Chockie Group International, Inc.

Future Directions
for the Inspection of CASS

Summary Report

2nd International Workshop on the Future Directions for the Inspection of Cast Austenitic Stainless Steel Piping

June 15 -16, 2009
Seattle, WA

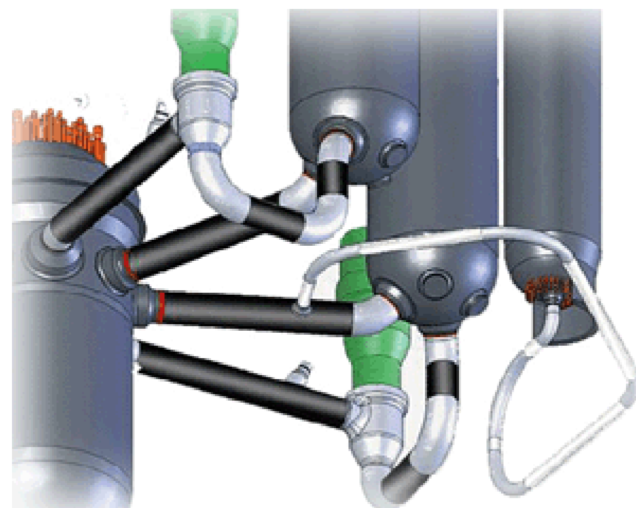
Inspection Challenge

Cast austenitic stainless steel (CASS) is widely used in the primary coolant piping system in pressurized water reactors (PWRs) in the United States, Japan, Sweden, France, and other countries. The attributes that make CASS a good candidate for the primary piping system significantly hamper the ability to effectively detect, locate, and size flaws within the material.

The service loads on PWR primary coolant piping are relatively low and even severely aged CASS is considered capable of tolerating major flaws. However, there is increasing pressure to continue to improve the inspection systems and to ensure the integrity of aging CASS piping systems.

The First Workshop

The first workshop on the future directions for CASS inspection was held in San Diego in 2006. The workshop led to the establishment of several important initiatives including the EPRI critical flaw evaluation project and the US/French international cooperative inspection research agreement. In the last three years there has been a number of advances in inspection techniques, critical flaw evaluation, low



frequency transducers, signal processing and, ASME Code actions. There has been continued interest and support by regualtory bodies in the inspection CASS.

The Second Workshop

The two-day workshop was held at the Bell Harbor Conference Center in Seattle, Washington, on June 15–16, 2009. The workshop was organized to bring together interested parties to review the current state-of-the-art in the inspection of CASS piping and to identify opportunities for future improvements.

A list of the registrants is provided on page 10 and 11. Approximately twenty-five to thirty people had initially indicated that they planned on attending. Unfortunately, a number of them were not able to participate as a result of travel restrictions from swine flu concerns, early outage planning activities, and utility budget constraints.

The participants wished to thank Zetec for their sponsorship of the reception Monday afternoon.

Workshop Objectives

- Build upon the results of the first workshop
- Review the current state-of-the-art in the inspection of CASS piping
- Determine what are the "gaps" and what can be done to fill the "gaps"
- Establish the foundations for cooperative improvement initiatives

Workshop Agenda

The workshop addressed:

- Recent and planned CASS inspection developments
- The impact of casting and fabrication on macrostructure and inspectability
- Critical flaw analysis
- ASME Code Case actions

Presentations

The initial portion of the workshop was devoted to a series of short presentations. These were to bring everyone up to speed on recent CASS-related activities and programs. There were presentations from:

- The US Nuclear Regulatory Commission (NRC)
- EPRI
- Vattenfall Ringhals AB
- The Pacific Northwest National Laboratory (PNNL)
- Structural Integrity Associates
- AREVA NP

Unfortunately several individuals that were planning on making presentations were not able to attend. However, they did submit their presentation slides which are included in the Workshop CD.

Dr. Yasuo Kurozumi from the Institute of Nuclear System Safety, Inc. (INSS) in Japan sent a presentation on recent CASS inspection development activities at INSS. Kazunobu Sakamoto of the Japan Nuclear Energy Safety Organization (JNES) prepared a review of recent and planned CASS research projects in Japan. Guy Maes from Zetec sent a presentation on the new Dynaray and UltraVision©3 that are being used in the inspection of CASS components.

Copies of all of the presentation slides are included on the Workshop CD. The CD can be obtained by contacting Alan Chockie at chockie@chockiegroup.com or (206) 367-1908.

Issues of Concern

An important aspect of the workshop was the time devoted to open discussions. A list of proposed discussion topics was provided at the

Proposed Discussion Group Issues

Inspection of Mitigated Alloy 82/182 Welds to CASS Components

- Inspection techniques that would facilitate robust design basis flaw assumptions

Critical Flaw Size

- Analysis of critical flaw size
- Probabilistic fracture analysis for various degradation mechanisms

Macrostructure

- Nondestructively determine the macrostructure
- Determine UT noise properties of each macrostructure
- Estimate macrostructure at each plant

Inspection Procedures, Equipment, & Signal Processing Techniques

- Beam penetration issues
- Enhance signal-to-noise ratio
- Reduce weight & complexity of automated scanning systems
- Consistent criteria for signal evaluation
- Inspections requirements from the outer surface & inner surface
- Relative ranking of the ability to inspect the primary coolant piping system welds

Physical Constraints

- Surface condition issues
- Accessibility issues

Inspection Personnel

- Experience and expertise issues
- Qualification concerns

Inspection Strategies

- Inspection of risk significant & accessible piping components from ID using UT & ET

beginning of the workshop. Over the two days many of these issues listed above were addressed to one degree or another.

Three key issues were identified during the discussion sessions[1]:

- Inspection of thin-walled material
- The need to focus inspections
- The categorization of CASS material

[1] The discussion summaries incorporate the notes kindly provided by Dan Sommerville of Structural Integrity Associates.

Inspection of Thin-Walled Material

CASS material used in PWR primary piping systems has had an incident-free service record for almost 40 years. CASS was selected for these installations based on such factors as its relative cost, corrosion resistance, and ease of welding.

The effectiveness of ultrasound (UT) to detect flaws in CASS piping is influenced by the coarse grain structure and anisotropic crystal properties of the CASS material (which can affect the direction and propagation velocity of the ultrasound). During his presentation, Clay Rudd from PNNL discussed how casting and fabrication practices can have a significant impact on the CASS macrostructure — and consequently the ability to inspect the material.

As pointed out by Carol Nove of the NRC, there is continued interest in the development of qualified non-destructive exam (NDE) techniques to inspect safety-related CASS piping and components. This is due to such factors as:

- NDE is part of the NRC's defense-in-depth approach to regulating
- There are currently no qualified NDE techniques for CASS
- Thermal embrittlement concerns with the aging CASS material
- The need for the NRC to ensure the structural integrity of the plant systems and components

In recent years there have been some major improvements in the use of ultrasound (UT) to detect flaws in CASS piping. However, the nature of the material still makes it difficult to reliably detect and size flaws from the OD especially in thick-walled primary pipe.

Aaron Diaz and Mike Anderson from PNNL mentioned that they and others had found that it is relatively easy to detect, length size, and

depth size circumferentially oriented thermal fatigue cracks in smaller bore CASS piping. This includes such small bore piping as found in the pressurizer surge lines in Combustion Engineering (CE) plants with nominal wall thicknesses of 1.2 to 1.7 inches.

PNNL has had good success with 800 kHz to 2 MHz phased array TRL probes. The PNNL team found it easy to see the embedded flaws in the surge lines samples from the CE WNP-3 plant.

It was suggested that EPRI independently confirm PNNL's findings using the WNP-3 samples. The samples could be sent to the EPRI NDE Center in order for EPRI determine whether or not standard conventional arrays may be adequate to inspect this thin-walled CASS material.

Robert Hardies from the NRC noted that if thin-walled CASS material is clearly shown to be inspectable then this will likely become a regulatory issue.

This led to the discussion of the ASME CASS Code Case. Burt Cheezum of AREVA suggested that it may be possible to develop an ASME Section XI Appendix VIII Supplement 9 for the inspection of CASS components that are less than 2 inches thick. For thicker CASS components it may be necessary to develop qualification requirements that are different than those in Appendix VIII.

Although a new Supplement 9 would give utilities an option to their current inspection practices, several attendees argued that it is not appropriate to provide utilities with an inspection option for which there are no flaw evaluation or acceptance guidelines in the Code. What would one do if a flaw was detected?

Without generally accepted methods for flaw evaluation the utility is placed in the situation of submitting a unique analysis to the NRC for their review and waiting during a potentially long NRC review and approval process.

The NRC stated that industry is already required to inspect affected welds. As a result, it is already an issue today. They noted that the NRC has been lenient to date but that may change in the future.

Focussed Inspections

There was considerable discussion on the identification of key factors so CASS inspections can be treated more realistically. Several participants stated that they would like to move away from deterministic to more risk informed inspection strategies. This would involve the development of a graduated approach based on such factors as:

- Component type
- Material type
- Delta ferrite level
- Loads
- Risk significance of the components
- Conditions and accessibility
- The combined use of the best available inspection techniques, such as:
    - – Visual
    - – UT
    - – Digital radiography
    - – Eddy current

The strategy would be to use a flaw tolerance approach with some inspections to demonstrate the structural margins against fracture.

An important element in focusing the inspectionsis to identify acceptable flaw sizes. Tim Greisbach from Structural Integrity pointed out that acceptable flaw sizes depend on fracture toughness, material strength properties, loads/stresses, and safety factors. He identified a number of questions that remain to be answered:

- Flaw length – should we assume a 360 degree flaw or a flaw of reasonable length?

- Fracture toughness - should we use the absolute lowest bound in the industry based on CF8M properties or representative (best estimate) toughness properties?
- Material strength properties - should we use the Code minimum values or should we use actual/more realistic tensile and yield properties?
- Loads/stresses - should we use the maximum bounding loads/stresses in the industry or typical loads/stresses?
- Safety factors - for management of CASS components, should we use the full Code safety margins (S.F. = 2.77) or something less?

The determination of safety margins for the components of interest can be improved if more is known about:

- Maximum stresses in the component
- Plant modifications or mitigations (e.g., weld overlay)
- Material type (CF3, CF8, CF8A or CF8M)
- Material ferrite content
- Material saturated fracture toughness
- Prior inspection results
- Future inspectability

According to Tim Griesbach, if one could ensure high safety margins for toughness and stress then one need not worry as much about the flaw size.

It was recommended that further efforts be undertaken to assess the flaw tolerance of CASS piping. This would include:

- Survey of materials and loads in the affected CASS components
- Develop criteria for determining analysis method (EPFM or limit load)

- similar to that in Appendix C of ASME Section XI for ferritic steels
- Develop flaw acceptance diagrams for typical CASS piping components (e.g., hot leg and cold leg pipes)

Categorization of CASS Material

The macrostructure of CASS material has and continues to pose a significant challenge to the ability to detect and size flaws.

Clay Rudd from PNNL is currently conducting a study to understand the fundamentals of CASS casting parameters and their effect on grain structure. He noted that grain structure is influenced by alloy composition/delta ferrite, mold wash or lining, pouring method, schedule, and temperature, and post pour cooling.

Based on the Structural Integrity work there was a discussion of the merits of categorizing plants based upon the delta ferrite in their CASS material. This was generally considered to be a good idea.

Of the three types of CASS material used in the plants, CF8, CF8A and CF8M, CF8M is the most susceptible to thermal aging.
As part of their work for EPRI, Structural Integrity had conducted a materials data survey. They found that only 6 of the 51 Westinghouse plants with primary piping CASS material used CF8M material.

There was some discussion on the need for a database on the "material in the fleet". Doug Kull from EPRI suggested that the plants do a walk-down of all the CASS in their plant for the database. There is a need to know the bounds and to classify the scope of the issues.

It was proposed to use the CRDM (Control Rod Drive Mechanism) Alloy 600 database

as a model for a similar information database for CASS issues. The CRDM database tracks information on inspections and repairs. There was some discussion about the appropriate organization to manage this database (since the issue includes both PWRs and BWRs). This brought up the concern that the industry would not want to fund any work for a subject that is "not yet a problem". However, the NRC participants reiterated that license renewal commitments and growing concerns with the aging of the CASS material currently makes this "a problem".

The Next Steps

The proposed next steps, in no specific order, are:

- Develop a plan for CASS
- Prepare thin-walled CASS Code Case
- Expand EPRI and NRC cooperation
- Prepare guidance documents
- Inspection strategy for CASS ≥2 inches
- Continue flaw tolerance evaluations
- Establish CASS database
- Improve international cooperation

Develop a Plan for CASS

The NRC indicated a desire to see a high level plan for the inspection and management of CASS material. The plan should identify the purpose, goals, and actions. The plan should eventually address all applications of CASS in the plants, including internals. It should also ensure coordinated international activities to avoid redundant efforts.

Doug Kull from the EPRI NDE Center indicated that he will review the EPRI CASS road map based on the information/discussions from the Workshop.

Prepare Thin-walled CASS Code Case

The participants agreed that in the near term it would be appropriate to divide the CASS piping and components into thin and thick-walled categories (<2 inches and ≥2 inches, respectively).

- PNNL will send pressurizer surge line samples to the EPRI NDE Center
- EPRI will use standard manual and automated techniques to evaluate the inspectability of thin-wall CASS
- ASME CASS Task Group will use PNNL and EPRI findings in preparing the Code Case

A follow-on CASS Code Case for thicker CASS components will be developed. However, this Code Case will have qualification requirements that are different than those in Appendix VIII.

Expand EPRI and NRC Cooperation

Wally Norris of the NRC proposed closer working arrangements with EPRI. This would include such activities as providing EPRI with pressurizer surge line samples for the independent verification of the PNNL thin-walled inspection findings.

PNNL will prepare parameters used to inspect both thin and thick-walled CASS. EPRI will use both manual and automated techniques for the inspection of the thin-walled samples.

Doug Kull of EPRI indicated that the thin-walled CASS samples need to be representative of what is out in the field. Robert Hardies of the NRC will check on availability of surge lines from Calvert Cliffs.

Prepare Guidance Documents

The NRC raised the question concerning guidance for new construction. Should the guidance define such factors as:

- ID Surface prep requirements that would enable effective ET or NDE
- OD surface requirements
- Delta ferrite requirements

Mike Anderson stated that there is a need for specification for inspectability of new construction CASS materials.
PNNL proposed to produce a "best practices" document on the inspection of large bore CASS piping.

Meeting Break

Inspection Strategy for CASS ≥2 inches

For CASS with a nominal thickness of greater than two inches, an inspection strategy will need to be developed. The strategy should specify where and when inspections are required. This will require:

- Acceptance criteria[2]
- Combinations of inspection techniques
- Qualification requirements

Continue Flaw Tolerance Evaluations

There is a need to know the impact of grain structure on fracture toughness and fatigue crack growth rate (propagation) in order to properly bound the critical flaw size. Considering the dramatic variation of grain structure within the same component it is important to ensure that the fracture toughness and crack growth data bounds the range of expected material grain structure.

Unfortunately, EPRI has no plans to continue the CASS flaw tolerance evaluation efforts. The NRC does not have any program plans for the development of acceptance criteria.

It was agreed that this work is essential and should continue. The NRC indicated they will contact EPRI to encourage the continuation of the flaw evaluation work.

Establish CASS Database

EPRI will send forms to the utilities to obtain walk-down information on the CASS in the plants. This should assist in establishing the bounds of the CASS population. Eventually the database could include material, geometry, repair, and service history information.

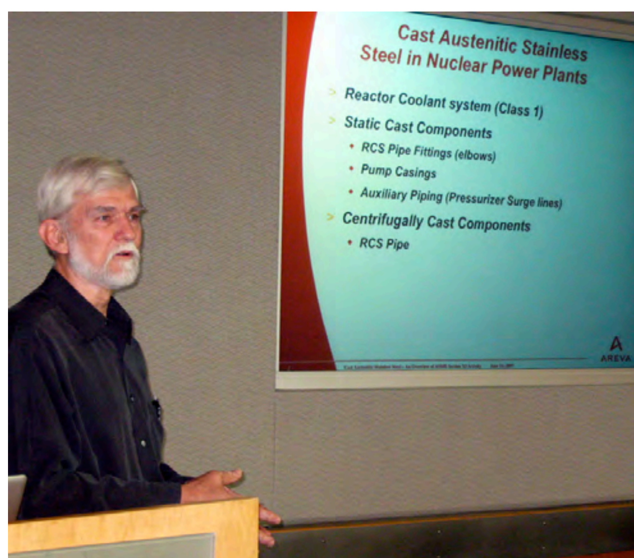
[2] This will likely involve the ASME Section XI Working Group on Pipe Flaw Evaluations.

The database could be organized into two parts, one for the more difficult material CF8M, and the other for CF3, CF8, and CF8A.

Improve International Cooperation

There is a significant amount of CASS related projects underway or completed in France, Japan, the US, Sweden, and other countries. There is a need for better coordination and cooperation to avoid duplication of efforts. One example is the cooperative research agreement between the NRC and the Institute for Radiological Protection and Nuclear Safety (IRSN) in France to assess the ability of advanced NDE methods to detect and size defects in coarse-grained steel components. The NRC will continue to focus on probes and equipment and the IRSN will focus on simulation and characterization.

It was proposed that this CASS Future Directions Workshop should be an annual event in order to facilitate improved international cooperation. The 3rd International Workshop will likely be held in early 2010.



List of Presentations

The following presentations are included on the Workshop CD:

1. *Workshop Agenda*
2. *NRC CASS Research*
3. *NRC Regulatory Issues Related to the Examination of Cast Austenitic Stainless Steel*
4. *EPRI NDE of Cast Stainless Steel:PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update*
5. *Swedish CASS Activities -- Ageing Results from Round Robin Feedback Experiences Inspection*
6. *Casting Parameters of CASS Pipe and the Effects on Grain Structure: Progress Report*
7. *Flaw Tolerance Evaluation of Thermally Aged Cast Austenitic Stainless Steel Piping*
8. *NRC Sponsored Efforts toward Addressing NDE Inspection of Cast Austenitic Stainless Steel (CASS) Piping – A Technical Overview of Work at PNNL*
9. *Recent CASS UT Activities on PZR Surge Line Welds*
10. *Dynaray: High-Performance Phased Array UT*
11. *Cast Stainless Steel Inspection An Overview of ASME Section XI Activity*
12. *Recent Ultrasonic Research and Development Activities and Results for CAST Stainless Steel in INSS*
13. *JNES Study on Nondestructive Inspection for the Cast Stainless Steel Piping*

Bell Harbor Conference Center

Acknowledgments

We wish to recognize the support and encouragement of the following organizations in making the Workshop a success:

- Zetec — for their encouragement and their sponsorhsip of the Monday reception
- PNNL
- Structural Integrity Associates
- The NRC
- EPRI
- AREVA NP
- Japan Nuclear Energy Safety Organization
- Institute of Nuclear System Safety
- WesDyne International
- The Bell Harbor Conference Center
- The Edgewater Hotel

We also wish to thank the presenters and participants for a very informative and productive two days.

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1 Guy Maes was unable to attend due to unforseen circumstances.

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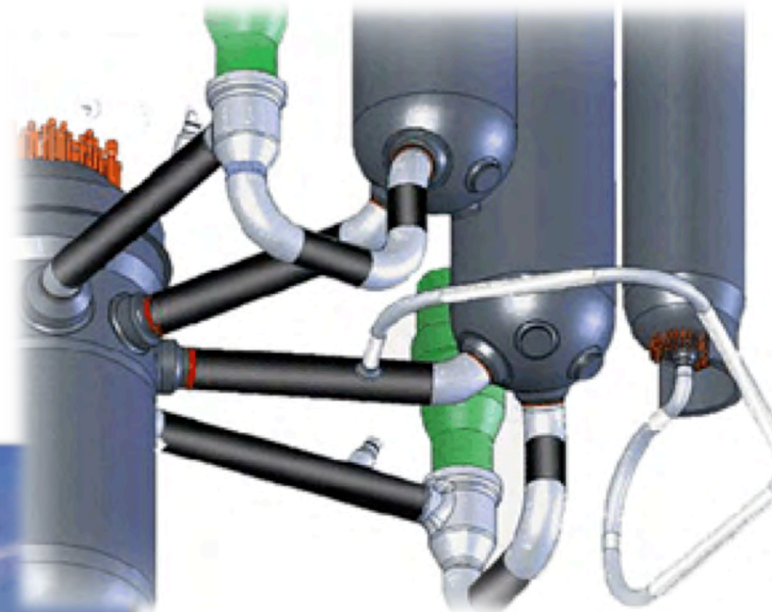
2nd International Workshop

Future Directions for the
Inspection of Cast Austenitic Stainless Steel Piping



2nd International Workshop

Future Directions for the
Inspection of Cast Austenitic Stainless Steel Piping

Workshop Agenda

Monday - June 15

8:30	Continental Breakfast
9:00	Introductions & Review of First Workshop
9:30	Regulatory Concerns
9:50	EPRI CASS Programs
10:10	Swedish CASS Activities
10:30	Break (15 minutes)
10:45	Casting & Fabrication Parameters
11:00	Structural Integrity Flaw Evaluation Analysis
12:00	Lunch
1:15	Overview of PNNL Inspection Development (with a review of DYNARAY and UltraVision© 3)
2:30	Break (15 minutes)
2:45	Breakout Discussion Groups
4:00	Summaries of Breakout Group Discussions
5:00	Reception - hosted
7:30	Dinner - no host

Workshop Agenda

Tuesday - June 16

8:30	Continental Breakfast
9:00	ASME Code Case & Actions
9:20	Japanese CASS Activities
9:40	French CASS Activities
10:00	Breakout Discussion Groups
10:30	Break (15 minutes)
11:30	Summaries of Breakout Group Discussions
12:00	Lunch
1:15	Breakout Discussion Groups
2:30	Break (15 minutes)
2:45	Summaries of Breakout Group Discussions
3:15	Identify Future Actions / Potential International Cooperative Initiatives
4:00	Workshop Conclusion

Discussion Group Issues

Inspection of Mitigated Alloy 82/182 Welds to CASS Components

- Inspection techniques that would facilitate robust design basis flaw assumptions

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- Analysis of critical flaw size
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- Inspections requirements from the outer surface & inner surface
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Physical Constraints

- Surface condition issues
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Inspection Personnel

- Experience and expertise issues
- Qualification concerns

Inspection Strategies

- Inspection of risk significant & accessible piping components from ID using UT & ET

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Protecting People and the Environment

Regulatory Issues Related to the Examination of Cast Austenitic Stainless Steel

Carol Nove, Materials Engineer, NRR/DCI

2nd International Workshop on the Future Directions for the Inspection of Cast Austenitic Stainless Steel Piping, June 15-16, 2009, Seattle, WA

Regulatory Requirements

- General Design Criteria-32 "Inspection of reactor coolant pressure boundary." Components which are part of the reactor coolant pressure boundary shall be designed to permit (1) periodic inspection and testing of important areas and features to assess their structural and leaktight integrity, and (2) an appropriate material surveillance program for the reactor pressure boundary pressure vessel.
- 10 CFR 50.55(a) incorporates ASME Code Section XI by reference. The Code requires inspection of welds adjacent to cast components.

Background

- Inspection is an integral aspect of defense-in-depth.
- Inspection requirements exist for components even when there are no known active degradation mechanism.
- Inspection are performed to monitor for the absence of active degradation or, if degradation occurs, to demonstrate integrity until the next inspection.
- Ability to inspect components is necessary to achieve these goal.

Background

- CASS components are in safety significant locations in reactor coolant system.
- Though operational experience has not identified failures, longer-term operation may present issues with embrittlement mechanisms or potentially with SCC.

Regulatory Issues

- CASS components on one side of a weld may interfere with the ability to inspect a weld resulting in coverage and quality issues.
- Single-sided exam leads to lower robustness and potentially missed indications.
- Geometry on the accessible side can challenge coverage.

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Regulatory Issues

- For the CASS components themselves, inspections are required; however, the inspections do not provide useful information and, currently, cannot be qualified.
- Variety of components:
  - Piping, surge lines, pump bowls, safe ends
    - Single-sided and "no-sided" exams (where castings are on both sides of the weld).
  - Cast internal components
    - Not a requirement to inspect now; however, in license renewal arena, there are postulated degradation mechanisms which may lead to a need for inspection.

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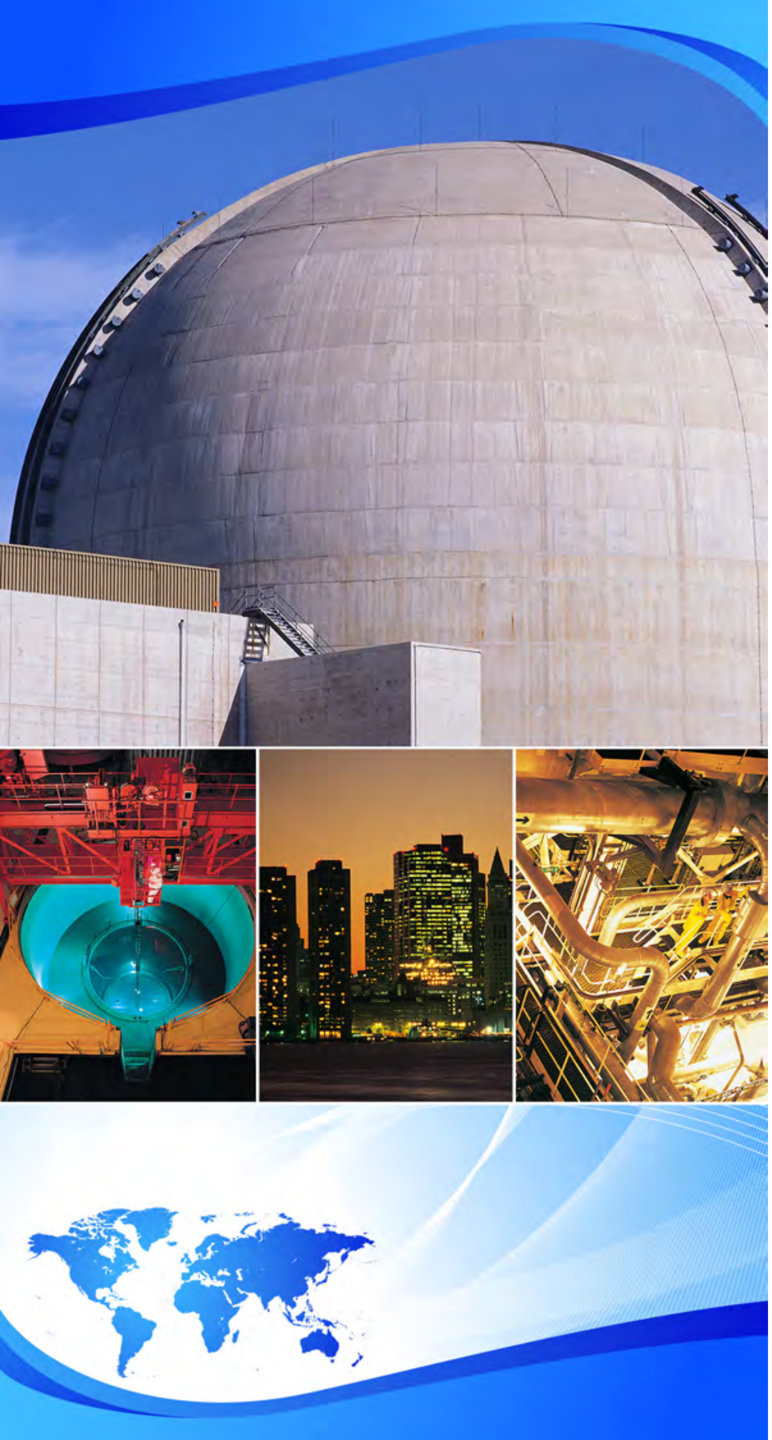
Summary

- Potential for new degradation mechanisms in CASS components could challenge structural integrity and functionality of the reactor coolant system.
- The inability to inspect CASS components challenges our ability to demonstrate the structural integrity of plants.



ELECTRIC POWER RESEARCH INSTITUTE

NDE of Cast Stainless Steel:
PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

June 15, 2009

Doug Kull

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NDE of Cast Stainless Steel: PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

- Nondestructive Evaluation of CSS:
  - Everyone has known for a long time that the UT capability has been less than optimum
  - The level of concern has not been high because CSS is a good material; there is no known degradation mechanism for CSS reactor coolant piping
    - No leaks
    - No Failures
  - Interest is growing however
    - Thermal aging embrittlement
    - License renewal commitments
  - The industry will soon have to address CSS NDE

NDE of Cast Stainless Steel: PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

- PWR SS NDE Capability & PD TAC Scope for CSS:
  - Identify degradation mechanisms and target flaws
  - Research and develop NDE solutions
  - Integrate into performance demonstration process
  - Align efforts with license renewal (LR) commitments

NDE of Cast Stainless Steel: PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

Cast Stainless Steel (CSS) Roadmap

License Renewal Commitments Review for CSS

Determination of Degradation Mechanisms for CSS

Review History of NDE Solutions for CSS

Investigate Alternatives to Inspection

Develop RI-ISI Methodology

Evaluate and Develop NDE Solutions

Fabricate CSS Mockups

Establish ASME Code Qualification Criteria

Develop CSS PD Program

Fabricate Additional CSS Mockups

CSS PD Program Maintenance

2005 2010 2015

Major Tasks

(start dates shown)

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NDE of Cast Stainless Steel: PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

- Recent projects related to this TAC
  - Cast Stainless Steel - Evaluation Process (Completed 2008)
    - Prioritizing areas of concern
    - Determining target flaw sizes
  - Inspection & Mitigation of Alloy 82/182 Butt Welds
    - Develop techniques to examine overlays that cover cast components
      - Mockups were built in 2008.
        - Reactor Coolant Pump (Carbon Elbow to CSS Pipe)
        - Shutdown Cooling (Nozzle to CSS Safe-End)
        - Surge (Nozzle to CSS Safe-End)
      - Studying optimized & full structural overlay configurations.
      - Performed automated UT examinations
        - Evaluated several search units to determine what probe characteristics improved performance
        - Evaluated detection and sizing capabilities

NDE of Cast Stainless Steel: PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

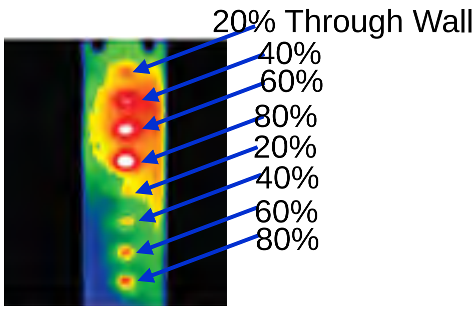
- Recent projects related to this TAC (con’t)
  - Centrifugally Cast Stainless Steel (CCSS) Inspection Technology (TI Funded) (Completed 2008)
    - Guided Wave technique development to determine the grain structure of CCSS
    - Finite-element modeling of bulk & guided wave propagation to optimize probe design for CCSS inspection
    - Simulated circumferential thermal fatigue cracks 50% through-wall were successfully detected using a low frequency tandem probe.

NDE of Cast Stainless Steel:
PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

- Current 2009 funded project proposals related to this TAC:
  - Flaw Fabrication in Cast Stainless Steel Components:
    - Research & development for cast stainless steel mockups
    - Develop and maintain a roadmap to address the issues and challenges surrounding the inspection of CSS materials. A status report will be published annually.
    - Identify sources for both vintage and new CSS material
    - EPRI Cast Austenitic Stainless Steel Project Review and Literature Search
    - Investigation of Thermal Aging Embrittlement Mechanisms in Cast Stainless Steel. This task covers an investigation into evaluating the severity of thermal aging embrittlement in CSS using ultrasonic materials characterization techniques. (e.g. UT backscatter, etc)
    - Refine flaw manufacturing processes
    - Develop, fabricate, and make available a well-characterized set of samples made out of CSS material
    - Publish reports on UT materials characterization measurements in CSS and Flaw fabrication technology in CSS

NDE of Cast Stainless Steel: PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

- Current 2009 funded project proposals related to this TAC (TI project)
  - NDE for Cast Stainless Steel
    - Coupled thermography
      - Heating up of defects
      - Infrared camera measures temperature gradient
      - Insensitive to grain structure
      - Crack detection independent of orientation
    - Potentially tomographic radiography
    - Low frequency ultrasonic transducers (See next slide)



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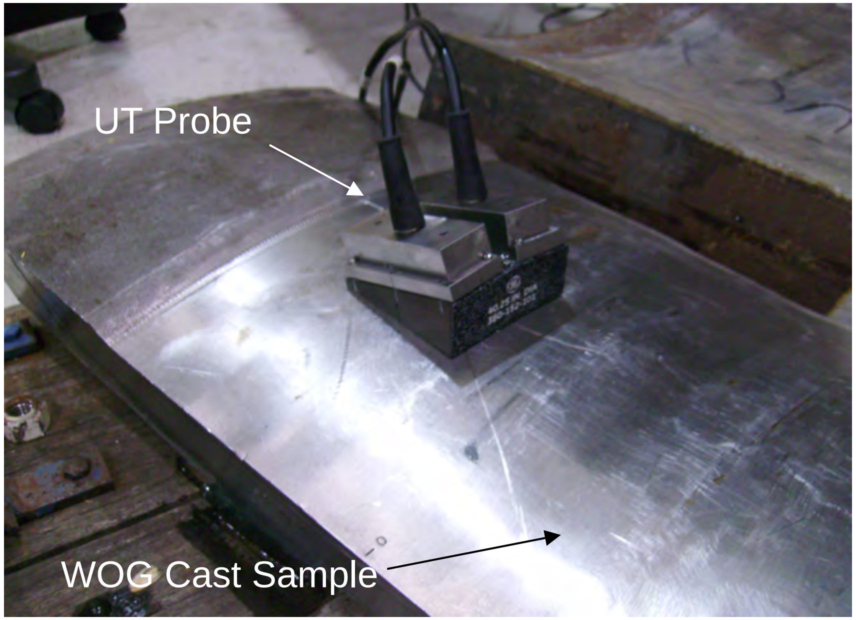
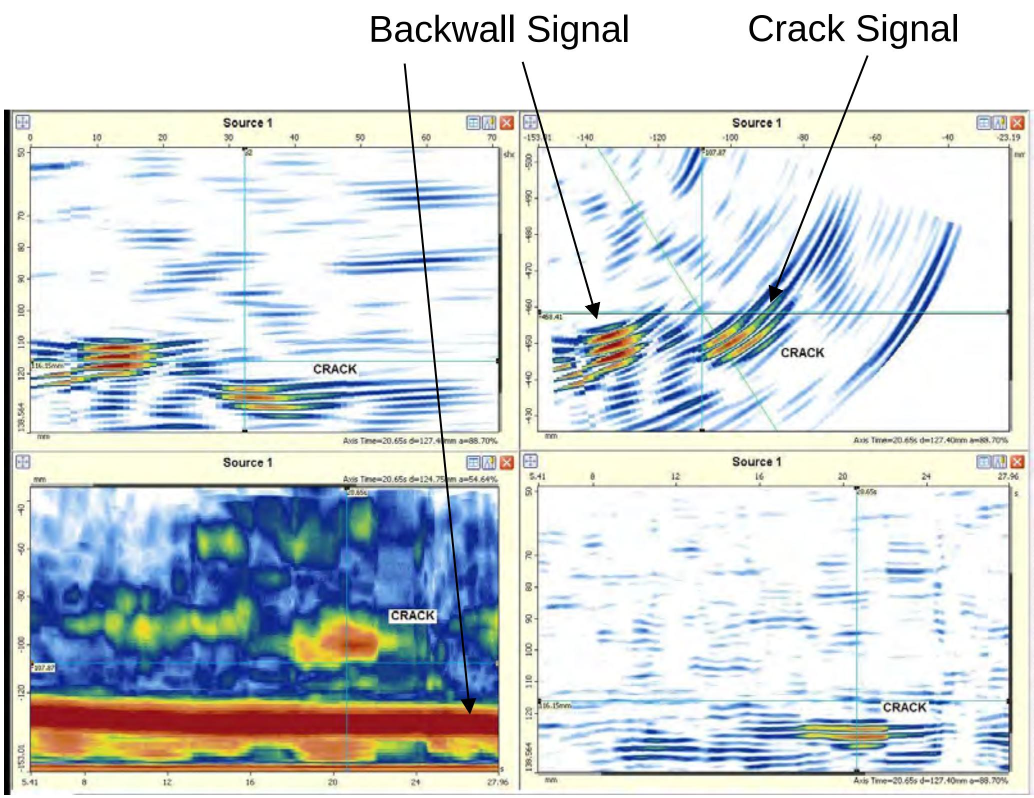
NDE of Cast Stainless Steel: PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

- Obtained Ultrasonic Phased Array Data using Low Frequency Probe (500 kHz) on WOG Cast Stainless Steel Sample containing Inside Surface Connected Circumferentially Oriented Crack





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NDE of Cast Stainless Steel:
PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

- 2010 Project Proposals Related to this TAC
  - Evaluation of Inside Surface Examination Techniques for Cast Stainless Steel Components
    - Evaluate ultrasonic & eddy current techniques on available cast samples.
    - If the industry can qualify techniques for examination of cast components from the inside surface they could be deployed on the accessible areas (terminal ends).
    - This may provide justification for reduction or elimination of examinations on the less critical welds.

NDE of Cast Stainless Steel:
PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

- 2010 Project Proposals Related to this TAC (con't)
  - Signal Processing Advancements for Cast Stainless Steel UT Examinations
    - Investigate and Apply Signal Processing Methods for More Reliable Flaw Detection in CSS
    - Survey of Potential Signal Processing Routines
    - Development of Signal Processing Routines
    - Perform Experiments on CSS samples

NDE of Cast Stainless Steel: PWR Stainless Steel NDE Capability & Performance Demonstration TAC Update

- Looking Forward at NDE of CSS
  - Short Term (The next 1 or 2 years)
    - Determine critical crack sizes and growth rates
    - Develop method of characterizing CSS material
    - Identify a method of fabricating flawed mockups that contain flaws that closely mimic the damage mechanism for CSS
    - Continue investigating NDE techniques other than UT
    - Explore NDE techniques deployed from the component ID
    - Evaluate a Risk-informed approach to the examinations
    - Better align efforts with License Renewal commitments
  - Long Term (2 years and beyond)
    - The development of a PD program will be complex and expensive
    - Additional Code development is needed to define qualification requirements

Swedish CASS Activities

Ageing
Results from Round Robin
Feedback Experiences
Inspection

Ringhals, Björn Forssgren Materials & Ageing/ Claes Sandelin Inspection

Ageing program

- Ringhals 2 (1974) replacement of Steam Generators (1989)
- Hot leg (temp 325) and crossover leg (temp 291).
- Hot leg showed a significant degradation in properties, crossover leg didn't
- The impact testing verified conservatism in the used fracture toughness values.

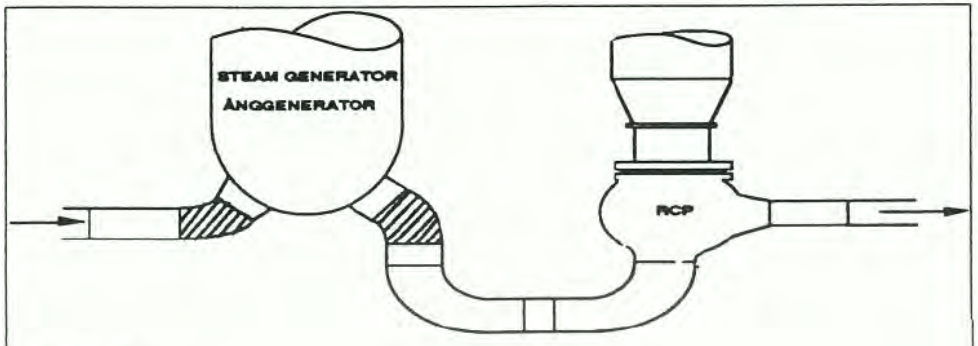


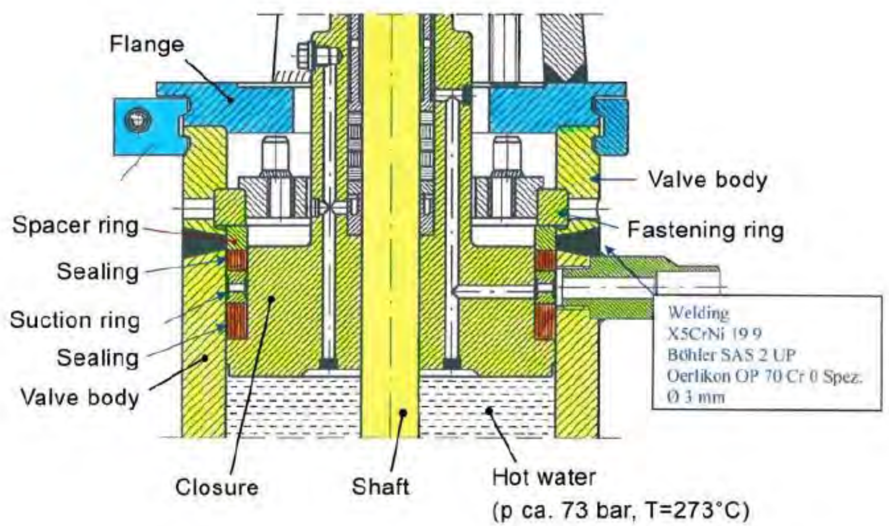
Fig. 1
PWR loop

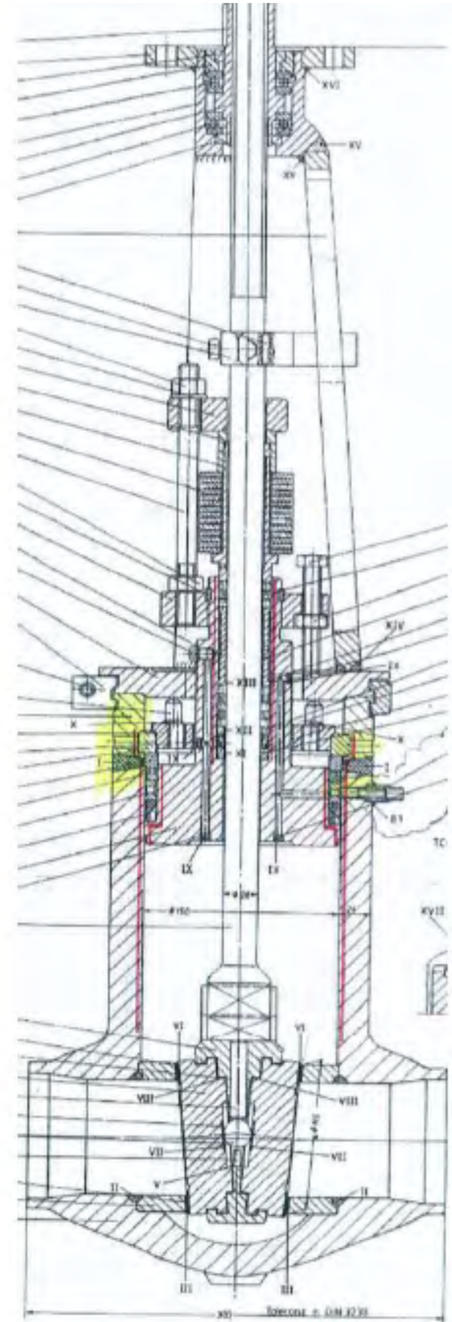
Round Robin (NDT) 1996

- 4 Teams, 3 Test Specimen, T 57, 60 and 208 mm Centrifugally and statically cast
- Defects were rather small, from 6-25 mm
- Technique Twin Crystals, Focusing probes, TOFT, Creeping waves, Eddy Current
- The detection performance was in general rather poor.
- Best results if the inspection is performed from the side where the defects starts

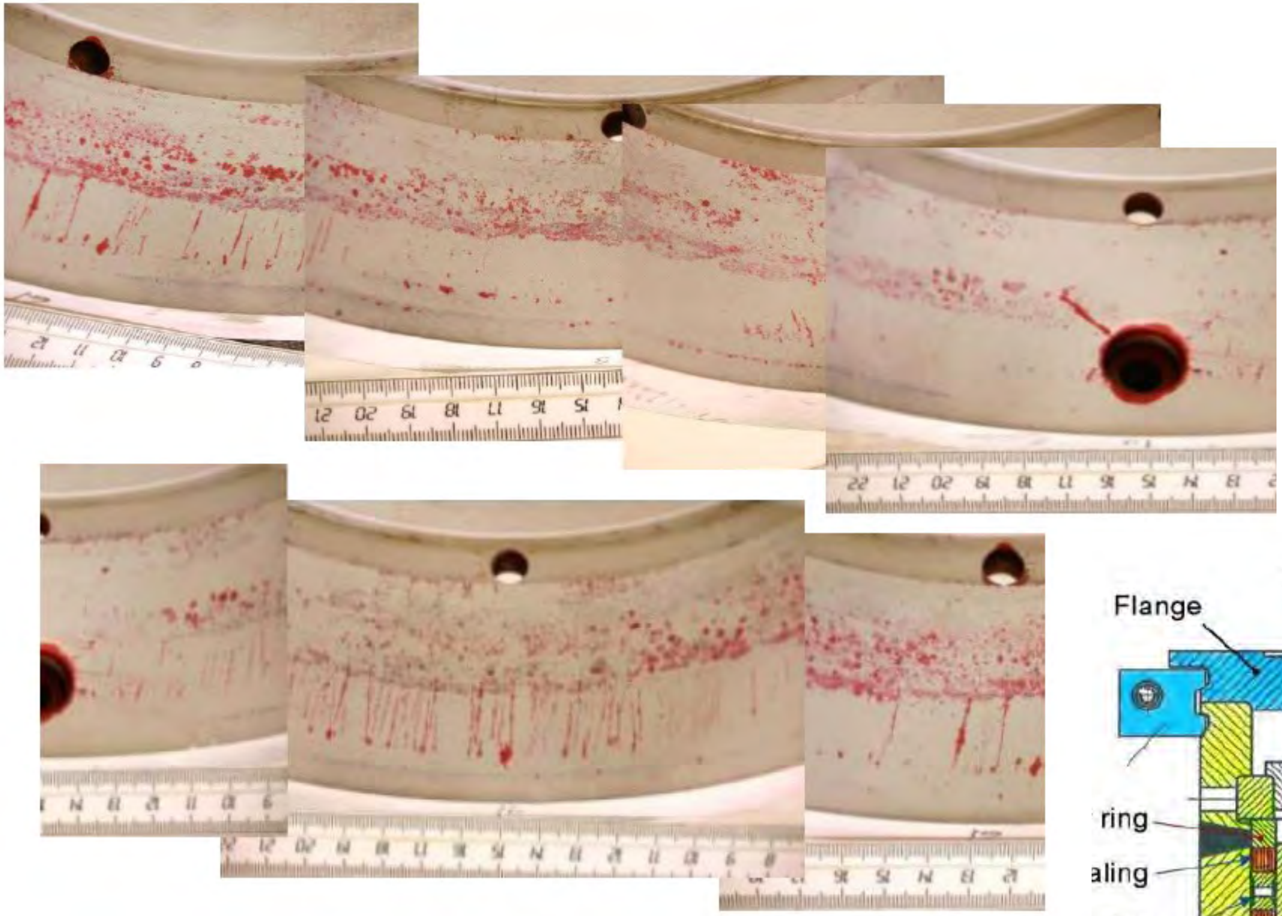
Experience Feedback / Valves

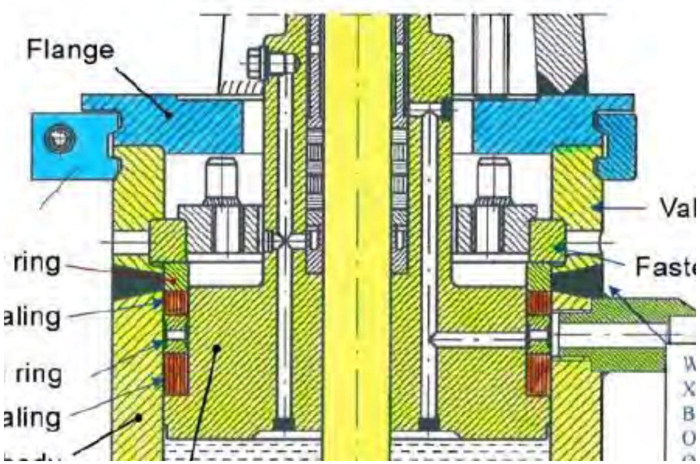
- All types of cast stainless steel
- German type ”Bredtschneider” -> valve with leakage indication and self sealing
- Also some other valves (not ”Bredtschneider”)
- Different dimensions!





