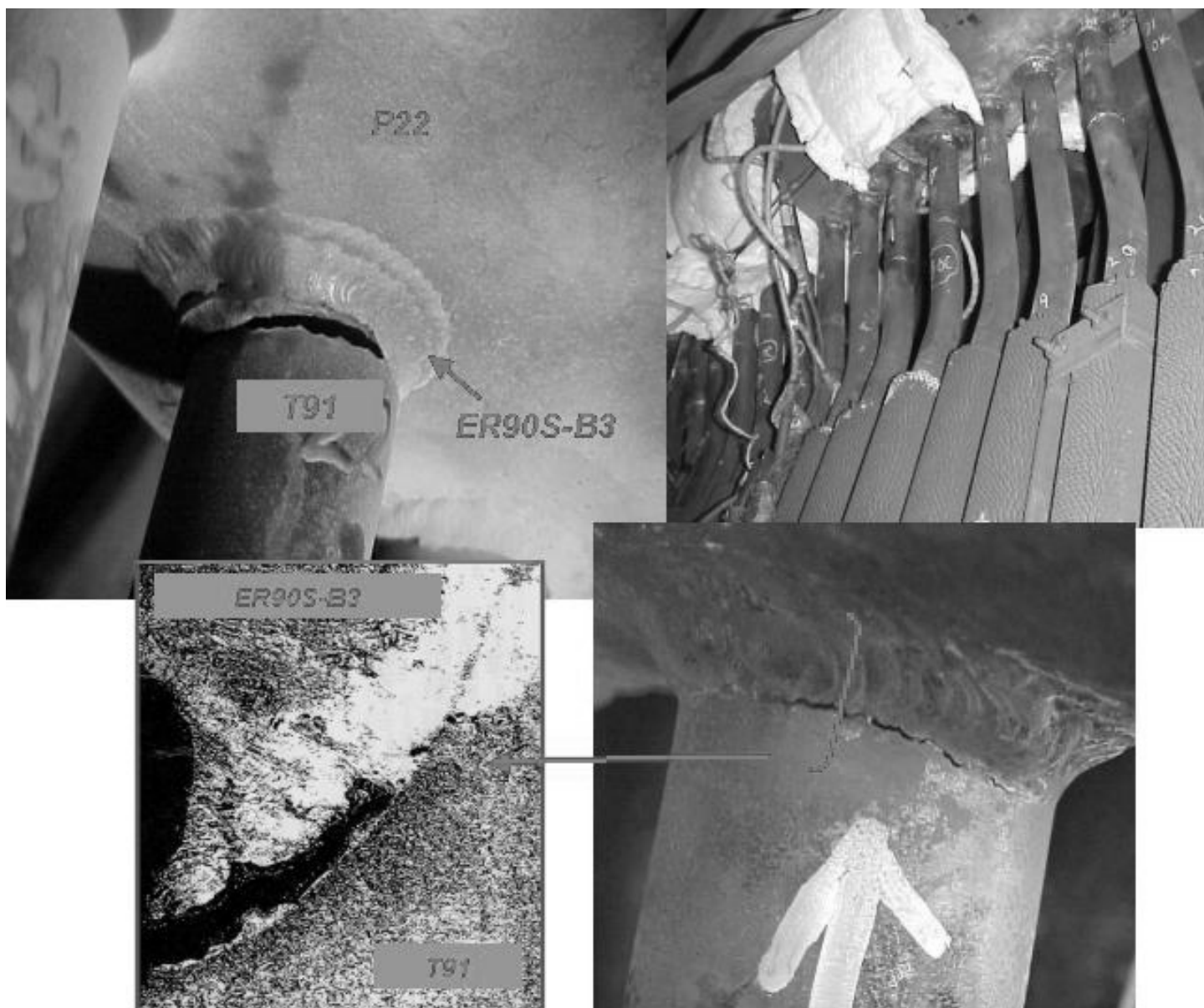


Guidelines for the Nondestructive Examination of Heat Recovery Steam Generators

Revision 1

Effective December 6, 2006, this report has been made publicly available in accordance with Section 734.3(b)(3) and published in accordance with Section 734.7 of the U.S. Export Administration Regulations. As a result of this publication, this report is subject to only copyright protection and does not require any license agreement from EPRI. This notice supersedes the export control restrictions and any proprietary licensed material notices embedded in the document prior to publication.



Guidelines for the Nondestructive Examination of Heat Recovery Steam Generators

Revision 1

1012759

Final Report, February 2007

EPRI Project Manager
S. Walker

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Electric Power Research Institute (EPRI)

Aptech Engineering Services, Inc.

Cornice Engineering

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2007 Electric Power Research Institute, Inc. All rights reserved.

CITATIONS

This report was prepared by

Electric Power Research Institute (EPRI)
1300 W.T. Harris Blvd.
Charlotte, NC 28262

Principal Investigator
S. Walker

Aptech Engineering Services, Inc.
1253 Reamwood Avenue
Sunnyvale, CA 95030

Principal Investigators
S. Paterson
T. Kuntz
J. Yavelak

Cornice Engineering
42 Aspen Drive, DW II
Durango, CO 81301-8300

Principal Investigator
W. McNaughton

This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Guidelines for the Nondestructive Examination of Heat Recovery Steam Generators: Revision 1.
EPRI, Palo Alto, CA: 2007. 1012759.

REPORT SUMMARY

As heat recovery steam generators (HRSGs) have become more complex over the last 15 years, operating with multiple pressures and temperatures, operators have experienced an increasing suite of HRSG tube failures (HTFs). This report provides guidance on the performance of nondestructive evaluation (NDE) of HRSGs so that operators will know what types of NDE to perform and where to perform them.

Background

Modern HRSGs have numerous varieties available within the basic designs, which—over the past decade—have become remarkably complex, operating at significantly higher pressures and temperatures. Although these more advanced units are relatively young, they have already begun to experience tube failures. Headers and piping have also experienced degradation. Failures are typically caused by mechanisms identical or analogous to boiler tube failures in conventional plants, about which there are some 30 years of research available for diagnosis and prevention. Applying the appropriate NDE methods to each of the components and damage mechanisms is key to maintaining safe continued operation.

NDE can be used to detect developing damage in HRSG pressure parts in a manner that will help prevent subsequent failures. Timely NDE can save money by allowing the HRSG operator to (1) monitor problematic areas for signs of incipient damage, (2) modify operating or maintenance procedures to lessen developing damage, (3) proactively schedule outages to deal with a developing problem rather than being forced into an expensive outage, and (4) monitor the effectiveness of implemented actions.

Objectives

- To provide NDE and inspection information derived from the experience in conventional plants and from the current HRSG experience base
- To address one of the overall goals for an HRSG pressure-part failure reduction program—less than one HRSG pressure-part failure per unit per year

Approach

The project team reviewed EPRI's *Heat Recovery Steam Generator Tube Failure Manual* (EPRI report 1004503) to note the locations and types of failures that have occurred in HRSGs. The team then compiled joint experiences in performing examinations of HRSG components, along with information contained in the *NDE Guidelines for Fossil Power Plants* (EPRI report TR-108450), to create this NDE guidelines document. The material contained here should be

considered interim and limited to the knowledge currently available because the experience related to NDE of HRSG tubing and pressure parts is relatively new and the technology needed to inspect some components is still evolving.

Results

These guidelines include comprehensive information on where HRSG failures occur, what damage mechanism is operative on various components, how to examine the components for damage, and how to establish subsequent reinspection intervals.

EPRI Perspective

This guidelines report is associated with six companion documents dealing with the problem of HRSG tube failures. *Heat Recovery Steam Generator Tube Failure Manual* (EPRI report 1004503) provides detailed descriptions of the HRSG tube failure mechanisms, including how to diagnose, correct, and prevent them. *Delivering High Reliability Heat Recovery Steam Generators* (EPRI report 1004240) applies the lessons learned from the evaluation of HRSG tube failures to the design, procurement, fabrication, and commissioning stages in the life of an HRSG; it describes how to avoid failures in HRSG pressure parts by addressing these issues throughout the HRSG life. *Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)* (EPRI report 1010438) assists operators and chemists in developing an effective overall cycle chemistry program that will prevent HTF. *HRSG Material Selection and Repair Guidelines* (EPRI report 1004875) provides repair practices and procedures currently being used to correct a number of problems attributed to poor design, improper operation, poor fabrication, or poor installation processes. *Repair Welding Technologies for Heat Recovery Steam Generators* (EPRI report 1010441) examines off-the-shelf tube welding equipment for tube-to-tube welds and provides details on the EPRI-developed HRSG tube-to-header welding device. *Development of Tube Repair Techniques for Heat Recovery Steam Generators* (EPRI technical update 1010512) addresses stress analyses that were performed to compare the EPRI tube-to-header welding approach with the original weld configuration, covers issues relating to Code interaction, and provides a discussion of the internal tube repair process.

This report provides detailed descriptions of the recommended NDE to apply to each component/damage mechanism combination and replaces the prior document *Interim Guidelines for the Nondestructive Examination of Heat Recovery Steam Generators* (EPRI report 1004506) with updated NDE techniques.

Keywords

Combined-cycle power plants
Heat recovery steam generators (HRSGs)
Nondestructive evaluation
Tube failures
Corrosion

ABSTRACT

Over the past 15 years, as heat recovery steam generators (HRSGs) have become more complex and have begun operating at multiple pressures and temperatures, with reheat, once-through, or once-through/drum designs, they have experienced an ever-increasing suite of HRSG tube failures (HTFs). Most of the failure mechanisms are identical to those that have occurred in conventional plants over the last 25 to 40 years; thus, the understanding developed can be directly applied to HRSGs.

This guidelines report is one of seven EPRI documents aimed at avoiding HTF. The *Heat Recovery Steam Generator Tube Failure Manual* (EPRI report 1004503) provides detailed descriptions of the HRSG tube failure mechanisms, including how to diagnose, correct, and prevent them. *Delivering High Reliability Heat Recovery Steam Generators* (EPRI report 1004240) applies the lessons learned from the evaluation of HRSG tube failures to the design, procurement, fabrication, and commissioning stages in the life of an HRSG; it describes how to avoid failures in HRSG pressure parts by addressing these issues throughout the HRSG life. *Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)* (EPRI report 1010438) assists operators and chemists in developing an effective overall cycle chemistry program that will prevent HTFs. *HRSG Material Selection and Repair Guidelines* (EPRI report 1004875) provides repair practices and procedures currently being used to correct a number of problems attributed to poor design, improper operation, poor fabrication, or poor installation practices. *Repair Welding Technologies for Heat Recovery Steam Generators* (EPRI report 1010441) examines off-the-shelf tube welding equipment for tube-to-tube welds and provides details of the EPRI-developed HRSG tube-to-header welding device. *Development of Tube Repair Techniques for Heat Recovery Steam Generators* (EPRI technical update 1010512) addresses stress analyses that were performed to compare the EPRI tube-to-header welding approach with the original weld configuration, covers issues relating to Code interaction, and provides a discussion of the internal tube repair process.

These guidelines contain information on where to inspect HRSGs and which nondestructive evaluation (NDE) methodology to use to identify the specific type of damage in specific locations. Information on performing NDE during shop fabrication, during on-site construction, during commissioning, and periodically during service is provided.

CONTENTS

1 INTRODUCTION	1-1
1.1 Introductory Comments.....	1-1
1.2 Purpose of These Guidelines and Objectives for an Overall HRSG Pressure- Part Failure Reduction Program.....	1-2
1.3 Significance of the Occurrence of HRSG Pressure-Part Failures.....	1-2
1.4 Overall Organization of This Report.....	1-3
1.5 References	1-4
2 HRSG PRESSURE-PART COMPONENTS AND THE CHALLENGES TO NDE.....	2-1
2.1 The Basic Building Blocks of an HRSG	2-1
2.1.1 HRSG Tubes and NDE	2-1
2.1.2 Tube Fin Design, Construction, and NDE	2-3
2.1.3 Tube Materials of Construction and NDE.....	2-3
2.1.4 NDE of Tube Bends and Welds	2-9
2.1.5 NDE of HRSG Headers and Transfer Pipes	2-9
2.1.6 HRSG Drums, Drum Internals, and NDE	2-10
2.1.7 HRSG Piping Systems and NDE	2-11
2.2 Post-Assembly Access Limitations	2-11
2.3 References	2-12
3 INTERNATIONAL CODE REQUIREMENTS AND NDE IMPLICATIONS	3-1
3.1 ASME Boiler and Pressure Vessel Code.....	3-1
3.1.1 Part PG: General, Inspection and Tests	3-2
3.1.2 Part PW: General, Design and Fabrication	3-3
3.1.3 Part PW: General, Inspection and Tests.....	3-3
3.1.4 Part PG: Certification by Stamping and Data Reports	3-3
3.1.5 Appendix A: Quality Control System	3-4
3.2 ASME B31.1 Power Piping Code.....	3-4
3.3 European Standard EN 12952.....	3-5

3.4	Code Clauses Pertaining to Examination Methods.....	3-6
3.4.1	ASME Boiler and Pressure Vessel Code	3-6
3.4.2	ASME B31.1.....	3-7
3.4.3	European Standard EN 12952	3-7
3.5	Code Clauses Pertaining to Acceptance Criteria.....	3-7
3.5.1	ASME Boiler and Pressure Vessel Code	3-7
3.5.2	ASME B31.1.....	3-8
3.5.3	European Standard EN 12952	3-8
4	ROADMAP FOR HRSG INSPECTIONS AND IN-SERVICE INSPECTION.....	4-1
4.1	Roadmap for HRSG Examination	4-1
4.2	In-Service Examinations—General Considerations	4-15
4.3	In-Service Examinations—Locations to Be Examined	4-16
4.4	How Often to Look—Setting Examination Intervals	4-17
4.4.1	Issues for Fatigue-Related Mechanisms.....	4-17
4.4.2	Issues for Corrosion-Related Mechanisms	4-19
4.4.3	Issues for Temperature-Related Mechanisms	4-20
4.4.4	Issues for Layup-Related Mechanisms	4-20
4.5	How Should the Examination Information Be Used?	4-21
4.6	Summary of Techniques	4-22
4.7	References	4-26
5	FOCUSING NDE SPECIFICALLY FOR KNOWN OR SUSPECTED MECHANISMS OF DEGRADATION	5-1
5.1	Service-Induced Damage Mechanisms	5-1
5.2	Reference	5-18
6	INTRODUCTION TO NDE METHODS AND SURFACE PREPARATION FOR HRSG EXAMINATIONS	6-1
6.1	Introduction	6-1
6.2	Surface Preparation.....	6-1
6.2.1	No Surface Preparation.....	6-2
6.2.2	Surface Debris/Scale Removal	6-2
6.3	Access Limitations	6-3
6.4	Related Literature	6-4

7 SURFACE AND NEAR-SURFACE EXAMINATION TECHNIQUES	7-1
7.1 Visual Examination	7-1
7.1.1 Introduction	7-1
7.1.2 Equipment.....	7-2
7.1.3 Implementation.....	7-3
7.1.3.1 Access	7-3
7.1.3.2 Diagrams and Plans.....	7-4
7.1.3.3 Temperature	7-4
7.1.3.4 Internal Conditions	7-4
7.1.3.5 Nearby Operations.....	7-4
7.1.3.6 Protection for Equipment	7-5
7.1.3.7 Establishing a Baseline.....	7-5
7.1.3.8 Care in Choosing Examination and Documentation Angles	7-5
7.1.4 Applications.....	7-6
7.1.5 Debris Removal.....	7-7
7.1.6 Related Literature for Visual Examination.....	7-9
7.2 Dimensional Measurements	7-9
7.2.1 Introduction	7-9
7.2.2 Component Application.....	7-9
7.2.3 Measurement Implementation.....	7-9
7.2.4 Measurement Application Methods.....	7-10
7.3 Magnetic Particle Examination.....	7-10
7.3.1 Introduction	7-10
7.3.2 Applications.....	7-11
7.3.3 Magnetic Particle Types.....	7-11
7.3.4 Implementation.....	7-12
7.3.5 Application Methods.....	7-14
7.3.6 Related Literature for Magnetic Particle Examination	7-15
7.4 Liquid Penetrant Examination	7-15
7.4.1 Introduction	7-15
7.4.2 Application Methods.....	7-16
7.4.3 Penetrant Types.....	7-16
7.4.4 Implementation.....	7-17
7.4.5 Applications.....	7-19

7.4.6	Reference and Related Literature for Liquid Penetrant Examination	7-19
7.5	Eddy Current.....	7-20
7.5.1	Introduction	7-20
7.5.2	Advantages and Disadvantages	7-20
7.5.3	Generation of Eddy Currents	7-21
7.5.4	Important Probe Design Criteria.....	7-22
7.5.5	Required Equipment	7-23
7.5.6	Surface Eddy Current Examination.....	7-24
7.5.7	Applications.....	7-25
7.5.8	Related Literature for Eddy Current Examination	7-25
7.6	AC Potential Drop	7-25
7.6.1	Introduction	7-25
7.6.2	Advantages and Disadvantages	7-26
7.6.3	Basic Theory	7-26
7.6.4	Implementation.....	7-28
7.6.5	Equipment.....	7-29
7.6.6	Applications.....	7-29
7.6.7	Related Literature for AC Potential Drop.....	7-29
8	VOLUMETRIC EXAMINATION TECHNIQUES	8-1
8.1	Ultrasonic Examination	8-1
8.1.1	Introduction	8-1
8.1.2	Generation of Ultrasonic Waves in Materials	8-3
8.1.3	Basic Ultrasonic Propagation Modes	8-4
8.1.4	Reflection, Refraction, and Mode Conversion.....	8-7
8.1.5	Ultrasonic Examination Techniques.....	8-11
8.1.6	Ultrasonic Data Display Formats.....	8-13
8.1.7	Important Ultrasonic Beam Characteristics.....	8-16
8.1.7.1	Near Field Limit.....	8-16
8.1.7.2	Beam Spread	8-17
8.1.8	Required Equipment for Ultrasonic Examination	8-22
8.1.9	Applications of Ultrasonic Examination	8-22
8.1.10	Special-Application Ultrasonic Techniques and Required Equipment.....	8-23
8.1.10.1	Focused Beam Techniques	8-24
8.1.10.2	Spatially Displaced Transducers.....	8-26

8.1.10.3	High-Angle Longitudinal Waves.....	8-28
8.1.10.4	Linear Phased Array Technology.....	8-29
8.1.10.5	Synthetic Aperture Focusing Technique	8-37
8.1.10.6	Time-of-Flight Diffraction Technique.....	8-38
8.1.10.7	Electromagnetic Acoustic Transducers.....	8-42
8.1.11	Related Literature for Ultrasonic Examination	8-43
8.2	Radiography	8-44
8.2.1	Introduction	8-44
8.2.2	Applications.....	8-46
8.2.3	Equipment.....	8-46
8.2.4	Examination	8-46
8.2.5	Recent Advances	8-46
8.2.5.1	High-Energy Portable X-Ray Machines	8-47
8.2.5.2	Direct Digital Detectors	8-47
8.2.5.3	Techniques for Reduced Exclusion Zones	8-47
8.2.5.4	Advances in Crack Depth Sizing.....	8-47
8.2.6	Related Literature for Radiography	8-48
8.3	Low-Frequency Electromagnetic Technique.....	8-49
8.3.1	Background.....	8-49
8.3.2	Concept.....	8-49
8.3.3	Application and Limitations	8-50
8.3.4	Related Literature for Low-Frequency Electromagnetic Technique	8-54
9	MATERIAL CHARACTERIZATION	9-1
9.1	Alloy Identification	9-1
9.1.1	Introduction	9-1
9.1.2	Manufacturer's Identification	9-1
9.1.3	Qualitative Alloy Identification	9-2
9.1.4	Quantitative Alloy Identification	9-3
9.2	Replication	9-4
9.2.1	Introduction	9-4
9.2.2	Casting Replication	9-4
9.2.3	Metallurgical Replication	9-4
9.3	Portable Hardness Testing	9-7
9.4	Etchants.....	9-8

9.4.1	Introduction	9-8
9.4.2	Component Application	9-8
9.4.3	Application Methods.....	9-8
9.4.4	Implementation.....	9-9
9.5	Miniature Sampling and Small Punch Testing	9-9
9.5.1	Introduction	9-9
9.5.2	Miniature Sampling	9-9
9.5.3	Small Punch Testing	9-10
9.6	Stress Measurement.....	9-11
9.6.1	Introduction	9-11
9.6.2	The Ultrasonic Method for Stress Measurement.....	9-12
9.6.3	The Magnetic Method for Stress Measurement.....	9-12
9.6.4	Applications.....	9-14
9.6.5	Advantages and Disadvantages	9-14
9.6.6	Required Equipment	9-15
9.7	Reference and Related Literature.....	9-15
10	OXIDE AND WALL THICKNESS MEASUREMENT TECHNIQUES	10-1
10.1	Ultrasonic Oxide Measurements	10-1
10.1.1	Applications	10-2
10.1.2	Ultrasonic Equipment for Oxide Measurements	10-2
10.2	Pulsed Eddy Current Technology	10-3
10.2.1	Implementation	10-3
10.2.2	Applications	10-4
10.2.3	Related Literature for Pulsed Eddy Current Examination	10-4
11	REMOTE NDE TECHNIQUES	11-1
11.1	Remote Methods: Infrared Thermography	11-1
11.1.1	Introduction	11-1
11.1.2	Fundamentals	11-1
11.1.3	Applications	11-2
11.2	Remote Methods: Transient Infrared Thermography	11-3
11.2.1	Introduction	11-3
11.2.2	Advantages and Disadvantages	11-3
11.2.3	Basic Theory	11-3

11.2.4	Implementation	11-4
11.2.5	Equipment.....	11-5
11.2.6	Applications	11-5
11.2.7	Related Literature for Infrared Thermography	11-6
12 NDE CONSIDERATIONS DURING DESIGN, PREFABRICATION, AND SHOP FABRICATION		12-1
12.1	Prevention of Potential Problems by Design Review	12-1
12.2	Prevention of Potential Flaws and Deficiencies Prior to Starting Fabrication	12-2
12.3	Prevention of Potential Flaws and Deficiencies During Fabrication (Construction).....	12-3
12.3.1	Overview of Fabrication Issues and General Considerations.....	12-3
12.3.2	Machining, Flame Cutting, and Grinding.....	12-3
12.3.3	Bending.....	12-4
12.3.4	Welding.....	12-5
12.3.4.1	General Welding Issues.....	12-6
12.3.4.2	Welder Performance Qualification and Training	12-6
12.3.4.3	Welding Process Controls.....	12-6
12.3.4.4	Weld Preparation	12-7
12.3.4.5	Welding Processes	12-7
12.3.4.6	Welding Filler Materials, Shielding, and Purging Gases	12-7
12.3.4.7	Preheat, Interpass Temperature, and Interstage Temperature Requirements	12-7
12.3.5	Post-Weld Heat Treatment	12-8
12.4	Common Weld Flaws and Nonconformances; Post-Weld NDE.....	12-9
12.5	Fabrication Hydrotests	12-10
12.6	Post-Fabrication Shipping and Storage	12-10
12.7	References.....	12-12
13 NDE CONSIDERATIONS AND FLAW PREVENTION DURING ON-SITE CONSTRUCTION		13-1
13.1	General Issues Pertaining to On-Site Construction QA/QC	13-1
13.2	General Issues Pertaining to On-Site Welding.....	13-1
13.3	General Issues Pertaining to On-Site Post-Weld Heat Treatment	13-3
13.4	General Issues Pertaining to On-Site Construction NDE	13-3
13.5	References.....	13-5

14 NDE DURING COMMISSIONING	14-1
14.1 Introduction	14-1
14.2 Baseline NDE Measurements	14-2
14.3 Diagnostic Troubleshooting and Monitoring	14-2
14.3.1 Measurements of Environmental Conditions	14-2
14.3.2 Temperature Measurements	14-2
14.3.3 Stress Measurements	14-4
14.3.4 Installation of Diagnostic NDE Equipment	14-4
14.4 Pressure Testing and NDE	14-4
14.5 References	14-5
 A GENERIC OWNER HRSG BID SPECIFICATION (NDE SECTIONS).....	A-1

LIST OF FIGURES

Figure 2-1 Photograph of a Partially Finished HRSG Assembly.....	2-12
Figure 4-1 Roadmap for HRSG Inspections with Three Starting Points for Use of Information Contained in This Report	4-2
Figure 4-2 Steps in Establishing a Periodic In-Service Examination Program	4-16
Figure 7-1 Recommended Photographic Angles to Highlight Tube Plastic Deformation (Left) and Overheating (Right)	7-6
Figure 7-2 Examples of Debris Found in HRSG Tubing (Shot Blast Media, Exfoliated Oxide Scale, and a Rock-Like Particle).....	7-8
Figure 7-3 Use of a Yoke to Detect Axial Cracks.....	7-13
Figure 7-4 Different Magnetization Directions and Impact on Flaw Orientation Sensitivity.....	7-14
Figure 7-5 Generation of Eddy Currents.....	7-21
Figure 7-6 A Surface Probe	7-24
Figure 7-7 Plus-Point Eddy Current Sensor.....	7-24
Figure 7-8 The Concept of AC Potential Drop	7-27
Figure 8-1 Variety of Ultrasonic Transducers	8-3
Figure 8-2 Zero Degree and Angle-Beam Transducers.....	8-4
Figure 8-3 Longitudinal and Shear Wave Modes Compared.....	8-5
Figure 8-4 Mode Conversion to Produce Shear and Surface Wave Modes	8-6
Figure 8-5 Symmetrical and Asymmetrical Lamb Waves	8-6
Figure 8-6 Examination of Multiple Surfaces	8-7
Figure 8-7 Single-Transducer Pulse-Echo Technique	8-8
Figure 8-8 Angle Beam Generation by Refraction	8-10
Figure 8-9 Critical Angles of Refraction	8-11
Figure 8-10 Pulse-Echo Ultrasonic Technique	8-12
Figure 8-11 Pitch-Catch Ultrasonic Technique	8-12
Figure 8-12 A-Scan Display Format.....	8-14
Figure 8-13 Orthogonal Image Views	8-15
Figure 8-14 Beam Axis Pressure Profile.....	8-17
Figure 8-15 Ultrasonic Beam Spread.....	8-18
Figure 8-16 Longitudinal-Wave Echodynamic Response	8-20
Figure 8-17 Shear-Wave Echodynamic Response.....	8-21
Figure 8-18 Beam Focusing.....	8-25

Figure 8-19 The LLT Ultrasonic Technique for Through-Wall Oriented Flaws.....	8-27
Figure 8-20 Mode-Converted Longitudinal Wave Ultrasonic Technique	8-28
Figure 8-21 Operating the Array with Constant Phase	8-30
Figure 8-22 Operating the Array with Linear Phase.....	8-30
Figure 8-23 Operating the Array with Nonlinear Phase	8-30
Figure 8-24 Using an Array to Examine a Cross-Section by Steering the Sound Beam Electronically	8-31
Figure 8-25 Using a Conventional Probe to Examine a Cross-Section by Scanning the Probe Mechanically	8-31
Figure 8-26 Example of a Raster Scan Pattern	8-32
Figure 8-27 Example of a Line Scan Pattern	8-33
Figure 8-28 Phased Array Probe, Mechanical Pipe Scanner, and Pipe Specimen	8-34
Figure 8-29 Phased Array Coverage of a Seam Weld from Two Probe Positions.....	8-35
Figure 8-30 B-Scan Image of a Crack Connected to the Inside Surface	8-35
Figure 8-31 Sector Scan Image of a Crack Connected to the Inside Surface at a Weld Fusion Line.....	8-36
Figure 8-32 Potential for Focusing Using Phased Array Technology	8-37
Figure 8-33 Diffracted Signals Associated with Time-of-Flight Diffraction	8-39
Figure 8-34 Graph Showing Measured Ligament Beneath Calibration Notches	8-48
Figure 8-35 Principles of LFET	8-49
Figure 8-36 LFET Sensor Applied for HRSG Tubing	8-50
Figure 8-37 LFET Sensor for HRSG Tubing	8-51
Figure 8-38 Example LFET Application—Detection of Outside Surface Flaws	8-52
Figure 8-39 Example LFET Application—Detection of Inside Surface Flaws	8-53
Figure 8-40 Additional Example LFET Application—Detection of Inside Surface Flaws	8-54
Figure 9-1 Examples of Conventional Metallography and Plastic Replication.....	9-5
Figure 9-2 Graphitization in C-Mo Steel.....	9-7
Figure 9-3 Small Punch Testing.....	9-11
Figure 10-1 Pulsed Eddy Current Examination Through Insulation	10-3
Figure 11-1 The Concept of Transient Thermography.....	11-4

LIST OF TABLES

Table 2-1 Common HRSG Tube Materials	2-4
Table 2-2 Tensile and Yield Strengths for Common HRSG Tube Materials	2-8
Table 3-1 Acceptance Criteria Summary for Selected Surface Conditions	3-8
Table 4-1 NDE Priorities for HRSG Life Phases	4-3
Table 4-2 Developing a List of Examination Locations—Likely Damage in Various HRSG Components	4-5
Table 4-3 Summary of Damage Mechanisms, Examination Locations, and Examination Techniques	4-10
Table 4-4 Overview of NDE Methods and Their Applicability to HRSGs	4-22
Table 5-1 Corrosion Fatigue	5-2
Table 5-2 Thermal-Mechanical Fatigue	5-3
Table 5-3 Creep Fatigue	5-4
Table 5-4 Flow-Induced Vibration Fatigue	5-5
Table 5-5 Flow-Accelerated Corrosion	5-6
Table 5-6 Acid Phosphate Corrosion	5-8
Table 5-7 Caustic Gouging	5-9
Table 5-8 Hydrogen Damage	5-10
Table 5-9 Internal Pitting	5-11
Table 5-10 Gas-Side Corrosion and Pitting	5-12
Table 5-11 Acid Dew Point Corrosion	5-13
Table 5-12 Stress Corrosion Cracking	5-14
Table 5-13 Short-Term Overheating	5-15
Table 5-14 Long-Term Overheating	5-16
Table 5-15 Thermal Quenching	5-17
Table 7-1 Selection of Penetrant Systems	7-19

1

INTRODUCTION

1.1 Introductory Comments

Modern heat recovery steam generators (HRSGs) have numerous varieties available within the basic designs, which over the past decade have become remarkably complex, operating at significantly higher pressures and temperatures. Although these more advanced units are relatively young, they have already begun to experience tube failures [1-1]. Headers and piping have also experienced degradation. Failures are typically caused by mechanisms identical or analogous to boiler tube failures in conventional plants, about which there are some 30 years of research available for diagnosis and prevention [1-2]. Applying the appropriate nondestructive evaluation (NDE) methods to each of the components and damage mechanisms is key to maintaining continued safe operation.

This guidelines report is associated with the following six companion documents that deal with the problem of HRSG tube failures:

- *Heat Recovery Steam Generator Tube Failure Manual* [1-1] provides detailed descriptions of HRSG tube failure mechanisms, including how to diagnose, correct, and prevent them.
- *Delivering High Reliability Heat Recovery Steam Generators* [1-3] applies the lessons learned from the evaluation of HRSG tube failures to the design, procurement, fabrication, and commissioning stages in the life of an HRSG. It describes how to avoid failures in HRSG pressure parts by addressing these issues throughout the HRSG life.
- *Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)* [1-4] assists operators and chemists in developing an effective overall cycle chemistry program that will prevent HTFs.
- *HRSG Material Selection and Repair Guidelines* [1-5] provides repair practices and procedures currently being used to correct a number of problems attributed to poor design, improper operation, poor fabrication, or poor installation practices.
- *Repair Welding Technologies for Heat Recovery Steam Generators* [1-6] examines off-the-shelf tube welding equipment for tube-to-tube welds and provides details of the EPRI-developed HRSG tube-to-header welding device.
- *Development of Tube Repair Techniques for Heat Recovery Steam Generators* [1-7] addresses stress analyses that were performed to compare the EPRI tube-to-header welding approach with the original weld configuration, covers issues relating to Code interaction, and provides a discussion of the internal tube repair process.

These guidelines provide detailed descriptions of the recommended NDE that should be applied to each component/damage mechanism combination and replace the interim guidance provided in *Interim Guidelines for the Nondestructive Examination of Heat Recovery Steam Generators* [1-8].

1.2 Purpose of These Guidelines and Objectives for an Overall HRSG Pressure-Part Failure Reduction Program

The primary purpose of these guidelines is to provide NDE and inspection information derived from the experience in conventional plants and from the current HRSG experience base. NDE can be used to detect developing damage in HRSG pressure parts in a manner that will help prevent subsequent failures. Timely NDE can save money by allowing the HRSG operator to:

- Monitor problematic areas for signs of incipient damage
- Modify operating or maintenance procedures to lessen developing damage
- Proactively schedule outages to deal with a developing problem rather than being forced into an expensive outage
- Monitor the effectiveness of implemented actions

The NDE described in this report is intended to address one of the overall goals for an HRSG pressure-part failure reduction program—less than one HRSG pressure-part failure per unit per year.

The material contained here should be considered interim and limited to the knowledge currently available, because the experience related to damage affecting HRSG tubing and other pressure parts is relatively new and the technology needed to inspect some components is still evolving.

1.3 Significance of the Occurrence of HRSG Pressure-Part Failures

Because the construction of most designs of HRSG severely restricts access unless many tubes are cut out, forced outages to repair tube lengths may be lengthy and costly. After the failed tubes are removed, new tubes must be reinstalled and receive a new heat treatment, a process that will occur in a much more difficult environment than the original factory construction. Because of the repair, the integrity of repaired HRSG modules, particularly in difficult locations such as tube-to-header attachment welds, is likely to be of lower quality than the original factory fabrication; consequently, further failures may occur after a relatively short time [1-1].

1.4 Overall Organization of This Report

This document is organized in four parts.

Part I, comprising Sections 1–5, provides background information that helps frame the issues of inspection of HRSG units:

- Section 1 is the introduction to this report.
- Section 2 contains information on how the various alloy types, component dimensions, and component clearances impact various NDE practices and capabilities.
- Section 3 contains a comparison of international codes and standards that pertain to NDE methods and flaw acceptance criteria.
- Section 4 provides an overall roadmap of the steps for examining HRSG units and how those steps are integrated with the avoidance and/or analysis of HRSG damage. Sections 4 and 5 form the backbone of the guidelines and are specifically recommended for careful reading. Section 4 also discusses issues of in-service examination of HRSGs.
- Section 5 provides information to focus NDE specifically for known or suspected mechanisms of deterioration. In this section, one- or two-page descriptions of damage types are provided, each containing a summary of the following:
 - The damage mechanism
 - Appearance of damage
 - Where the damage occurs
 - How to find the damage
 - How to quantify the severity of damage
 - Optional NDE
 - What amount of this type of damage is acceptable
 - Repair options
 - Corrective actions
 - Other related, potentially active damage mechanisms
 - Other comments

Part II, comprising Sections 6–11, provides an overview of the primary, most commonly used NDE techniques for application to the examination of HRSG pressure parts [1-9]:

- Section 6 provides an overview of NDE methods and surface preparation.
- Section 7 looks at surface and near-surface examination techniques such as:
 - Visual examination
 - Dimensional measurements

- Magnetic particle examination
- Liquid penetrant examination
- Eddy current examination
- AC potential drop
- Section 8 provides detailed information about volumetric techniques, specifically ultrasonic and radiographic examination.
- Section 9 provides an overview of methods used for material characterization, including alloy identification, replication, portable hardness testing, etchants, miniature sampling, small punch testing, and stress measurement.
- Section 10 provides information on ultrasonics-based oxide and wall thickness measurements for remaining creep life determination.
- Section 11 concludes the discussion of NDE methods by looking at thermographic techniques.

Part III looks at the inspection/NDE requirements at each stage of the life of the HRSG unit. The material is divided into life stages:

- Section 12 contains descriptions of NDE considerations and flaw prevention during design, pre-fabrication, and shop fabrication.
- Section 13 covers on-site construction NDE considerations and flaw prevention.
- Section 14 contains descriptions of NDE to be performed during commissioning, how to perform as-built baseline examinations, and what to do if damage or failure occurs.

Appendix A provides a generic bid specification example that owners might use when planning for NDE and hiring NDE contractors.

1.5 References

- 1-1. *Heat Recovery Steam Generator Tube Failure Manual*. EPRI, Palo Alto, CA: 2002. 1004503.
- 1-2. *Boiler Tube Failures: Theory and Practice, Volume 1: Boiler Tube Fundamentals; Volume 2: Water-Touched Tubes; Volume 3: Steam-Touched Tubes*. EPRI, Palo Alto, CA: 1996. TR-105261.
- 1-3. *Delivering High Reliability Heat Recovery Steam Generators*. EPRI, Palo Alto, CA: 2003. 1004240.
- 1-4. *Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)*. EPRI, Palo Alto, CA: 2006. 1010438.
- 1-5. *HRSG Material Selection and Repair Guidelines*. EPRI, Palo Alto, CA: 2004. 1004875.

- 1-6. *Repair Welding Technologies for Heat Recovery Steam Generators*. EPRI, Palo Alto, CA: 2005. 1010441.
- 1-7. *Development of Tube Repair Techniques for Heat Recovery Steam Generators*. EPRI, Palo Alto, CA: 2006. 1010512.
- 1-8. *Interim Guidelines for the Nondestructive Examination of Heat Recovery Steam Generators*. EPRI, Palo Alto, CA: 2004. 1004506.
- 1-9. *NDE Guidelines for Fossil Power Plants*. EPRI, Palo Alto, CA: 1997. TR-108450.

2

HRSG PRESSURE-PART COMPONENTS AND THE CHALLENGES TO NDE

This section describes the various pressure-part components, product forms, subsystems, and completed HRSGs in a manner that will highlight the challenges put forth for the NDE of constructed and operating units. The basic elements and building blocks are discussed, emphasizing susceptibility to various mechanisms of deterioration and useful NDE techniques to gauge and monitor damage progression.

2.1 The Basic Building Blocks of an HRSG

HRSGs are complex systems of tubing, headers, drums, and piping that work together to transfer the heat energy from hot combustion turbine exhaust and/or duct burner gases into the kinetic energy of pressurized steam. The ultimate goal of the HRSG is to transfer heat in the most efficient manner. This requires close tolerances and dense packing of the HRSG. To optimize the heat transfer efficiency, most of the tubing includes segmented or solid spiral-wound fins. The individual elements of the system are brought together in close proximity to one another in an attempt to optimize the heat transfer efficiency. It is the presence of tube fins and the close proximity of HRSG components that provide the bulk of the challenges to effective NDE.

Modern HRSGs are made up of modules that are positioned along the gas path and designed to extract heat uniformly from the flowing exhaust gases. Each module contains some number of elements, or “harps,” as they are known in current construction. Harps are made up of tubes and headers that are welded together in the shop and then shipped to the site for erection.

After assembly has taken place, access to most segments of the HRSG tube circuits is limited. Currently used examination techniques such as visual, liquid penetrant, magnetic particle, wet fluorescence magnetic particle, and ultrasonic are practical only at the module leading and trailing edges and within the header enclosures. Therefore, it is important for quality control/quality assurance (QC/QA) during manufacture and installation to be capable of finding all manufacturing defects.

2.1.1 *HRSG Tubes and NDE*

The primary purpose of an HRSG tube is to transfer heat generated by the combustion process to the water and/or steam within the tube. The tube must have both sufficient mechanical strength (a function of its diameter, wall thickness, and material of construction) to contain the internal

pressure and adequate resistance to corrosion on both surfaces. These requirements must be continuously met over the required life of the HRSG, usually well in excess of 100,000 operating hours.

HRSG designers predominantly use finned tubes to increase the convective heat transfer from the exhaust gas through the tube wall. The use of finned tubes makes the circuits more compact but also more difficult to access. The integrity of the bare tubing (which, in the case of SA-178, SA-226, and SA-250 will contain a seam weld) and the fin bond to the tube must be verified during the shop fabrication stage of life. Incomplete fusion in the electric resistance seam welds has been identified as the initiation site for numerous in-service failures. Bare tubes are sometimes used downstream of supplementary burners to limit the metal temperature of the tubes, because they are exposed to increased radiant heat transfer and higher gas temperatures.

Standard tube sizes supplied in the bare tube condition are most often used to begin the HRSG building process in the shop. Most tubes purchased are constructed of carbon steel in the sections operating below 800°F (427°C). The carbon steel tubing is often made with electric resistance welding in order to reduce costs. Suppliers send the tubes to the shop for attaching fins, bending, and welding.

Close visual examination during the attachment of fins and select destructive mechanical strength tests of the fin-to-tube bonds on completed tubes will locate some manufacturing defects, for example, incomplete fusion.

