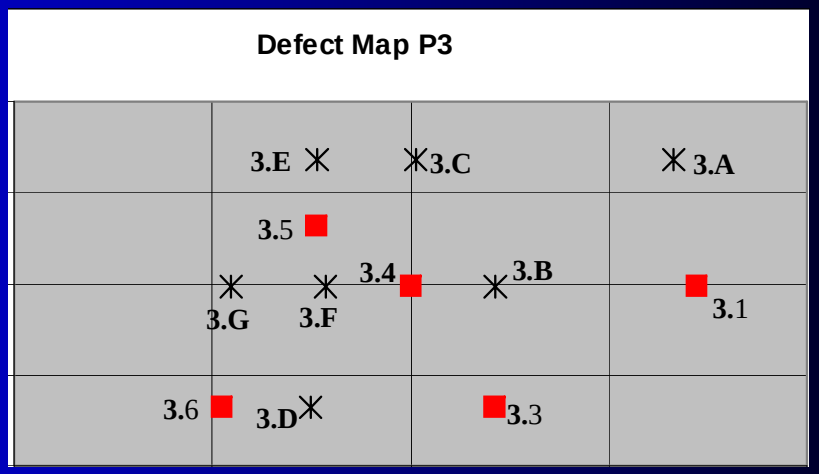


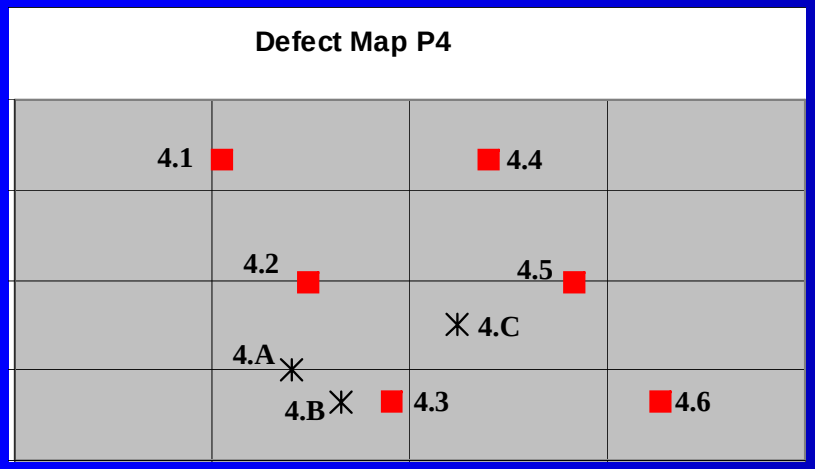
2000 psi

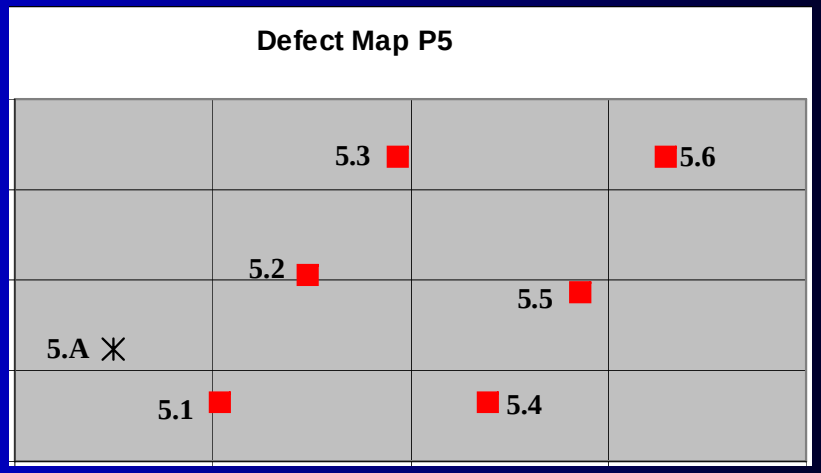
CONCLUSION: NLH did not detect cracks because of relative large extraneous strains and/or magnetic property anomalies in pipe.

Task 4: NLH Measurements on Cyclically Pressurized Damaged Pipes



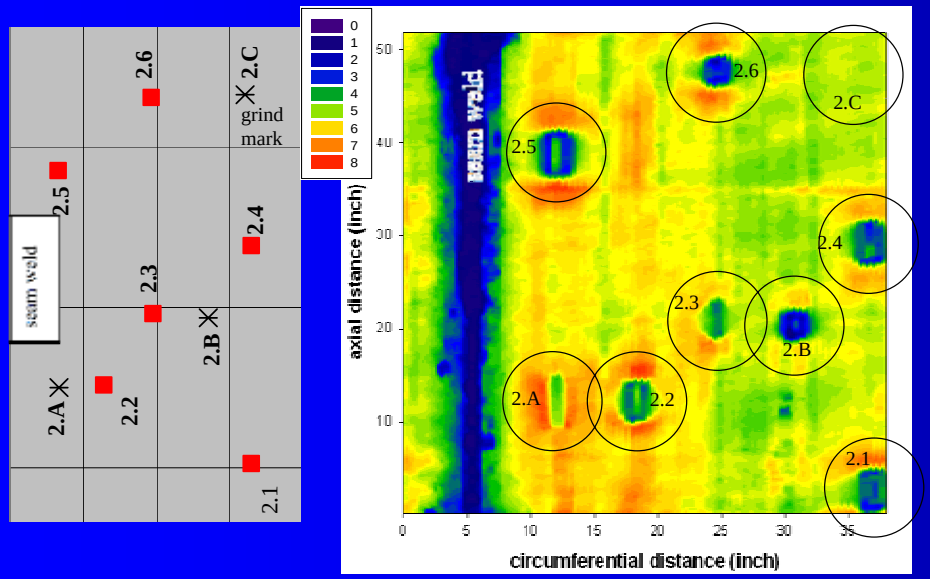






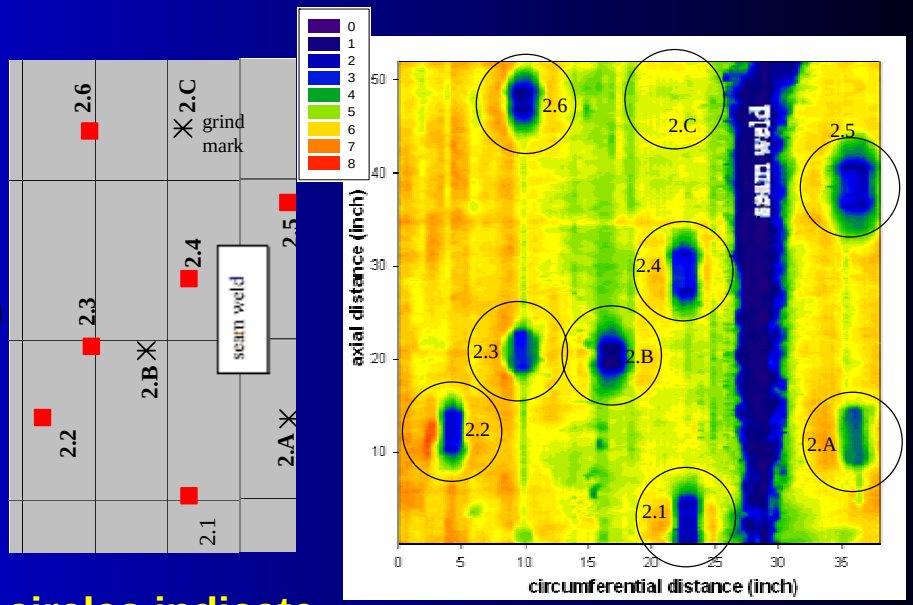
Locations of gouges: "intentional" (red squares) and "unintentional" (black stars)