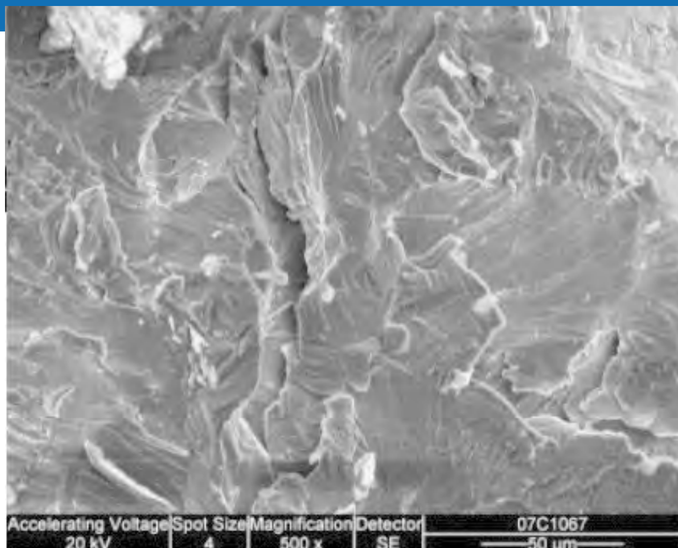
Defect picture (PT)

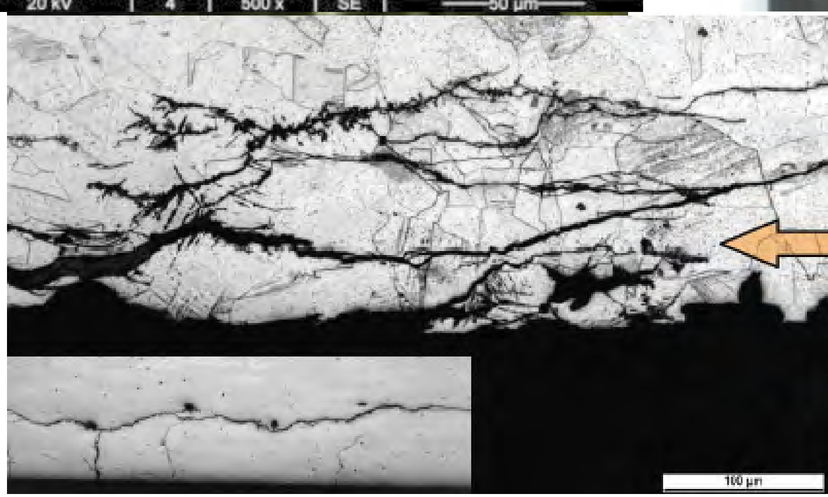


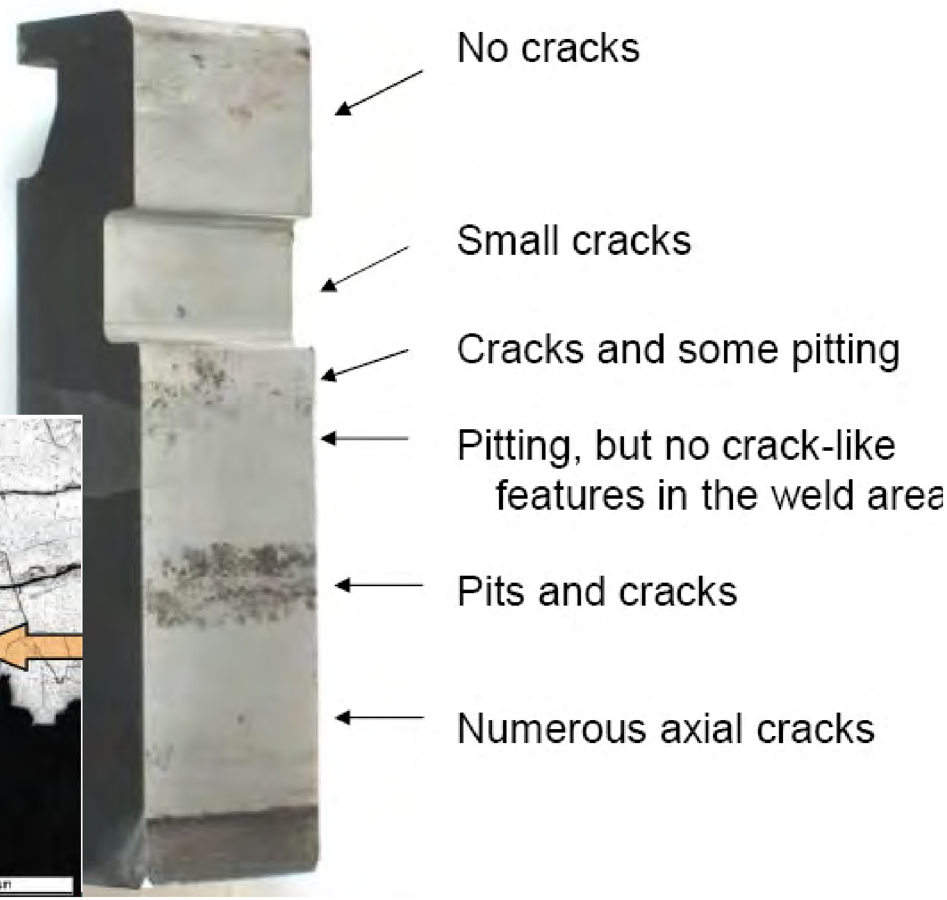


VATTENFALL

Defects in metallographic/fractographic

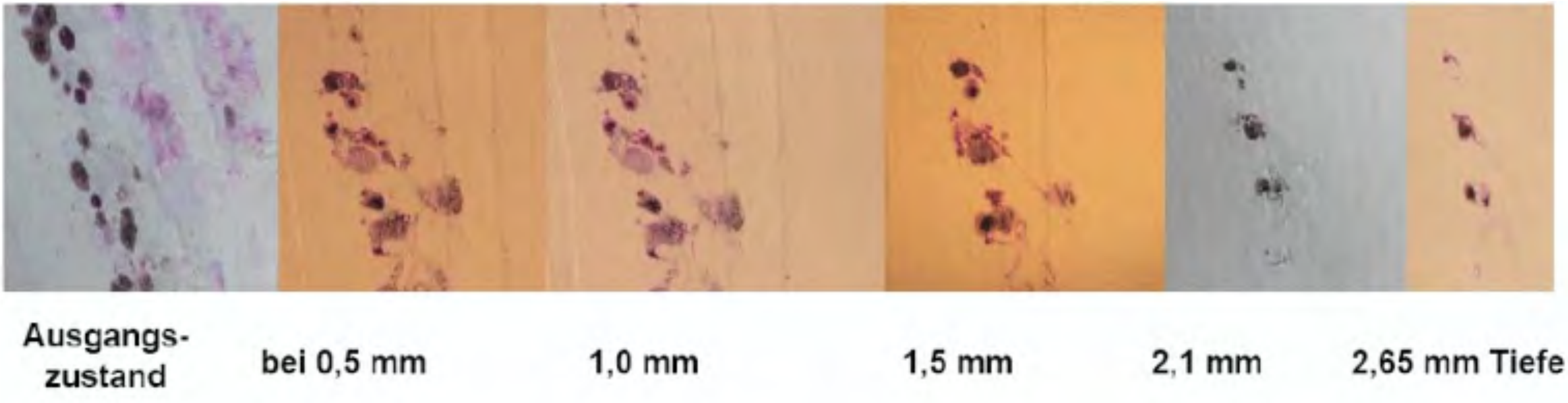






VATTENFALL

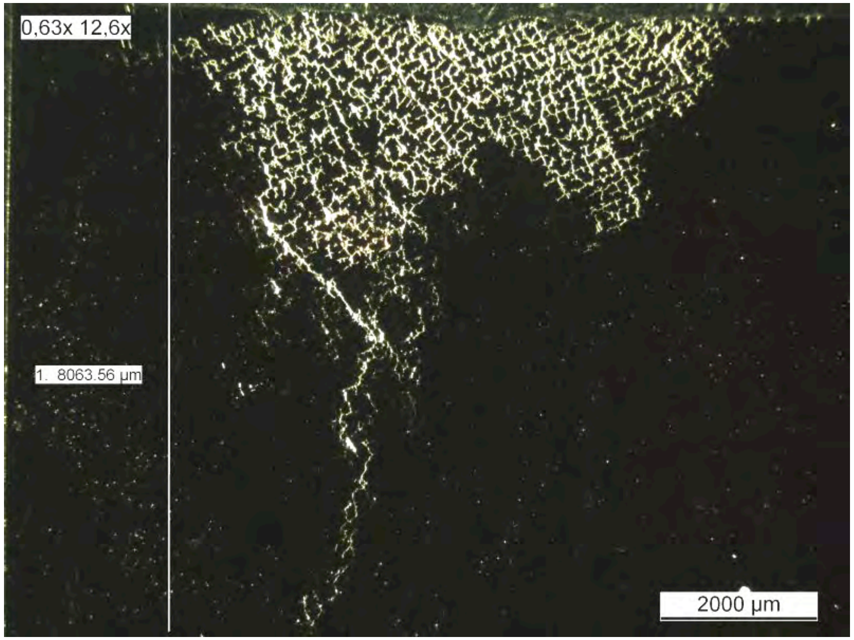
Mechanical treatment over defect area



- Pitting defects down to >10 mm
- Chloride induced transgranular cracking
- TGSCC down to 34 mm
- Defect length 84 mm (circumferential)

VATTENFALL

R1 Residual heat removal system 10-321V10

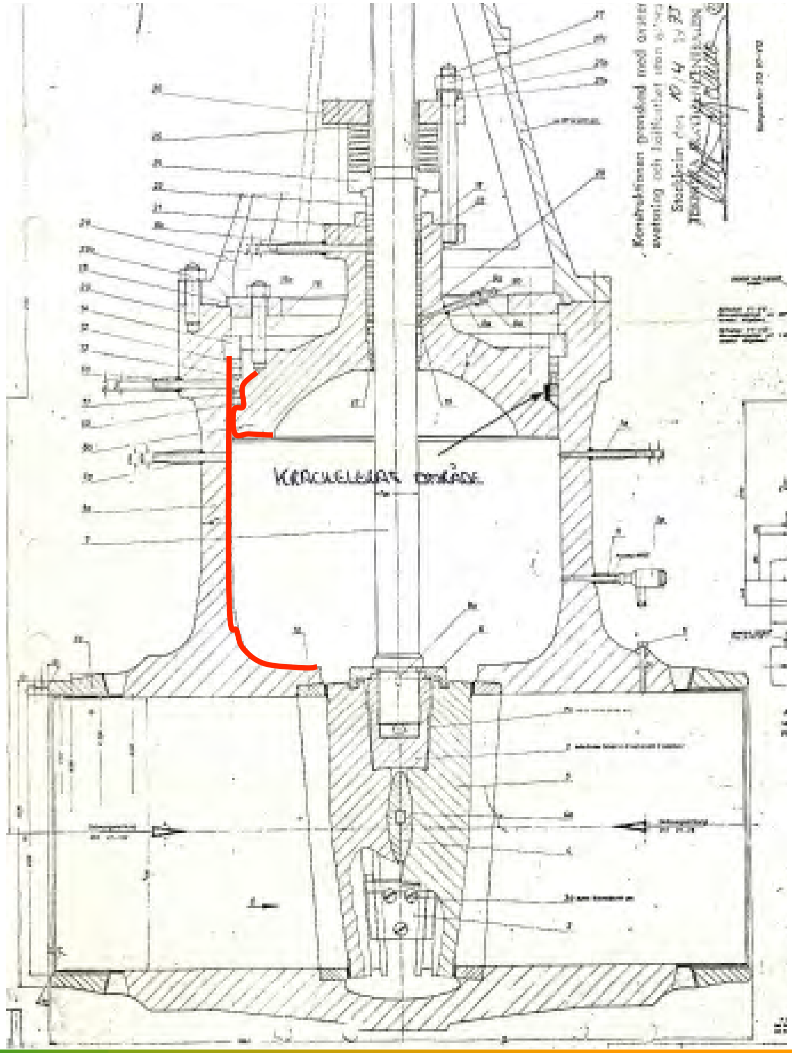


VATTENFALL

Ringhals 1 – MCS Indications in valve house and valve plate 97

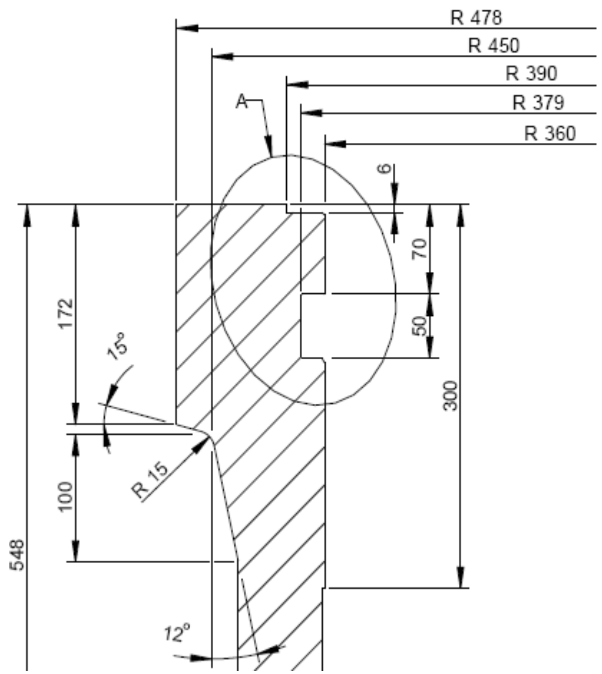
- Main Circulation System
  - KSB (“Bredtschneider”)
  - 1.4552 (CA, no Mo)

- VT of
  - Valve plate
    - Visible cracks!
  - Valve house
    - No visible cracks
- PT of Valve plate



VATTENFALL

MCS - valve test piece



VATTENFALL

Compilation of ”Bretschneider”-type valves

- ”Hot” valves
  - 321 V3-4
  - 321 V12-13
  - 415 V9 (n.i. of c. – 2008)
  - 415 V12-13
  - 415 V30-33

  - 415 V4-5 (removed –97, no ind. of concern)
  - 321 V10 (removed –97, defected)

”Cold” valves
- 321 V5-8
- 321 V11 (assumed worst case)
- 323 V7-8

- 321 V5-8 inspected during RFO-09, PT indications in all
  - From V6, 3 material samples, defect depths around 3-4 mm

Defect Tolerance Analysis

System	Ventil	Tillverkare Leverantör	Ritning	Risk för stort läckage vid brott på ventilbröst	Godtjocklek vid mellandrtänge [mm]	Acceptabelt defektdjup [mm] [1]
10313	V1-V12	KSB	26.64-348-00	JA	117.5	70.5
10323	V3 – V6	NAF	311 7332	JA	85.0	51.0
	V7 – V8	NAF	311 7339	JA	82.5	49.5
10415	V9	KSB	130.99-305	JA	52.5	31.5
	V12 – V13	NAF	311 7324	JA	102.5	61.5
	V30 – V33	NAF	311 7813	JA	73.5	44.1
30/40-313	8000A/B	WEMD	115E417	NEJ	36.1 [3]	21.7
	PCV444C	FISHER	53A3301F	NEJ	19.05 [3]	11.5
30323	8808B	WEMD	115E418	NEJ	51.5 [3]	30.9
30334	8147	FISHER	52A2238D	NEJ	15.9 [3]	9.5
	FCV113A	FISHER	51A9958E	NEJ	5.6 [3]	3.4

Defect tolerance is generally good, but we need an inspection technique !!

VATTENFALL

What has been done and what is needed

- Inspection trials on one MCS valve from outside
- Manufacturing of testpieces
- Mandatory inspection rules – defect sizes according to defect tolrance analysis/fracture mechnical analysis
- EPRI investigation on the testpieces with optimized PA transducers

CASTING PARAMETERS OF CASS PIPE AND THE EFFECTS ON GRAIN STRUCTURE: PROGRESS REPORT

by C. O. Ruud, A. A. Diaz, and M. T. Anderson

Pacific Northwest National Laboratory

Presented at The 2nd International Workshop: Future Directions for the Inspection of Cast Austenitic Stainless Steel Piping

June 15 and 16, 2009 Seattle, Washington, USA

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OBJECTIVES

I - Understand the Fundamentals of CASS Casting Parameters and Their Effect on Grain Structure

II - Document Foundry Casting Procedures Used for LWR CASS Piping

III - Document and Collate CASS Grain Structures Associated with LWR Piping

IV - Initiate Development of a Strategy to Relate CASS Piping Grain Structure to Casting Parameters

INVESTIGATIVE PROCESS AND PROGRESS

- Literature Review – Reports, Journals, Handbooks, Text Books, Etc.
- Networking – Foundry Personnel, Academics, Engineers, Metallurgists, Scientists
- Internet – Casting, CASS, Centrifugal Casting, Etc.

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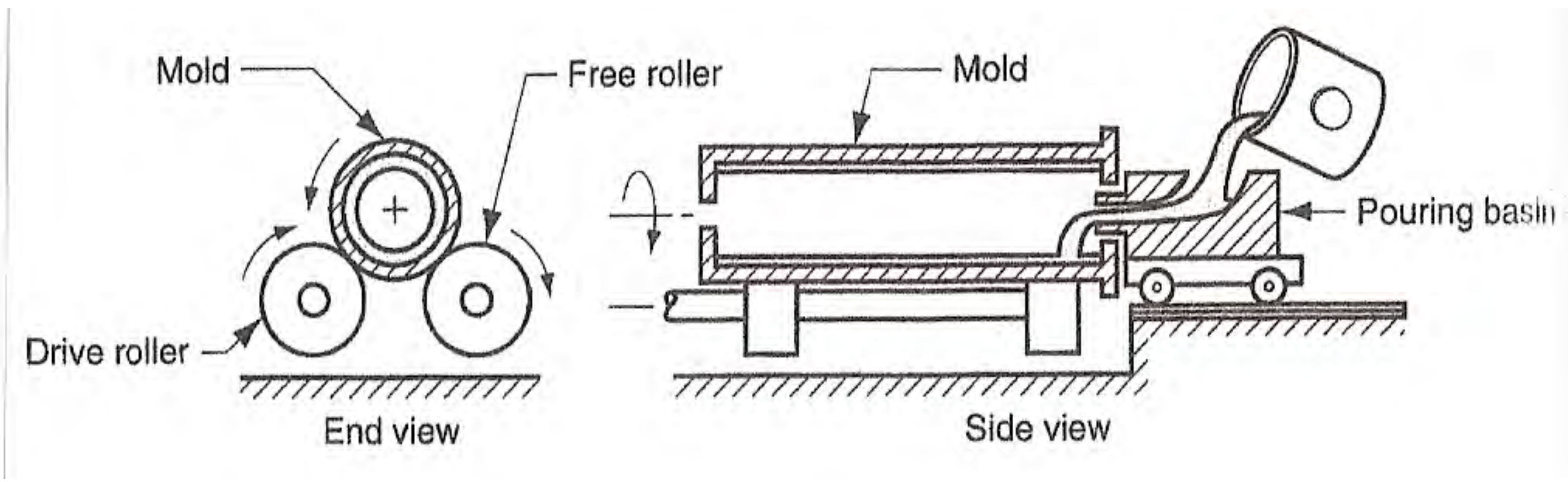
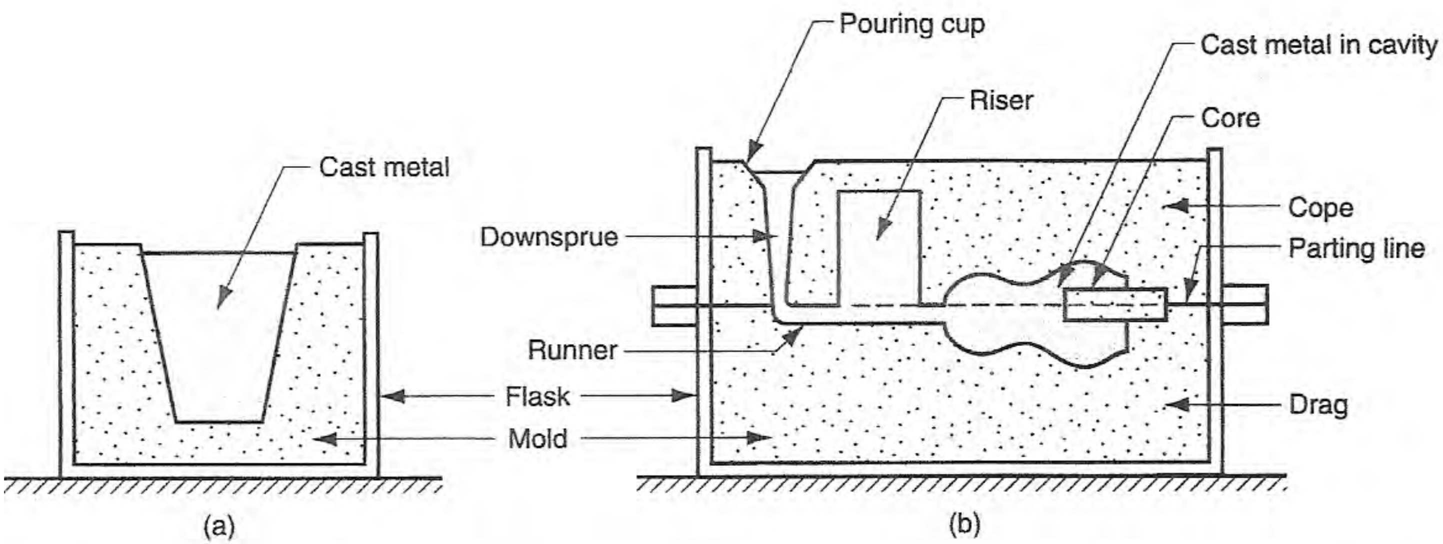
OBJECTIVE I - UNDERSTAND THE FUNDAMENTALS (Complete)

Horizontal Centrifugal Casting



OBJECTIVE I - UNDERSTAND THE FUNDAMENTALS (Complete)

Sand Mold Casting



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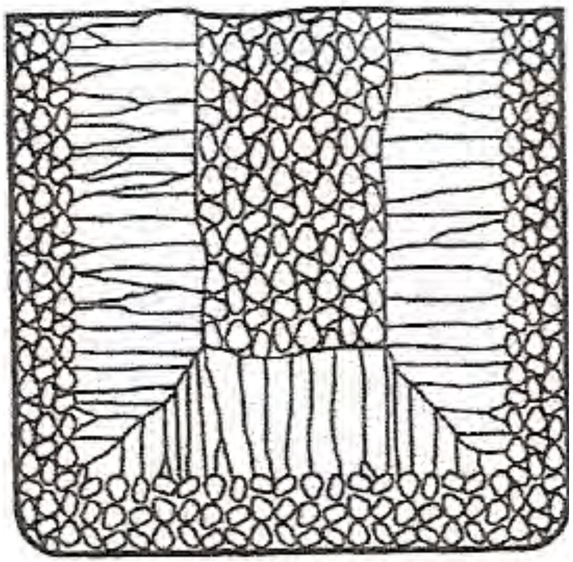
OBJECTIVE I - UNDERSTAND THE FUNDAMENTALS (Complete)

Characteristic Grain Structure of An Alloy Casting



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OBJECTIVE I - UNDERSTAND THE FUNDAMENTALS (Complete)

CCSS Pipe

- Mold Material – Slight
- Mold Wash or Lining – Moderate
- Mold Temperature at Pouring – Slight
- Alloy Composition – Major
- Pouring Method, Rate and Schedule – Major
- Pouring Temperature – Major
- Rotation Rate and Schedule – Major
- Vibration Amplitude, Frequency and Schedule – Major
- Cooling Mechanisms and Schedule - Moderate

OBJECTIVE II - DOCUMENT THE CASTING PROCESSES (In Progress)

- Identified Organizations and Individuals With Knowledge About Past LWR CASS Pipe Production
  - WESDYNE
  - Sandusky Foundry and Machine
  - ESCO
  - U. S. Pipe
- Visited and Toured CASS Production Foundries
  - ESCO
  - U. S. Pipe
  - Delta Centrifugal

OBJECTIVE II - DOCUMENT THE CASTING PROCESSES (In Progress)

Parameter	CCSS @ U. S. Pipe	SCSS @ ESCO
Mold Material	Forged Low Alloy Steel or Cast Iron	Silica & Zircon Bond by Sodium Silicate
Mold Wash or Lining	Ceramic Slurry 0.1 Inch Thick	N/A
Mold Temp. @ Pouring	~ 150 F	Room Temperature
Alloy Composition	CF8M	CF3, CF8, CF8M
Pouring Method	Both Ends - Horizontal	N/A
Pouring Temperature	2750- 2800 F	2750-2850 F
Rotation Rate	200 to 300 rpm - Constant	N/A
Vibration	Few 1/1000 Inches	N/A
Cooling Method & Schedule	Dry Diatomaceous Flour Shoveled to ID	Flask Removed in ~ 1 to 2 Days

OBJECTIVE III - DOCUMENT AND COLLATE GRAIN STRUCTURES

(In Progress)

Available Photomacrographs

- Six of the Pressurized Water Reactor Owners Group (PWROG) Specimens
- EPRI Spanish Spool Piece Ring
- SwRI Pipe Segment (cut from larger IHI spool piece)
- Westinghouse Spool Piece
- IHI SwTech Spool Piece
- The PNNL CCSS RRT Specimens

OBJECTIVE III - DOCUMENT AND COLLATE GRAIN STRUCTURES Progress

(In Progress)

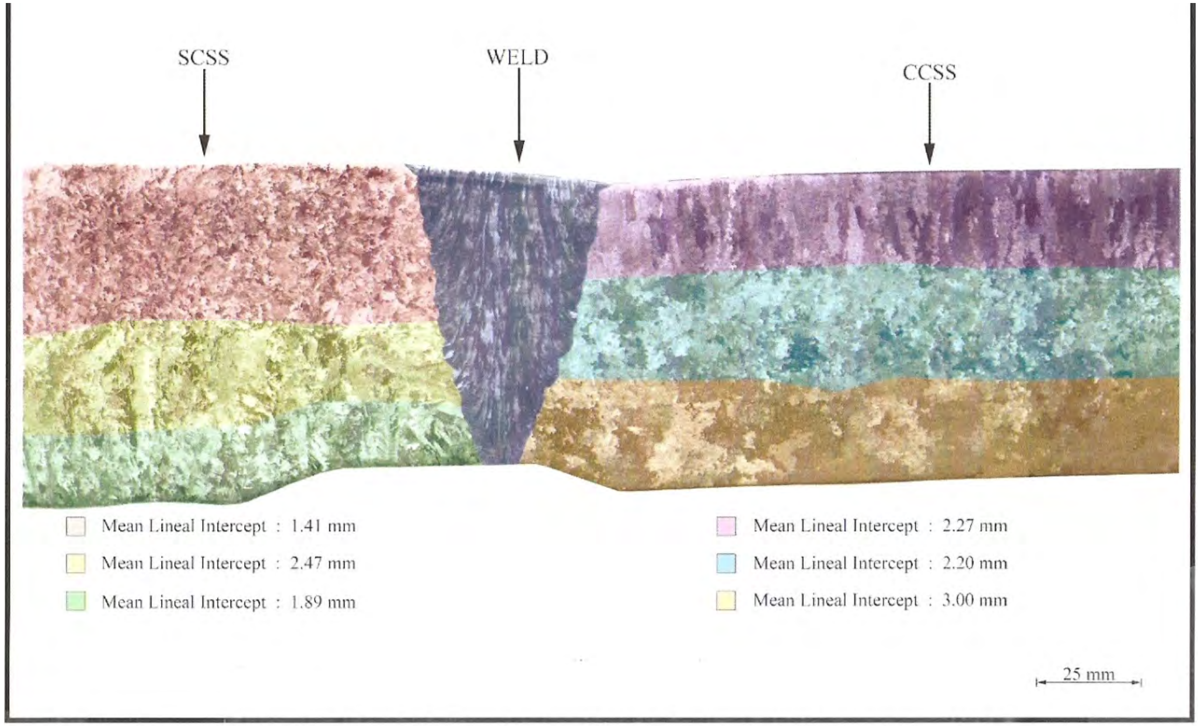
Features of Grain Structures

- Grain Size
- Equiaxed Shape
- Columnar Shape
- Bands (Layering)

OBJECTIVE III - DOCUMENT AND COLLATE GRAIN STRUCTURES

(In Progress)

WOG Specimen MPE 06-CCSS Cast at SFM as Ht. 15652



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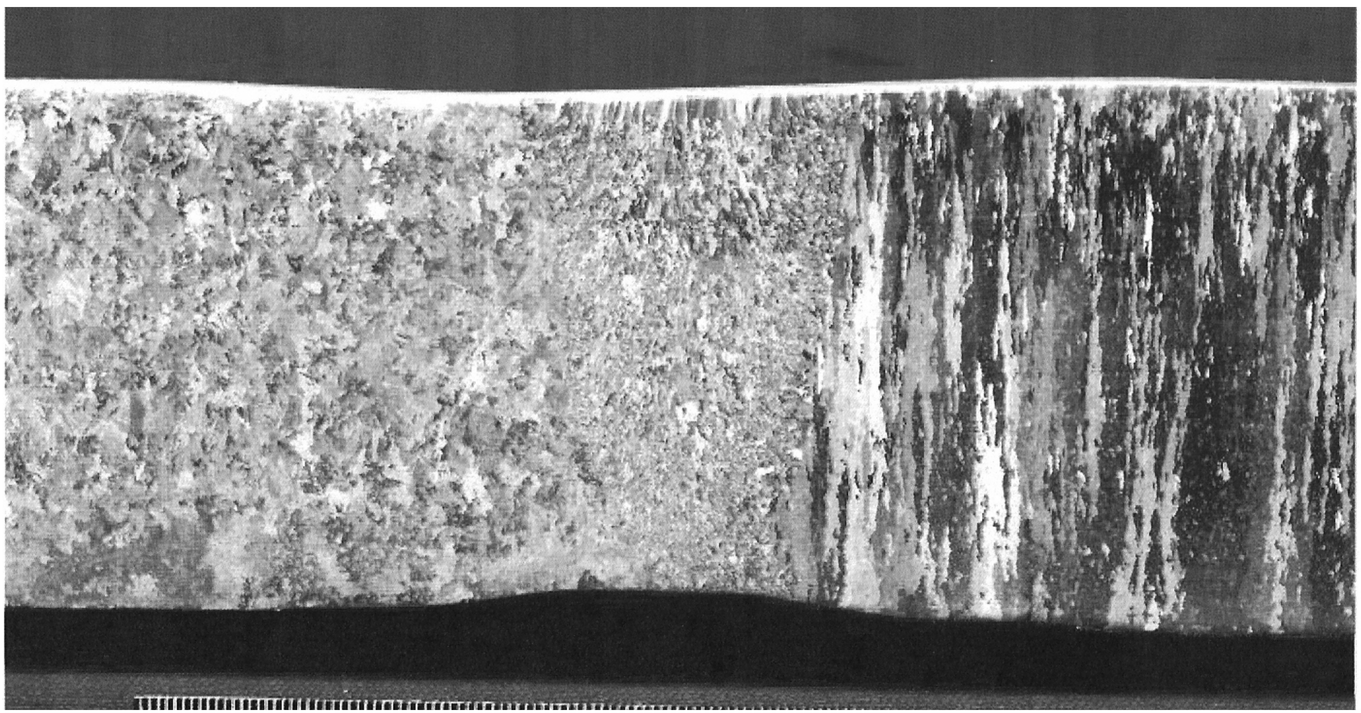
OBJECTIVE III - DOCUMENT AND COLLATE GRAIN STRUCTURES
(In Progress)

PNNL CCSS-RRT Specimen

CCSS on both sides of weld cast by SFM



OBJECTIVE III - DOCUMENT AND COLLATE GRAIN STRUCTURES

(In Progress)

Westinghouse Spool Piece

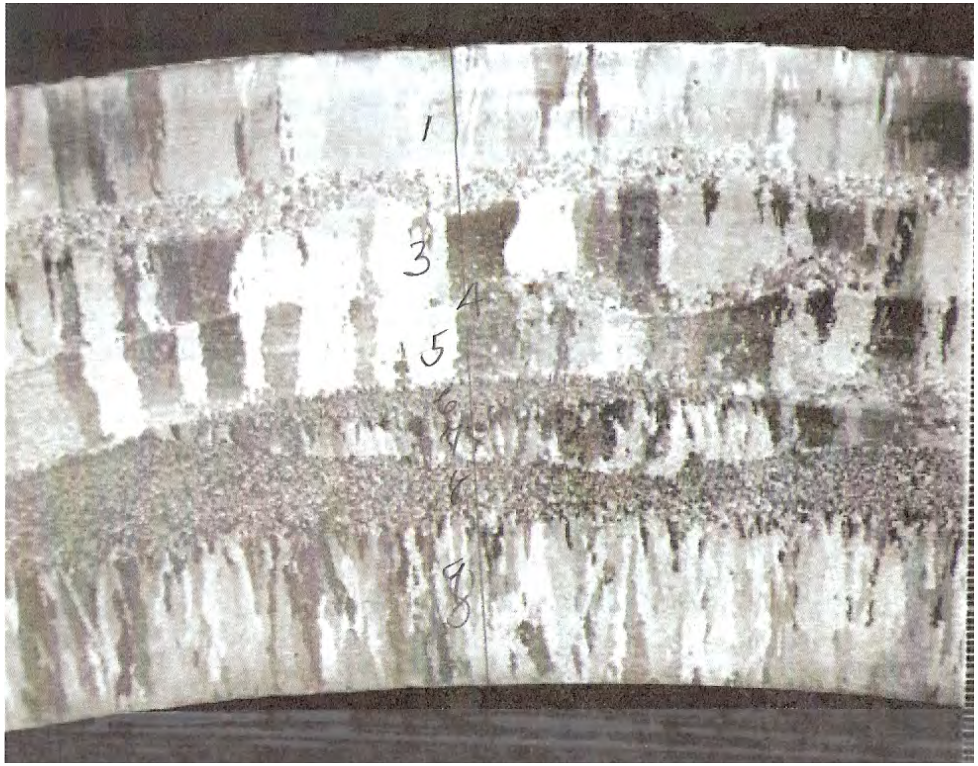
Foundry Unknown

OBJECTIVE III - DOCUMENT AND COLLATE GRAIN STRUCTURES

(In Progress)

IHI CCSS Spool Piece

Foundry Unknown



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OBJECTIVE III - DOCUMENT AND COLLATE GRAIN STRUCTURES

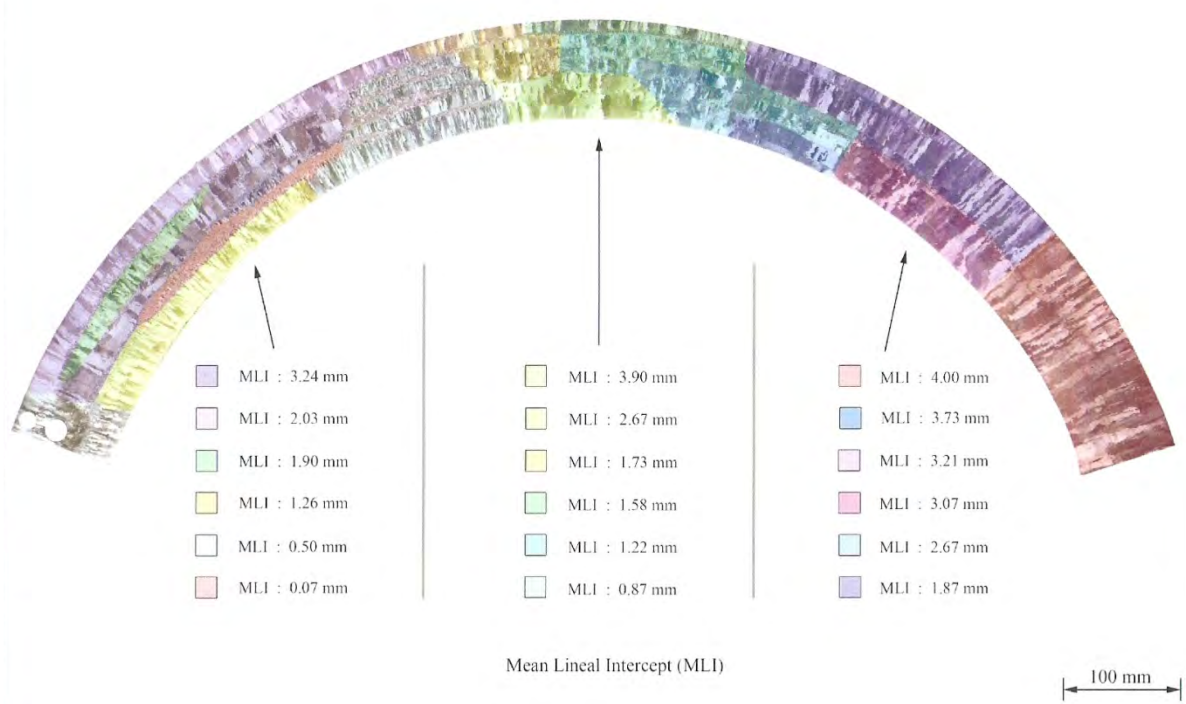
(In Progress)

IHI CCSS

Spool Piece

Foundry

Unknown



OBJECTIVE IV - INITIATE DEVELOPMENT OF A STRATEGY TO RELATE CASS PIPE GRAIN STRUCTURE TO CASTING PARMETERS

(In Progress)

PRELIMINARY TRENDS

- Alloy Composition – Delta Ferrite
- Mold Wash or Lining
- Pouring Method and Schedule
- Pouring Temperature
- Post Pour Cooling

PRELIMINARY CONCLUSIONS

CASS CASTING PARAMETER EFFECTS

- Banding/Layering is Common, in Both CCSS and SCSS
- Large Grains in Thick CASS Sections Are Common
- Both Equiaxed and Columnar Grains Are Common
- Alloy Composition (Delta Ferrite) May Have a Primary Effect on Grain Structure
- Mold Lining or Wash May Have a Primary Effect on Grain Structure In CCSS
- Pouring Rate, Method and Schedule May Have a Primary Effect on Grain Structure in CCSS
- Axial Position, e.g. End or Center, Will Have a Primary Effect on Grain Structure in CCSS

Flaw Tolerance Evaluation of Thermally Aged Cast Austenitic Stainless Steel Piping

Presented at 2nd International Workshop on CASS Piping

Seattle, WA

June 15 - 16, 2009

Timothy J. Griesbach

Structural Integrity Associates, Inc.

Structural Integrity Associates, Inc.

Introduction

- CASS piping material is known to be very ductile, flaw tolerant, and resistant to stress corrosion cracking
- Unfortunately, the CASS materials are also difficult to inspect using UT exam and are susceptible to thermal aging (embrittlement)
- Long-term management of the aging concerns in CASS materials is a priority for plant license renewal
- It is desirable to use a flaw tolerance approach with some inspections to demonstrate structural margins against fracture

Objectives of EPRI Study

- Provide a methodology for developing acceptable flaw sizes for inspection of cast austenitic stainless steel (CASS) piping using the flaw tolerance approach
  - *Acceptable Flaw Size* – Initial flaw size from inspection such that the allowable flaw size will not be reached during operation (includes consideration of potential flaw growth)
- Establish a reasonable acceptable flaw size that the inspection technology should be capable of detecting
- Present a Code methodology for managing aging of CASS materials

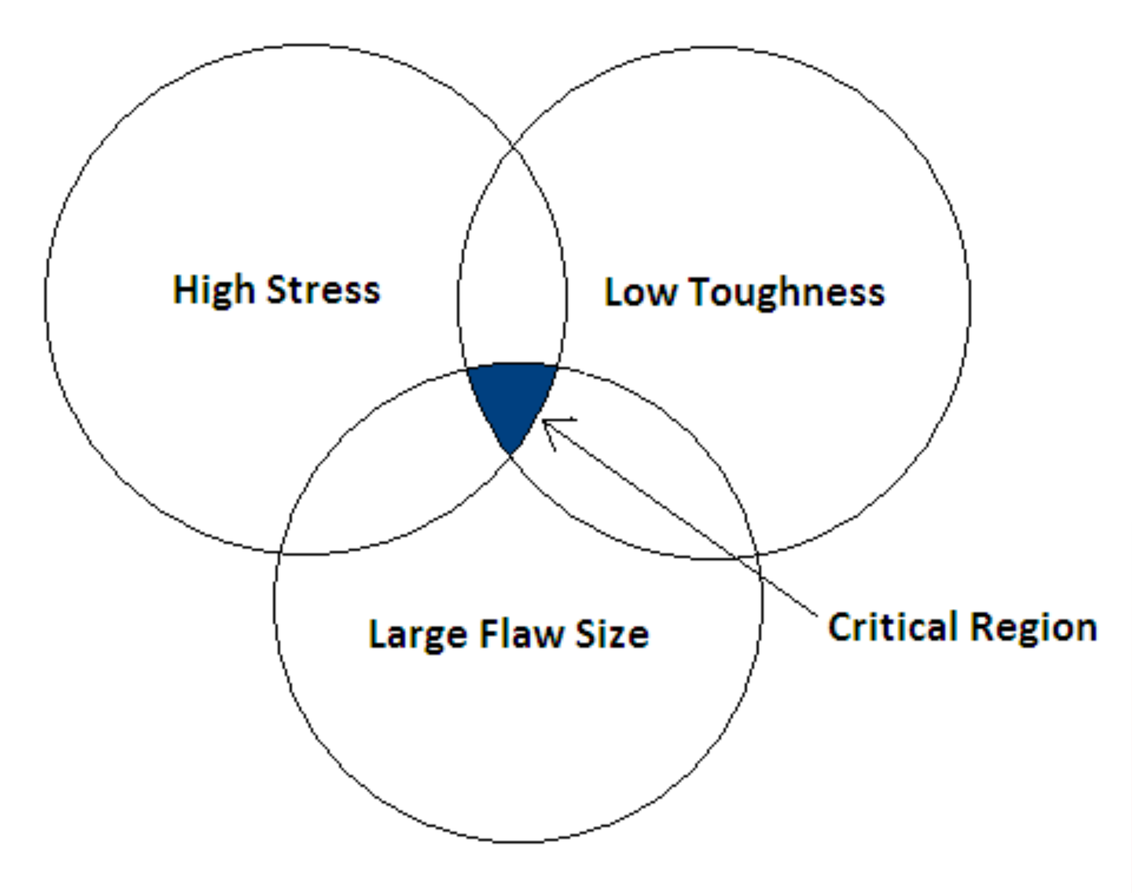
Note: This work was sponsored by EPRI under contract EP-P27921/C13262. Project Manager, Patrick O'Regan

Areas for Consideration

- CASS materials present a challenge for conventional UT inspection methods
- The flaw tolerance approach can be useful to quantify margins of safety against brittle, ductile, or limit load failure
- Inspection techniques, used judiciously, can confirm that there are no critical flaws and that margins against fracture exist

Question: How can we use the current technologies to manage risk in CASS piping systems?

Background of Fracture Prevention



- Fracture may occur in a structure under a combination of conditions involving high stress, low toughness, and the presence of a large (critical size) flaw
- The ASME Code defines margins to prevent failure
- Where is the margin?

ASME Code Issues and Questions

- The NDE person asks, "What is the flaw depth I need to detect to assure structural integrity of these CASS components?"
- The answer is not a simple one. It depends on:
  - **Flaw length** – should we assume a 360 degree flaw or a flaw of reasonable length?
  - **Fracture toughness** - should we use the absolute lowest bound in the industry based on CF8M properties or representative (best estimate) toughness properties?
  - **Material strength properties** - should we use the Code minimum values or should we use actual/more realistic tensile and yield properties?
  - **Loads/stresses** - should we use the maximum bounding loads/stresses in the industry or typical loads/stresses?
  - **Safety factors** - for management of CASS components, should we use the full Code safety margins (S.F. = 2.77) or something less?

Flaw Tolerance Evaluation of CASS Piping

- Survey materials and loads in the affected CASS components
- Develop criteria for determining analysis method (EPFM or limit load) similar to that in Appendix C of ASME Section XI for ferritic steels
- Develop flaw acceptance diagrams for typical CASS piping components (e.g., hot leg and cold leg pipes)
- Develop an overall approach for CASS management
  - Graduated approach based on component type, material type, delta ferrite level, loads, etc.
  - Consider all available technologies

Components in PWRs Made from CASS Materials

- Cold Leg Piping (Westinghouse-designed plants)
- Hot Leg Piping (Westinghouse-designed plants)
- Main Coolant Piping Elbows and Safe Ends
- Surge Line Piping
- Surge Line Nozzles
- Accumulator Injection Nozzles in the Cold Leg
- Reactor Coolant Pump Casings

CASS Materials Data Survey

- More than 70 heats of cast pipe and 70 heats of cast fittings were included in the survey
- About 20 plants were sampled plus research studies of CASS
- Material is from primary loop cast piping and stainless fittings
- Survey concentrated on CF8, CF8A & CF8M CASS materials
- Data included both mechanical and chemical properties
- Delta ferrite was either measured or estimated from chemistries
- Cast fittings are primarily from one supplier, cast piping contains data from two suppliers
- Data can be analyzed statistically to obtain mean and bounding properties (e.g., DFN and J-R curves)
- Other data searches were performed to validate CASS material properties and to identify flaw characteristics

Summary of Survey Results

Primary System Piping Materials for Westinghouse Designed Plants in the U.S.