Seamless carbon steel and alloy steel tubing should also be examined in the shop prior to fin attachment. Specific concerns include:

- Internal corrosion of improperly capped tubes
- Residue from corrosion inhibitors
- Dents
- Abrasions
- Out-of-specification chemistry
- Dimensions
- Mechanical properties
- Other imperfections

Examiners should spot-check tube dimensions, hardness, and alloy chemistry to verify that alloy tubing meets the specification before further processing the tubes. For seam-welded tubes, hydrotesting (perhaps with a prolonged hold time) should be performed to verify that the seam-welding process produced adequate fusion. Because only a small fraction of the wall thickness needs to be fused to survive a hydrotest, even prolonged hydrotesting of seam-welded tubing will not verify that the seam welds have complete fusion across the entire wall thickness; accordingly, NDE methods such as eddy current or ultrasonic examination have been proposed as a QC/QA test for seam-welded tubing.

2.1.2 Tube Fin Design, Construction, and NDE

Finned tubes are predominant in HRSG units. They have significantly larger surface areas than non-finned tubes; therefore, fewer tubes are needed to achieve the desired fluid thermal energy output. The use of finned tubes can increase the effective heating surface of a tube by a factor of 10 [2-1]. The effective heat flux of finned tubes is higher because of the large ratio of external to internal surface area. Tube wall temperatures will be higher with finned tubes because of the heat flux difference. Unfinned or bare tubes are used in the highest-temperature parts of superheat (SH) circuits in some units, most commonly downstream of supplementary burners in order to avoid excessive peak temperatures.

Tube fins naturally operate at higher temperatures than the tube, and thinner/taller fins operate at higher temperatures than thicker/shorter fins. For every tube diameter, there is an optimum fin height that results from balancing the increased heating surface, fin tip temperature, and heat conduction through the contact surface of the fin to the tube.

Fins may be segmented or plain. It has been estimated that 90% of the fins in HRSGs are segmented, with plain fins being used primarily in SH tube bundles [2-2]. Fin type and density will vary depending on the fuel used. Plain fins and slightly lower fin densities are used for ash-bearing fuels, such as heavy oil. Segmented fins and higher fin densities may be used for natural gas and No. 2 diesel oil. Thicker fins, which may or may not be spaced farther apart, are used in colder sections of the economizer or feedwater preheater section for corrosion protection. Downstream of selective catalytic reduction (SCR), fin spacing needs to be larger to limit the performance degradation effects of ammonium bisulfite/sulfate deposition and to facilitate periodic cleaning to remove the deposits.

By using high-frequency resistance welding to attach strip material to the outside surface, fins are joined to the pressure tubing. The process results in very little melting at the interface, even though a sound and continuous joint results; thus, there is not typically a problem with dissimilar metals used for the pressure tubing and for the fins [2-1]. Fin materials will vary according to expected service conditions. For example, near the gas inlet, stainless steel fins on carbon manganese steel pressure tubing may be used to resist oxidation.

The NDE of finned tubes ready to be assembled into HRSG modules consists of visual and destructive testing of the fin bond strength. The bond must have sufficient strength and ductility to withstand service loads and provide good heat transfer.

2.1.3 Tube Materials of Construction and NDE

Table 2-1 provides an overview of the typical HRSG tube materials, giving their basic composition, alloy designation, and general properties. A list of the minimum tensile and yield strengths of some commonly used HRSG tube materials is provided in Table 2-2. For economic reasons, the majority of materials currently used in the construction of HRSGs are carbon steels. They are classified by their carbon content and are used for tubing, drums, casings, and ducts.

Table 2-1
Common HRSG Tube Materials

Class of Material	General Properties	Typical Tube Alloys			
		U.S. ASTM/ASME	British BS 3059 Part 2	German DIN	Japanese JIS
Carbon steel	Hypoeutectoid steels. Mild corrosion resistance. Moderate strength up to 1000°F (538°C). Susceptible to graphitization above 800°F (427°C).	SA-178: Welded carbon steel: Grade A Grade C Grade D	360	17177 St37.8 17177 St42.8	G3461 STB35E G3461 STB42C G3461 STB52E
		SA-192: Seamless carbon-silicon steel	440	17175 St35.8	G3461 STB35C
		SA-210: Seamless carbon-manganese-silicon steel: Grade A-1 Grade C	360		
			440	17175 St45.8	G3461 STB42C
Carbon-molybdenum (Mo) steel	Greater creep strength than carbon steels. Susceptible to graphitization with prolonged exposure above 875°F (468°C).	SA-209: Seamless carbon-1/2 Mo steel: Grade T1	243	17175 15Mo3	G3462 STBA12Mo G3462 STBA13Mo
		Grade T1a Grade T1b SA-250: Welded carbon-1/2 Mo steel: Grade T1 Grade T1a			

Table 2-1 (continued)
Common HRSG Tube Materials

Class of Material	General Properties	Typical Tube Alloys			
		U.S. ASTM/ASME	British BS 3059 Part 2	German DIN	Japanese JIS
Chromium (Cr)-molybdenum (Mo) steel	Most common boiler tube materials (particularly T22 and T11). Each increase in chromium content yields improved properties, particularly higher strength, creep properties, and improved corrosion resistance. Resistant to graphitization.	SA-213-T2: Seamless 1/2 Cr-1/2 Mo steel	620-460	17175 13CrMo4-4 17175 13CrMo4-4	G3462 STBA20CrMo
		SA-213-T12: Seamless 1 Cr-1/2 Mo steel			G3462 STBA22CrMo
		SA-213-T11: Seamless 1 1/4 Cr-1/2 Mo steel			G3462 STBA23CrMo
		SA-213-T23: Seamless 2 1/4 Cr-1/4 Mo-V-X (W/Cb/B/N/Al) steel	622-490	17175 10CrMo910	
		SA-213-T22: Seamless 2 1/4 Cr-1 Mo steel			17175 X10CrMoVNb9-1
		SA-213-T21: Seamless 3 Cr-1 Mo steel		G3462 STBA26CrMo	
		SA-213-T5: Seamless 5 Cr-1/2 Mo steel			
		SA-213-T5b: Seamless 5 Cr-1/2 Mo steel		629-470 or 629-590	91
		SA-213-T7: Seamless 7 Cr-1/2 Mo steel			
		SA-213-T9: Seamless 9 Cr-1 Mo steel	G3462 STBA28		
		SA-213-T91: Seamless 9 Cr-1 Mo-V-X (Cb/N/Ni/Al) steel		G3462 STBA28	
		SA-213-T92: Seamless 9 Cr-1 Mo-V-X (W/Cu/Cb/B/N/Ni/Al) steel	G3462 STBA28		

Table 2-1 (continued)
Common HRSG Tube Materials

Class of Material	General Properties	Typical Tube Alloys					
		U.S. ASTM/ASME	British BS 3059 Part 2	German DIN	Japanese JIS		
Austenitic stainless steel	Excellent oxidation resistance and good elevated temperature strength. An H following the designation indicates a higher carbon content and slightly higher solution heat treatment temperature.	SA-213: Seamless 18 Cr-8 Ni austenitic stainless steel:	304S51	17456 X2CrNi1911	G3463 SUS304TB		
		TP304			316S51	17455 X5CrNiMo 17122	G3463 SUS304HTB
		TP304H					321S51
		SA-213: Seamless 16 Cr-12 Ni-2 Mo austenitic stainless steel:	347S51	17456 X5CrNiNB 1810			
		TP316			G3463 SUS321TB		
		TP316H				G3463 SUS321HTB	
		SA-213: Seamless 17 Cr-11 Ni-Ti austenitic stainless steel:	G3463 SUS321TB				
		TP321		G3463 SUS321HTB			
		TP321H			G3463 SUS321HTB		
		SA-213: Seamless 18 Cr-10 Ni-Cb austenitic stainless steel:	G3463 SUS321HTB				
TP347	G3463 SUS321HTB						
TP347H		G3463 SUS321HTB					
Grade 253MA: 21 Cr-11 Ni-N austenitic stainless steel			G3463 SUS321HTB				
	G3463 SUS321HTB						
		G3463 SUS321HTB					

Table 2-1 (continued)
Common HRSG Tube Materials

Class of Material	General Properties	Typical Tube Alloys			
		U.S. ASTM/ASME	British BS 3059 Part 2	German DIN	Japanese JIS
Ferritic stainless steel	For use in highly aggressive or high-temperature environments.				
Martensitic stainless steel	For use in highly aggressive or high-temperature environments.				
Duplex stainless steel	For use in highly aggressive or high-temperature environments.	2205: 22 Cr-6 Ni-3 Mo-N duplex stainless steel			
Nonferrous alloys	For use in highly aggressive or high-temperature environments.	Ni-Cr (Alloy 600)			
Nickel-chromium-iron	For use in highly aggressive or high-temperature environments.	Alloy 800 or 800 H			

Note:

Alloy comparisons are for reference only. Refer to the actual specifications for design purposes.

Table 2-2
Tensile and Yield Strengths for Common HRSG Tube Materials

Tube Steel Type	ASME Specification ^a	Grade	Minimum Tensile Strength in ksi (MPa)	Minimum Yield Strength in ksi (MPa)
Carbon Steel				
Electric resistance welded	SA-178	A C	47 ^b (324.1) 60 ^b (413.7)	26 ^b (179.3) 37 (255.1)
Seamless	SA-192	-	47 ^b (324.1)	26 ^b (179.3)
Seamless		A-1 C	60 (413.7) 70 (482.6)	37 (255.1) 40 (275.8)
Electric resistance welded	SA-226	-	47 ^b (324.1)	26 ^b (179.3)
Ferritic Alloy				
Electric resistance welded	SA-250	T1	55 (379.2)	30 (206.8)
Seamless	SA-209	T1	55 (379.2)	30 (206.8)
		T1a	55 (379.2)	30 (206.8)
		T1b	55 (379.2)	30 (206.8)
	SA-213	T2	60 (413.7)	30 (206.8)
Seamless	SA-213	T5 ^c	60 (413.7)	30 (206.8)
		T9 ^c	60 (413.7)	30 (206.8)
		T11	60 (413.7)	30 (206.8)
		T12	60 (413.7)	30 (206.8)
		T22	60 (413.7)	30 (206.8)
		T23	74 (510.2)	58 (399.9)
		T91 ^d	85 (586.1)	60 (413.7)
		T92 ^d	90 (620.5)	64 (441.3)
Austenitic Stainless Steel				
Seamless	SA-213	TP304H	75 (517.1)	30 (206.8)
		TP316H	75 (517.1)	30 (206.8)
		TP321	75 (517.1)	30 (206.8)
		TP347	75 (517.1)	30 (206.8)
		TP347H	75 (517.1)	30 (206.8)
		253MA	87 (599.7)	45 (310.3)
Duplex Stainless Steel				
		2205	99 (682.6)	70 (482.6)

Notes:

- ASME Boiler and Pressure Code, Section I, Power Boilers – Part PG-9, Pipes, Tubes, and Pressure-Containing Parts.
- Not required by ASME material specification. For purposes of design, these tensile properties may be assumed.
- Not commonly used in modern boilers.
- Recently approved.

Typical NDE applied to ensure that the proper tube material is used during shop fabrication includes review of the tube certification reports, application and judicious checking of the tube identification markings throughout construction, hardness checks, and portable alloy analysis. These same techniques can be employed to ensure that the proper fin material is mated to the correct tubes.

2.1.4 NDE of Tube Bends and Welds

Many designs using HRSG tubes require tube bending and welding during manufacture. Tube ovality is a common concern following tube bending. In general, 2% ovality is an acceptable limit that will not result in constricted flow within the tube. Tube bend ovality is defined as the maximum diameter minus the minimum diameter divided by the average diameter. Most HRSG tube bends are gradual over a radius of three tube diameters or greater, although one- or two-diameter “hairpin” bends are common in horizontal tube HRSGs and in regions of vertical tube HRSGs where lower headers are not installed. Visual examination and dimensional measurements should be made to verify tube bend ovality.

Most HRSG tube welds are end weld attachments to headers. Some long tubes and/or bent tube sections may require joining of two tubes by welding. Weld quality is verified by visual examination and radiography for both carbon steel and alloy tubing, although there is considerable debate regarding the usefulness of radiography to detect undesirable imperfections in the tube-to-header connections. Welding procedures, welder qualifications, and weld parameters should also be reviewed for alloy tubing welds. Weld joints are often the weak link in HRSG tubes because of the wide range of microstructures and properties in the weld metal and the base metal heat-affected zone (HAZ) and the geometric features that create local stress/strain concentrations.

2.1.5 NDE of HRSG Headers and Transfer Pipes

Headers serve as the local collection points for steam, water, and two-phase mixtures generated within the HRSG tubes. One, two, or three tube rows are usually attached to the headers, depending on the design requirements of the HRSG. Headers are normally located at the top and bottom in a vertical HRSG to promote mixing of the heated fluids. HRSG headers differ in size from those commonly found in large boilers. Most HRSG headers are 6–20 in. (0.15–0.51 m) in diameter and 10–15 ft (3.05–4.57 m) in length and are of varying thickness to accommodate the design temperatures and pressures.

The process of making a header usually includes starting with sections of seamless pipe or hollow forgings. Transfer pipes are used to feed the headers and carry off the heated fluid. There are usually between one and four transfer pipes per header. Headers are first drilled for attachment of the specified connections, which have been formed from pierced and drawn material. Each connection is circumferentially welded to the header. Visual, magnetic particle, and/or liquid penetrant examination is performed on the header and attachments prior to attachment of the tube rows. After the tubes are installed, visual examination combined with magnetic particle examination and liquid penetrant examination may also be performed. The

final “harp” assembly is then hydrostatically tested to verify the integrity of the welded connections. Harps are in a convenient form for shipping to the job site, where they are placed into position within the HRSG modules. This is the point in construction at which access becomes increasingly limited because the spacing between harps is kept to a minimum.

Further limits to access of the finned tubing occur from the positioning of baffles between the headers. As the harps are placed into position and support structures are completed, the HRSG assembly becomes more complete and less accessible. The erection of the upper casing and a small stagnant air space in the header enclosures that limit thermal losses essentially seal the harps into place within the HRSG modules.

Transfer pipes are welded into place to link adjacent harps and in-line flow paths. Sometimes, it is necessary to force the alignment of transfer pipes, which could lock in stresses or distort harp alignment. Transfer pipe weld quality is evaluated by radiography. It is advisable to maintain close control of welds made to high-alloy materials such as P91 grade. Visual examination and dimensional checks should be made to verify that harp positions are symmetrical throughout the HRSG and do not yield excessive clearances that may create areas for exhaust gases to bypass flow paths through the finned tubing.

2.1.6 HRSG Drums, Drum Internals, and NDE

As with all boiler drums, HRSG drums offer a unique perspective on boiler operation by providing access to fluid side surfaces.

Shop assembly of the drums includes longitudinal and circumferential welds used to attach formed plate material into the final drum dimensions. Radiographic examination of 100% of each of these welds is required, and the code also requires that the radiographic film (the stored image of the radiographic process, which may either be stored on film or digitally) be kept for 10 years. HRSG owners should make provisions to either copy or otherwise secure the film before discarding it. The radiographic film may be useful as a baseline NDE tool for the drum components. Drum attachments are positioned and welded to the vessel in the shop. The completed drum and attachments are stress relieved and then shipped to the job site for erection.

Many of the new, large-capacity HRSG designs feature triple-pressure operation, meaning that they are equipped with three drums. Each of the three drums offers a unique perspective into water chemistry control and future susceptibility to corrosion problems. Drum internals should be examined prior to operation to verify proper positioning of steam sampling, blowdown, and chemical injection lines. Threaded connections between segments of these lines should be tack-welded to prevent in-service rotation from dynamic upset conditions.

HRSG drums are connected to headers and feed piping by risers and downcomers, which are welded in place in the field. Weld quality is verified using visual and radiographic techniques.

2.1.7 HRSG Piping Systems and NDE

HRSG piping systems may have differing levels of complexity, depending on the service duty of the plant. Some HRSGs may be cogenerators that supply steam to an adjacent facility. Other facilities may be the product of repowering where the steam turbine of the existing unit has been retained. These scenarios may require long lengths of steam piping. Some modern HRSGs use P91 material for main steam and hot reheat piping in order to reduce the weight of the piping system. This material requires close QC/QA, especially with regard to the review of welding procedures, welder qualifications, welding parameters, post-weld heat treatment procedures, and parameters used to avoid susceptibility to creep and/or fatigue damage at weld joints.

The most widely used forms of NDE for HRSG pipe welds are magnetic particle and liquid penetrant examination for surface flaw detection and radiography and ultrasonics for volumetric examination. Visual examination should be performed to evaluate the overall condition of the piping system, supports, attachments, routing, and clearances during thermal expansion. Piping supports should be monitored in both the hot and cold positions during commissioning to verify that system design movements are as predicted.

2.2 Post-Assembly Access Limitations

Access to HRSG components becomes increasingly limited as the building blocks of the HRSG are put into place. Figure 2-1 illustrates that point, showing the partial field erection of an HRSG. When the erection process is completed, traditional NDE methods may not be practical as a result of access limitations. The challenge for the HRSG operator following commissioning is to combine on-line operating information with periodic in-service examinations and a proactive HRSG pressure-part plan to avoid costly failures.



Figure 2-1
Photograph of a Partially Finished HRSG Assembly

2.3 References

- 2-1. P. J. Bygate and D. Bell, "Material Selection and Fabrication in Heat Recovery Steam Generators." 1995.
- 2-2. J. Makansi, "HRSGs, Steam Turbines, and Auxiliaries for Combined Cycles," *Power*, September 1994.

3

INTERNATIONAL CODE REQUIREMENTS AND NDE IMPLICATIONS

This section contains an overview of some of the applicable international codes and standards and their implications for NDE and inspection of HRSGs. Because the codes, examination methods, and acceptance criteria summarized in this section are quite lengthy and complex, the intent here is to provide a general discussion with references to where to find more details rather than listing specific rules and procedures.

3.1 ASME Boiler and Pressure Vessel Code

Section I of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code provides the rules for design and construction of power boilers, with *power boiler* defined as “a boiler in which steam or other vapor is generated at a pressure of more than 15 psi (103 kPa) for use external to itself.” As stated in the foreword of the Code, construction “is an all-inclusive term comprising materials, design, fabrication, examination, inspection, testing, certification, and pressure relief.” Section I applies to the boiler itself (superheaters, reheaters, economizers, and other pressure parts connected directly to the boiler without intervening valves) as well as to portions of the boiler external piping.

Section I is subdivided into 10 parts plus appendices, references, and other information. The specific parts with the most relevance to QC/QA issues are:

- Part PG: General requirements for all methods of construction
- Part PW: Requirements for boilers fabricated by welding
- Appendix A: Explanation of the Code

Specific rules for inspection and tests are provided in PG-90 through PG-100 and in PW-46 through PW-54.

3.1.1 Part PG: General, Inspection and Tests

PG-90 states that “each boiler, superheater, waterwall, or steel economizer shall be inspected during construction and after completion by an Authorized Inspector (AI).” Each manufacturer or assembler is required to arrange for the services of an AI to perform inspections on all work (shop or field) within the scope of this Code section. An AI, who is accredited by ASME in accordance with ASME QAI-1 Qualification for Authorized Inspection (PG-91 Qualification of Inspectors), performs duties that include:

- PG-90.1.1: Verifying that the manufacturer or assembler has a valid ASME Certificate of Authorization covering the scope of the Code activities being performed.
- PG-90.1.2: Monitoring compliance with the accepted quality control program and verifying that any changes meet the requirements of this Code section.
- PG-90.1.3: Verifying that the Certificate Holder has the necessary Code books, Addenda, and Code Cases to cover the work being performed.
- PG-90.1.4: Reviewing a selected number of the manufacturer’s design calculations to verify compliance with Section I.
- PG-90.1.5: Witnessing and approving proof tests to establish maximum allowable working pressure (MAWP).
- PG-90.1.6: Verifying that the Certificate Holder has sufficient material control to ensure that material used for construction complies with the applicable requirements of this Code section.
- PG-90.1.7: Verifying that the Certificate Holder’s controls provide a positive means of identification to maintain traceability of materials, when cutting plate material into two or more pieces is necessary.
- PG-90.1.8: Verifying that the Certificate Holder’s personnel are examining cut edges (for joint preparation and cleanliness) before welding.
- PG-90.1.9: Verifying that all welding procedure specifications, procedure qualification records, and welder and welding operator qualification records conform to the requirements of this Code section.
- PG-90.1.10: If welded repairs are necessary, accepting the method and extent of repairs and verifying that only qualified repair welding procedures, welders, and welding operators are used.
- PG-90.1.11: Verifying that all required heat treatments have been performed and are properly documented.
- PG-90.1.12: Verifying that required nondestructive examinations and tests have been performed by qualified personnel and that the results are properly documented.
- PG-90.1.13: Performing the required inspections and witnessing hydrostatic tests (described in PG-99 Hydrostatic Test).

- PG-90.1.14: Verifying that the responsible representative of the Certificate Holder has signed the data report and that it is correct before being signed.
- PG-90.1.15: Prior to stamping, verifying that the item is in compliance with the requirements of this Code section. After stamping, verifying that the stamping is correct and that the nameplate, if used, has been properly attached.

3.1.2 Part PW: General, Design and Fabrication

PW-1 states that “Each Manufacturer is responsible for the welding done by his organization and shall establish the procedures and conduct the test required in Section IX to qualify the welding procedures he uses in the construction of the weldments built under Section I and the performance tests of welders who apply these procedures.” Specific design (PW-8 through PW-19) and fabrication (PW-26 through PW-43) rules, which should be familiar to the inspector, are also provided.

3.1.3 Part PW: General, Inspection and Tests

PW-46 states that “The Manufacturer shall submit the vessel or other pressure part for inspection at such stages of the work as may be designated by the Inspector.” Specific duties to be performed by the inspector include:

- PW-47: Verifying that the welding procedures being used have been qualified under the provisions of B&PV Code Section IX Welding and Brazing Qualifications. If desired, the inspector can call for and witness qualification test welding and testing.
- PW-48: Verifying that all welders or welding operators are qualified under the provision of Section IX and, if desired, call for and witness qualification test welding and testing.
- PW-49: Verifying that all heat treating operations required by the Code have been correctly performed.

3.1.4 Part PG: Certification by Stamping and Data Reports

Parts PG-104 through PG-113 describe the rules for certification by stamping and data reports when inspections have been completed. Example data report forms are provided in Appendix A of the ASME B&PV Code, A-350 through A-357.

3.1.5 Appendix A: Quality Control System

Appendix A of the ASME B&PV Code, A-300 through A-302, describes the features that must be included in a manufacturer's or assembler's QC system "which will establish that all Code requirements, including material, design, fabrication, examination (by the Manufacturer) and inspection of boilers and boiler parts (by the Authorized Inspector), will be met." Specific features that must be addressed include:

- A-302.1: Authority and responsibility
- A-302.2: Organization
- A-302.3: Drawings, design calculations, and specification control
- A-302.4: Material control
- A-302.5: Examination and inspection program
- A-302.6: Correction of nonconformities
- A-302.7: Welding
- A-302.8: Nondestructive examination
- A-302.9: Heat treatment
- A-302.10: Calibration of measurement and test equipment
- A-302.11: Records retention
- A-302.12: Sample forms
- A-302.13: Inspection of boilers and boiler parts

HRSGs can also be built to Section VIII of the ASME B&PV Code. Division 1 requirements for NDE are listed in Parts UG-103 and UW-11. Division 2 requirements for inspection and radiography are provided in Part AI.

3.2 ASME B31.1 Power Piping Code

Examination, inspection, and testing of piping installations are addressed in Chapter VI of B31.1. The Code distinguishes between "examination" and "inspection." Examination "denotes the functions performed by the manufacturer, fabricator, erector or a party authorized by the Owner which include visual observations and nondestructive examination, such as radiography, ultrasonic, eddy current, liquid penetrant, and magnetic particle methods." Inspection "is the responsibility of the Owner" and is required prior to initial operation to "assure compliance with the engineering design and with the material, fabrication, assembly, examination, and test requirements of this Code." General guidelines for the qualification and certification of personnel who perform NDE of welds are provided in Paragraph 136. Recommended Practice No. SNT-TC-1A and American Welding Society (AWS) QC1 are also referenced as alternative sources for personnel qualification and certification.

The mandatory minimum nondestructive examinations for pressure welds or welds to pressure retaining components are listed in Table 136.4. Specific examination methods for welds are discussed in 136.4.2 (visual examination), 136.4.3 (magnetic particle testing), 136.4.4 (liquid penetrant examination), 136.4.5 (radiography), and 136.4.6 (ultrasonic examination). Pressure testing of piping systems to ensure leak tightness is discussed in Paragraph 137.

3.3 European Standard EN 12952

European Standard EN 12952, “Water-tube boilers and auxiliary installations,” supersedes British Standard BS 1113. Of most relevance are Part 5, “Workmanship and construction of pressure parts of the boiler” and Part 6, “Inspection during construction; documentation and marking of pressure parts of the boiler.”

Part 5 contains the following subsections:

1. Scope
2. Normative references (to provisions from other EN publications)
3. Definitions (specifically for “cold forming” and “hot forming”)
4. Symbols and abbreviations
5. General (specifies accordance with approved drawings, procedures, specifications and good engineering practice, provision for suitable manufacturing, inspection, testing, personnel qualification, and records maintenance)
6. Pressure parts
7. Cutting, forming, and fabrication tolerances
8. Welding
9. Mechanical connections
10. Thermal treatment

Annexes (A—Tube bending, B—Welded pressure connections and non-pressure attachments, C—Manufacture of welded tubewalls, D—Coiled boilers and superheaters, E—Chemical recovery boilers, F—Guidelines for determining boiler manufacturer competency (with example Manufacturer’s competency declaration form), ZA—Safety requirements or other provisions of the Pressure Equipment Directive)

Part 6 contains the following subsections:

1. Normative references (to provisions from other EN publications)
2. Terms and definitions (specifically for “inspection”)
3. General organization
4. Nondestructive examination of parent materials
5. Approval of welding procedure specification
6. Welder and welding operator approval
7. Production control test plates for drums
8. Nondestructive examination of welds (including nondestructive examination methods and acceptance criteria)
9. Final inspections
10. Documentation
11. Marking

Annexes (A—Chemical recovery boilers, ZA—Safety requirements or other provisions of the Pressure Equipment Directive)

3.4 Code Clauses Pertaining to Examination Methods

3.4.1 ASME Boiler and Pressure Vessel Code

Section V of the ASME B&PV Code, “Nondestructive Examination,” contains Subsection A, methods of examination, and Subsection B, standards and specifications for performing the various methods. The following methods are included:

- Radiography (RT)
- Ultrasonics (UT)
- Magnetic particle (MT)
- Liquid penetrant (PT)
- Visual (VT)

- Leak testing (LT)
- Electromagnetic/eddy current (ET)
- Acoustic emission (AE)

3.4.2 ASME B31.1

For piping, Part 136.4 of Chapter VI of the ASME B31.1 Power Piping Code provides a similar listing of examination methods of welds. This includes visual examination (136.4.2), magnetic particle examination (136.4.3), liquid penetrant examination (136.4.4), radiography (136.4.5), and ultrasonic testing (136.4.6). Except for visual testing, all of the specific tests refer back to the relevant article in Section V of the ASME B&PV Code.

3.4.3 European Standard EN 12952

Section 9 of European Standard EN 12952, Part 6, specifies that “all welds carried out during the manufacture and erection of a water-tube boiler shall be visually examined.” Additionally, surface examination is specified using magnetic particles or liquid dye penetrant.

Volumetric examination is specified using ultrasonic examination (preferred) or radiographic examination. Examinations are to be carried out in accordance with the applicable standard:

- Visual examination: EN 970
- Magnetic particle examination: EN 1291
- Dye penetrant examination: EN 571-1 and EN 1289
- Ultrasonic examination: EN 1714
- Radiographic examination: EN 1435

3.5 Code Clauses Pertaining to Acceptance Criteria

Acceptance criteria are a function of multiple criteria, including type of examination method, intended service (environment, temperature, and pressure), weld joint geometry, material type and thickness, and accessibility. For this reason, each situation will require the careful application of criteria that are specific to the conditions. What follows is a general description of relevant acceptance criteria and where they can be found.

3.5.1 ASME Boiler and Pressure Vessel Code

Section I of the ASME B&PV Code lists acceptance standards for finished joints in PW-35. Radiography acceptance standards are listed in PW-51, and acceptance standards for rounded indications in welds are listed in Appendix A-250. Acceptance standards for ultrasonic examination are listed in PW-52. Appendix A-260 gives acceptance criteria for magnetic particle examination. Appendix A-270 gives acceptance criteria for liquid penetrant examination.

Additional detail on specific acceptance criteria can be found in Section VIII Division 1, Appendices 4 (radiography), 6 (magnetic particle examination), 8 (liquid penetrant examination), and 12 (ultrasonic examination), as well as in Section VIII Division 2, Appendix 8 (radiography) and Appendix 9 (magnetic particle, liquid penetrant, and ultrasonic examination).

3.5.2 ASME B31.1

For piping, Paragraph 136.4 of Chapter VI of the ASME B31.1 Power Piping Code also provides acceptance criteria for visual examination (136.4.2), magnetic particle examination (136.4.3), liquid penetrant examination (136.4.4), radiography (136.4.5), and ultrasonic examination (136.4.6).

3.5.3 European Standard EN 12952

Section 9 of European Standard EN 12952-6 gives acceptance criteria for weld surface imperfections (Table 9.3-1) found by visual, magnetic particle, or liquid dye penetrant examination. Acceptance criteria for internal (volumetric) imperfections found by radiography are given in Table 9.4-1. Acceptance criteria for indications found by ultrasonic examination are provided separately in EN 1712.

Table 3-1 summarizes some of the acceptance criteria for specific surface conditions as listed in the ASME B&PV Code, ASME B31.1, and EN 12952-6.

Table 3-1
Acceptance Criteria Summary for Selected Surface Conditions

Condition	ASME B&PV Section I	ASME B31.1	EN 12952-6
Cracks	Not permitted.	Not permitted.	Not permitted.
Lack of fusion	Not permitted.	Not permitted.	Not permitted.
Lack of penetration	Not permitted.	Not permitted.	Not permitted.
Porosity	No relevant rounded indications greater than 3/16 in. (4.7 mm) or four or more rounded indications separated by 1/16 in. (1.6 mm) or less edge to edge in any direction (relevant indications are those that have any dimension greater than 1/16 in. [1.6 mm]).	No surface porosity with rounded indications having dimensions greater than 3/16 in. (4.7 mm) or four or more rounded indications separated by 1/16 in. (1.6 mm) or less edge to edge in any direction.	Diameter must be $\leq 1/16$ in. (1.6 mm) or depth must be $\leq 1/32$ in. (0.8 mm).

Table 3-1 (continued)
Acceptance Criteria Summary for Selected Surface Conditions

Condition	ASME B&PV Section I	ASME B31.1	EN 12952-6
Inclusions	No relevant linear indications (relevant indications are those that have any dimension greater than 1/16 in. [1.6 mm]).	No linear indications longer than 3/16 in. (4.7 mm).	Not permitted.
Undercut	Not permitted if >1/32 in. (0.8 mm) deep or 10% of wall thickness, whichever is less.	Not permitted if >1/32 in. (0.8 mm) deep.	Depth must be ≤1/64 in. (0.4 mm); smooth transition required.
Overlap	Must avoid stress raisers and allow for proper interpretation of required NDE.	Must allow for proper interpretation of required NDE.	Not permitted.

4

ROADMAP FOR HRSG INSPECTIONS AND IN-SERVICE INSPECTION

This section provides a roadmap that sets the role for NDE in helping to prevent HRSG pressure-part damage and in analyzing unit damage if it does occur. The section also discusses issues pertaining to in-service examination.

4.1 Roadmap for HRSG Examination

Figure 4-1 provides an overall roadmap for HRSG examination. As shown in the figure, three primary paths can be taken. Boxes with **bold** text indicate steps for which information is contained in this report. The companion reports [4-1; 4-2], particularly the *Heat Recovery Steam Generator Tube Failure Manual* [4-1] (the HTF manual) provide detailed guidance on the other steps in the roadmap.

Path A, the left side of Figure 4-1, presents the route to be taken prior to the occurrence of damage in the unit. It begins, as shown in the first three boxes, with the implementation of appropriate NDE practices during design, prefabrication, and shop fabrication; on-site construction; and commissioning. General considerations for NDE during these critical phases in the life cycle of the unit are discussed in Sections 12, 13, and 14 of this report, respectively. A summary of issues for each phase of the life cycle of the unit is provided in Table 4-1.

Path A will allow the user to set NDE practices to avoid HRSG pressure-part damage throughout the life cycle of the unit. If damage is found during an in-service examination (or as a result of a failure during operation), Path B or C can be followed to address the damage, with the choice of path depending on whether the damage mechanism is known or unknown.

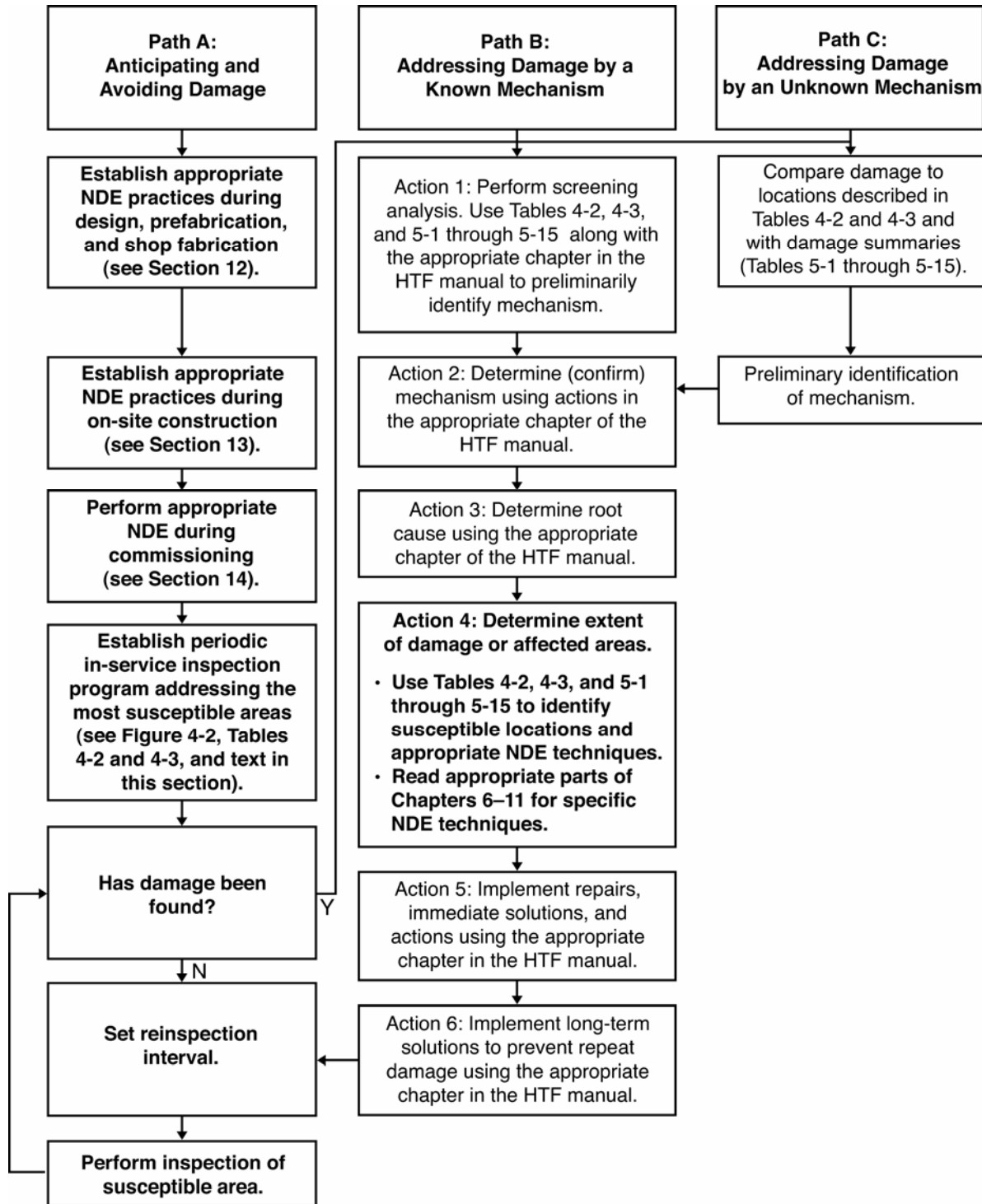


Figure 4-1
Roadmap for HRSG Inspections with Three Starting Points for Use of Information Contained in This Report

Table 4-1
NDE Priorities for HRSG Life Phases

HRSG Life Phase	NDE Priorities
Design (Section 12)	• Incorporate strong consideration of fabrication and access for examination.
Prefabrication (Section 12)	• Ensure proper identification and labeling of raw materials. • Verify dimensions, particularly minimum wall thickness. • Ensure quality (bond strength and dimensions) of fins for tubing.
Shop fabrication (Section 12)	• Perform careful review of manufacturer's quality control system. • Establish and follow examination procedures for machining, burning, grinding, and bending processes during fabrication. • Ensure appropriate weld qualification and execution, particularly of weld quality, heat treatments, and process controls. • Ensure that proper shipping and storage procedures are followed.
On-site construction (Section 13)	• Maintain essentially the same requirements as for shop fabrication. • Make certain that qualification of weld procedures and operators will remain paramount. • Ensure on-site protection of fabricated components to avoid corrosion-related damage.
Commissioning (Section 14)	• Ensure that appropriate baseline measurements are taken. • Ensure that an adequate number of properly located thermocouples are installed and are operational.

Table 4-1 (continued)
NDE Priorities for HRSG Life Phases

HRSG Life Phase	NDE Priorities
Periodic in-service examination (this section)	• Formulate an examination plan for the unit including: – Locations to be examined – Initial examination period – Techniques to be employed – Acceptability standards for damage • Perform periodic examinations as required. • Proactively use information obtained from examinations to: • Determine the status of the unit. • Check on the rate of damage accumulation compared to the design. • Provide feedback on setting the next examination. • Monitor the performance of repairs or other mitigation actions taken.

As indicated in the fourth step of Path A in Figure 4-1, establishing an in-service examination program is a critical step for anticipating and avoiding HRSG damage. Details of the steps represented in that box are discussed in Section 4.2. Issues will include:

- Setting the initial examination interval
- Delineating potential damage mechanisms
- Determining locations to be examined
- Identifying examination methods to be used
- Making preexamination preparations
- Conducting the examination
- Resolving any indications found
- Setting the reexamination interval

As shown in Figure 4-1, if no damage is found during the in-service examination, a reexamination interval is established and later examinations are conducted. If damage is found during an in-service examination it will be necessary to determine the active mechanism, diagnose the root cause, and determine the extent of the damage (does it extend to other areas? how deep or long are indications? has it spread to other parts of the HRSG?), and then to implement repairs and solutions to prevent reoccurrence of the problem. These steps are shown in Path B and C in Figure 4-1; the appropriate path depends on whether the damage mechanism is known or unknown to the investigator.

In either event, Tables 4-2 and 4-3, plus the one-page summaries of damage mechanisms (Tables 5-1 through 5-15) should be consulted. These tables are used to help screen damage, based on the location found, in order to determine the mechanism causing the damage. From this knowledge, the balance of the indicated steps in Figure 4-1 can proceed. If the correct mechanism is not identified and the root cause determined, a de facto commitment to ongoing repair/replacement will have been made because the wrong solutions will inevitably be chosen.

Table 4-2 provides a list of mechanisms that have been confirmed in the field, organized by HRSG component. For example, in the high-pressure superheater, eight damage mechanisms have been seen in field experience to date. The order of the mechanisms in the table follows the order in the HTF manual but otherwise has no significance. Footnotes to Table 4-2 provide some specific location information for selected damage types, and where available, a cross-reference to a figure in the HTF manual is given that illustrates the appearance of the specific damage type and/or location. Table 4-2 consists of three sections: one each for high-pressure, intermediate-pressure, and low-pressure components (a triple-pressure design has been used to standardize the information). The final column of Table 4-2 provides some mechanisms that have not yet been confirmed in the field but—given their root causes—are likely to become active as accumulated operating hours increase.

As the experience base with HRSG units expands, there will undoubtedly be additions to the “Mechanisms” columns of this table. Therefore, if the detected damage cannot be tied to one of the mechanisms listed in the table through subsequent investigation, the investigator needs to review other potential damage types in the HTF manual. When a list of potential damage types for the specific component has been compiled, the investigator can review Table 4-3 and/or the summaries of each mechanism (Section 5, Tables 5-1 through 5-15) for additional information about how to proceed.