Task 4: NLH Measurements on Cyclically Pressurized Damaged Pipes



axial magnetic field

Typical NLH scan results: Pipe 2



circles indicate defects

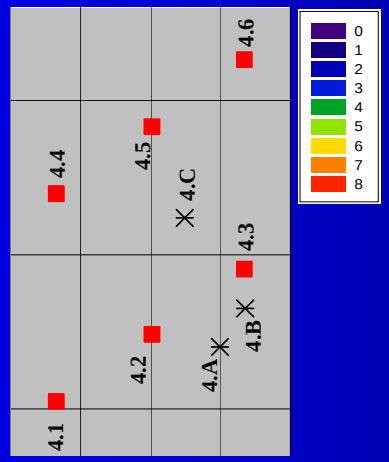
circumferential magnetic field

NLH sensors detected all defects on the outside of the pipe except for 2.C, a shallow grind mark. The seam weld is also detected.

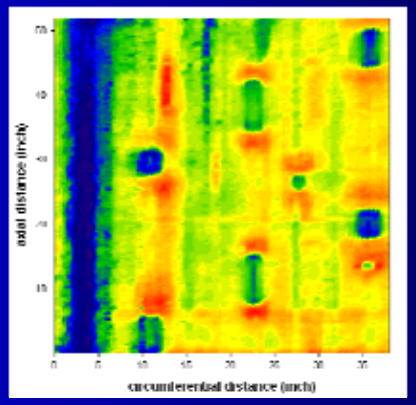
Task 5: Processing of NLH Measurements on Cyclically Pressurized Damaged Pipes: Pipe 4

Axial Magnetic Field

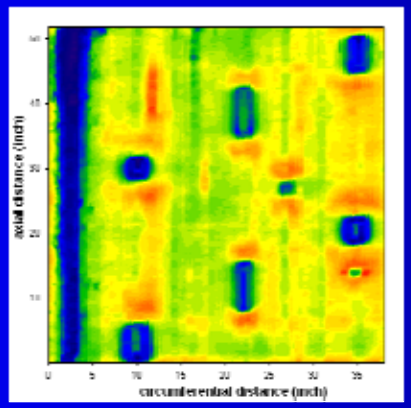
Evolution of NLH signal maps with cycles: scans 2, 5 and 8.



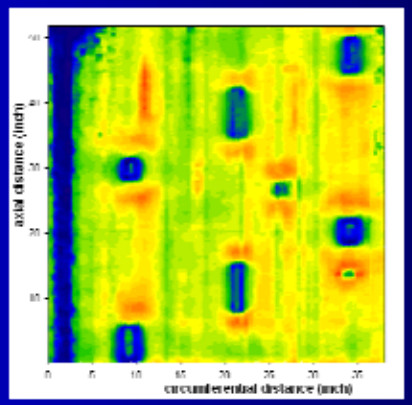
Pipe4 Scan2 – Axial Field
Cycles = 0



Pipe4 Scan5 – Axial Field
Cycles = 4899

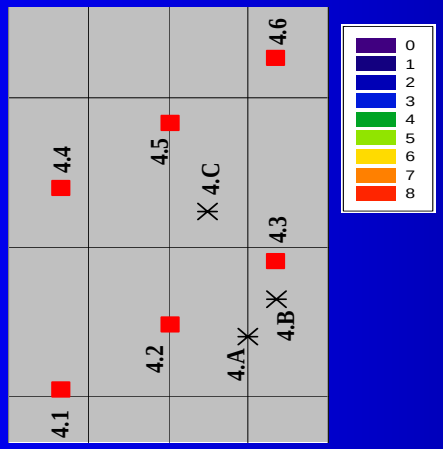


Pipe4 Scan8 – Axial Field
Cycles = 18675

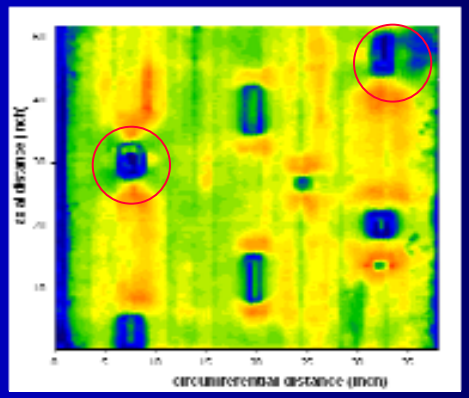


Task 5: Processing of NLH Measurements on Cyclically Pressurized Damaged Pipes: Pipe 4

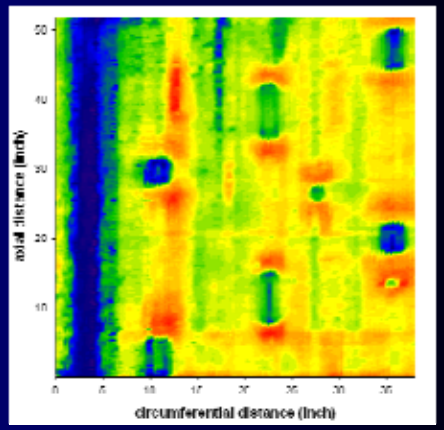
Axial Magnetic Field



Pipe4 Scan11 – Axial Field
Cycles = 28224

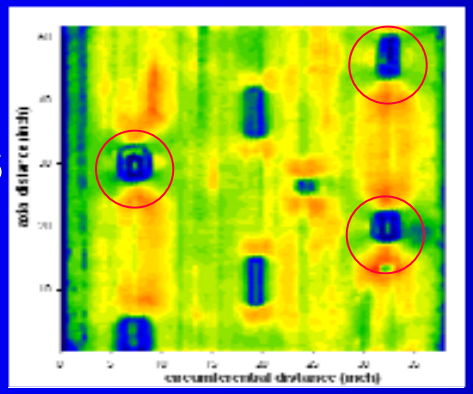


Pipe4 Scan2 – Axial Field
Cycles = 0

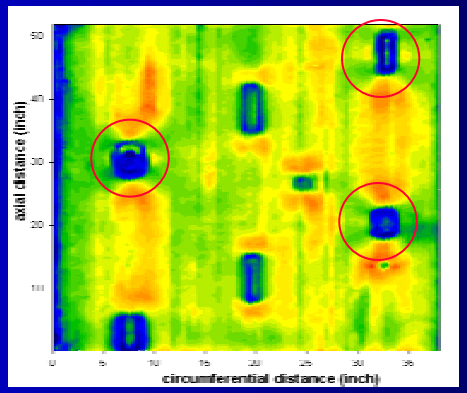


Evolution of NLH signal maps with cycles: scans 11, 12 and 13.