Total No. of Plants	No. with Wrought Piping	No. with CASS Piping	No. with CF8M
51	25	26	6*

* Of the 51 W designed plants, nearly half do not have CASS piping and only 6 used the worst type of CASS material (CF8M)

Results of CASS Material Surveys

CF8

Mean DFN = 20.6, Upper Bound DFN = 25.5

CF8A

- Mean DFN = 15.0, Upper Bound DFN = 16.0

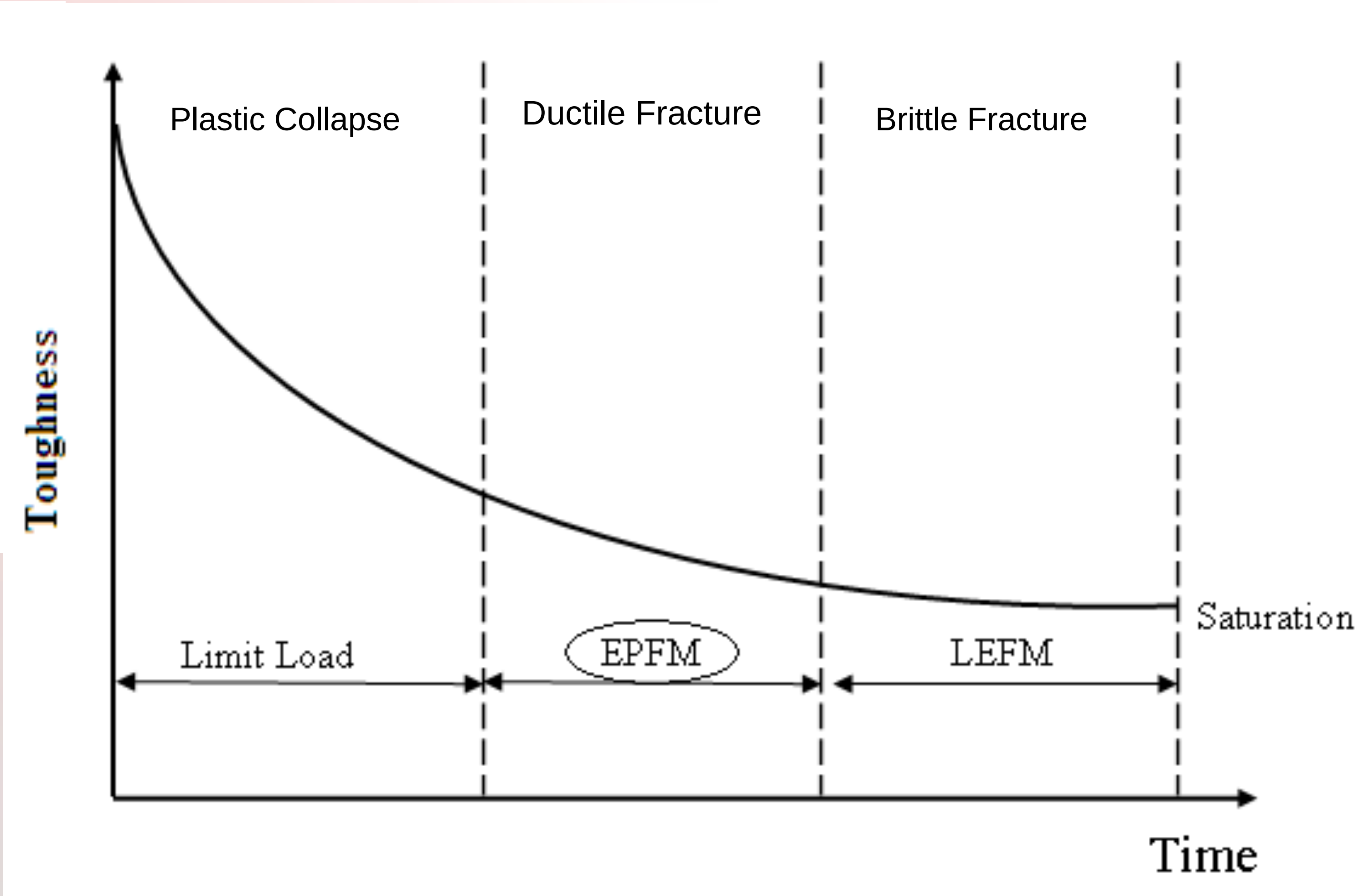
CF8M (most susceptible to thermal aging)

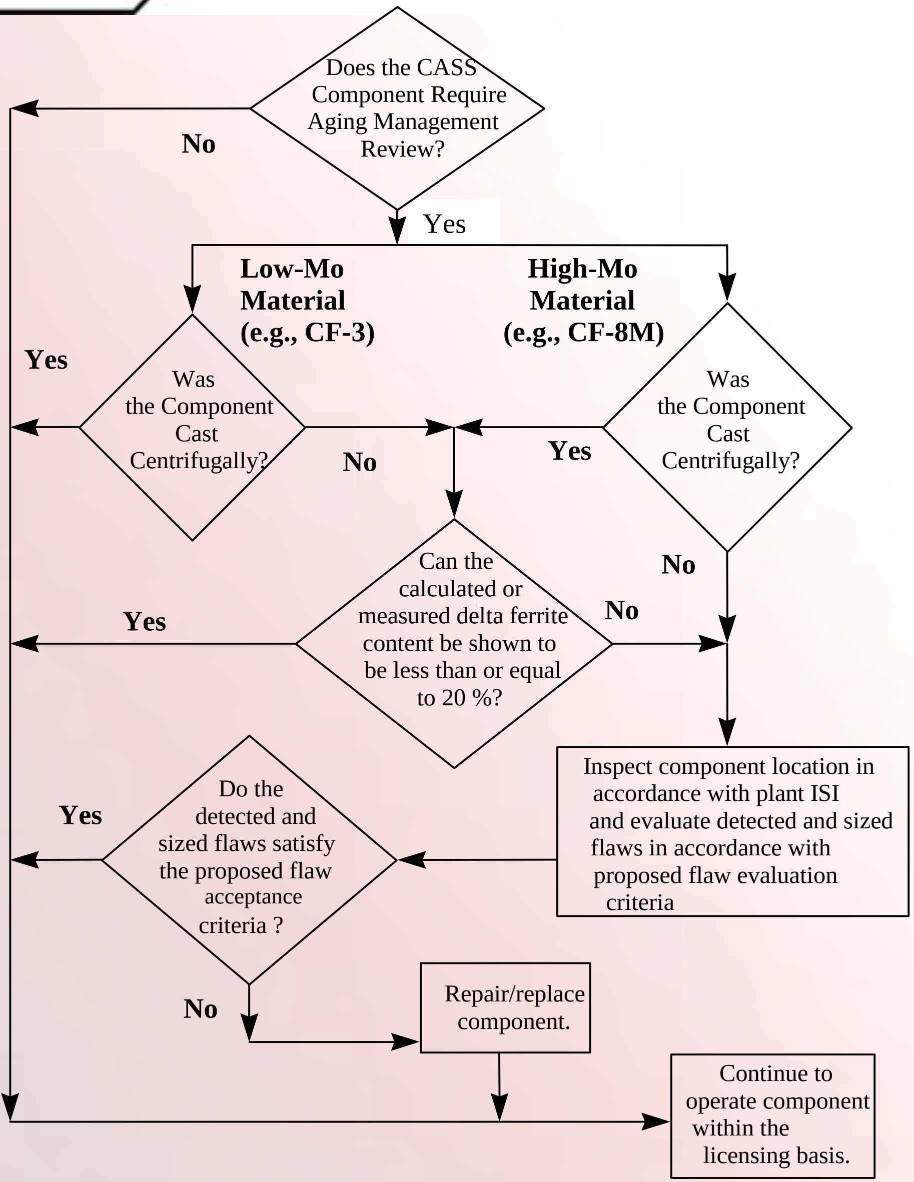
- Mean DFN = 21.2, Upper Bound DFN = 29.3

Flaw Tolerance Evaluation

- Determine fracture toughness for a representative set of CASS piping materials
- Determine stress-strain properties
- Determine typical loads/stresses
- Determine both critical flaw size (safety factor of unity) and allowable flaw size (ASME Section XI safety margins)
- Account for crack growth
- Determine acceptable flaw size for an example CASS piping application

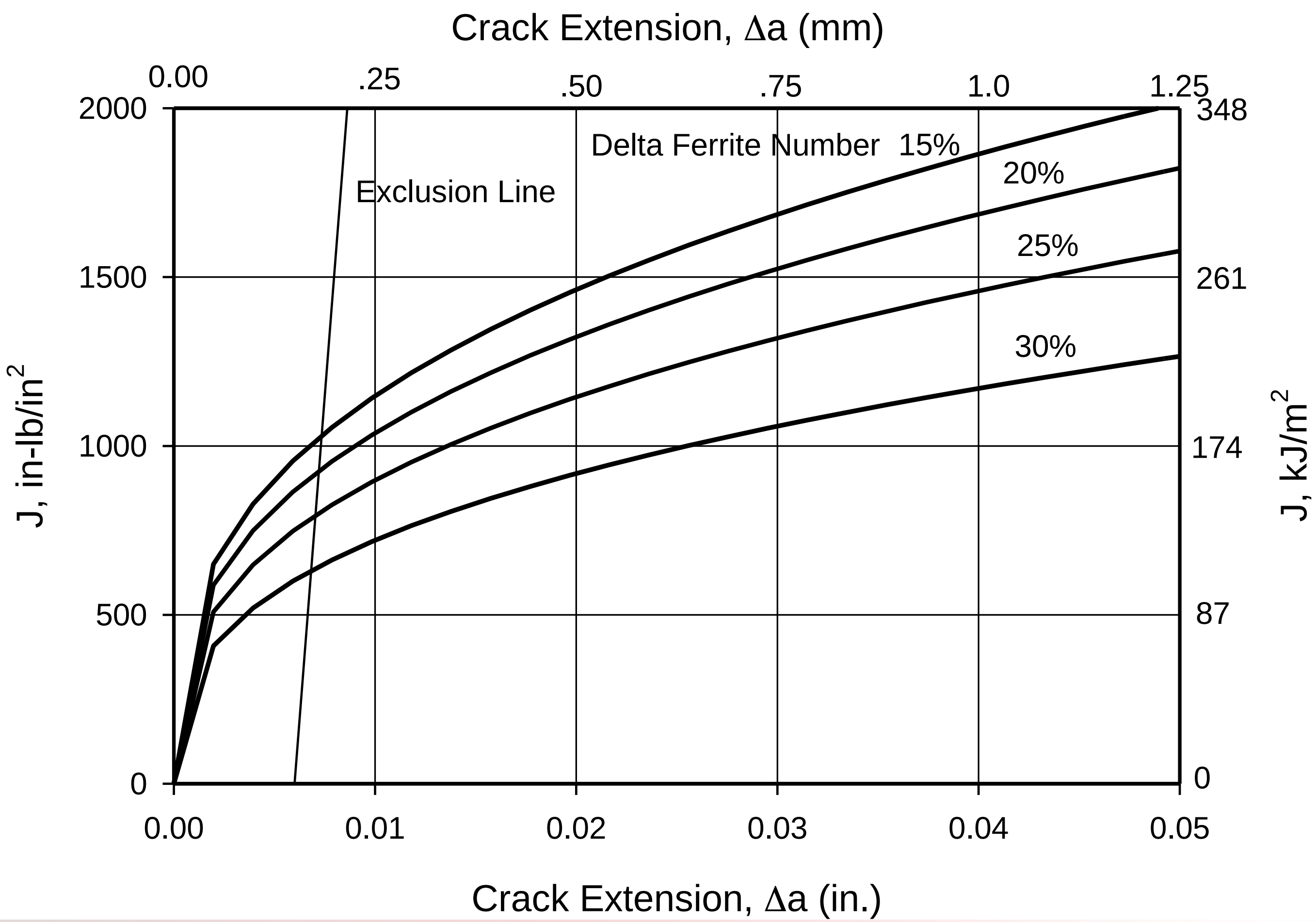
Flaw Tolerance Regimes for CASS





Proposed Flaw Tolerance Approach for CASS Piping

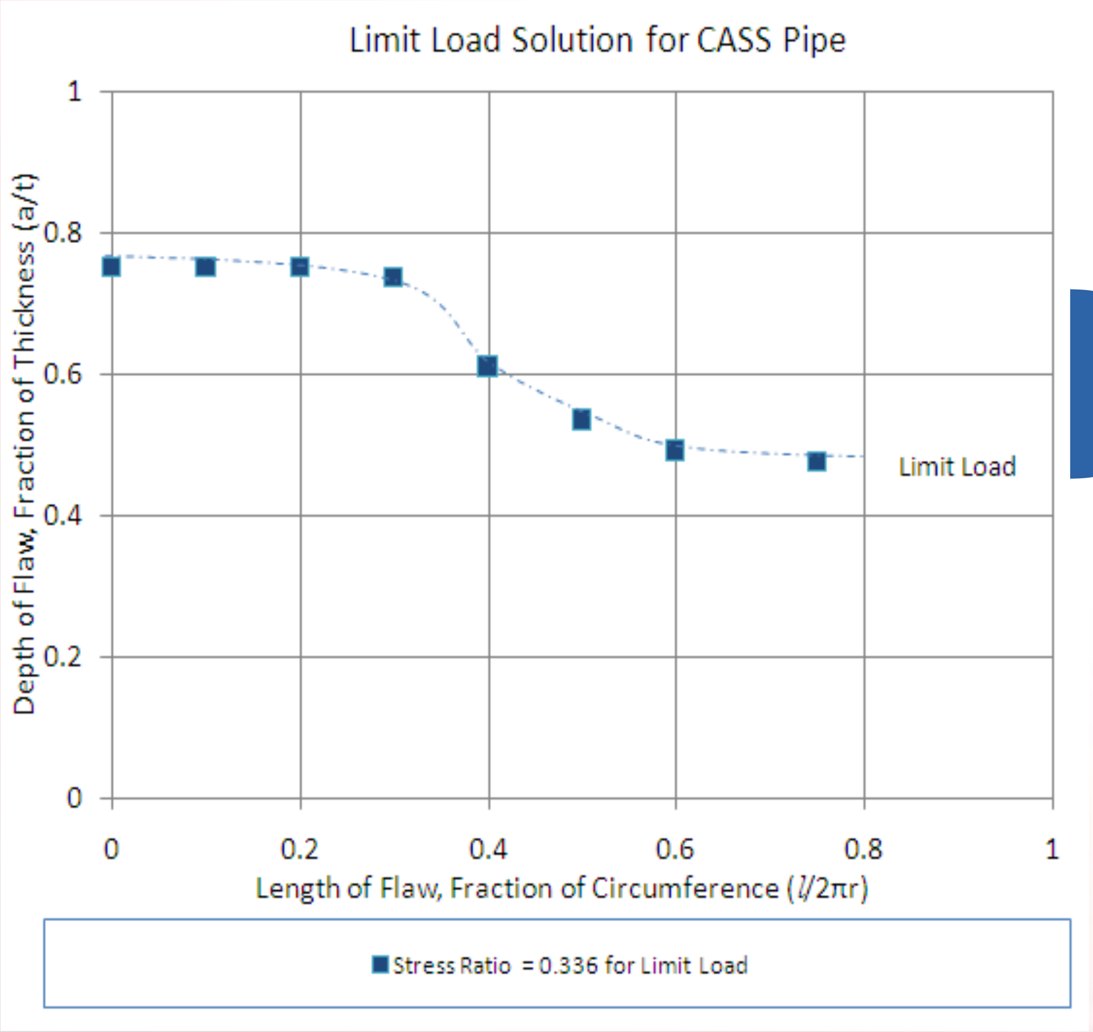
Aged J-R Material Resistance Curves for CASS piping at Various DFN Levels



Consider a Limit Load Solution for CASS Piping (DFN < 20%)

- Consider sample Cold Leg Pipe made from CASS material
- Use typical tensile properties to determine flow stress
- Use sample load combinations to determine stress ratio = $(\sigma_m + \sigma_b)/\sigma_f$
- Use C-5000 procedure (Table C-5310-1) to determine maximum allowable flaw depths and lengths

Limit Load Solution Results

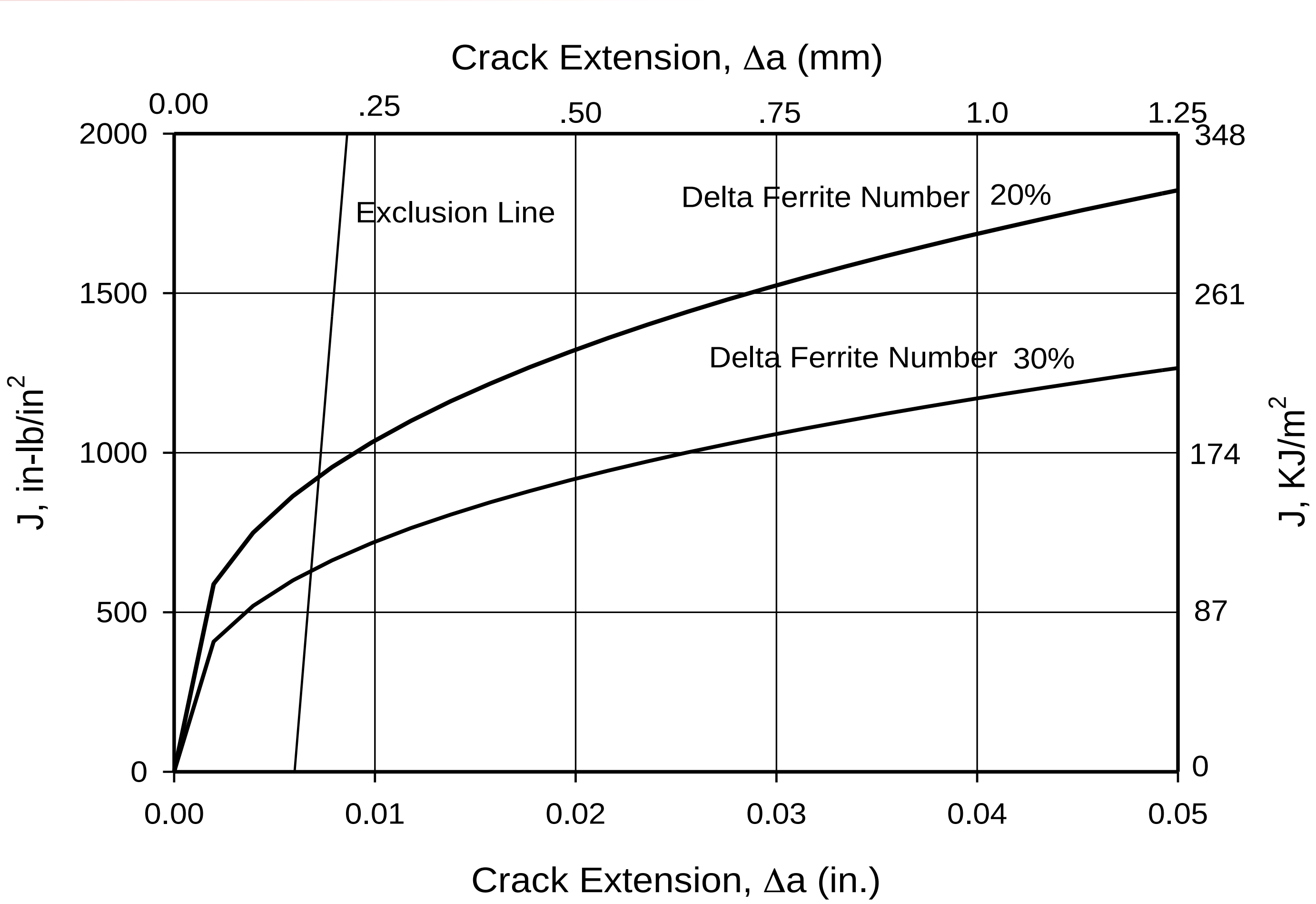


Limit Load solution typical of unaged and low delta ferrite (<20%) CASS piping materials

Consider EPFM Analysis for CASS Piping

- Consider sample Cold Leg Pipe made from CASS material (R = 15 in., t = 2.25 in.)
- Use J-R Curve as a function of delta ferrite content (from Chopra report)
- Use load combinations to determine stress ratio
- Use EPFM to evaluate critical and allowable flaw depths and lengths

Aged J-R Material Resistance Curves for CF-8M CASS Piping at Various DFN Levels



Structural Integrity Associates, Inc.

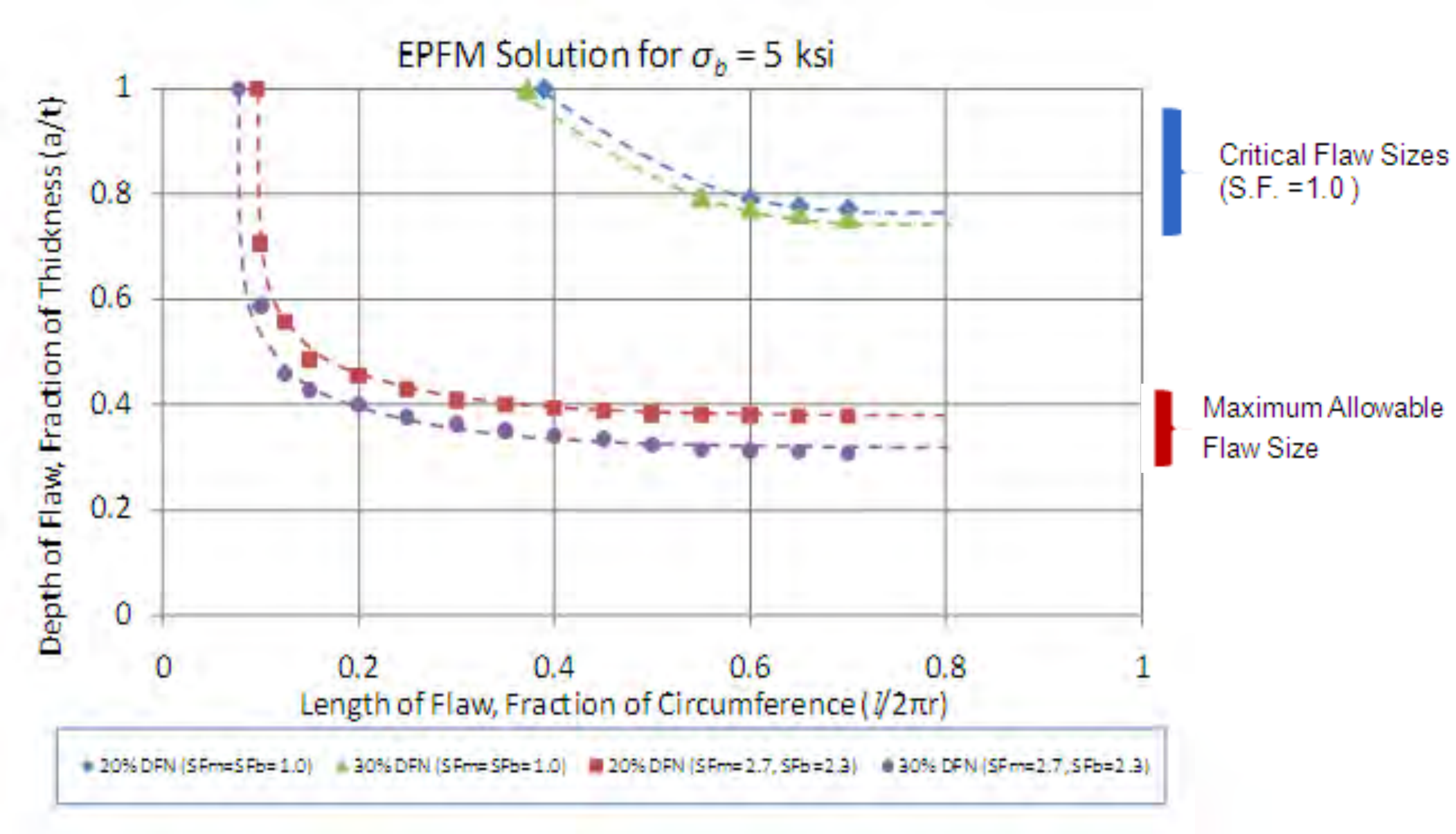
Survey of Stresses in CASS Cold Leg Piping in PWRs

Estimated stresses in cold leg piping:

- Range of membrane stress (axial)
  - P_m = 6 – 9 ksi
- Range of thermal + dead weight bending stress
  - P_b = 1.5 - 11 ksi
- Assume P_m = 8.89 ksi, and P_b = 10.28 ksi
- Stress Ratio = $(\sigma_m + \sigma_b)/\sigma_f$ = (8.89 + 10.28)/57.1

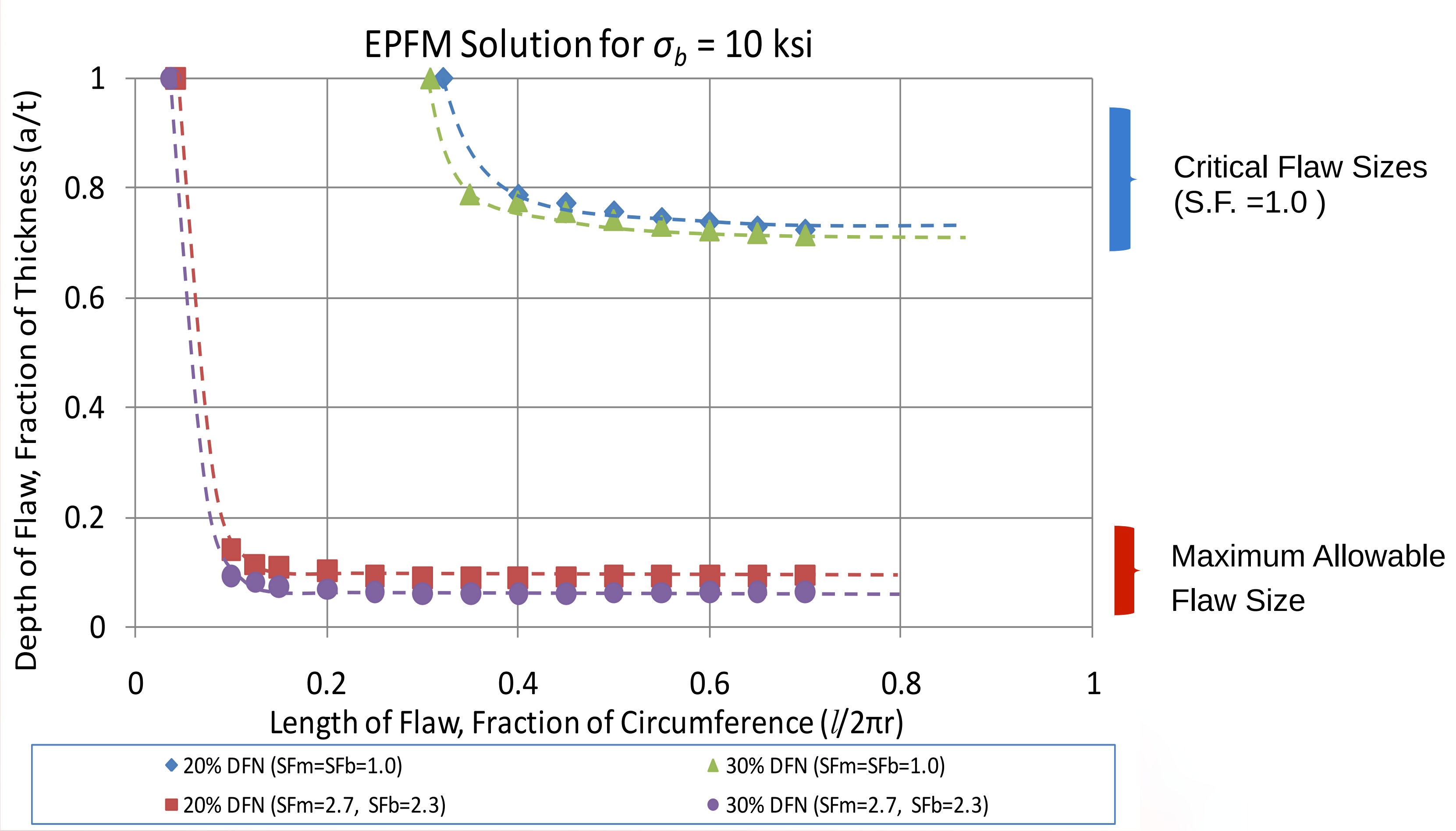
  = .336

Sample EPFM Results

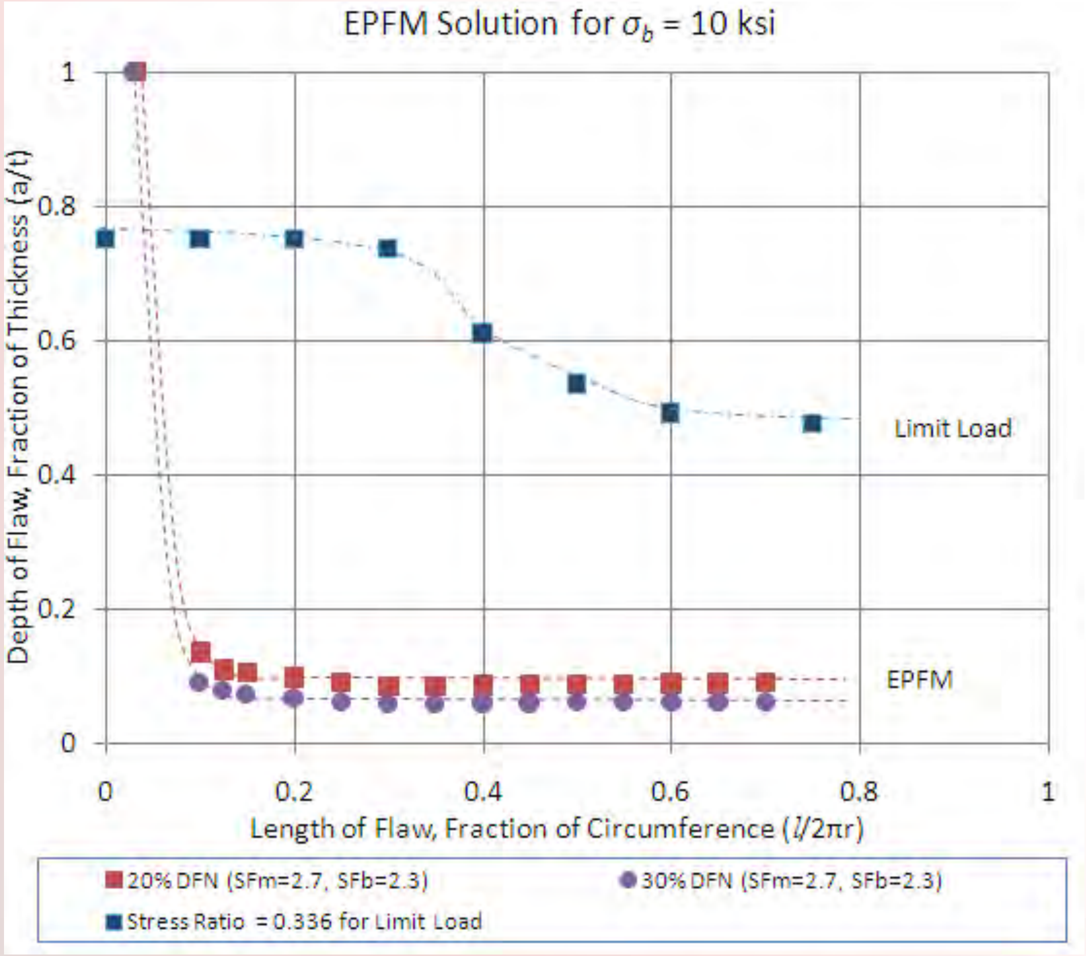


Structural Integrity Associates, Inc.

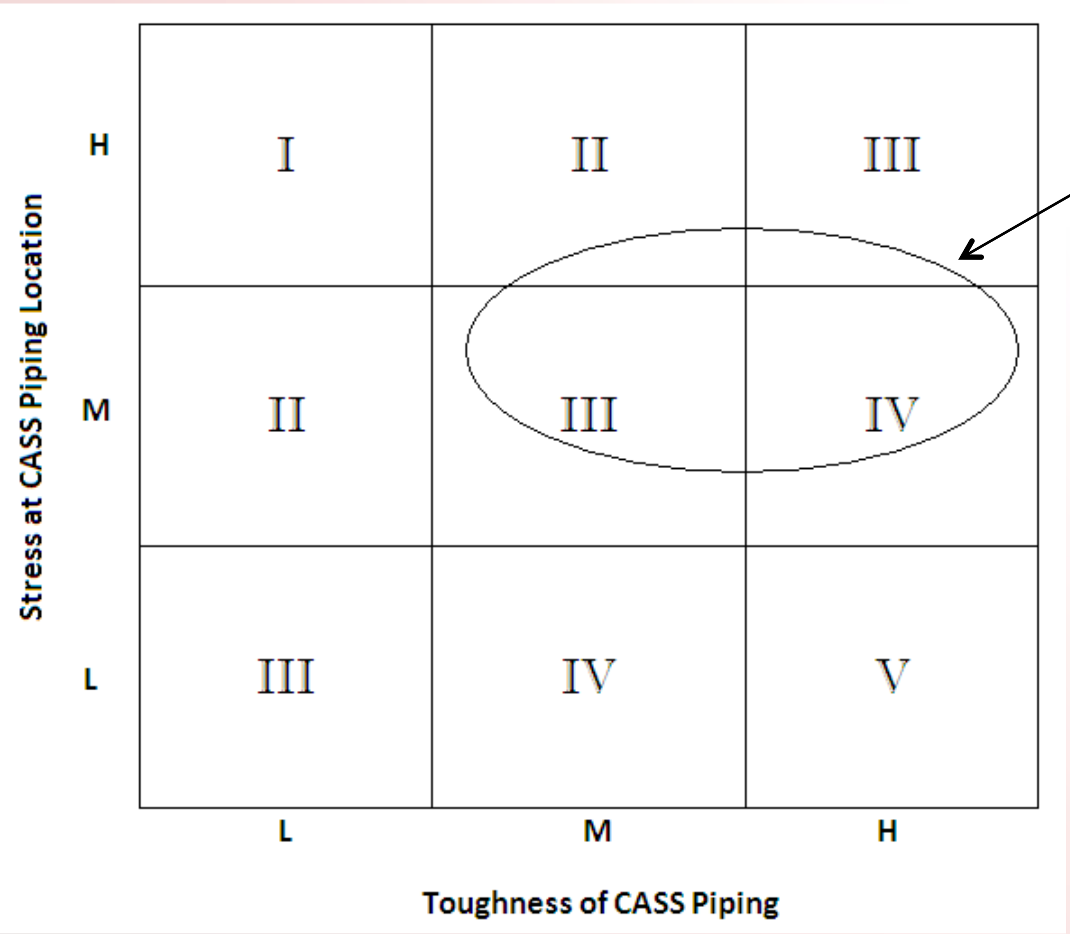
Sample EPFM Results



Comparison of EPFM and Limit Load Solutions for CASS Piping



Consider Relative Risk of Fracture (Including Uncertainties)

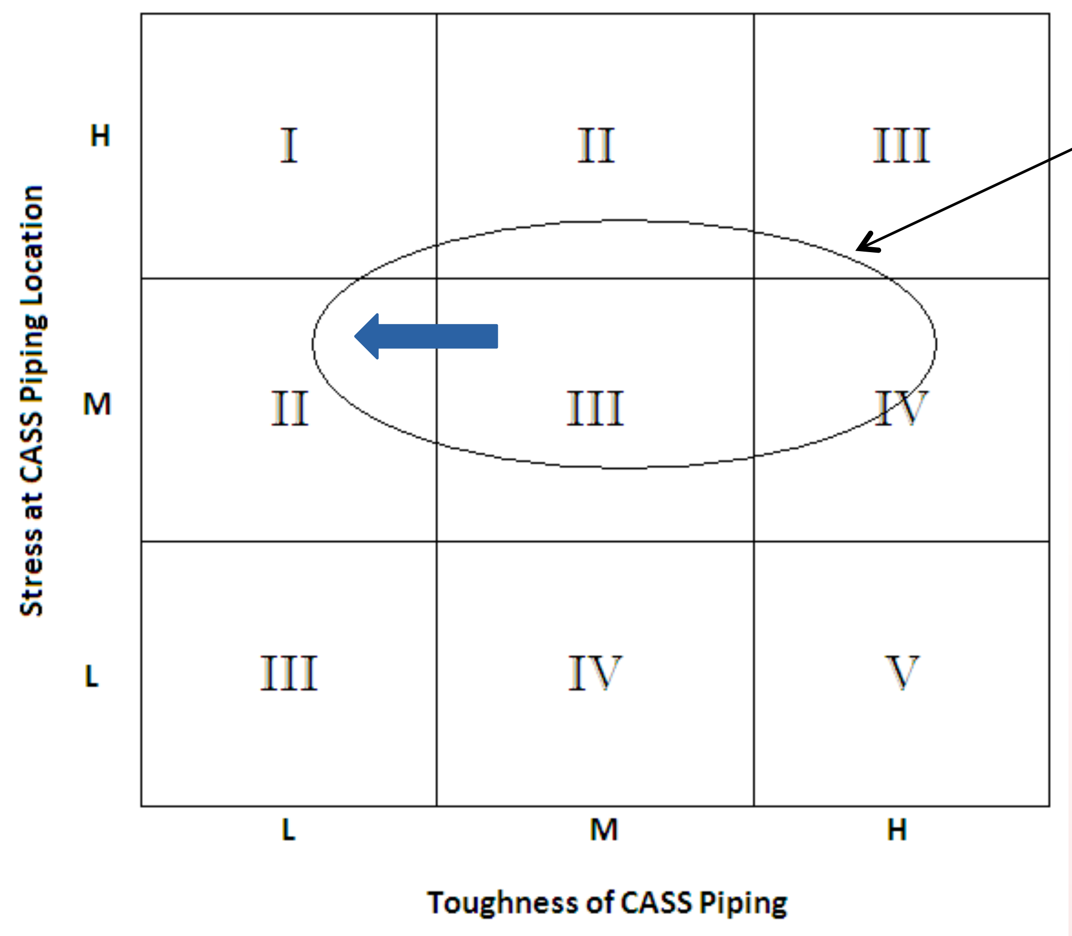


- Most plants initially would fall within a range of design stress and (unaged) material toughnesses shown by the oval region
- Characterizing risk equates to determining a safety margin

Relative Risk Ranking of CASS Piping Locations:

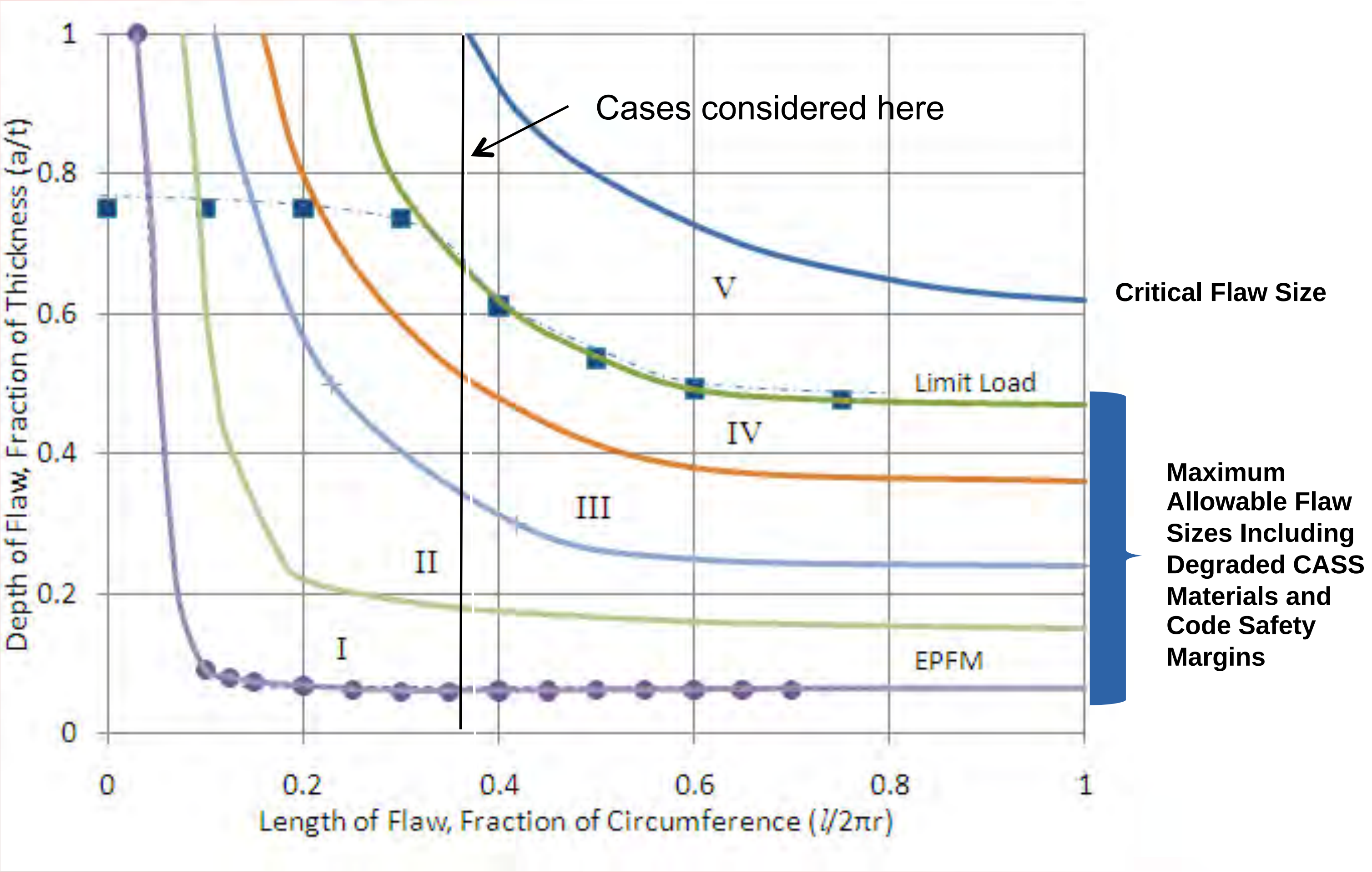
I. High Risk Category (lower safety margin)
II. Medium-High Risk Category
III. Medium Risk Category
IV. Medium-Low Risk Category
V. Low Risk Category (highest safety margin)

Changes in Relative Risk Due to Thermal Aging of CASS Materials

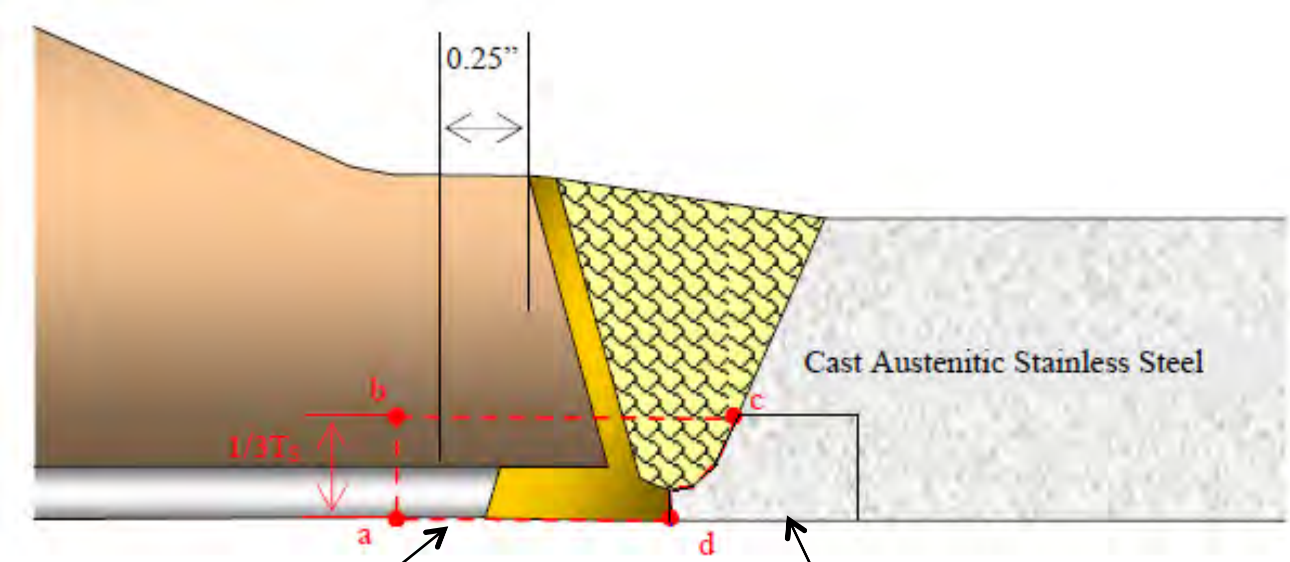


- Plants with high delta ferrite piping materials experience a decrease in toughness
- This decrease in toughness may put some plants in a higher risk category

Examples of Relative Flaw Acceptance Limits in CASS Piping



Exam Volume for DMW with CASS

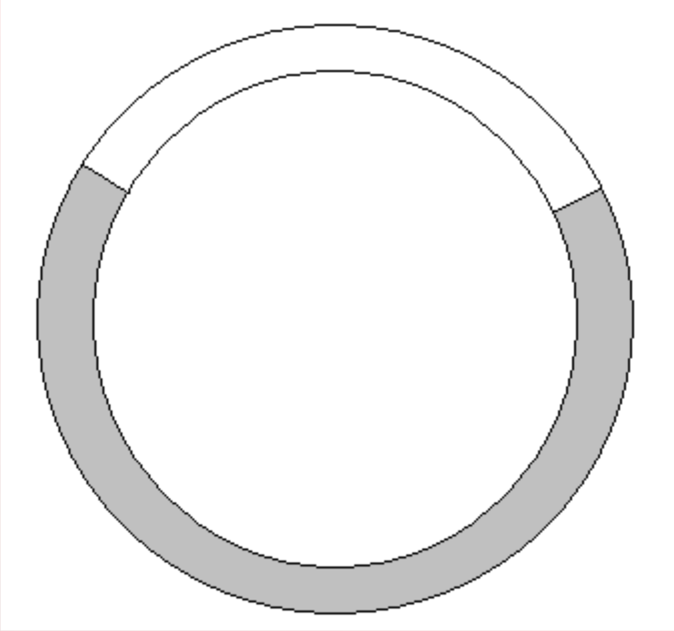


Current Examination Volume per ASME Section XI, Appendix VIII Supplement

Proposed CASS Piping Examination Volume

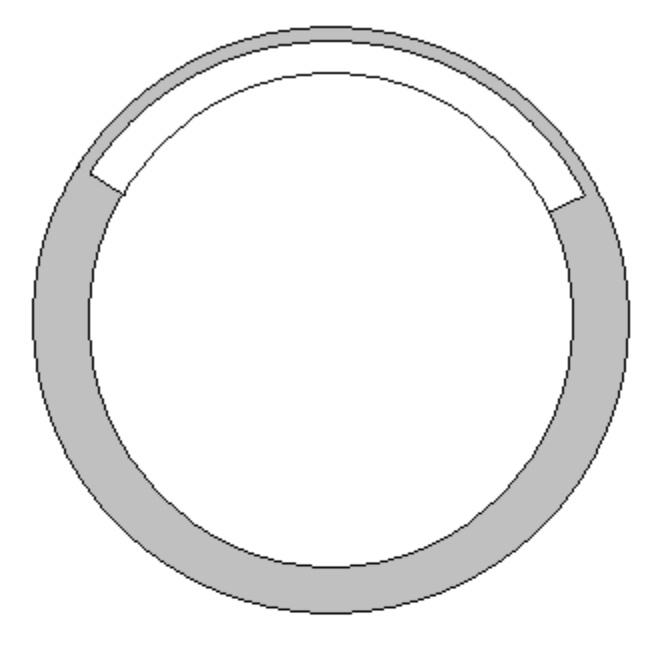
Note: At present, volumetric examination of the CASS material is not required because a qualified examination method does not exist

Example of Critical Flaw Size in CASS Piping (Using S.F. = 1.0)



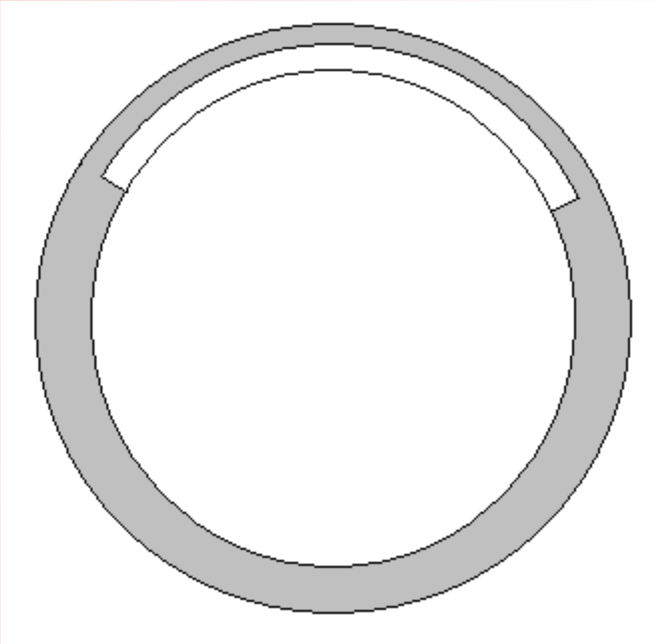
- Consider the maximum critical flaw size to be a through-wall flaw approx. 35% of the circumference
- The critical flaw size uses a safety factor of 1.0
- This is the flaw size that would be required to fail the pipe

Example of Maximum Allowable Flaw Size for a Category V Case



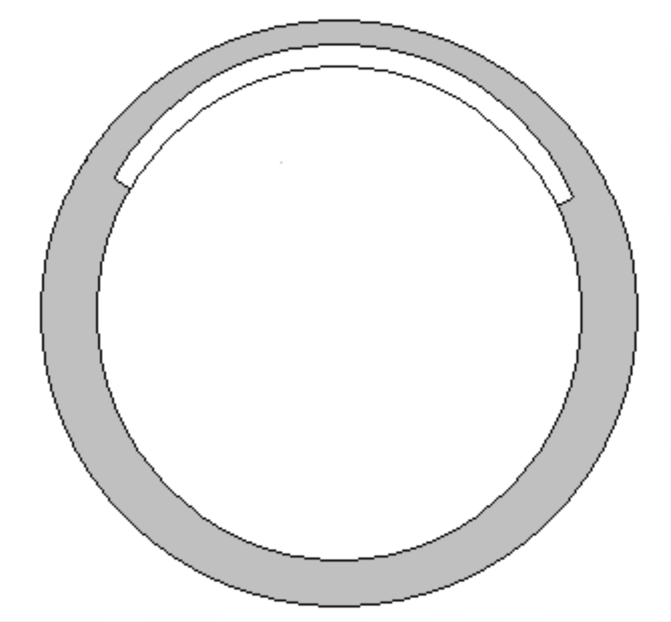
- Example showing the maximum allowable flaw size for the case of unaged or low delta ferrite CASS piping
- Maximum depth (a/t) = 0.65 for a 35% circumference flaw

Example of Maximum Allowable Flaw Size for a Category IV Case



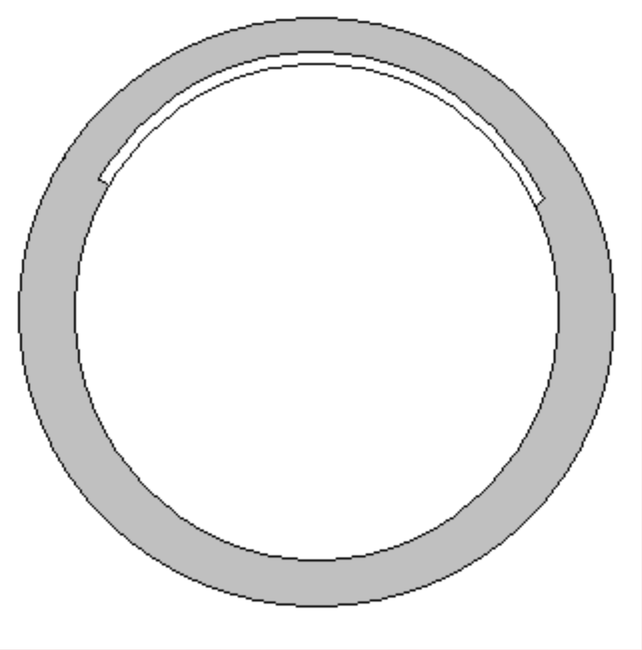
- Example showing the maximum allowable flaw size for the case of aged low delta ferrite (< 20%) CASS piping
- Maximum depth (a/t) = 0.50 for a 35% circumference flaw

Example of Maximum Allowable Flaw Size for a Category III Case



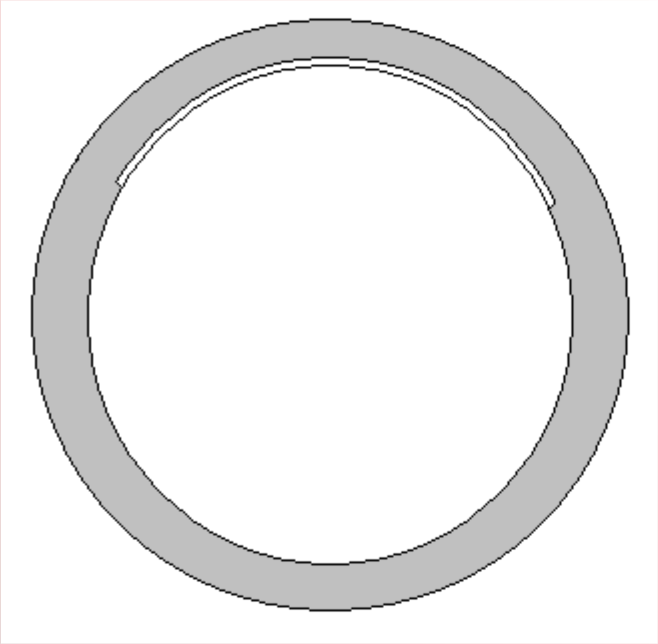
- Example showing the maximum allowable flaw size for the case of aged moderate delta ferrite (> 20%) CASS piping and medium-to-high design stress levels and EPFM analysis
- Maximum depth (a/t) = 0.35 for a 35% circumference flaw

Example of Maximum Allowable Flaw Size for a Category II Case



- Example showing the maximum allowable flaw size for the case of aged high delta ferrite (~30%) CASS piping and medium-to-high design stress levels using EPFM analysis
- Maximum depth (a/t) = 0.18 for a 35% circumference flaw

Example of Maximum Allowable Flaw Size for a Category I Case



- Example showing the maximum allowable flaw size for the case of aged high delta ferrite (~30%) CASS piping with low toughness and high design stress levels using EPFM analysis
- Maximum depth (a/t) = 0.10 for a 35% circumference flaw

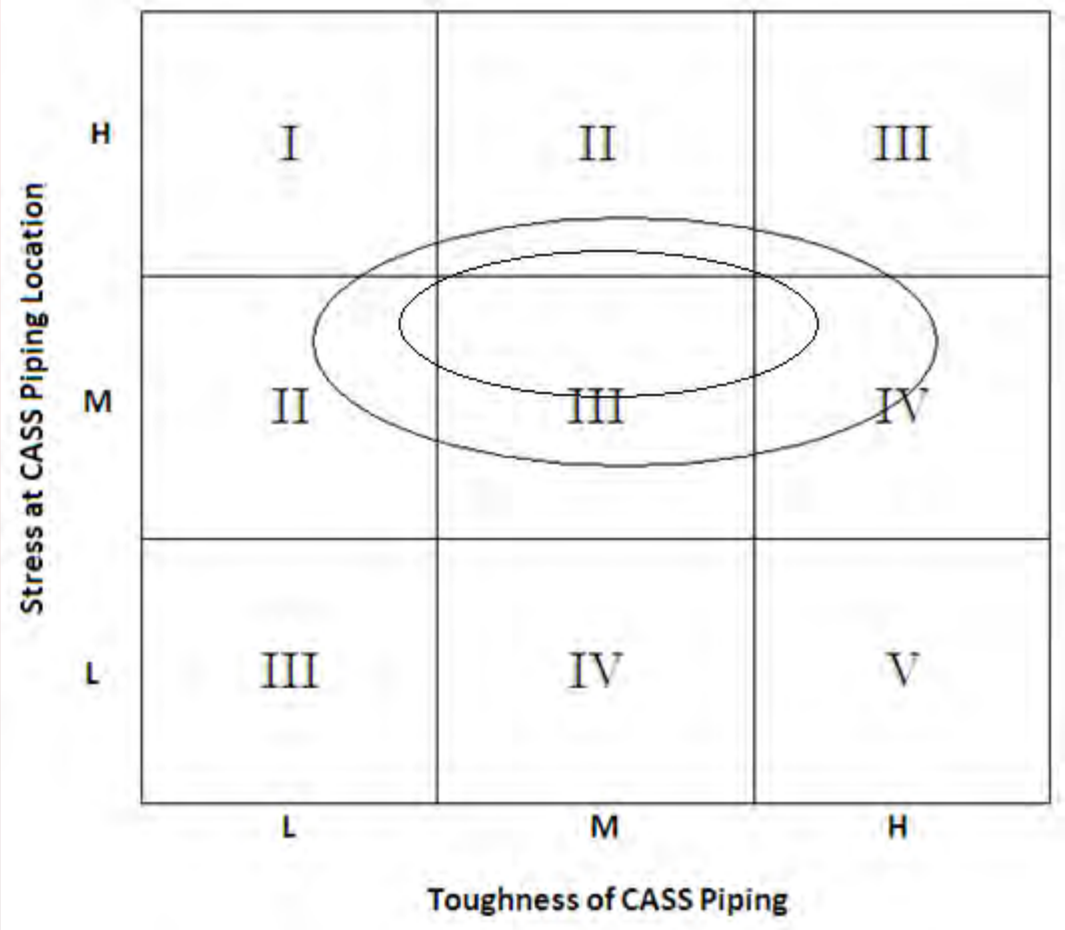
What is the "Real" Allowable Flaw Size Limit?