Table 4-2
Developing a List of Examination Locations—Likely Damage in Various HRSG Components

Component	These Mechanisms Have Been Confirmed in the Field	Potential Exists for These Mechanisms
High-Pressure (HP) Components		
HP superheater	Thermal-mechanical fatigue Creep fatigue ¹ Flow-induced vibration Pitting Stress corrosion cracking ² Short-term overheating ³ Long-term overheating Thermal quenching ⁴	

Table 4-2 (continued)
Developing a List of Examination Locations—Likely Damage in Various HRSG Components

Component	These Mechanisms Have Been Confirmed in the Field	Potential Exists for These Mechanisms
High-Pressure (HP) Components		
HP evaporator	Thermal-mechanical fatigue ⁵ Flow-induced vibration Water-side and steam-side deposits Acid phosphate corrosion ⁶ Caustic gouging Hydrogen damage ⁷ Pitting ⁸ Acid dew point corrosion Short-term overheating ⁹	Corrosion fatigue Flow-accelerated corrosion
HP drum	Thermal-mechanical fatigue Flow-accelerated corrosion ¹⁰	Pitting
HP economizer (high temperature)	Thermal-mechanical fatigue ¹¹ Flow-accelerated corrosion ¹²	Flow-induced vibration fatigue
HP economizer (low temperature)	Thermal-mechanical fatigue Pitting Acid dew point corrosion Stress corrosion cracking	Flow-induced vibration fatigue

Notes:

1. Cracking at the weld toe of the tube-to-outlet header connection (see Figure 6-2 in the HTF manual).
2. On 2¼ Cr-1 Mo tubing, straight section just above the lower header, cracking from ID surface at an obvious waterline.
3. Leading row vertical tube (see Figure 17-1 in the HTF manual).
4. Tube-to-header welds, tubes in line with the header nozzle (containing the attemperator—see Figure 19-1 in the HTF manual), or in bend close to weld.
5. On downcomer pipes and risers to drum.
6. Corrosion in straight vertical tube (see Figure 10-2 in the HTF manual).
7. Localized deposition, corrosion, and hydrogen damage in the top of a horizontal tube (see Figure 12-1 in the HTF manual).
8. See Figure 13-1 in the HTF manual.
9. Carbon-steel leading-edge vertical tube.
10. Affected parts are HP drum internals or water/steam mixture inlet tubes.
11. Tube-to-header weld, tube side of the weld, or in bend close to weld (see Figure 5-2 in the HTF manual).
12. Flow-accelerated corrosion at inlet.

Table 4-2 (continued)
Developing a List of Examination Locations—Likely Damage in Various HRSG Components

Component	These Mechanisms Have Been Confirmed in the Field	Potential Exists for These Mechanisms
Intermediate-Pressure (IP) Components		
Reheater	Thermal-mechanical fatigue Flow-induced vibration fatigue ¹³ Thermal quenching	Creep fatigue Stress corrosion cracking Short-term overheating Long-term overheating
IP superheater	Corrosion fatigue ¹⁴	Thermal-mechanical fatigue Flow-induced vibration fatigue Pitting
IP evaporator	Thermal-mechanical fatigue ¹⁵ Water-side and steam-side deposits Flow-accelerated corrosion Acid phosphate corrosion Caustic gouging Hydrogen damage Pitting	Corrosion fatigue Flow-induced vibration fatigue
IP economizer	Pitting	Thermal-mechanical fatigue Flow-induced vibration fatigue Flow-accelerated corrosion
IP drum		Thermal-mechanical fatigue Flow-accelerated corrosion

Notes:

13. Tube-to-outlet header weld (see Figure 7-1 in the HTF manual).
14. Cracking in return bends and at socket welds in a frequently cycled HRSG with poor layup practices (see Figure 4-2 in the HTF manual).
15. On downcomer-to-bottom header pipes.

Table 4-2 (continued)
Developing a List of Examination Locations—Likely Damage in Various HRSG Components

Component	These Mechanisms Have Been Confirmed in the Field	Potential Exists for These Mechanisms
Low-Pressure (LP) Components		
LP superheater		Corrosion fatigue Thermal-mechanical fatigue Flow-induced vibration fatigue Pitting
LP reheater		Corrosion fatigue Thermal-mechanical fatigue Flow-induced vibration fatigue Pitting
LP evaporator	Flow-accelerated corrosion ¹⁶ Pitting Stress corrosion cracking ¹⁷	Corrosion fatigue Thermal-mechanical fatigue Flow-induced vibration Gas-side corrosion/pitting
LP economizer/ preheater	Corrosion fatigue ¹⁸ Thermal-mechanical fatigue Flow-accelerated corrosion Pitting Gas-side corrosion/pitting ¹⁹ Acid dew point corrosion ²⁰ Stress corrosion cracking ^{21, 22}	Flow-induced vibration fatigue
LP drum	Flow-accelerated corrosion	Thermal-mechanical fatigue

Notes:

16. Carbon steel just upstream or within the outlet bend (see Figures 9-1, 9-2, 9-10, and A-2 in the HTF manual); observed in both vertical and horizontal tube designs.
17. Cracking has occurred both from the gas side and from the water side in carbon steel bends and in 21Cr-11Ni-N (UNS S30815) austenitic stainless steel material.
18. Cracking from the ID surface near a drain line to U-bend connection (see Figure 4-1 in the HTF manual).
19. Horizontal tubing in the section of the tube bundle directly below a malfunctioning stack damper (see Figure 14-1 in the HTF manual).
20. Vertical tubes near the inlet end, fin-to-tube interface corrosion (see Figure 15-1 in the HTF manual).
21. On ferritic steel hairpin bends, circumferential cracking from the OD surface at the bend intrados.
22. Cracking near the lower header of Type 304 stainless steel tubing (see Figure 16-2 in the HTF manual); cracking has also been seen near the lower header drain nozzle welds.

Table 4-3 provides a list of abbreviations, along with the relevant section of the report for additional information, of the terms used in Table 4-4.

Table 4-4 can be used in conjunction with Table 4-2 to help screen for potential damage types. It provides the following:

- A listing of all major damage mechanisms (column 1)
- Some additional information about where each type of damage generally occurs (column 2)
- Example locations (column 3)
- The most generally applied examination techniques (column 4)
- A cross-reference to the information about that damage type contained in Section 5 (column 5)

Table 4-3
Summary of Damage Mechanisms, Examination Locations, and Examination Techniques

Legend	Examination Technique	Section of Report for Information
ACPD	AC potential drop	7.6
ET	Eddy current testing	7.5
	Exploratory grinding	
Internal Visual	Remote visual or internal videoscopic examination	7.1
PT	Liquid dye penetrant	7.4
PET	Pulsed eddy current	10.2
	Replication	9.2
	Tube sampling	
UT	Ultrasonic examination	8.1
UT-Attenuation	Ultrasonic attenuation measurements	8.1
UT-Oxide	Oxide thickness measurement by ultrasonics	10.1
UT-Shear	Ultrasonic shear wave examination	8.1
UT-PA	Ultrasonic phased array examination	8.1
UT-TOFD	Ultrasonic time-of-flight diffraction	8.1
UT-Thickness	Ultrasonic thickness measurements	10.1
VT	Visual examination	7.1
MT	Magnetic particle examination	7.3
WFMT	Wet fluorescent magnetic particle examination	7.3
RT	Radiographic examination	8.2
CRT	Computed radiography using phosphor plates	8.2
DRT	Digital radiography using solid state detectors	8.2
LFET	Low-frequency electromagnetic technique	8.3

Table 4-4
Summary of Damage Mechanisms, Examination Locations, and Examination Techniques

Damage Mechanism	Where Damage Occurs—General	Example Locations	Examination Techniques	For More Information
Corrosion fatigue	- Water-touched components, especially LP economizer - Steam-touched tubing containing condensate during operational transients - Welded connections, bends, and attachments with high thermally induced forces and bending moments - Locations with significant thickness transitions	- Tube-to-header welds - Socket welds - U-bend-to-drain-line welds	- Internal visual (video probe, borescope) - UT-thickness (internal rotary probe) - Phased array UT - Digital RT or computed RT - Quantify by tube sampling	Table 5-1
Thermal-mechanical fatigue	- All HRSG sections, most likely at welded connections and attachments, occasionally at bends - Locations with significant thickness transitions	- Tube-to-header welds - Tube bends near header attachments	- VT, WFMT, PT - Quantify with UT, ACPD, exploratory grinding, or RT density measurements	Table 5-2
Creep fatigue	- Components in creep regime, notably HP superheaters - Locations with welded connections, bends, attachments, and header boreholes	- Tube-to-header connections - Superheater header boreholes	- VT, WFMT, PT - Quantify with UT, ACPT, replication, exploratory grinding	Table 5-3
Flow-induced vibration fatigue	- All sections, most notably HP superheaters and reheaters - Welded connections, bends, and attachments	Mid-span between supports and restraints	- VT, WFMT, PT - Quantify with UT, ACPD, exploratory grinding	Table 5-4

Table 4-4 (continued)

Summary of Damage Mechanisms, Examination Locations, and Examination Techniques

Damage Mechanism	Where Damage Occurs—General	Example Locations	Examination Techniques	For More Information
Flow-accelerated corrosion	Water-touched components in the temperature range 212–482°F (100–250°C) and high flow velocities	- LP evaporator, near the outlet of the LP economizer; bends in piping; tube bends near headers - Steam drum internals—riser/downcomer pipe bends, drum steam separators	- Internal visual (video probe, borescope) - UT-thickness (internal rotary probe or from the outside surface) - Pulsed eddy current (for insulated piping components) - Quantify with UT-thickness	Table 5-5
Acid phosphate corrosion; caustic gouging; hydrogen damage	- HP and IP evaporators - Locations where stable steam films are likely to form	- Downstream of welds - Locations with internal deposits - Locations with high heat transfer or high steam quality - Gas inlet row tubes - Horizontal tubes - Module end tubes	- Internal visual (video probe, borescope) - Quantify with UT-thickness (internal rotary probe or from the outside surface); tube sampling	Table 5-6 Table 5-7 Table 5-8

Table 4-4 (continued)**Summary of Damage Mechanisms, Examination Locations, and Examination Techniques**

Damage Mechanism	Where Damage Occurs—General	Example Locations	Examination Techniques	For More Information
Internal pitting	• Oxygen pitting prevalent in economizers, possible at any wet surface, especially nondrainable, horizontal surfaces • Pitting caused by improper chemical cleaning possible at any surface in contact with cleaning solvents, especially severe at weld HAZ and surface deposits • Pitting from sodium sulfate carryover in reheater section		• Internal visual (video probe, borescope) • Quantify with UT-thickness (internal rotary probe); tube sampling	Table 5-9
Gas-side corrosion and pitting	• Uncommon; potential at gas-touched surfaces or those open to environment		• VT • Quantify with UT-thickness	Table 5-10
Acid dew point corrosion	• Gas-touched surfaces where the metal temperatures are below the acid dew point	• Tubes, fins, casings, ducts, and stacks	• VT • Quantify with UT-thickness	Table 5-11
Stress corrosion cracking	• Locations with the highest potential for concentration of contaminants as well as high stresses	• Condensate collection points (concentration of contaminants) • Bends, welds, attachments, supports (high-stress locations)	• VT, WFMT (for magnetic materials), PT, ET • Quantify with exploratory grinding	Table 5-12

Table 4-4 (continued)
Summary of Damage Mechanisms, Examination Locations, and Examination Techniques

Damage Mechanism	Where Damage Occurs—General	Example Locations	Examination Techniques	For More Information
Short-term overheating	• Locations where overheating is likely • Locations where partial or complete blockage of flow through tubes is likely	• Just downstream of supplemental burners • Downstream of bends where blockage by oxide, condensate, debris, and so on can occur	• VT for tube damage, flame patterns, and so on • Internal visual (video probe, borescope) for blockages • Quantify with tube sampling	Table 5-13
Long-term overheating	• Steam-cooled tubing where overheating is likely	• Just downstream of supplemental burners • Tubing near material changes (the lower grade material) • Tubing with longer gas-touched lengths • Tubing just before the outlet header	• UT-oxide, internal scale, and wall thickness survey • Quantify with remaining creep life assessment using internal scale and wall thickness survey results	Table 5-14
Thermal quenching	• Steam-cooled tubing, HP superheaters and reheaters	• Typically at or near tube-to-header connections	• VT (for deformation and cracking), WFMT, PT	Table 5-15

4.2 In-Service Examinations—General Considerations

Given the variety of potential issues that might arise for a specific unit and the variety of designs available, it is not the objective of this section to pinpoint specific locations and details to be examined for all HRSG designs. However, based on industry experience to date, it is possible to describe what issues need to be addressed by the operators of each unit to build their own unit-specific examination program.

Figure 4-2 shows the general steps that might be included in preparing for and executing an in-service examination. First, an initial examination interval is set. Next, the locations to be examined and methods to be used are established, using knowledge of types of damage that are being looked for. The boxes in Figure 4-2 provide some sources of information in this report and in the HTF manual [4-1] that will help in making these decisions.

After the in-service examination, resolution of the damage or indications found is required. Resolution is driven by the type of damage encountered and its severity. Specific guidance, by damage type, is provided in the HTF manual [4-1]. A reexamination interval should then be established based in part on the results of the current examination.

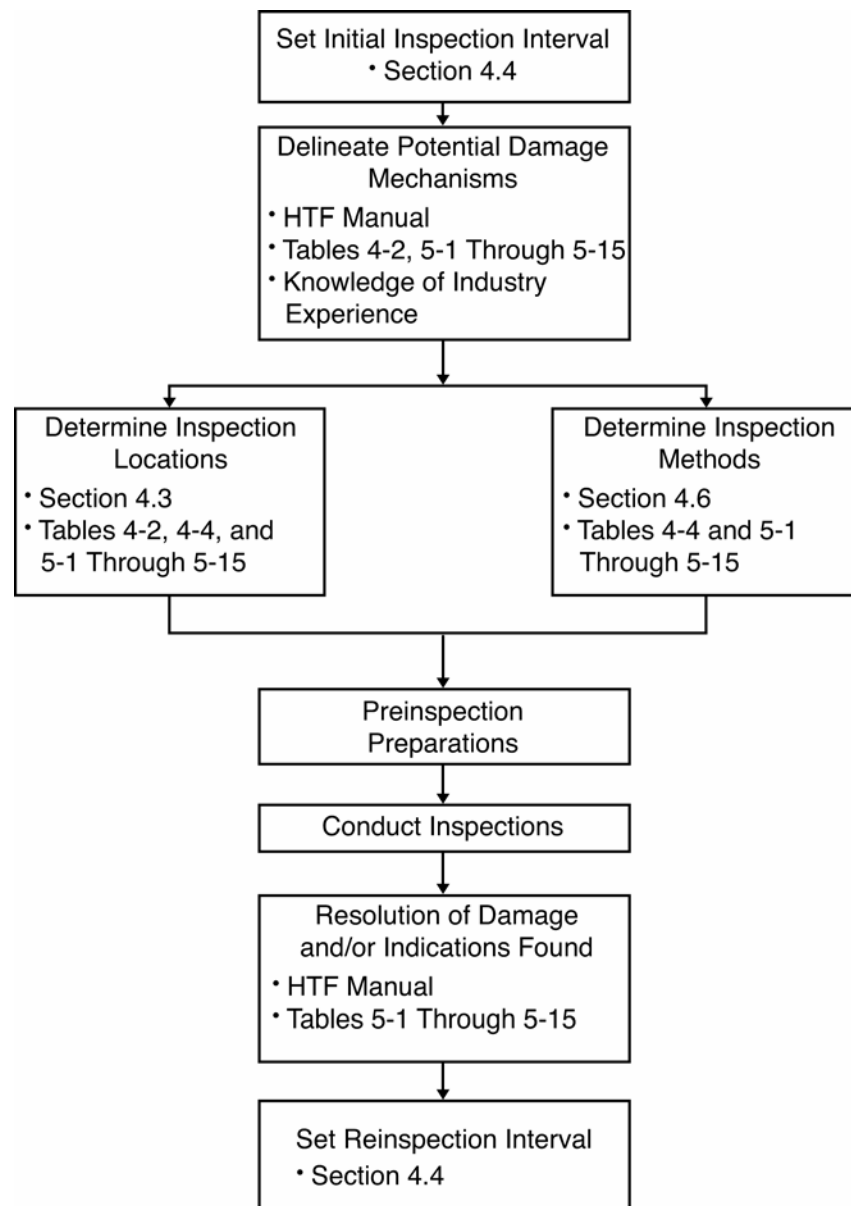


Figure 4-2
Steps in Establishing a Periodic In-Service Examination Program

4.3 In-Service Examinations—Locations to Be Examined

There are a number of ways to determine where to look during repeated periodic examination programs. These include:

- Locations where previous industry experience has indicated that damage is likely to occur. Tables 4-2 and 4-4 provide a summary of typical locations. See also the locations identified in the HTF manual [4-1].
- Locations where previous problems have occurred and repairs have been instituted.

- Locations where previous examinations have identified a progressive or developing problem. For example, for the initial in-service examination, any problems uncovered during the construction and commissioning periods that would tend to favor more detailed examination of particular components or locations will be factored into the decision.
- Locations where monitoring systems (thermocouples, thermography, acoustic emission equipment, and so on) indicate a developing problem (temperatures in excess of design expectations, excessive stresses, and so on).
- Locations in “sister” or similar units that have been identified as potential sites for problems to develop.
- Locations that have similar characteristics (stress levels, restraint, weld design detail, environment, operating temperature, expected cyclic stresses, material type, flow rates, and so on) as locations with a known problem.

4.4 How Often to Look—Setting Examination Intervals

Setting the initial examination interval for the operating unit will depend on a number of factors, but the interval must take into account both unit design and operating history. In general, examination intervals for cycling units will be set according to the number of unit cycles; intervals for baseloaded units will be set according to the number of operating hours. For prevention of damage that occurs as a result of shutdown practice, documentation of the number of start/stop cycles and the number of hours in wet layup will prove to be a valuable asset during exercises in life prediction and component replacement.

There are three general paths of life consumption to be tracked during the assumed degradation of HRSG pressure-part components. These are:

- Accumulated number of cycles—which allows a measure of consumption of fatigue life
- Total operating hours—which is on-line time-dependent degradation
- Total standby hours—which is off-line time-dependent degradation

The choice among these paths of life consumption will vary according to the anticipated damage. For example, the very significant damage mechanisms of thermal-mechanical fatigue, creep fatigue, and corrosion fatigue are all primarily dependent on the number and severity of unit transients that lead to thermally induced cycles.

4.4.1 Issues for Fatigue-Related Mechanisms

Cycling units are subjected to fatigue loading at numerous locations. The severity of damage at any one location depends on the design and the strain range, which is a function of the temperature ramp rate and the range of temperature. Daily cycling at high thermal ramp rates is typically less detrimental to the components than cold starts at a similar ramp rate (unit off-line 48 hours or more). Depending on the unit design and operation, the relative amount of damage from one cold start may be an order of magnitude greater than damage from a hot start. Most

HRSG components are relatively thin walled, which minimizes the accumulation of severe thermal stresses during cycling. However, sudden cooling by rapid shutdown during daily cycling or quenching due to the formation and forward flow of condensate associated with the restart can be very damaging.

Based on this discussion, it is obviously important to differentiate between cold, warm, and hot starts during cycling. The effective number of starts may be a summation of cold plus hot starts, with the cold starts carrying the most weight because they create the most damage. Due to variations in design and operating practices, the damage ratio of cold to hot starts will be difficult to determine either experimentally or analytically. Some use has been made of combining data into a term called *effective starts*. A suggested method for keeping track of effective starts on HRSG components could take the form of the following equation:

$$\text{Effective starts} = (\text{No. of normal shutdowns} + \text{hot starts}) + X1 (\text{No. of normal shutdowns} + \text{warm starts}) + X2 (\text{No. of normal shutdowns} + \text{cold starts}) + X3 (\text{trips} + \text{hot starts})$$

Using analytical life estimates of a tube-to-header connection as an example (see Table 7-1 in *Delivering High Reliability Heat Recovery Steam Generators* [4-2]), the estimated values of X1, X2, and X3 would be approximately 3, 16, and 6, respectively.

The expected time to failure for thermal-mechanical fatigue depends on the susceptibility of the unit design and the severity of the thermal ramp rate. Experience has shown that failures can occur in as few as 100 effective cycles when ramp rates are significantly greater than 1000°F/hr (555°C/hr) in a susceptible, bent-tube HRSG design. More moderate cycling ramp rates of 500–1000°F/hr (278–555°C/hr) may yield failures in 1000–1500 effective cycles. It is interesting to note that HRSG manufacturers recommend ramp rates slightly less than 500°F/hr (278°C/hr) with a not-to-exceed ramp rate of 900°F/hr (500°C/hr).

Some older HRSGs are beginning to experience failures in 1500 startup cycles at the ends of the headers and the outermost bent tubes. These failures are due to thermal-mechanical fatigue and may be aggravated by bowing of the sidewalls after numerous cycles. Horizontal tube designs and units with ramp rates below 500°F/hr (278°C/hr) may not experience failures for 3000–5000 effective cycles if the enclosure stays intact. The slower ramp rates reduce the magnitude of temperature differences, which lowers the strain range.

The added influence of creep and/or corrosion can be expected to significantly reduce the number of cycles to failure. These effects are less pronounced at high thermal ramp rates because the fatigue life is dominated by the high strain range conditions and the expected life is relatively short and would not change significantly. Moderate ramp rates will show some influence by corrosion processes reducing the time necessary for crack initiation. Low ramp rates will exhibit the greatest effect, with the total number of cycles to failure reduced by 50% or more from that expected purely from fatigue.

The time to the first examination for tube-to-header weld fatigue flaws depends primarily on the thermal ramp rates followed during unit transient operation. Assuming that a moderate ramp rate within the range recommended by the HRSG original equipment manufacturer (OEM) is followed and allowing for corrosion influences, experience shows that the unit should operate at least 100–200 effective cycles before examinations are made to detect fatigue cracking prior to failure. Keep in mind that crack initiation may occur after 30–90% of the total expected cycles to failure have accumulated; as a result, early examinations may detect little or no damage, which could give rise to a false sense of security and reduced future vigilance.

4.4.2 Issues for Corrosion-Related Mechanisms

Unlike fatigue, the HRSG corrosion-based mechanisms generally accumulate damage as a function of operating hours. However, corrosion is also somewhat dependent on the number of operating cycles, because many of the upsets in water chemistry occur during unit starts prior to steady-state operation. On-line monitoring of water chemistry and rating the number and severity of events outside the water chemistry limits established by EPRI for HRSG cycle chemistry [4-3] will provide valuable information on the risk of corrosion-related HTF and help to set examination requirements.

Flow-accelerated corrosion (FAC), for example, is likely to be dependent on the number of operating hours under steady-state fired, unfired, and low-load operating conditions. Experience has shown that FAC in susceptible locations can occur and cause HTF during the first few years of operation. Metal wastage rates can be as high as 0.5 in./yr (12.7 mm/yr) under aggressive conditions of temperature, flow velocity, and water chemistry.

Acid dew point corrosion in a natural-gas-fired HRSG is a low-probability event because of the low level of impurities present in the combustion turbine (CT) exhaust gases. It can occur during normal operating conditions when there are periods of low exhaust gas or tube metal temperatures (less than 300°F [150°C]). Visual examination of the HRSG cold end tubing is recommended after 10,000 operating hours or when the HRSG has been off-line for more than 10% of the available hours.

Examination for the time-dependent HRSG failure mechanisms attributable to on-line corrosion can be estimated from tubing corrosion rates and failures that have been observed. Corrosion rates of 0.003–0.005 in./yr (0.08–0.13 mm/yr) would be expected to cause failure in a typical 1/8-in. (3.2-mm) thick tube after about 12–20 years. However, corrosion rates exceeding 0.060 in./year (1.6 mm/year) have occurred in units with poor water chemistry, resulting in tube failures in less than 4000 hours of operation. In general, the time to the first examination for corrosion mechanisms should be in the range of 10,000–15,000 operating hours. This could be shortened if information is available warning of the risk of more aggressive chemical attack or rapid deposit formation (for example, out-of-specification water chemistry, increased pressure drop across a tube bundle, or elevated iron levels in the water). The examination process should include some form of internal visual examination from the drums that may require the removal of drum internals. Suspect areas should be evaluated by ultrasonic thickness measurements, if accessible.

It is also advisable to obtain some measure of internal deposit loading after 10,000 operating hours to gauge when and where thick deposits may be present. The final row of the HP evaporator should be a high-priority examination location for deposit buildup and corrosion. The LP evaporator outlet tube bends, drum internals, and riser and downcomer piping bends should be a high-priority examination location for FAC.

4.4.3 Issues for Temperature-Related Mechanisms

Long-term overheating is another time-dependent failure mechanism. Long-term overheating is not anticipated to occur in HRSG tubes operating within the first 100,000 operating hours if the metal temperatures do not exceed the design values. However, steam flow maldistributions, gas laning, and auxiliary firing have created conditions conducive to short-term overheating failures after only a few years of operation.

Steam-side scale formation is an excellent indicator of variations in tube operating temperatures. Advanced nondestructive oxide thickness measurement techniques are capable of accurately measuring steam-side scale thicknesses of 0.002 in. (0.05 mm) or more. These measurements can be made on the unfinned outlet tubes, and then selected measurements can be made on the finned, heat-absorbing sections of tubing after removal of the fins from a small area. After approximately 50,000 hours of operation, a 2¼ Cr-1 Mo steel tube would exhibit about 0.015 in. (0.38 mm) of steam-side scale if it were operating at a metal temperature of 1050°F (556°C). Tube metal temperatures of 1000°F (538°C) would produce a 0.007-in. (0.18-mm) thick scale.

Evaluation of actual temperatures being experienced (compared to design temperatures) as determined by thermocouple or thermography data may help determine when the first examinations for long-term overheating should take place. If these data are not available, nondestructive measurement of steam-cooled tube internal oxides should be performed after 10,000–20,000 hours of operation.

4.4.4 Issues for Layup-Related Mechanisms

The severity of water-side pitting corrosion and acid dew point corrosion is dependent on the choice and execution of layup procedures and the number of exposure hours. Pitting in evaporator and economizer tubes during periods of out-of-service corrosion can result in HTFs within 2–4 years if the unit experiences extended periods of layup. Under these conditions, examinations to detect pitting should be performed after approximately 1,000–2,000 hours of layup.

4.5 How Should the Examination Information Be Used?

Examination results will serve a number of purposes, including:

- **Serving as an indication of the current condition of the unit.** This is the primary purpose of the examination. It is important that the results of all examinations are kept in a form that enables comparison with future examination results.
- **Allowing a check to be made of the rate of damage accumulation.** The results of the current examination should be evaluated along with prior results to provide an indication of how damage accumulation is progressing in the unit. Is the rate of damage accumulation exceeding the expectation from the original design? If so, are there operating changes, maintenance activities, or other steps that need to be taken to decrease the rate of damage and thus ensure the desired lifetime of the unit?
- **Providing feedback for setting the next examination interval and scope (extent) of the examination.** If the rate of damage is varying or increasing, adjustments to the frequency and extent of examination will be required. Findings of a deteriorating condition in one area will also highlight other similar areas or related areas (same mechanism that has not yet manifested itself elsewhere) to be added for periodic examination.
- **Monitoring performance of short- and long-term actions or repairs.** The objective of a pressure-part damage reduction program is to identify potential failures before they occur and take the necessary steps to avoid them. Barring this, such a program will address any failures with the appropriate actions to prevent, to the greatest extent possible, the reoccurrence of damage. A properly conducted examination will enable the operator to determine whether preventive, repair, and mitigation methods have been successfully applied.

4.6 Summary of Techniques

Table 4-5 provides an overview of the NDE methods presented in Sections 6–11 of this report; applications of the techniques are discussed throughout the report.

Table 4-5
Overview of NDE Methods and Their Applicability to HRSGs

Technique	HRSG Use	Comments	Covered in
Surface and Near-Surface Techniques			
Visual examination (VT) and dimensional measurements	- Used to examine HRSG tubes, headers, drums, and piping throughout manufacture, assembly, and operation of the unit. - Used to examine internal and external surfaces. - Commonly used in the detection of most forms of HRSG pressure-part damage.	- Most effective and informative method. - Often augmented with magnifiers, mirrors, video probes, and so on.	Sections 7.1 and 7.2
Magnetic particle examination (MT)	- A frequently applied technique for routine examination. - Commonly used to evaluate external cracking mechanisms (thermal-mechanical fatigue, flow-induced fatigue, and creep fatigue).	- Detection of surface-connected and near-surface discontinuities in ferromagnetic material. - Typically uses dry magnetic particles for larger (wide) indications and wet fluorescent magnetic particles for small/tight discontinuities.	Section 7.3

Table 4-5 (continued)
Overview of NDE Methods and Their Applicability to HRSGs

Technique	HRSG Use	Comments	Covered in
Surface and Near-Surface Techniques			
Liquid penetrant examination (PT)	- A frequently applied technique for finding discontinuities open to the surface. - Commonly used to evaluate external cracking mechanisms (thermal-mechanical fatigue, flow-induced fatigue, and creep fatigue).	Requires very careful surface preparation to provide definitive results.	Section 7.4
Eddy current examination (ET)	Alternative technique for external cracking mechanisms.	Detection of surface and near-surface flaws in electrically conducting materials.	Section 7.5
AC potential drop	Secondary technique for measuring the depth of surface-breaking cracks initially detected by other techniques.	- Determination of the depth of surface-breaking cracks. - Particularly applicable on strong surface curvature components.	Section 7.6
Volumetric Techniques			
Ultrasonic examination (UT)—conventional techniques	- UT-shear wave used for evaluation of internal cracking (corrosion fatigue, creep fatigue). - UT-thickness methods used for characterizing wall thinning such as that caused by flow-accelerated corrosion, acid phosphate corrosion, hydrogen damage, and caustic gouging. - UT-attenuation used for pitting and gas-side corrosion/pitting. - UT-oxide used for quantifying long-term overheating.	- Specific techniques and applications generally developed for each application. - Primary applications for (i) flaw detection, classification, and sizing; and (ii) thickness measurement. - Also used for material structure, stress measurement (residual and applied), hardness, and anisotropy.	Section 8.1
Radiography (RT)	Can be used for cracking and pitting mechanisms, as well as fabrication and repair quality control. In HRSGs, generally secondary to use of UT, VT, MT, and PT.	Has traditionally been a primary weld examination technique.	Section 8.2
UT—focused beam techniques	Refinement to basic UT technology to improve detection and size determination.	For refined flaw size determination.	Section 8.1

Table 4-5 (continued)
Overview of NDE Methods and Their Applicability to HRSGs

Technique	HRSG Use	Comments	Covered in
Volumetric Techniques			
UT—spatially displaced transducers	Special application technique when location and orientation of flaws are known, for example sidewall incomplete fusion in circumferential pipe/header girth welds with fixed and known weld preparation groove dimensions.	- Most often used for detection only, not for sizing. - An array of custom-designed transducers is usually required to examine the entire wall thickness.	Section 8.1
UT—high angle longitudinal waves	Good for detection and sizing of through-wall-oriented flaws, such as weld fusion line cracking.	Requires a highly trained and skilled operator.	Section 8.1
UT—linear phased array technology	Could be used instead of RT for weld acceptance testing, but most commonly used to look for in-service cracking.	- Very rapid scanning. - Requires expensive equipment and well-trained operators.	Section 8.1
UT—synthetic aperture focusing technique (SAFT)	Can provide enhanced flaw size and characteristic information.	Is a post-processing algorithm that can significantly enhance the effective signal-to-noise and beam spread effects but is slow and complex.	Section 8.1
UT—time-of-flight diffraction technique (TOFD)	Has been extensively used in fossil-fueled plant piping to detect, characterize, and size fabrication and service-induced flaws.	- Very rapid scanning possible. - Requires specialized, expensive equipment and skilled operators.	Section 8.1
Electromagnetic acoustic transducers (EMATs)	Primarily used for wall thickness measurements.	Requires specialized, expensive equipment.	Section 8.1
Low-frequency electromagnetic technique (LFET)	Used for cracking and pitting detection on finned tubes.	Requires specialized equipment.	Section 8.3
Pulsed eddy current	Primarily used to measure wall thickness reductions due to flow-accelerated corrosion in insulated piping without the need to remove the lagging or insulation.	Can find external wall losses from corrosion.	Section 10.2

Table 4-5 (continued)
Overview of NDE Methods and Their Applicability to HRSGs

Technique	HRSG Use	Comments	Covered in
Remote Methods			
Infrared thermography	Potential for use in scanning for oxide and deposit buildup or nonuniform fluid circulation.	Survey technique for finding thermal differences	Section 11.1
Transient infrared thermography	Potential for use in locating flow blockages or severe corrosion.	Induces thermal differences in order to detect subsurface flaws and conditions.	Section 11.2
Material Characterization			
Alloy identification	- Used as a QC/QA tool during fabrication and commissioning. - Used as a root cause investigation tool.		Section 9.1
Replication	- Used to characterize flaws found by other NDE methods. - Used to determine the severity of microstructural damage and remaining life of superheater/reheater component welds.		Section 9.2
Portable hardness testing	Can be used to characterize weld repairs.		Section 9.3
Etchants	Primarily used to locate and characterize welds and weld repairs.	- Requires careful preparation and handling of etchant. - Requires careful surface preparation prior to etching, especially for welds that may have been annealed or normalized.	Section 9.4
Miniature sampling	Primarily used during root cause or fitness-for-service investigations.		Section 9.5
Stress measurement—ultrasonic	Occasionally used as a construction QA check. More often used during root cause investigation.		Section 9.6
Stress measurement—magnetic	Occasionally used as a construction QA check. More often used during root cause investigation.		Section 9.6

Table 4-5 (continued)
Overview of NDE Methods and Their Applicability to HRSGs

Technique	HRSG Use	Comments	Covered in
Miscellaneous NDE Techniques			
UT—oxide	Used to measure tube wall thickness and internal oxide scale thickness.	Results of measurements can be used to identify temperature variations and also predict remaining creep life.	Section 10.1

4.7 References

- 4-1. *Heat Recovery Steam Generator Tube Failure Manual*. EPRI, Palo Alto, CA: 2002. 1004503.
- 4-2. *Delivering High Reliability Heat Recovery Steam Generators*. EPRI, Palo Alto, CA: 2003. 1004240.
- 4-3. *Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)*. EPRI, Palo Alto, CA: 2006. 1010438.

5

FOCUSING NDE SPECIFICALLY FOR KNOWN OR SUSPECTED MECHANISMS OF DEGRADATION

Fifteen damage mechanisms have been identified that are known to cause HRSG tube failures [5-1]. Many of these mechanisms can also cause damage to piping and headers. Four of the mechanisms are forms of fatigue, seven are forms of corrosion, two are types of overheating, and two are special cases of cracking mechanisms.

5.1 Service-Induced Damage Mechanisms

Tables 5-1 through 5-15 provide a concise guide to each of the known service-induced damage mechanisms. The format for each damage mechanism includes:

- A brief summary of the mechanism
- A description and pictures showing the appearance of the damage
- A listing of where the damage occurs
- How to find and quantify the damage
- Optional NDE techniques
- Acceptable levels of damage
- Repair options
- Correction actions
- Any interrelated damage mechanisms that may also be active
- Other comments

Table 5-1
Corrosion Fatigue

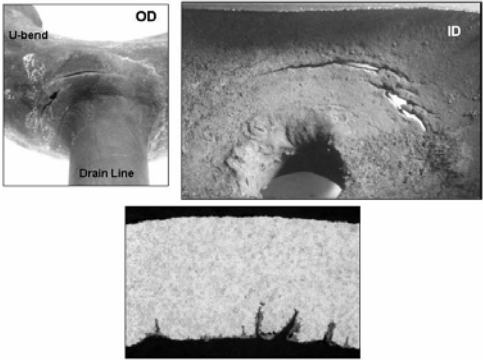
Damage Mechanism: Corrosion fatigue	
Summary of Mechanism: Damage and cracking resulting from the combined action of cyclic stresses and a corrosive environment. Crack initiation involves the repeated mechanical disruption and healing of the protective oxide scale on water-touched surfaces, resulting in aligned corrosion pits, then crack-like pits, and finally, multiple, transgranular, oxide-filled cracks oriented normal to the predominant tensile stress field. Cracking is influenced by a complex interaction of the rate and magnitude of loading (strain), fluid pH and dissolved oxygen levels, and alloy chemistry.	
Appearance of Damage: • Outside surface: Since corrosion fatigue initiates at the inside surface, damage may not be visually apparent; damage that has progressed through-wall may first appear as a pinhole leak. • Inside surface: Multiple, parallel cracks, often associated with corrosion pits or surface discontinuities, can be either axial or circumferential, but cracks are oriented normal to the predominant tensile stress.	 The images illustrate corrosion fatigue damage. The top left image shows a U-bend with labels 'U-bend', 'OD' (Outside Diameter), and 'Drain Line'. The top right image shows the inside diameter ('ID') of a tube with visible corrosion. The bottom image is a cross-section of a tube showing multiple parallel cracks oriented normal to the tensile stress.
Where Damage Occurs: • Water-touched components, especially economizers; can also occur in steam-touched tubing that contains air-saturated condensate during outages • Locations with welded connections and bends, attachments where thermally induced forces and moments are highest, and at header/drum boreholes	
How to Find Damage: • Internal visual (video probe, borescope) • Ultrasonic examination (angle beam with custom transducers for specific locations of concern or phased array) • Digital or phosphor plate radiography	
How to Quantify the Severity of the Damage: • Ultrasonic flaw sizing • Radiographic density measurements • Tube sampling	
Optional NDE:	
What Is Acceptable: • No cracks. If cracks are detected, a fitness-for-service analysis should be performed to justify continued operation.	
Repair Options: • Replace the affected area. Temporary pad weld repairs are not recommended.	
Corrective Actions: • See Chapter 4 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].	
Other Potentially Active Damage Mechanisms: • Thermal-mechanical fatigue	
Other Comments:	

Table 5-2
Thermal-Mechanical Fatigue

Damage Mechanism: Thermal-mechanical fatigue	
Summary of Mechanism: Damage and cracking that occur when thermal expansion and contraction are restrained sufficiently to produce localized material yielding. Repeated thermal cycles eventually result in crack initiation and growth.	
Appearance of Damage: • Outside surface: Single cracks are most common, oriented normal to the predominant tensile stress field; they can be oriented axially or circumferentially and may be multidirectional at attachments. • Inside surface: Since cracking most often initiates on the outside surface, only cracks that have penetrated the wall thickness will be visible on the inside surface.	
Where Damage Occurs: • Water- and steam-touched components in all HRSG sections, most likely at welded connections (such as tube-to-header welds) and attachments, occasionally at bends • Locations with significant thickness transitions, locations where thermally induced forces and moments are highest	
How to Find Damage: • Visual • Magnetic particle • Liquid penetrant	
How to Quantify the Severity of the Damage: • Ultrasonic • AC potential drop • Exploratory grinding • Radiographic density measurements	
Optional NDE: • Eddy current	
What Is Acceptable: • No cracks. If cracks are detected, a fitness-for-service analysis should be performed to justify continued operation.	
Repair Options: • Leave cracks in place (if justified). • Local excavation. • Excavation and weld repair. • Complete replacement of connection.	
Corrective Actions: • See Chapter 5 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].	
Other Potentially Active Damage Mechanisms: • Corrosion fatigue • Creep fatigue	
Other Comments: • Careful weld toe profile dressing may be required to discriminate discontinuities (overlap, undercut, and so on) from cracking.	

Table 5-3
Creep Fatigue

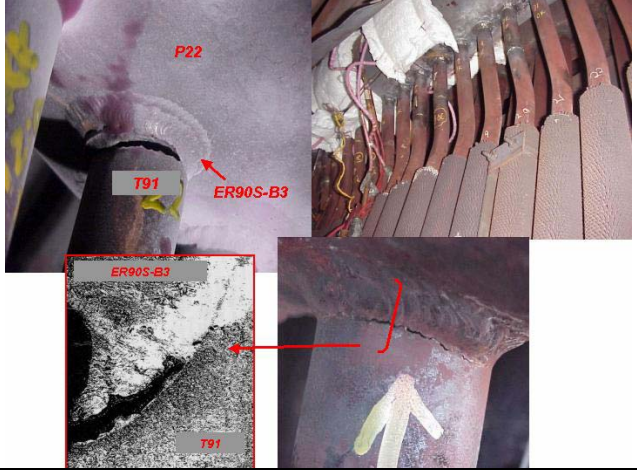
Damage Mechanism: Creep fatigue	
Summary of Mechanism: Damage and cracking resulting from the synergistic effects of cyclic stresses and exposure to an elevated-temperature environment. Sources of stress include internal pressure, thermal gradients, constraint during thermal expansion, and dead weight loads. The formation and fracture of thermally grown surface oxide scale may strongly influence creep fatigue life.	
Appearance of Damage: • Outside surface: Typically, single cracks oriented normal to the predominant tensile stress field, typically circumferential near tube-to-header connections, can be axial (in bends) or multidirectional (at attachments). • Inside surface: Borehole cracking in headers can be multidirectional.	
Where Damage Occurs: • Locations exposed to temperatures in the creep regime, typically steam-cooled and not water-cooled components, HP and IP superheaters and reheaters • Locations with welded connections, bends, attachments, and header boreholes	
How to Find Damage: • Visual • Magnetic particle • Liquid penetrant	
How to Quantify the Severity of the Damage: • Ultrasonic • AC potential drop • Replication • Exploratory grinding	
Optional NDE: • Eddy current	
What Is Acceptable: • No cracks. If cracks are detected, a fitness-for-service analysis should be performed to justify continued operation.	
Repair Options: • Local excavation (including all creep-damaged material) and weld repair • Complete replacement of connection	
Corrective Actions: • See Chapter 6 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].	
Other Potentially Active Damage Mechanisms: • Thermal-quenching induced fracture • Thermal fatigue	
Other Comments: • Careful weld toe profile dressing may be required to discriminate discontinuities (overlap, undercut, and so on) from cracking.	