Pipe4 Scan12 – Axial Field
Cycles = 44224



Pipe4 Scan13 – Axial Field
Cycles = 84344

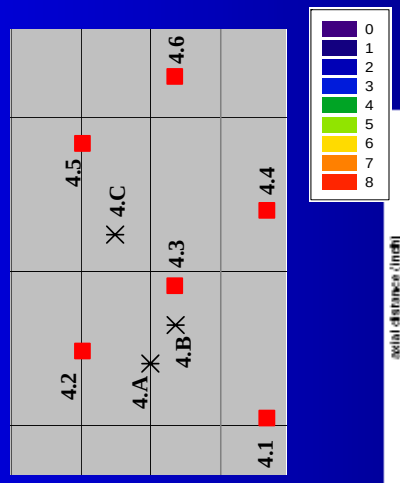


circles indicate failed defects

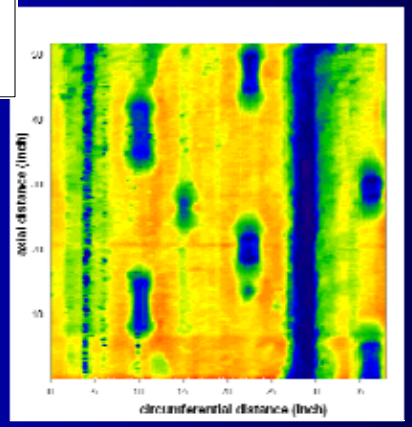
Task 5: Processing of NLH Measurements on Cyclically Pressurized Damaged Pipes: Pipe 4

Circumferential Magnetic Field.

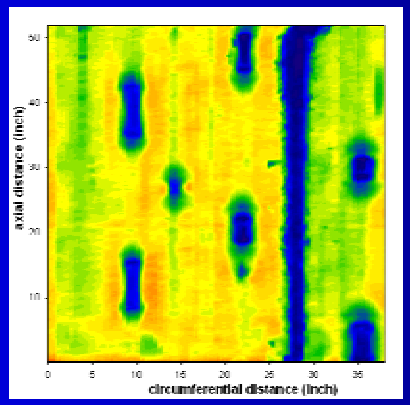
Evolution of NLH signal maps with cycles: scans 2, 5 and 8.



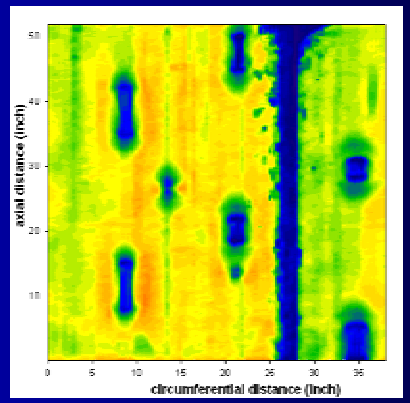
Pipe4 Scan2 – Circ. Field
Cycles = 0



Pipe4 Scan5 – Circ. Field
Cycles = 4899



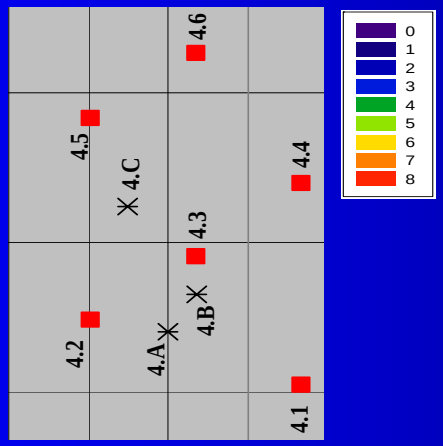
Pipe4 Scan8 – Circ. Field
Cycles = 18675



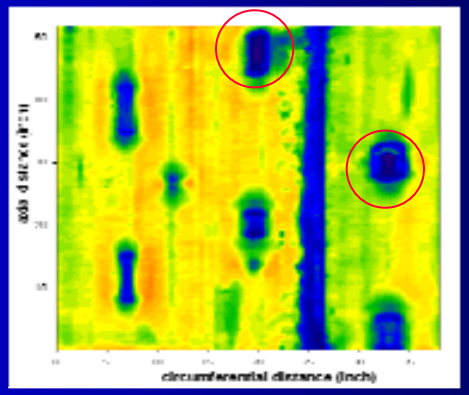
Task 5: Processing of NLH Measurements on Cyclically Pressurized Damaged Pipes: Pipe 4

Circumferential Magnetic Field

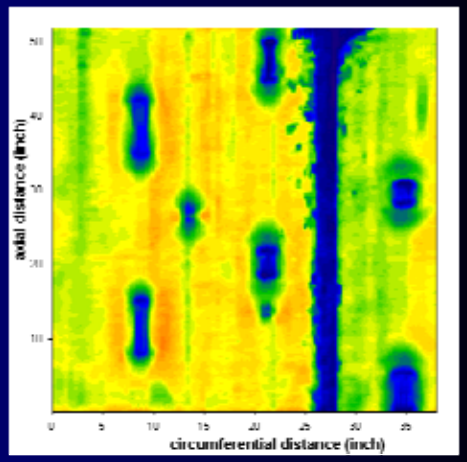
Evolution of NLH signal maps with cycles: scans 11, 12 and 13.



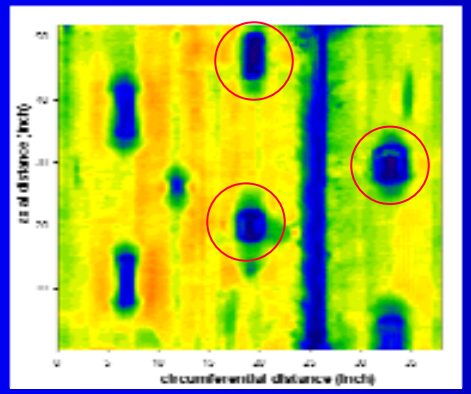
Pipe4 Scan11 – Circ. Field
Cycles = 28224



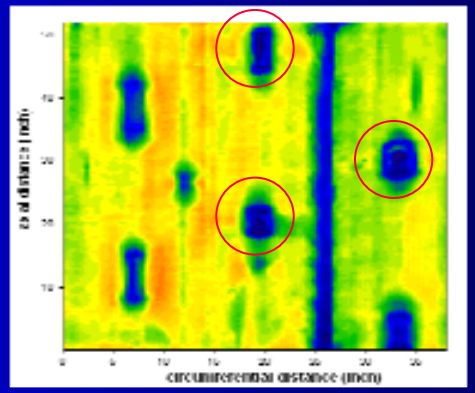
Pipe4 Scan8 – Circ. Field
Cycles = 18675