- Category I is unrealistic (i.e., too conservative) because it assumes the maximum design stresses, worst case material properties, and maximum Code safety factors simultaneously

- There are probably no plants that contain these worst case combination of factors (can we prove it?)

- Individual plants will probably be Category II, III, or IV depending on loads (design stresses) and material properties (material type and delta ferrite)

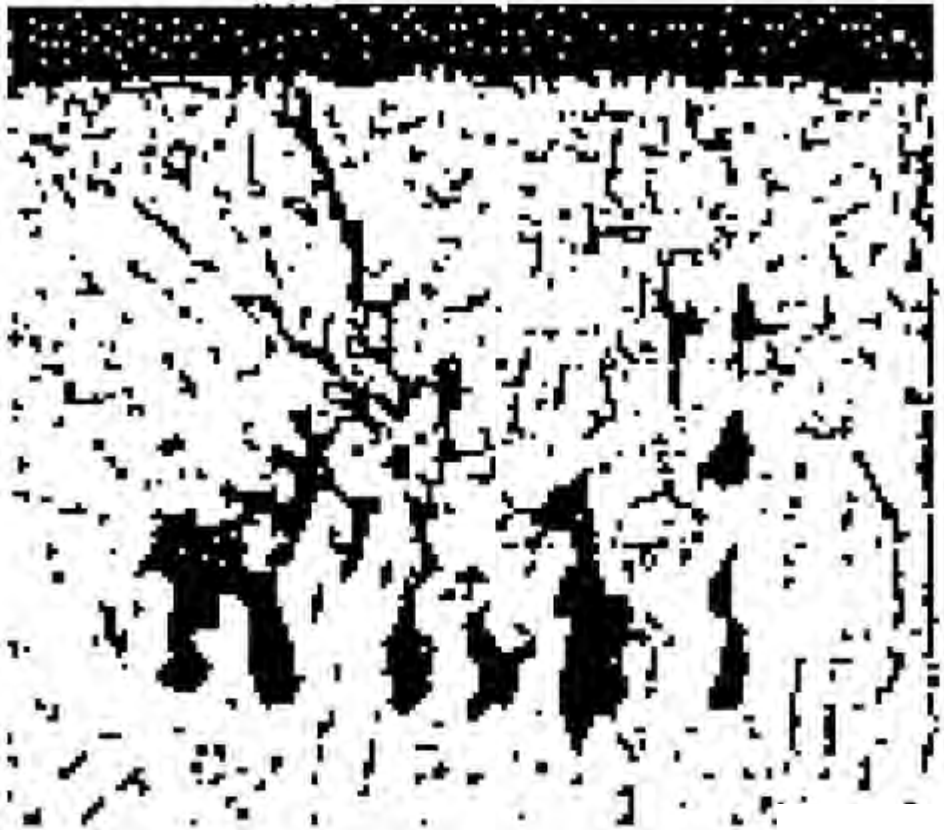
Can We Reduce the Uncertainties?



- A more accurate survey may reduce the uncertainties and better define the range of possibilities

- This would help to narrow the range of maximum allowable flaw sizes to be considered

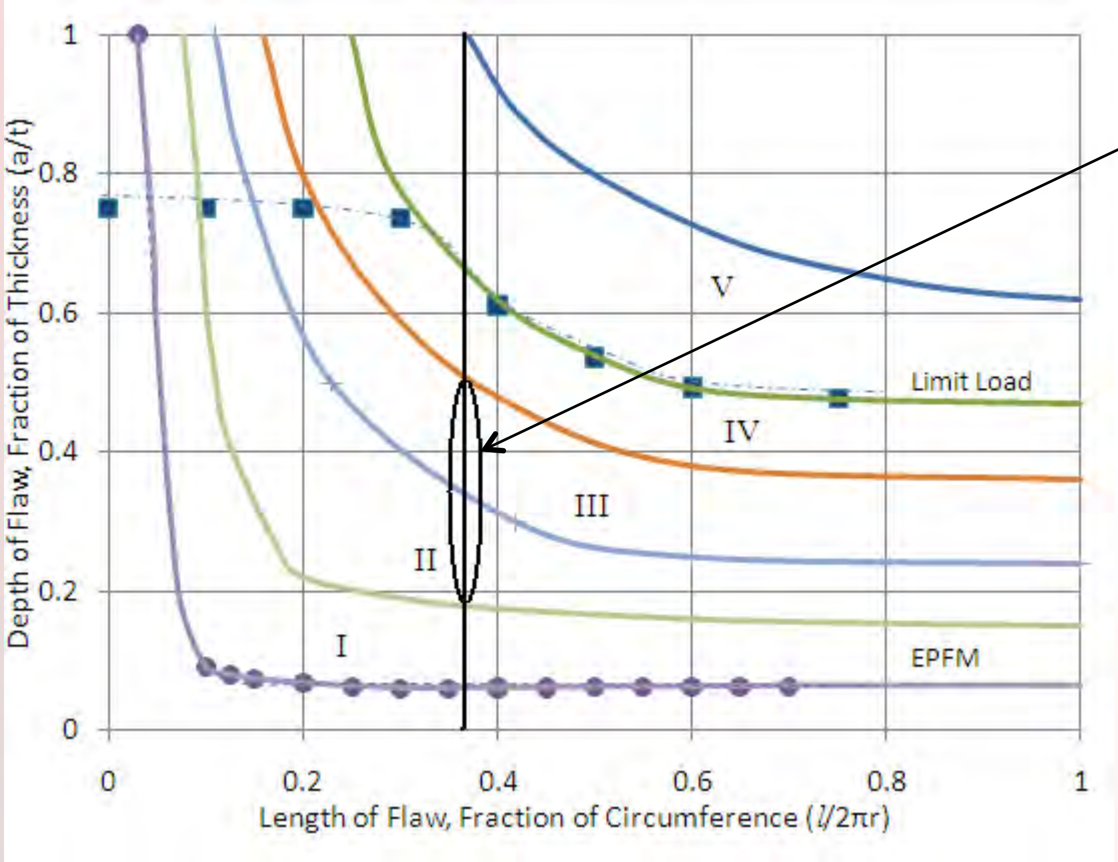
What Types of Actual Defects Might Exist in CASS Components?



Shrinkage Flaw (excised)

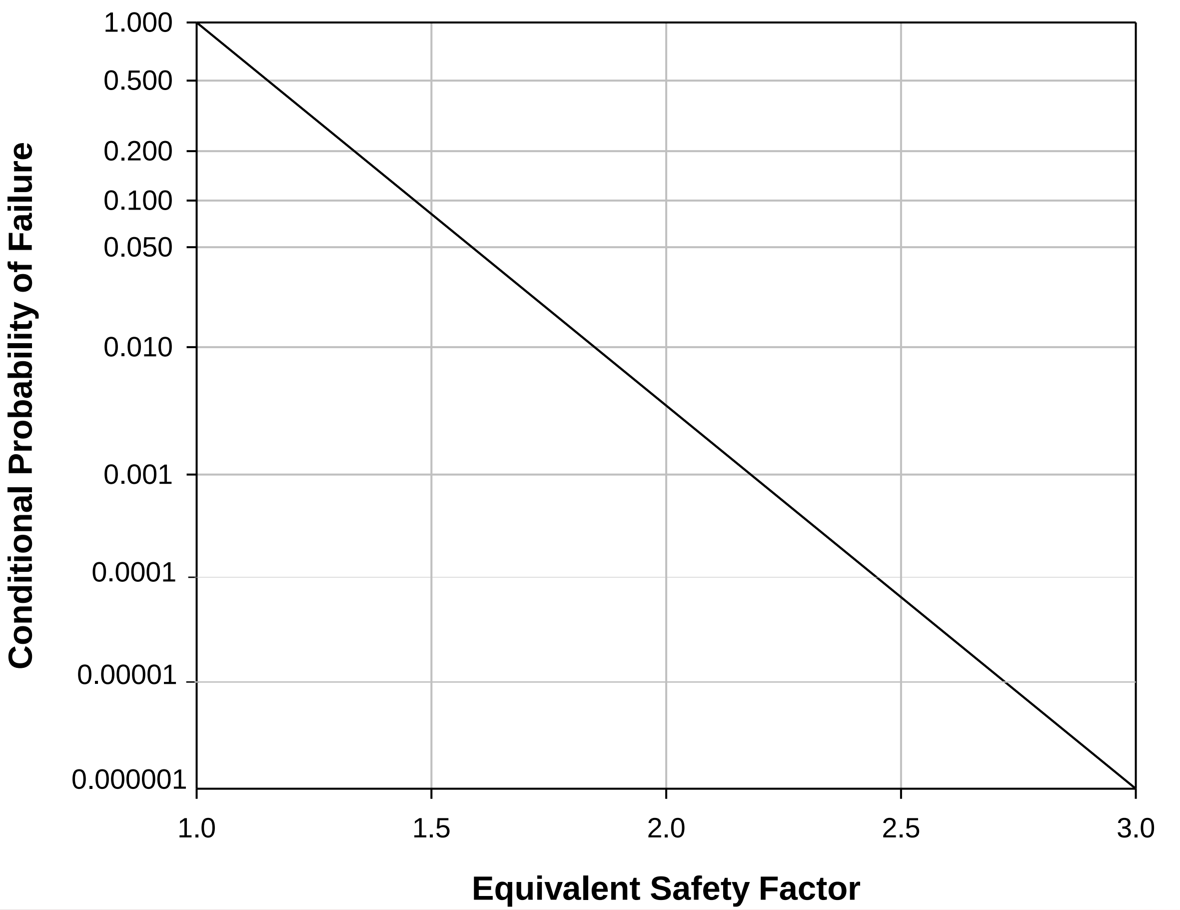
- Lack of Solidification
- Appears to be nonplanar
- May be inside surface breaking
- Resembles Swiss cheese
- Has both length and depth
- No evidence of fatigue type cracks
- No evidence of stress corrosion cracking in CASS

What is the Effect on Maximum Allowable Flaw Size?



- Target flaw sizes can be estimated based on reduced uncertainties
- This may improve the possibility of using inspections to manage risk and to demonstrate structural margins
- Structural margins can be roughly equated to risk significance

Risk Significance of Safety Factors



- Large safety factors are used to ensure that the risk of failure is very low
- Large safety factors are also used to account for uncertainties in stress levels, material properties and flaw sizes
- Should the “burden of proof” to maintain safety margins be placed mainly on inspections and inspectability?

How Can this Issue be Managed?

- One "issue" is that CASS piping is difficult to inspect and there are uncertainties in the material properties, stresses and flaws that are needed to calculate safety margins
- Determination of margins can be improved if we know more about the component(s) of interest, such as:
  - Maximum stresses in the component
  - Plant modifications or mitigations (e.g., weld overlay)
  - Material type (CF3, CF8, CF8A or CF8M), ferrite content, and saturated fracture toughness
  - Any prior inspection results
  - Future inspectability?

Methods for Improved Evaluation of CASS Piping

- Use plant-specific design and materials information
- Characterize material toughness using correlations with chemistry or by measuring delta ferrite with a ferrite meter
- Screen and categorize risk significance of components and locations using risk-based methods
- Use best-available inspection techniques selectively to confirm margins
  - Visual (VT-1, EVT-1)
  - Ultrasonic (e.g., phased array, low-frequency SAFT)
  - Digital Radiography (w/tomography)
  - Eddy Current
  - Combination of several techniques

2nd International Workshop: Future Directions for the Inspection of Cast Austenitic Stainless Steel Piping – Seattle, Washington USA
Sponsored by Chockie Group International, Inc.

NRC Sponsored Efforts toward Addressing NDE Inspection of Cast Austenitic Stainless Steel (CASS) Piping – A Technical Overview of Work at PNNL

AA Diaz and MT Anderson
Pacific Northwest National Laboratory, Richland, WA. USA

June 15-16, 2009

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Topics of Discussion

- Objective of PNNL's Work
- Relevance of the Work
- The CASS Inspection Challenges
- Technical Overview
  - Historical evolution of previous work, from PISC III round robin to the most recent assessment of Phased Array ultrasonic methods for inspecting CASS components
- Future Work
- Questions

Work Objective:

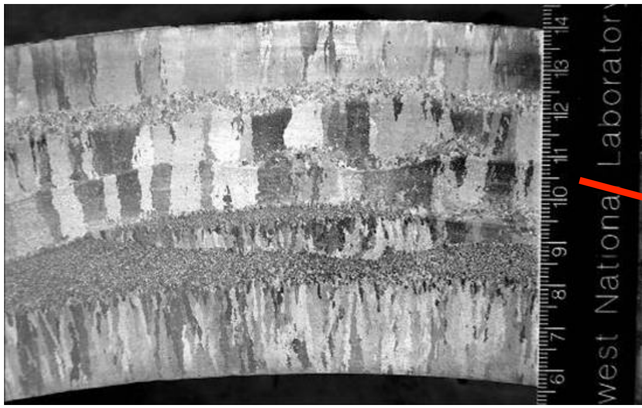
- To determine the effectiveness and reliability of ultrasonic inspection techniques on LWR components containing cast stainless steel (CASS) and dissimilar metal weld (DMW) material and to assess advanced NDE methods.
  - This includes evaluations such as far-side examination methods for austenitic welds, inspection of CRDM components and corrosion resistant cladding, inlays and onlays.
  - This task addresses a wide range of NDE issues associated with coarse-grained steels and challenging material/ component configurations (e.g., CASS, DMWs, Alloy 600/182/82)
- Work is sponsored by the U.S. Nuclear Regulatory Commission (NRC), RES Project JCN N6398
  - Wallace Norris, NRC Program Manager

Relevance of PNNL's Work:

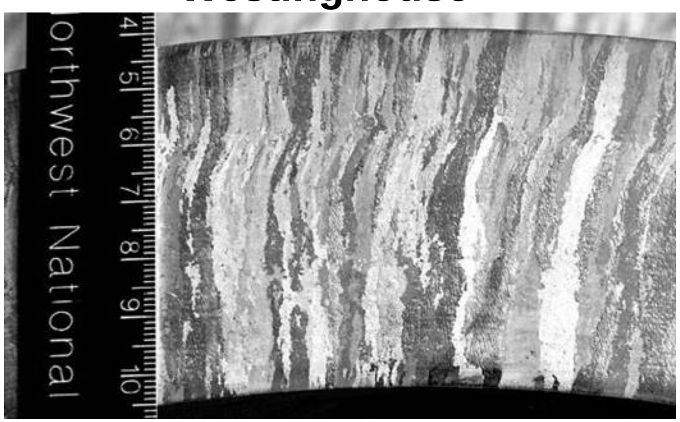
- Coarse grained materials were used in the manufacture of components in U.S. BWRs and PWRs, including:
  - CASS and DMW piping components
  - Pumps, valve bodies and statically cast elbows
  - Cladded pipe and pressure vessels
  - Weld-overlay-repaired pipe joints
  - Austenitic Welds

CASS Inspection Challenges

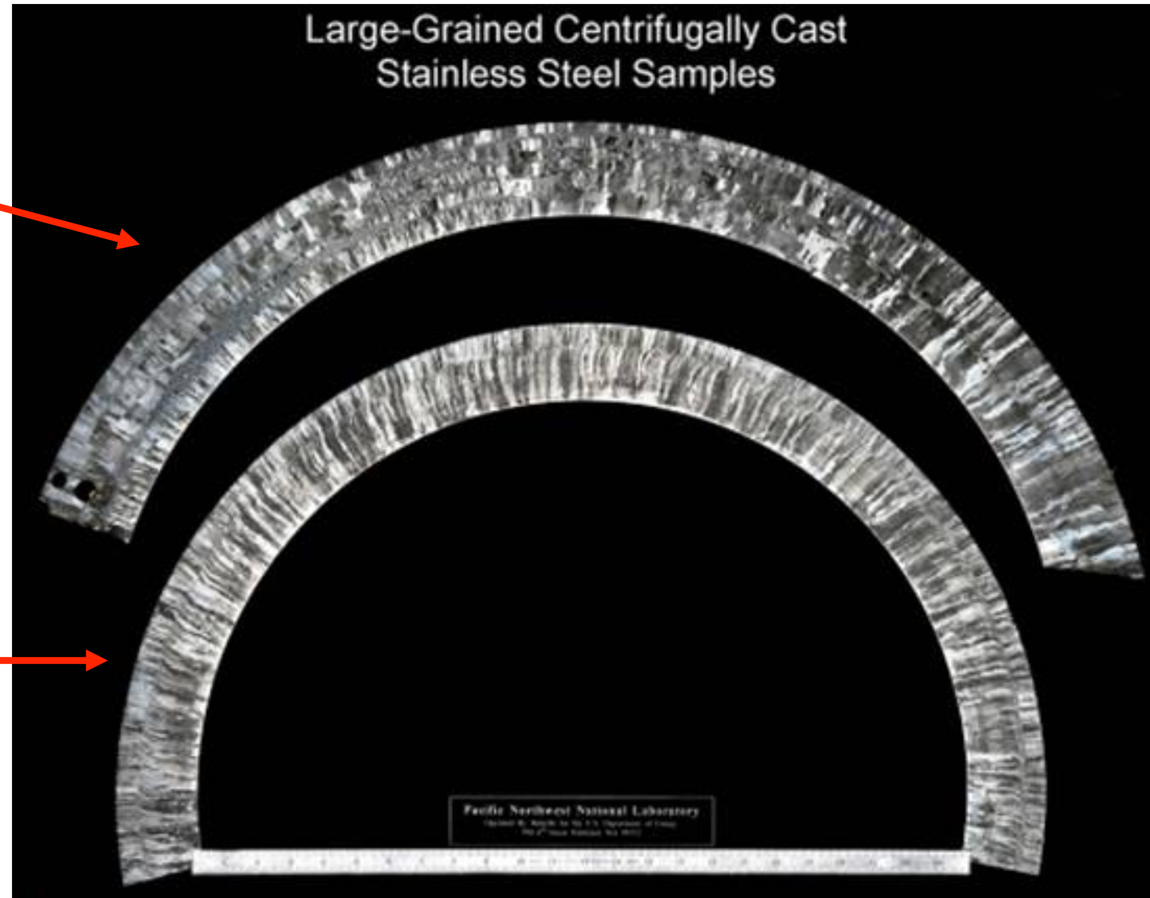
IHI Southwest



Westinghouse



Chemically Etched and Polished Cross-Sections



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CASS Inspection Challenges

- Conventional UT inspections are challenging due to the anisotropy and inhomogeneity of the coarse microstructures in CASS components affecting sound field propagation
- CASS component inspections continue to yield poor results due to:
  - Large size/orientation of anisotropic grains (relative to the acoustic pulse wavelength)
    - Severe attenuation (primarily scattering)
    - Beam skewing
    - Changes in acoustic velocity as a function of position
    - Refraction/reflection of sound at grain boundaries, root conditions, counterbore, weld fusion lines
- This translates into lower SNR, difficulties in signal (echo) discrimination and the potential for incomplete insonification of the part

Historical Overview:

- Early 1980's
  - Initial studies on Cast Stainless Steel materials
  - PNL – Westinghouse Cooperative Program
    - Limited Round Robin
    - Acoustic Velocity Characterization
- Mid-1980's, the International community became involved with the issue of NDE capability and reliability of inspecting CASS components

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Historical Overview (continued):

- In 1985, the Program for the Inspection of Steel Components (PISC III) decided to conduct an international test called the Centrifugally Cast Stainless Steel Round Robin Test (CCSSRRT)
  - This effort was conducted in the US by the NRC and in Europe by the JRC; PNNL coordinated the US portion of the testing for the NRC
  - 18 inspection teams participated
  - Procedures used included:

    Manual UT, Automated UT, Automated UT with Signal Processing and non-UT based techniques
  - Most common technique utilized a dual probe using L-waves at 1 MHz
  - Each team spent approximately 1 week performing the inspections

Historical Overview (continued):

- Results indicated that existing NDE techniques could not effectively discriminate between thermal fatigue cracks and uncracked material
- A post-CCSSRRT study was conducted at PNNL
  - Using SAFT, and 500 kHz shear waves, the focus was to determine if relevant information could be extracted from the frequency spectrum of UT signals from various reflectors in CASS
  - Data was compiled from zones containing defects and defect-free zones
  - FFTs were performed on all A-scan data
  - Results were summed together and sorted into classes:
    - Equiaxed
    - Columnar
    - High probability detections
    - Low probability detections

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Historical Overview (continued):

Post-CCSSRRT Conclusions

- Detections were most likely based on signal amplitude
- No simple filter exists for both columnar and equiaxed material to reject unwanted coherent grain scattered signals
- The problem is not totally one of signal-to-noise since the spectrum (frequency response) of defects and noise are quite similar

Historical Overview (continued):

During the late 80’s and early 90’s, work at PNNL focused on evaluating and quantifying coherence and sound field distortion in CASS materials:

- Ultrasonic beam profiles (sound field mapping)
  - As a function of wave mode, frequency, incident angle, microstructure, and other inspection parameters
- Phase imaging of the back surface echo
- Imaging the sub-surface microstructure
  - Useful for classification and texture mapping
  - Various frequencies, Rayleigh waves

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Historical Overview (continued):

Results Provided:

- Better understanding of sound field propagation as a function of inspection parameters
- Data showing high spatial coherence for pure microstructures (columnar and equiaxed)
- Data showing moderate spatial coherence for mixed-layered microstructures
- Improved capability to adjust inspection parameters by using classification/texture maps

Historical Overview (continued):

In the early 90's the focus shifted to a more direct approach applying effective inspection techniques:

- Develop, investigate and test inspection methodologies that are inherently less sensitive to microstructural effects
  - Lower frequencies, longer wavelengths
- Use fracture mechanics (FM) calculations to determine realistic flaw sizes that affect structural integrity in CASS components
- Couple the technique of choice with FM data and determine the smallest flaw dimensions that can be reliably detected

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Historical Overview (continued):

FM calculations were performed for thermally aged cast stainless steel material with bounding conditions of degraded toughness

- For the loadings of normal operation, the sizes of unstable circumferential cracks are both deep (50% of wall) and long (180°)
- For the accident loadings, the sizes of unstable circumferential cracks depend on the assumed levels of accident loads and on the assumed flaw lengths (30° versus 180°).
- For assumed worst case accident conditions, in combination with conservative flaw lengths, the depths of unstable flaws can be as small as 15% of the wall thickness.
- For less conservative accident assumptions, the depths of unstable flaws become greater than 50% of the wall thickness.

Historical Overview (continued):

- Estimates of critical flaw sizes for primary coolant piping, using Argonne's toughness data, published data on piping loads, and one of Battelle-Columbus's methodologies were completed. Service loads on PWR primary coolant piping are relatively low, and thus even severely aged CASS can tolerate 50% through-wall circumferential flaws. A detection capability for flaws of about 50% of wall could provide a meaningful inspection for most locations within the PWR primary coolant loop piping.

Historical Overview (continued):

This new guidance led to (’92 to ’95):

- Initial development of the Low-Frequency/SAFT inspection methodology and fracture mechanics studies on CASS
- Examination of advanced processing techniques that compensate for sound field degradation in CASS materials
  - Time Reversal Mirroring Technique
  - Adaptive Ultrasonic Technique (Phase Aberration Correction)
- PNNL participation in a limited round robin sponsored by EPRI NDE Center, Yankee Atomic Electric Company and Northeast Utilities
  - 13 teams participated (6 manual UT and 7 automated UT)
  - Best automated system performance 70% PODCI vs 30% FCP

Historical Overview (continued):

Ongoing work included (’96 to ’97):

- Continued evolution of the Low-Frequency/SAFT technique
- Field exercise at Seabrook Station Unit #2
  - With NRC Region 1 Inspection Team
  - Assessment of current industry standard inspections and Low-Frequency/SAFT methodology
  - Lessons learned and some very promising results
- Evaluation of PISC III CASS specimens at PNNL
- Field exercise at EPRI NDE Center
  - With D. Jackson and H. Gray (PWROG CASS and DMW specimens)
  - Developed crack identification criteria - again very promising results

Historical Overview (continued):

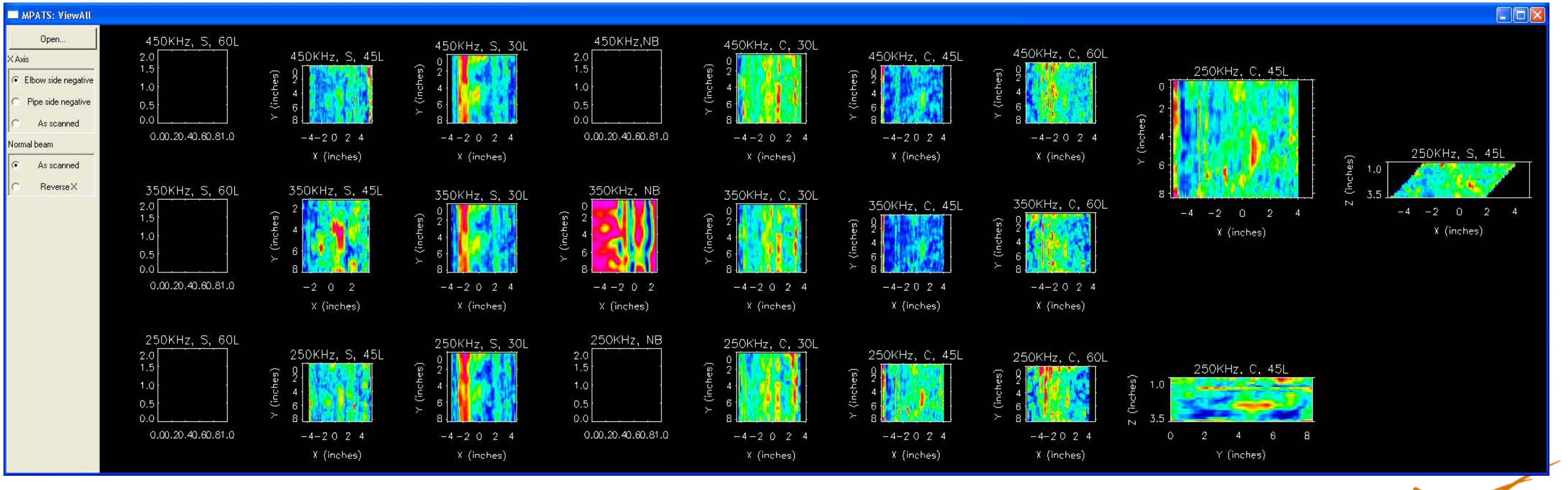
Ongoing work included (’98 to ’00):

- Continued evolution of the Low-Frequency/SAFT technique
  - Transducer enhancements
  - Inspection system enhancements
- Hosting a visiting professor (Dr. Shayne Johnston)
  - Studied Noise/Clutter reduction techniques (post processing)
  - NRC HBCU Faculty Research Participation Program (2 summers)
  - Wavelet processing vs Maximum Entropy processing algorithms
- Material property measurements (L-wave v and α) on PISC and PNNL specimens

Historical Overview (continued):

Ongoing work included (’01 to ‘03):

- Continued evolution of the Low-Frequency/SAFT technique
  - SAFT functionality enhancements
  - Inspection system enhancements
  - Development of Multi-Parameter Analysis Tool-Set (MPATS) for LF-SAFT Data Fusion



Historical Overview (continued):

Why Use Low Frequency Ultrasound?

- Previous work has shown conventional ultrasonic inspection methods are ineffective for these types of materials
- Lower frequency equates to a longer wavelength, resulting in less sensitivity to the effects of the microstructure
- Longer wavelengths provide better penetration for thick-section components and higher incident angle examinations

Historical Overview (continued):

Low-frequency/SAFT-UT methodology

- Low frequency ultrasound in the range of 250 kHz to 500 kHz, in the pitch-catch mode
- Multiple inspection angles from 0° to 70°
- Longitudinal and shear wave modalities
- Near- and far-side inspection data (where access permits)
- Custom designed, variable-angle, high-bandwidth, dual-element transducers
- Low-frequency, low-noise signal conditioning
- SAFT post-processing
- Capability to acquire both ID and OD ultrasonic data
- Redundancy-based inspection protocol and detection criteria

Historical Overview (continued):

Ongoing work included (’01 to ‘03):

- At the same time, PNNL Initiated comparative work with Phased Array examining far-side detection and sizing performance on wrought piping with austenitic welds
- While the application of LF-SAFT resulted in improved detection and sizing for flaws in CASS components, it was a very time-consuming and complex inspection/analysis process that included:
  - Multiple rastor scans at multiple frequencies
  - Both sides of the weld
  - Hours of SAFT post-processing time
  - Hours of complex analysis and data registration/fusion
- It was deemed impractical from a field-inspection standpoint

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Historical Overview (continued):

Over the past 28 years, PNNL has taken a systematic approach to this inspection problem

- Assessing state-of-the-art inspection capabilities
- Collaborating with utilities, vendors, regulatory agencies, and the international community
- Improving our understanding of microstructural effects, sound field degradation, crack morphologies, cracking mechanisms, etc.
- Improved detection and sizing techniques, leading to:
  - The development of a low-frequency/SAFT technique for inspecting anisotropic, non-homogenous, coarse-grained steels
  - The evolution of low-frequency Phased Array methods for CASS inspections

Direction of More Current Work

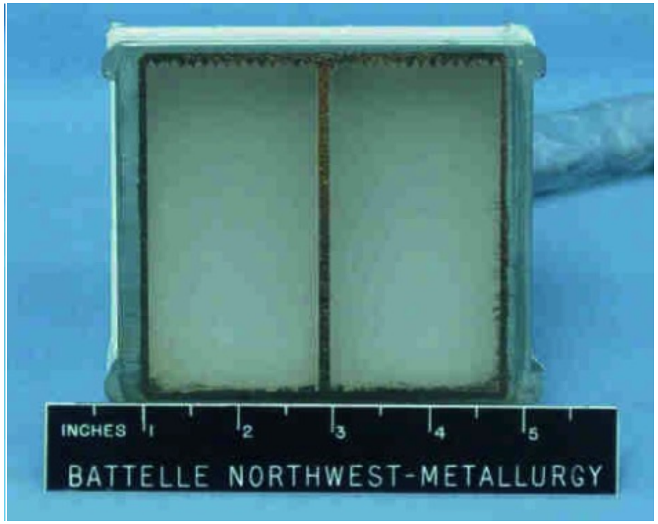
Since 2002-2003 PNNL has

- Employed low-frequency, ultrasonic phased array methods on specimens
- Evaluated use of ET to ID surface of CASS specimens
- Dimensional analysis of various microstructures
- Evaluated sound field propagation through microstructures
  - Sound field mapping and modeling efforts
- Studied CASS fabrication processes to determine any correlations between manufacturing parameters and resultant microstructures
  - Via existing fabrication records, interviews with casting experts and foundry visits
- Investigated in-situ NDE methods for microstructural characterization (classification) from the OD

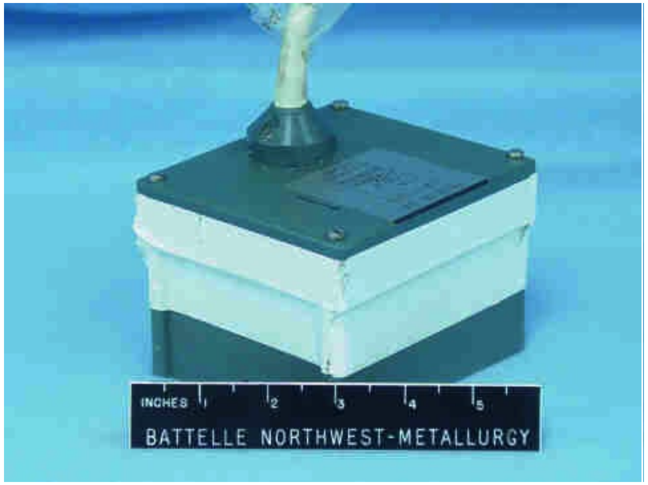
Evolution of Low-Frequency PA Probe

▶ 1st Generation LF PA Probe

Initial low-frequency PA work was performed with a first-generation prototype transducer developed by Michel DeLaide at AIB-Vincotte in Belgium. Mr. DeLaide designed and constructed the prototype with piezo-ceramic elements, as these were the only low-frequency materials available in late 2003.



Material	Piezoelectric (ceramic)
Configuration	2 × (2 × 10)
Element length	8.44 mm (0.33 in.)
Element width	21.2 mm (0.83 in.)
Active aperture	84 mm (3.31 in.)
Passive aperture	42 mm (1.65 in.)
Total footprint (includes housing)	115 mm × 115 mm (4.5 in. × 4.5 in.)



Evolution of Low-Frequency PA Probe

▶ 2nd Generation LF PA Probe

The 2nd generation probe was designed to improve lower angle (30°-50°) flaw responses by reducing footprint (size); enhance the crossover point with more effective focusing at various depths; improve the element-matrix design for better skew in the passive direction; use of piezo-composite elements for higher BW and enhanced dynamic range.

	500-kHz Improved Design
Material	**Piezocomposite**
Configuration	**2 × (4 × 8)**
Element length	**9.19 mm (0.36 in.)**
Element width	**9.29 mm (0.37 in.)**
Active aperture	**72.8 mm (2.87 in.)**
Passive aperture	**36.4 mm (1.43 in.)**
Total footprint	**85 mm × 85 mm (3.35 in. × 3.35 in.)**

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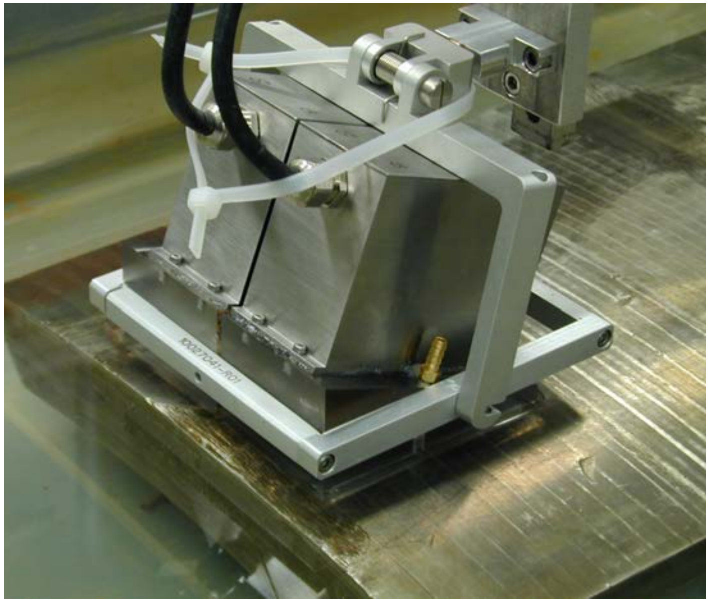
Evolution of Low-Frequency PA Probe

► 3rd Generation LF PA Probe

The 3rd generation probe was designed to further improve lower angle (30°-50°) flaw responses by again reducing footprint (size); enhancing focal capabilities at various depths; improving the element-matrix design for better skew in the passive direction; use of piezo-composite elements for higher BW and enhanced dynamic range.

Acoustical characteristics

Centre frequency (-6dB):	0.5MHz ± 10 % (1) (2)
Acoustical impedance matching:	Rexolite (2.45 MRayl)
Bandwidth (-6dB):	≥ 45% (1) (2)
Array type:	2D Matrix array
Number of channels:	10 X 5 elements (total number of elts 50)
Mechanical focusing:	none, flat active area
Active dimensions	64 mm ± 0.1mm x 34 mm ± 0.1mm
Elementary pitch:	6.5 mm in primary axis
	7.0 mm in secondary axis
Inter element spacing	1.0 mm in both directions



2nd and 3rd Generation PA Probe Performance Comparison (PWROG specimens)

PWROG Specimen	Side	Length, mm (inch) - 6dB drop True State Length	2nd Gen 500 kHz	3rd Gen 500 kHz	Reported Depth (%)
ONP-3-5	CCSS	66 (2.60)	ND*	ND*	25
OPE-5	CCSS	61 (2.40)	41 (1.61)	42 (1.66)	23
	SCSS	61 (2.40)	64 (2.52)	60 (2.37)	23
MPE-6	CCSS	59 (2.32)	94 (3.70)	47 (1.85)	18
	SCSS	59 (2.32)	ND*	34 (1.34)	18

*ND = Not Detected

ASME Code Section XI-acceptable criterion is Length RMSE less than 19.05 mm (0.75 in.)

Length RMSE (3rd gen) 500 kHz probe: **16.8 mm (0.66 in.)**

Length RMSE (2nd gen) 500 kHz probe: **23.3 mm (0.92 in.)**

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ET Technical Approach

- Probe type Zetec Z0000857-1
  - Coil diameter 3.05 mm (0.12 in.)
  - Plus point coil design
  - Nominal probe operating frequency of 240 kHz
- Instrument Zetec MIZ-27 SI
- Frequencies 100 kHz, 250 kHz, 500 kHz
- Cracks generally exhibited phase angles of about 90 degrees or 270 degrees
- Used C-scans of both magnitude and phase responses for image analysis
- Degaussing approach was also implemented

Technical Approach using ET (continued)

ET Probe, Sled Fixture and Gimbals Apparatus

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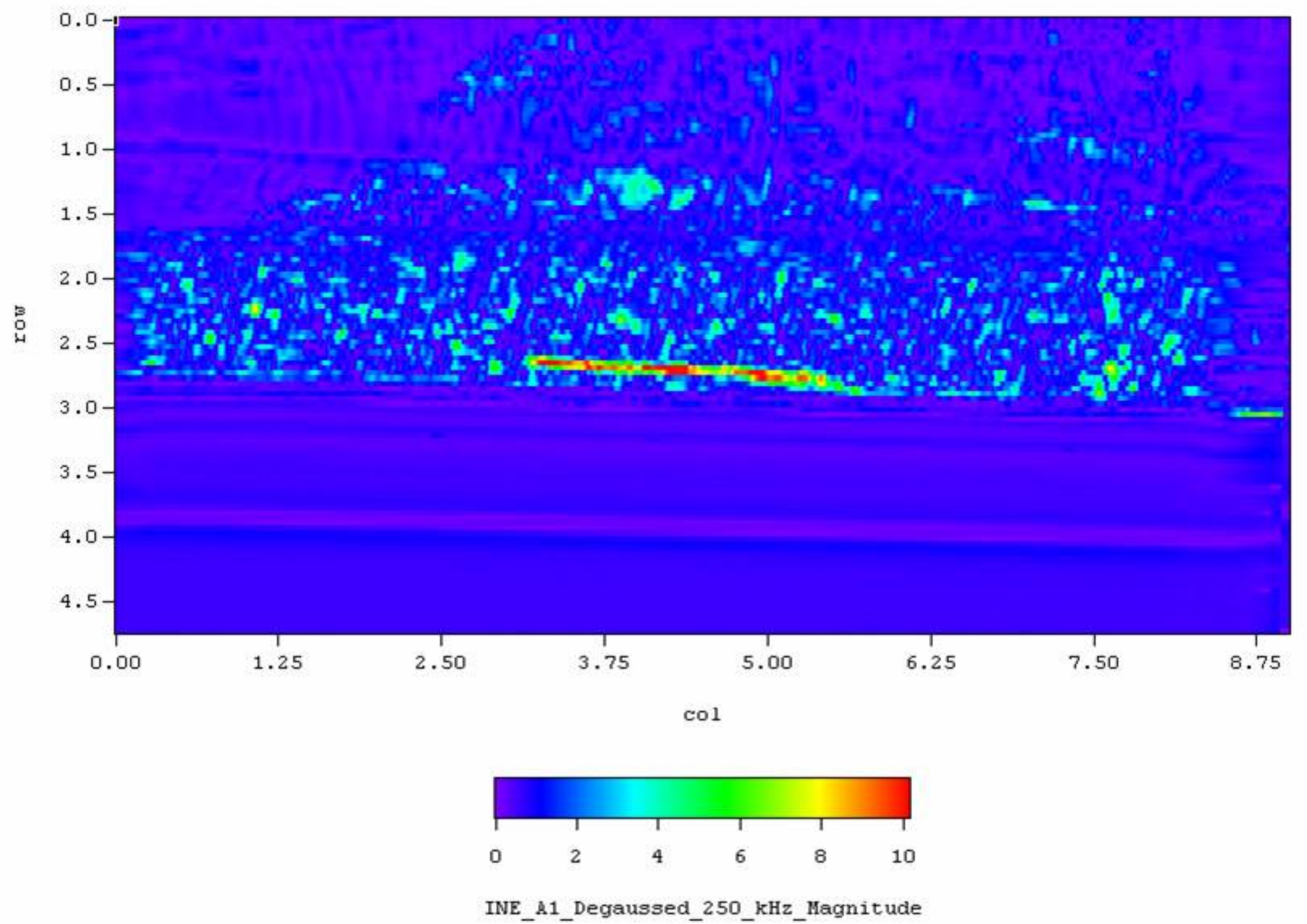
Examples of ET Data (continued)
(Scale on plot in inches)

WOG Specimen with MFC on Elbow Side of Weld



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Conclusions from ET work on CASS

- ET scans were performed for crack detection, localization and length sizing on the ID
- ET was very effective in that all of the cracks were detected
- Both magnitude and phase response images were useful in detecting the cracks
- Demagnetizing the inspection zones was useful 42% of the time (improved SNR in 8 out of 19 specimens)
- Further studies need to be conducted to address closure weld ID conditions
- Probe rotation is required for effective detection of off-angle cracking, branching and crazing
- Circumferential cracks longer than about 12.5 mm (0.5 in.) should be reliably detected using ET

Evaluation of PA Inspection Approach

- Ultrasonic PA data were acquired and analyzed on
  - Pressurizer (PZR) surge-line (pipe-to-elbow) specimens
    - Centrifugally cast to statically cast component configuration
  - PWROG traveling set specimens on loan from the EPRI NDE Center in Charlotte, NC., USA
- Line Scan Data were analyzed for
  - Flaw detection capability
  - Both depth and length sizing in PZR surge line specimens
  - No depth sizing attempted for PWROG specimens (tips not detected); length sizing only
- Raster Scans taken and currently being analyzed

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Evaluation of PA Inspection Approach

- Crack morphology and true state data were known for all specimens
- 500 kHz and 800 kHz used for PWROG samples
  - λ = 11.6 mm (0.45") and 7.2 mm (0.29") respectively
- 800 kHz and 1.5 MHz used for PZR surge-line samples
  - λ = 7.2 mm (0.29") and 3.9 mm (0.15") respectively
- 1.0 MHz and 2.0 MHz PA probes were also employed on all PZR surge-line specimens
  - Data currently being analyzed and reported

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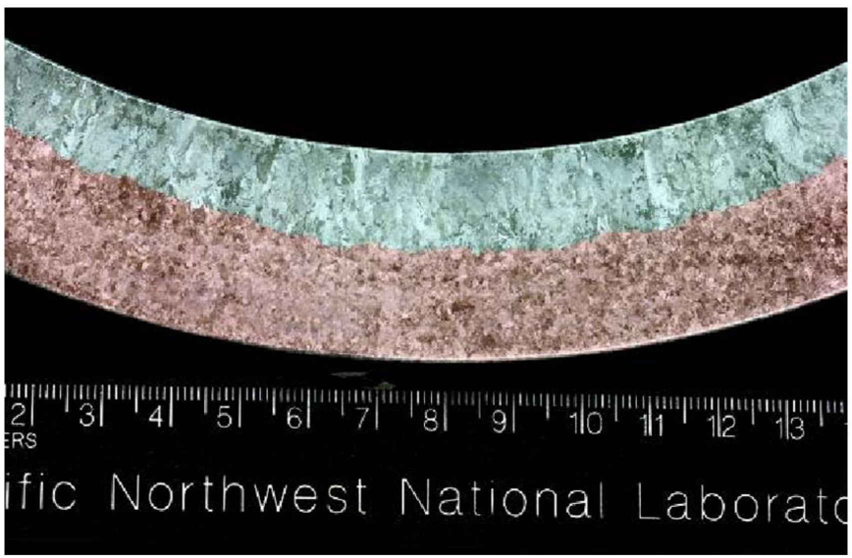
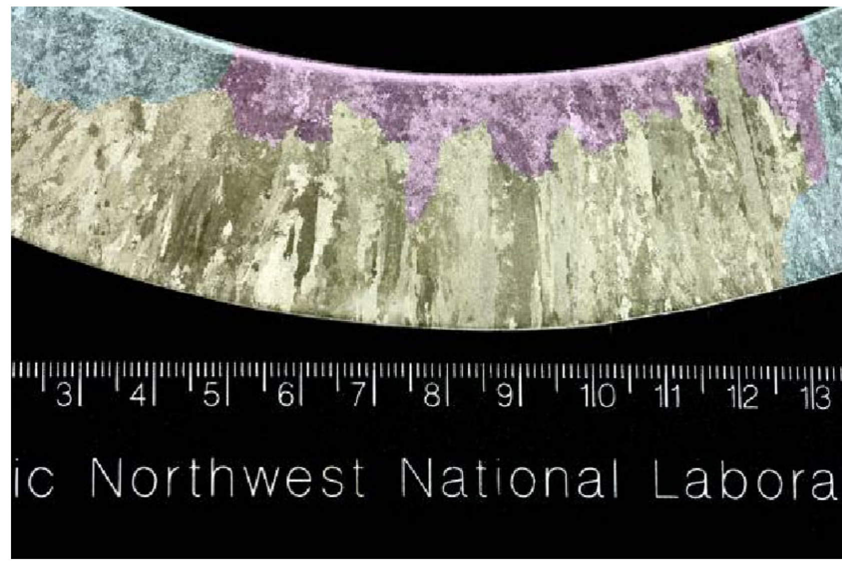
PZR Surge Line Specimens

Sample 7C-059



Pipe Side – CCSS
30 mm (1.2 in.) wall



Elbow Side – SCSS
39 mm (1.5 in.) wall

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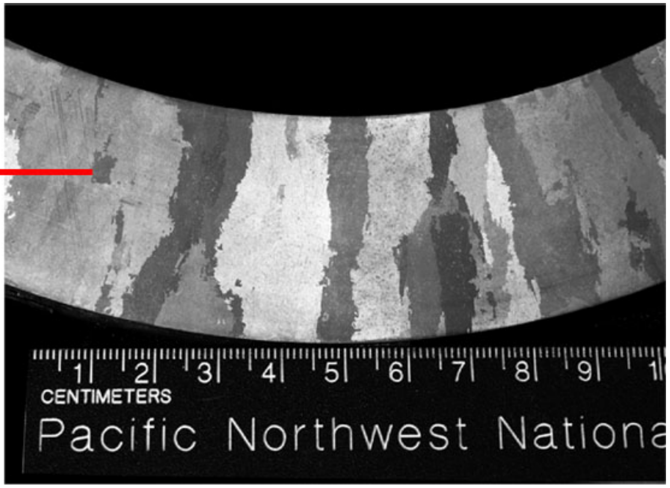
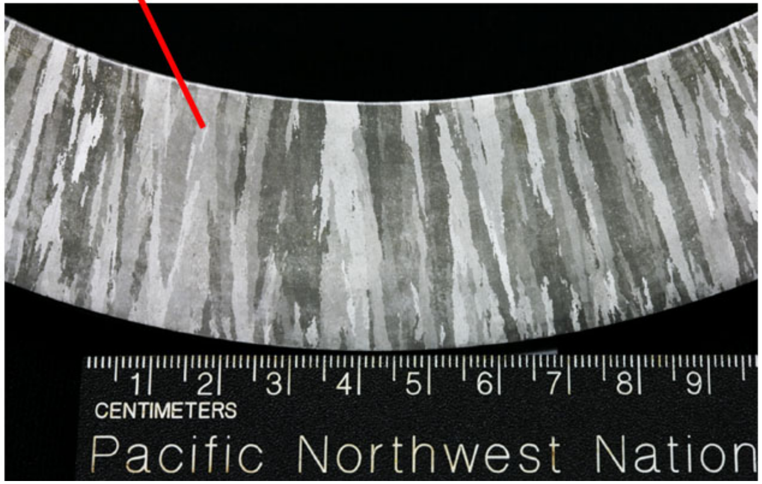
PZR Surge Line Specimens (WNP-3)