Table 5-4
Flow-Induced Vibration Fatigue

Damage Mechanism: Flow-induced vibration fatigue
Summary of Mechanism: Damage and cracking resulting from very high-frequency, cyclic loading. Sources of flow-induced vibration include the buildup of self-reinforcing pressure fluctuations within a tube array, gas flow eddy currents (vortex shedding) that occur near the natural frequency of a tube array, acoustically induced vibration, and flow instability (turbulence).
Appearance of Damage: • Outside surface: Typically, single, tight cracks oriented normal to the predominant tensile stress field; typically, circumferential near tube-to-header connections. Separate cracks may be present on opposite sides of the tube. Impact damage or cracking of tube fins may be present. • Inside surface: Cracking initiates at the outside surface and will not be visible from the inside unless it has penetrated through-thickness.
Where Damage Occurs: • All sections of the HRSG, most predominant in HP superheaters and reheaters • Locations with welded connections, bends, and attachments
How to Find Damage: • Visual (visual evidence of fin cracking, impact marks, and so on) • Wet fluorescent magnetic particle • Liquid penetrant
How to Quantify the Severity of the Damage: • Ultrasonic • AC potential drop • Exploratory grinding
Optional NDE:
What Is Acceptable: • No cracks.
Repair Options: • Excavate and weld repair • Complete replacement of the connection
Corrective Actions: • See Chapter 7 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].
Other Potentially Active Damage Mechanisms: • Eddy current
Other Comments: • Careful weld toe profile dressing may be required to discriminate discontinuities (overlap, undercut, and so on) from cracking.

Table 5-5
Flow-Accelerated Corrosion

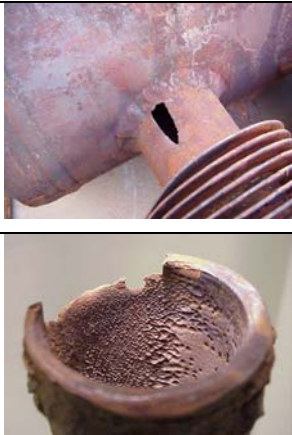
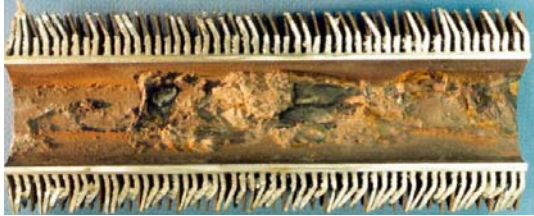
Damage Mechanism: Flow-accelerated corrosion (FAC)	
Summary of Mechanism: Accelerated dissolution and transport of the normally protective magnetite oxide scale due to the formation of locally reducing, low-pH water chemistry conditions, high flow velocity, and temperatures in the range of 212–482°F (100–250°C). Affects carbon and low-alloy steels (but not steels with significant [>0.1 weight %] chromium).	
Appearance of Damage: • Outside surface: Damage may not be visually apparent; damage that has progressed through-wall may first appear as a pinhole leak. • Inside surface: Scalloped or wavy (“orange-peel”) surface, may be partially covered with a thin, shiny, black-colored oxide or may be bare-metal surface with or without reddish rust.	
Where Damage Occurs: • Water-touched components in the temperature range 212–482°F (100–250°C). This typically includes the entire LP evaporator circuit, including the steam drum internals and vent/drain lines, near the outlet of the LP economizer, and the HP feedwater system. • Locations with high flow velocities (outlet header tube bends, riser/downcomer pipe bends, and drum steam separators).	
How to Find Damage: • Internal visual (visual, video probe, borescope) • Ultrasonic thickness measurements (internal rotary probe, or from the outside surface) • Pulsed eddy current (for insulated piping components) • Radiography (for small bore drain lines, using tangential or perpendicular beam)	
How to Quantify the Severity of the Damage: • Ultrasonic thickness measurements (use a grid pattern or scan the entire surface or the area within each grid; typical grid spacing is pipe or tube OD/4; examine a distance three pipe or tube diameters upstream and downstream and within susceptible fittings)	
Optional NDE: • Removal of metal shavings or grindings for alloy chemistry evaluation	
What Is Acceptable: • If the predicted minimum wall thickness at the end of the next service period (time to next re-examination) is greater than the specified minimum wall thickness, the component is acceptable. For predicted thickness less than the Code-allowable minimum, calculations of acceptable local wall thickness must be made.	

Table 5-5 (continued)
Flow-Accelerated Corrosion

Repair Options: • Replace component with chromium-containing alloy (such as 1 1/4 Cr-1/2 Mo). • Restore wall thickness with pad weld (temporary repair).
Corrective Actions: • See Chapter 9 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].
Other Potentially Active Damage Mechanisms: • Deposit buildup and underdeposit corrosion in the HP evaporator
Other Comments: • If FAC-resistant low-alloy (such as 1 1/4 Cr-1/2 Mo) bends are present, examine immediately upstream and downstream of the material transition.

Table 5-6
Acid Phosphate Corrosion

Damage Mechanism: Acid phosphate corrosion	
Summary of Mechanism: Corrosion resulting from the breakdown of the protective water-side oxide layer due to the buildup of internal deposits and the local concentration of phosphate salts, leading to underdeposit corrosion.	
Appearance of Damage: - Outside surface: Since this is a water-side damage mechanism, no outer surface damage will be visible unless damage has progressed to cause a pinhole leak. - Inside surface: Internal tube gouges, partially or completely filled with layered deposits, often with a distinct transition between mild and very severe corrosion.	
Where Damage Occurs: - HP and IP evaporators on the leading-edge side of the tubes - Locations with internal deposits, locations with high heat transfer or high steam quality, gas inlet row tubes, horizontal tubes, and module end tubes	
How to Find Damage: - Internal visual (video probe, borescope) - Radiography	
How to Quantify the Severity of the Damage: - Ultrasonic thickness measurements (internal rotary probe or from the outside surface) - Tube sampling	
Optional NDE: - Thermography - Pulsed eddy current - Internal visual (video probe, borescope) after chemical cleaning - Low frequency electromagnetic technique (LFET)	
What Is Acceptable: Predicted minimum wall thickness at the end of the next service period (time to next reexamination) is greater than the minimum Code-allowable wall thickness.	
Repair Options: Replace tubing when wall thickness is less than the specified minimum.	
Corrective Actions: See Chapter 10 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].	
Other Potentially Active Damage Mechanisms: Heavy deposition in the HP and IP evaporators may indicate that flow-accelerated corrosion is occurring elsewhere in the cycle.	
Other Comments:	

**Table 5-7
Caustic Gouging**

Damage Mechanism: Caustic gouging
Summary of Mechanism: Corrosion resulting from the breakdown of the protective water-side oxide layer due to the buildup of internal deposits and the local concentration of caustic to high pH levels, leading to underdeposit corrosion.
Appearance of Damage: • Outside surface: Since this is a water-side damage mechanism, no outer surface damage will be visible unless damage has progressed to cause a pinhole leak. • Inside surface: Internal hemispherical or elliptical depressions, partially or completely filled with thick layered deposits (see acid phosphate corrosion or hydrogen damage mechanisms for examples of internal deposits and wall loss). • The inside surface of a tube containing caustic gouging will appear similar to that for one subject to acid phosphate corrosion; refer to Table 5-6 for a photograph showing the typical surface appearance.
Where Damage Occurs: • HP and IP evaporators on the leading-edge side of the tubes • Locations with internal deposits, locations with high heat transfer or high steam quality, gas inlet row tubes, horizontal tubes, and module end tubes
How to Find Damage: • Internal visual (video probe, borescope) • Radiography
How to Quantify the Severity of the Damage: • Ultrasonic thickness measurements (internal rotary probe or from the outer surface) • Tube sampling
Optional NDE: • Thermography • Pulsed eddy current • Internal visual (video probe, borescope) after chemical cleaning • LFET
What Is Acceptable: • Predicted minimum wall thickness at the end of the next service period (time to next reexamination) is greater than the minimum Code-allowable wall thickness.
Repair Options: • Replace tubing when wall thickness is less than the specified minimum.
Corrective Actions: • See Chapter 11 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].
Other Potentially Active Damage Mechanisms: • Heavy deposition in the HP and IP evaporators may indicate that flow-accelerated corrosion is occurring elsewhere in the cycle.
Other Comments:

Table 5-8
Hydrogen Damage

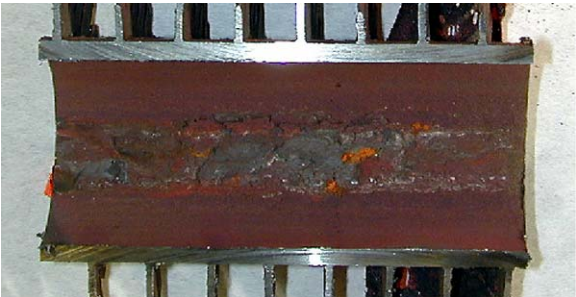
Damage Mechanism: Hydrogen damage	
Summary of Mechanism: Tube damage and wall loss resulting from breakdown of the protective water-side oxide layer due to the buildup of internal deposits and the local concentration of acidic contaminants (chlorides and sulfates), leading to underdeposit corrosion.	
Appearance of Damage: • Outside surface: Since this is a water-side damage mechanism, no external surface damage will be visible. • Inside surface: Localized internal deposition, wall loss, pitting, or gouging may or may not be present beneath the deposits.	
Where Damage Occurs: • HP and IP evaporators, on the leading-edge side of the tubes • Locations with internal deposits, locations with high heat transfer or high steam quality, gas inlet row tubes, horizontal tubes, and module end tubes	
How to Find Damage: • Internal visual (video probe, borescope) • Radiography	
How to Quantify the Severity of the Damage: • Ultrasonic thickness measurements (internal rotary probe or from the outer surface) • Tube sampling	
Optional NDE: • Thermography • Pulsed eddy current • Internal visual (video probe, borescope) after chemical cleaning	
What Is Acceptable: • Predicted minimum wall thickness at the end of the next service period (time to next reexamination) is greater than the minimum Code-allowable wall thickness.	
Repair Options: • Replace tubing when wall thickness is less than the specified minimum.	
Corrective Actions: • See Chapter 12 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].	
Other Potentially Active Damage Mechanisms: • Heavy deposition in the HP and IP evaporators may indicate that flow-accelerated corrosion is occurring elsewhere in the cycle.	
Other Comments: • If the fin spacing is large enough for ultrasonic examination from the outside surface, ultrasonic attenuation will provide qualitative estimates of the severity of hydrogen fissuring in the tube metal.	

Table 5-9
Internal Pitting

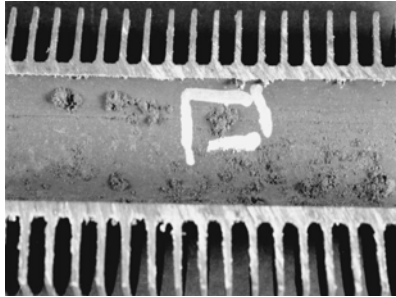
Damage Mechanism: Internal pitting	
Summary of Mechanism: Localized dissolution of metal in any component in contact with an aqueous solution. May occur due to air ingress (high oxygen and carbon dioxide levels) created during improper preservice storage, poor shutdown and layup practices, or acidic attack during chemical cleaning.	
Appearance of Damage: • Outside surface: Since this is a water-side damage mechanism, no external surface damage will be visible unless the pitting has progressed through-wall. • Inside surface: Localized wall loss in the form of pits, which may be open or filled with deposits and/or corrosion products. A bright red internal oxide scale is evidence of high oxygen levels.	
Where Damage Occurs: • Any component in contact with an aqueous solution, including water- and steam-touched tube surfaces, as well as the condenser, condensate piping, deaerating heater and storage tank, and feedwater heaters. In seam-welded tubing, localized pitting at the seam weld is common.	
How to Find Damage: • Internal visual (visual, video probe, borescope) • LFET	
How to Quantify the Severity of the Damage: • Ultrasonic thickness measurements (internal rotary probe) • Tube sampling	
Optional NDE: • Radiography	
What Is Acceptable: • Minimum wall thickness is greater than the specified minimum wall thickness. For greater pit depths, a fitness-for-service analysis should be performed to justify continued operation.	
Repair Options: • Replace tubing that has unacceptable pit depths.	
Corrective Actions: • See Chapter 13 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].	
Other Potentially Active Damage Mechanisms: • Corrosion fatigue	
Other Comments:	

Table 5-10
Gas-Side Corrosion and Pitting

Damage Mechanism: Gas-side corrosion and pitting	
Summary of Mechanism: Localized dissolution and/or general wall loss of metal from tubes and/or fins, due to the presence of corrosive species in the flue gas (sulfur compounds if fuel oils are burned or selective catalytic reduction additives are used, atmospheric chlorides, and so on)	
Appearance of Damage: • Outside surface: Surface pitting and/or wall loss to tubes and/or fins. Deposits and/or corrosion products may also be present. • Inside surface: No visible features unless the damage has progressed through-wall.	
Where Damage Occurs: • Gas-touched surfaces, most often in the cold end of the HRSG	
How to Find Damage: • Visual	
How to Quantify the Severity of the Damage: • Ultrasonic thickness measurements • Micrometer or other dimensional measurement	
Optional NDE: • LFET	
What Is Acceptable: • Minimum tube wall thickness is greater than the specified minimum wall thickness. For more severe tube wall loss, a fitness-for-service analysis should be performed to justify continued operation. Fin corrosion may degrade performance.	
Repair Options: • Replace tubing. Consider the need for material upgrade.	
Corrective Actions: • See Chapter 14 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].	
Other Potentially Active Damage Mechanisms:	
Other Comments: • Uncommon for gas-fired units due to generally low sulfur levels	

Table 5-11
Acid Dew Point Corrosion

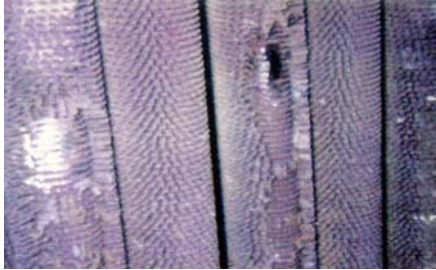
Damage Mechanism: Acid dew point corrosion	
Summary of Mechanism: Localized dissolution and/or general wall loss of metal due to the presence of sulfuric acid condensed from sulfur oxides and water vapor in the flue gas at the exhaust end of the HRSG.	
Appearance of Damage: • Outside surface: Surface pitting and/or wall loss to affected surfaces. Deposits and/or corrosion products may also be present; the underlying metal may have a gouged or “orange peel” appearance. Fins may be missing or corroded and easily broken off. • Inside surface: No visible features unless the damage has progressed through-wall.	
Where Damage Occurs: • Gas-touched surfaces (including tubes, fins, casing, ducts, and stacks) where the metal temperatures are below the acid dew point	
How to Find Damage: • Visual	
How to Quantify the Severity of the Damage: • Ultrasonic thickness measurements. (However, this method is applicable only to smooth tube surfaces that would require removal of fins to examine finned tubes.)	
Optional NDE: • LFET	
What Is Acceptable: • Minimum tube wall thickness is greater than the specified minimum wall thickness. For more severe tube wall loss, a fitness-for-service analysis should be performed to justify continued operation. Fin corrosion may degrade performance.	
Repair Options: • Replace tubing. Consider the need for material upgrade.	
Corrective Actions: • See Chapter 15 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].	
Other Potentially Active Damage Mechanisms:	
Other Comments: • Uncommon for gas-fired units due to generally low sulfur levels	

Table 5-12
Stress Corrosion Cracking

Damage Mechanism: Stress corrosion cracking	
Summary of Mechanism: The initiation and growth of cracks in susceptible materials due to the simultaneous exposure to tensile stress (applied and/or residual) and an aggressive aqueous environment	
Appearance of Damage: • Outside surface: Fine, very tight (and difficult to see), branched cracking oriented perpendicular to the dominant stress. The photograph to the right contains such cracks, and as indicated, the damage may be difficult to see with a global visual examination. Damage often appears as a pinhole leak that will extend in length with exploratory grinding. • Inside surface: Fine, tight, branched cracking oriented perpendicular to the dominant stress.	
Where Damage Occurs: • Locations with the potential for the highest concentration of contaminants (for example, condensate collection points) as well as high stresses (both residual and applied, including at bends, welds, attachments, supports, and so on). Cracking has been found in a variety of components, including feedwater heater tubing, evaporator tubing, and steam-cooled tubing and in carbon, low-alloy, and austenitic stainless steels.	
How to Find Damage: • Visual (removal of oxide and use of magnifying lens may be required) • Magnetic particle (for magnetic materials) • Liquid penetrant • Eddy current	
How to Quantify the Severity of the Damage: • Exploratory grinding	
Optional NDE: • LFET	
What Is Acceptable: • No cracks.	
Repair Options: • Replace damaged sections.	
Corrective Actions: • See Chapter 16 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].	
Other Potentially Active Damage Mechanisms:	
Other Comments:	

Table 5-13
Short-Term Overheating

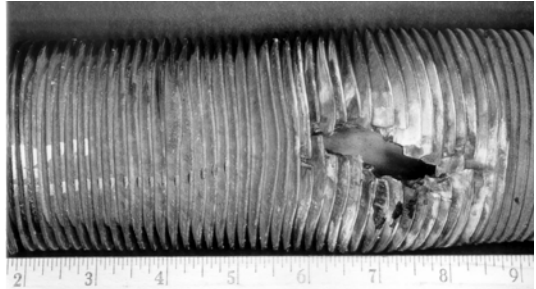
Damage Mechanism: Short-term overheating	
Summary of Mechanism: Tube metal temperature excursion to well above the design temperature for a short period of time (minutes to months), due to a partial or complete loss of steam flow. The reduced material strength results in microstructural creep damage, tube swelling, and eventual rupture.	
Appearance of Damage: • Outside surface: Deformation and distortion of tubing, possible localized swelling or bulging (but swelling may not be visually apparent due to the tube fins). • Inside surface: No visual evidence of short-term overheating damage; blockages may be present.	
Where Damage Occurs: • Typically, steam-cooled tubing, especially just downstream of supplemental burners	
How to Find Damage: • Visual for tube damage or deformation, flame patterns downstream of supplementary burners • Internal visual (video probe, borescope) for blockages	
How to Quantify the Severity of the Damage: • Tube sampling	
Optional NDE: • Radiography of bends for blockages (mainly relevant to vertical tube, horizontal gas path HRSGs)	
What Is Acceptable: • Dimensions of tube samples (OD and wall thickness) within specified limits. A fitness-for-service analysis could be used to justify continued operation with more severe damage.	
Repair Options: • Replace damaged tubing.	
Corrective Actions: • See Chapter 17 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].	
Other Potentially Active Damage Mechanisms: • Thermal fatigue, creep fatigue, long-term overheating	
Other Comments:	

Table 5-14
Long-Term Overheating

Damage Mechanism: Long-term overheating
Summary of Mechanism: Gradual increase in tube metal temperature and/or stress levels to slightly above the design temperature over a long period of time (many years or decades). The gradual accumulation of microstructural creep damage leads to eventual end-of-life rupture.
Appearance of Damage: • Outside surface: External oxidation and wall thinning may be visible. • Inside surface: Thick internal oxide scale, which may be exfoliated.
Where Damage Occurs: • Steam-cooled tubing, especially near the HP superheater and reheater outlet or just downstream of supplemental burners. Tubing near material changes (the lower-grade material), tubing with longer gas-touched lengths, and tubing just before the outlet header is most susceptible.
How to Find Damage: • Ultrasonic examination—oxide, internal oxide scale, and wall thickness survey. May require removal of tube fins from selected areas, or measurements can be taken on bare tubes near the outlet header and extrapolated into the tube bank.
How to Quantify the Severity of the Damage: • Calculation of remaining creep life using internal scale and wall thickness survey results • Tube sampling and metallurgical evaluation
Optional NDE:
What Is Acceptable: • Estimated or measured tube wall thickness, diameter, and metal temperature are within specified or design limits, and estimated creep life exceeds desired life.
Repair Options: • Replace tubing with insufficient remaining creep life. Evaluate the need for thickness increase or material upgrade.
Corrective Actions: • See Chapter 18 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].
Other Potentially Active Damage Mechanisms: • Solid particle erosion or valve blockages if steam-side oxide scale exfoliation is active.
Other Comments:

Table 5-15
Thermal Quenching

Damage Mechanism: Thermal quenching	
Summary of Mechanism: High stress overload-type damage and fracture resulting from thermal quenching of hot tubing from attemperator sprays or condensate	
Appearance of Damage: • Outside surface: Tube ovalization, distortion (plastic deformation), or cracking • Inside surface: Distortion or cracking	
Where Damage Occurs: • Steam-cooled tubing, HP superheaters, and reheaters, typically at or near an outlet or intermediate tube-to-header connections	
How to Find Damage: • Visual for deformation and cracking • Magnetic particle • Liquid penetrant	
How to Quantify the Severity of the Damage: • Crack depth measurements with AC potential drop, angle beam ultrasonic examination, or exploratory grinding	
Optional NDE:	
What Is Acceptable: • No cracking or out-of-specification deformation	
Repair Options: • Replace affected tube-to-header connections. Evaluate the need to replace adjacent tube bends.	
Corrective Actions: • See Chapter 19 of the <i>Heat Recovery Steam Generator Tube Failure Manual</i> [5-1].	
Other Potentially Active Damage Mechanisms:	
Other Comments: • If thermal quenching has occurred, examine all upper and lower header connections.	

5.2 Reference

- 5-1. *Heat Recovery Steam Generator Tube Failure Manual*. EPRI, Palo Alto, CA: 2002. 1004503.

6

INTRODUCTION TO NDE METHODS AND SURFACE PREPARATION FOR HRSG EXAMINATIONS

6.1 Introduction

This is the first of six sections that provide information on the mainstream NDE techniques as well as several less commonly used techniques. This section discusses surface preparation and access limitations that are relevant to all examination methods. Sections 7–11 discuss the techniques themselves. For completeness, descriptions of NDE techniques that are used for material characterization, rather than flaw detection, are also included.

Only techniques that are currently commercially available (and therefore accessible to the HRSG plant engineer) have been included. There are many new techniques and methodologies being developed or refined in research laboratories that tackle some of the remaining NDE problems, but in most cases they are not yet suitable for application in HRSG plants. It is anticipated that additional NDE technologies will be included in future revisions of these NDE guidelines after they become available.

It is important to note that the information in these guidelines does not specify the practical details of an examination (for example, sensitivity levels, reporting thresholds, or operator qualifications). These parameters are the responsibility of a suitably qualified and experienced NDE manager who is knowledgeable about both HRSG plant components and the applicable NDE technology. The guidelines are intended as a vehicle to facilitate the dialogue between the power plant customer and the NDE service provider.

6.2 Surface Preparation

Preparation of various HRSG component surfaces for examination is governed by many variables, including:

- NDE techniques to be used
- Type of NDE procedures to be applied
- Sequence of NDE techniques to be used
- Materials involved
- Component size and portability
- Cost of various surface preparation techniques

- Time required, including scaffolding, access, and so on
- Interference with other projects in the plant

Planning of the overall outage and examinations, along with coordination between the NDE personnel and contractors, is critical to minimizing the cost and time involved in surface preparation, as well as the impact on parallel plant projects being performed during the outage.

6.2.1 No Surface Preparation

Often, it is recommended that a walkdown of the equipment be conducted with no surface preparation of the components, because signs of unusual operation of the unit can sometimes provide valuable evidence of the abnormal condition and aid in subsequent examination and the overall condition assessment. Signs of steam or water leakage, aggressive air penetration, or local overheating can be detected quickly and visually by experienced personnel during the walkdown before any cleaning is conducted. Damage to insulation and sagging can indicate hanger/support problems in piping systems. One of the first questions to be asked after the unit is scheduled to be brought down is “What information might I lose by cleaning component surfaces?”

Most examination techniques require that a clean surface be obtained; however, this is not always the case. Some exceptions may include electromagnetic acoustic transducer (EMAT) systems, focused beam ultrasonic examination, and internal eddy current examination of tubing, which can be performed with no surface preparation if deposits and debris accumulation are not excessive. Magnetic flux leakage examinations and even some general ultrasonic techniques can be performed with no surface preparation, depending upon the as-found component surface condition, the criticality of the examination, and other factors. Infrared thermography and radiographic examinations can often be done with no surface preparation. The need to perform any cleaning operations should be verified with the cognizant NDE personnel before proceeding with the cleaning.

6.2.2 Surface Debris/Scale Removal

One of the most popular surface preparation techniques is grit or sand blasting. Large areas can be cleaned very quickly, and if air pressure and media density are kept to a reasonable level, very little damage is done to the surface. For smaller areas requiring examination, local cleaning with wire brushes or light grinders might be preferred because of their portability. There is a possibility that some small, shallow cracks will be “peened over” using these latter techniques, and particular care is recommended for thin or soft materials to ensure that small cracks are detected.

The use of such surface preparation methods can lead to severe NDE limitations when certain surface examinations are to be conducted, particularly liquid penetrant and to a lesser degree magnetic particle and eddy current. The materials involved should also be considered when selecting appropriate cleaning methods. Some material, for example, cannot be exposed to chemicals and must be cleaned using purely mechanical means. Other components must be

cleaned using chemicals because of surface finish requirements or dimensional tolerances that cannot be disturbed. Consequently, it is important to coordinate the type of surface preparation to be performed with cognizant NDE personnel and with materials specialists to make certain that the selected cleaning means are compatible with the NDE methods and techniques to be applied and with the materials involved.

HRSG tight tolerances and finned tubes limit the surfaces available for grit blasting to 1–3 tube rows at the front and rear of the component. In cases where the surface contamination is a by-product of the combustion process (for example, in oil-fired combustion turbines), deposits are most prevalent on the leading-edge tubes. Removing deposits from large areas can cause further deposition by imbedded grit or deposit/grit mixtures. This can lead to losses in efficiency and pluggage of HRSG components. Recently, frozen carbon dioxide has been used as a blasting medium to prevent adding grit contamination to the HRSG gas path.

Local, state, or federal regulations may dictate that cleaning techniques that can cause potential airborne contamination in confined spaces (for example, grit blasting of tubes inside the HRSG) require monitoring during and after the cleaning cycle. In these cases, the NDE personnel may be required to wear protective breathing apparatuses, which can slow down the examination process.

For parts or components that can be moved, cleaning is often accomplished in a confined area, such as an erected tent. This limits the export of cleaning media or the import of airborne contaminants into the cleaning environment, which can be important for cleaning parts with tight fit-ups and clearances that must be disassembled for examination. In addition, the use of cleaning/examination enclosures can often be required as a means of controlling ambient light. As an example, a darkened area is required in order to perform examinations that rely on fluorescence, such as fluorescent magnetic particle or liquid penetrant examinations. For some components, temperature and humidity control is very important. Often, the same enclosures used for cleaning provide suitable environmental protection for the examination and storage of the components until they are ready for return to service.

6.3 Access Limitations

Structural modifications may be necessary in order for personnel to gain access to all HRSG components so that they can perform internal examinations. If the component is to be examined frequently, consideration should be given to designing and implementing a convenient means of access that can be reused, thus eliminating cutting and rewelding at each outage. Modifications to provide access should include consideration for both personnel and equipment and can involve larger access doors, new or larger manways, and so on. Where modifications are required to perform certain examinations, permanent modification may be cost-efficient, because improved access usually results in more timely maintenance, examination, and repair during future outages.

Specific access ports can be installed in evaporator and economizer headers to facilitate the internal examination of these components for corrosion damage. The access ports should be designed as blind nipples to facilitate easy removal and replacement of the nipple ends. Internal access by borescope or video camera is the preferred method for examinations for internal corrosion damage.

6.4 Related Literature

NDE Guidelines for Fossil Power Plants. EPRI, Palo Alto, CA: 1997. TR-108450.

7

SURFACE AND NEAR-SURFACE EXAMINATION TECHNIQUES

This section provides an overview of examination methods that are applicable to surface and near-surface regions of HRSG components. It covers visual examination, dimensional measurements, magnetic particle examination, liquid penetrant examination, eddy current examination, and the AC potential drop technique.

7.1 Visual Examination

7.1.1 Introduction

Visual examination is the most effective and informative method of finding flaws and degradation among the various HRSG components. It is the principal NDE method used for examination of HRSG tubes, headers, drums, and piping systems throughout manufacture, assembly, and operation of the unit. Quality visual examination is one of the least appreciated (and possibly the most demanding) NDE activity currently being used in power plant examinations. Whereas visual examination once consisted of “looking over” a component, by current standards it typically involves a great deal of training and practical experience before an examiner is qualified for this examination method.

A qualified visual examiner must have a good working knowledge of a vast array of plant components, metallurgy, potential flaw types for various components, failure mechanisms, and so on. The examiner must be capable of recognizing the presence of different damage forms and classifying the damage in terms of severity and implications relative to ongoing operation of the component, based solely on what normally is very limited visual evidence. The American Society for Nondestructive Testing (ASNT) currently recognizes visual examination as a specific examination discipline, and the requirements for acquiring certification are extremely demanding.

Although not an NDE technique in itself, debris removal is often a substantial part of a visual examiner’s job. It is common for items such as screwdrivers, grippers, welding rods, nuts, and bolts to drop into a component during maintenance operations. If not removed, they could cause considerable damage when the plant is brought back to power. Various devices and attachments have been developed to facilitate this task.

7.1.2 Equipment

Visual examination encompasses a vast array of tools to access specific locations and observe surfaces for damage indicative of certain detrimental conditions. This list can range from the simple to the sophisticated and may include:

- Inspection mirrors
- Magnifying glasses
- Portable microscopes
- Fiber-optic devices of various lengths, diameters, and tip articulations
- Rigid borescopes (also known as endoscopes), which can view forward or sideways and can be either fixed or rotating
- Video image scopes, which are similar to fiberscopes in appearance but use a charged coupled device (CCD) chip rather than optics to transmit the image
- Miniature cameras (analog and digital)

A host of devices is available to carry the examination equipment to the point of interest. The simplest method is to connect a camera to a stiff, but flexible, rod to gain access to the interior of components such as headers, but the complexity can increase to purpose-built crawlers and manipulators for steam pipes, ducts, drains, and other difficult-to-access areas.

To facilitate a visual examination, it is becoming more common to display the image on a monitor. This not only prevents the examiner from becoming tired from peering through a fiberscope for long periods of time, thereby increasing the risk of missing a flaw, but it also enables colleagues and plant personnel to view the image and offer their advice and interpretation. Recording the image digitally or on videotape is an attractive option because an assessment can be made off-line. If examinations are performed in later years, flaw growth can be assessed from the multiple video recordings.

If video recording is performed, it is essential that annotations be made while the examination progresses. Many parts of power plants look very similar from the inside, and it is vitally important to know precisely where the camera/viewer was looking in order to provide the best guidance for subsequent examinations or operations. As an example, consider the case of a visual examination for ligament cracks in a header when subsequent ultrasonic examination is used to size any cracks that are found by visual examination. It is very easy to mistakenly count the rows, particularly in headers that have staggered rows, so there is a risk that the ultrasonic examiner could perform NDE on the wrong ligament without an accurate visual examination record.

A video typewriter is usually used to caption the screen and permanently label the videotape. A microphone can also be used to provide an audio commentary, but this is prone to error if the examiner makes a mistake in row counting or loses his bearings, and loud plant noises can sometimes cover the commentary.

Several systems are on the market that use PC technology to assist in the examination, particularly in the interpretation and assessment functions. For example, some systems allow the user to input a wire mesh model of a component (for example, a header), and this model is superimposed on the live image and moves as the camera/viewer moves. This enables a better sense of perspective to be realized so that close and distant features can be scaled correctly.

Computer software has appeared in recent years that can capture video images and convert them into appropriate formats for use in word processing packages and databases such as EPRI's Boiler Maintenance Workstation (BMW) for Windows. This greatly enhances the speed and value of an examination report. Digital cameras are also available that will transfer images directly to a PC.

Photographs can also provide a permanent record of both the macroscopic positions of a component system and the surface features that may change during exposure to stress, temperature, and environment.

7.1.3 Implementation

Visual examination uses a wide range of equipment and provides access to many types of components, so there is no universal "procedure" that describes how to implement it. However, there are several common factors that should be considered when planning any visual examination.

7.1.3.1 Access

No examination is possible unless the examiner can gain access to the component. In addition to the access needed for a camera or viewer, access may also be needed for a light source and possibly a carriage or transport vehicle used to move the examination head. This places constraints on the diameter of the entry port, how straight it is initially (there may be a bend to pass before entering the component proper), and how much room exists between the port and the adjacent component or wall.

The challenges to performing a complete visual examination of an operational HRSG that has seen some amount of service are difficult due to the tight spaces and close tolerances. The higher-efficiency HRSGs are more densely packed with pressure parts and assembled in a complex manner in order to extract the maximum amount of steam from the exhaust gases.

Access to tubes within the HRSG enclosure is limited. The best access is at the leading- and trailing-edge tubes. Some access is also available at the tight spaces between modules and around the SCR. Tube ends located outside the gas path are, in some designs, somewhat more accessible due to the absence of fins near the headers. However, the close proximity of multiple headers in a component, enclosed header vestibules, and the short tube lengths outside the gas path also make direct visual examination difficult. Mirrors are often necessary to examine these

locations. Examination of transfer pipes between headers, header vents, drains, and supports is usually possible in the upper and lower vestibule enclosures. Examination of risers, downcomers, piping, and drums outside the vestibule must contend with insulation and lagging coverings.

7.1.3.2 Diagrams and Plans

It is important for the visual examiner to have detailed layout and dimensional information about the component, because this will invariably determine the examination system to be used. Good diagrams will also help the examiner assess what is being looking at. It is very easy to lose sense of scale when looking at an image on a screen—what appears to be an enormous hole may be a small pit in reality.

7.1.3.3 Temperature

Many optical devices rely on glue to cement the component lenses and prisms together, and the glue becomes soft as the temperature rises. Eventually, the device may cease to function as the optics slip out of alignment or the image clouds over. A practical rule of thumb is to never let the device exceed 120°F (50°C). Bear in mind that many fiberscopes and endoscopes are intended for the medical market and are not expected to survive in the harsh conditions found in an HRSG. This temperature sensitivity means that it is unwise to plan a visual examination during the first week of an overhaul or during a breakdown unless there is some forced cooling.

7.1.3.4 Internal Conditions

Dust and grit can enter delicate camera parts or prevent crawler wheels from gripping properly.

Standing water may not be a problem if the water is shallow, but sometimes the heat from the illuminating light source may cause the lenses to steam up if standing water is present.

7.1.3.5 Nearby Operations

When examining long pipe runs, the examiner must be aware of any other operations that are happening in the vicinity. Welding and grinding operations can impair the quality of the image by interfering with the signals transmitted along the cables. Also, welding operations may raise the temperature of the component locally but out of sight of the examiner located at the access port. See the remarks about temperature above.

7.1.3.6 Protection for Equipment

A visual examination can involve a large amount of equipment (camera, cables and drum, monitor, videocassette recorder, video typewriter, crawler controller, and so on), all of which is delicate and will be impaired by the typical conditions found in most HRSGs. Care should be taken to prevent dust, grit, and water from falling onto the equipment from above by erecting a tent or tarpaulin sheet over the equipment.

7.1.3.7 Establishing a Baseline

Comparisons offer the best approach to visual examination of HRSG components. Therefore, it is important to establish a baseline condition from which comparisons can be made to identify service-induced damage. Keep in mind that the objective of comparison is to locate differences created by stress, temperature, and/or environmental deviations. Baseline measurements of header/harp positions, tube alignment, and concentricity of enclosure penetrations will help identify movements that occur during startup and shutdown that are indicative of high stresses. The initial HRSG visual examination should document all areas of slight misalignment resulting from manufacture and erection so that these anomalies will not be mistaken for service-induced damage.

7.1.3.8 Care in Choosing Examination and Documentation Angles

The viewing direction of a set of photographs or a video recording should be selected with forethought to how changes may occur. For instance, bent tubes entering a header should be photographed at a slight angle that would emphasize slight misalignment due to plastic deformation. Photographs taken to emphasize subtle differences in operating temperature should be taken nearly straight on. This will highlight the surface condition of the components and the natural emissivity of the tube surfaces. The camera flash is effective in bringing out subtle discoloration effects due to differences in operating temperature, scale formation, oxidation, and exfoliation suggestive of overheating. Figure 7-1 illustrates these two photographic techniques.

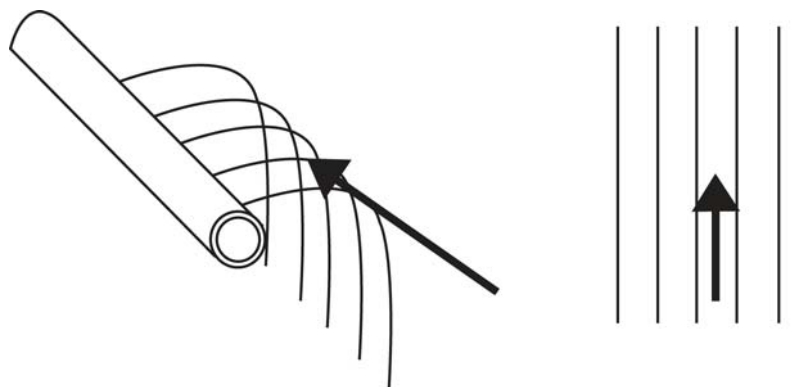


Figure 7-1
Recommended Photographic Angles to Highlight Tube Plastic Deformation (Left) and
Overheating (Right)

7.1.4 Applications

Visual examination can be applied to any component in which the damage manifests itself at accessible surfaces to a degree permitting detection by visual means. Ingenuity can often be exercised to produce a viewing and transport system for most plant components.

It is strongly recommended that a complete set of digital recordings, photographs or videotapes of all accessible areas of each component be generated during the commissioning phase of the HRSG life cycle.

Visual examination of drum internal surfaces offers a unique perspective on the water quality maintained during HRSG operation. A visual observation of wall loss and damage to separators, particularly in LP drums, is a key indicator of FAC. Drum deposits, residues, pitting, and the color of the internal oxide are all indicative of the potential for internal corrosion damage. Visual examination of evaporator tubing can detect heavy internal deposits, which can be weighed and analyzed via tube sampling during planned examinations. Dividing the total weight per unit area by the effective service hours since the last examination/cleaning will establish a rate of formation. Changes to this rate of formation may be representative of the risk for corrosion-activated damage and deterioration. Analysis of internal tube deposits should be accomplished to evaluate the possibility of active underdeposit corrosion mechanisms (hydrogen damage, acid phosphate corrosion, or caustic gouging).

Each drum will develop its own natural rate of deposition. Photographs of the drum internal surfaces can be used to track the amount of pitting and the formation of oxides. The coloration of the drum internals is affected by the oxidizing reducing potential (ORP), the pH, and the presence of impurities or additives that have deposited. In a multipressure HRSG, each drum (LP, IP, HP) may exhibit different characteristics. For example, if the feedwater entering the LP drum is controlled with all-volatile treatment (reducing) (AVT(R)), the LP drum may exhibit black magnetite deposits (indicating that the LP evaporator and economizer circuits may be

prone to FAC). This would signal the need for extra examination of the LP evaporator outlet bends and the drum steam separator cylinders. Variations may also be present on either end of the drum or above and below the water line in the steam drum.

Steam drum internal piping systems are used to feed boiler water, inject chemicals, extract samples, and remove unwanted solids. Visual examination should verify that the chemical injection, feedwater inlet, and blowdown piping holes are free of obstructions and deposits. The orientation of the blowdown holes is crucial for optimum removal of solids entrained in the circulating water systems.