Pipe4 Scan12 – Circ. Field
Cycles = 44224



Pipe4 Scan13 – Circ. Field
Cycles = 84344



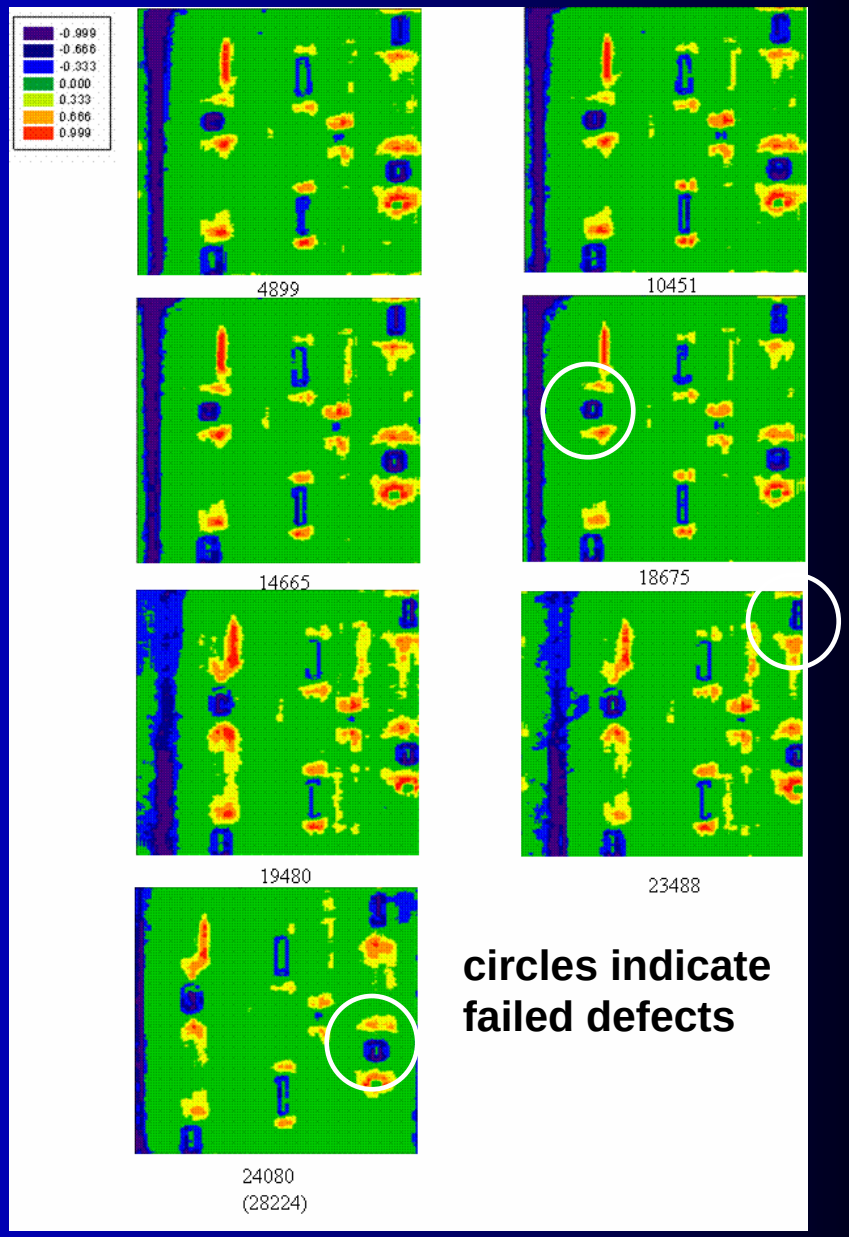
circles indicate failed defects

Task 5: Processing of NLH Measurements on Cyclically Pressurized Damaged Pipes: Pipe 4

Axial Magnetic Field

Time evolution of filtered NLH signal maps with increasing pressure cycles: scans 5 through 11.

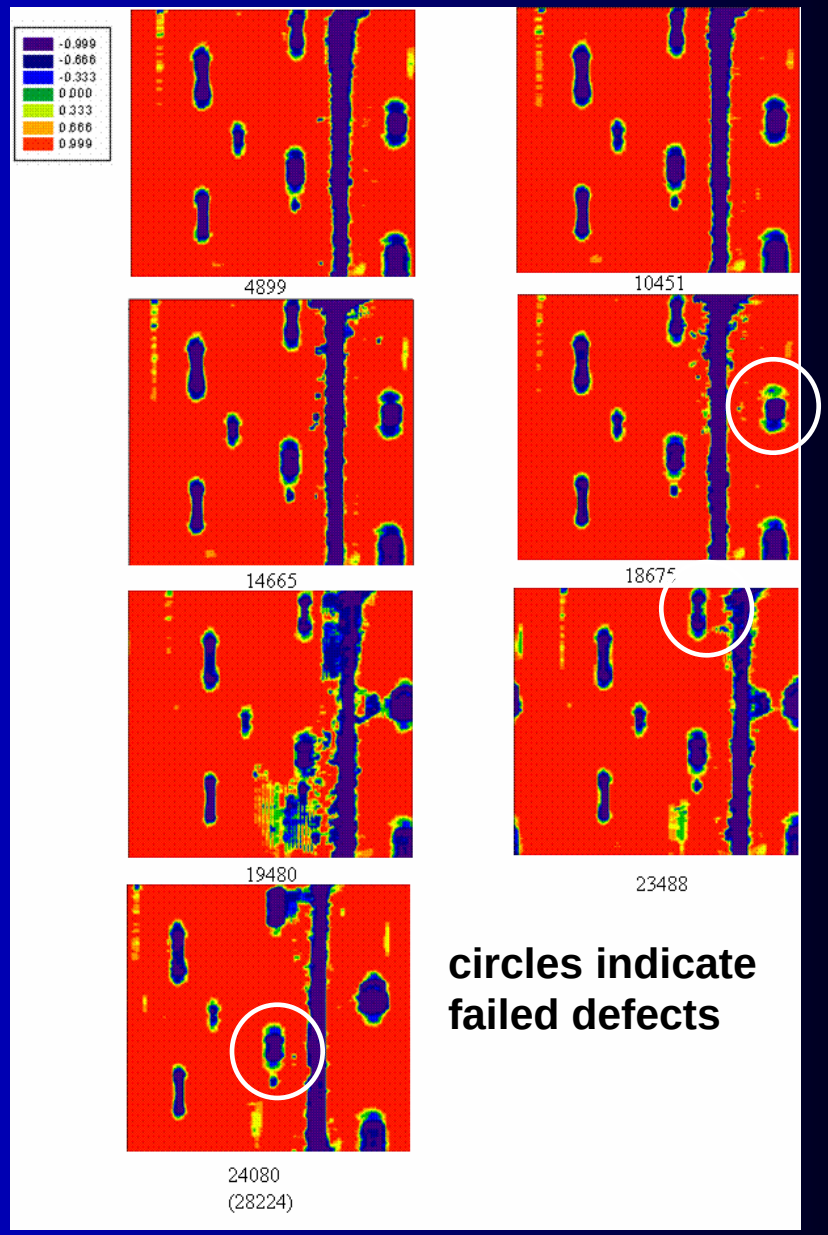
[Note: gouges are clearly identified from other anomalies due to red regions signifying the entry and exit points of the gouging tool.]



Task 5: Processing of NLH Measurements on Cyclically Pressurized Damaged Pipes: Pipe 4

Circumferential Magnetic Field

Time evolution of filtered NLH signal maps with increasing pressure cycles: scans 5 through 11.



Task 5: Processing of NLH Measurements on Cyclically Pressurized Damaged Pipes

CONCLUSIONS

- NLH probes readily detected strain anomalies on the inside surfaces of pipes generated by gouges on the outside.
- Analysis of NLH signals indicated they provide a measure of gouge lengths, gouge depths (minimum NLH signal intensity) and possibly gouge widths.
- NLH probes detected the seam welds in the pipes and other anomalies due to the manufacturing process.
- NLH scans made at different times are reproducible.
- NLH signal maps did not to display consistent changes as a function of pressure cycles (time) that would unambiguously indicate onset of failure .