9C-002
Pipe Side
33 mm
(1.3 in.) wall



9C-001
Pipe Side
33 mm
(1.3 in.) wall

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PZR Surge Line Specimens (WNP-3)

Microstructure of elbow segment from WNP-3 PZR surge line specimen
34 - 44 mm (1.3 - 1.7 in.) wall

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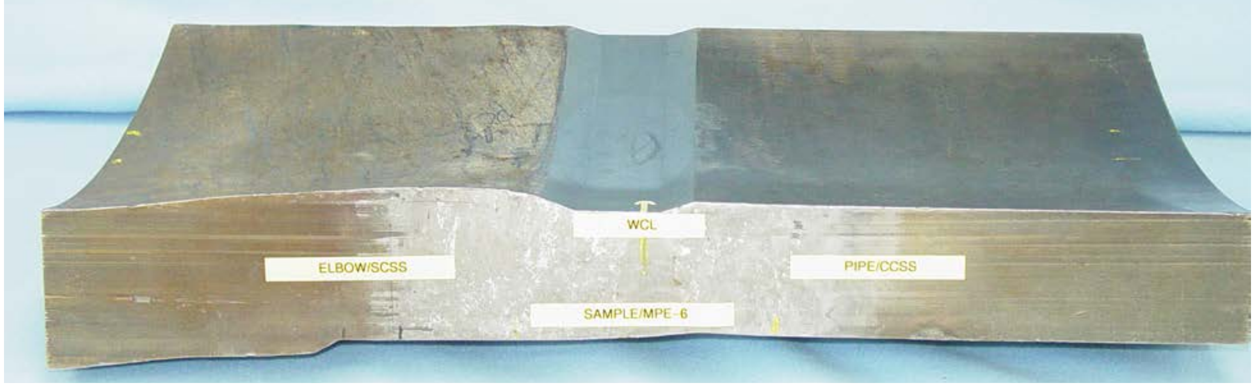
PWROG Specimens

OPE-5, SCSS elbow 7.1 cm (2.8 in.) wall, CCSS pipe 5.8 cm (2.3 in.) wall

ONP-3-5, clad CS outlet nozzle to forged SS safe end to CCSS pipe 6.4 cm (2.5 in.) wall



MPE-6, SCSS elbow 8.4 cm (3.3 in.) wall, CCSS pipe 6.6 cm (2.6 in.) wall

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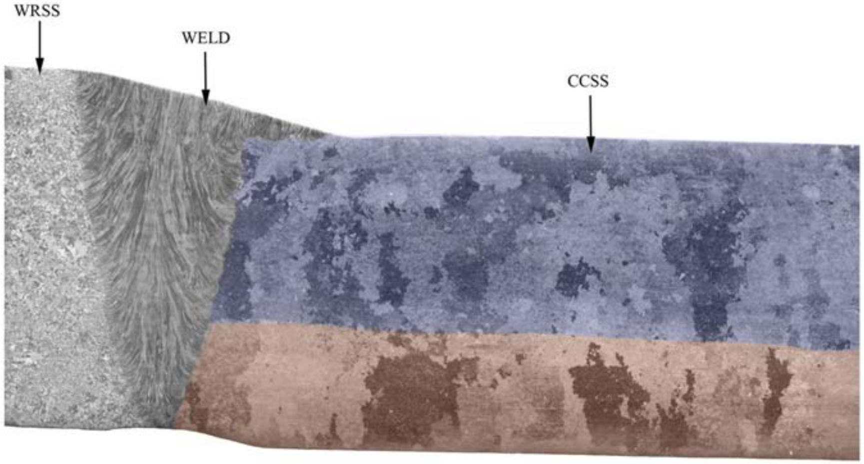
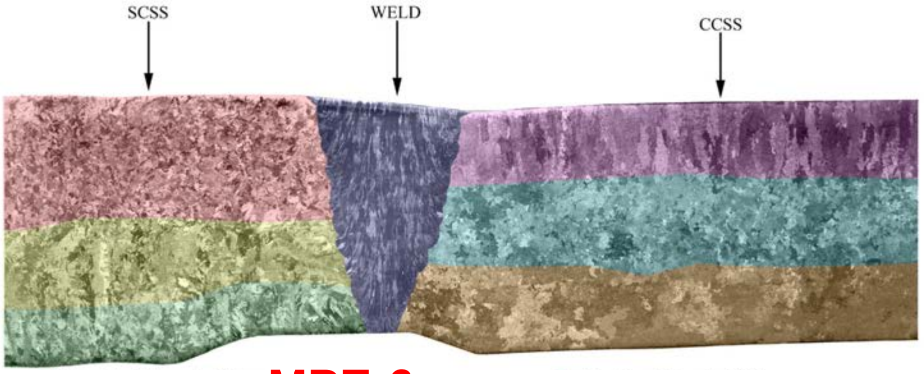
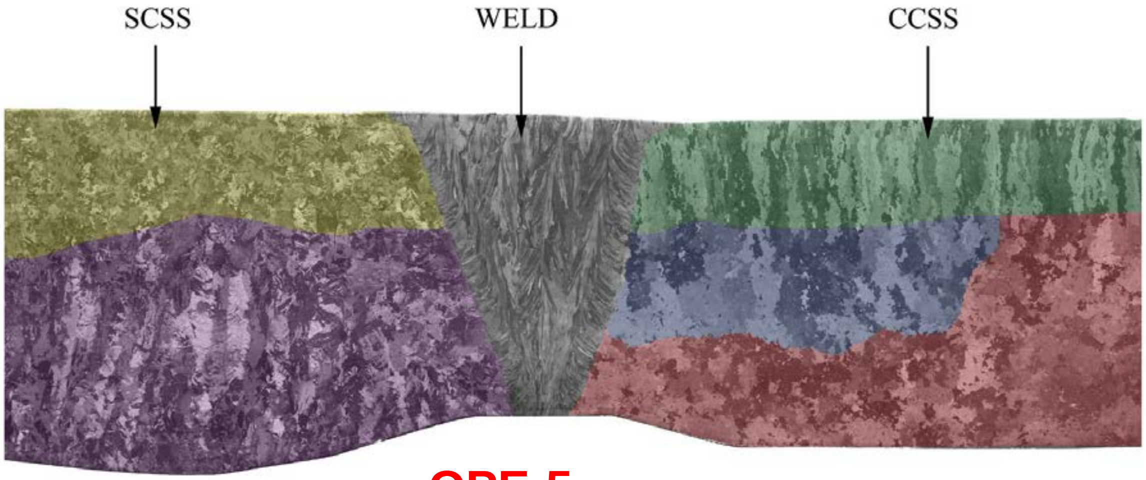
PWROG Specimen Microstructures



ONP-3-5



MPE-6



OPE-5

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Grain Diameter Dimensional Analysis

Specimen	CCSS (Pipe Side)		SCSS (Elbow Side)	
	Minimum mm (in.)	Maximum mm (in.)	Minimum mm (in.)	Maximum mm (in.)
PZR Surge Line 7C-059	0.6 mm (0.02 in.)	6.7 mm (0.26 in.)	0.5 mm (0.02 in.)	6.3 mm (0.25 in.)
PZR Surge Line 9C-001	0.8 mm (0.03 in.)	13.9 mm (0.55 in.)	2.6 mm (0.10 in.)	41.0 mm (1.61 in.)
PZR Surge Line 9C-002	1.3 mm (0.05 in.)	25.6 mm (1.01 in.)	2.6 mm (0.10 in.)	41.0 mm (1.61 in.)
MPE-6	0.56 mm (0.02 in.)	26.81 mm (1.06 in.)	0.28 mm (0.01 in.)	5.59 mm (0.22 in.)
ONP-3-5	0.33 mm (0.01 in.)	26.67 mm (1.05 in.)	n/a Carbon-Forged SS	n/a Carbon-Forged SS
OPE-5	0.21 mm (0.01 in.)	16.67 mm (0.66 in.)	0.21 mm (0.01 in.)	5.21 mm (0.21 in.)

PZR Surge Line Implanted Flaw Data (True State)

	Flaw	Flaw Type	Flaw Location	Flaw Orientation	Flaw Length	Flaw Depth (Height)	Degree Location
7C-059	1-1	Thermal Fatigue	Weld Center Line	Circumferential	4.0 in. (10.2 cm)	35.2% T	45°
	1-2	Thermal Fatigue	Pipe Side Near Fusion Line	Circumferential	2.0 in. (5.1 cm)	30.3% T	120°
	1-3	Thermal Fatigue	Weld Center Line	Circumferential	2.0 in. (5.1 cm)	29.8% T	210°
	1-4	Thermal Fatigue	Weld Center Line	Circumferential	6.0 in. (15.2 cm)	30.4 / 50.2% T	300°
9C-001	2-1	Thermal Fatigue	Weld Center Line	Circumferential	3 in. (7.6 cm)	10 / 20% T	0°
	2-2	Thermal Fatigue	Weld Center Line	Circumferential	2 in. (5.1 cm)	28.6% T	90°
	2-3	Thermal Fatigue	Weld Center Line	Circumferential	2.5 – 3 in. (6.4–7.6 cm)	27.1%	270°
9C-002	3-1	Thermal Fatigue	Weld Center Line	Circumferential	3 in. (7.6 cm)	16 / 25.1% T	0°
	3-2	Thermal Fatigue	Weld Center Line	Circumferential	2 in. (5.1 cm)	20.6% T	90°
	3-3	Thermal Fatigue	Weld Center Line	Circumferential	2.5 – 3 in. (6.4–7.6 cm)	16% T	270°

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PWROG Specimen Flaw Data (True State)

PWROG Specimen Flaw Data (True State)						
PWROG Sample ID	**Side UT Applied[1]**	**Crack Type[2]**	**Flaw Thru-wall Depth[3] %, cm., (in.)**	**Flaw Area[4] (cm^2)**	**Flaw Orientation**	**Flaw Length cm. (in.)**
ONP-3-5	CCSS	TF	28% 1.78 cm (0.7 in.)	11.7	Circumferential	6.6 cm (2.6 in.)
OPE-5	CCSS SCSS*	TF	23% 1.63 cm (0.64 in.)	10	Circumferential	6.15 cm (2.42 in.)
MPE-6	CCSS SCSS*	TF	18% 1.5 cm (0.59 in.)	8.8	Circumferential	5.9 cm (2.33 in.)

Notes and Definitions:

*) Denotes side of weld on which flaw is located

1) Denotes from which side of the weld the PA UT was applied; CCSS = centrifugally cast stainless steel, SCSS = statically cast stainless steel
2) TF = thermal fatigue
3) Flaw depth information as determined by Westinghouse
4) Assume rectangular aspect ratio using depth and length information to show potential area available for specular reflections

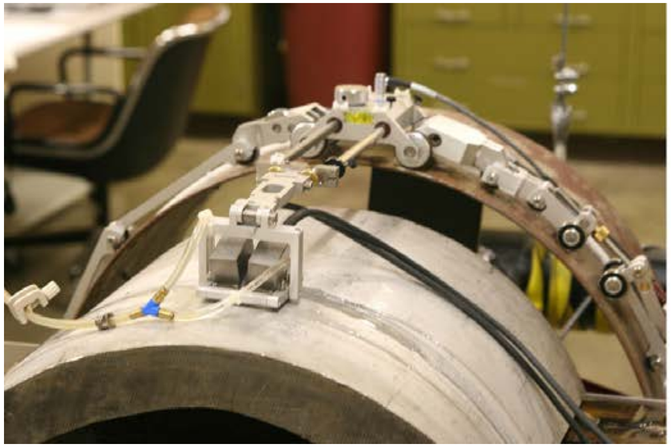
Phased Array Data Acquisition System

Dynaray® PA System

0.2 – 20 MHz

256 channels

Ultravision® software



Scanner arm, probe and coupling configuration

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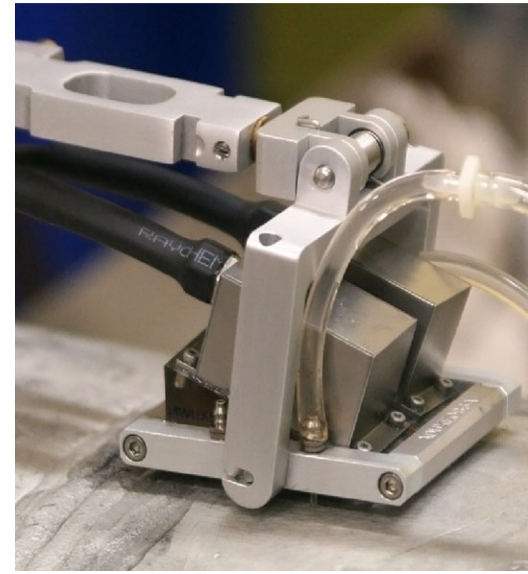
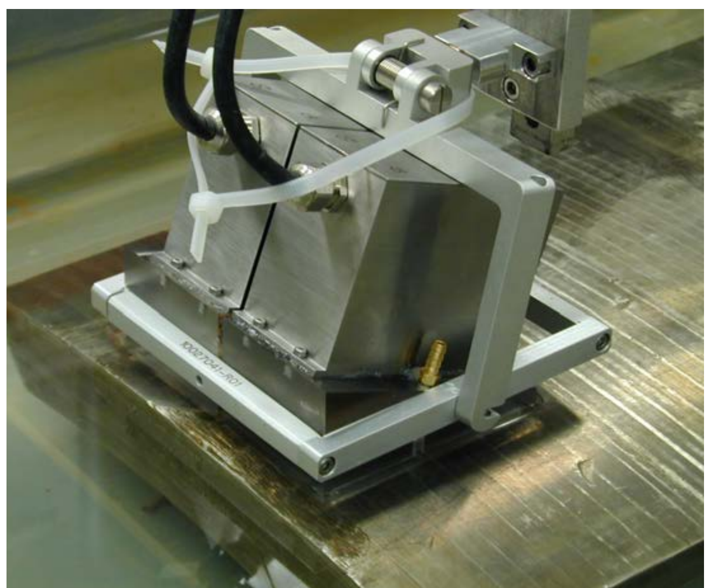
Phased Array Probes Employed:
1.5 MHz TRL, 800 kHz TRL, 500 kHz TRL

800 kHz, 10 x 5, TRL
Active Aperture: 44 mm
Passive Aperture: 22 mm



1.5 MHz, 10 x 3, TRL
Active Aperture: 35 mm
Passive Aperture: 17.5 mm

500 kHz, 10 x 5, TRL
Active Aperture: 65 mm
Passive Aperture: 35 mm



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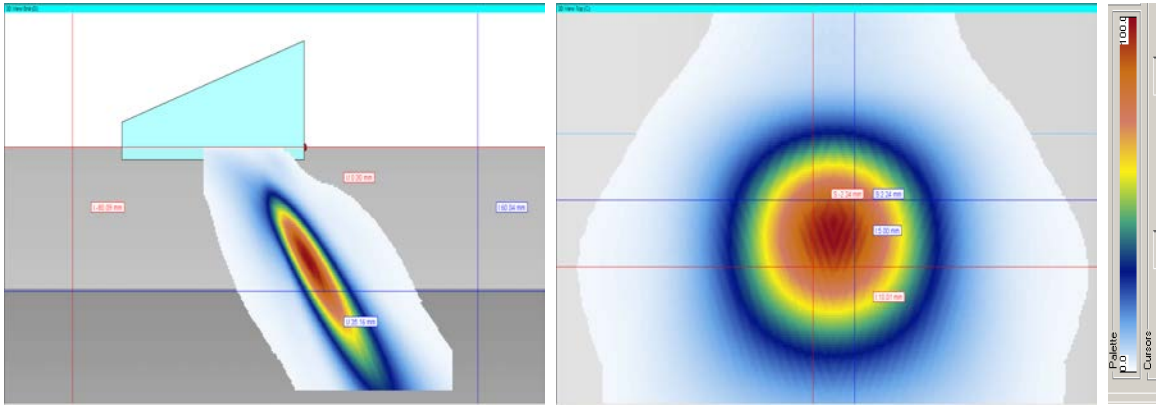
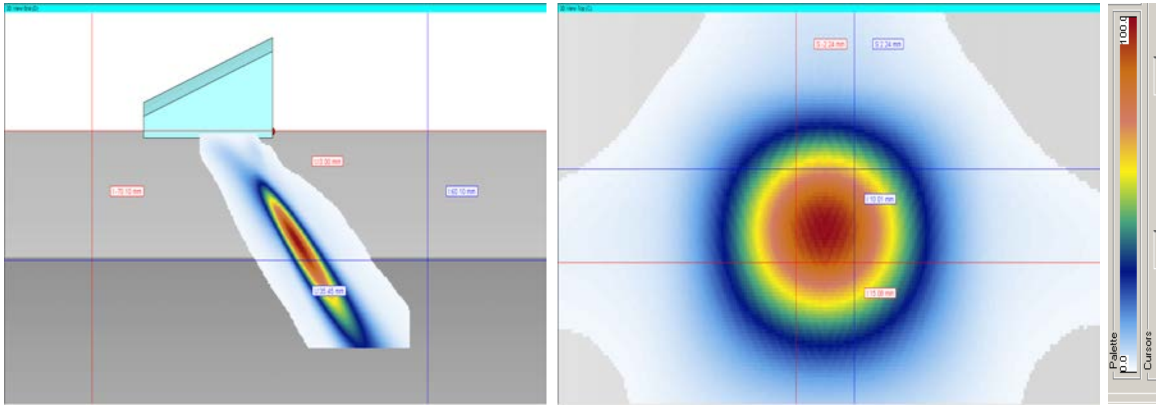
Modeled Sound Field Beam Profiles for Inspecting PZR Surge Line Specimens (-3dB point)



800 kHz TRL, 50 mm half path focus, 7.2 mm x 5.7 mm spot size



1.5 MHz TRL, 50 mm half path focus, 5.0 x 3.8 mm spot size

= - 6dB point

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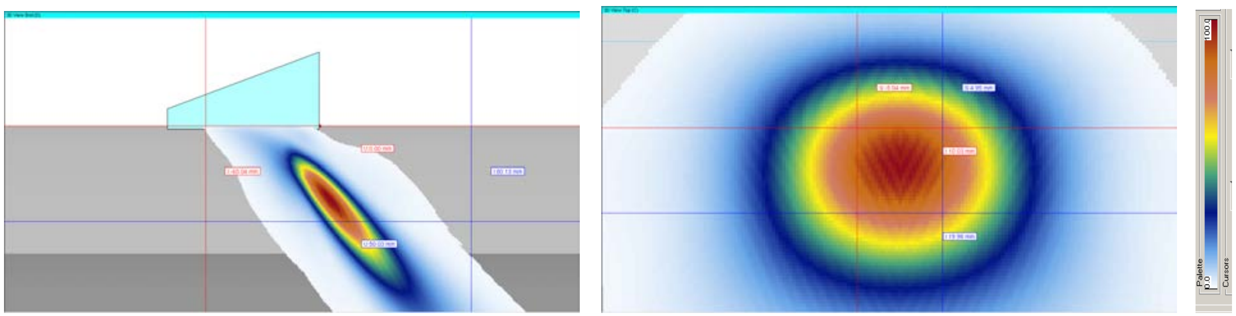
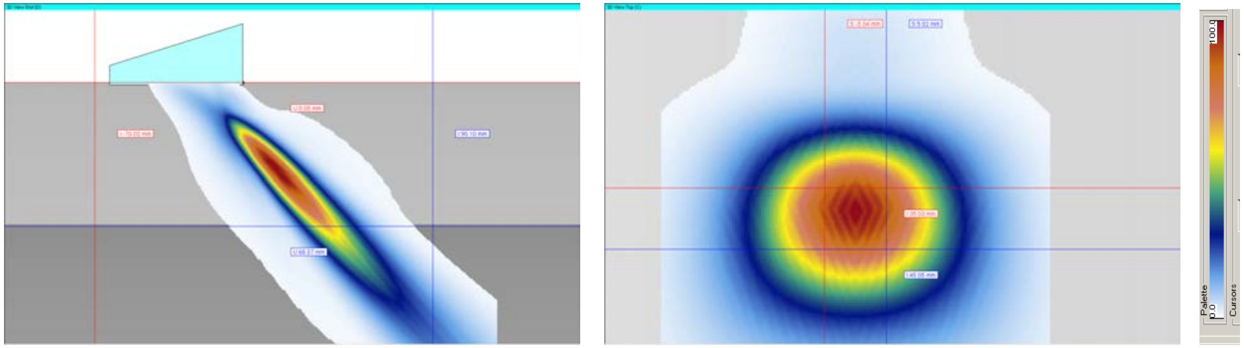
Modeled Sound Field Beam Profiles for Inspection of PWROG Specimens (-3dB point)



500 kHz TRL, 50 mm true depth focus, 10.5 mm x 7.9 mm spot size



800 kHz TRL, focal plane focus, 5.1mm x 3.9 mm spot size

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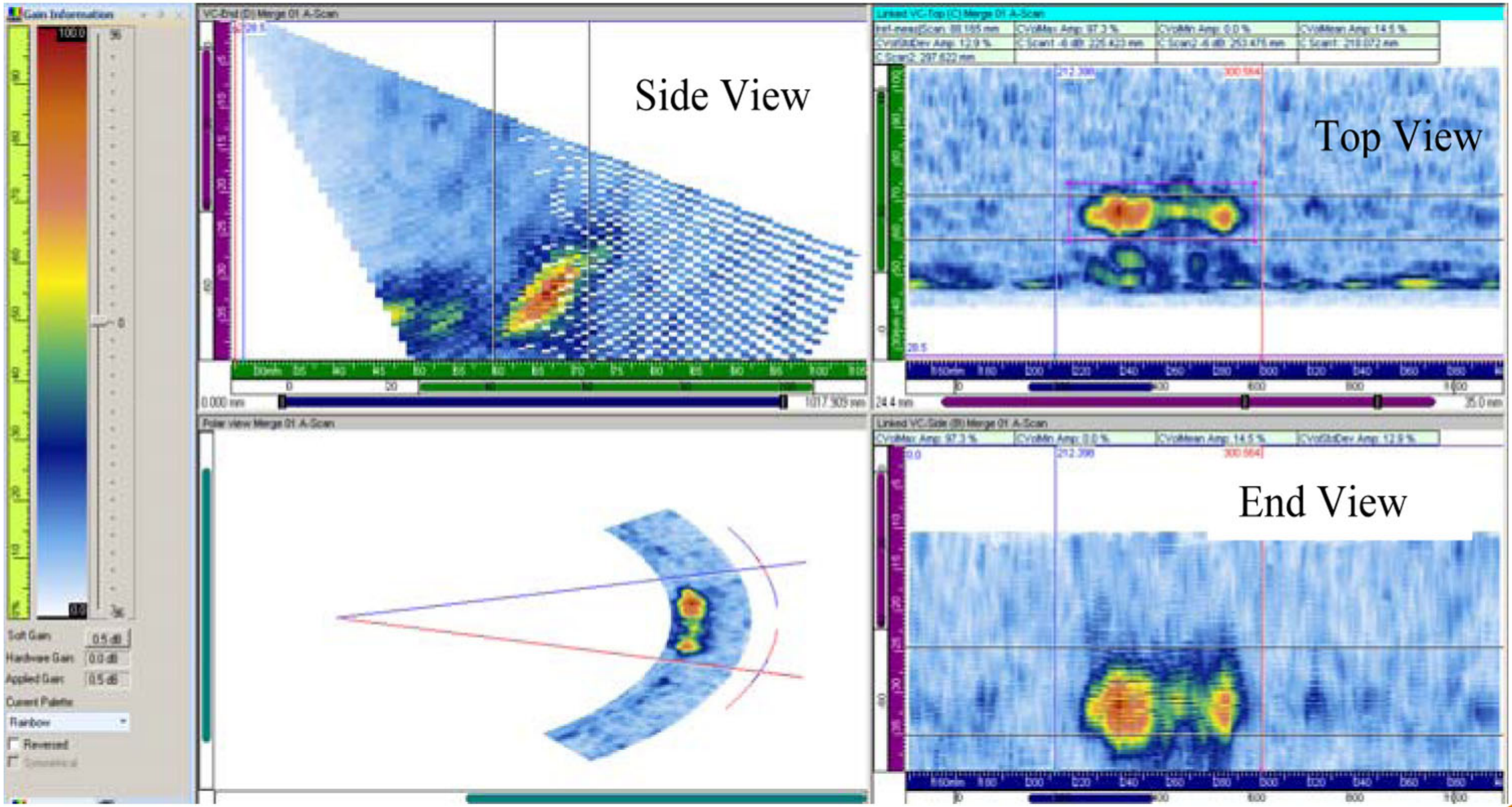
PZR Surge Line Data

Flaw 2-2, 1.5 MHz TRL, 9C-001, From the CCSS Pipe Side



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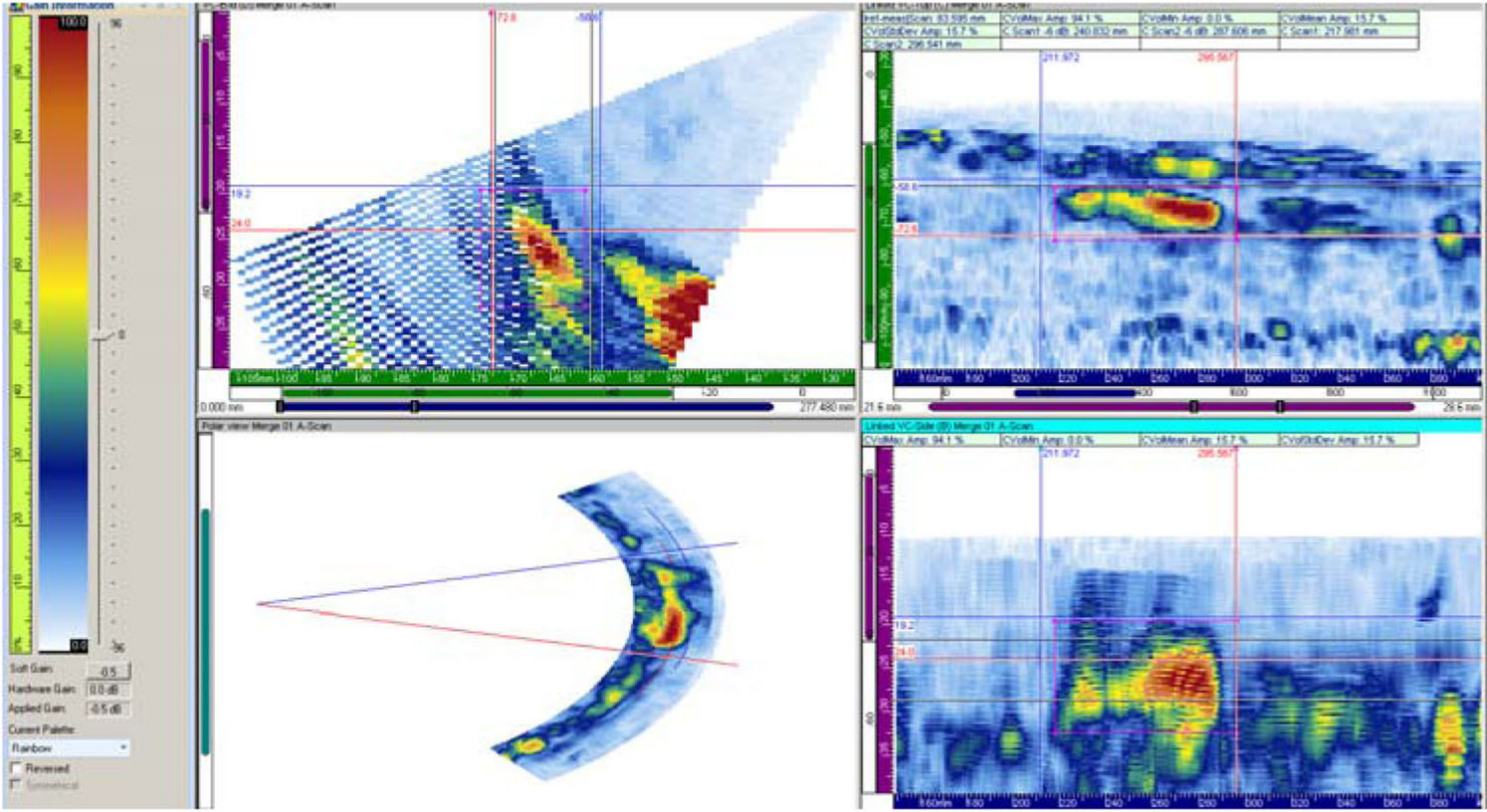
PZR Surge Line Data

Flaw 2-2, 1.5 MHz TRL, 9C-001, From the SCSS Elbow Side



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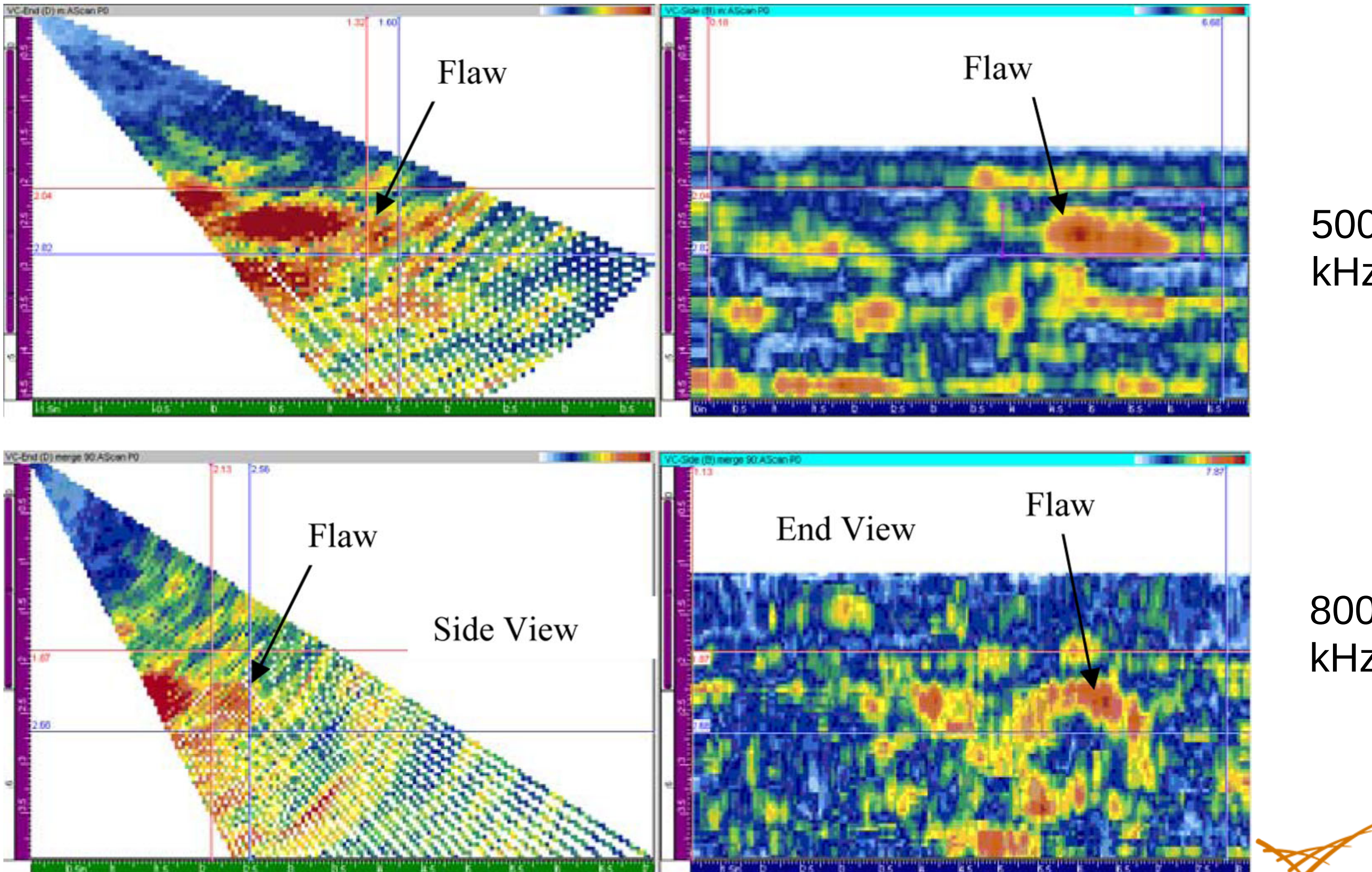
PWROG Specimen Data

OPE-5 Pipe Side (Far Side) PA Data at 500 kHz (top) and 800 kHz (bottom)



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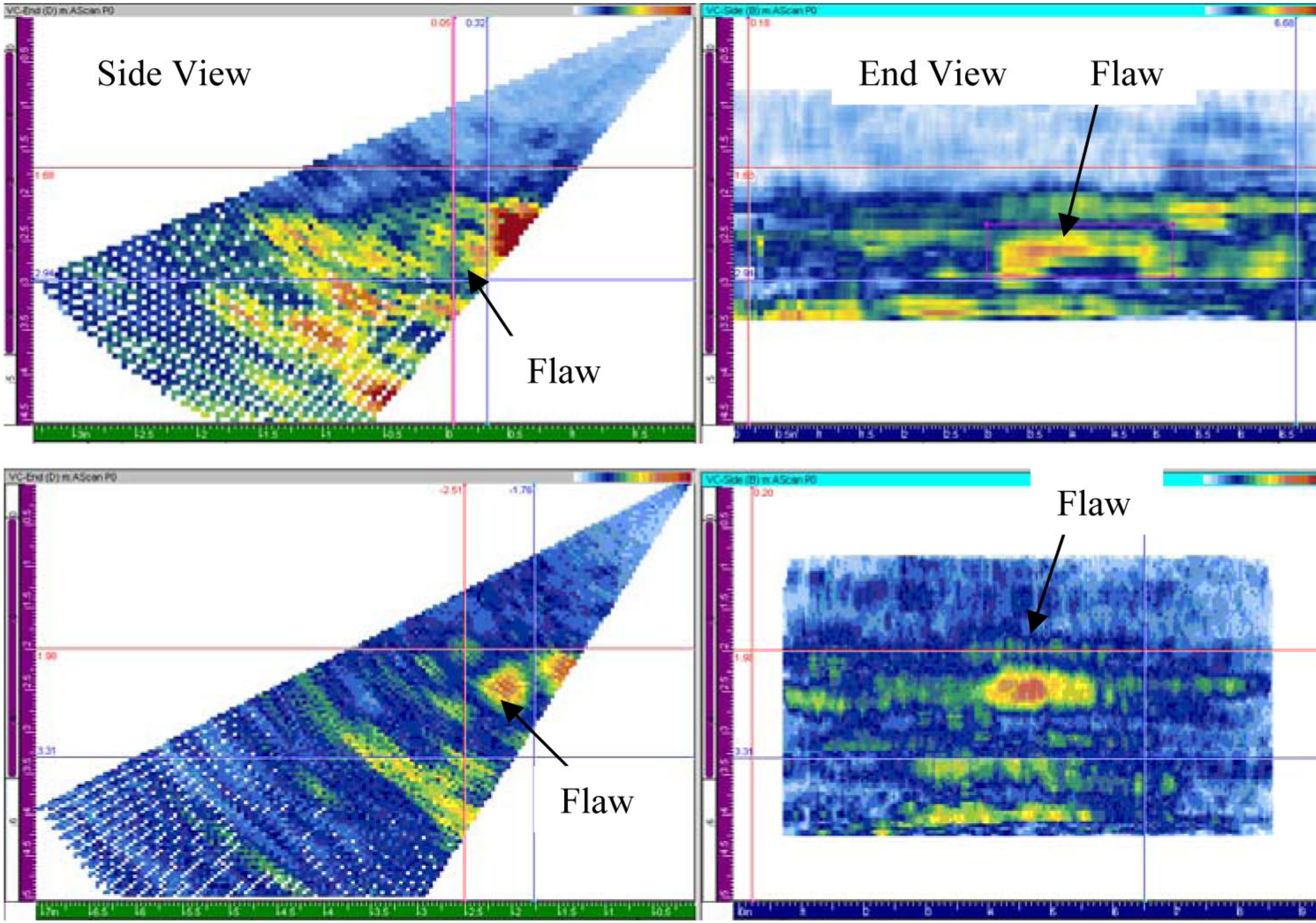
PWROG Specimen Data

OPE-5 Elbow Side (Near Side), PA Data at 500 kHz (top) and 800 kHz (bottom)



500 kHz

800 kHz

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PZR Surge Line Results: Length Sizing Units: mm. (in.)

		800 kHz		1.5 MHz	
Flaw	**True**	**CCSS**	**SCSS**	**CCSS**	**SCSS**
7C-059_1	104 (4.09)	122 (4.80)	88 (3.47)	111 (4.37)	83 (3.27)
7C059_2	51 (2.01)	52 (2.04)	54 (2.13)	37 (1.46)	72 (2.84)
7C059_3	50 (1.97)	56 (2.21)	--	40 (1.56)	--
7C059_4	152 (5.98)	78 (3.07)	132 (5.20)	190 (7.48)	161 (6.34)
9C-001 _1	76.6 (3.02)	89.3 (3.52)	92.3 (3.63)	93.7 (3.69)	83.4 (3.28)
9C-001 _2	51.1 (2.01)	56.4 (2.22)	74.5 (2.93)	64.1 (2.52)	46.8 (1.84)
9C-001 _3	69.7 (2.74)	77.1 (3.04)	69.4 (2.73)	88.4 (3.48)	69.5 (2.74)
9C-002 _1	76.7 (3.02)	72.6 (2.86)	79.9 (3.15)	62.0 (2.44)	79.0 (3.11)
9C-002 _2	50.5 (1.99)	53.2 (2.09)	54.1 (2.13)	53.3 (2.10)	63.3 (2.49)
9C-002 _3	69.7(2.74)	60.8 (2.39)	70.2 (2.76)	55.3 (2.18)	55.3 (2.18)
RMSE	***ASME Code Section XI-acceptable criterion is Length RMSE less than 19.05 mm (0.75 in.)***				
Specimen					
7C-059		**38 (1.50)**	15 (0.59)	**21.1 (0.83)**	17.9 (0.71)
9C-001		9.0 (0.35)	16.3 (0.64)	16.5 (0.65)	4.6 (0.18)
9C-002		5.9 (0.23)	2.8 (0.11)	12.0 (0.47)	11.2 (0.44)

PZR Surge Line Results: Depth Sizing (1.5 MHz) Units: mm. (in.)

Flaw	True	CCSS Side	SCSS Side
7C-059_1	10.9 (0.43)	13.0 (0.51)	12.0 (0.47)
7C-059_2	9.3 (0.37)	12.0 (0.47)	10.0 (0.39)
7C-059_3	9.3 (0.37)	13.5 (0.53)	--
7C-059_4	15.6 (0.61)	16.0 (0.63)	11.0 (0.43)
9C-001_1	6.4 (0.25)	10.6 (0.42)	7.9 (0.31)
9C-001_2	8.9 (0.35)	15.4 (0.61)	8.0 (0.32)
9C-001_3	8.3 (0.33)	13.3 (0.52)	7.2 (0.28)
9C-002_1	7.5 (0.30)	7.4 (0.29)	10.5 (0.41)
9C-002_2	6.3 (0.25)	6.6 (0.26)	4.4 (0.17)
9C-002_3	4.8 (0.19)	5.3 (0.21)	5.1 (0.21)
RMSE **Specimen**	***ASME Code Section XI-acceptable criterion is Depth RMSE less than 3.81 mm (0.125 in.)***		
7C-059		2.7 (0.11)	2.8 (0.11)
9C-001		**5.3 (0.21)**	1.2 (0.047)
9C-002		0.35 (0.014)	2.1 (0.083)

PWROG Specimen Results: Length Sizing

PWROG Specimen	Side	Length, mm (inch) True State Length	Length, mm (inch) 500 kHz	Length, mm (inch) 800 kHz	Reported Depth (%)
ONP-3-5	CCSS	66 (2.60)	ND*	ND*	25
OPE-5	CCSS	61 (2.40)	42 (1.66)	74 (2.91)	23
	SCSS	61 (2.40)	60 (2.37)	43 (1.69)	23
MPE-6	CCSS	59 (2.32)	47 (1.85)	36 (1.42)	18
	SCSS	59 (2.32)	34 (1.34)	62 (2.44)	18

*ND = Not Detected

ASME Code Section XI-acceptable criterion is Length RMSE less than 19.05 mm (0.75 in.)

Length RMSE: 500 kHz = 16.8 mm (0.66 in.)

Length RMSE: 800 kHz = 16.0 mm (0.63 in.)

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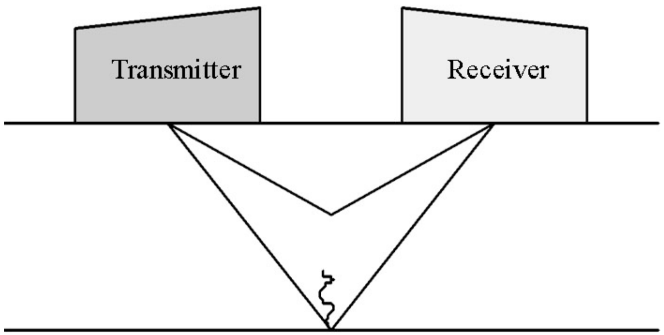
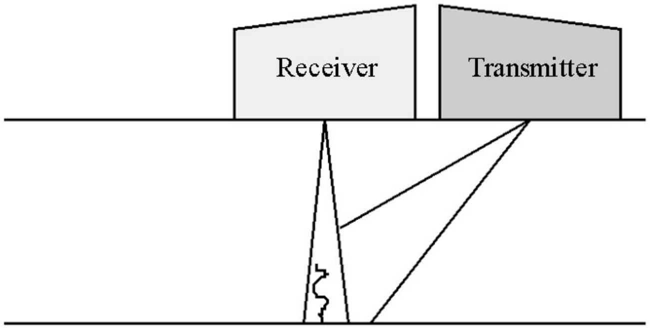
Additional Investigations – Delta Technique



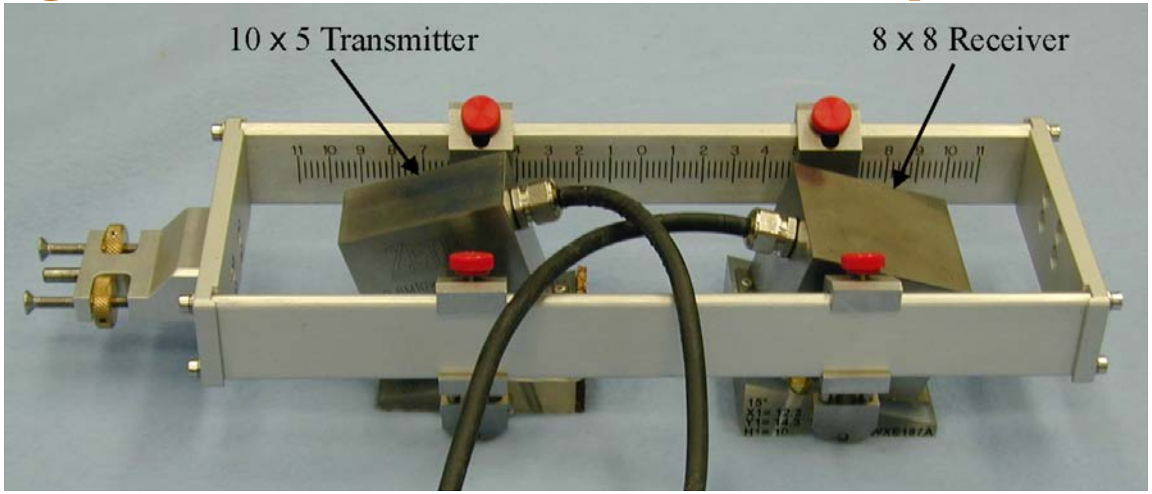
Receiver positioned directly over flaw

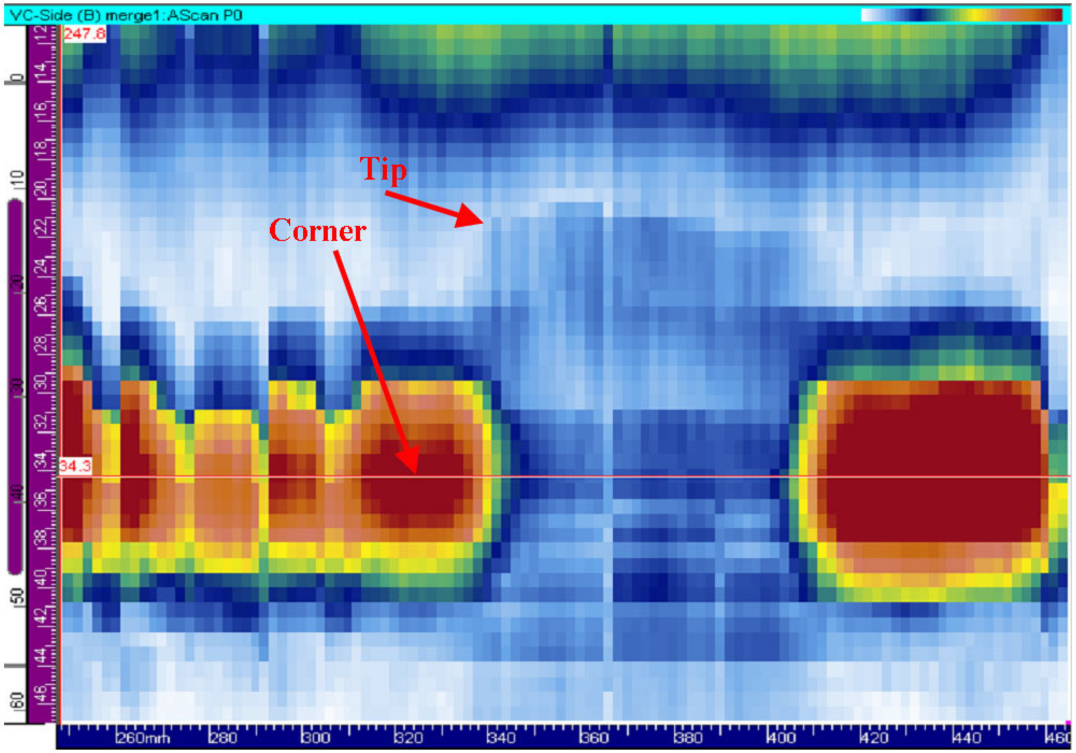
Probes positioned equidistant from center of flaw

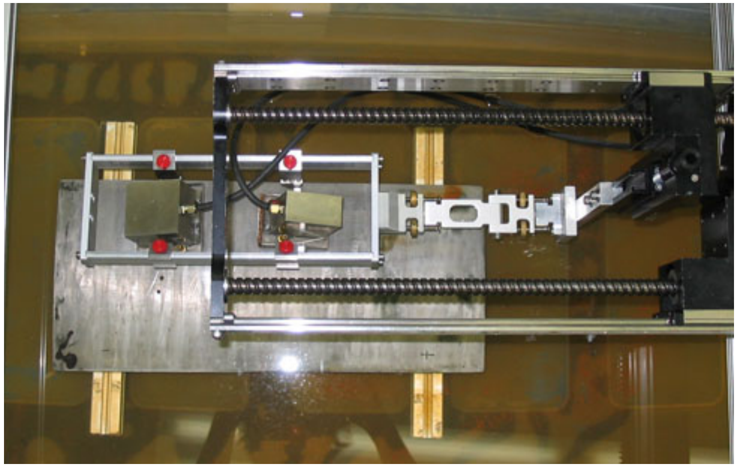


Additional Investigations – Delta Technique

800 kHz Delta Approach:
Weak tips coupled with
loss of back wall echo







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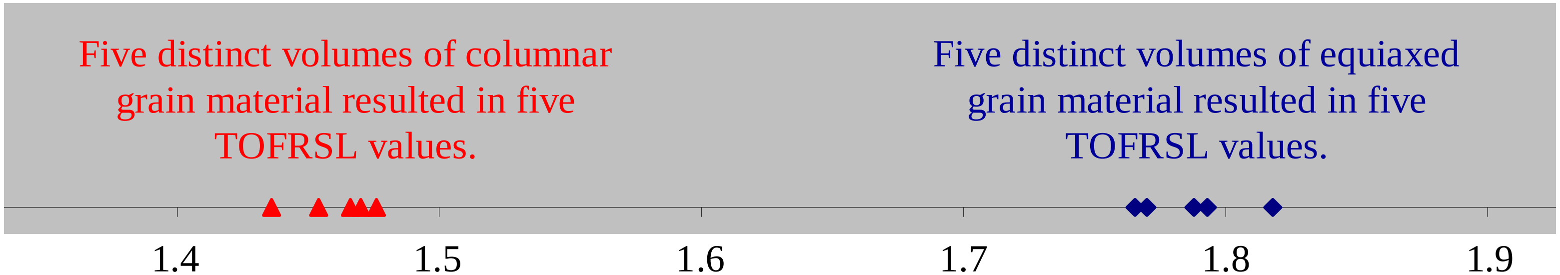
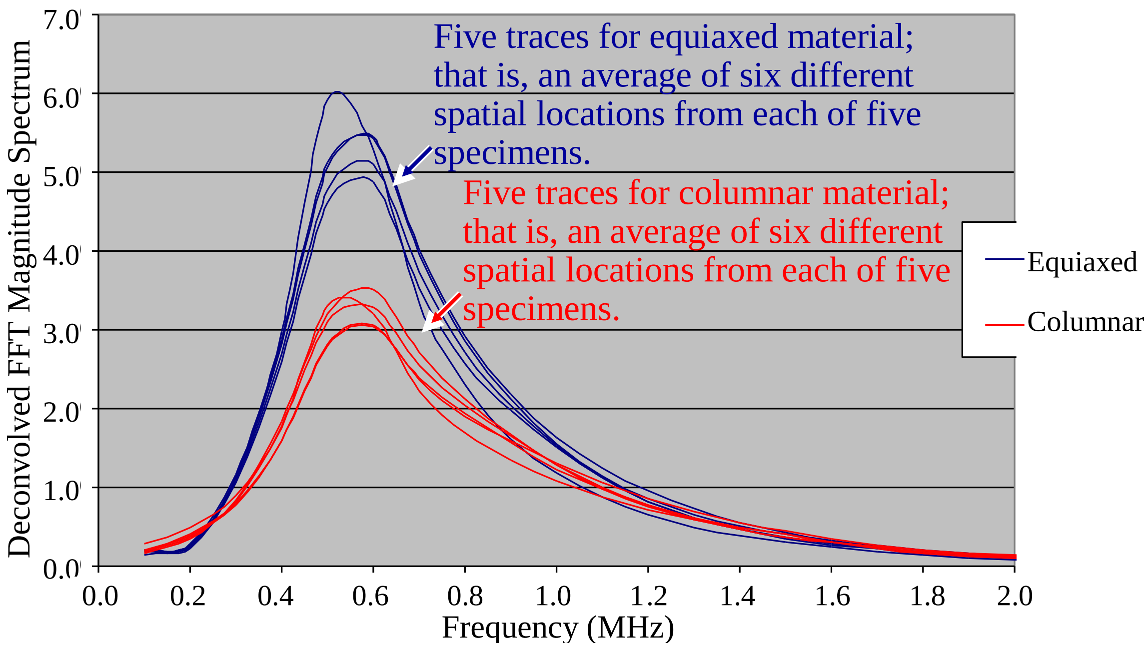
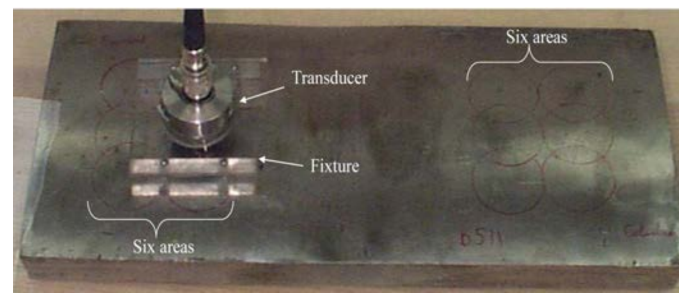
Additional Investigations – In-Situ, OD Microstructural Characterization of CASS



500 kHz

Time-of-Flight Ratio Shear Wave to Longitudinal Wave Measurements





10 Spatially Averaged, Deconvoluted FFT Magnitude Spectra Illustrating Difference between Data Obtained from Equiaxed Grain and Columnar Grain Microstructures

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Conclusions from PA Work on CASS

- PA examinations of coarse-grained CASS components remain a challenge, but provide promise for:
  - Improved detection of circumferentially oriented flaws
  - Accurate length sizing of circumferentially oriented flaws
- Removal of weld crowns to allow scanning over the weld may allow
  - Peaking of ultrasonic signals
  - Specimen profiling in critical areas
  - Enhanced detection
  - Better depth sizing of flaws

Conclusions from PA Work on CASS

- As expected, signal to noise ratios vary:
  - PWROG Specimens: SNR ≈ 4 – 9 dB
  - Surge Line 7C-059: SNR ≈ 11 – 19 dB
  - Surge Line 9C-001 and 2: SNR ≈ 17 – 23 dB

- For smaller bore piping (PZR Surge-lines where nominal wall thicknesses range from 1.2" to 1.7") PA inspection capability for both detection and sizing of circumferentially oriented thermal fatigue cracks, has been shown to be very effective over the range of 800 kHz to 2 MHz.