Visual examination is also a valuable tool for assessing the extent of degradation when HRSG tube failures have occurred. Fatigue failures may exhibit evidence of deformation, misalignment, and rubbing. These signs should be sought out during repair of a leak, and adjacent tubing should be evaluated to prevent additional failures. Analysis of any external corrosion or overheating will also benefit from careful visual documentation. Internal corrosion failures are not likely to exhibit any signs of deterioration on the external surfaces, and a drum internal surface examination may be quite valuable.

7.1.5 Debris Removal

The removal of debris from inside a component is not an NDE technique, but it is a task that often falls to the visual examiner. The first task is to find the debris so that all of the techniques that are used to find component flaws can be brought to bear on locating unwanted material. Once located, the second task is to retrieve the debris. Examples of debris that has been found in HRSG tubing are shown in Figure 7-2.



Figure 7-2
Examples of Debris Found in HRSG Tubing (Shot Blast Media, Exfoliated Oxide Scale, and a Rock-Like Particle)

A wide variety of devices have been constructed to remove debris; some are made for that purpose, and others can be improvised when required.

Examples of debris-retrieval equipment include:

- Vacuum cleaner
- Magnets for steel objects
- Claws and grippers
- Impalers for softer debris such as rags or foam
- Baskets, nets, and cages that drop over the object
- Rotating spiral (rotating a horizontal-axis spiral forward over an object traps the debris between the turns, and then the spiral can be pulled backward)
- Sticky tape
- Suction cups
- Blowers (to move the debris to a section with easier access)

Care must always be taken to prevent the examination equipment itself from becoming stuck inside a component.

7.1.6 Related Literature for Visual Examination

NDE Guidelines for Fossil Power Plants. EPRI, Palo Alto, CA: 1997. TR-108450.

M. J. Fletcher. “A Review of Optical Inspection Methods,” *Insight*, Vol. 38, No. 4, April 1996.

Nondestructive Evaluation of Component Interiors. EPRI, Palo Alto, CA: 1990. NP-6832.

7.2 Dimensional Measurements

7.2.1 Introduction

Physical measurement of component position, motion, and size are often critical to assessing failure occurrence. Measurement methods can range from verifying elevations, clearances, and so on using tape measures to measuring material strain using strain gages or displacements using scratch gages or displacement gages. During unit operation, boilers, piping, and turbine components function at elevated temperatures that can lead to relaxation, creep damage, and distortion. By routinely measuring critical dimensions, it is possible to identify areas of excessive damage accumulation, target examination locations, and detect the occurrence of step-changes signaling structural failure.

7.2.2 Component Application

Single point-in-time measurements can be used to detect permanent distortion or swelling in headers, tubes, and piping components. For example, measurements of header bowing can assist in determining whether the bow is due to relaxation or plastic strain caused by large temperature gradients. On-line measured positional data can be used to detect the occurrence of header humping during transient boiler conditions.

7.2.3 Measurement Implementation

Generally, acquiring the data requires that the examiners have direct contact with the component to either take the measurements or mount appropriate measurement devices. If an optical level (or equivalent) is used, an unobstructed view between the level and the measurement points is typically required.

7.2.4 Measurement Application Methods

For most applications, measuring component position is easily achieved using tape measures and levels. Consistent reference points, such as grating elevations or structural building steel, should be selected to permit accurate reproduction. Occasionally, indicator rods are physically attached to the component to permanently mark the measurement point.

Measuring component movement during operation can be achieved by frequently measuring the reference points over the desired period of time. On-line monitoring of most boiler components requires some type of reference to be extended beyond the boiler skin. If relatively short duration movements are of concern, electromechanical devices and high-speed computers permit rapid and continuous data acquisition.

Measuring component size is typically done on high-temperature components to monitor the accumulation of creep strain. Techniques can vary from taking diameter and circumference measurements using calipers and pi-tapes to using high-temperature strain gauges and computer data collection.

7.3 Magnetic Particle Examination

7.3.1 Introduction

Magnetic particle examination is a fairly simple examination method that is useful for the detection of surface-connected and near-surface discontinuities in ferromagnetic material. The method is applicable to a variety of components, including raw materials and finished components.

In any ferromagnetic material, each molecule has magnetic poles that are randomly oriented in an unmagnetized specimen. In such case, the magnetic fields of the molecules cancel because of the random orientation, resulting in no overall magnetic field. Upon magnetization of the specimen, the poles of the individual molecules become aligned; thereby creating magnetic poles in the component that will attract iron. Magnets can be permanent (retaining their magnetic poles permanently) or temporary (retaining their magnetism only while the magnetizing force is applied).

If a magnet (for example, a bar magnet having only north and south poles—one at each end) is cut into two pieces at some point along its length, each piece becomes a bar magnet having north and south poles. When the two pieces are rejoined, north pole on one bar to the south pole on the second, the bar reverts to a single bar with two primary poles. However, at the junction point a concentrated leakage field will remain. The same is true of a partial cut in the bar; that is, two opposite poles will be created at the cut, and the leakage field will attract iron. In this case, the magnetic lines of flux are parallel to the length of the bar magnet, and the presence of the transverse slit creates a leakage field of sufficient magnitude to attract iron. In general, a greater flaw depth produces a greater disruption in the magnetic lines of force.

For a material that is ferromagnetic but not a permanent magnet, the part can be magnetized in one of several ways. The fundamental principle behind magnetic particle examination lies in the ability to attract iron at leakage fields that are produced, in the same way as described above for the bar magnet, by magnetizing the part in a direction essentially normal to the major dimension of the discontinuity. Iron particles, either colored to contrast with the material under visible light or containing a fluorescent compound to make them visible under ultraviolet illumination, are then applied to the surface. These particles are attracted to the discontinuity, yielding a visual indication of its presence.

7.3.2 Applications

Magnetic particle examination is one of the most frequently used of the NDE methods applied in power plants for routine examination. It can be applied to essentially any exposed surface of any ferromagnetic material. Surface preparation is not as demanding as it is for liquid penetrant examination, and reasonable sensitivity can be achieved, particularly if using the wet fluorescent method. This method can even be applied over thin surface coatings such as paint, although surface finish can affect both mobility and retention of the particles.

A special type of magnetic particle examination that is useful for examination of tight spaces that otherwise cannot be examined with this method involves the use of rubber compounds for the suspension medium. Commonly referred to as *rubber-mag*, the particles are mixed into the rubber compound while it is in a liquid state. Magnetization is accomplished by the most appropriate technique to produce directional magnetization for optimum detection of the prevalent flaw orientation, and the magnetic particles are applied via the rubber suspension. The rubber compound used must have very specific properties to maintain particle mobility while in the liquid state and to provide a contrasting background to the particles. Once set, the molded rubber is removed and viewed for indications of surface flaws.

A variation of this technique, which is sometimes easier to interpret, is to magnetize the area to be examined and disperse visible magnetic particles onto the surface. Then, while maintaining the magnetic field, a rubber dental mold material or piece of clear adhesive tape is applied over the region. If indications are present, they will stick to the molding material or tape, creating a permanent record of the indication length and shape.

7.3.3 Magnetic Particle Types

Three types of magnetic particles are available for different applications:

- Dry, visible powder
- Wet, visible suspension
- Wet, fluorescent suspension

The suspension medium varies depending on the application, and wet particle suspensions can be acquired in aerosol cans. A key parameter in wet magnetic particle examination is to keep the suspension agitated and the particles well mixed so that they are applied evenly and in the correct proportions relative to the suspension medium.

Visible particle materials are usually red (oxide) or gray in color and should be selected on the basis of the component surface color and finish. Particles are also available in different sizes to suit specific application requirements for ease of application, ability to hold to a particular surface under specific leakage field strengths, particle mobility, and so on. Although the sensitivity of visible magnetic particle materials is generally considered lower than that achievable with fluorescent particles, it is adequate for many examination applications.

Fluorescent magnetic particles fluoresce yellow or yellow/green when subjected to ultraviolet (UV) light. Normally accepted as the more sensitive of the magnetic particle methods, fluorescent magnetic particle examination is reliant on its ability to form indications where particles are attracted and therefore accumulate at surface and somewhat subsurface discontinuities when viewed under UV light illumination. Suitable lighting in the examination area is required for the visible method, whereas suitable shielding from visible light (that is, darkening) in combination with suitable UV illumination intensity is required for the fluorescent methods to perform the examination effectively. The UV source (black light) must meet specific wavelength and intensity requirements and must be used at prescribed distances from the component surface.

In HRSG applications, examination tents are used for fluorescent magnetic particle examination, where possible, to provide the appropriate dark viewing conditions.

7.3.4 Implementation

Regardless of the particles used, the examination follows four basic steps: surface preparation, magnetization, particle application, and viewing.

1. **Surface Preparation.** Prior to application of the magnetic material, all surfaces of the component must be cleaned and completely dried. Cleaning the surface improves the detection of discontinuities by removing contaminants (for example, oil or water) that otherwise limit the effectiveness of the examination. Cleaning can involve any number of processes, depending on the application. These include:
 - Detergent cleaning
 - Vapor degreasing
 - Steam cleaning
 - Solvent cleaning
 - Ultrasonic cleaning

- Mechanical rust, scale, and paint removal
- Etching

For HRSG applications, a mechanical means of removing rust, scale, paint, and so on, followed by solvent cleaning, is recommended. Because magnetic particle examination provides some degree of penetration below the accessible surface, mechanical surface preparation does not require the care that must be exercised for liquid penetrant examination. Care must be taken to ensure that the cleaning method does not remove any significant tube base metal, especially when examining thin-walled HRSG tubing.

2. **Magnetization.** Various devices can be used to perform magnetization:

- Coil wraps.
- Current injection using prods. Current introduced through contact prods can arc to the part and cause damage.
- Proximity conductors. This approach involves a central conductor that is passed through holes and bores or a conductor positioned beside the component.
- Yokes. A yoke is a U-shaped electromagnet that introduces magnetic flux directly into the part between the two legs of the magnet.
- Fixed magnetic particle machines. This type of device can be used for relatively small components and typically has head stocks that hold the part for circular magnetization by passing the current through it. It also typically has a fixed coil to encircle components for longitudinal magnetization.

The use of a magnetic yoke to detect axial cracks in a cylindrical object is shown in Figure 7-3.

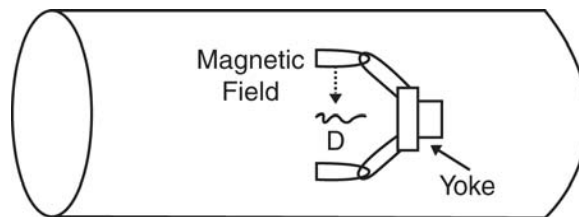


Figure 7-3
Use of a Yoke to Detect Axial Cracks

3. **Particle Application.** Particles are applied using various sprays, aerosols, dusters, and so on. In the continuous method, the particles are applied during magnetization. In the residual method, particles are applied after the magnetizing current has been removed.
4. **Viewing.** Viewing requires no special considerations except the UV or visible lighting requirements defined earlier.

Proper ventilation is important while performing wet fluorescent magnetic particle examination in order to avoid the buildup of fumes that could ignite or suffocate the examiner. Also, the proper quality checks recommended by the manufacturer for the passing of current and settling tests for the suspensions should be performed before the examination.

7.3.5 Application Methods

The magnetic field can be induced in the component in one of two basic ways:

- By passing current through the component, in which case the magnetic field is around the component in a direction normal to the direction of current flow (for example, a circular magnetic field is created by passing current axially through a round bar).
- By passing current through a conductor held in proximity to the component. (For example, current passing through a central conductor placed inside a cylinder will produce a circular magnetic field in the cylinder. Similarly, current passing through a coil wrapped around a rod will produce axial, or longitudinal magnetization in the rod.)

Figure 7-4 shows various magnetization directions and the impact of the resulting magnetic fields on the sensitivity of the examination to flaw orientation.

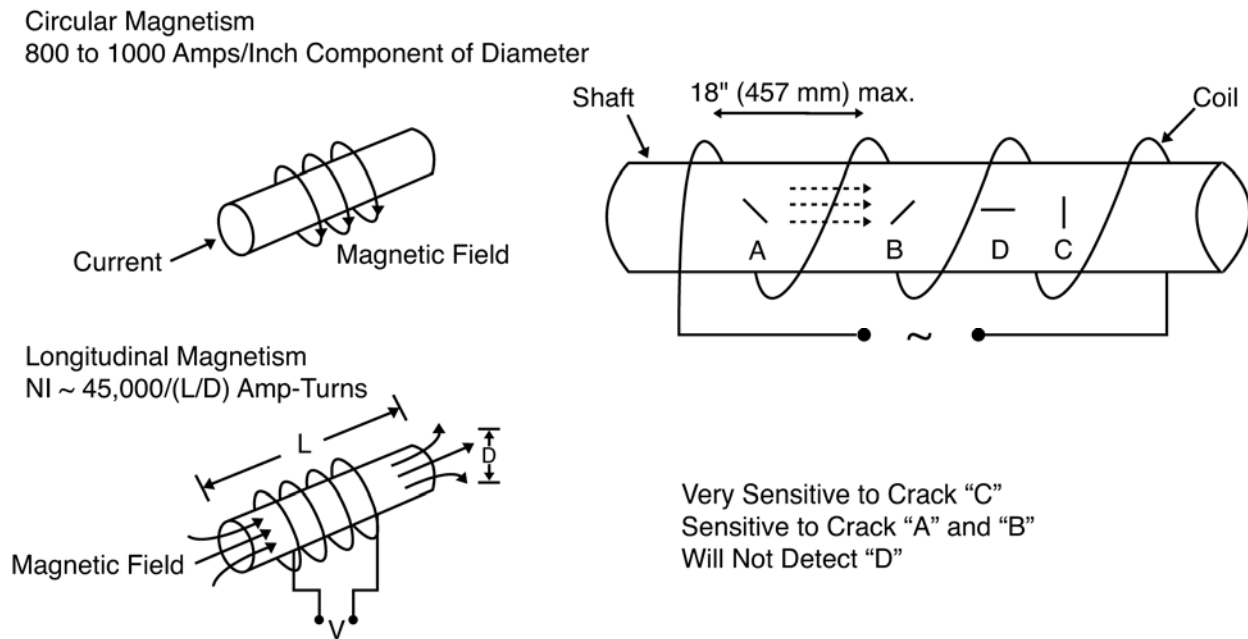


Figure 7-4
Different Magnetization Directions and Impact on Flaw Orientation Sensitivity

Implementation methods can involve the use of direct current (DC), alternating current (AC), or half-wave rectified current, the latter two being the preferred types of magnetizing current for most applications and, therefore, the most prevalent. AC produces maximum flux at the surface and is better suited for the detection of surface imperfections. Relative to DC, the reversal of magnetic fields of AC improves particle mobility. Half-wave rectified current provides deeper penetration of the magnetic field into the material while maintaining good particle mobility via the pulsed nature of half-wave rectification.

7.3.6 Related Literature for Magnetic Particle Examination

NDE Guidelines for Fossil Power Plants. EPRI, Palo Alto, CA: 1997. TR-108450.

Nondestructive Examination of Welds Through Painted Surfaces. EPRI, Palo Alto, CA: 1988. NP-5834.

Reliability of Magnetic Particle Testing Performed Through Coatings. EPRI, Palo Alto, CA: 1988. NP-5951.

7.4 Liquid Penetrant Examination

7.4.1 Introduction

Liquid penetrant examination is an NDE method for finding discontinuities that are open to the surface. Indications that are open to the examination surface can generally be found regardless of the flaw size (above the detection threshold), configuration, or orientation. Due to capillary action, penetrant materials are drawn into various types of surface imperfections, making the method well suited for detecting most imperfections in both ferrous and nonferrous metals if the flaws are open to the examination surface. Liquid penetrant examination can be applied to a variety of components, including raw materials and finished components. The examination of complex geometries is possible, as long as the surfaces are accessible and the complexity of the surface geometry does not preclude complete removal of excess penetrant.

The theoretical basis of this examination is relatively simple. A liquid penetrant containing a visible liquid (also called *color contrast*) or fluorescent compound is applied to the component surface. The penetrant is allowed to remain on the surface for sufficient time to be drawn into the openings of the surface discontinuity by capillary action. Excess penetrant materials are then removed and a developer is applied to the surface. Where the developer contacts the residual penetrant material held in the surface discontinuities, the developer draws the penetrant back to the exposed surface, providing both an indication of the presence of a surface discontinuity and a contrasting background that makes the indication more apparent under visual observation of the surface. The developer may be a fine powder, a solution that dries to a fine powder, or a suspension (for example, solvent, water, or alcohol) that dries and leaves an absorbent film on the surface.

7.4.2 Application Methods

Liquid penetrant examination can be broadly classified into one of three application methods:

- Water-washable penetrant, which contains an emulsifier and therefore can be directly removed using water as the cleaning agent
- Post-emulsifiable penetrant, which requires application of an emulsifier (liquid that combines with the penetrant to make it water-washable) prior to water cleaning
- Solvent-removable penetrant, which can be removed adequately only by using the appropriate solvent

7.4.3 Penetrant Types

Two basic penetrant materials are used: visible and fluorescent. Visible penetrant materials are usually red, producing a vivid contrast with the applied developer, which is typically white. Although the sensitivity of visible penetrant materials is generally considered lower than that achievable with fluorescent penetrants, it is adequate for many examination applications.

Fluorescent penetrants fluoresce yellow or yellow/green when subjected to UV light. Normally accepted as the more sensitive of the liquid penetrant types, fluorescent liquid penetrant is reliant on its ability to form indications where discontinuities are open to the surface and viewed under UV light. Suitable lighting in the examination area is required for visible penetrants, while suitable shielding from visible light (that is, darkening) in combination with suitable UV illumination intensity is required for the fluorescent penetrant methods to perform the examination effectively. The UV source (black light) must meet specific wavelength and intensity requirements and must be used at prescribed distances from the component surface. In HRSG applications, examination tents are normally used for fluorescent liquid penetrant, where possible, to provide the appropriate dark viewing conditions.

Penetrant “systems” have been developed with differing characteristics to enhance performance in specific applications. These systems involve the various penetrant variations (visible versus fluorescent, water-washable versus post-emulsifiable versus solvent removable), appropriate emulsifier and cleaning agents, and appropriate developers. The viscosity and surface tension of the penetrant materials are precisely controlled and vary from system to system to enhance certain performance characteristics. Normal-sensitivity systems and high-sensitivity systems, for example, can be found within a particular type of penetrant system.

It is important that liquid penetrant examinations be performed throughout using only compatible materials (that is, using materials only from the same system unless compatibility has otherwise been assured) and that the examination steps be performed according to the prescribed processes for the particular system selected. Penetrant systems can be found in aerosol containers and in bulk form. In HRSG applications, the most commonly used penetrant systems are those that are provided in aerosol cans.

Performing liquid penetrant examinations requires no special equipment with the exception of a source of ultraviolet (black) light for fluorescent penetrants. For most field applications, portable examination kits for either visible liquid penetrant or fluorescent liquid penetrant are available. A typical examination kit for visible liquid penetrant systems would include cleaner, penetrant, and developer, each in aerosol containers. Lint-free towels or wipes are used for precleaning, removal of excess penetrant, and postexamination cleaning. A similar kit including a small black light would be provided for fluorescent examinations.

7.4.4 Implementation

Regardless of the method selected for the application, liquid penetrant examination requires a minimum of five steps: surface preparation, penetration, removal of excess penetrant, development, and interpretation.

1. **Surface preparation.** Prior to application of the penetrant material, all surfaces of the component must be thoroughly cleaned and completely dried. Cleaning the surface improves the detection of discontinuities by removing contaminants (for example, oil or water) that otherwise limit the effectiveness of the examination. Cleaning can involve any number of processes, depending on the application. These include:

- Detergent cleaning
- Vapor degreasing
- Steam cleaning
- Solvent cleaning
- Ultrasonic cleaning
- Mechanical rust, scale, and paint removal
- Etching

For HRSG applications, mechanical means of removing rust, scale, paint, and so on, followed by solvent cleaning, is common. Care must be exercised in performing mechanical cleaning operations to prevent smearing metal over the flaw, thereby sealing it and preventing detection. Any heavy mechanical cleaning using grinders, grit blasting, and so on should be followed sequentially by surface preparation with finer and finer grits to remove the surface smearing caused by the previous step. Proper surface preparation to a fairly smooth surface is also important to facilitate adequate removal of excess penetrant. Excess penetrant left on the surface results in a background that causes difficulty in resolving fine indications. When examining thin-walled components such as HRSG tubing, care must be taken to avoid removing excessive base metal.

2. **Penetration.** Liquid penetrant is applied to the examination surface to form a film over the area of interest. The penetrant should remain on the surface for sufficient time (dwell time) to allow penetration into any surface openings that may be present. Two types of penetrant are generally available: lipophilic (oil based) and hydrophilic (water based). Typically, the post-emulsifiable penetrant process involves lipophilic penetrant materials.

3. **Removal of excess penetrant.** Excess penetrant is removed using a cleaning method consistent with the type of penetrant material used. Care must be exercised during removal to avoid overcleaning the component and removing the penetrant material from the discontinuities. In certain production applications, where parts can be easily washed with a water spray, water-washable and post-emulsifiable penetrants are commonly found.

However, solvent-removable penetrants or special cleaning processes using post-emulsifiable penetrants are more common for penetrant examinations in HRSGs. In these processes, excess penetrant is first removed from the surface using dry, clean, lint-free cloth or other suitable absorbent material. Final cleaning is accomplished using the cleaning material appropriate to the penetrant system being used. Improper or incomplete cleaning can leave a background that interferes with the visibility of indications. For visible penetrants, cleaning should be continued until no penetrant is removed onto a clean cloth. Fluorescent penetrant systems provide the advantage that the surface and cleaning cloths can be viewed under UV illumination to ensure adequate cleaning.

4. **Development.** A developing agent (typically, a suspended powder) that acts as a blotter is applied in a thin film over the examination surface to aid the natural seepage of penetrant from the discontinuities and, in some form, improve the examination sensitivity. A contrasting background produced by the developer assists in the visual interpretation of the examination results.
5. **Interpretation.** Visual observation of the component surface is conducted from the time of initial application of the developer and for a sufficient time thereafter to allow penetrant to bleedout from the surface openings. The time required for an indication to become visible by drawing the penetrant material back to the surface is a function of flaw characteristics, particularly the tightness of the flaw, and significant time is required in certain applications. In addition, the well-trained and experienced examiner can often estimate flaw significance by observing the surface during the bleed-out period and noting the rate at which the indication becomes apparent and spreads over the developed surface.

7.4.5 Applications

Table 7-1 provides guidance for the selection of the appropriate penetrant type for various applications, based on the examination conditions and detection requirements.

Table 7-1
Selection of Penetrant Systems [7-1]

Examination Condition/Requirements	Preferred Process	Remarks
Highest sensitivity to fine imperfections required	Post-emulsifiable fluorescent	Brightest indication, most sensitive
Parts have rough surfaces	Water-washable fluorescent	
Parts have medium rough surfaces	Water-washable fluorescent, Post-emulsifiable fluorescent	Choice depends on production and sensitivity requirements
Spot testing of local areas only is desired	Solvent-removable	
Portable equipment necessary	Solvent-removable	
Water and electricity not available	Solvent-removable	
Leak detection	Water-washable fluorescent, Post-emulsifiable fluorescent	Penetrant only

7.4.6 Reference and Related Literature for Liquid Penetrant Examination

Reference

- 7-1. R. C. McMaster, ed., *Nondestructive Testing Handbook*. American Society for Nondestructive Testing, 1959.

Related Literature

NDE Guidelines for Fossil Power Plants. EPRI, Palo Alto, CA: 1997. TR-108450.

7.5 Eddy Current

7.5.1 Introduction

Eddy current examination is used to examine the surface, or near surface, of electrically conducting materials. If a flaw is present, the currents are disturbed (by being forced to flow under or around the flaw), and this change can be detected using suitable instrumentation.

The depth of the surface region that can be examined is governed by three parameters: the frequency of the AC excitation current, the electrical conductivity, and the magnetic permeability. For nonferromagnetic materials, the magnetic permeability is equal to 1 and the electrical conductivity is a property of the metal, so the only parameter that can be altered by the examiner is the excitation frequency. By choosing a suitable frequency, the user can tailor an eddy current system to examine for flaws lying at different depths below a surface.

However, in ferromagnetic materials, the magnetic permeability does not equal 1. It can be large, and perhaps more importantly, it varies from point to point because of the magnetic domain structure in the metal. Eddy currents are still produced, but their depth of penetration is small, and the signals are dominated by the large variations in local permeability. Flaws are very hard to detect against this fluctuating background, so alternative methods have been developed for ferromagnetic materials. These generally involve applying a large external magnetic field at the surface that saturates, or partially saturates, the magnetic properties (aligns the domains) so that the permeability is reduced to near 1, as in the case of nonferromagnetic metals. NDE techniques for ferromagnetic materials include remote field eddy current, flux leakage, and partial saturation.

7.5.2 Advantages and Disadvantages

Eddy current examination is limited to the surfaces of conducting materials, so it is an alternative technique to magnetic particle and liquid penetrant examination.

The main factors in favor of eddy current examination are:

- Probes can be constructed to be very small so they can enter components that are inaccessible to other techniques.
- There is little need for surface preparation; in many cases it is possible to examine through surface layers such as paint.
- There is no need for the application of dyes, developers, and such, which can make the technique attractive in applications where waste and contamination must be minimized.

The main disadvantages are that the signals produced can be complex and require a higher level of training and experience to interpret, and the equipment is relatively expensive. However, much recent work has been aimed at developing equipment that can assist with data interpretation and flaw classification so the main objections are diminishing with time.

Another drawback is that the presence of geometric features and discontinuities near the region where flaws are expected can affect the flows of eddy currents, making flaws difficult to detect and/or size. This problem can be partially overcome by using coils wound around a ferrite former to concentrate the eddy currents under the probe, but the presence of corners and drilled holes in a component should always be kept in mind when deciding to perform an eddy current examination.

7.5.3 Generation of Eddy Currents

Eddy current generation depends on electromagnetic induction. If a probe, consisting of a coil of wire carrying AC, is held in air, then an alternating magnetic field is produced around the probe. If the probe is now brought up to the surface of a conductor, then the changing magnetic field will couple to the surface and induce currents to flow in the conductor (induction). These currents are the eddy currents.

The eddy currents in the conductor will, in turn, produce a changing magnetic field that will interact to generate other currents in the original coil, producing a change in impedance as seen by that probe. This is the normal, or null, condition when the probe is over a flaw-free part of the component. Figure 7-5 depicts the generation of eddy currents in a component.

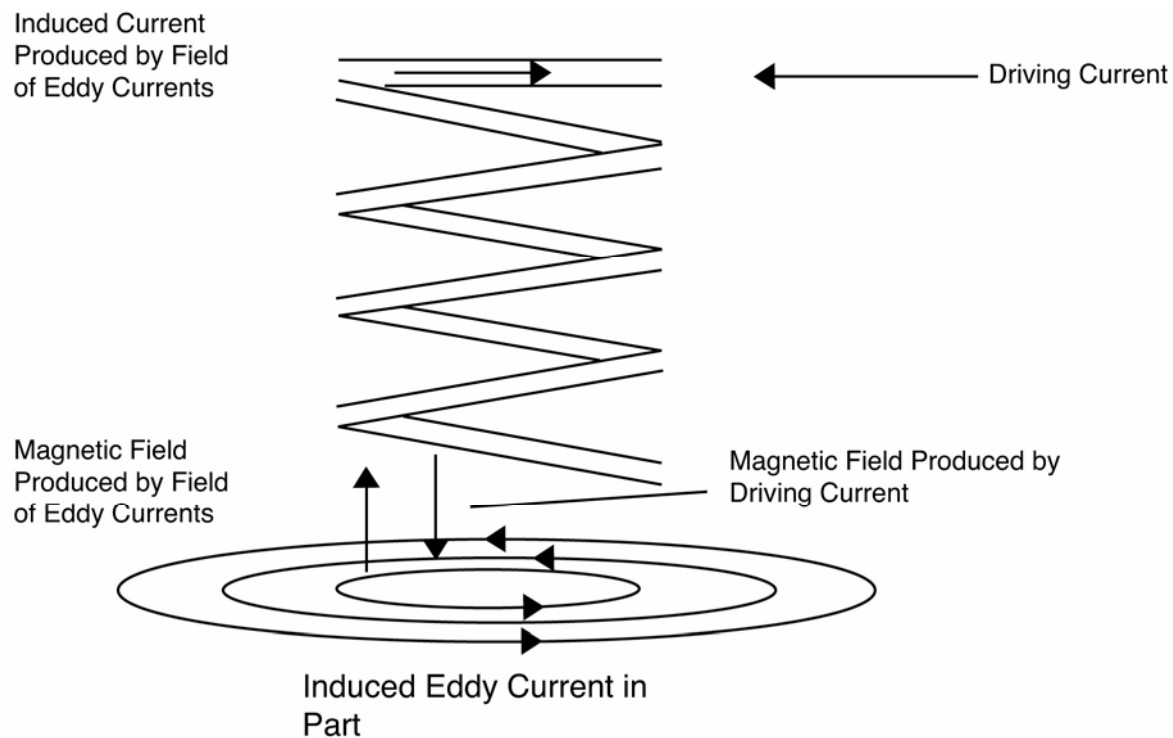


Figure 7-5
Generation of Eddy Currents

If the probe is now moved so that it lies above a flawed region, then the eddy currents induced in the component must divert so that they flow around or under the flaw. The different current flows (flawed compared to unflawed) produce a different magnetic field, which registers as a change in currents and impedance of the probe. In this way, flaws can be detected.

Depth of Penetration. The depth of penetration of eddy currents (δ), also known as the skin depth, is defined as the distance where the eddy current density falls to $1/e$ (37%) of the surface density, and is given by:

$$\delta = 50 (\rho/f \mu_r)^{1/2}$$

or

$$\delta = 50 (172.41/\%IACS f \mu_r)^{1/2}$$

where δ is in mm, ρ is the electrical resistivity (inverse of conductivity) in $\mu\Omega\cdot\text{cm}$, %IACS is the copper standard conductivity, f is the excitation frequency in Hz, and μ_r is the relative magnetic permeability (no units).

From this we see immediately that the materials with a high permeability (ferromagnetic metals) have a small depth of penetration, and that the depth of penetration can be increased by lowering the excitation frequency.

In stainless steel alloys, the depth of penetration is typically on the order of 0.040 inch (1 mm) at frequencies near 100 kHz.

Phase and Amplitude Information. Because the excitation is AC, the impedance seen by the probe has resistive and reactive components. Thus, the eddy current signals contain phase as well as amplitude information. It is customary to display eddy current signals on an impedance plane screen and to use both amplitude and phase information to characterize flaws, although some examinations are possible using amplitude alone.

7.5.4 Important Probe Design Criteria

The designer of the examination can design a probe to fit a particular application. The electrical conductivity and magnetic permeability are generally beyond control, but the following parameters can be changed:

- **Excitation frequency.** This governs the depth of penetration of the eddy currents and can be set so that currents flow in the zone where flaws are expected. In addition, the frequency can be adjusted so that different types of flaws produce signals having different phases when displayed on an impedance plane instrument.
- **Diameter of the coils.** For surface examinations, the diameter of the coils is determined primarily by the size of the flaw being sought: a small coil for smaller flaws and so on. The diameter governs the size of the region in which eddy currents flow. For tube examination, it is preferable to have the coils lie as close to the tube's inner surface as possible to ensure that the eddy current flow is as uniform as possible (that is, the probe should be a close fit in the

tube). However, in practice, tubes are always slightly noncircular in cross-section, often contain minor dents, and may contain silt residues or corrosion products that restrict the diameter. Consequently, bobbin probes are designed to have a certain fill factor that minimizes the effects of probe wobble but ensures that the probe will actually traverse a reasonable proportion of the tubes being examined without becoming blocked. The fill factor is the ratio of probe diameter to tube diameter squared and is typically 80–90%.

- **Number of turns.** Once diameter is set, the designer can vary the number of turns per unit length. In general, the length of the coil is a small fraction of the diameter, and is comparable to the minimum dimension of the flaw being sought, perhaps 0.040 inch (1 mm) in a tube examination. The number of turns that can be wound in a given channel depends on the gauge of the wire being used, but a further constraint—the impedance of the instrumentation that measures and displays the signals—is fixed, so this tends to dictate the remaining options.
- **Core material.** In some applications, it is desirable to have a concentration of eddy currents directly underneath the probe. This could be because flaws are expected close to a geometric feature of the component (such as a corner or drilled hole) that will interfere with the current flows if they spread out around the coil for some distance. The geometric features may mask the signals from the flaw and make them undetectable. The concentration of eddy currents is achieved by winding the coils around a ferrite former rather than a nonconducting material like lucite.

7.5.5 Required Equipment

Apart from the required probe, discussed elsewhere, an eddy current examination requires the following equipment:

- **Probe cable.** This connects the probe to the flaw detector. It should be well screened to protect from radio-frequency pickup, particularly when performing an examination at high frequency.
- **Eddy current flaw detector.** A wide range of flaw detectors exists, ranging from a simple needle gauge that is primarily used for material sorting to single-frequency impedance plane displays to multifrequency systems. Detectors range from basic models to fully digital models that store traces, self-balance, and even assess the signals. Many of the recent systems are based around PC technology, which also streamlines the reporting aspects of an examination.
- **Calibration standard.** Perhaps the most critical part of an examination is the calibration standard that allows an examination to be repeated using exactly the same configuration (even if the flaw detector and probe have changed) so that changes in the component's condition can be monitored, or so that results from one component, or plant, can be compared with another. There are many different formats of calibration standard, each geared toward the particular component and/or type of flaw being sought.
- **Recording device.** External digital media may be used to acquire the scanned data, which will be used later during evaluation.

7.5.6 Surface Eddy Current Examination

Surface eddy current examination works on the principle of using pancake coils, which may be operated in differential and/or absolute modes. Coils are typically wound parallel to the surface being examined, that is, the axis of the coil is perpendicular to the surface. Eddy currents will, therefore, flow in circles around the location of the probe, so a flaw in any orientation will interrupt the eddy current flow at some point, and hence be detectable, as depicted in Figure 7-6.

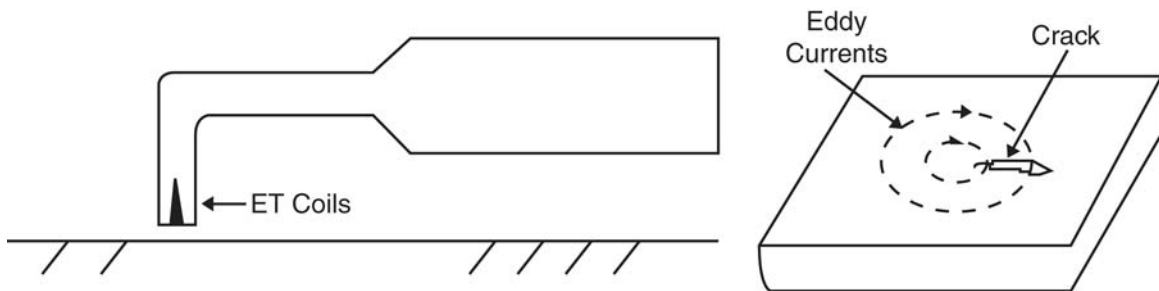


Figure 7-6
A Surface Probe

New-generation surface probes use the plus point technology operated in transmit-receive modes to interrogate circumferentially and axially oriented flaws in a one-scan sweep. Up to 20 channels operated in multifrequency modes may be included in an examination to support flaw detection and sizing capabilities. These sensors may even be adapted to portable eddy current equipment, making it conducive to use in a confined-space environment. A schematic drawing of a plus-point sensor is provided in Figure 7-7.

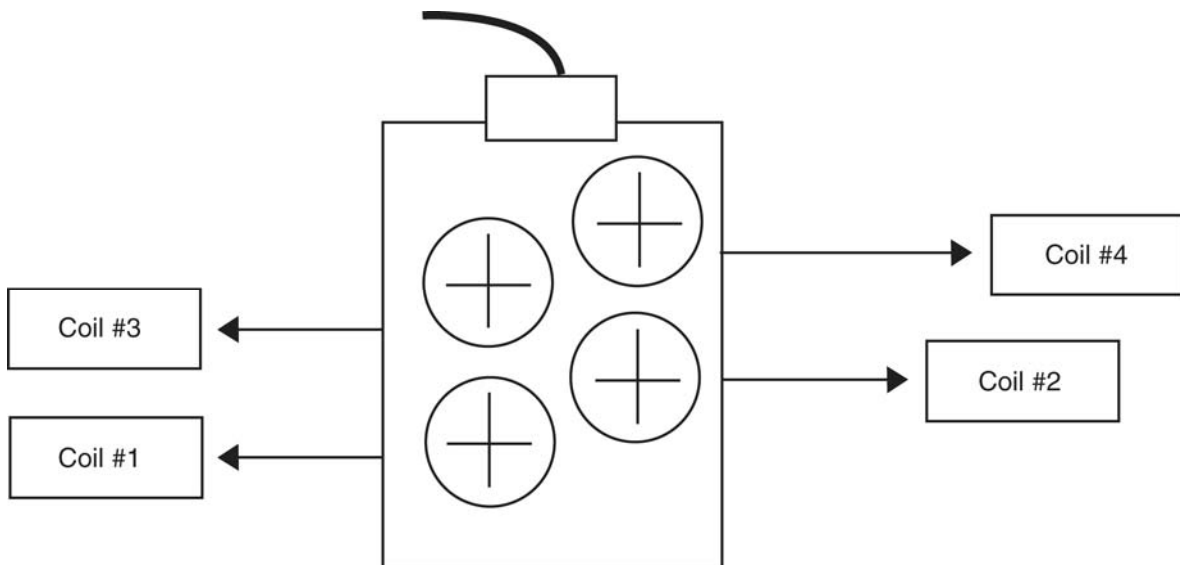


Figure 7-7
Plus-Point Eddy Current Sensor

Typically, in surface eddy current examination, the signal responses are primarily evaluated using the amplitude response from a flaw. Phase is sometimes used to decipher the circumferential flaws from axial flaws. By using known reference reflectors, amplitude and phase may be established and applied to actual field examinations.

7.5.7 Applications

Historically, liquid penetrant and magnetic particle examinations sensitive to surface flaws are used in flaw detection. This detection is then augmented with ultrasonic or radiographic examination methods for accurate flaw depth sizing. Although these methods have proven to be very efficient, they are extremely time-consuming and create a high potential for waste and in some cases unnecessary personnel exposure to radiation. Surface eddy current application, on the other hand, provides sufficient sensitivity for surface and subsurface flaw detection and sizing, eliminates waste, and minimizes personnel exposure. Surface eddy current examination has been used extensively for examination of aircraft, pressure vessels, pipes, nozzles, bolting, and rotating components.

Additionally, because the generation of eddy currents depends on metal properties such as electrical conductivity and magnetic permeability, the procedure can be used for sorting different metals. This should be regarded as a relative, rather than absolute, measurement but can be useful in detecting rogue bolts and the like.

Following logically from this, eddy currents can also be used to detect the presence of a weld, again relying on the fact that weld metal properties are different from the parent metal properties. The technique can therefore be an attractive alternative to the use of acid etchants.

7.5.8 Related Literature for Eddy Current Examination

NDE Guidelines for Fossil Power Plants. EPRI, Palo Alto, CA: 1997. TR-108450.

7.6 AC Potential Drop

7.6.1 Introduction

The AC potential drop technique is used to measure the depth of surface-breaking cracks in electrically conducting materials.

Whereas magnetic particle and liquid penetrant examinations can detect such cracks, they provide no information on the depth of the crack. If the crack must be removed from a component, then it is necessary to know precisely how much metal should be removed in order to remove the entire crack. This may mean multiple applications of magnetic particle or liquid penetrant examination to establish that the crack has been eliminated.

Ultrasonic examination can be used to provide crack depth information, but this is difficult for cracks that are shallow and close to the ultrasonic probe. Ultrasonic examination is also difficult to apply on tight-radiused surfaces, such as tube-to-header connections.

AC potential drop is able to make these crack depth measurements, even on tightly curved surfaces. Application of AC potential drop, therefore, allows the depth of grinding to be determined beforehand, resulting in a time savings by minimizing the need for repeat examinations using other techniques.

7.6.2 Advantages and Disadvantages

The main strength of AC potential drop is its ability to measure the depth of surface-breaking cracks, which the magnetic particle and liquid penetrant examination techniques cannot do. In many cases, AC potential drop may be the only way to measure the depth of a crack without grinding it out.

The main disadvantage is that it is not practical to use this technique to detect cracks, although it is physically possible. Measurements are made point by point, so it would take a very long time to scan a surface. In practice, this means that AC potential drop is a secondary (or evaluation) technique, rather than a primary (or detection), technique.

An important consideration is that crack measurements also tend to lead to slight underestimation of the true depth, because the electric current will take the shortest distance beneath the crack. As a crack tapers to a point, there comes a depth at which the current can jump across the opposing faces, resulting in a reduction in the voltage across the crack, and hence a reduction in the apparent depth.