Task 7: NLH Based Defect Severity Criteria

Results of previous work (GRI 8076: Report GRI-03/0154: "Enhanced Assessment Criteria for Mechanically Damaged Pipes.") suggest defect severity can be expressed in terms of a severity parameter, *S*

$$S = \text{constant} \times \frac{d^{\alpha} L^{\beta}}{w^{\gamma}}$$

where:

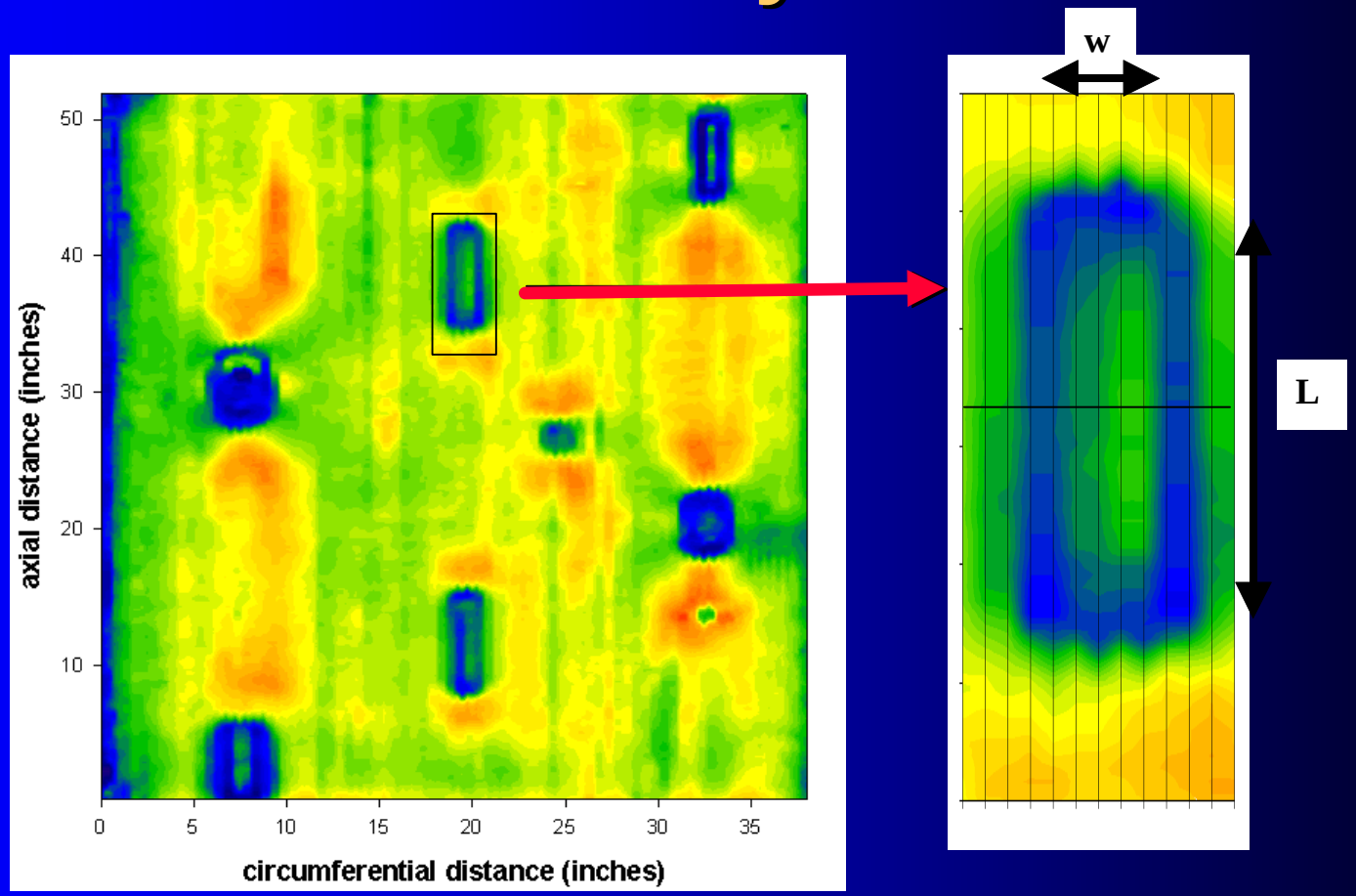
***d* = residual gouge depth**

***L* = gouge length**

***w* = gouge width**

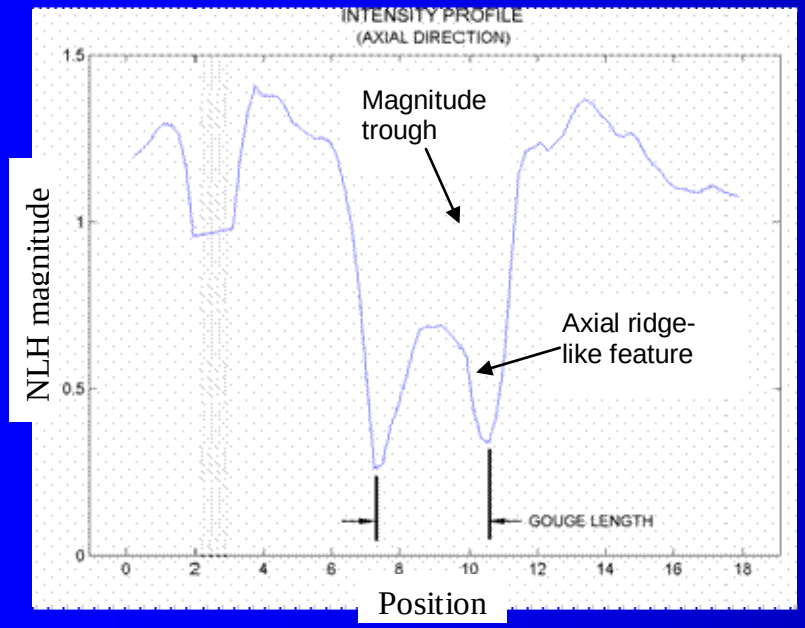
and the other parameters are constants.

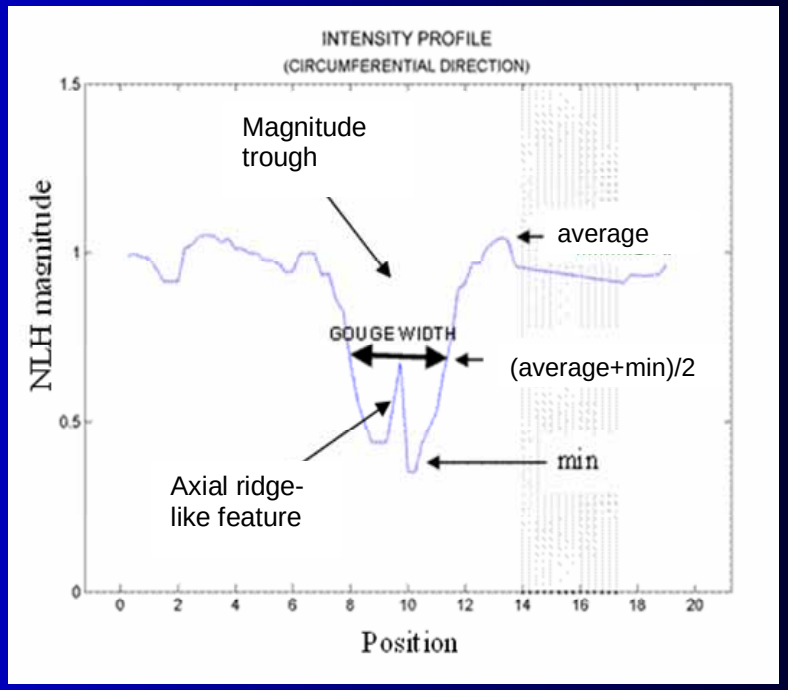
Task 7: NLH Based Defect Severity Criteria



Defects detected in NLH signal maps were isolated in "gouge location boxes" to facilitate detailed analysis.