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Future Work

- Continue sound field mapping of various CASS microstructures as a function of:
  - Incident angle, Inspection frequency, Focal depth, Modality, etc.
  - Provide validation data for theoretical modeling results
- Continue refinement of in-situ microstructural characterization methods
  - Measure acoustic backscatter as a function of angle
  - Investigate mixed and layered microstructures
- Complete assessment of casting fabrication processes and their impact on resultant microstructures
- Continue to conduct confirmatory research of advanced signal processing methods, enhanced transducer/probe design, and other alternatives for improved detection and sizing in CASS materials

Questions

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ZETEC

DYNARAY™

HIGH-PERFORMANCE PHASED ARRAY UT

2nd Int. CASS Workshop,

Seattle (WA), 15-16 June 2009

DYNARAY™

As the leading supplier of phased array UT inspection solutions for the power generation industry, Zetec's objective is to:

» Set a new ***phased array UT standard*** for the ***next 5 years***

» Put emphasis on ***performance,*** "no compromise" design

» Cover a wide range of ***challenging inspections***

» Support ***advanced phased array UT techniques***:

- 2D matrix arrays
- Inspection of attenuating materials (DMW, CASS, …)
- Inspection of complex geometries

» Offer high system integrity and ***reliability***

DYNARAY™

- » Configuration : up to ***256 phased array beam forming channels***, in Tomoscan III housing
- » Up to ***4 Hypertronics*** connectors, compatible with existing probes
- » ***16 conventional UT*** channels available through ***Lemo00*** adapter
- » ***Modular concept***, allowing for "reduced configurations and "upgrading" :
  - Non-multiplexed : 64/64PR
128/128PR
256/256PR
  - Multiplexed: 64/256PR

DYNARAY™ - Specification

- Up to 4096 different focal laws
- 16-bit amplitude resolution of phased array signal
- High data throughput: up to 20 MB/s
- Digitization frequency: up to 100 MHz
- Bandwidth from 0.20 to 25 MHz (-6 dB)
- Excitation pulse : up to 200 V (on 50 Ω load)
- Pulse width : up to 1,000 ns
- A-scan length: up to 256,000 points
- Linear and Logarithmic mode
- Dynamic Depth Focusing
- Automatic self-diagnostics
- Code related diagnostics (scheduled)
- Full Matrix Capture: individual A-Scan storage (scheduled)

DYNARAY™ - Availability

» ***May 2008 :***

– Non-multiplexed : 64/64PR
128/128PR
256/256PR

» ***December 2008 :***

– Multiplexed: 64/256PR

» ***27 units sold*** up to now, in USA, Canada, Europe and Asia

» Early 2009, PDI qualified for RPV welds (Supplements 4 and 6)

UltraVision® 3 – Design Objectives

UT & Phased Array software platform, replacing:

» UltraVision®1.1

» Zetec Advanced PA Calculator

» 3D Modeling & Visualization Package

Complete UT & Phased Array inspection management package, allowing for:

» Probe design

» Inspection technique development

» Inspection coverage and capability assessment

» Data acquisition

» Data analysis

» Reporting

UltraVision® 3 – Key Features

» User Interface ***similar to UltraVision® 1.1***
➔ easy transition for experienced operators

» ***Full 3D capability*** for inspection development, data visualization and analysis

» "Native" support of ***complex geometries***

» Large ***data files (up to 20 GBytes)***

» Support for ***position dependant focal law groups***

» Controls DYNARAY (other hardware scheduled in 2009)

» ***Multi-language*** support

» ***Open architecture***, using UltraVision® SDK (scheduled)

DYNARAY™ & UltraVision® 3

Key features for inspection of Cast Stainless Steel Components:

»High-Performance Beam Forming, using 2D Matrix Arrays

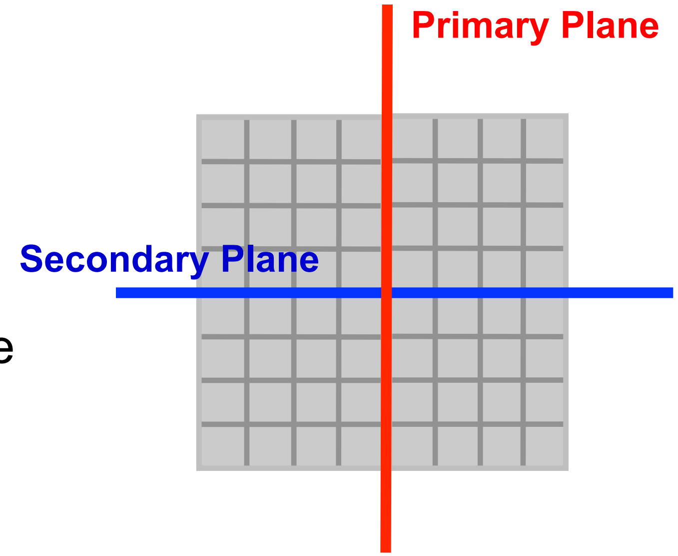
»Low-Frequency Operation

»Full 3D Capability

»Inspection on Complex Surface

2D Matrix Arrays - Principles

» In ***primary and secondary planes***, beam steering, focusing and linear scanning can be performed electronically



- Primary steering capability : refracted angle
- Secondary steering capability : skew angle

» The 2-plane steering capability can be used to ***vary refracted angle and skew angle*** of the ultrasonic beam ***simultaneously***

» In practice, ***between 8 and 16 elements are required*** in each plane to combine adequate steering capability and sufficient active aperture (acoustic energy)

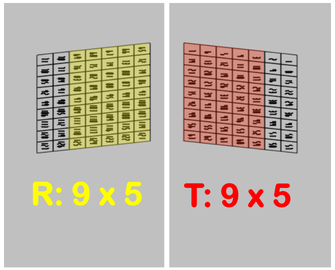
2D Matrix Arrays – Weld Inspection

- Examination of CS and SS piping welds (T = 50 mm), “in lieu of RT”, for both ***circumferential*** and ***axial flaws***

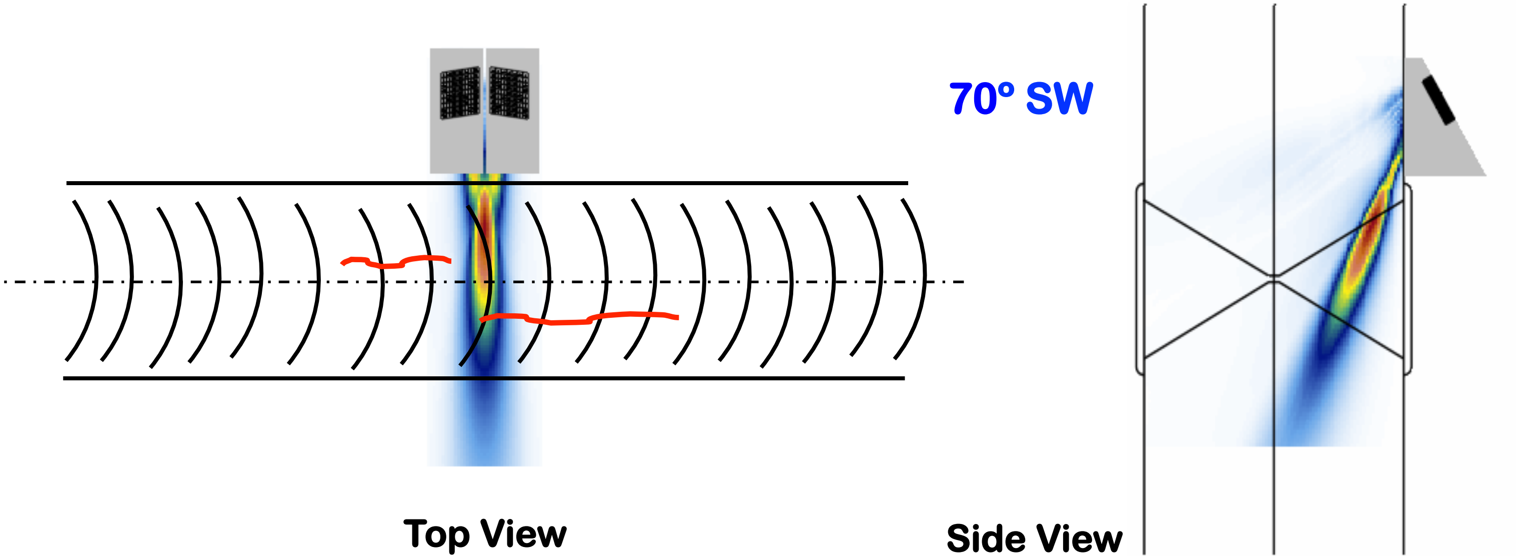
- Proposed inspection technique:
  - 2.25 MHz, dual 2D matrix array probe, 2 x 63 elements
  - Sectorial scanning from 40° to 70° SW
  - Skewing from “nominal - 60°” to “nominal + 60°”
  - ***Multiple line scan*** using ***two probes,*** on either side of the weld

2D Matrix Arrays – Weld Inspection

Circumferential flaws, nominal beam orientation

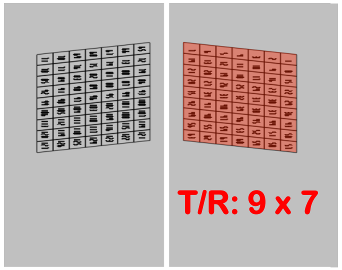


- Dual array (separate T/R)
- Active aperture: 2 x (9 x 5) elements.
- Refracted angle : 40° to 70° SW, resolution 1°
- Skew angle : nominal (90°)
- 31 focal laws (beams)

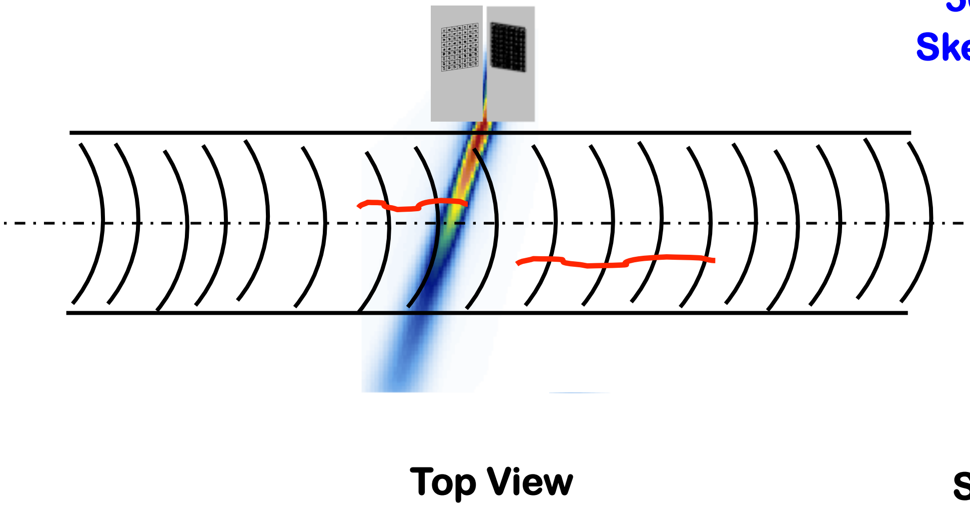


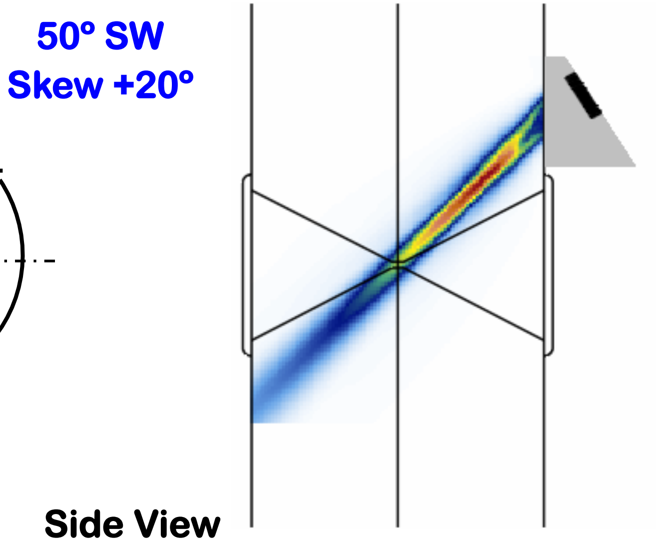
2D Matrix Arrays – Weld Inspection

Circumferential flaws, optional skewed beams



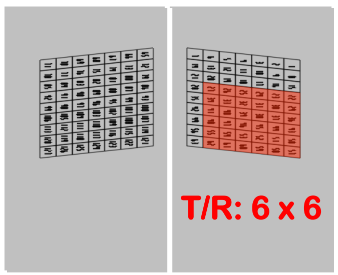
- Single array (T/R)
- Active aperture: 9 x 7 elements
- Refracted angle : 40° to 70° SW, resolution 1°
- Skew angle : nominal ± 20° (70°, 110°)
- 62 focal laws (beams)



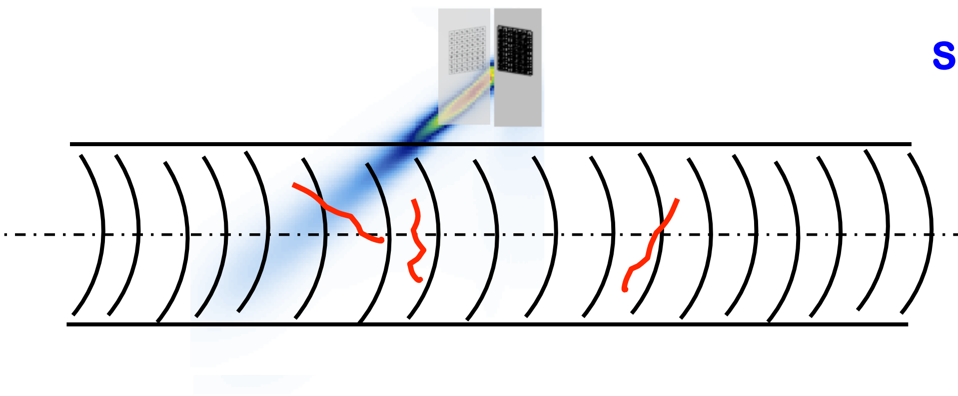


2D Matrix Arrays – Weld Inspection

Axial flaws, various skewed beams

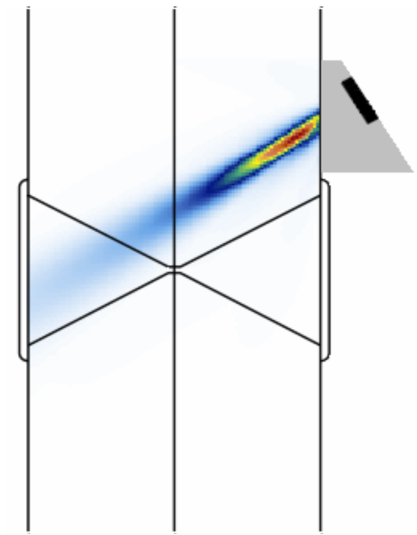


- Single array (T/R)
- Active aperture: 6 x 6 elements
- Refracted angle : 40° to 60° SW, resolution 2°
- Skew angle : nominal ± 35°,± 45°,± 55°
- 66 focal laws (beams)



Top View

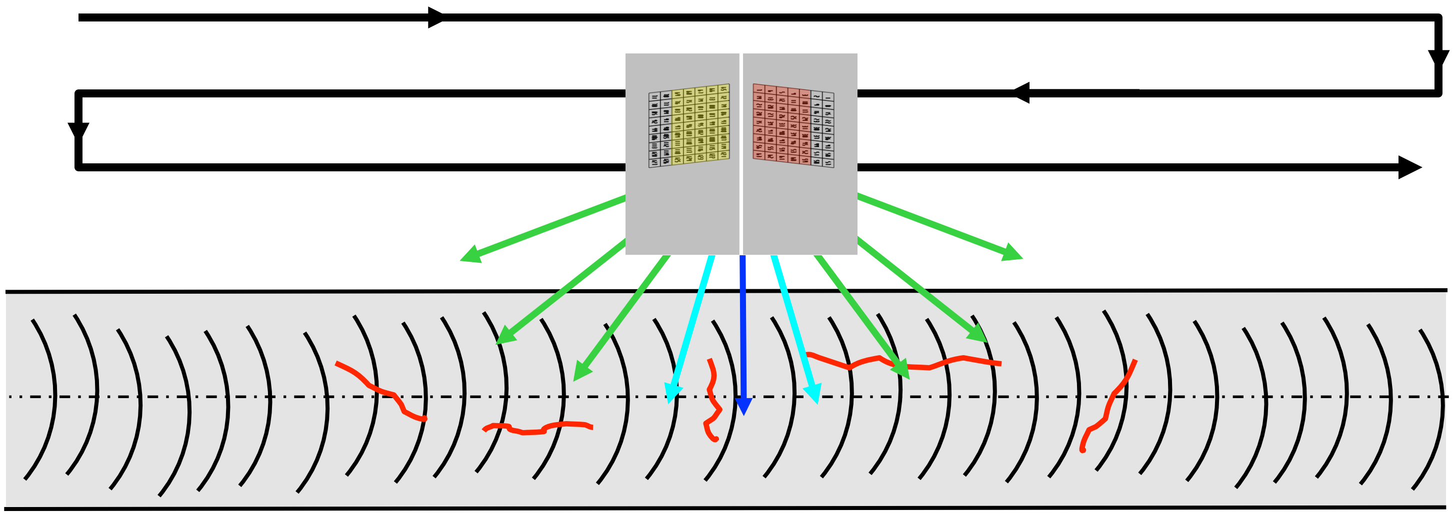
50° SW
Skew +55°



Side View

2D Matrix Arrays – Weld Inspection

Summary : all flaws, all beam orientations



2.25 MHz, 2D array, 40º- 70º SW

skews: nominal (90º), ± 20º, ± 35º, ± 45º, ± 55º (2 x 159 focal laws)

Complete Weld inspection in less than 15 minutes !!!

Comparison: typically **6 hours for conventional UT**,
typically **2 hours for 3 probe PA technique**

2D Matrix Arrays – Conclusions

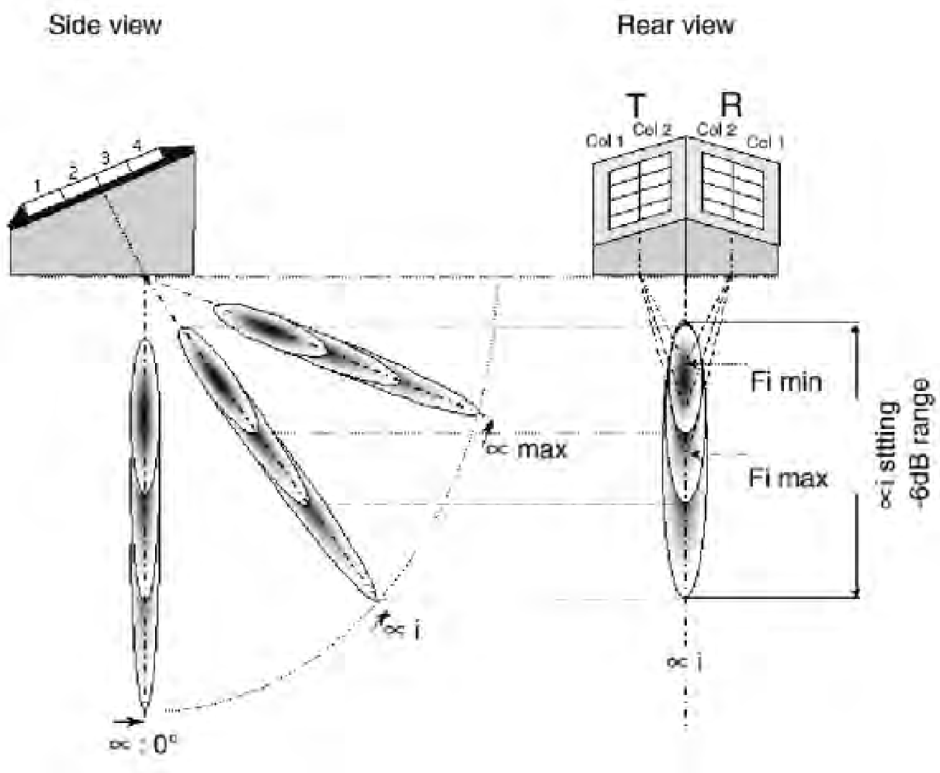
» Using 2D matrix arrays with a ***sufficient number of elements*** allows for ***adequate steering capability*** in both planes and ***sufficient active aperture*** (acoustic energy) to efficiently detect cracks with various orientations

DYNARAY™ - Low-Frequency Operation

DYNARAY offers all features required to ***efficiently drive low-frequency arrays***:

- Bandwidth from 0.20 MHz to 25 MHz (at -6 dB)
- Excitation pulse 200 V (at 50 Ohm)
- Pulse width up to 1,000 ns
- High PRF, even for long pulses at 200 V

Cast SS Weld Inspection - Principles

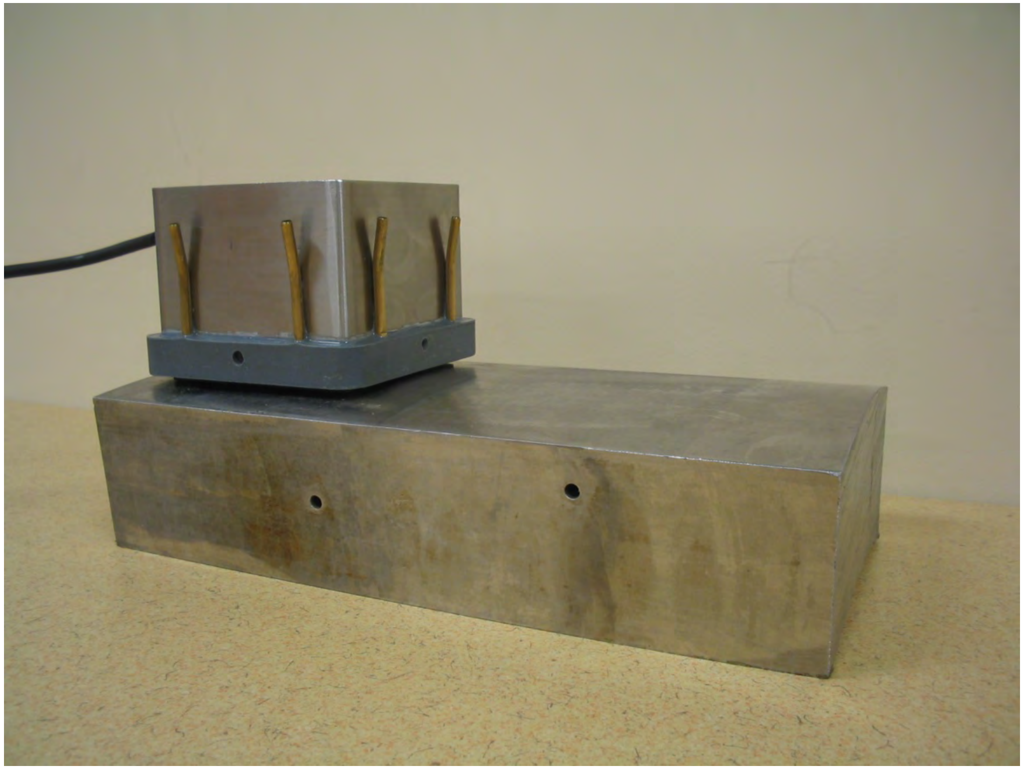


Inspection solution : low-frequency TRL PA

Cast SS Weld Inspection - Principles

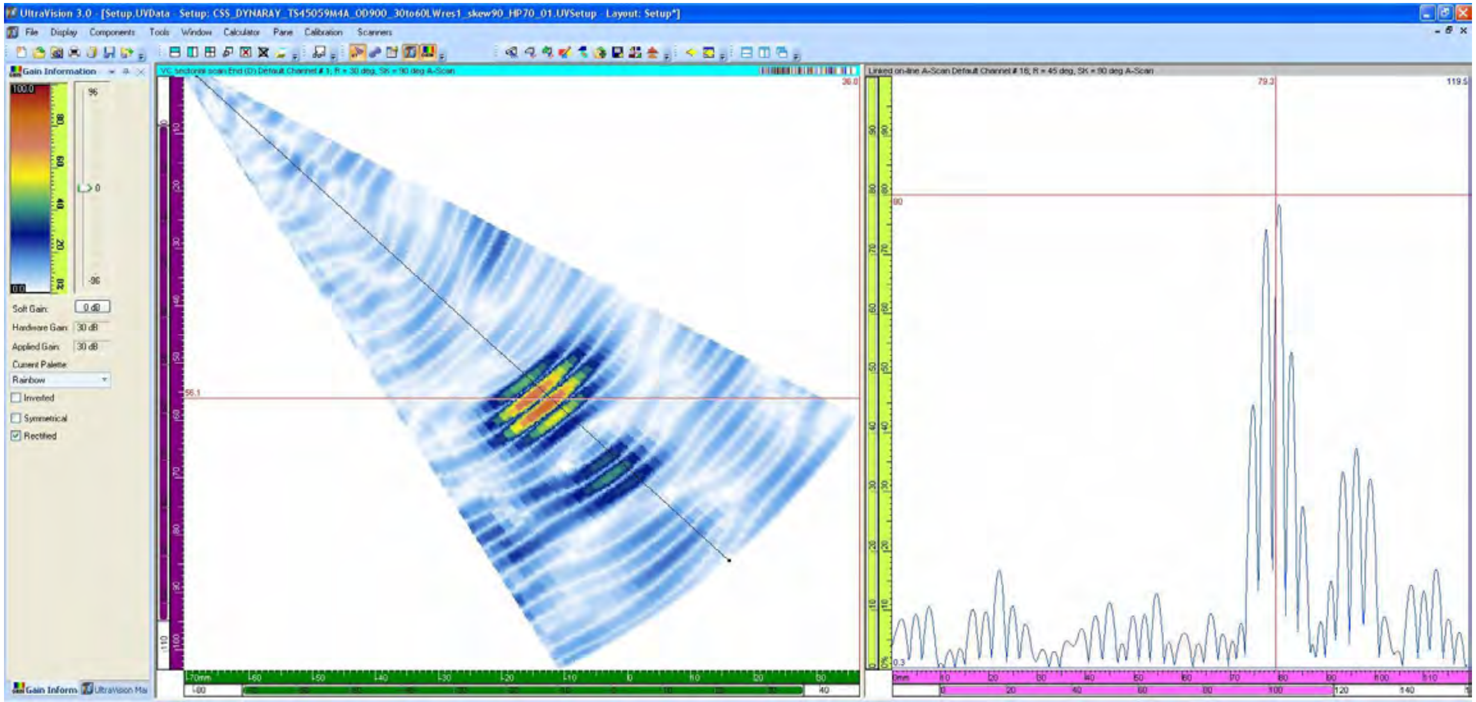
- » ***Transmit-Receive*** configuration yields ***better sensitivity, SNR***, due to convolution of beams (reduces ultrasonic noise level)
- » TR***L*** probe generates ***compression waves,*** less affected by anisotropic structure than SV waves (reduces attenuation, beam distortion and local propagation variations)
- » ***Low frequencies (0.5 – 1.5 MHz),*** for reduced attenuation
- » Use of ***large bandwidth*** probes : reduces attenuation and effect of low-pass filter
- » ***2D Phased Array technology*** allows for :
  - – ***Optimized focusing***, at different depths, improves sensitivity in the near-surface and intermediate regions, and may improve flaw sizing and characterisation
  - – ***Optimized beam steering***: capability to generate beams at different refracted angles and different skew angles will improve detection capability

Cast SS Weld Inspection - Validation



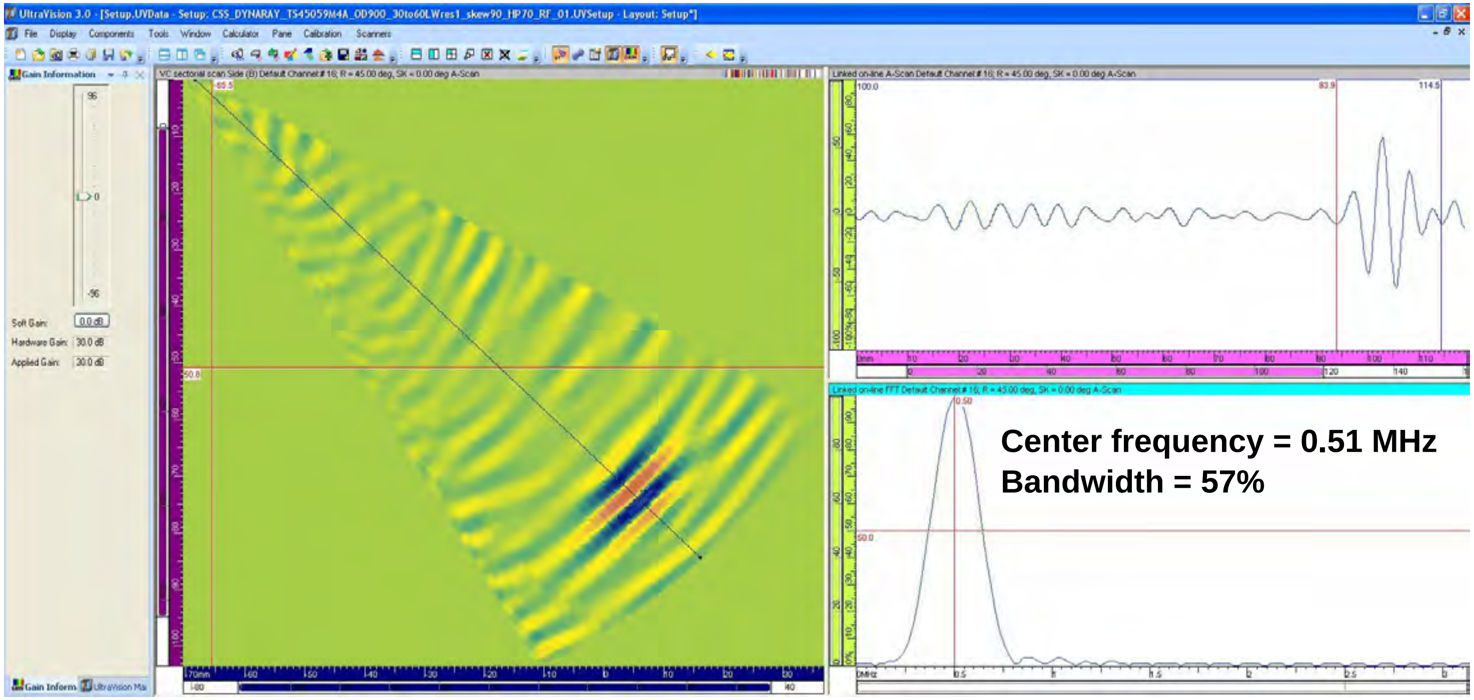
Dual 2D array probe, 0.5 MHz (Courtesy of PNNL)
on SCSS Calibration block MU-6 (Courtesy of EPRI)

Cast SS Weld Inspection - Validation



45°LW beam, SDH at 3T/4 in SCSS Calibration block MU-6

Cast SS Weld Inspection - Validation

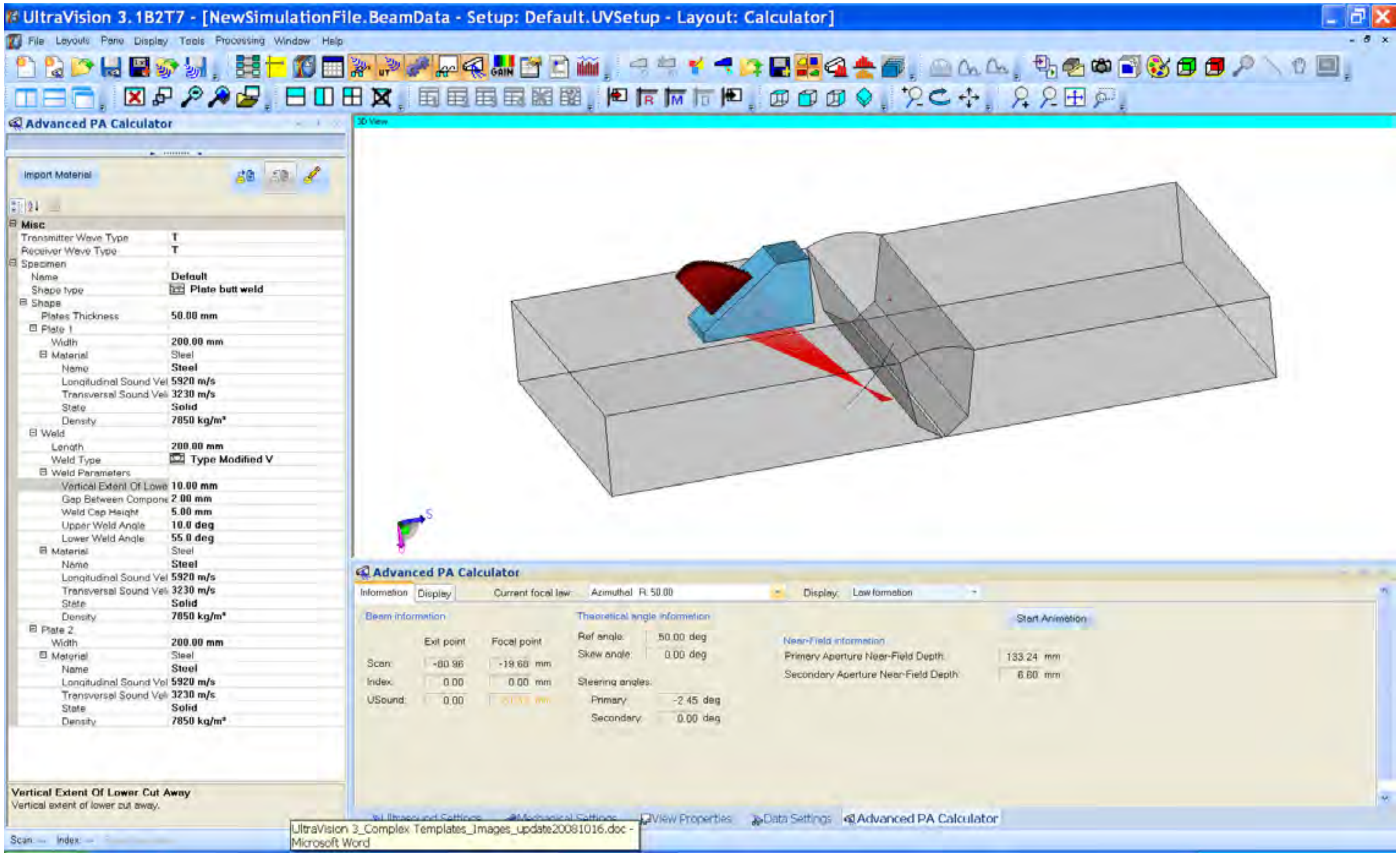


45°LW beam, Corner reflection in SCSS Calibration block MU-6

UltraVision® 3 – Full 3D Capability

UltraVision® 3 offers the necessary tools for ***phased array beam forming*** and ***3D UT data visualisation*** in complex components

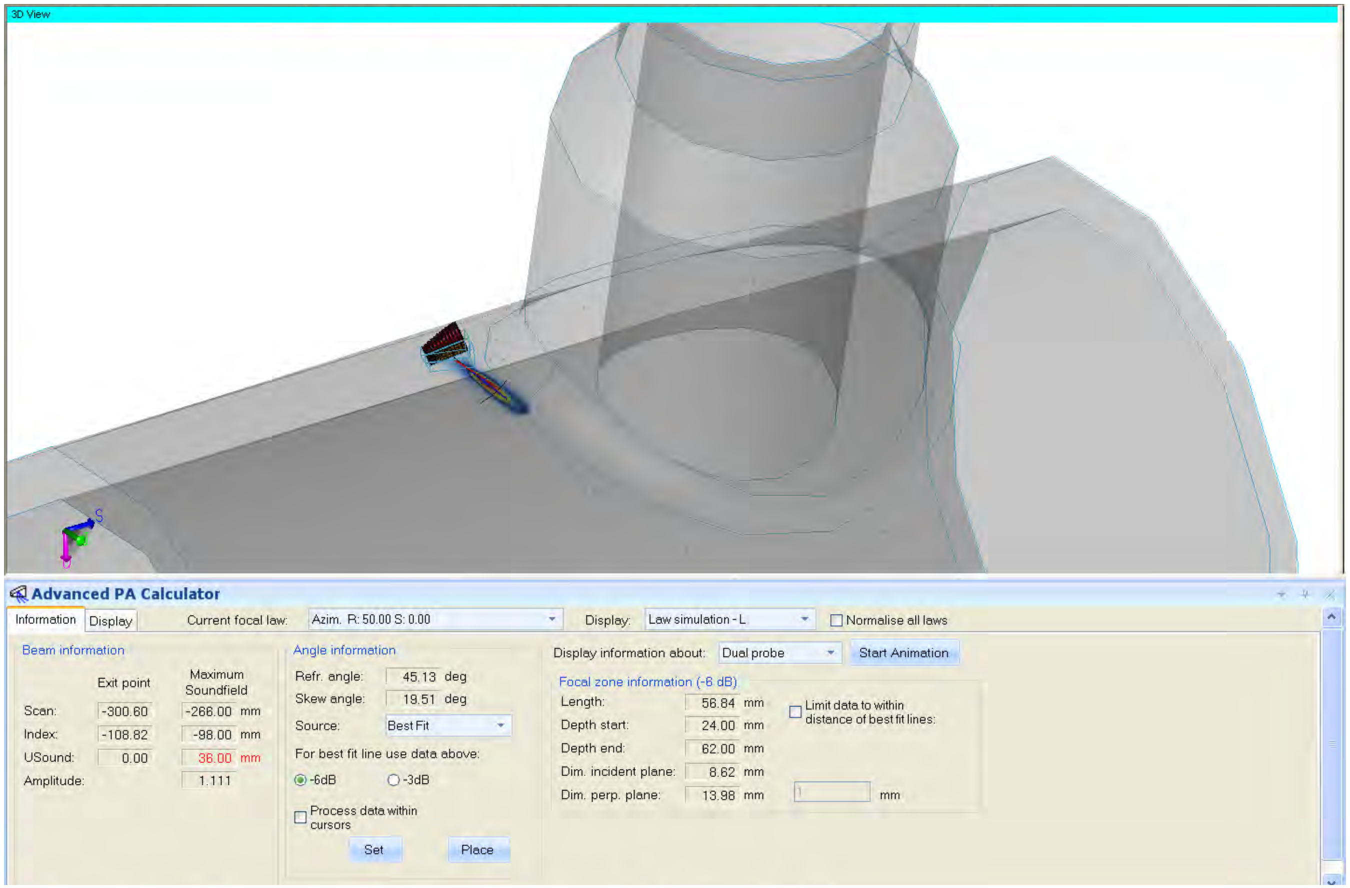
UltraVision® 3 – Full 3D Capability



Support of pre-defined weld configurations,

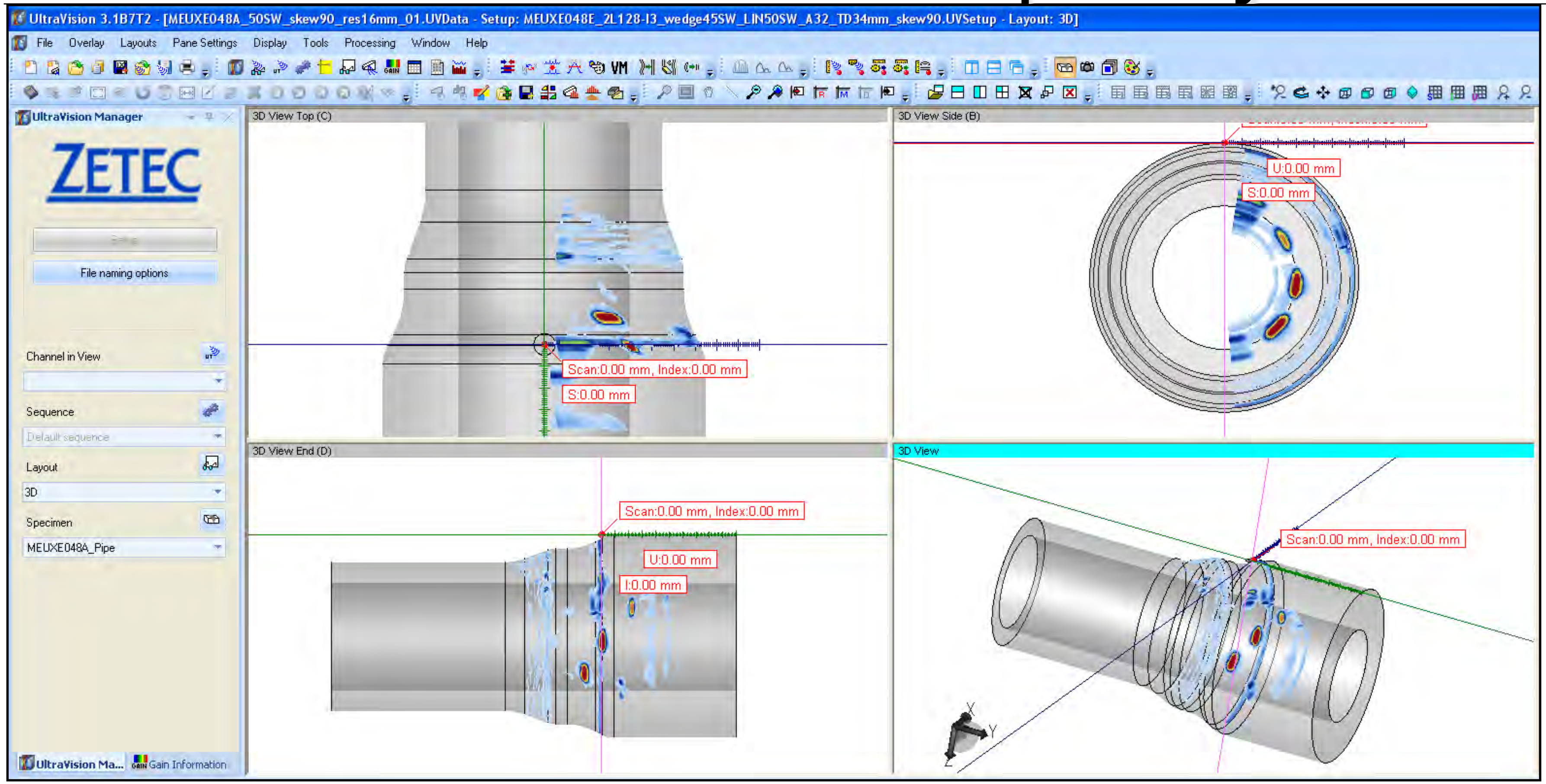
with operator adjustable parameters

UltraVision® 3 – Full 3D Capability



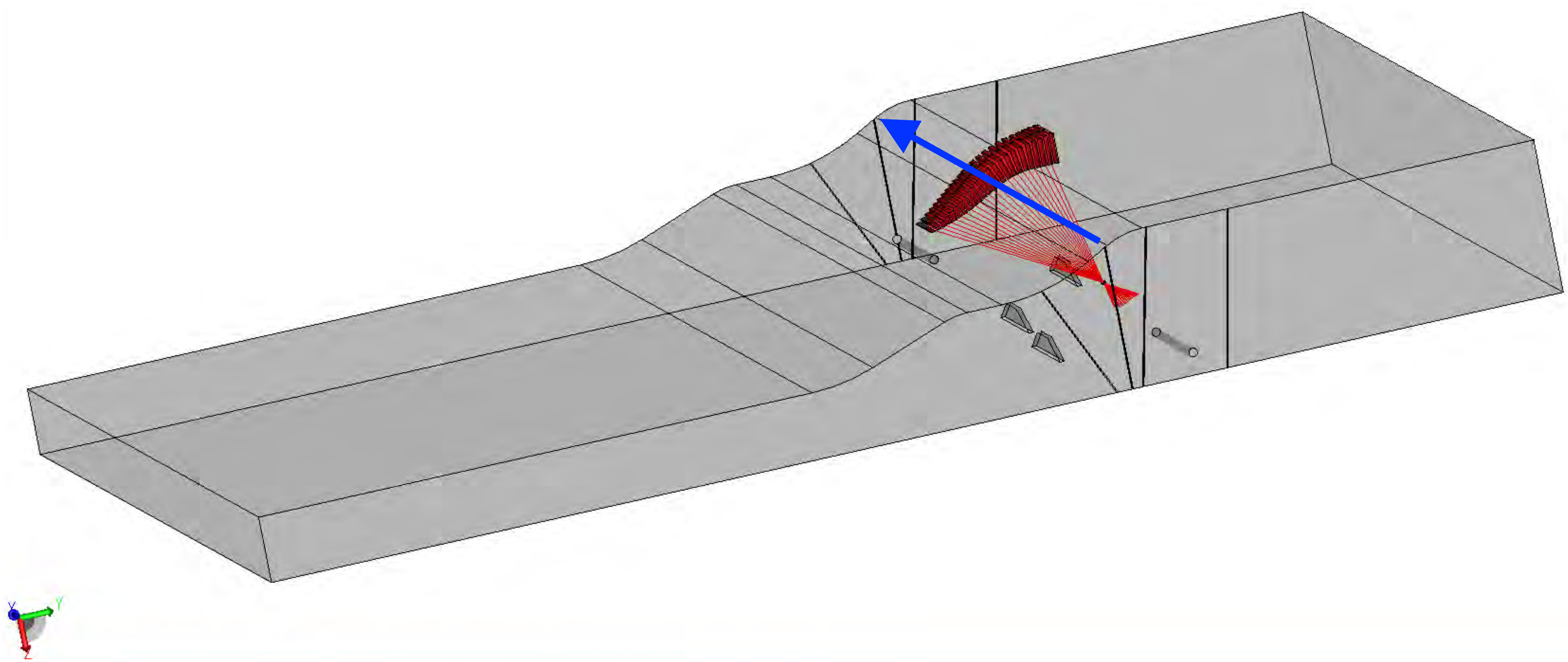
Acoustic beam simulation for single and dual 2D matrix arrays, in custom components with complex geometry

UltraVision® 3 – Full 3D Capability



3D UT visualisation of phased array UT data
in custom specimen with complex geometry