The same effect is produced by conducting debris trapped inside the crack and by heavily oxidized surfaces. Tight or rough-faced cracks may also create a bridge for the current. Consequently, the AC potential drop technique works best on wide, smooth-faced cracks, such as those characteristic of damage from corrosion fatigue, thermal fatigue, or creep fatigue.

7.6.3 Basic Theory

AC potential drop works by directing AC across the component's surface, perpendicular to the crack to be measured. AC is used so that the current density is concentrated near the surface of the component, trapped within a layer given by the depth of penetration.

If an electric current is injected into a component at one point and extracted at another, there will be a voltage drop between the two points. If the examiner uses a probe that consists of two metal contacts a fixed distance apart, the probe can be used to measure the voltage difference between any two points within the current distribution. If the probe is held in such a way that the two contacts are in line with the current injection and extraction points, the examiner will measure a

given voltage regardless of how close the examiner is to either current contact—that is, the voltage drop per unit length is constant along a current path. This voltage is called the *reference voltage*.

If a crack runs perpendicular to the current path, the crack will be in the way of the current, so that the current is forced to pass underneath the crack to reach the current extraction contact. The current travels an extra distance, equal to twice the depth of the crack, compared to the distance that would be traveled with no crack present.

If the same voltage-measuring probe is held over the crack, the voltage recorded will be an increased voltage because of the extra distance traveled. The ratio of the voltage measured at the crack and the voltage measured at a nearby (not cracked) location enables the crack depth to be inferred. The concept of AC potential drop is shown schematically in Figure 7-8.

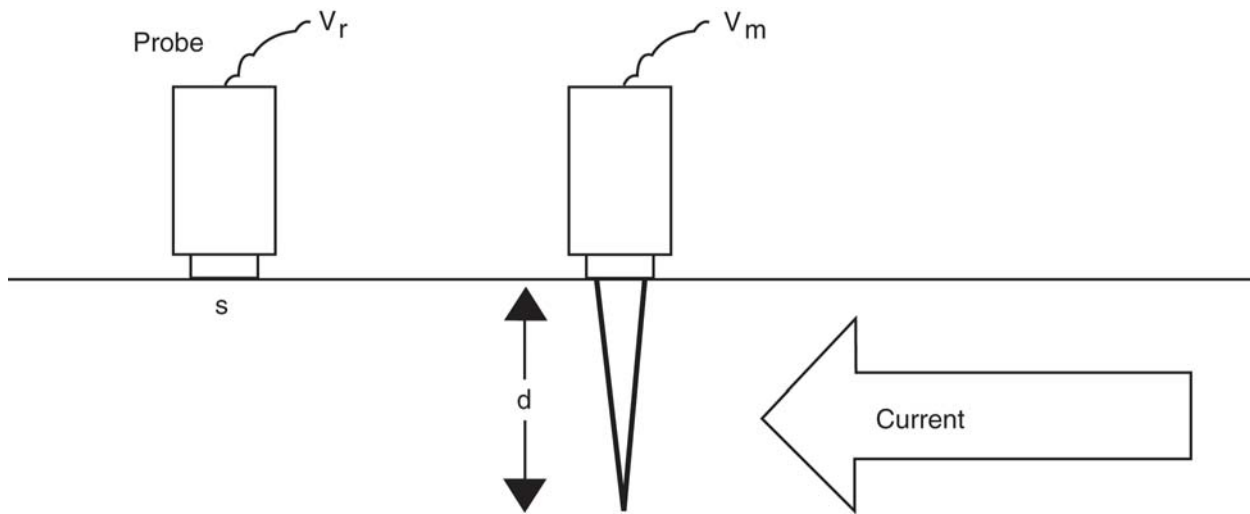


Figure 7-8
The Concept of AC Potential Drop

The one-dimensional theory is straightforward. If the separation between the contacts in the probe is s , the crack depth is d , and the measured and reference voltages are V_m and V_r , respectively. Then at a portion of the component that contains no cracking, the voltage gradient (electric field) is:

$$\text{voltage gradient} = V_r/s$$

Over the crack, the voltage gradient is:

$$\text{voltage gradient} = V_m/(s + 2d) \text{ because the current flows an extra distance } 2d$$

Because the voltage gradients must be equal (the same current flows between the same contacts), the right sides of the above equations are also equal. Simple manipulation gives the following formula for the depth of the crack d :

$$d = s/2 * \{ (V_m/V_r) - 1 \}$$

Corrections must be made to this simple formula for cracks that are short in comparison to their depth because some current is diverted around the sides of the crack, as well as underneath. The formula is a good approximation in most cases, however.

7.6.4 Implementation

A measurement proceeds in the following way:

1. The crack is first detected using another NDE technique that reveals the location of the crack but not its depth.
2. The AC potential drop crack depth gauge is calibrated using a calibration block with various crack depths that has been fabricated from material similar to the material to be tested.
3. If the metal does not already have a shiny surface, it must be prepared to it one. An important consideration is that the probe must make an electrically conducting contact with the component at two locations—over the crack itself and immediately adjacent to the crack—so that the reference voltage can be obtained. The measurements cannot be made through adhering paint, scale, and the like. A 100 grit surface finish is usually adequate to obtain reliable readings. Compressed air should be used to ensure that the crack is free of cleaning debris.
4. The current injection and extraction contacts are placed on either side of the crack.
5. AC potential drop relies on the injected current passing perpendicular to the crack face, so the probe is first used to establish that the field is uniform. If it is not uniform, then the current contacts must be moved until the field is uniform. Occasionally, on tight-radiused surfaces like those in many steam chests, it may take considerable time to optimize the positioning of the contacts with respect to the crack.
6. A reference voltage is obtained adjacent to the crack position. The contacts in the probe are both on the same side of the crack. The voltage is noted or stored in the instrument, or the null voltage calibration is set to zero.
7. The probe is then moved so that the contacts straddle the crack. A second voltage measurement is made. During steps 5 and 6 the probe is rotated slightly clockwise and counterclockwise to ensure that the voltage drop is maximized, that is, so that the probe is aligned along a line of current and not at an angle to the field.

8. Using the formula in the previous subsection, the crack depth is calculated at that point (or, for some instruments, the crack depth is directly presented).
9. Repeat measurements can be obtained at other points along the crack front to produce a crack profile. Care must be taken at all stages to ensure that the directions of the current and the orientation of the probe are correct.

A typical examination rate is one crack depth measurement every 5 minutes, with 1–2 hours for preparation. This takes into account the adjustment of the current contacts, as well as the actual crack measurement.

7.6.5 Equipment

An AC potential drop probe consists of two metal contacts mounted a fixed (and known) distance apart. These contacts are often spring-retractable to ensure that they are held firmly to a surface. They can be designed to have different separations and configurations, for example, the contacts could be side-by-side or on two faces of a corner so that the probe fits tightly over the crack being measured. It is common to use custom-made probes for particular applications. In general, most probes are designed for crack measurements in tight, confined spaces (where ultrasonic examination cannot be implemented), so the probes tend to be held in two fingers like a pencil.

The current generators and injection leads are usually in the same housing that measures the probe voltages and performs the crack depth calculation. The whole unit is easily portable around the power plant. Older units use a printer to output the results, but there are now PC-based models available that store the measurements for later analysis.

7.6.6 Applications

Any application where there is strong surface curvature is a candidate for the AC potential drop technique, as access to the location of the crack may be hindered for other techniques.

The technique has been successfully used to measure crack depths in steam drums, tube-to-header connections, and many other components.

7.6.7 Related Literature for AC Potential Drop

NDE Guidelines for Fossil Power Plants. EPRI, Palo Alto, CA: 1997. TR-108450.

8

VOLUMETRIC EXAMINATION TECHNIQUES

This section discusses the most common volumetric examination techniques: ultrasonic and radiographic. Included is information on several advanced and/or less frequently used ultrasonic techniques as well as information on recent advances in technology for radiographic examination. A subsection on low-frequency electromagnetic techniques is also included.

8.1 Ultrasonic Examination

8.1.1 *Introduction*

Ultrasonic examination technology encompasses a wide range of applications that vary dramatically in technological sophistication, complexity, required equipment, implementation constraints, speed of application, detection reliability, sizing accuracy, and requisite operator skills. The technology has evolved to a point at which very few components are examined according to generic procedures. That is, specific techniques and application procedures that are designed to address certain desired performance characteristics are used for most components. What is optimum for one application may simply not be adequate, or in some cases even possible, for another. Consequently, it is difficult to provide guidance that is short, concise, and easy to understand, while at the same time providing sufficient detail to enable the reader to make informed decisions. The information here will hopefully strike the right balance.

As a general description, ultrasonic examination can be defined as the introduction of high-frequency sound waves, generally in the low-megahertz (MHz) range of 0.5–50 MHz, into a component, part, or structure for the purpose of determining some characteristic of the material from which the component, part, or structure is made. Material characteristics that can be (and have been) determined ultrasonically include material structure, stress (both residual and applied), hardness, anisotropy, and others. However, for power plant examination, ultrasonic examination is used primarily for flaw detection, classification, sizing, and dimensional measurement (thickness). In this document, discussions are limited to the latter applications. The reader should be aware that other applications are possible and should be considered along with competing or complementary technologies where determination of material characteristics is the objective.

Ultrasonic examination, as used for flaw detection and thickness measurement, is analogous to active sonar. A short-duration ultrasonic pulse is generated in the component by a transmitter. Immediately thereafter, the ultrasonic instrumentation is switched to a “listening” mode. Any

detected return signal is indicative of the presence of a “reflector” that has redirected the propagating wave in the direction of the receiver. Flaw detection and thickness measurement applications of ultrasound operate on two fundamental principles.

First, for a specific propagation mode, sound travels in a given material at constant velocity. Therefore, a precise measurement of the propagation time between initiation of the pulse and detection of a signal at the receiver provides the basis for calculating the position of the reflector relative to the transmitter and receiver positions. Second, the response from a reflector is a function of the characteristics of the transmitted beam, the material through which it propagates, and certain characteristics of the reflector that cause the response. If the ultrasonic practitioner can extract those characteristics of the response that are attributable to the beam and propagation material, then what is left is a response that is characteristic of the reflector. If the practitioner can further extract from this remaining reflector response the information that is related most directly to the feature of interest (for example, flaw size), he or she can have a reasonable chance of estimating that feature.

More material will be presented later on flaw sizing, flaw classification, and extraction of other useful information. However, at this point in the presentation of ultrasonic examination practices, it is more important to concentrate on basic examination approaches, displays, and other key factors.

The traditional ultrasonic implementation means and display were developed on the basis of the same two basic principles defined above, that is, that time and amplitude are the main features of interest. Short-duration sound pulses are used in such a way that the instrumentation can quickly be switched to the listening mode for the detection of reflectors located close to the transducer(s), therefore having short propagation paths and correspondingly small propagation times. Conventionally, a visual display is used in which the horizontal axis of the display represents time, increasing from left to right, and the vertical axis represents intensity, increasing from the base level to saturation. The “listening” interval is set at sufficient duration to allow the wave to propagate to the maximum examination depth and back to the receiver before the next pulse is generated.

Because propagation velocities are typically in the range up to an inch per microsecond, pulse repetition rates in the hundreds or even thousands of pulses per second are achievable for most materials and typical material thicknesses, while still providing sufficient “listening” time. By synchronizing the display sweep with the pulse rate so that each sweep represents a new pulse, the display appears as continuous without perceptible flicker. In more modern, computer-based ultrasonic systems, these same features (plus others) are converted to graphical displays that present responses in spatially correlated images, thereby adding position to the presented time and amplitude information.

8.1.2 Generation of Ultrasonic Waves in Materials

Ultrasonic waves can be generated in a material in a number of ways, the most prevalent of which is via a piezoelectric transducer. Other means of generating ultrasonic waves include EMATs and lasers. Laser-induced ultrasound, at the time of this writing, remains experimental, and consequently is not used in routine applications in power plants, nor is it presented in this document. EMATs, on the other hand, have been reduced to practice for specific applications and are therefore included here (later in this section).

A piezoelectric material is one that exhibits a change in physical dimension when an electrical voltage is applied to it and that returns to its original shape when the voltage is removed. The opposite is also true, that is, the piezoelectric material generates an electrical voltage when mechanically deformed. Certain natural and manmade materials exhibit these characteristics and are used for ultrasonic transducers. A variety of transducers are shown in Figure 8-1.

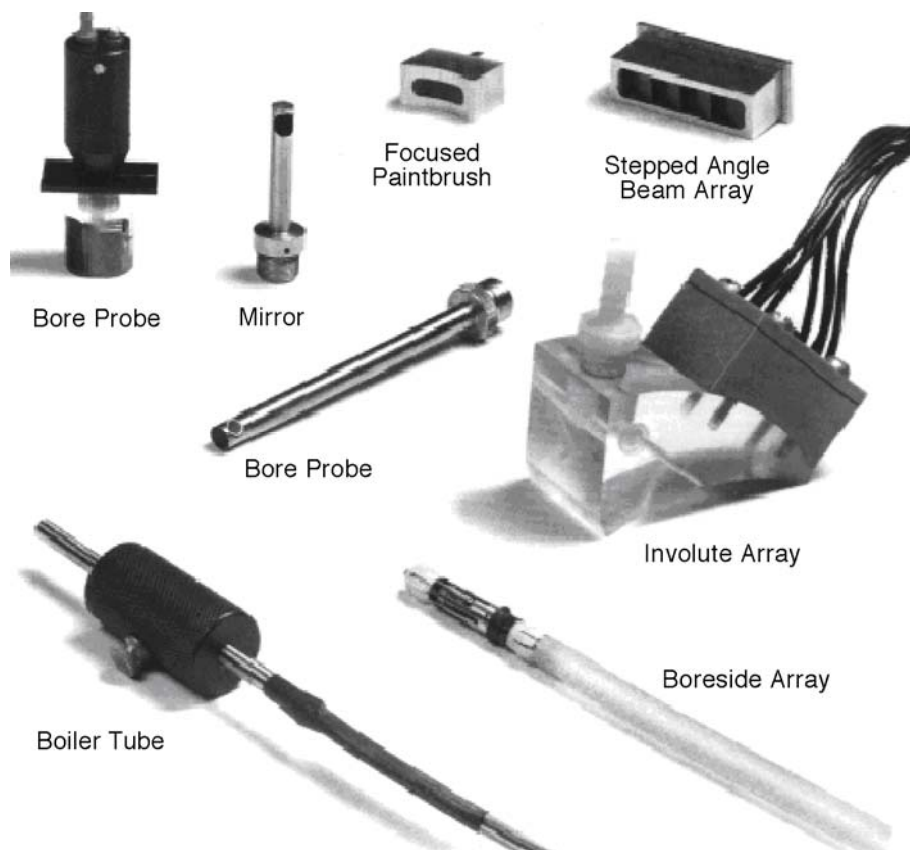


Figure 8-1
Variety of Ultrasonic Transducers

The voltage is typically applied as a short-duration spike, causing the transducer element to resonate. The inherent damping of the piezoelectric material and other material (backing) bonded to the back of the element control the length of the oscillation. Schematic drawings of a transducer that produces an ultrasonic beam perpendicularly into the component and one that produces ultrasonic beams at an angle are shown in Figure 8-2.

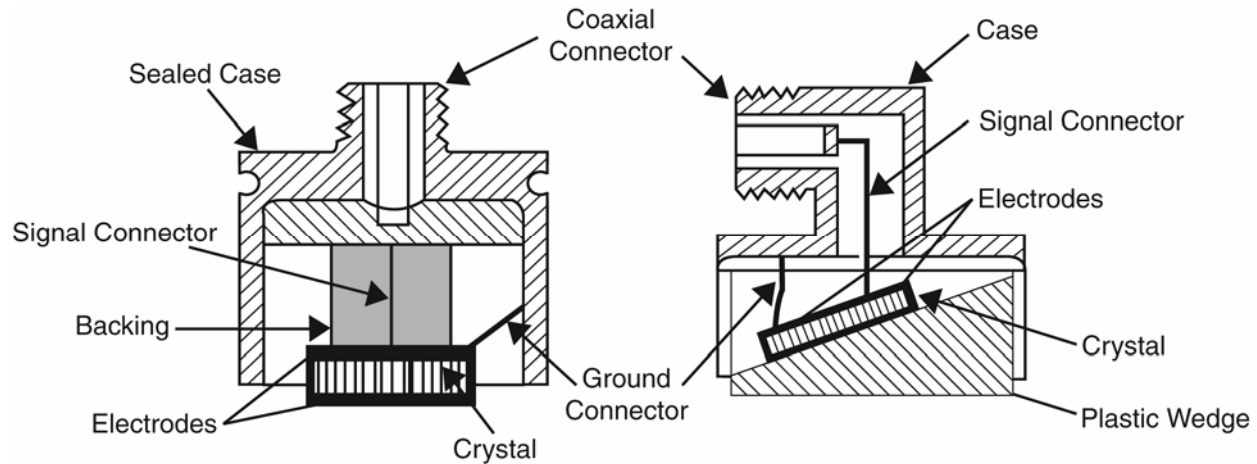


Figure 8-2
Zero Degree and Angle-Beam Transducers

If the element is properly coupled to the component being examined (typically using a liquid or gel that transmits sound readily—the couplant), the mechanical deformation produced in the piezoelectric material can be effectively transferred into the part, where it propagates through the material in an oscillatory manner. Reflections from component surfaces and flaws return to the transducer, excite the piezoelectric element, and thereby produce a measurable voltage. Transducer design establishes the beam characteristics such as the frequency, bandwidth, duration, beam spread, and others. Consequently, a large variety of standard transducers are made, by a number of manufacturers. In addition, customized transducers can be built to provide specific beam characteristics for nonstandard applications. Transducer selection is a key component of examination design. Similarly, the pulse shape, duration, and voltage can affect the beam and should be considered as well.

8.1.3 Basic Ultrasonic Propagation Modes

Ultrasonic waves can propagate through materials in several different propagation modes. The most common ultrasonic examination techniques rely on the detection of specular (that is, mirror-like) reflections. In this reflection mode, beam propagation direction is a key parameter. Performance is generally enhanced by directing the beam normal to the major dimension of the anticipated flaw.

A *compression wave* is one in which the particle motion in the material lattice alternates compression and tension (rarefaction) in a direction parallel to the beam propagation direction. These waves are also commonly called *longitudinal waves* because the particle motion is parallel

to propagation direction. Because they are typically introduced normal to the test surface, longitudinal waves are best suited for the detection of laminar flaws lying parallel to the surface and volumetric flaws having some area in a plane parallel to the surface. As a general rule (unless using special procedures that will be described later), longitudinal waves are not particularly useful for flaws that are oriented normal or nearly normal to the test surface. Longitudinal waves are used almost exclusively for thickness measurement by using the backwall reflection and appropriate longitudinal wave propagation velocity to determine thickness.

A *shear wave* is one in which the particle motion is perpendicular to the propagation direction by oscillating shear deformation of the material lattice. Because the particle motion is transverse to the propagation direction, shear waves are often also called *transverse waves*. Because of the way in which shear waves are generated, they generally propagate at an angle relative to the test surface; as a result, they are also often called *angle beams*. However, this is really a misnomer because angulation is not limited to the shear propagation mode. In fact, high-angle longitudinal waves have become popular for certain applications. Shear waves are not typically used for thickness measurement, because they are usually introduced at an angle. Consequently, shear waves usually produce no measurable backwall reflection (that is, the reflected energy reflects away from, rather than back to, the transducer).

Figure 8-3 depicts longitudinal and shear wave modes of ultrasonic propagation.

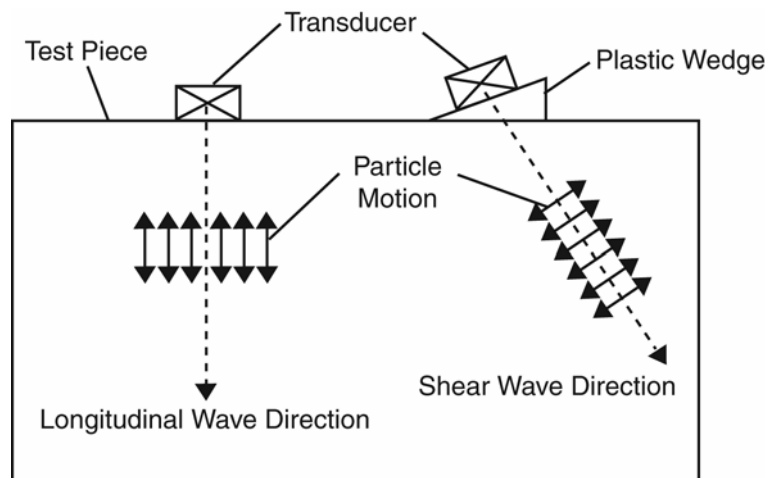


Figure 8-3
Longitudinal and Shear Wave Modes Compared

A *Rayleigh wave*, or *surface wave*, is created when a shear wave travels along a surface of the component. The interaction of the beam with the surface creates a propagation mode in which particle motion is elliptical about the beam propagation axis. This wave can exist only at a surface and is sensitive only to surface flaws. Figure 8-4 shows how surface waves are produced. An advantage of the surface wave lies in its ability to traverse geometric changes as long as the geometric discontinuity is not sharp. Therefore, surface waves can travel around radiused corners to inaccessible surfaces. Unfortunately, surface waves are sensitive to minor surface

imperfections such as weld spatter and even drops of liquid on the surface; therefore, surface waves are prone to lead to false calls.

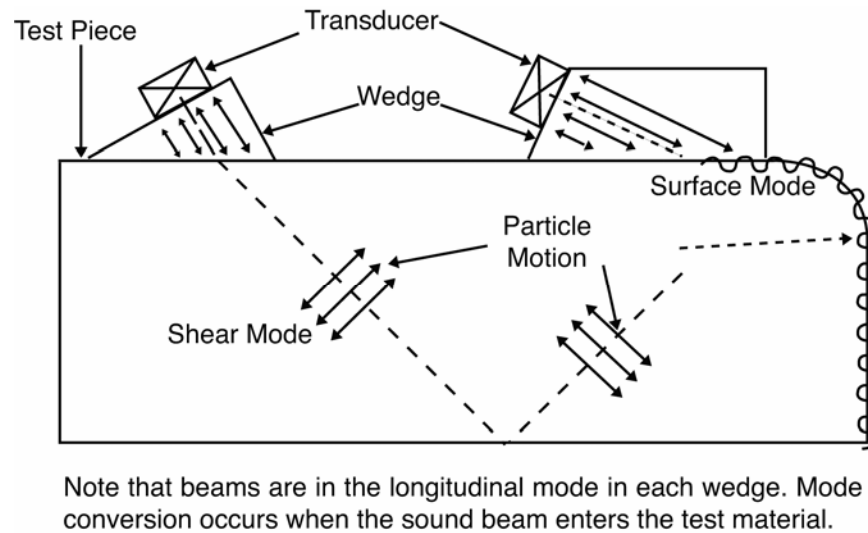


Figure 8-4
Mode Conversion to Produce Shear and Surface Wave Modes

When a second surface is introduced parallel to the first and the distance between the two surfaces is limited relative to the wavelength of the shear wave propagating along the surfaces, yet another propagation mode is created. The wave is called a *plate wave* or *Lamb wave* and is shown in Figure 8-5. Plate waves are typically used to detect through-wall-oriented flaws in thin material such as tubes and thin plate.

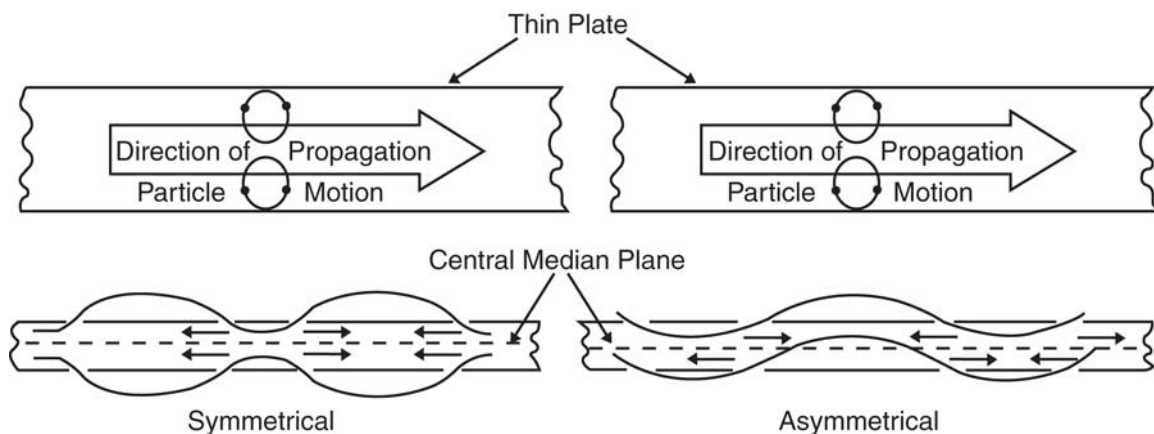


Figure 8-5
Symmetrical and Asymmetrical Lamb Waves

For in-service examination, a flaw of special interest is the one that is connected to an inaccessible surface. Other than in limited cases involving subsurface creep or linkup of inherent subsurface flaws, most damage mechanisms initiate flaws at surfaces, rather than in the subsurface. For accessible surfaces, other NDE surface methods such as magnetic particle, liquid penetrant, or eddy current are more appropriate for flaw detection. However, for inaccessible surfaces, flaw detection normally relies on the use of ultrasonic examination. A surface-connected flaw creates a corner trap that produces a very large response when using a shear wave at an angle between 30° and 60° but that produces little response when using longitudinal waves. Consequently, other than for thickness measurement and detection of laminar flaws, shear waves are used almost exclusively in reflection-type examinations. Multiple surfaces can be examined by reflecting the beam from one surface to the next. For example, both surfaces of a plate or ring component can be examined simultaneously by observing the time increment representative of travel to the side opposite the transducer and back (half node) and also observing the full node time interval representative of the full bounce back to the contact surface. This is shown in Figure 8-6.

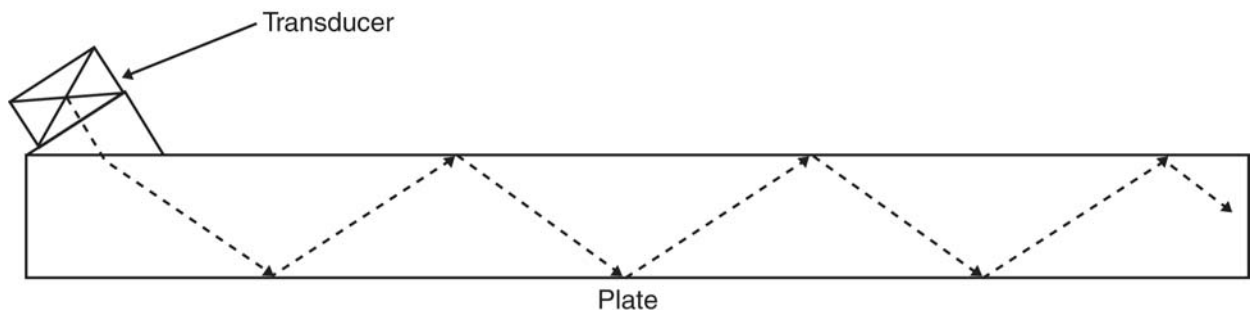


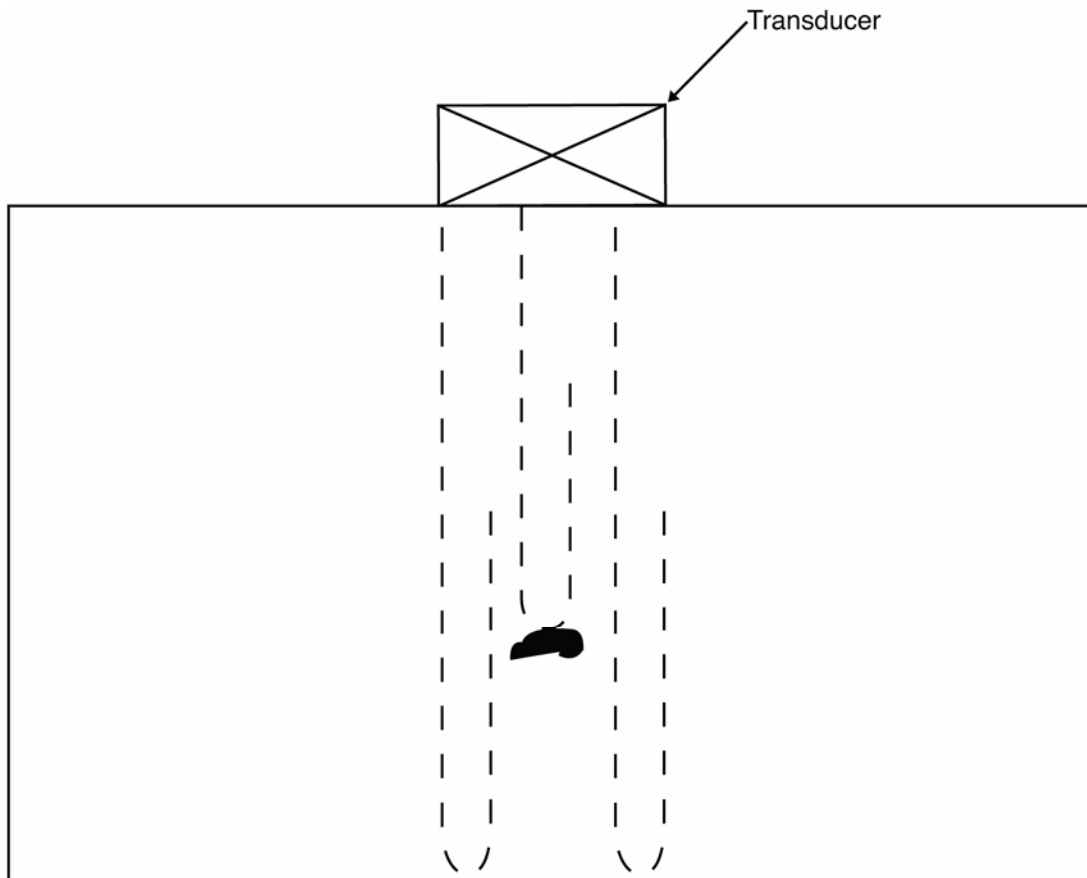
Figure 8-6
Examination of Multiple Surfaces

Each of these propagation modes has a characteristic velocity that is specific to the propagation medium (material), and the propagation velocity for a specific mode in a specific material is constant. As a result, flaw location can be determined regardless of the propagation mode as long as the characteristic velocity is known. In general, the longitudinal wave velocity is greater (by a factor of about 2) than the shear wave velocity. Rayleigh and Lamb waves propagate at velocities very close to the shear wave velocity for the material. It is also important to note that the presence of specific beam propagation modes depends on the ability of the material to support a given mode. For example, shear waves cannot propagate in liquids because liquids cannot support shear deformation.

8.1.4 Reflection, Refraction, and Mode Conversion

When a propagating wave reaches an interface that involves different materials, as shown in Figure 8-7, several things can occur. Part of the energy can be reflected from the boundary back into the first material. If the impinging beam is normally incident on the interface, the reflected component will return along the same beam path. Similarly, part of the energy can be transmitted through the interface where the beam path will be along the same axis as the incident beam in a

case of normal incidence. Certain material properties of the two materials dictate the energy in the reflected and transmitted components. Specifically, the acoustic impedance (product of velocity and density) mismatch between the two materials comprising the interface determines the energy in the transmitted and reflected components. For example, a steel/air interface constitutes a large impedance mismatch; consequently most of the energy is reflected back into the steel. For a plastic/steel interface, the impedance mismatch is not as severe; therefore, more energy is transmitted with corresponding reduction in the reflected component.



Sound is reflected back to the transducer from the discontinuity and the back surface.

Figure 8-7
Single-Transducer Pulse-Echo Technique

If the beam is incident on the interface at some angle, additional changes occur. Part of the transmitted and reflected energy can be converted to different propagation modes. For example, an incident longitudinal wave can mode-convert to transmitted longitudinal wave and shear wave components and to reflected longitudinal wave and shear wave components.

In addition, these different beams propagate at characteristic angles that are, with the exception of the reflected component of the same propagation mode as the incident beam, different from the angle of the incident beam, that is, refracted. In such a case, the energy in each of the beams is determined by the acoustic impedance mismatch between the materials and by the angles

involved. The angles are determined by the propagation velocities of the different modes in the different materials. While all of these relationships are well known, making it possible to calculate angles and energy levels, the mathematical relationships are fairly complex and well beyond the scope of this document. However, it is important to know that the different components can be useful for specific applications, and it is imperative for mode conversions and refractions to be considered in examination design.

These exact principles are used in transducer design to develop the type of beam desired and to optimize angle and beam intensity for specific applications. If a longitudinal wave transducer is used, but the sound is introduced into the component through an intermediate material having a different propagation velocity than the component and at an angle relative to the component surface, the transmitted longitudinal wave refracts to a different propagation angle relative to the incident angle. If the intermediate material is of lower velocity than the component material (which is typically the case by design), the refracted angle is greater than the incident angle, both being measured relative to a line normal to the examination surface. In such cases where a refracted longitudinal wave is produced in the component in this manner, a trailing shear wave is also generated. Lucite or similar wedge materials are typically used for contact examination, and water is typically used in immersion testing. In immersion testing, the “wedge” is simulated by merely tilting the transducer in the immersion fluid relative to the surface.

As the incident angle is increased from normal incidence, certain critical angles that delineate specific conditions are achieved. Starting with the incident beam normal to the surface, in which case only a longitudinal wave also normal to the surface is produced, and increasing the incident angle slightly, the two beams are produced with the refracted longitudinal wave refracting to a higher angle than the shear wave, as shown in Figure 8-8.

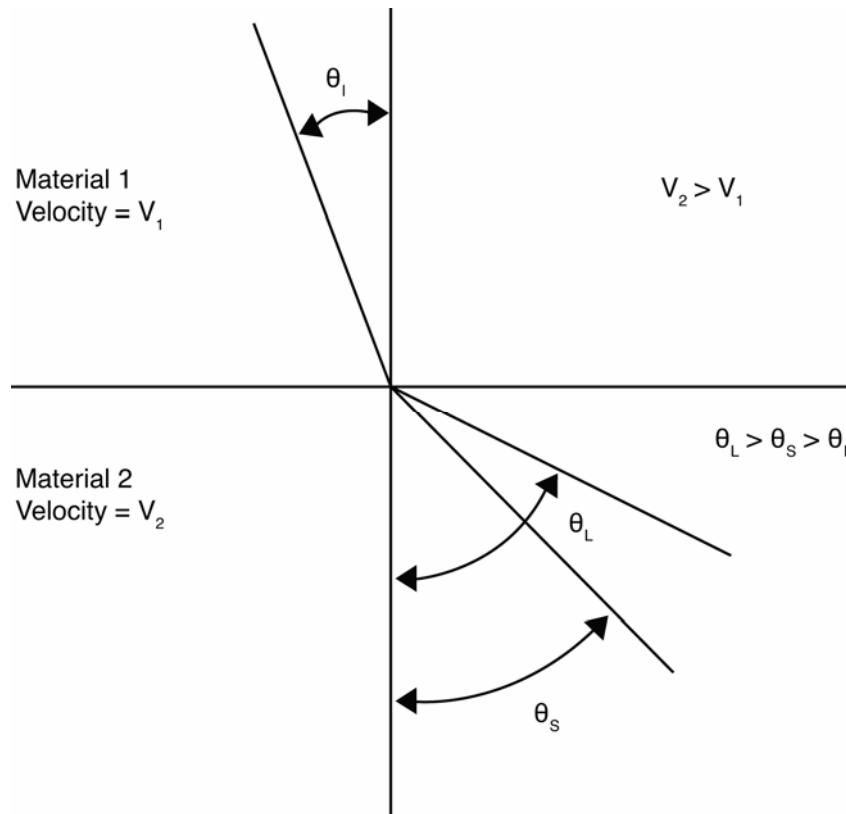


Figure 8-8
Angle Beam Generation by Refraction

As the incident angle is increased, both refracted angles increase, with the longitudinal wave angle increasing at a greater relative rate due to a higher propagation velocity. At some point, called the *first critical angle*, the longitudinal wave is refracted to the component surface. Further increase in the incident angle beyond the first critical angle produces only a refracted shear wave. At some point, with additional increase in incident angle to the second critical angle, the shear wave is refracted to the component surface. Surface waves are developed at the second critical angle. Figure 8-9 shows the generation of both the first and second critical angles.

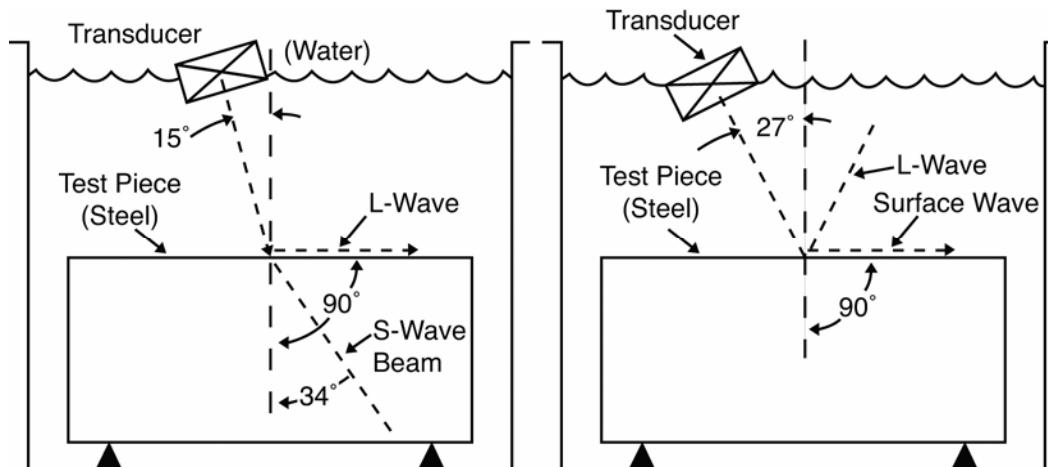


Figure 8-9
Critical Angles of Refraction

It is generally good practice to operate refracted shear waves above the first critical angle in such a way that the longitudinal wave is no longer present, particularly if using a pitch-catch (side-by-side transmitter and receiver) or pulse-echo technique. If the system is operating below the first critical angle, a longitudinal wave is still present, and it becomes difficult to discriminate between reflections related to the longitudinal wave and reflections related to the shear wave. Because these waves propagate at different angles and at different velocities, accurate spatial placement of the reflector is predicated on proper identification of the detecting beam.

The same principles (as well as a number of additional variables that will be discussed later) also determine the amount of energy existing in reflections from flaws in the material. For example, an air or vacuum interface (at a flaw) results in nearly total reflection. A flaw that is made up of some other material relative to the bulk material, for example, a nonmetallic inclusion, allows for some transmission and a lower reflectivity. In some cases, as will also be presented later, reflected mode conversions at flaws provide improved detection opportunity.

8.1.5 Ultrasonic Examination Techniques

Implementation has evolved to a number of standard examination techniques. The pulse-echo ultrasonic technique is one in which a single transducer is used as both the transmitter and the receiver. This is, by far, the predominant technique found in practical applications of ultrasound for flaw detection and thickness measurement and is shown in Figure 8-10.

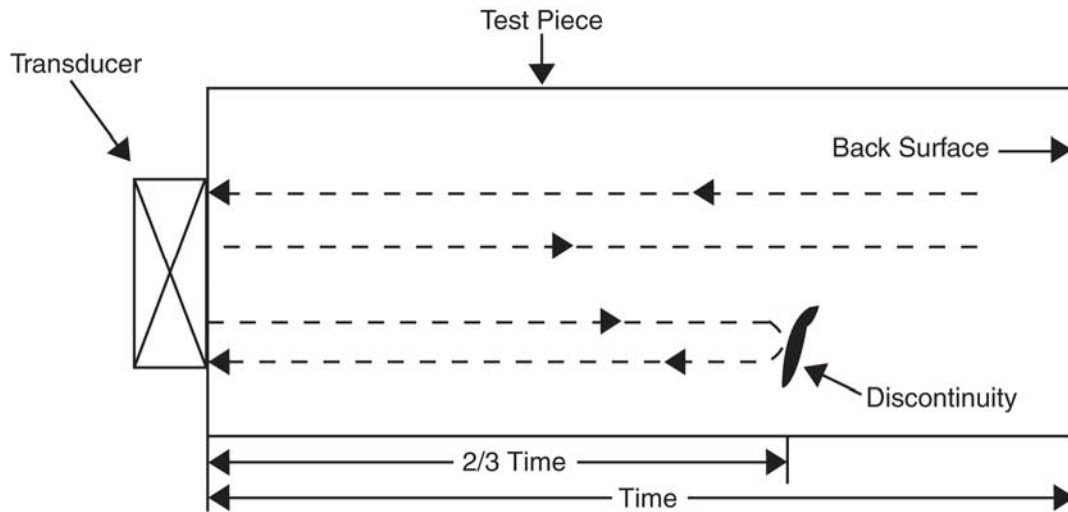


Figure 8-10
Pulse-Echo Ultrasonic Technique

A pitch-catch ultrasonic technique, as shown in Figure 8-11, involves the use of two transducer elements: one used as the transmitter and the other as the receiver. While other dual transducer techniques have also been developed, pitch-catch testing normally involves placement of the transducers fairly close together, often in a single housing. This arrangement is used mainly to improve near-surface detection capabilities. In the pulse-echo examination mode, near-surface detection is often impeded by reflections and mode conversions within the search unit itself, which give rise to noise immediately following the initial pulse. By using a separate transmitter and receiver, reverberations within the transmitter assembly can effectively be isolated from the receiver; consequently, near-surface reflectors are much more readily detected.