Task 7: NLH Based Defect Severity Criteria

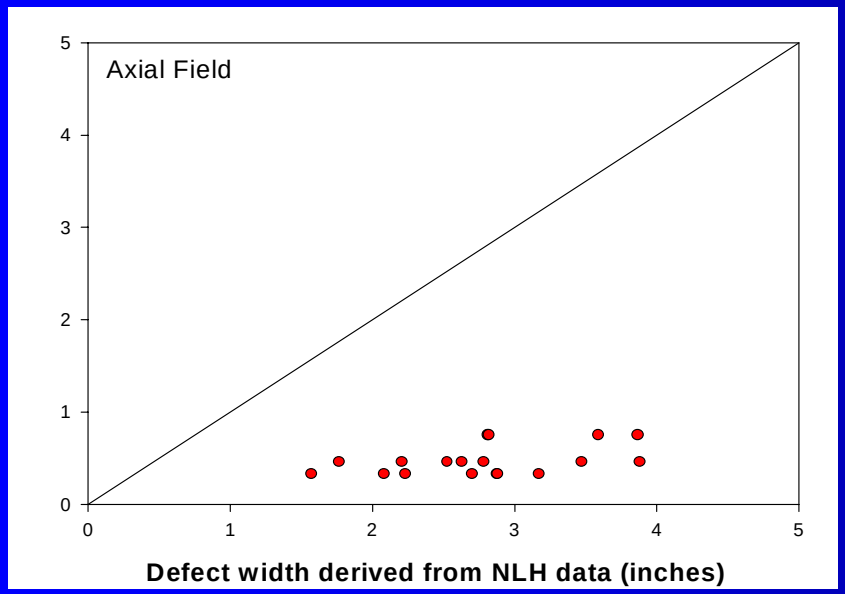


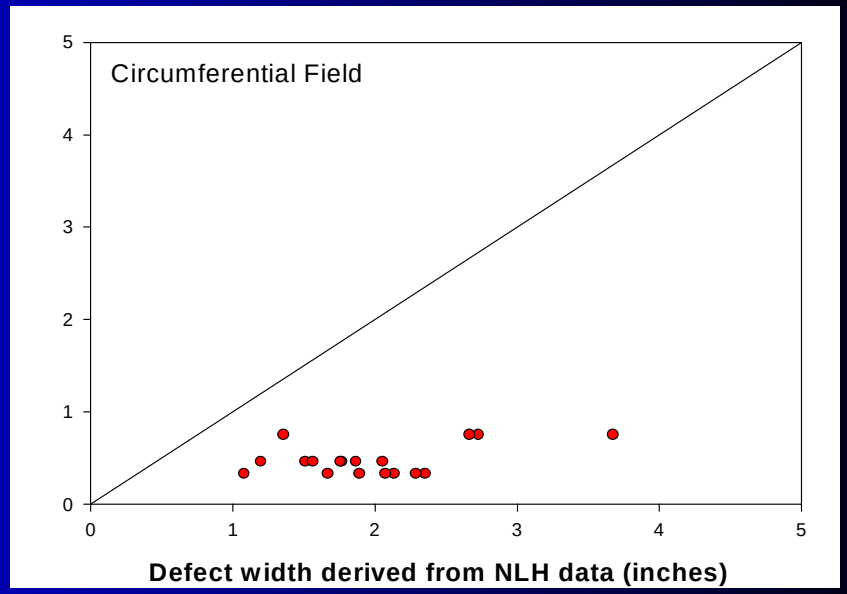


Example NLH results for axial and circumferential scans over defect strain anomalies on the inside of a pipe.

These results indicate features in the NLH signals related to gouge length and gouge width.

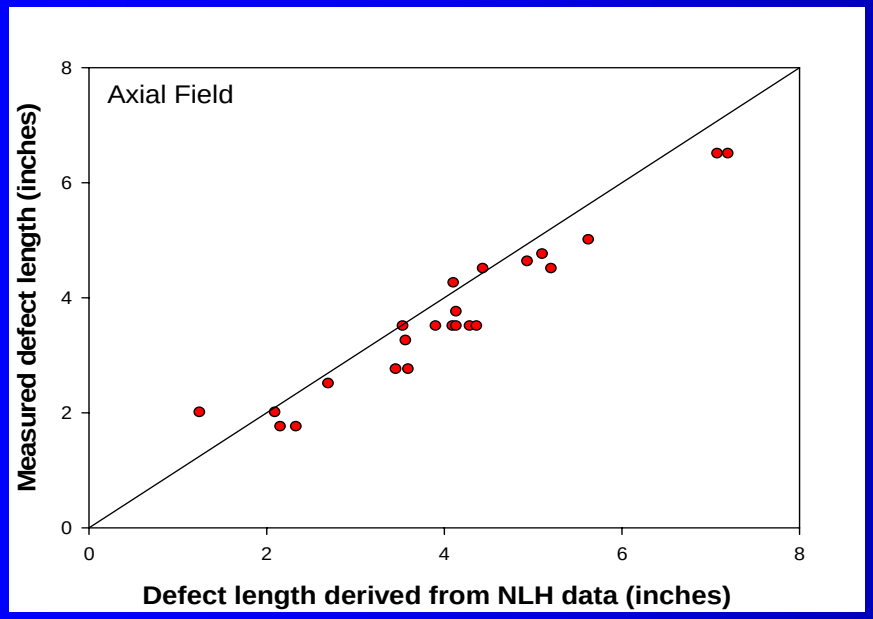
Task 7: NLH Based Defect Severity Criteria

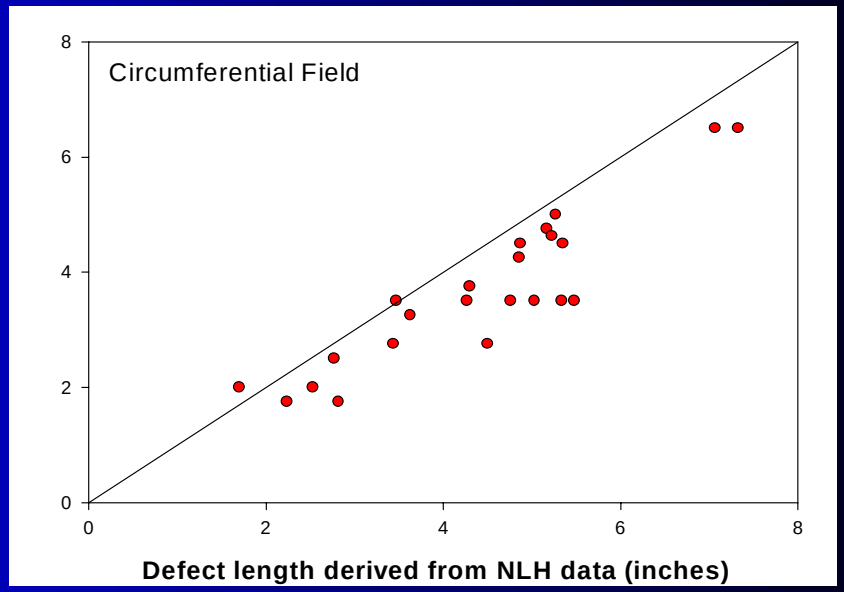




Features in the NLH signals related to gouge width do not appear to correlate with measured gouge widths.