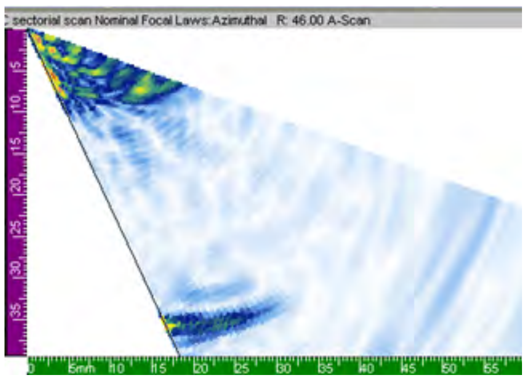
Complex Surface – Flexible Array

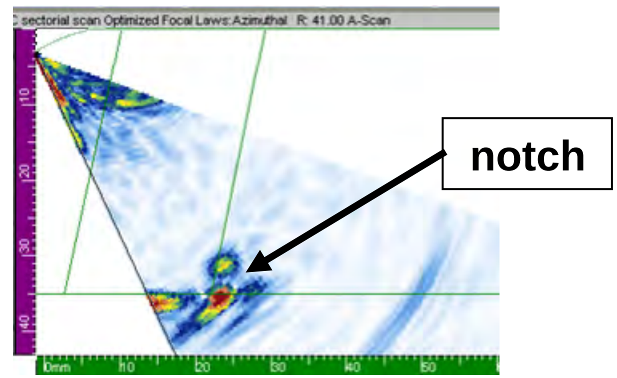


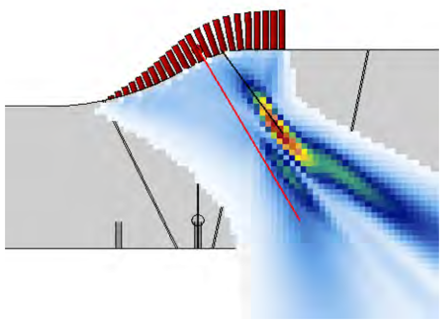
- Reference specimen (T = 35 mm) with artificial reflectors, and tapered surface similar to PWR pressurizer nozzle configuration
- Inspection sequence: sectorial scanning 20° to 70° LW, combined with mechanical movement along the virtual weld

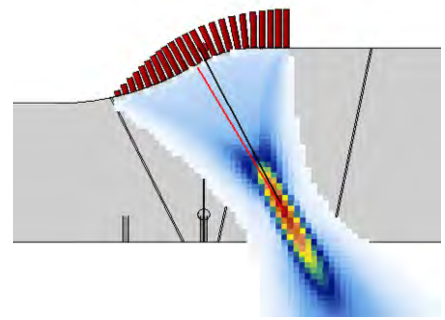
Complex Surface – Flexible Array

Actual data **and** ***beam modeling*** **for azimuthal sweep (from 20° to 70°LW) with 1D flexible array on realistic tapered specimen**









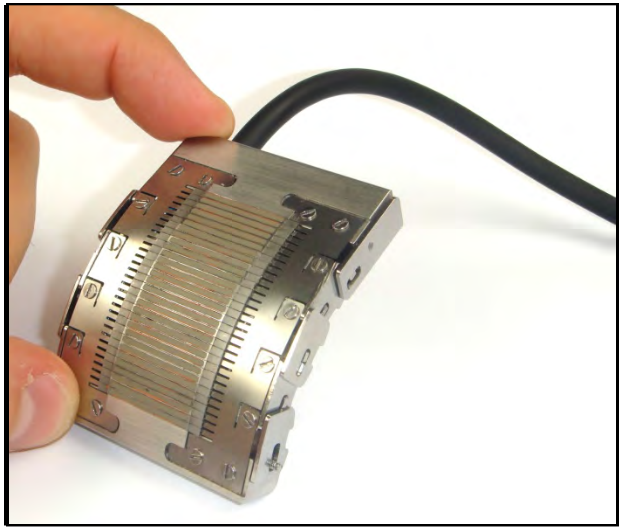
realistic tapered specimen, nominal focal laws

realistic tapered specimen, optimized focal laws on-line sector scan correction

Complex Surface – Flexible Array

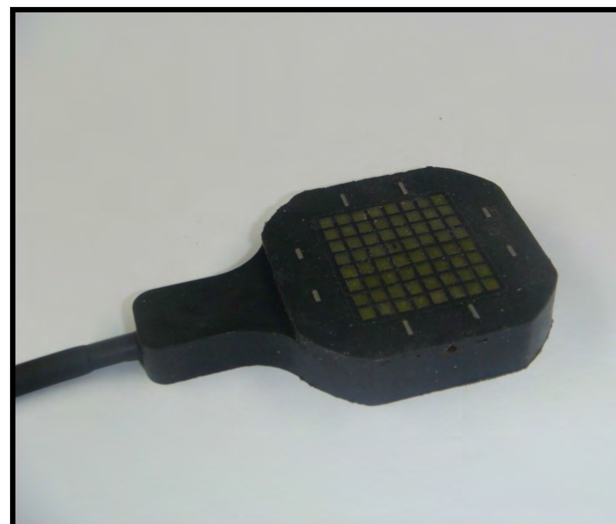
- Flexible arrays obviously ***improve transmission of acoustic energy*** through complex surfaces
- The ***use of optimized focal laws is essential*** to obtain adequate examination capability
- ***Enhanced UT imaging***, taking into account surface geometry, drastically improves data interpretation
- Industrialization of flexible array design is on-going

Complex Surface – Flexible Array



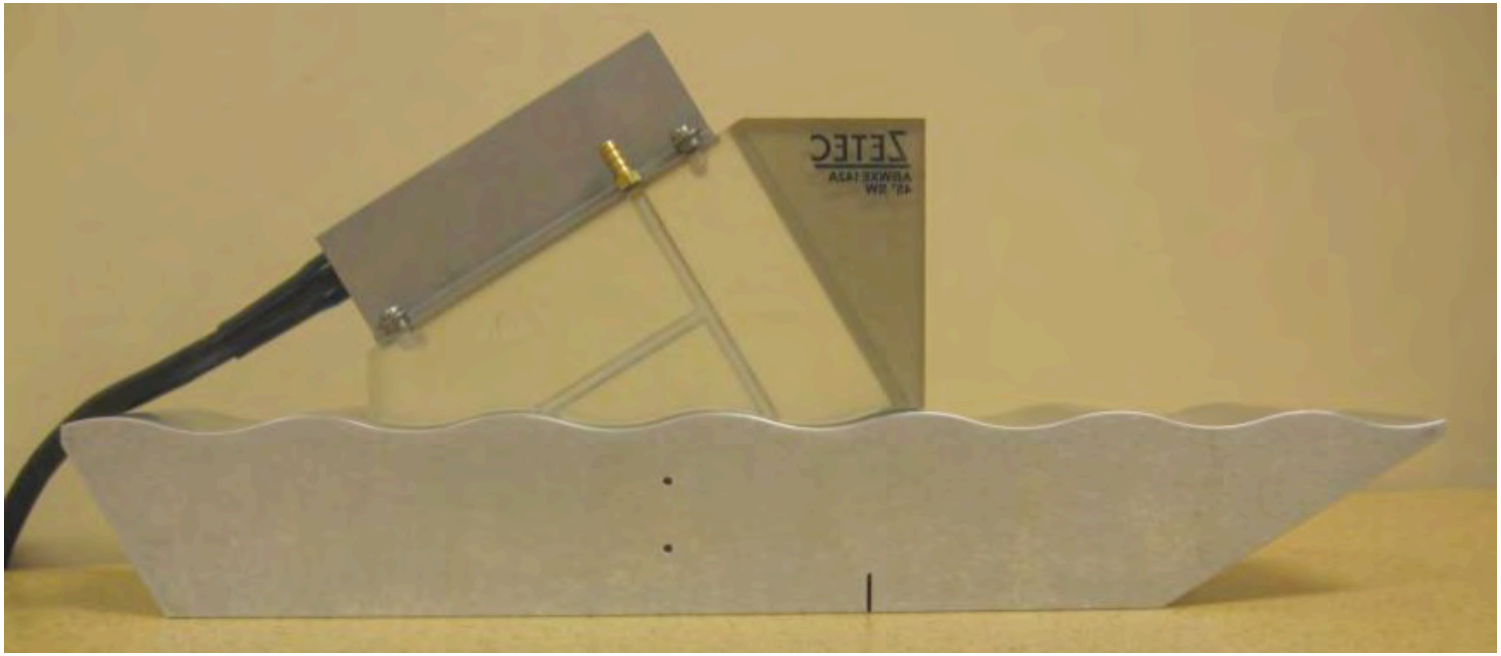
1D linear array,
first generation
second generation

2D matrix array



Courtesy of Imasonic

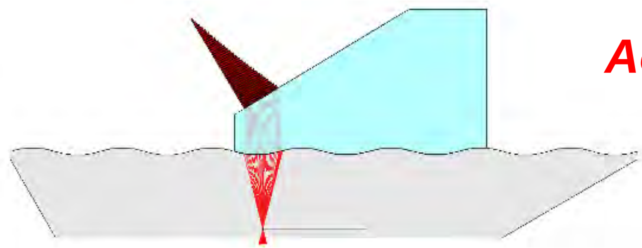
Complex Surface – Custom Footprint



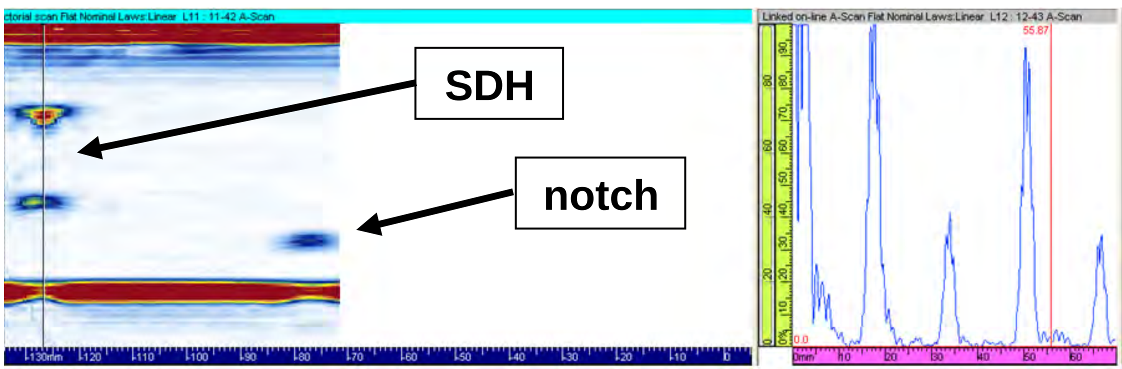
Specimen: T = 50 mm, wavy surface, with SDH and notch

Inspection sequence: electronic linear scanning along the complex geometry

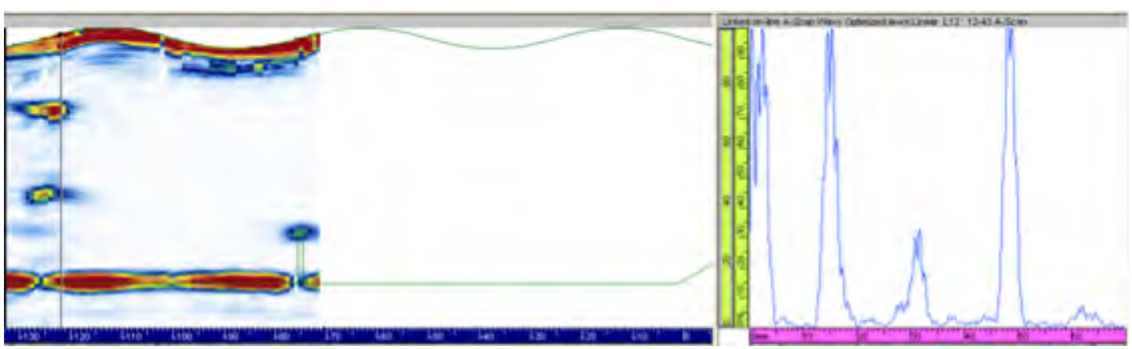
Complex Surface – Custom Footprint



Actual data **from electronic linear scanning at 0°LW, with rigid 1D linear array and custom wedge**



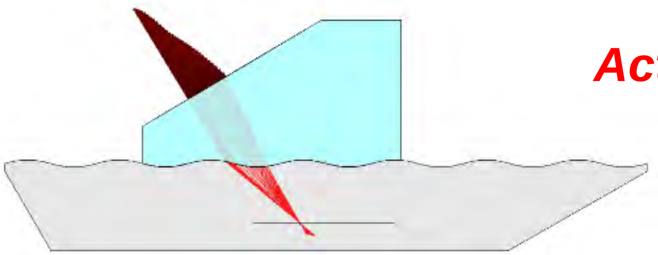
flat specimen, nominal focal laws



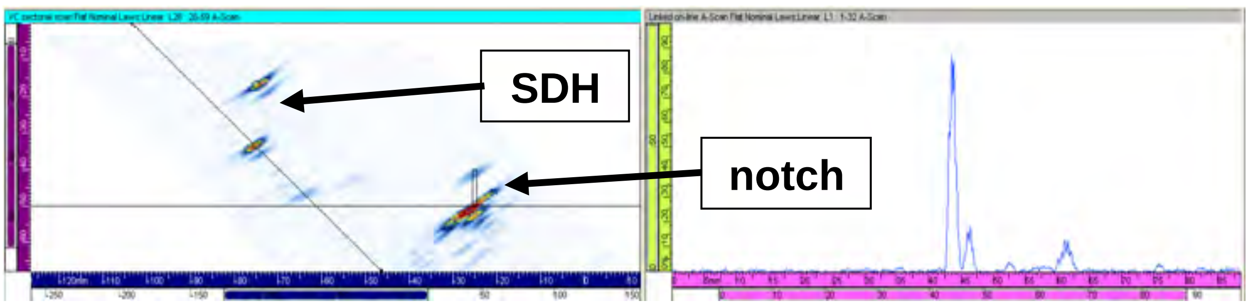
wavy reference specimen, optimized focal laws, on-line sector scan correction

wavy reference specimen, nominal focal laws

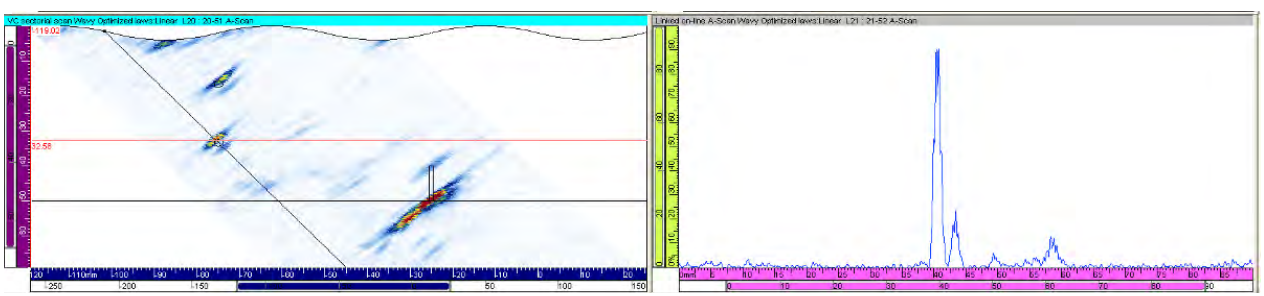
Complex Surface – Custom Footprint



Actual data **from electronic linear scanning at 40°SW, with rigid 1D linear array and custom wedge**



flat reference specimen, nominal focal laws



wavy reference specimen, optimized focal laws, on-line sector scan correction

wavy reference specimen, nominal focal laws

Complex Surface – Custom Footprint

- Custom footprint wedges obviously ***improve acoustic energy transmission,*** and allow for efficient ***generation of LW and SW***
- The ***use of optimized focal laws is essential*** to obtain adequate examination capability; still, ***limitations*** caused by ***refraction*** can occur; this effect increases with "waviness amplitude" and with higher refracted angles
- ***Enhanced UT imaging***, taking into account surface geometry, drastically improves data interpretation

Key Features Summary (I)

Challenging Applications	Inspection Methodology	DYNARAY & UltraVision® 3 Specifications & Features
» Complex geometries » « One-pass » weld inspections (axial & circumferential flaws) » Turbine blade roots	» 2D matrix arrays, allowing for variations of refracted angle & skew angle	» Up to 256 simultaneous beam forming channels » Up to 4096 focal laws
» Rough & wavy weld surfaces » Complex geometries (nozzles, J-welds, …)	» Flexible array probes » Conformable wedges » Custom footprint wedges	» Focal law calculation through complex surfaces » Position dependant focal laws » Up to 4096 focal laws » 3D visualisation capability
» Cast SS welds & components » Complex DM welds	» Low-frequency TRL PA probes	» Bandwidth 0.20 – 25 MHz » 200 V excitation pulse » High PRF at low frequencies

Key Features Summary (II)

Challenging Applications	**Inspection Methodology**	**DYNARAY & UltraVision® 3 Specifications & Features**
» RPV welds » Other vessel welds	» Multiple phased array probes	» Large data files, up to 20 GBytes » Data flow up to 20 MBytes/s » 16-bit A-scan data » On-line data processing » *Parallel firing* » *Interleaved averaging* » *Channel related resolution*
» All types of R&D work	» Any phased array UT technique	» High processing capability » 16-bit A-scan data » Open architecture » *Individual A-scans available*
» Any inspection requiring long soundpaths (shafts, axes, …)	» Conventional UT techniques » Phased array UT techniques	» 200 V excitation pulse » Up to 256,000 points in A-scan » 16-bit A-scan data

Recent CASS UT Activities on PZR Surge Line Welds

Michael Anderson

IRSN/NRC Collaborative Meeting

June 4, 2009

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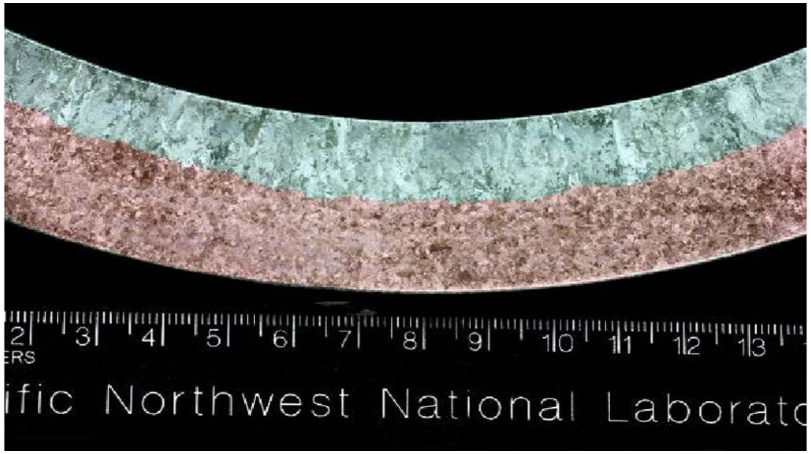
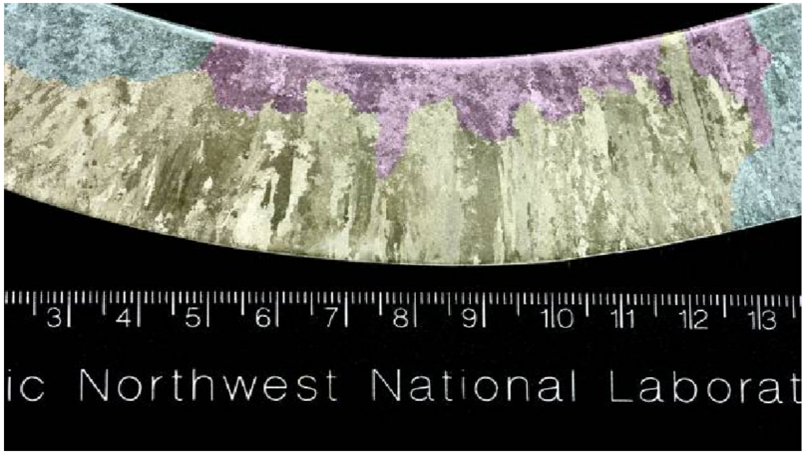
PZR Surge Line Specimens

Sample 7C-059 – from Battelle

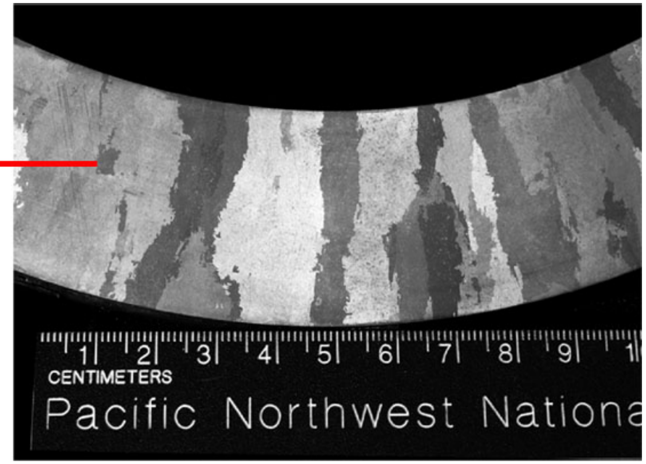


Pipe Side – CCSS
30 mm (1.2 in.) wall

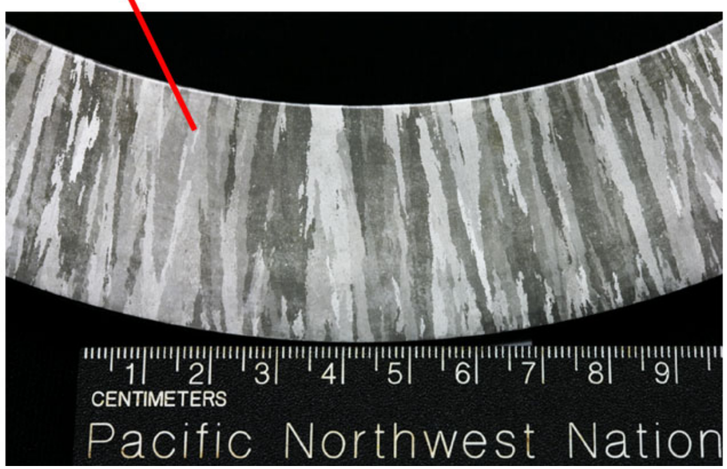


Elbow Side – SCSS
39 mm (1.5 in.) wall

PZR Surge Line Specimens (WNP-3)



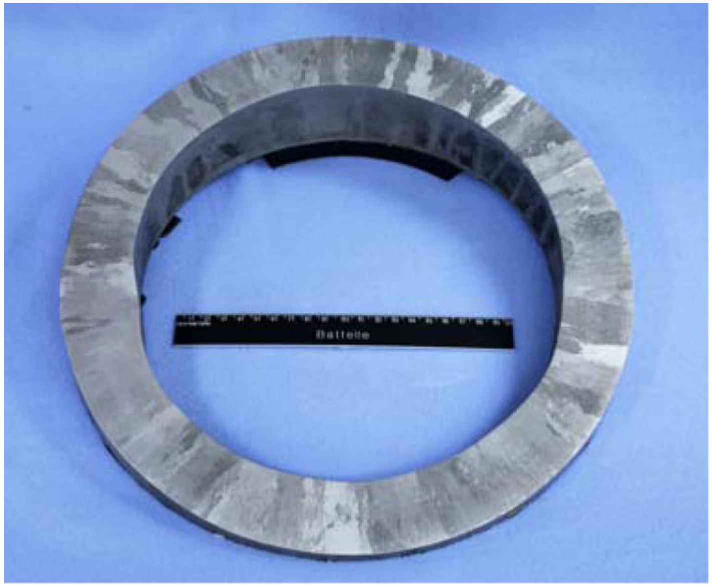
9C-002
Pipe Side
33 mm
(1.3 in.) wall



9C-001
Pipe Side
33 mm
(1.3 in.) wall

PZR Surge Line Specimens (WNP-3)

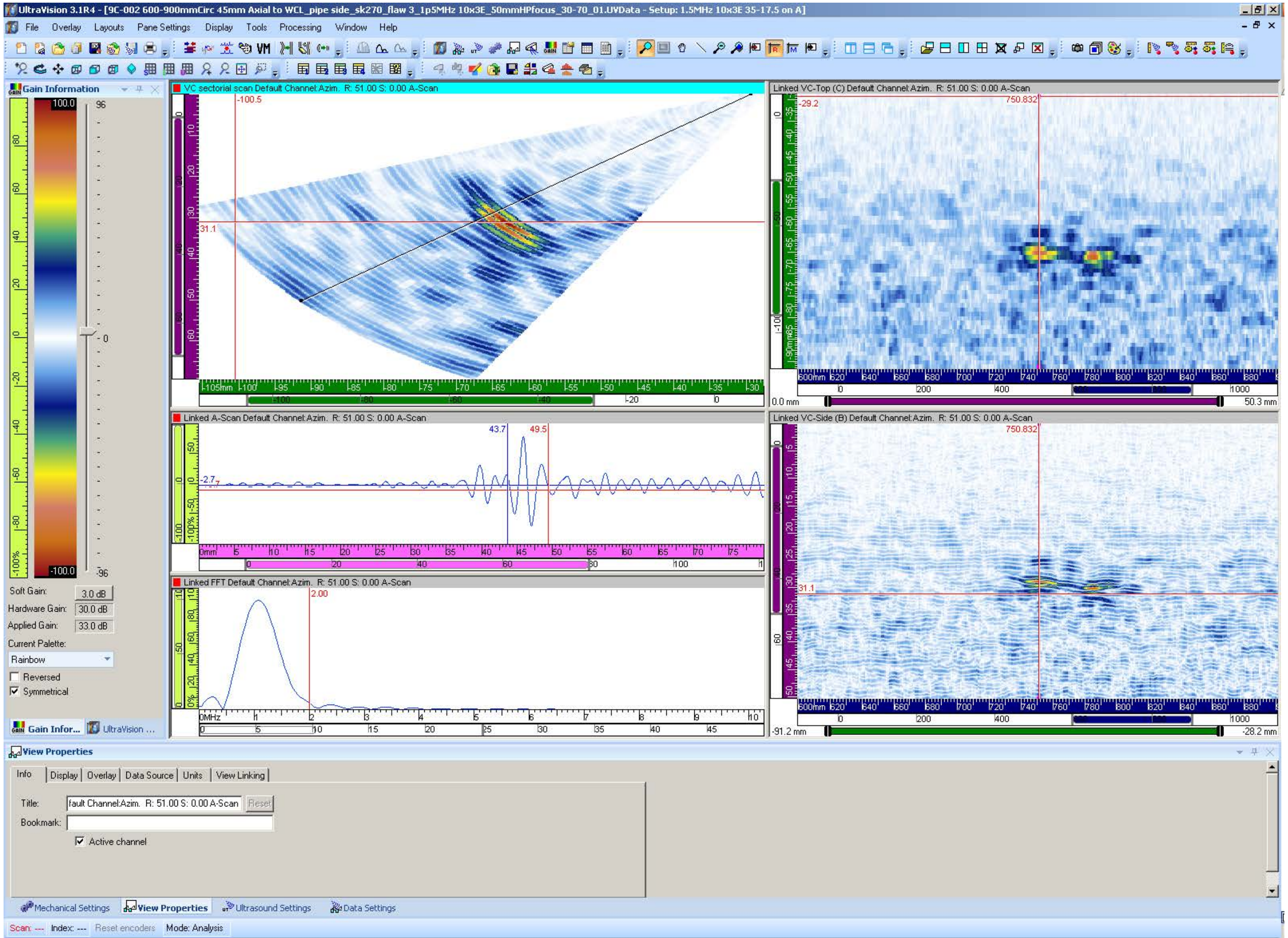
Microstructure of elbow segment from WNP-3 PZR surge line specimen
34 - 44 mm (1.3 - 1.7 in.) wall



PZR Surge Line Implanted Flaw Data (True State)

	Flaw	Flaw Type	Flaw Location	Flaw Orientation	Flaw Length	Flaw Depth (Height)	Degree Location
7C-059	1-1	Thermal Fatigue	Weld Center Line	Circumferential	4.0 in. (10.2 cm)	35% T	45°
	1-2	Thermal Fatigue	Pipe Side Near Fusion Line	Circumferential	2.0 in. (5.1 cm)	30% T	120°
	1-3	Thermal Fatigue	Weld Center Line	Circumferential	2.0 in. (5.1 cm)	30% T	210°
	1-4	Thermal Fatigue	Weld Center Line	Circumferential	6.0 in. (15.2 cm)	30%–50% T	300°
9C-001	2-1	Thermal Fatigue	Weld Center Line	Circumferential	3 in. (7.6 cm)	10 - 20% T	0°
	2-2	Thermal Fatigue	Weld Center Line	Circumferential	2 in. (5.1 cm)	25 – 30% T	90°
	2-3	Thermal Fatigue	Weld Center Line	Circumferential	2.5 – 3 in. (6.4–7.6 cm)	25%	270°
9C-002	3-1	Thermal Fatigue	Weld Center Line	Circumferential	3 in. (7.6 cm)	15 – 25% T	0°
	3-2	Thermal Fatigue	Weld Center Line	Circumferential	2 in. (5.1 cm)	20% T	90°
	3-3	Thermal Fatigue	Weld Center Line	Circumferential	2.5 – 3 in. (6.4–7.6 cm)	15% T	270°

9C-002 Flaw 3-3, Pipe Side: 1.5 MHz TRL, Line Scan (tip?)



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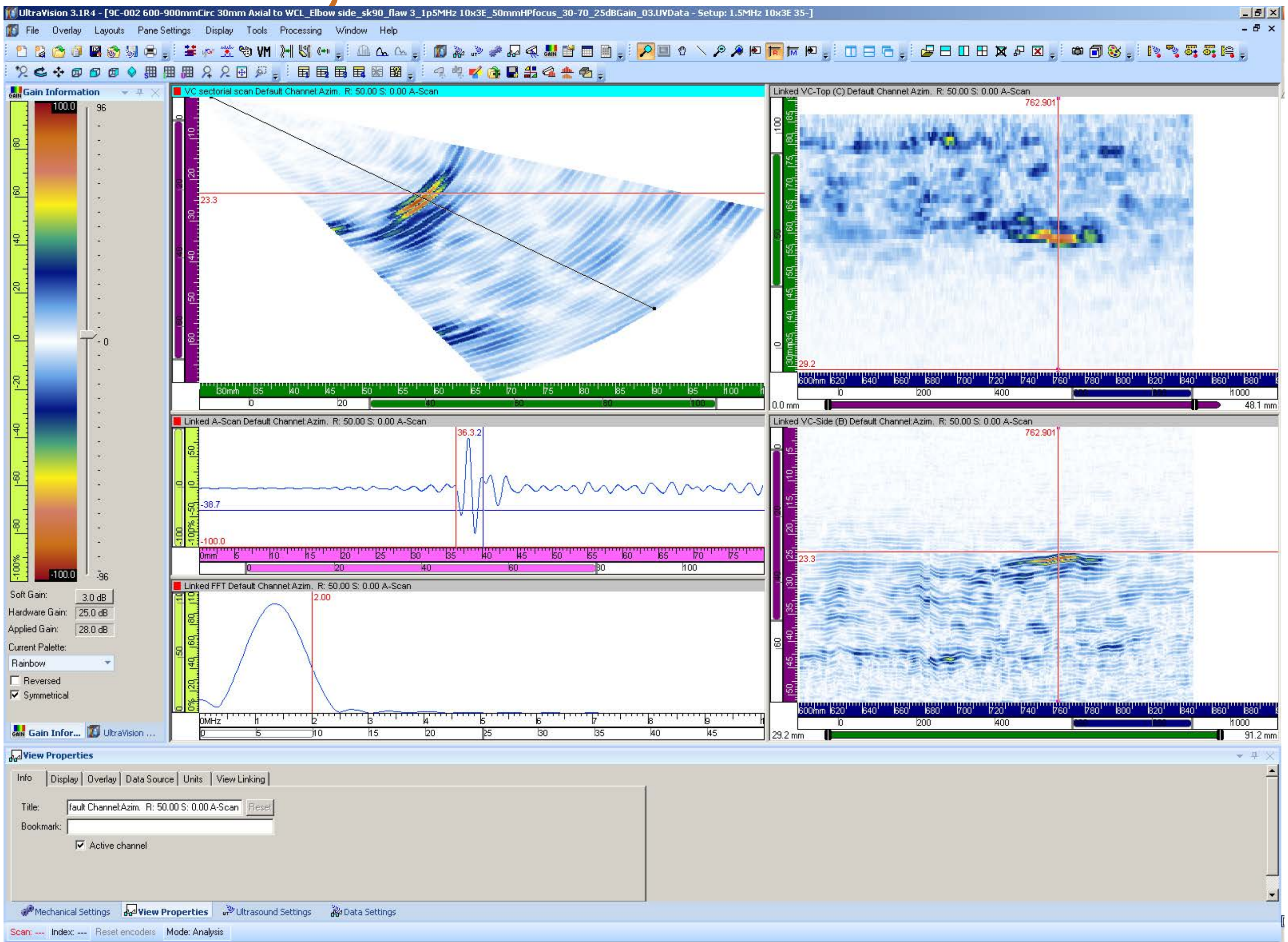
9C-002 Flaw 3-3, Elbow Side: 1.5 MHz TRL, Line Scan



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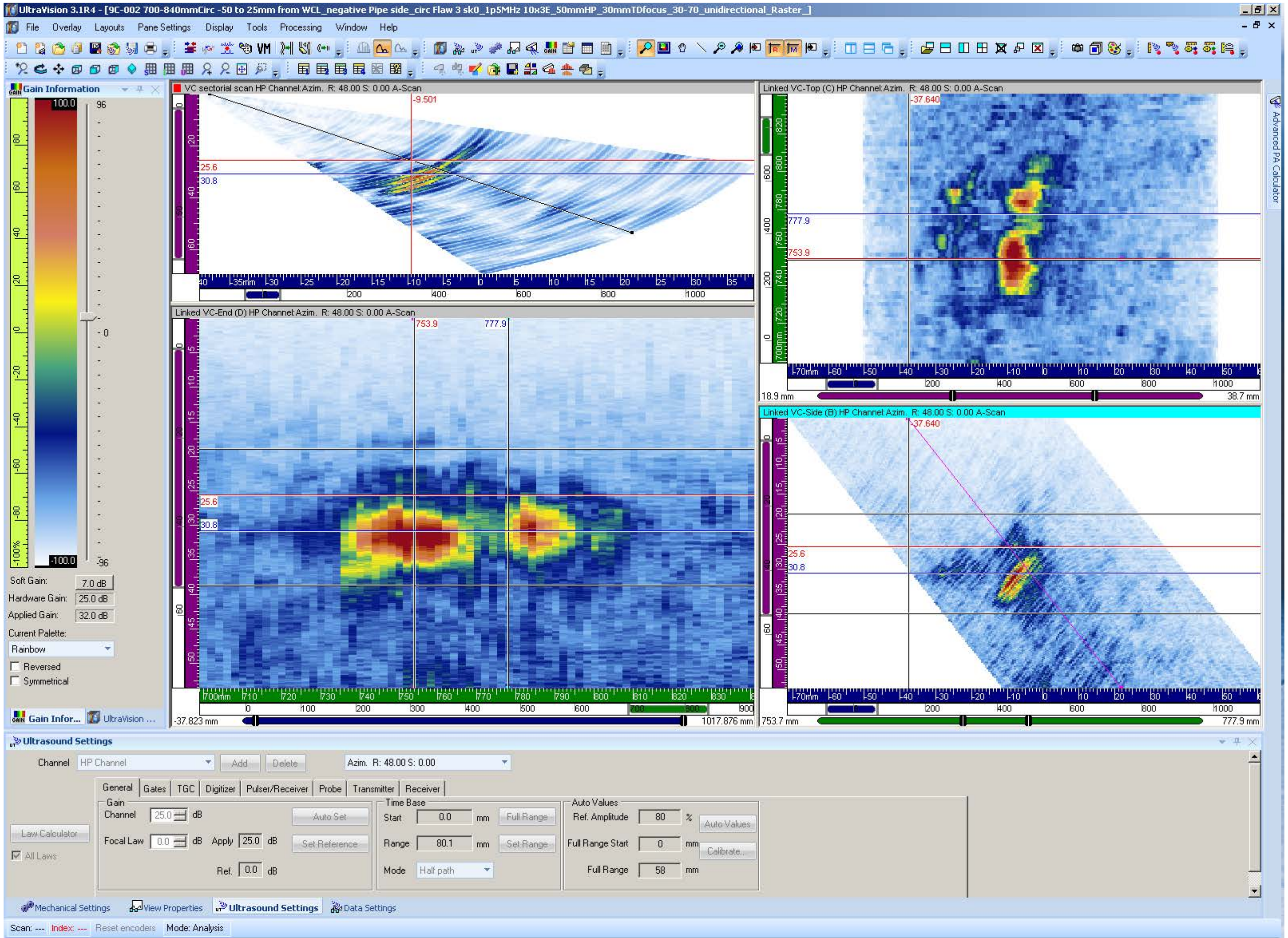
9C-002, Flaw 3-3, Pipe Side:
1.5 MHz TRL, Raster Scan



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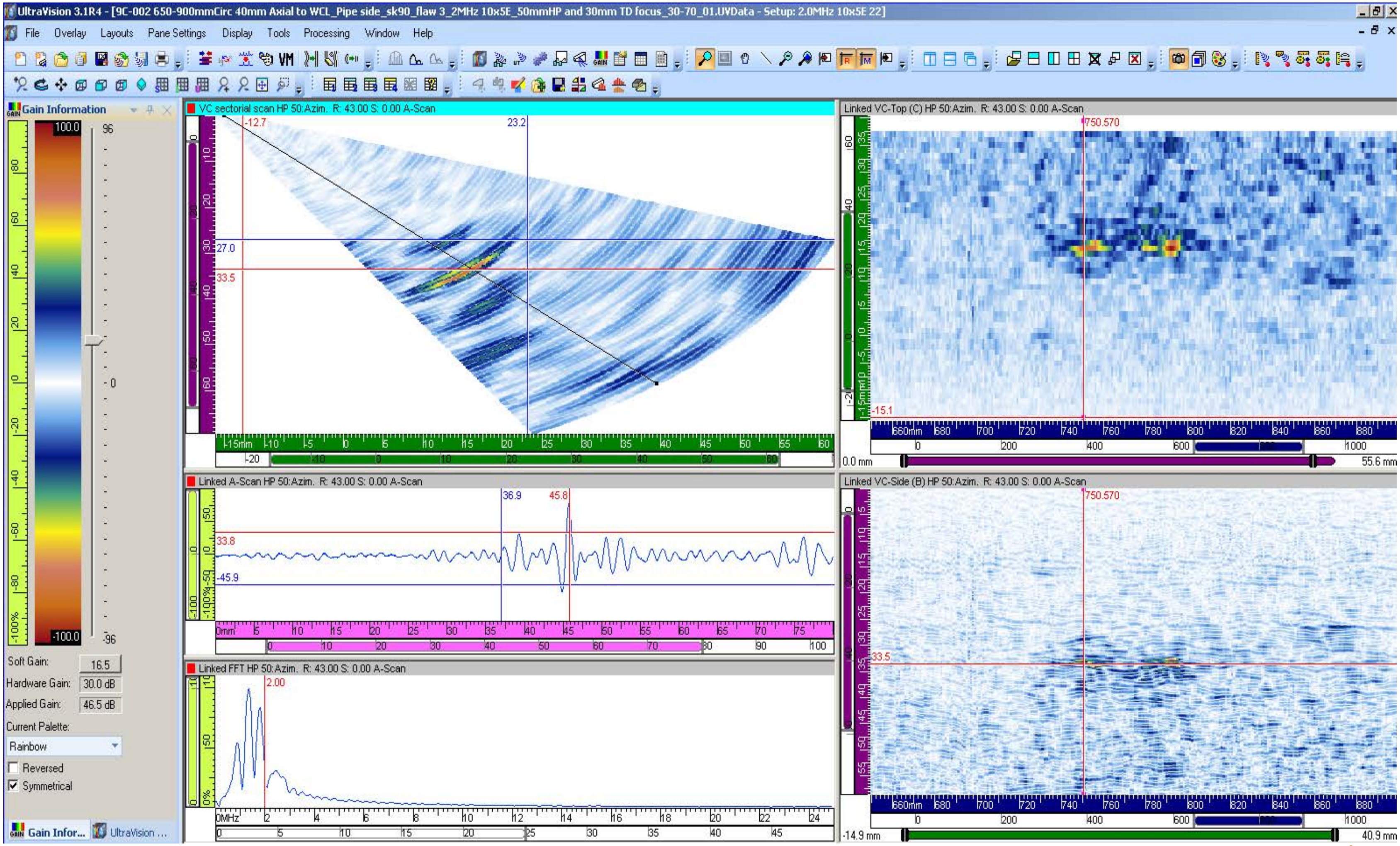
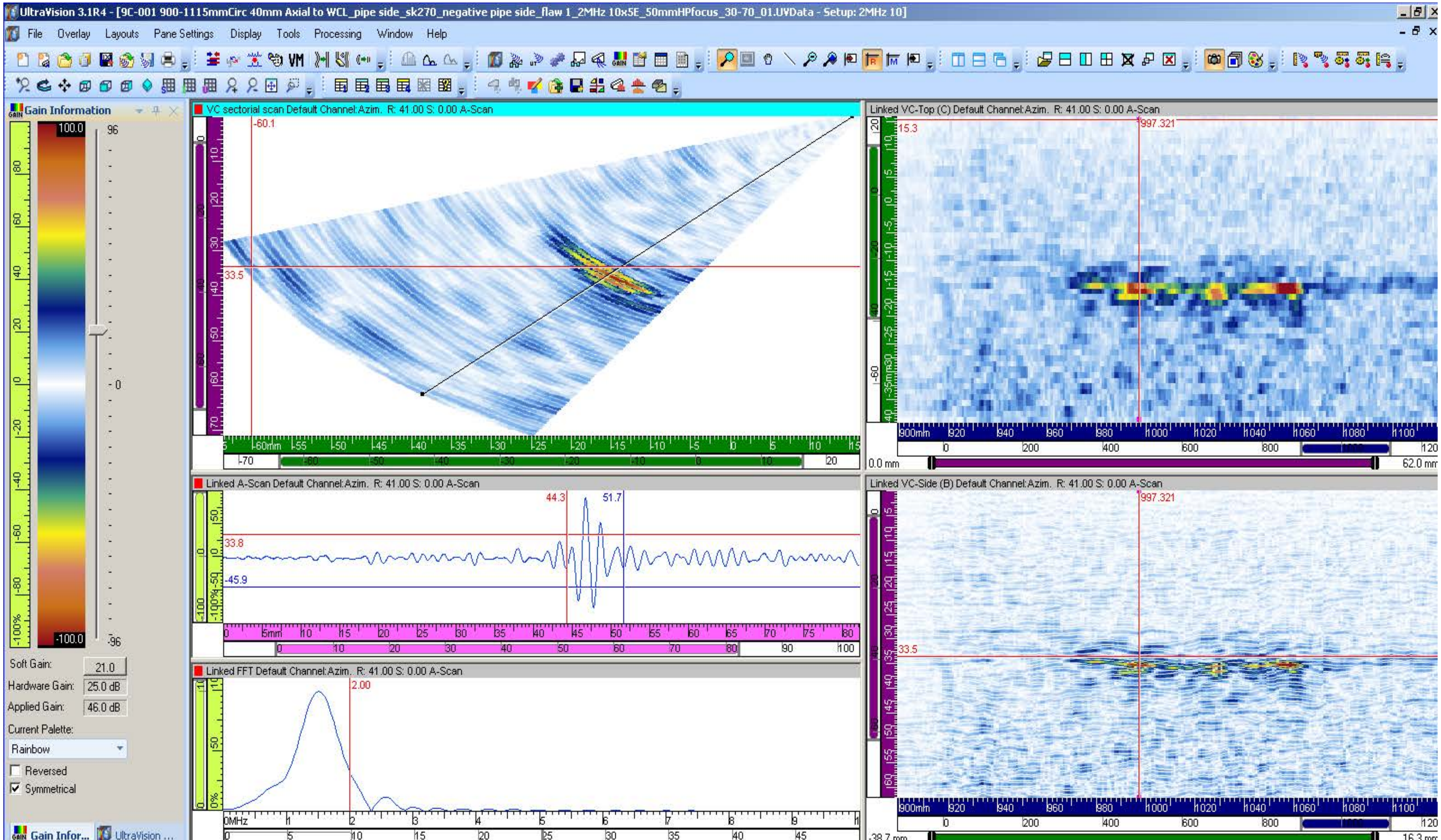
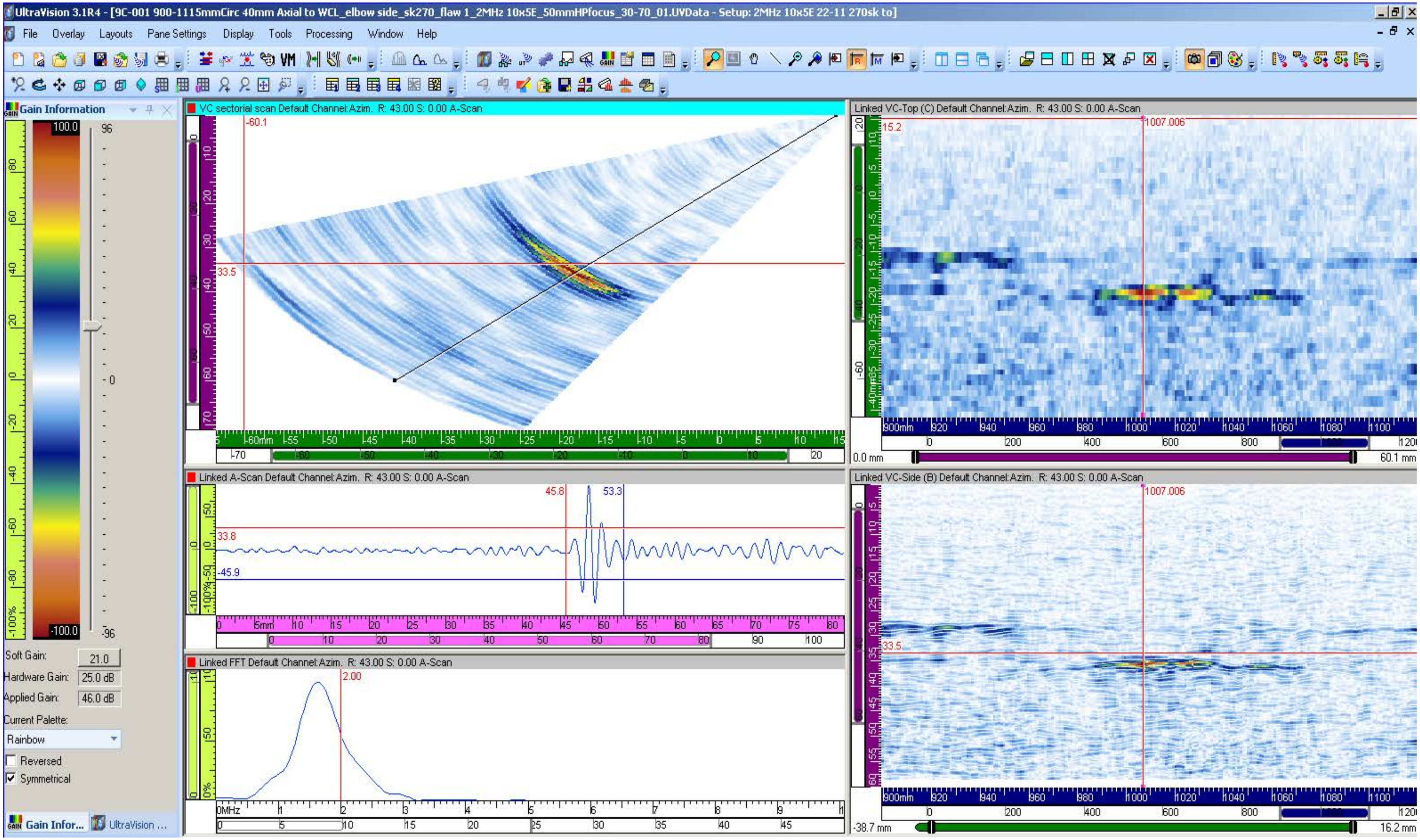
9C-002 Flaw 3-3, Pipe Side: 2 MHz TRL – Tip and Specular Responses



9C-001 Flaw 2-1, Pipe Side: 2 MHz TRL



9C-001 Flaw 2-1, Elbow Side: 2 MHz TRL



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Proudly Operated by Battelle *Since 1965*

Summary

- All implanted flaws in CASS PZR surge line welds were detected using TRL phased arrays operating at 1.5 and 2.0 MHz
- Specular responses with high S/N; some tip diffraction evident
- Preliminary conclusion: Relatively thin-walled (less than 2.0-inch) CASS can be reliably inspected with current methods

2nd International Workshop
Future Directions for the Inspection of Cast Austenitic Stainless Steel Piping

Wallace Norris

Office of Nuclear Regulatory Research

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June 15-16, 2009
Seattle, Washington

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NRC Research Program

- NRC initiated research program to investigate the reliability of NDE for ISI
- The effort is being conducted at PNNL
  - One of the tasks is to investigate difficulties associated with the inspection of large-grained, anisotropic materials
  - CASS in primary reactor coolant loop piping in 27 PWRs
    - A focus on CASS given use in Class 1 systems
    - Also, CASS is one of the more difficult inspection problems. Successes here can be translated to other problems such as dissimilar metal welds.
  - Effective and reliable inspection techniques for these components are needed

NUREG/CR Reports

- Several reports have already been published
  - NUREG/CR-6929, *Assessment of Eddy Current Testing for the Detection of Cracks in Cast Stainless Steel Reactor Piping Components*
    - Evaluate the effectiveness and determine capabilities of ET to detect surface-breaking flaws from pipe ID

NUREG/CR Reports (cont'd)

- NUREG/CR-6933, *Assessment of Crack Detection in Heavy-Walled Cast Stainless Steel Piping Welds Using Advanced Low-Frequency Ultrasonic Methods*
  - Low frequency ultrasonic testing applied from OD for detection of ID cracking
    - 400-kHz to 1.0 MHz

NUREG/CR Reports (cont'd)

- NUREG/CR-6984, *Field Evaluation of Low-Frequency SAFT-UT on Cast Stainless Steel and Dissimilar Metal Weld Components*
  - Reports earlier work performed by PNNL at PNNL and at EPRI NDE Center
    - Demonstrated potential for low-frequency UT
    - Experiments with noise reduction algorithms
  - Investigation was semi-blind so it was believed that the data would be valuable relative to future performance demonstration assessments

Cooperative Agreement with IRSN

- On June 24, 2008, NRC and the Institute for Radiological Protection and Nuclear Safety (IRSN) signed a cooperative research agreement to assess the ability of advanced NDE methods to detect and size defects in coarse-grained steel components
  - NRC research conducted through PNNL
  - IRSN research conducted through Commissariat à l'Énergie Atomique (CEA)

NRC/IRSN Agreement Tasks

- Assess NDE methods to improve the ability to detect, localize, and, if possible, size cracks in coarse-grained steel components
  - State-of-the-art phased array methods operating at low frequencies
- Develop an ultrasonic method to classify and size the grain structure in field conditions
  - Develop a dedicated method to classify and size the grain structure of a CASS component in situ

NRC/IRSN Agreement Tasks (cont'd)

- Improve and/or develop and validate simulation to get a better understanding of the effect of grain structures on ultrasonic propagation

- Develop new phased array techniques for application on CASS, taking into account the simulation studies and the previous method developed to classify the grain size and to optimize the acoustic field

Reports Scheduled

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- FY11
  - Letter report on effects of fabrication processes regarding inspectability of SCSS and CCSS
  - NUREG - final assessment of CASS

Cast Stainless Steel Inspection
An Overview of ASME Section XI Activity

June 16, 2009

Cast Austenitic Stainless Steel in Nuclear Power Plants

- Reactor Coolant system (Class 1)
- Static Cast Components
  - RCS Pipe Fittings (elbows)
  - Pump Casings
  - Auxiliary Piping (Pressurizer Surge lines)
- Centrifugally Cast Components
  - RCS Pipe

Evolution of CASS Inspection

> *1970 Edition*

- **Earliest ASME Section XI rules required volumetric inspection of Class 1 piping welds.**
- **No distinction made in material type or fabrication method.**

> *Mid-1970's*

- **More detailed rules in 1974 and 1977 Editions and addenda**
- **Still no specific distinction made for material characteristics**
- **Industry was beginning to recognize challenges concerning ultrasonic inspection of CASS material**

Evolution of CASS Inspection

> *Development of Enhanced Techniques*
  - **Several inspection suppliers developed enhanced UT techniques to attempt to improve CASS inspection capability**
    - Water column technique
    - Low frequency, dual element refracted L-wave

> *Regulatory Action*
  - **IGSCC issues, primarily in BWR piping, led to actions to improve reliability of NDE processes used in ISI**
  - **Variety of regulatory processes in different regions**
  - **1984: Proposed NRC rules led to creation of ASME Task Group to address NDE Performance Demonstration**

AREVA

ASME Section XI Appendix VIII

> ***ASME formed Task Groups in early 1985***
- **Appendix VII – Training and Qualification**
- **Appendix VIII – Performance Demonstration**

> ***1989 – Appendix VIII Published***
- **Included a Supplement for each type of inspection to be performed**
- **Supplement 9 – Cast Austenitic Stainless Steel was "In Course of Preparation"**

> ***1990 – 1997***
- **Performance Demonstration Initiative (PDI) was formed to implement the rules of Appendix VIII**
- **Initial emphasis was on RV welds and wrought austenitic piping**

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ASME Section XI Appendix VIII

- ***ASME formed Task Group on CASS Inspection in 1997***
  - **Charter is to resolve the issues concerning CASS inspection and propose Code actions to complete Appendix VIII Supplement 9**
- ***2001 - Proposed Code Case***
  - **Followed requirements of existing Code Case for inspection of pump casings**
  - **Proposed engineering analysis and VT inspection during hydro in lieu of volumetric inspection**
  - **Proposal was not approved**

AREVA

ASME Section XI Appendix VIII

> *Current Activity*

- **Inspection technique research (PNNL) sponsored by NRC**
- **Engineering analysis to determine allowable flaw size**
- **Draft Code Case to incorporate the results of these activities into an implementable set of Code rules**

Study on Nondestructive Inspection for the Cast Stainless Steel Piping

Kazunobu Sakamoto

Nuclear Energy System Safety Division

JNES

Background

-Detection capability of UT on CASS was verified about 10years ago.
It was concluded that 20% TW crack was detectable.
But, only one type of material (most recent material) was used as the test specimens.