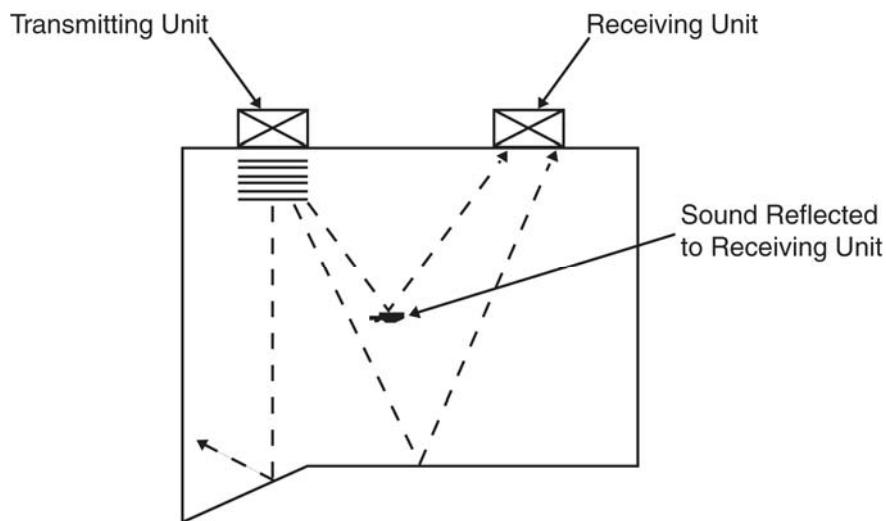


Figure 8-11
Pitch-Catch Ultrasonic Technique

The pitch-catch technique is also used for situations in which the anticipated reflectors in the component direct the reflection in a direction other than back to the transmitter. In such cases and where the direction of the reflection can be predicted reliably, the response can often be improved by proper placement of the receiver at the appropriate point on the component away from the transmitter. Special pitch-catch techniques have also been developed to similarly take advantage of the presence of a reflected mode-converted response.

Pitch-catch transducer pairs mounted in a single housing and operating similarly to pulse-echo but with separate transmit and receive elements often are “focused” to optimize performance over a specific, but limited, depth range. These are particularly useful for applications in which the predominant flaw of interest is at a specific location and orientation. In this case, a distinction must be made between two definitions of focus. It is possible to create true focus of the ultrasonic energy by using either focusing lenses or special curved transducer elements. In such cases, beam spread can be either reduced or eliminated, and in fact, the available energy can be reduced to a very small beam “spot.” This is covered in detail elsewhere in this report.

In pitch-catch pairs, the term “focus” normally implies that the elements are tilted toward each other at some predefined roof angle in such a way that the performance is optimized for flaws at a certain depth. In this regard, beam characteristics are unaffected, and the transmitted beam is broad, although depth performance is optimum over a limited depth range.

Through-transmission ultrasonic examination is another dual-transducer technique in which the transmitter and receiver are typically placed on opposite sides of the component. In this approach, the absence of a discontinuity within the material is indicated by the presence of a strong receive signal, and the presence of a discontinuity is indicated by loss of signal or diminished signal strength. Through-transmission testing is typically used for the detection of laminations, unbonding in bonded structures, and attenuation measurement.

8.1.6 Ultrasonic Data Display Formats

The A-scan display is the traditional time/amplitude display first used for ultrasonic information and described earlier. When the pulse is applied to the transducer, a vertical spike is produced by the initial pulse, or *main bang*, at the left of the screen. Any similar vertical spike at other positions along the time base indicates the presence of a reflector, and the position along the horizontal axis indicates its position relative to transducer(s) in terms of propagation time. The A-scan presentation of amplitude versus time (depth) on a display screen (shown in Figure 8-12) is the most common display found in manual, conventional ultrasonic examination. The screen time base is typically calibrated to limit the extent of the display to the depth range of interest. Similarly, instrument sensitivity is adjusted to produce a measurable response from the smallest flaw of interest. The operator typically moves the transducer(s) over the component by hand, observing the A-scan display for any “indication” that appears on the screen. Positions (both spatial in the scan and depth) are determined and recorded manually.

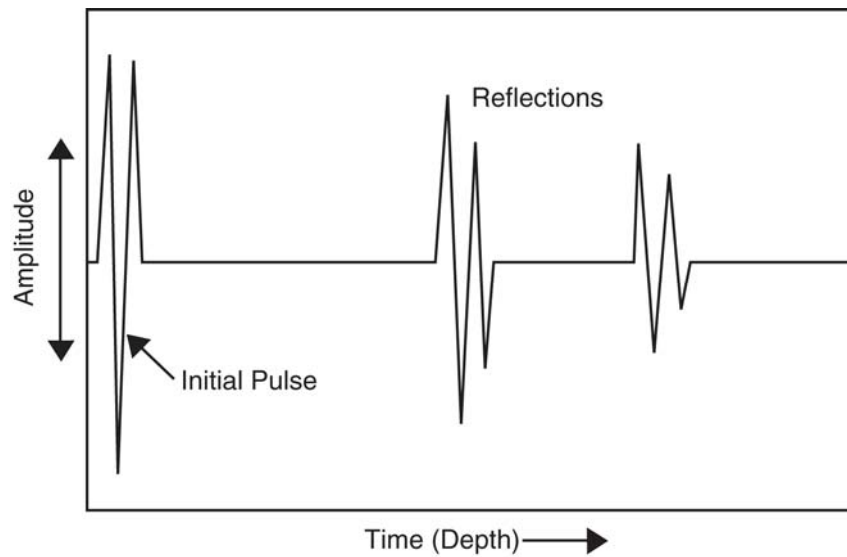


Figure 8-12
A-Scan Display Format

Other common display formats found in use involve automated or semiautomated data acquisition and processing. The transducer is moved over the surface of the part in a precise fashion, recording response amplitude as a function of transducer position throughout the scan. Typically, the transducer is moved in a raster scan. In this type of two-dimensional surface scan, with the beam directed at some angle into the material, the full volume can be examined. Acquired data include the time and amplitude and can involve a single peak only (usually the first peak above a specified threshold or the largest above the threshold), multiple peaks, or the entire waveform. Because the positional information is recorded along with the time/amplitude information, all indications can be correlated spatially within the volume covered by the scan.

Different planar views of this volumetric information can then be produced to aid the operator in data analysis. Three orthogonal views, as shown in Figure 8-13, are typically used. A C-scan display is a plan view of the scanned region, showing both scan coordinates but not flaw depth. Typically, this display involves only the peak signal along each waveform; consequently, only the most significant flaw of a possibly larger number detected simultaneously can be displayed. The C-scan image can be displayed in a two-color map, where the background is one color and all flaws exceeding an amplitude threshold are presented in a contrasting color. Alternatively, different amplitudes can be coded to different colors so that amplitude significance can be evaluated directly from the image. In this presentation, all depth information is lost; however, pulse transit time can be similarly color-coded so that depth, rather than amplitude, can be evaluated directly from the image.

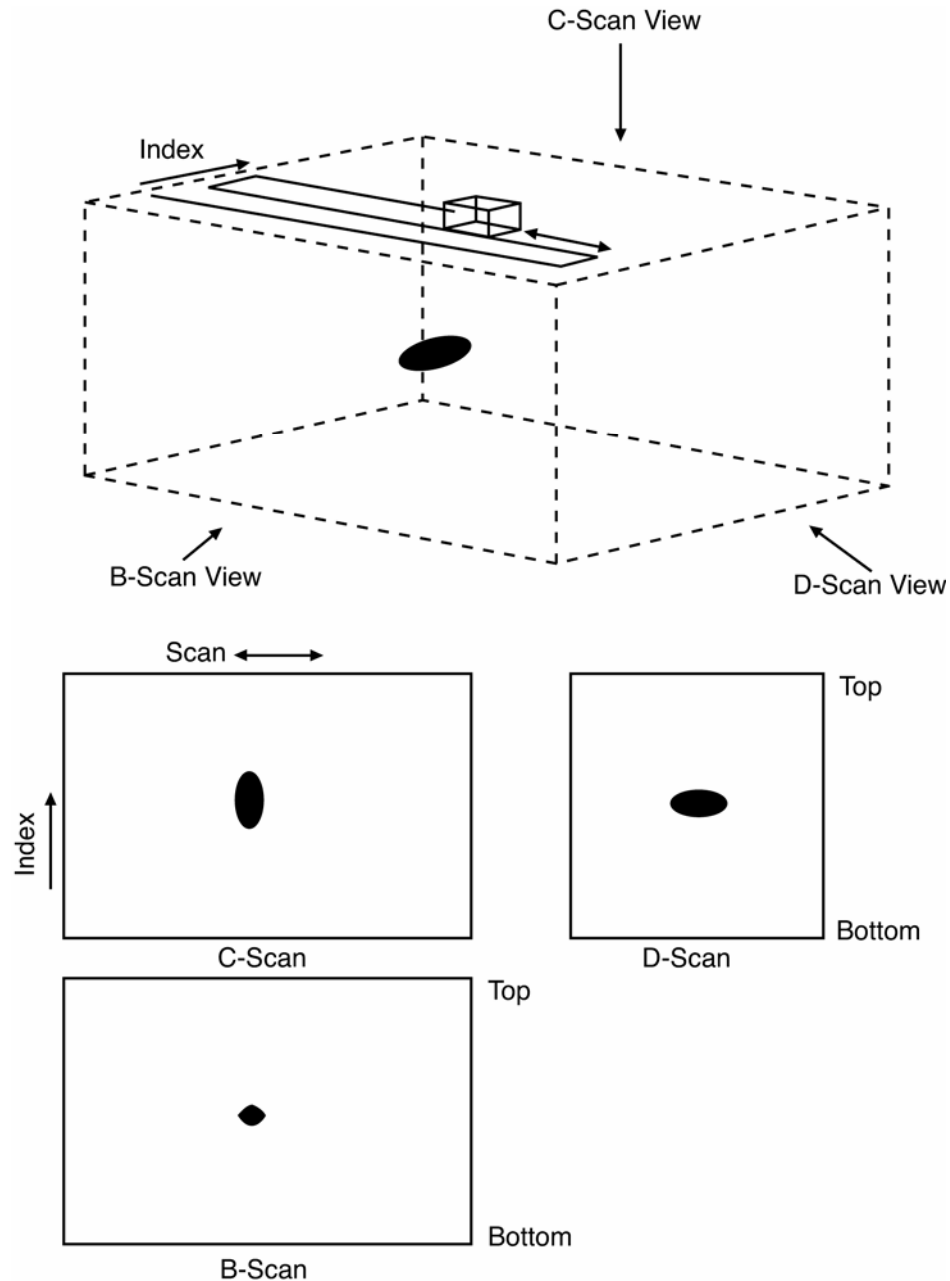


Figure 8-13
Orthogonal Image Views

A B-scan image represents a planar section through the volume in the plane of the beam. This image can present only the largest signal along the waveform or, more often, the entire color-coded waveform. In the latter implementation, all flaws detected in the plane, regardless of their response amplitudes, can be shown simultaneously. In the B-scan image, depth and position along the beam direction are shown, but position normal to the beam direction is lost. However, an operator can sequentially display consecutive B-scan images or sections through the volume, thereby quickly evaluating all data representative of the volume.

A D-scan image (or B'-scan image; both names are used for the same image) is an image very similar to a B-scan image except that it presents the data in a perpendicular plot, that is, a section through the volume in a plane that cuts the beam direction. In most cases, where the beam direction is in the primary scan direction, the D-scan image is made up of one waveform from each sequential scan line.

If the beam direction is angled out of the plane of the major scan axis, the B-scan image is normally considered to be the composite of one waveform from each scan line, and the D-scan image is considered to represent the section along the scan direction. That is, B-scan and D-scan orthogonal directions are determined by the beam direction, rather than the scan direction.

8.1.7 Important Ultrasonic Beam Characteristics

In any ultrasonic measurement, it is extremely important to understand that the measured response is a composite of a number of factors:

- The characteristics of the ultrasonic beam, as determined by the transducer selected for the particular material velocity involved
- The efficiency of the transducer(s) and coupling medium in terms of transfer of the ultrasonic energy into the component and back out again upon receipt of a reflection
- The effects of the material in terms of absorption and/or scattering of the sound
- The characteristics of the reflector

For many years, flaw size estimates were based on the amount of energy reflected. To some extent, this practice is still used successfully for certain applications. In order to use this approach for sizing, certain features of the ultrasonic beam must be considered in converting response amplitude to an estimate of flaw size.

8.1.7.1 Near Field Limit

Close to the transmitter (that is, in the near field of the beam) the beam is characterized by pressure maxima and minima across a section through the beam. These maxima and minima decrease in number and significance with increasing propagation distance, and at some point (defined as the *near field limit*), the beam effectively forms a uniform propagation front and begins to propagate as a spherical wave. Figure 8-14 represents a typical response curve along the beam axis as a function of distance from the transmitter. At other points within the beam, but away from its propagation axis, the fluctuations within the near field take on completely different characteristics in terms of time (depth) and amplitude. Beyond the near field limit, the response curve varies only in amplitude, relative to the beam axis response. The near field limit is controlled by the element size (diameter) and the wavelength, which is directly related to frequency.

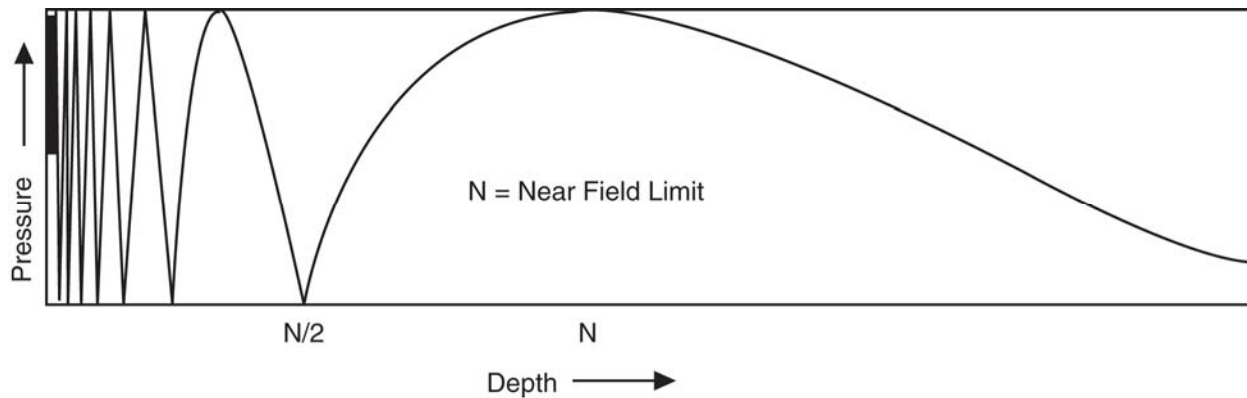


Figure 8-14
Beam Axis Pressure Profile

The intensity variations found throughout the near field are controlled by diffraction and can be predicted mathematically. For practical application, however, it would be very difficult to predict intensity variations within the near field with any degree of accuracy. In addition, any measurement is further dependent upon the exact conditions under which the measurement is being made, that is, upon precise determination of the point within the complex beam at which the measurement is being made. As a result, measurements based on response amplitude within the depth range of the near field are subject to error and are not generally recommended.

As a matter of course, the near field limit (as controlled by transducer size and frequency) should be considered during examination design to provide valid response over the depth range of interest for a particular application. The near field limit increases by the square of the transducer dimension and inversely by the wavelength of the propagating wave. That is, smaller transducers and lower frequencies both reduce the extent of the near field. With proper selection of conventional transducers, it should be possible to make longitudinal wave thickness or angle beam flaw evaluation readings on material that has a local thickness that is more than 0.050 in. (1.3 mm). For very thin tubing or when the anticipated remaining wall thickness is less than approximately 0.050 in. (1.3 mm), more advanced, custom transducer setups may be required to obtain meaningful measurements.

8.1.7.2 Beam Spread

Beyond the near field limit, the wave travels away from the transducer in a spreading fashion, which is readily predictable and can be approximated as a Gaussian distribution. As the travel path length increases, the peak intensity decreases, and the size of the field increases. As a general rule of thumb, neglecting the effects of material scattering and attenuation, the response amplitude for equivalent reflectors drops by the inverse of the distance to the reflector squared. Beam spread is controlled by the wavelength of the propagating wave (and therefore by the frequency) and by the transducer element size. As with other beam characteristics, beam spread should be considered in designing an examination for a particular application. As shown in Figure 8-15, beam spread increases with reduced test frequency and smaller transducer size.

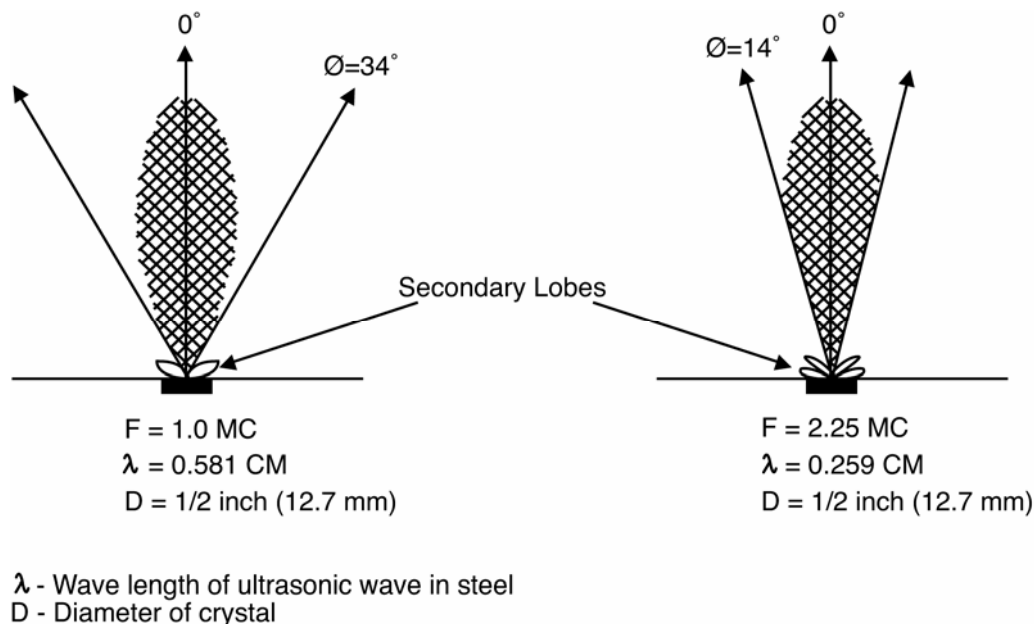


Figure 8-15
Ultrasonic Beam Spread

In applying conventional ultrasonic techniques, it is common practice to set the instrumentation for detection of a specific flaw size. Even though actual reflectivity varies depending on numerous flaw variables in addition to size, detection can be normalized to an equivalent reflector size, for example, specific-size flat-bottom holes or electrodischarged-machined (EDM) slots at different depths. This is normally accomplished using a detection gate that has a threshold level set according to the depth variable amplitude response from the equivalent reflectors. Distance/amplitude correction (DAC) is accomplished in one of two ways. One way uses a depth variable threshold level, called a *DAC curve*, set to correspond to the amplitude decay accountable to beam spread. The other way uses time-corrected gain (TCG) and a uniform threshold level. With TCG, the gain is adjusted as a function of time (depth) in such a way that all equivalent reflectors at the different depths produce the same amplitude response; consequently, a uniform threshold is appropriate.

Echodynamic response, or target motion, is the apparent motion of a target caused by the combined effects of beam spread and transducer motion. As a transducer is scanned so that the beam approaches and then crosses a reflector, beam spread provides for detection of the reflector before the center, peak intensity portion of the beam reaches the reflector. However, response amplitude is diminished relative to the amplitude produced when the peak intensity point of the beam is directed toward the reflector. In addition, the transducer is farther from the reflector than when the response is maximized at beam center alignment with the reflector; consequently, pulse transit time is greater. As the scan progresses and the beam approaches center alignment with the reflector, pulse transit time decreases and amplitude increases.

For 0-degree beam examination, the process reverses after the center of the beam has moved past the reflector. That is, amplitude decreases and transit time increases until the transducer

displacement no longer provides for detection. For an angle beam examination, amplitude decreases after the reflector is past beam center alignment, but transit time continues to decrease. This type of response occurs in some form regardless of the reflector type. For a small, ideal reflector (that is, a small sphere), the echodynamic characteristics are continuous and representative of only the beam shape, not the flaw shape and size. This is how beam profiles are determined. When the operator is using a 0-degree beam directed perpendicular to the laminar-type reflector lying parallel to the test surface, the echodynamic response will occur in the described fashion until the transducer is fully over the lamination. From this point, time and amplitude remain relatively constant until the beam reaches the opposite side of the lamination and the echodynamic “tail” is produced. Similar combined effects of beam and flaw characteristics are produced for other flaw types as well.

An A-scan presentation of echodynamics for a small spherical reflector produces a “walking” indication that is first detected as a minimal signal (amplitude) at a certain depth. The indication then “walks” toward the initial pulse (that is, shorter time) until it peaks in amplitude, following which it reverses direction, increasing in apparent depth and decreasing in amplitude until it is no longer detectable. When images of the data are viewed, as described earlier, the B-scan image will best exhibit echodynamic effects. Because the position of the reflector within the beam cannot be predetermined, imaging algorithms are based on beam centerline plotting. That is, it is always assumed that the reflector is along the beam center, and the data are plotted accordingly. Consequently, the 0-degree beam B-scan image for the ideal flaw will produce a hyperbolic echodynamic image. A schematic representation is shown in Figure 8-16.

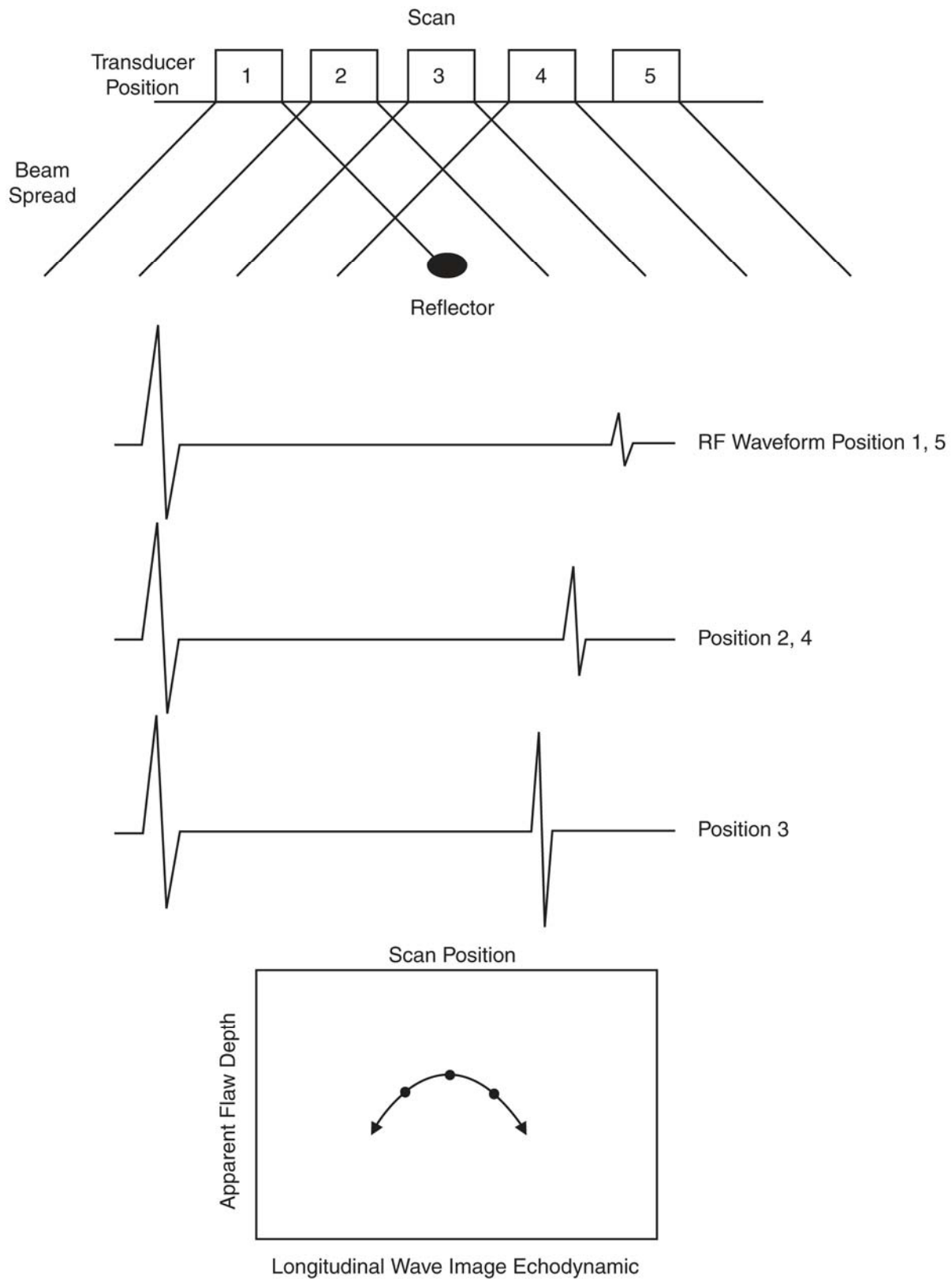


Figure 8-16
Longitudinal-Wave Echodynamic Response

For an angle beam examination, amplitude decreases and pulse transit time also decreases after the center of the beam has moved past the reflector. That is, the indication continues to walk shorter in time throughout the scan rather than reversing. In a B-scan image, the ideal reflector produces an angled echodynamic, as represented in Figure 8-17.

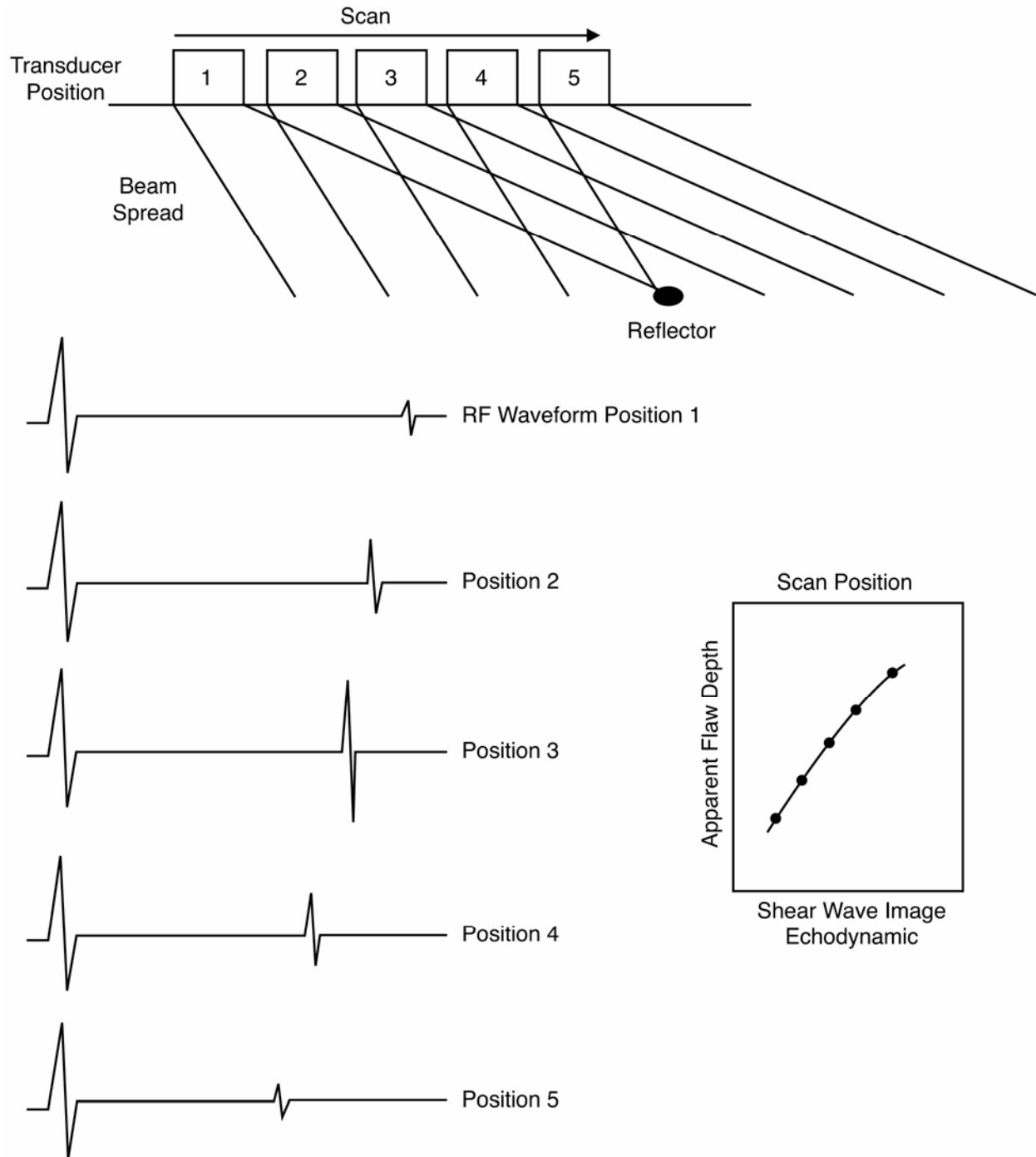


Figure 8-17
Shear-Wave Echodynamic Response

From this discussion, it is obvious that the response to any target is a composite of the beam characteristics and the flaw characteristics. To properly evaluate flaws, it is therefore essential that the beam characteristic contribution to the response be removed or deconvoluted. Specific procedures and algorithms, which will be discussed later, have been developed for this analysis.

8.1.8 Required Equipment for Ultrasonic Examination

As with the techniques described previously, equipment covers a broad range—from simple, handheld thickness meters to complex test systems involving computerized data acquisition and analysis stations, fully automated scanners, support systems (motor controllers, pneumatic actuators, couplant supplies, and so on), and even integral packaging in a housed “control room” environment. Portable analog and digital ultrasonic instruments with A-scan displays are typically used for routine manual examinations. For more technically complex applications requiring image displays and/or computer analysis and requiring remote operation at various locations within the power station, portable PC systems are the norm. For complex examination of components that can be moved to the ultrasonic system during maintenance outages, the housed units described above are more prevalent.

The key to optimized selection of the appropriate examination is to first define the examination requirements in terms of component geometry and detection and sizing requirements. Appropriate examination approaches can then be selected to fulfill these requirements, and equipment can be specified for optimum delivery of the appropriate approach. Examination costs increase proportionally with increased sophistication and corresponding equipment requirements. Consequently, it is economically advantageous to select the overall examination approach that meets requirements without significantly surpassing them.

8.1.9 Applications of Ultrasonic Examination

Ultrasonic examination is widely used for a variety of applications within power stations. In general, any application requiring volumetric coverage or examination of inaccessible surfaces is a candidate. Ultrasonic examination has the capability to locate, size, and characterize (that is, determine if the indication is continuous, planar, round, and so on) discontinuities or flaws. This NDE method has been used to verify construction quality (looking for laminations, weld flaws, insufficient wall thickness, and so on). For periodic in-service examination, wall thickness, steam-side oxide scale thickness (used to estimate the local metal temperature and long-term overheating—that is, creep life), microstructural damage (for example, hydrogen damage), and cracklike flaws can be located, characterized, and sized using ultrasonic techniques. When ultrasonic examination is performed on finned tubing, the removal of a small region of tube fins in selected, damage-susceptible locations may be required.

8.1.10 Special-Application Ultrasonic Techniques and Required Equipment

Probably 75% of all ultrasonic examinations performed in power plants involve conventional shear wave or longitudinal wave techniques. The term “conventional” is used as a descriptive term for pulse-echo or pitch-catch examination (pitch-catch only when the transducer elements are operated on the same surface in close proximity to each other) using broad beams whose beam characteristics are controlled only by transducer size and frequency and the inherent material considerations.

However, these techniques have been found to be unsuitable for certain applications—in some cases even for detection, but more often because of unacceptable sizing error. In certain instances, flaw detection is inadequate because sufficient beam intensity cannot be produced in a conventional examination mode to detect the flaw of interest. This is normally attributable to flaw orientation (misorientation) relative to the achievable beam angle and/or is simply because detection requirements are beyond the detection capabilities of this type of examination, as affected by certain material characteristics including material attenuation. To a degree, the design of a particular examination approach can affect detection capabilities.

Careful selection of transducer size and frequency, to optimize detection over the required depth range (for example by moving the peak beam intensity point, or near field limit, to the appropriate depth) and properly control beam spread, can have a significant effect. Material attenuation is a function of frequency, with higher frequencies being more susceptible to attenuation than lower frequencies. In addition, basic detection capabilities, as dictated by physics, improve with increased frequency (that is, smaller flaws are theoretically more readily detected). Consequently, optimum examination design often involves a compromise among basic detection sensitivity, attenuation, near field limit, and beam spread, as controlled by transducer size and frequency.

Flaw sizing is even more variable than detection when using conventional ultrasonic approaches in all but very limited cases for very specifically defined flaws. Keep in mind that the measured parameters are limited to time and amplitude. Here, time is generally utilized to determine reflector location, and amplitude is therefore the basis of size estimates. Response amplitude is affected by a number of parameters, including some that are attributable to the beam and others that are attributable to the flaw.

Beam characteristics, primarily the beam shape and intensity at the flaw, can be removed using deconvolution algorithms that will be described later or can at least be accounted for during calibration. Similarly, compensation can be applied for material effects (mainly attenuation). However, reflector efficiency is a function of many other variables in addition to reflector size. The list includes, but is not limited to, reflector shape, reflector orientation relative to the beam, reflector morphology or surface roughness, and material composition of the reflector. For specific cases in which shape, orientation, and morphology are uniform, regular and known size can be estimated from response amplitude with reasonable accuracy. For flaws that are flat, smooth, of regular shape, and oriented normal to the beam, amplitude-based sizing is acceptable. However, any unknown deviations can have a profound impact on sizing accuracy.

To address these detection and sizing limitations, a number of special, sometimes application-specific techniques have evolved. These are often associated with special transducer and/or instrumentation requirements to support the technique. For improved detection, these techniques involve one or more of the following features:

- Focused beams to increase beam intensity
- Spatially displaced pitch-catch transmitter and receiver transducer pairs, placed to best detect specular (mirror) reflections of the same propagation mode
- Spatially displaced pitch-catch transmitter and receiver pairs, placed to best detect mode-converted reflections
- High-angle longitudinal waves and derivatives, including creeping waves
- Electronically variable beam angulation using a phased array system

Improved sizing accuracy has evolved through the use of:

- Minimization of beam effects on echodynamics through the use of focused beams
- Dynamic beam angle optimization using electronically variable phased array systems
- Flaw tip diffraction techniques

8.1.10.1 Focused Beam Techniques

Focused beam examination provides both improved detection and improved size determination. Relative to detection, the underlying principle is quite simple. Specifically, increased beam intensity, achieved by focusing the otherwise widely distributed energy into a small focal spot, provides increased reflection energy and therefore enhanced detection. If properly focused, backscatter from facets and other flaw surface irregularities can be sufficient for detection, even for flaws whose major orientation causes the specular reflection to be directed well away from the transducer.

Improved sizing results directly from a combination of the improved sensitivity, that is, detection of facets and surface irregularities, and the reduced echodynamic characteristics that result from elimination of beam spread and minimization to a small beam spot. If beam spread effects on dynamic response are eliminated, then one is left with only the response characteristics that are related directly to the flaw. With increased sensitivity to the point that even facets and surface irregularities produce measurable response, one is assured of detection when the beam is directed toward nearly any point on the flaw.

Together, these advantages mean that a response can be produced as long as the beam is aimed at some point on the reflector, but no response is produced when the finely focused beam is moved off of the flaw, even by a very small amount. Consequently, the boundary of a flaw can be defined fairly accurately by simply defining the envelope over which detections occur and correcting spatially for beam direction. Further refinement in the size measurement can be accomplished by subtracting the beam spot size from the boundary of the detection envelope.

Focus is achieved in one of two ways. In the first (shown in Figure 8-18), the transducer operates within a fluid (normally water), and a focusing lens is placed between the transducer and the test object, normally attached to the face of the transducer. The liquid is required to provide coupling between the shaped lens and the component surface geometry. In this implementation, the water coupling scheme can be implemented by immersing the component and the transducer in the immersion fluid, through the use of a bubbler arrangement in which a water column is maintained through a transducer housing that contacts the test object (in which case a water feed is required and water leaks over the component), or via water column squirters in which a water column is used without the housing contacting the component (this option is seldom, if ever, found in use in power plant applications).

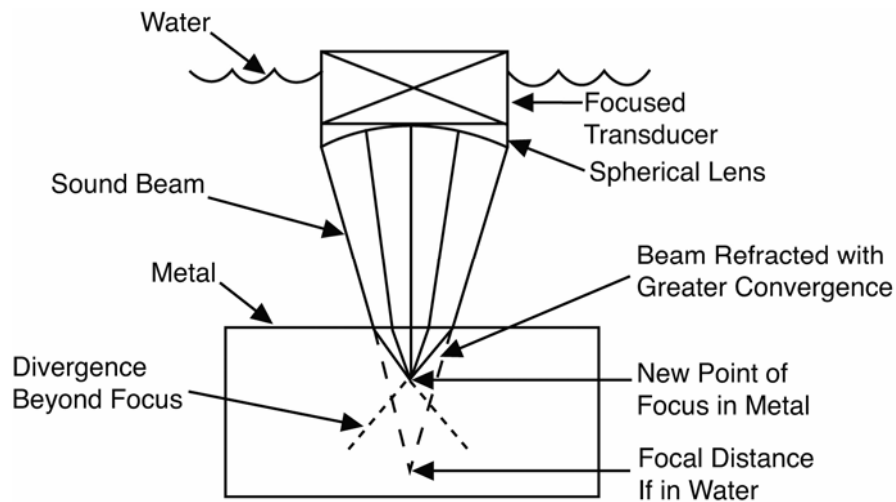


Figure 8-18
Beam Focusing

The second focusing method involves the transducer, lens, and water in a sealed housing with a membrane that contains the water but allows transmission of ultrasound into the part. In this latter case, a couplant between the sealed housing and the component is required, just as in conventional contact testing. The disadvantages of this approach are obvious. The use of various immersion techniques either involves complete immersion (which can be completely impractical for many applications), water flow (which may be prohibited and at best is inconvenient), or rather large housings for the sealed immersion shoes. The main advantage of this focusing method lies in the ease with which focus can be varied and optimized for a particular application or for various depths within the application. Different lens configurations can be implemented quickly and easily while using a single immersion transducer. This provides very significant economic advantages.

Alternatively, special contact transducers with hard shoes can be built. These typically have curved piezoelectric elements such that focus can be achieved by a combination of the curved lens, an intermediate refracting material, and the contact/refracting wedge. The advantage of this approach lies in the elimination of the immersion fluid. Search units that are physically not appreciably different from conventional transducers can be built and operated in the same way as conventional contact transducers. The disadvantage of this approach is primarily economic. Each

variation requires a different transducer, including the element(s), lenses, housing, connectors, and so on. In addition, the manufacture of such transducers is in itself not inexpensive because of the requirement for contoured elements, exactly contoured refracting lenses, and so on.

A disadvantage of fixed focused beam examination, regardless of the transducer design, stems from the fact that the beam can be maintained in focus only over some finite depth range. This is analogous to the aperture, focal depth, and depth of field relationships of optical lenses, for example, as used in cameras. In general, focal spot size can be reduced by increasing the aperture (that is, the transducer size) and by increasing frequency. Focal depth is controlled by the focusing optics, and depth of field (that is, the depth range over which reasonable focus can be maintained) increases with increasing focal depth. All of these variables should be factored into the design and a number of focal depths used, depending on the required depth range of in-focus examination.