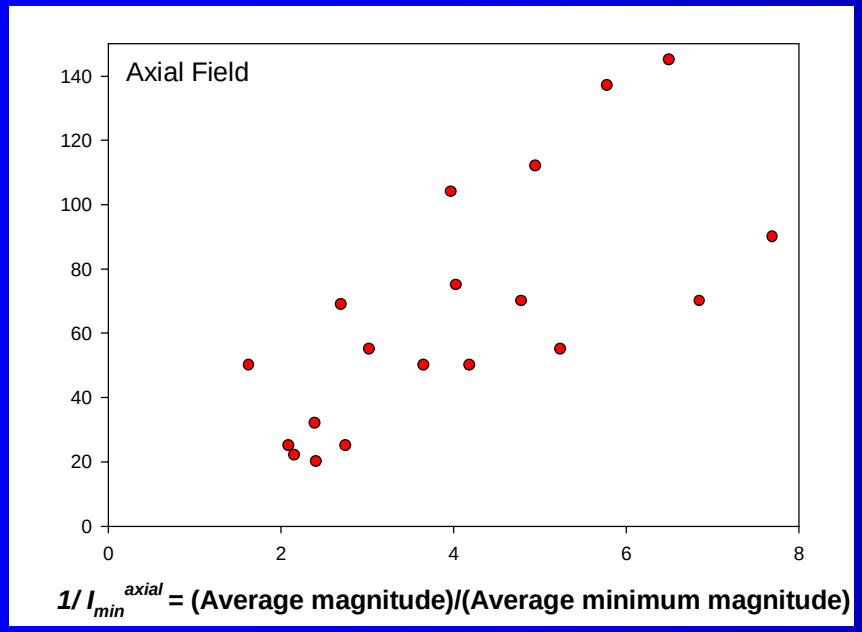
Task 7: NLH Based Defect Severity Criteria

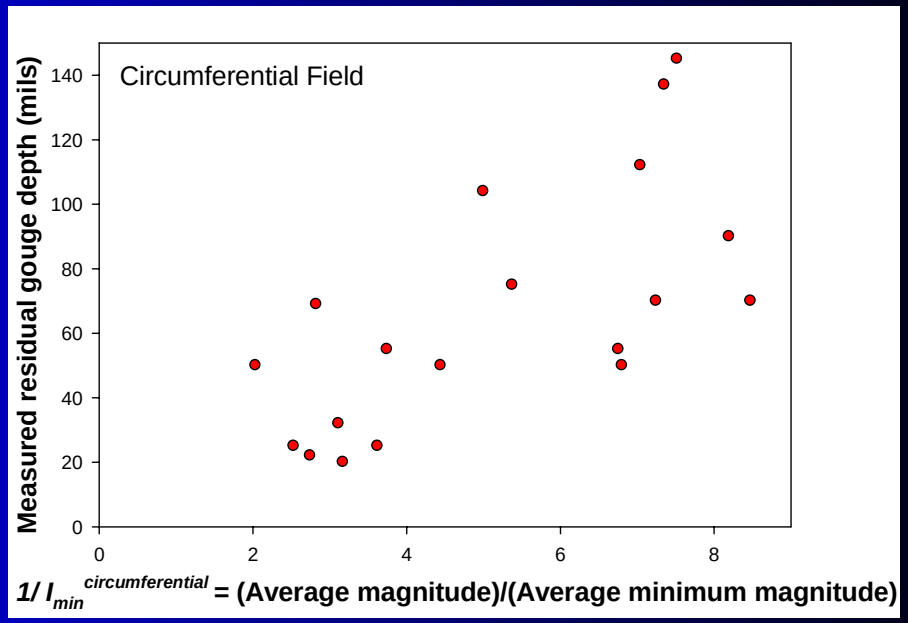




Features in the NLH signals related to gouge length are linearly correlated with measured gouge widths.

Task 7: NLH Based Defect Severity Criteria





The minimum value of the NLH signal obtained from NLH measurements over a gouge imprint is inversely related to the measured residual gouge depth.

Task 7: NLH Based Defect Severity Criteria

Proposed NLH-based defect severity criterion is:

$$S^{axial,circumferential} = \frac{L}{(I_{\min}^{axial,circumferential})^2}$$

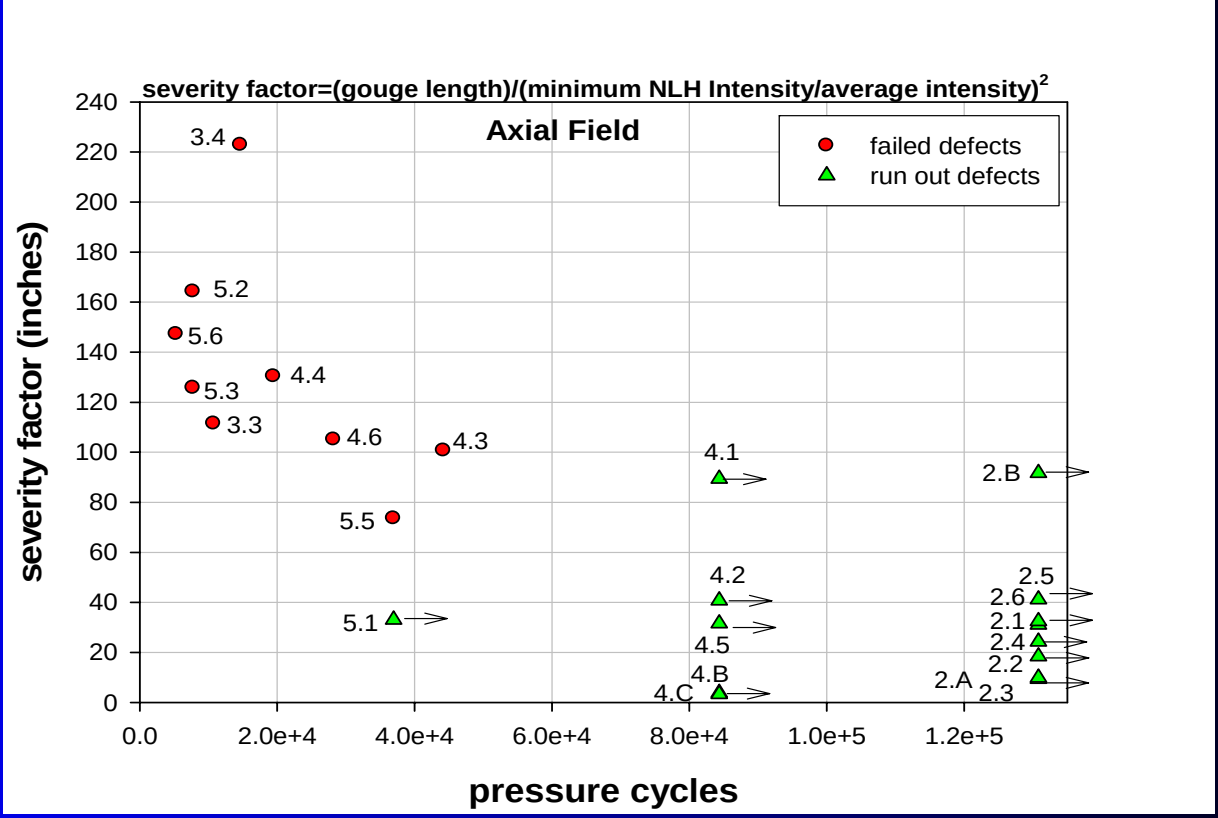
where:

I_{min} **= minimum value of the NLH signal measured over the imprint of a gouge**

L **= gouge length inferred from NLH measurements**

Task 7: NLH Based Defect Severity Criteria: Validation

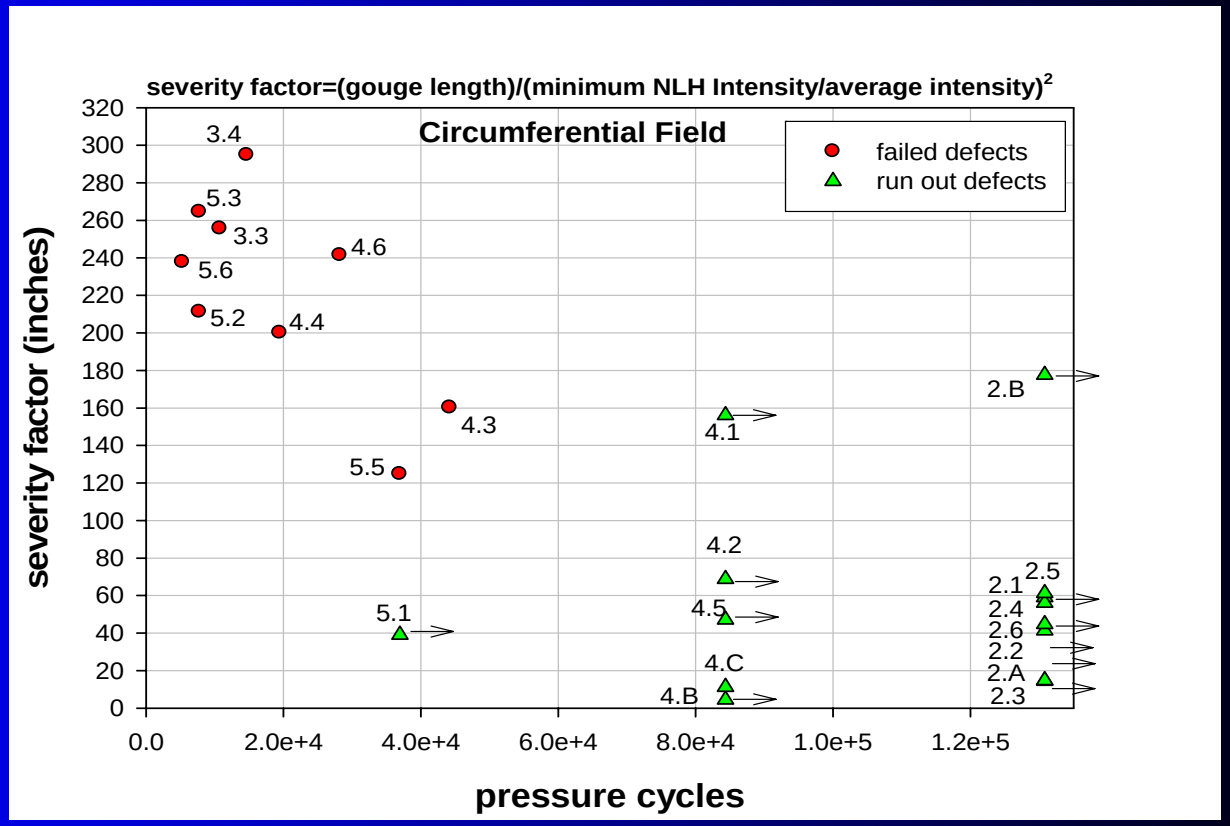
Axial Magnetic Field



Conclusion: The NLH-based severity factor, *S*, characterizes remaining fatigue lives.

Task 7: NLH Based Defect Severity Criteria: Validation

Circumferential Magnetic Field



Conclusion: The NLH-based severity factor, *S*, characterizes remaining fatigue lives.

Task 7: NLH Based Defect Severity Criteria

CONCLUSIONS

- The proposed NLH-based severity parameter, *S*, can be used to assess and rank the severity of gouged dents against delayed failures due to fatigue damage from pressure cycling.

- NLH measurements can be used to evaluate gouge lengths and residual gouge depths, the two parameters that appear in the expression for the NLH-based severity factor.

Task 8: Technology Transfer and Tuboscope Software Development

Tuboscope Pipeline Services (TPS)

TPS made an in-kind contribution to the project described in:

Pipeline Engineering Technical Report TR-2006-06:
"Implementation of NLH Gouge Severity Algorithm into *LinaView*®"

(Appendix B of Final Report)

LinaView®: A suite of integrated management, analysis and risk assessment software used by TPS to process inspection data.

Task 8: Technology Transfer and Tuboscope Software Development

TPS in-kind contribution consisted of:

- Development of software related to analysis of NLH signal maps of gouge defects
- Implementation of NLH-based defect severity criteria algorithms into a special test version of *LinaView*®
- Development of a preliminary pipeline survey and management system related to potential commercialization of NLH Technology
- Consideration of how NLH sensors could be improved and implemented onto an ILI tool

Task 8: Technology Transfer and Tuboscope Software Development

Summary of TPS Achievements

- Implemented SwRI NLH data analysis procedures
- Incorporated NLH algorithms in *LinaView*®
- Employed *LinaView*® to extract gouge lengths and minimum NLH signal intensities from NLH signal maps provided by SwRI
- Derived defect severities compatible with SwRI derived values from NLH signal map data
- Determined that although the derived defect severities fluctuated from NLH scan to NLH scan, the relative severities of the gouges remained unchanged

Task 8: Technology Transfer and Tuboscope Software Development

TPS <u>conclusions</u> regarding implementation of NLH sensors on ILI tools:

- **A field deployable design of NLH sensors and electronics could be implemented on ILI tools for detecting and evaluating the severity of shallow, gradual or re- rounded gouged dents in pipelines**

- **An improved NLH sensor design and suspension system is needed to ensure intimate contact of a NLH probe with the pipe surface in the region of very severe gouged dents (i.e. to minimize lift-off effects)**

Task 8: Technology Transfer and Tuboscope Software Development

TPS <u>conclusions</u> regarding implementation of NLH sensors on ILI tools (continued):

- **Comparison of gouge severity within a pipeline using the NLH-based defect severity criteria will give a relative severity ranking of detected defects**

- **Work is still needed to improve the ability of NLH to measure the time evolution of severity in order to reduce uncertainties between scans made at different times**

- **TPS demonstrated its developed algorithms and software were robust and ready to be added to a new release version of *LinaView*® when appropriate**

Summary of DOT/PRCI Program and Conclusions

- **Objective: Characterize change in strain anomalies due to mechanical damage in terms of NLH signals and derive NLH-based defect severity criteria related to remaining fatigue life (delayed failure).**

  Outcome: Successful.

- **Objective: Transfer the developed NLH-based technology to ILI companies.**

  Outcome: Successful.

Research Recommendations for Improved Development of NLH Sensors for ILI Tools

- Improve accuracy of NLH scan results by quantifying and controlling lift-off and increasing spatial resolution
- Investigate the capability of NLH probes to detect and rank the severity of non-axially oriented defects against pipe rupture and fatigue lifetimes
- Investigate the capability of NLH sensors to detect and rank the severity of defects that occur in welds