-Although UT inspection is required on CASS piping as ISI program, no sizing capability has been verified yet

-Progress in NDE techniques have been seen over the past 10 years

-The research on CASS inspection has been active in the US and other countries

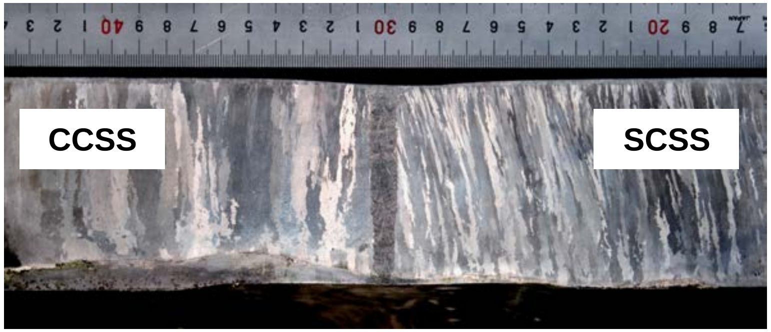
Background (Cont.)

- What JNES has done so far -

-Regional cooperative research program in North East Asia (RCOP2) has been carried out.

-Participants: China, Korea and Japan

-Round Robin Tests on CASS

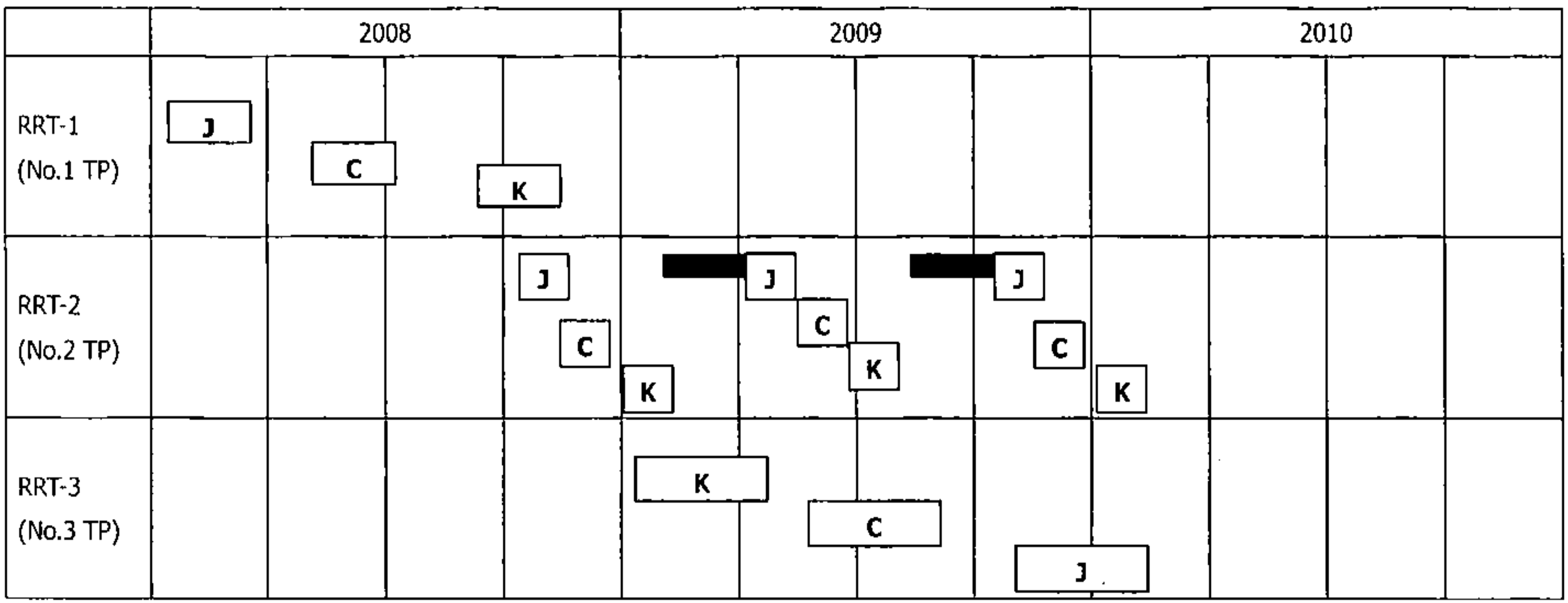


Japanese test block for the Round Robin Test

Background (Cont.)

- RCOP2 Round Robin Schedule -

Tentative Schedule of Round Robin Test



: Crack Growth Treatment

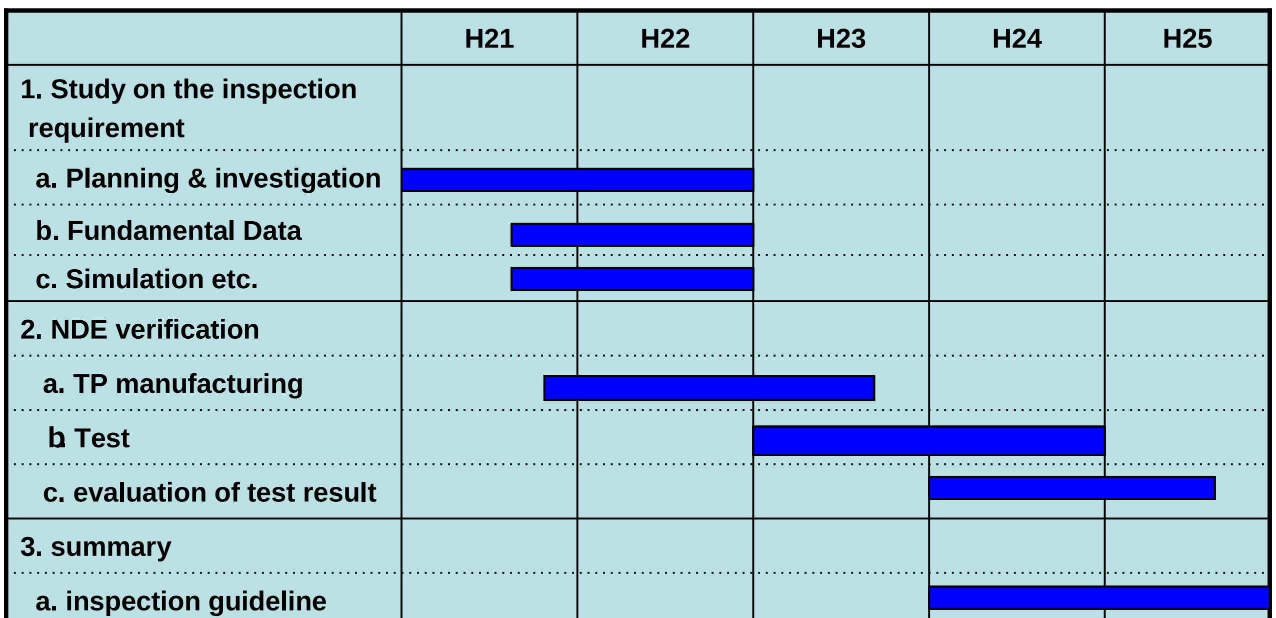
J: Japan, C: China, K: Korea

New research plan (2009FY-2013FY)

Objective;

- To comprehend the UT and ECT capability on CASS, using up to date technologies
- To identify the optimal inspection interval
- Summarize the regulatory requirement regarding CASS inspection

Planed Schedule



Recent Ultrasonic Research and Development Activities and Results for CAST Stainless Steel in INSS

March 3, 2009

Yasuo Kurozumi
Institute of Nuclear Safety Systems, Inc.

Contents

- Detection performance on each weld design
- Depth and Length Sizing of Fatigue Cracks in Cast Stainless Steel Test Piece
- On-site verifications

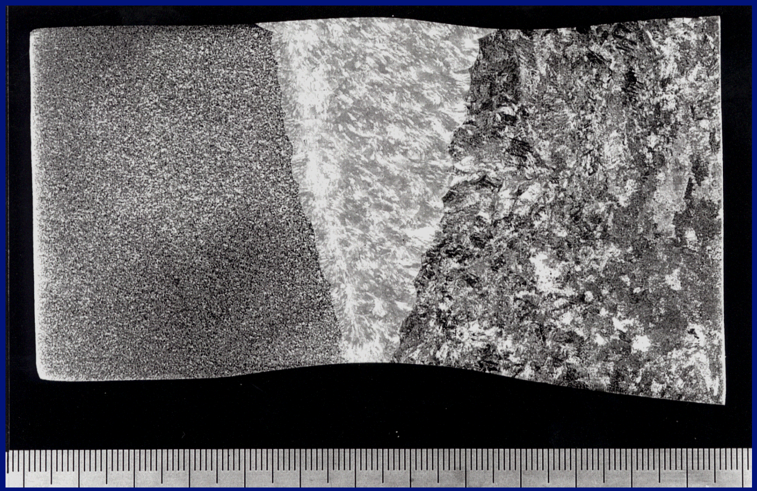
Cast Stainless Steel

1. Type CF-8M cast stainless steel
   Pipe side → Centrifugal Casting
   Elbow side → Static Casting
2. Dimension
   thickness： 65～75mm
   outer diameter： 830～930mm
3. Chemical Composition
   similar to type 304 and 316
4. Grain Structure
   Coarse Grain ; 2～5mm(diameter)
   Dendritic Structure

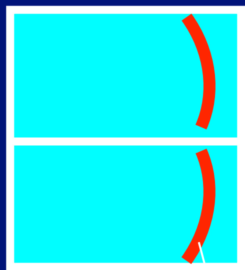
- scattering of the ultrasonic wave
- shift in the direction of ultrasonic beams

- difficult to do an ultrasonic inspection

Cross section of the pipe



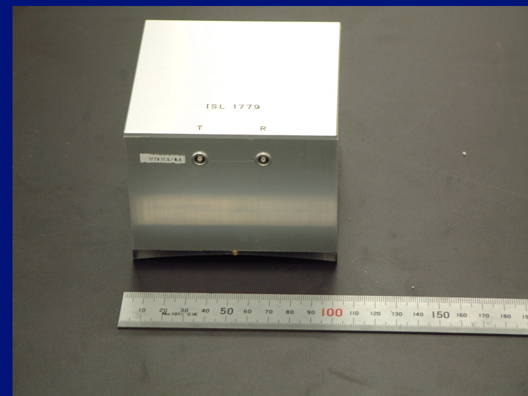
Automated ultrasonic inspection system with large aperture TRL transducers



Transmitter

Receiver

Large spherical crystal 76mmϕ

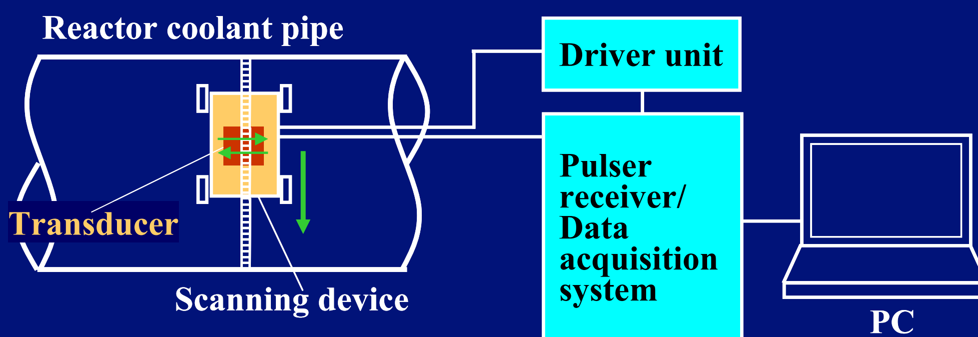


Wide band, High SN ratio

Size ;
100L x 100W x 80H(mm)

Weight ; 1.6 kg

Scanning device



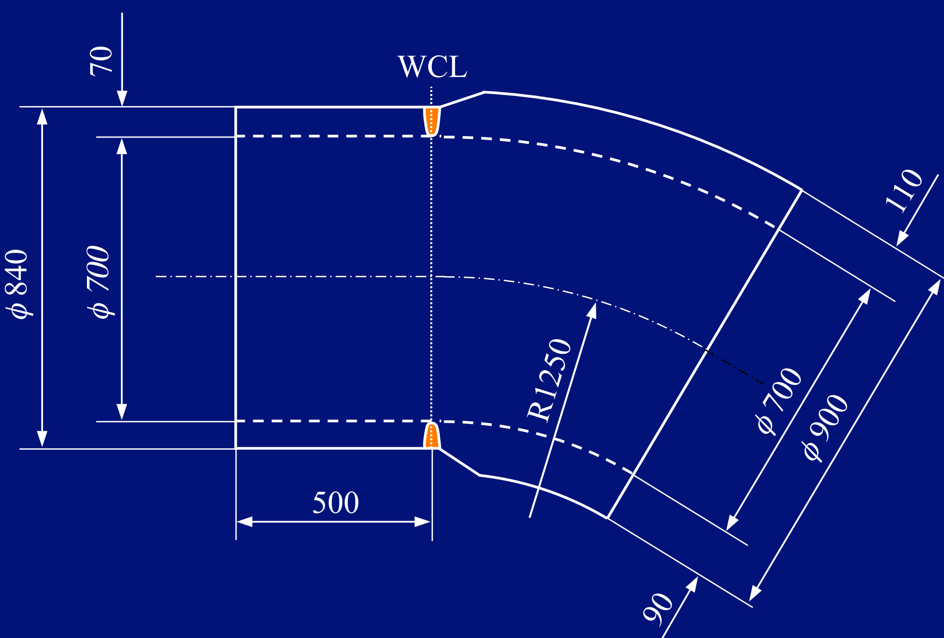
Specifications of probes used in this study

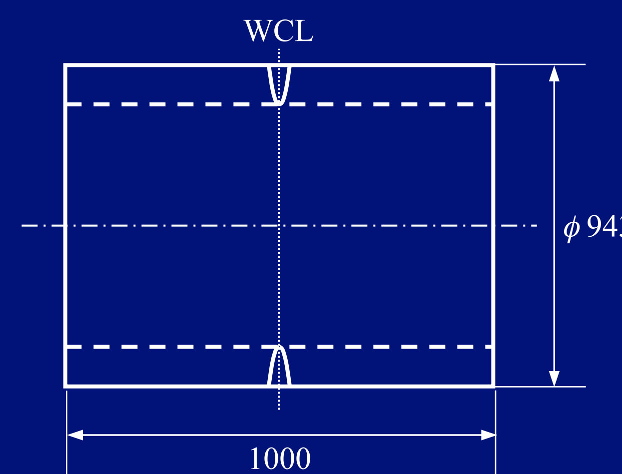
Probe	Type A	Type B	Type C
Type	Longitudinal-wave angle, twin crystal	Longitudinal-wave angle, twin crystal	Longitudinal-wave angle, twin crystal
Outside Dimensions (mm)	100 x 100 x 80	100 x 100 x 80	100 x 100 x 80
Frequency	1 MHz	1 MHz	1 MHz
Transducer Shape	Spherical surface	Spherical surface	Spherical surface
Angle of Refraction	40.7°	47.4°	55°
Focal Depth(mm)	65-75	45-65	40-60

We used only type A probe for detection performance test.
Roof angles are ranged from 6.7 to 7.6°.

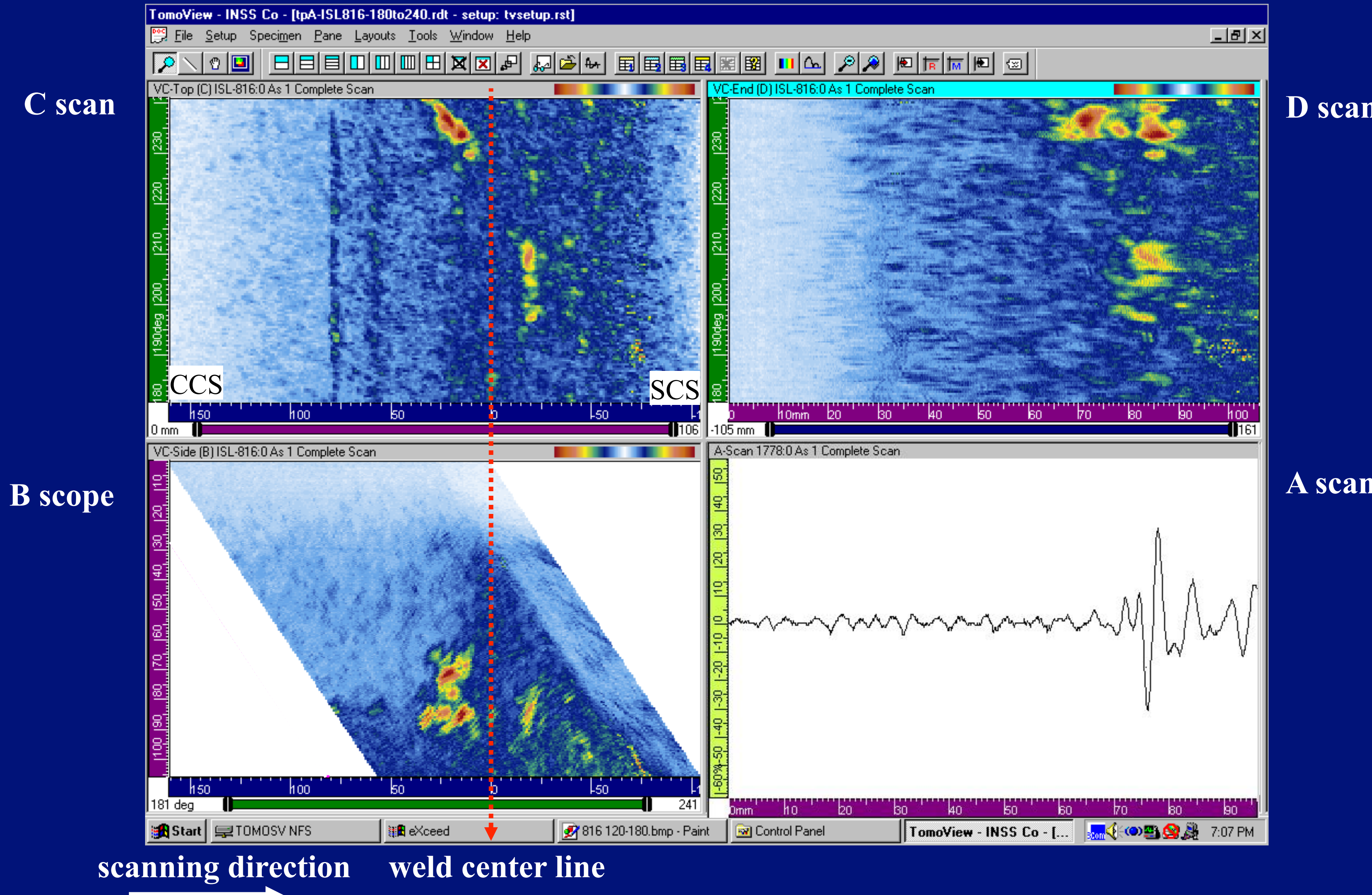
Mock-up test assemblies used for detection test

Type	Category I	Category III
Configuration	Pipe + Elbow	Pipe + Pipe
Material	CCS + SCS	CCS + SCS
Weld process	SMAW + SAW	narrow gap TIG
Defects	EDM slit, Fatigue crack Incomplete penetration	EDM slit, Fatigue crack





Ultrasonic data image sample (Detection test)

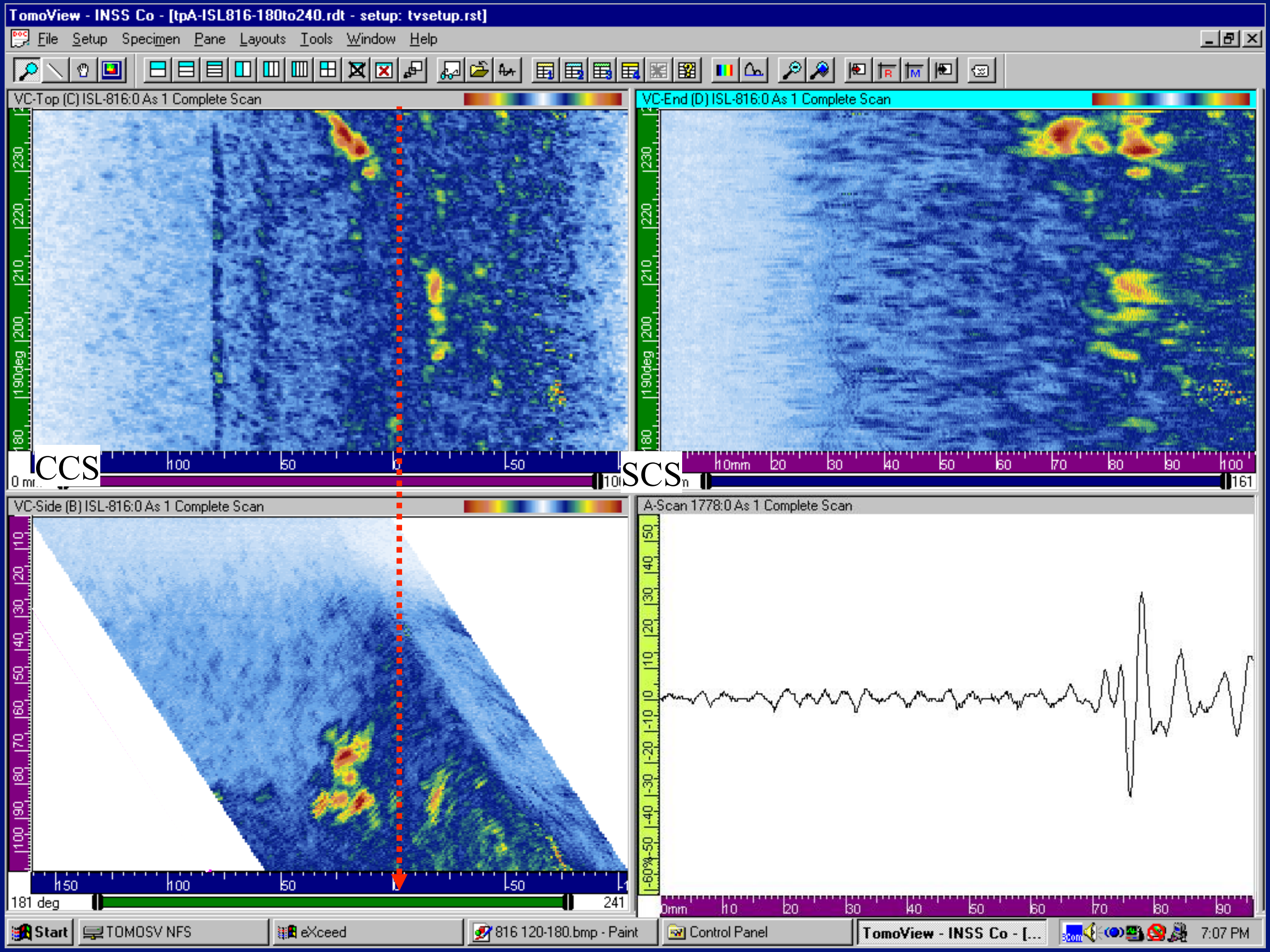


Ultrasonic data image sample (Detection test)

- Category I test assembly -

C scan

D scan



B scope

A scan

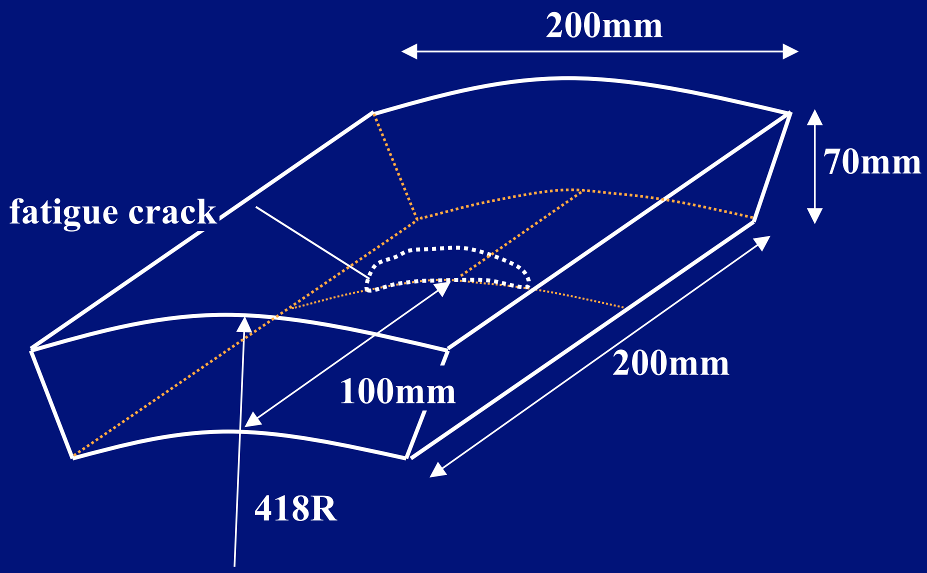
scanning direction

weld center line

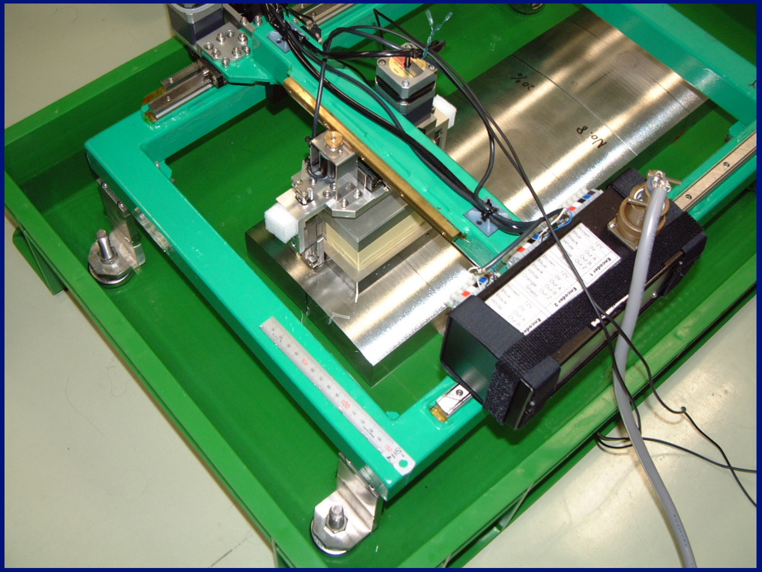
Detection performance

Category I Test assembly	Category III Test assembly
Detected all defects. Some false call were observed. Flaw detection rate = 1.0 False call rate = 0.25	Detected all defects. No false call was observed. Flaw detection rate = 1.0 False call rate = 0

Depth and length sizing test

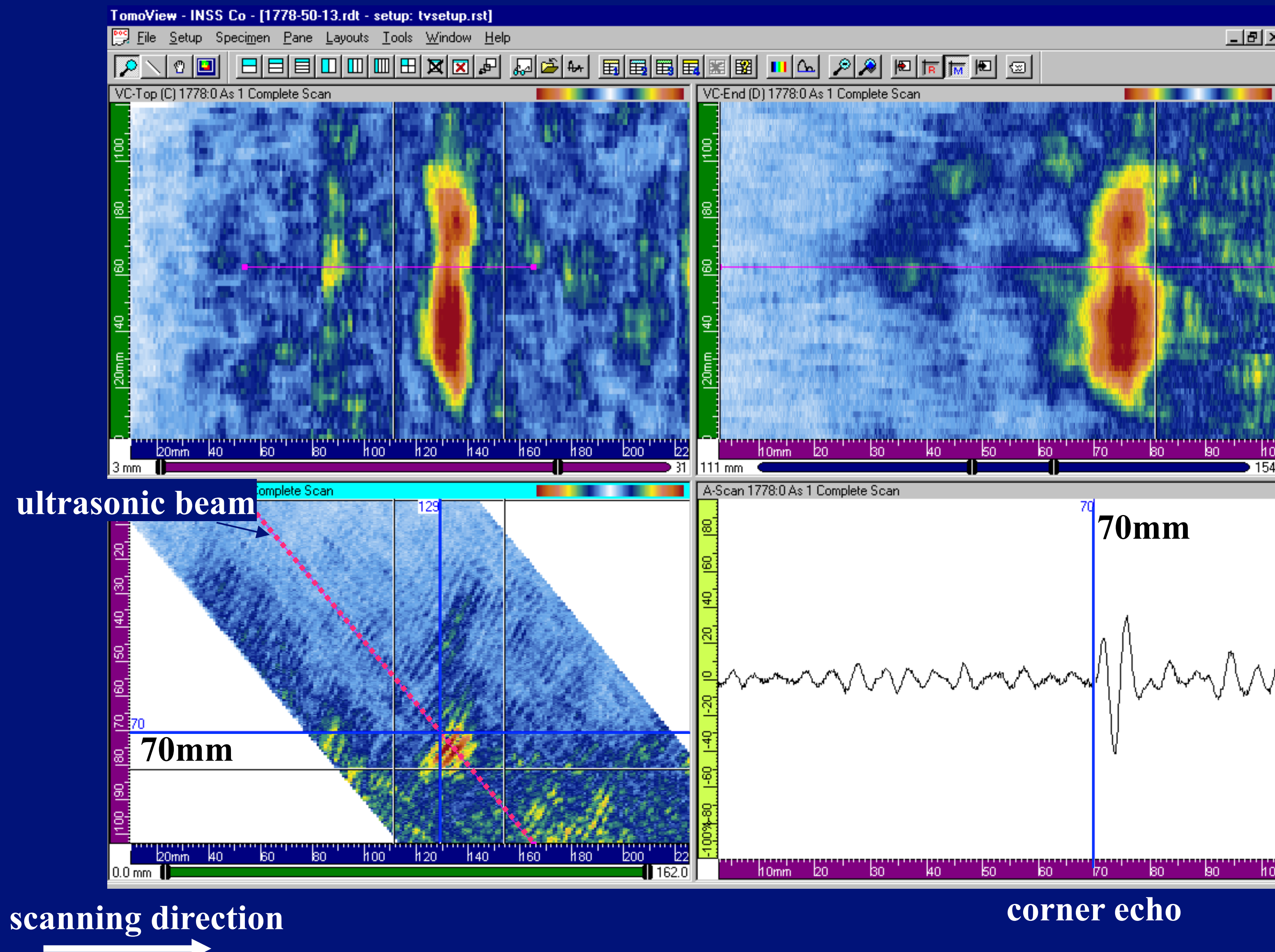


Fatigue test piece

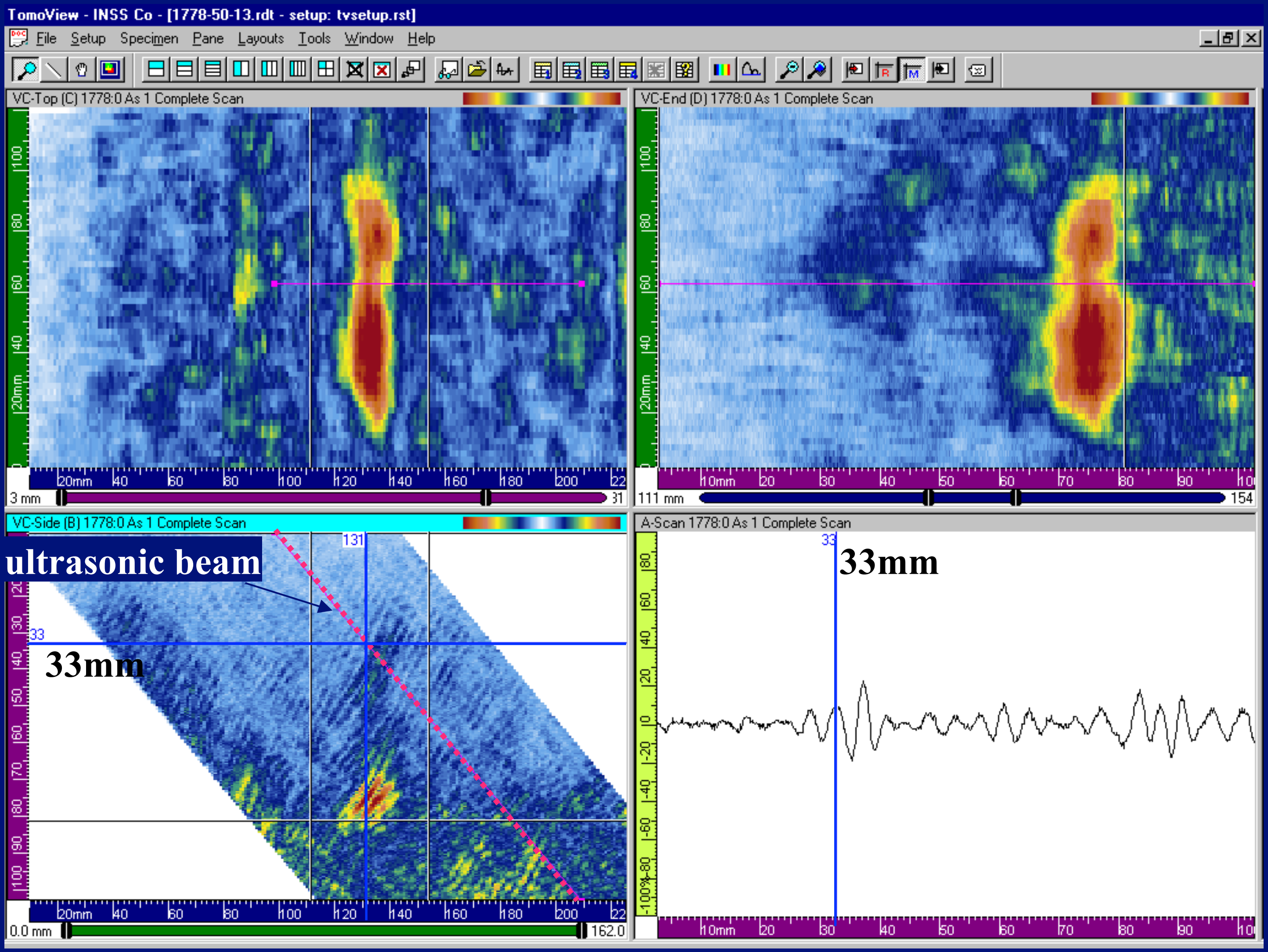


Actual testing

Sample of depth sizing (Type B probe)(1)



Sample of depth sizing (Type B probe)(1)

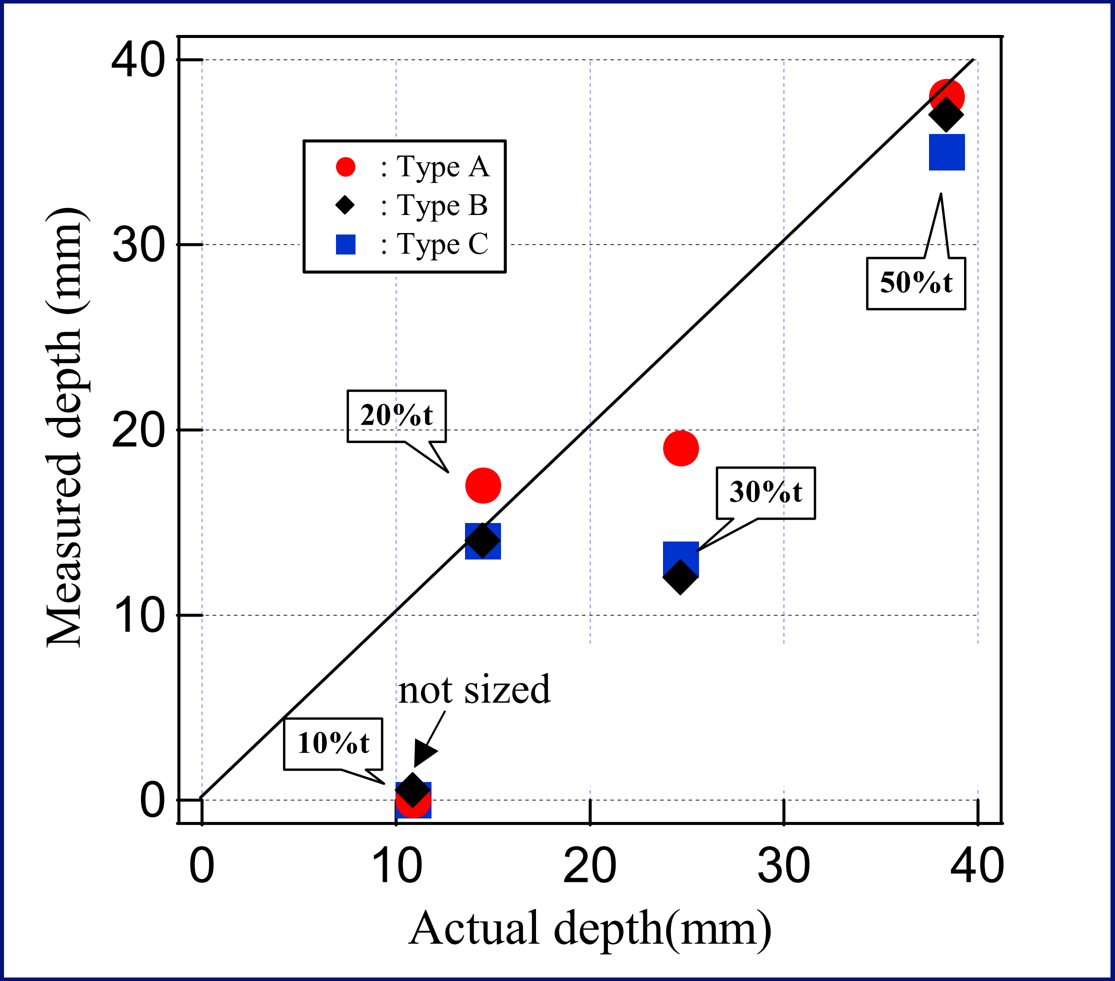


tip echo

scanning direction

measured depth : 70 - 33=37mm (actual depth 38.4mm)

Result of depth sizing for all probes

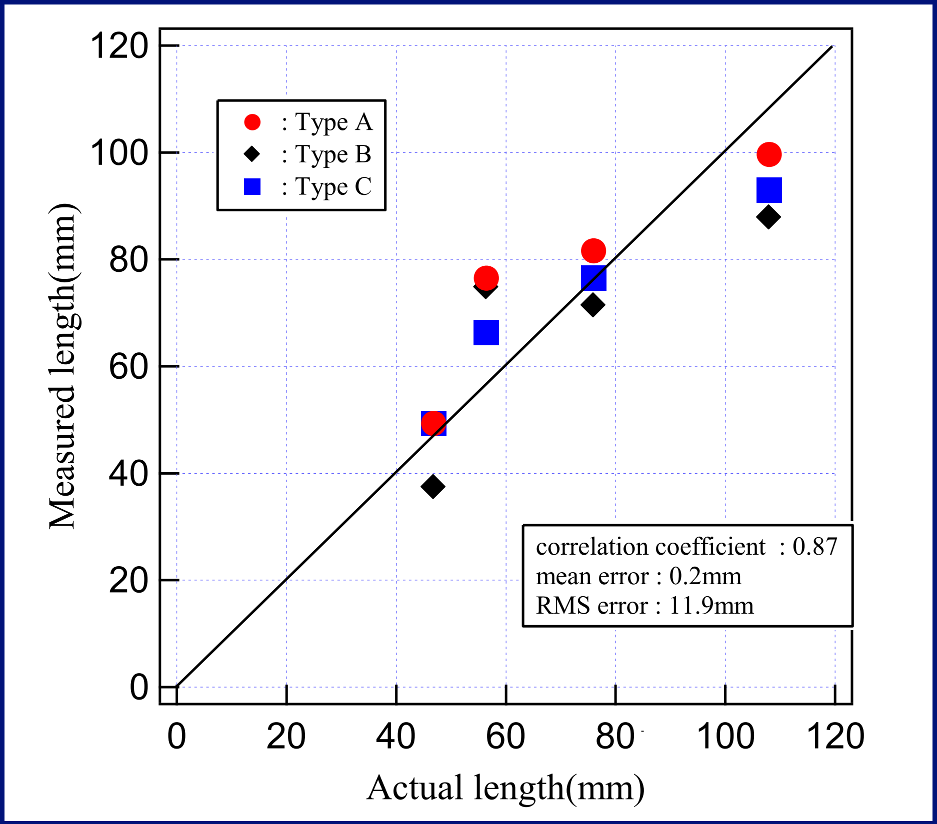


Fatigue cracks over 20%t could be sized.

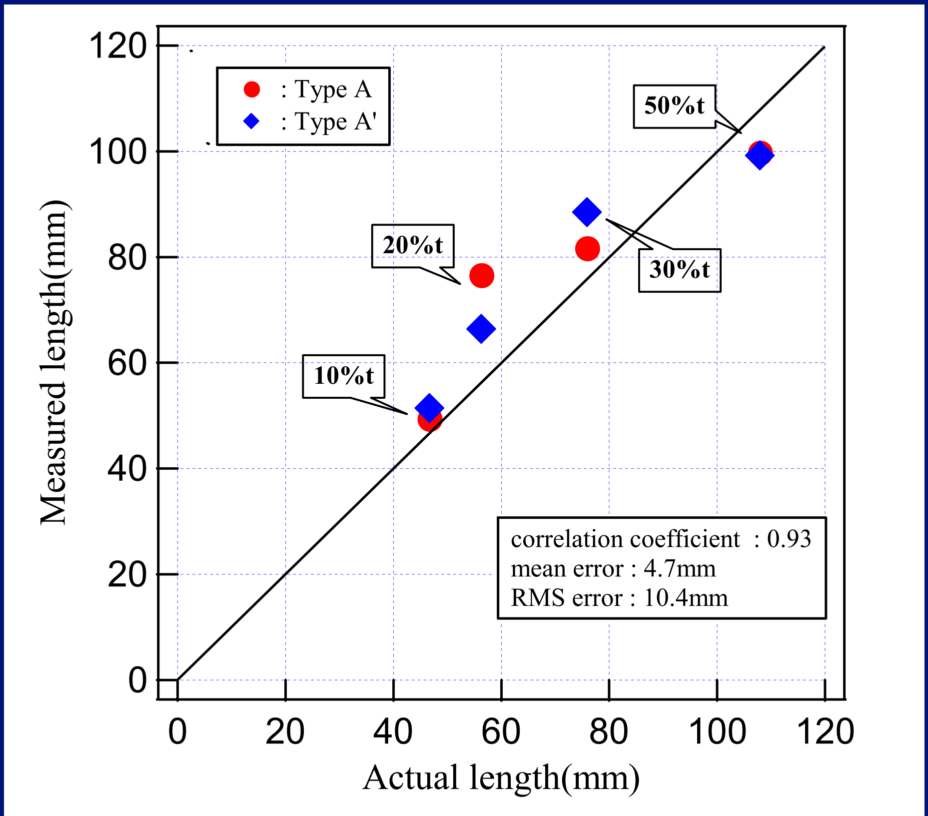
Correlation coefficient : 0.88

RMS error : 6.2 mm

Results of length sizing



All probes



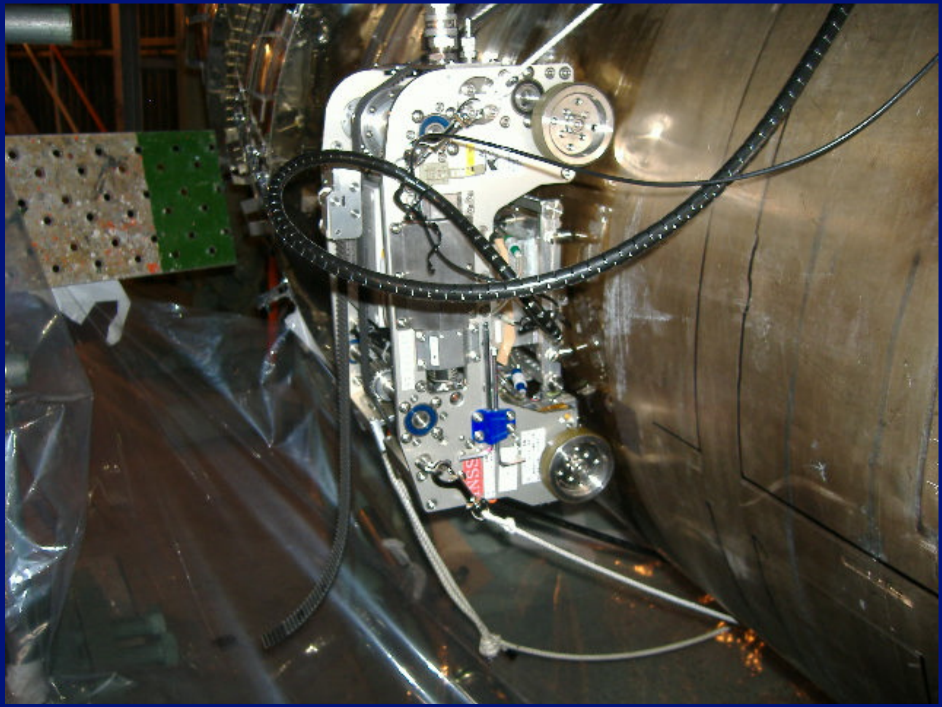
Optimized probes

Optimized probe improves length sizing performance

On-site verification

Operability of automated scanning device was verified at 7 NPPs in Japan. (from 1999 to 2006)

No specific indication was found.



Conclusion

Detection performance

a. INSS automated ultrasonic inspection system detected all the defects with good SN ratio.
b. Some false calls were observed in Category I test assembly.

Depth and length sizing performance

a. Fatigue cracks over 20%t could be sized.
b. Use of probes with different focal depths is very effective in improving depth sizing accuracy.
c. Length sizing performance was good. It can be improved with optimized probes.

On-site verification

a. We have conducted on-site verification at 7 NPP's in Japan from 1999 to 2006.
b. Whole system operated with no problem.

END