8.1.10.2 Spatially Displaced Transducers

Another technique that can provide appreciable improvement in detection sensitivity involves the use of spatially displaced pitch-catch transmitter and receiver transducer pairs. This technique is typically used for special applications in which the location and orientation of the flaw of interest, while not providing reliable detection with the receiver at or near the transmitter, are known and reasonable consistent. For such flaws, the direction of the primary specular reflection can be determined and a receiver transducer placed appropriately, not necessarily even on the same surface as the transmitter, to best detect the specular reflector. Such techniques are generally used for detection only, not for sizing, and are limited to the specified condition in which the flaw location and orientation are known fairly precisely. A significant complication arising from the use of this technique is that the scanning motion of the two transducers must be carefully and accurately coordinated. Relative position of the transducers can be significant, and coordination of the motions can be difficult.

A modification of this technique, which can place the transducers close together and even possibly in the same housing, is used to minimize the difficulty of transducer position coordination. This technique and its derivatives involve the detection of mode-converted signals rather than the primary specular reflection. As described earlier, a beam angularly incident on a boundary of mismatched acoustic impedance results in a direct reflection signal and a mode-conversion reflection signal. If the likely flaw orientation is known and the component geometry is considered, a transducer pair can be designed such that a mode converted signal emerges near the transmitter.

One specific implementation of this approach is the longitudinal-longitudinal-transverse (LLT) technique. This technique is specifically intended for the detection of through-wall oriented flaws. A longitudinal wave of relatively low refracted angle (again, relative to surface normal) is transmitted into the material toward the back wall, where it reflects at equal angle, also in longitudinal mode. The angle is selected such that, in the presence of a through-wall oriented flaw, the backwall reflection strikes the flaw at the appropriate angle to mode-convert a significant portion of the energy to shear mode at an angle that returns to the test surface fairly

close to the transmitter. A shear wave receiver is then used to detect the presence of a reflector. In the absence of a flaw, the longitudinal wave continues to reflect repeatedly at the test surface and backwall, always away from the receiver such that no reflection is detected.

This technique, named LLT because of the modes of the three legs of its path, typically involves a transmitter (longitudinal wave) and receiver (shear wave) housed in a single assembly as shown in Figure 8-19, although multiple combinations are required for detection through the entire wall thickness. (That is, a particular transducer pair is sensitive only over a portion of the wall thickness. Typically, three such transducer arrangements are required to cover the entire wall thickness.)

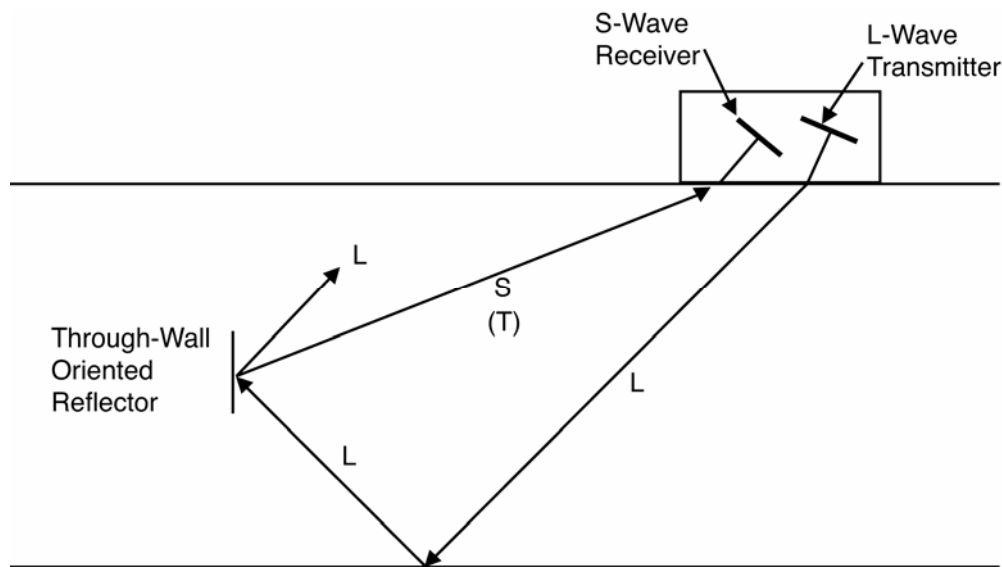


Figure 8-19
The LLT Ultrasonic Technique for Through-Wall Oriented Flaws

Another mode-conversion technique, the mode-converted longitudinal wave technique, is used for the detection of shallow, opposite-surface cracks that must be distinguished from geometric features of components that contact the surface being examined. Although shear waves are ideal for the detection of opposite-surface flaws in most instances, geometric features of other components that are in intimate contact can often be detected when using shear waves. In such cases, it is difficult to distinguish between the geometry reflectors and shallow flaws. In the mode-converted longitudinal wave technique, shown in Figure 8-20, a shear wave is introduced at higher than normal incidence, typically somewhat above 60° at the far surface so that the geometric reflectors (as well as the flaws) do not produce significant specular reflections. At this incident angle, a corner trap created by a crack at the opposite surface mode-converts much of the energy to a longitudinal wave that returns to the examination surface almost directly above the flaw. Placement of a longitudinal wave receiver at the appropriate point on the examination surface provides for detection of this flaw without any signal from the geometry reflectors.

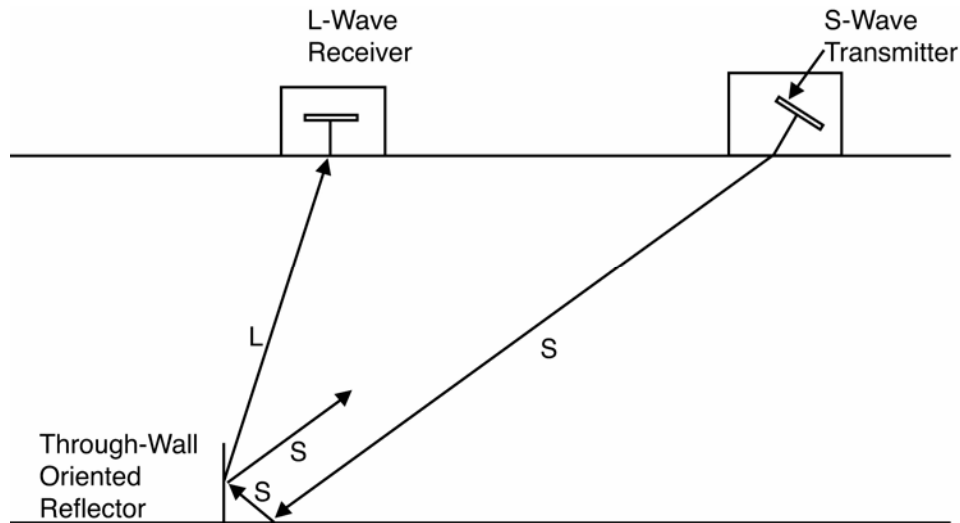


Figure 8-20
Mode-Converted Longitudinal Wave Ultrasonic Technique

8.1.10.3 High-Angle Longitudinal Waves

High-angle longitudinal waves are typically in the range of 60° to 75° and have been found to provide certain advantages for the detection of through-wall oriented flaws such as weld fusion line cracking. The presence of the component surface influences the beam and creates an outside surface creeping wave that is sensitive to flaws close to, or connected to, the examination surface. Unlike the Rayleigh wave, however, creeping waves are not affected by liquid drops, weld spatter, or other surface conditions. The main longitudinal wave provides for detection of deeper flaws, and the trailing shear wave provides for detection of yet deeper flaws. The longitudinal wave also radiates a shear wave at the correct angle to generate an inside surface creeping wave that is sensitive to inside surface and near-outside surface flaws. This multiplicity of detection beams and modes creates a display that can be very confusing to all but expert practitioners. Flaws of appreciable size can be detected by more than one of the different possibilities. However, in the hands of a well-trained operator, the presence or absence of these signals, and the relative strength of each, provide not only an indication of the presence of certain reflectors, but also a good indication of the flaw size. High-angle longitudinal waves can also produce measurable tip diffraction signals that can be invaluable in determining flaw size. Tip diffraction techniques will be discussed later.

A number of transducers have been designed to take advantage of these features. While it is beyond the scope of this document to describe each of these in detail, it is important to note that specific transducers and analysis techniques are available for such applications. Techniques such as the relative arrival time technique, absolute arrival time technique, multipulse observation sizing technique, and others have been developed and are well documented.

8.1.10.4 Linear Phased Array Technology

A large number of critical power plant components and welds are examined periodically using the widely available conventional ultrasonic examination techniques and procedures. For these applications, the ultrasonic examinations are normally performed using one or more ultrasonic transducers. Typically, each transducer is designed to produce a sound beam in the component that will travel to an area of interest and reflect from any discontinuities that might be present. The transducer then receives the reflected sound beam and displays the resultant data to the ultrasonic examiner. Each transducer produces a sound beam of a single characteristic angle. In some cases, special transducers that produce focused beams are used. In order to examine a component, one or more transducers must be placed in contact with the component and then scanned in a two-dimensional pattern over the surface until the entire area of interest has been covered. This raster scan process may be accomplished manually or using automated examination equipment.

In applications such as seam-welded high-energy piping, execution of these raster scans can be time-consuming, particularly because several transducers and beam angles must always be used to completely examine the examination volume. Furthermore, analysis of the data can be complex, requiring highly skilled and experienced operators. But with phased array, the analysis of the resulting data is much simpler than with conventional transducers.

An “array” is a type of ultrasonic transducer that has been segmented into many individual parallel elements. Each of these array elements is connected to a separate pulser, receiver, and analog-to-digital converter. The system operator can control the time at which each element is pulsed and the time delay applied to the response received by each element. After application of the reception delays, the individual elements’ received waveforms are added to form a single, resultant waveform.

If all of the elements are pulsed simultaneously and no delays (or equal delays) are applied upon reception, then the array functions as if it were still intact as a single monolithic element, and the array produces a sound beam that is normal to its surface (see Figure 8-21). If the pulsing times and reception delays are varied linearly along the array, then the array produces an angled sound beam (see Figure 8-22). The angle of the beam is controlled by the delay between adjacent elements and by the acoustic velocity in the propagation medium. If a nonlinear delay function is applied, the sound beam may be caused to focus (see Figure 8-23).

Nominal Beam - No Phasing

- All Elements Pulsed Simultaneously; No Delay Is Used
- Array Produces Same Beam as a Single, Large Element

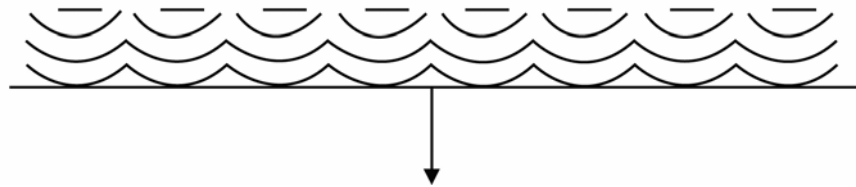
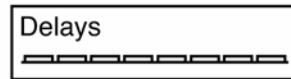


Figure 8-21
Operating the Array with Constant Phase

Steering the Beam - Linear Phasing

- Pulse Delay Between Adjacent Elements Is Constant
- Array Produces a Plane Beam (Not Focused)
- Beam Angle Depends on Delay Between Elements

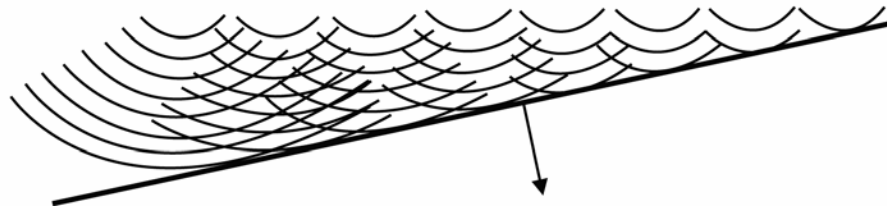


Figure 8-22
Operating the Array with Linear Phase

Focusing the Beam - Nonlinear Phasing

- Pulse Delay Between Adjacent Element Is Not Constant
- Array Produces a Curved Wavefront (Focused)
- Nominal Angle, Focal Distance Depends on Shape of Delay Function

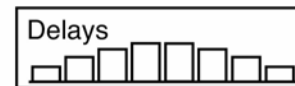


Figure 8-23
Operating the Array with Nonlinear Phase

Therefore, by controlling the timing, or “phase,” of each element’s excitation and reception, a single array probe can be made to simulate many different conventional probes. Without moving the probe, sound beams of many angles can be generated sequentially, examining a large portion of the component’s cross-section (see Figure 8-24). To achieve this same coverage using conventional techniques, the probe would have to be moved over the component’s surface (see Figure 8-25).

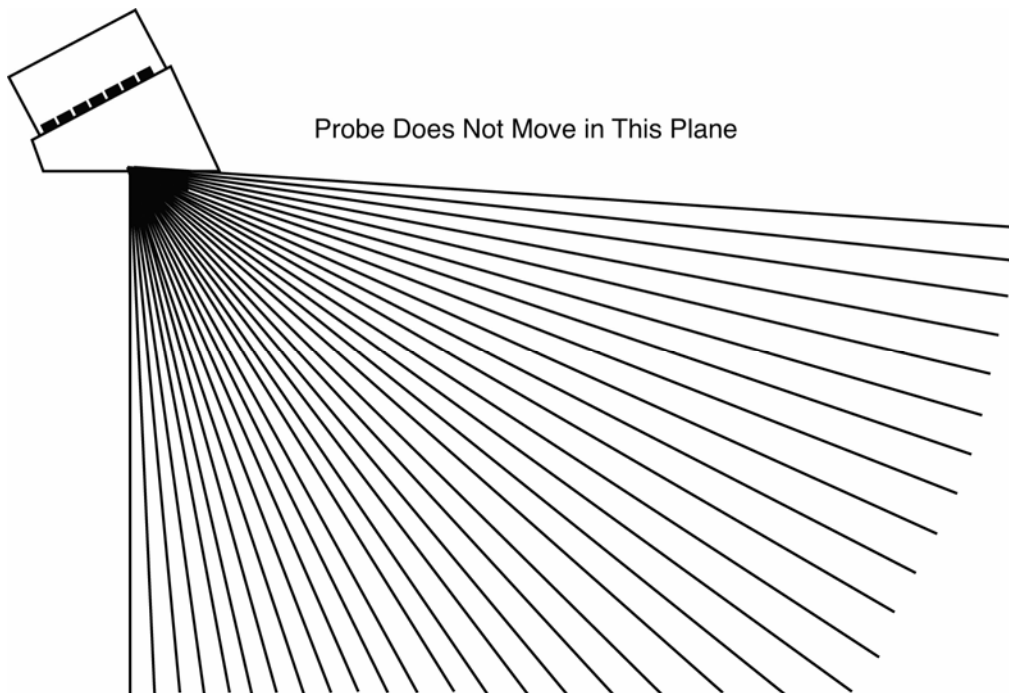


Figure 8-24
Using an Array to Examine a Cross-Section by Steering the Sound Beam Electronically

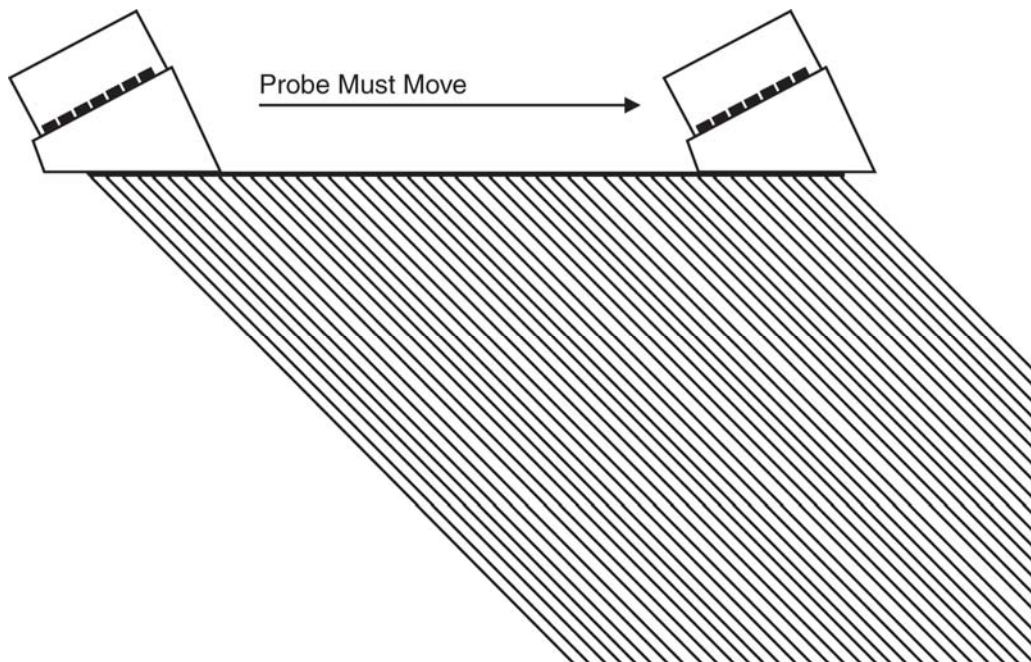


Figure 8-25
Using a Conventional Probe to Examine a Cross-Section by Scanning the Probe Mechanically

In this manner, a slice of a component can be scanned electronically in milliseconds instead of being scanned mechanically in a few seconds. The image produced from this type of polar electronic sweep is called a *sector scan*. (This type of image is already familiar to most people; the familiar wedge-shaped, black-and-white ultrasound images of fetuses are sector scans. In fact, the fetal ultrasound imaging technique is nearly the same as ultrasonic sector scan imaging technique used for examination of power plant components.) Instead of the slow, two-dimensional scan pattern necessary to scan a weld joint using conventional methods, the probe may simply be swept along the length of the weld one or more times at different array setback positions to achieve similar results. The comparison between the line scan and the more common raster scan is shown in Figures 8-26 and 8-27. Use of this approach can reduce scan times by at least an order of magnitude.

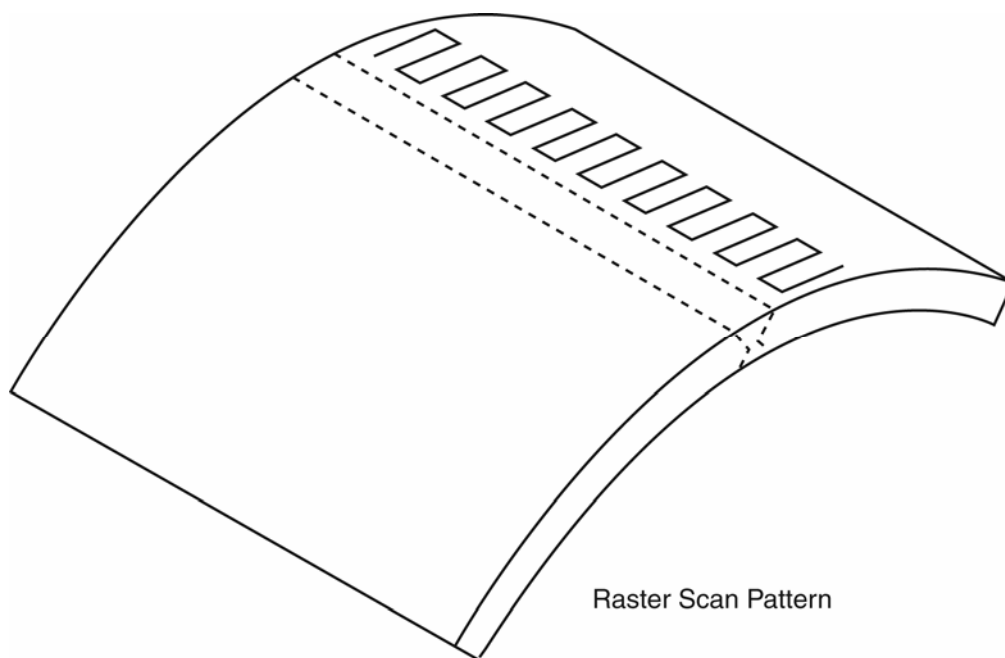


Figure 8-26
Example of a Raster Scan Pattern

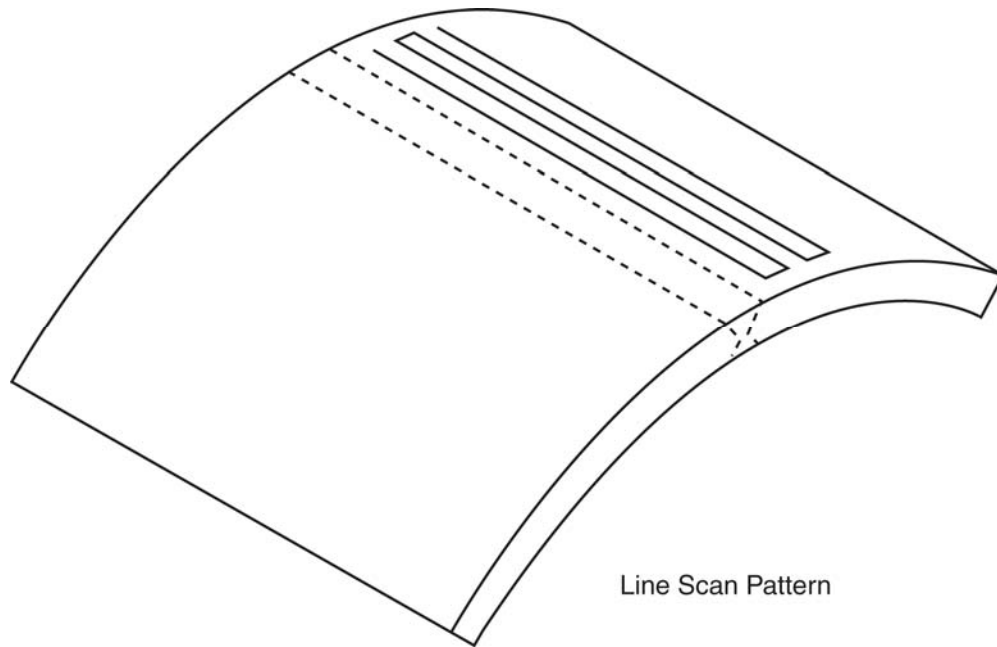


Figure 8-27
Example of a Line Scan Pattern

Required Equipment—the Automated Ultrasonic Phased Array System. Investigations of phased array technology for application to seam-welded high-energy piping examinations were conducted using a portable TOMOSCAN system upgraded to include a phased array option. The portable UT system is manufactured by Tecrad and can be used to drive either a piezoelectric or EMAT. The system makes it possible to perform examinations with various beam angles and focal lengths using a single array of transducers. Beam focusing and angle control involve the application of precisely controlled delays to both the emission pulse and the received pulse for each element in an array of transducers (thus the term *phased array*). The setting of these delays is referred to as a *focal law*.

A typical phased array setup includes a portable TOMOSCAN, a phased array unit, a piezoelectric probe driver (also called a *piezodriver*), an automated scanning device, and an associated driving unit. The console portion of the TOMOSCAN is used during analysis and acquisition and displays various image presentations such as A-, B-, and C-scans. Although the system can operate a wide range of probes, EPRI NDE Center investigations were performed using a 3.5-MHz piezoelectric phased array transducer (see Figure 8-28) capable of producing a wide range of beam angles in both shear and longitudinal wave modes. The transducer was arranged in a dual configuration containing 16 elements for transmission and 16 elements for reception. Ultrasonic data were collected and stored on optical disk for subsequent review and analysis.

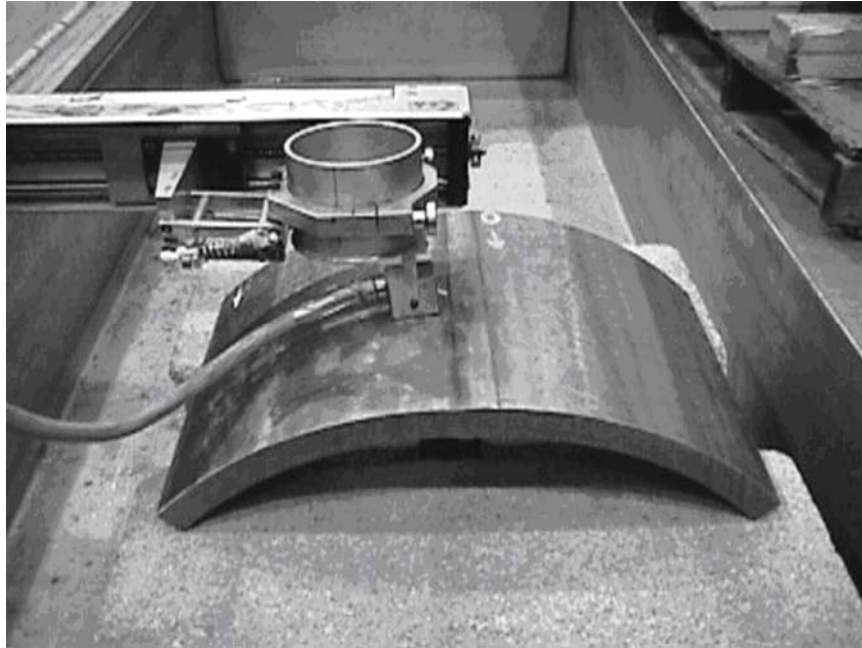


Figure 8-28
Phased Array Probe, Mechanical Pipe Scanner, and Pipe Specimen

Improvements in Speed and Data Analysis. By using a phased array probe with the line scan approach, the potential exists for achieving improvements in speed and data analysis. As is the case with conventional ultrasonic examination, examination sensitivity is still an important variable that must be considered during the data acquisition process.

The line scan procedure using the phased array probe permits examination of a cross-sectional area of interest to be covered from a minimum number of probe positions. Additional probe positions are sometimes added to improve coverage or in an attempt to improve the accuracy of flaw sizing. Figure 8-29 shows the coverage on a typical double-V seam weld that is being examined using a phased array probe and a line scan technique. As shown in Figure 8-29, the multiple beam angles effectively interrogate the entire fusion line region of the seam weld. By employing a large number of angles, it is easy to visualize the potential improvements that can be realized both in speed and in flaw detection/sizing capabilities.

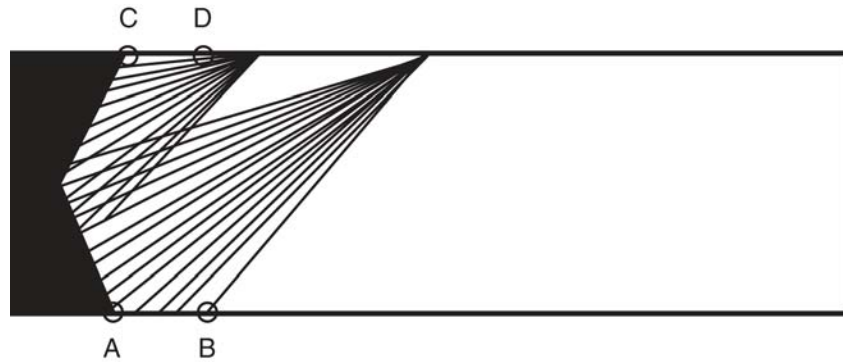


Figure 8-29
Phased Array Coverage of a Seam Weld from Two Probe Positions

In addition to improved coverage, the automated phased array technique offers a much simpler means of analyzing the resultant data. Even when using conventional automated ultrasonic techniques, the analysis of the ultrasonic data generally takes longer than the acquisition of the data, especially if many flaws are detected. Using phased array technology, the data analysis process tends to be simpler, faster, and more reliable than conventional data analysis. By reviewing the B-scan images of the different beam angles, a flaw can be very clearly identified. Figure 8-30 shows an example of a B-scan presentation of a crack connected to the inside surface at the fusion line of the weld.

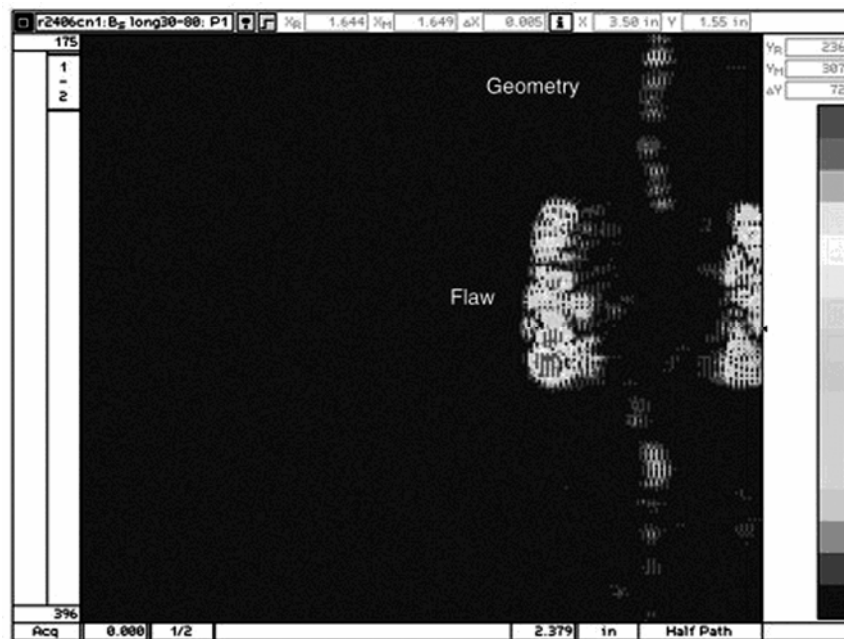


Figure 8-30
B-Scan Image of a Crack Connected to the Inside Surface

Another technique that can be useful in analyzing phased array data is commonly referred to as the *sector scan* method of analysis. An example of how this technique can be used is shown in Figure 8-31. This figure shows an actual sector scan response of a crack connected to the inside surface at the fusion line of the weld. The weld configuration has been added to more clearly show how the image can be used during analysis. Once the analyst understands the configuration of a seam weld, the task is reduced to noting the presence of crack reflections and measuring the crack depth by noting the beam angle and probe position associated with the extremity of the crack. The simple and intuitive nature of the data presentation also makes it easier for the analyst to explain the results to the appropriate plant personnel.

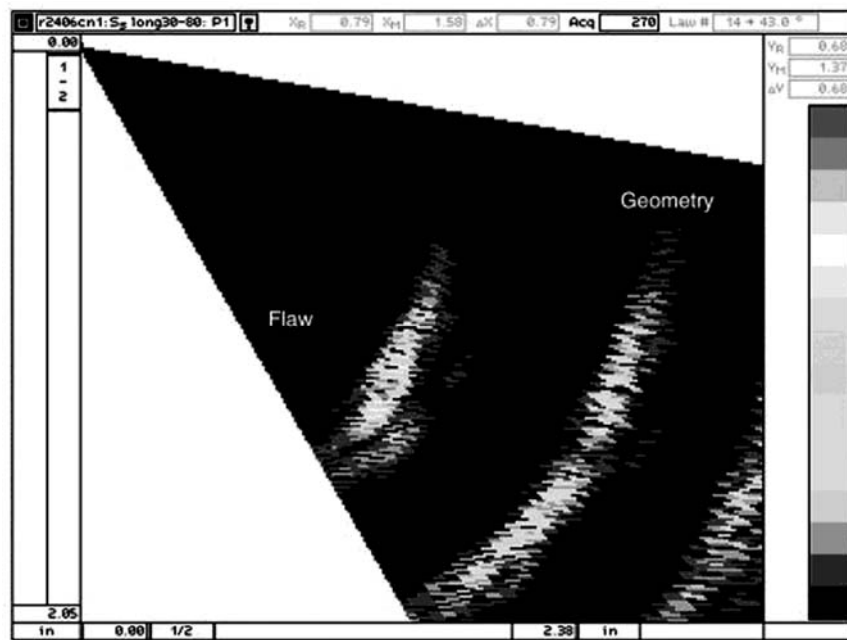


Figure 8-31
Sector Scan Image of a Crack Connected to the Inside Surface at a Weld Fusion Line

If subsequent field trials of the phased array technology indicate that improvements in detection and sizing capabilities are needed, it is still possible to apply the phased array technique using beam focusing (see Figure 8-32). As previously discussed, the central elements of the transducer array can be fired with longer delays compared to those of the lateral elements. This process results in each of the individual wave fronts arriving in phase at a desired focal point. The resulting ultrasonic beam will be effectively focused at that point. The goal of using focused beams is to increase sensitivity to smaller areas of incipient creep damage and to improve the sizing capability of the phased array techniques.

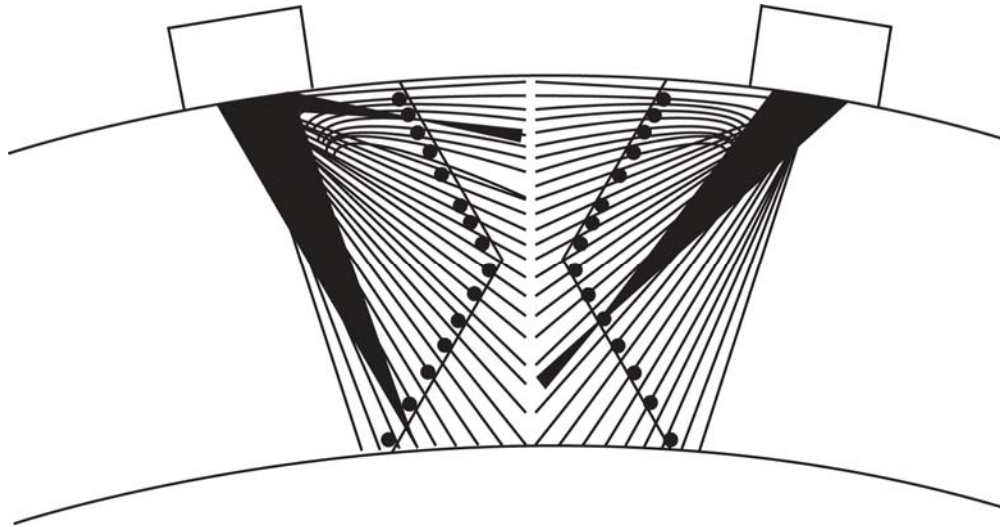


Figure 8-32
Potential for Focusing Using Phased Array Technology

8.1.10.5 Synthetic Aperture Focusing Technique

The synthetic aperture focusing technique (SAFT) is a postprocessing algorithm that can be implemented on data acquired in a broad beam examination to remove echodynamic effects attributable to beam spread and thereby simulate the characteristics of a focused beam examination. For any broad beam propagation direction, the time variations that occur for a given flaw from one pulse to the next due to beam spread can be predicted very accurately. Mathematical expressions can therefore be developed accordingly.

SAFT operates by looking at each digitization point on each acquired waveform in a systematic fashion. At each point, the time shifts that would occur for the same flaw on prior and subsequent waveforms is calculated and the waveforms are shifted in time accordingly and then added. The number of waveforms included in the process at any point is set to match the beam spread at that depth. Any coherent signal that behaves in the prescribed manner on a series of waveforms will add constructively and therefore will be reinforced. At points where the signals do not behave in the prescribed manner, the signals will destructively interfere, thereby suppressing noise. The net effect is appreciable signal to noise (S/N) enhancement and minimization of beam spread effects.

Two-dimensional SAFT, or line SAFT, performs the computations only in a line scan, that is, looking only at waveforms before and after the SAFT point in the same scan line. Line SAFT therefore does not address the S/N enhancement and beam minimization in the perpendicular direction. A three-dimensional SAFT also includes consideration of waveforms in previous and subsequent scan passes and therefore increases processing time by nearly the square of the line SAFT processing time. For example, if a line SAFT includes 10 waveforms before and 10 after the SAFT waveform (a total of 20), then an equivalent three-dimensional SAFT would include 21 waveforms in each of the previous and subsequent 10 scan passes (a total of 440), assuming of course that the scan index between scan passes is the same as the pulse index within a scan

pass. In reality, the number of waveforms included can be reduced as the distance from the SAFT waveform (scan line count away from the SAFT waveform) increases. That is, beam spread would be expected to detect a given flaw in a cylindrical volume, not a rectangular volume.

It is important to note that the SAFT calculations must be performed at each digitization point on each waveform collected. In addition, if the SAFT processing is to be optimized in terms of synthetically simulating a true focused beam, then the data must be acquired in a fashion similar to that required for focused beam examination. That is, data must be acquired at high density, using small steps between pulses for line SAFT and additionally small increments between scan passes for three-dimensional SAFT. Consequently, SAFT is a time-intensive operation. Although modern PC technology now provides for reasonably efficient line SAFT, three-dimensional SAFT for any significant scan size still requires more powerful computers.

8.1.10.6 Time-of-Flight Diffraction Technique

The ultrasonic time-of-flight diffraction (TOFD) technique was originally developed in the late 1970s by the Atomic Energy Authority's Harwell Laboratory in the United Kingdom for flaw sizing in the nuclear industry. The technique was also found to be effective for the detection of flaws of various types and orientations in welds and base materials. Examination vendors have increasingly been using TOFD for examination tasks at electric generating stations for fabrication and service-induced flaws. A primary examination task has been to examine longitudinal seam welds for cracking associated with creep damage.

The technique employs two longitudinal wave, angle beam transducers (probes) arranged symmetrically opposite and facing each other, straddling the weld or base material being examined. For most weld examinations, the probes are located on the parent material clear of the weld crown. One probe acts as the transmitter of ultrasonic energy while the other probe receives the ultrasonic energy. The transducer, pulser, and amplifier characteristics are selected to generate as broad a distribution of energy as possible over the material being examined. For weld examinations, this generally includes the weld, the HAZ (if present), and adjacent base material. Figure 8-33 shows the typical probe arrangement and diffracted signals associated with an embedded flaw.

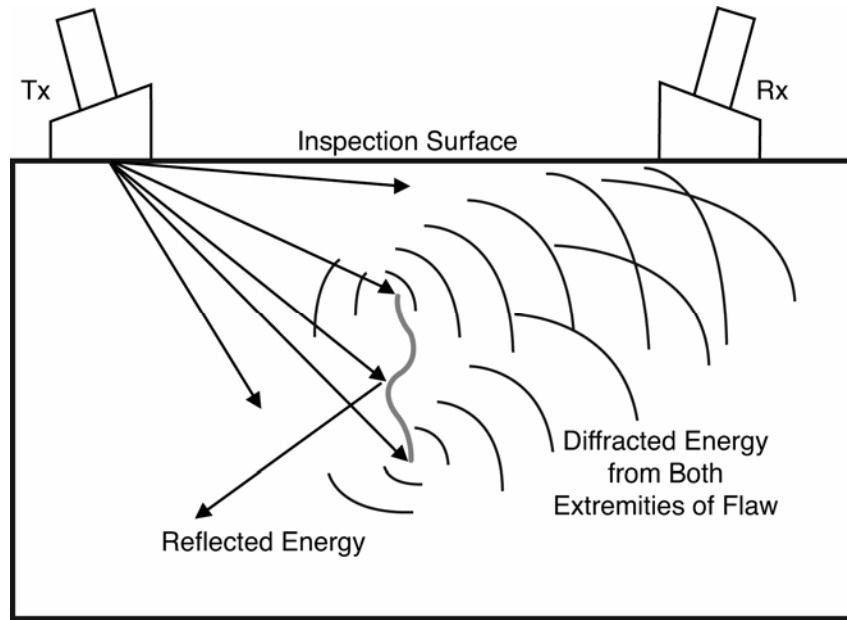


Figure 8-33
Diffracted Signals Associated with Time-of-Flight Diffraction

In reaction to an impinging wave front, a flaw will oscillate, emitting and scattering waves from its edges, branches, or tips. The detection of these scattered or “diffracted” waves provides the mechanism through which the dimension of a flaw can be directly measured. Both of the primary ultrasonic methods—shear wave and longitudinal wave modes of propagation—simplistically generate diffracted waves in the same manner. However, the longitudinal mode generates tip-diffracted signals of greater intensity. Furthermore, because conventional shear wave techniques are intended primarily for the detection of specular reflections from flaws, tip-diffracted signals are often difficult to resolve from the higher-amplitude specular reflections.

Diffracted signals are generally of low amplitude regardless of the mode of wave propagation. Proper employment of the technique involves accurate analysis of the echodynamic patterns generated from reflectors and diffractors within the volume under examination. If examination is via manual mode involving the analysis of an A-scan presentation, these patterns may be indiscernible from the material noise signature. Improved reliability is achieved through the use of digital imaging and mechanized scanners that have been simplified to provide the means to collect, store, display, and analyze the data. This methodology significantly reduces the duration of the acquisition and analysis processes.

TOFD techniques are routinely being used for high-energy seam-welded piping examinations. Because TOFD requires only a single-motion axis along the weld, data acquisition is accomplished using a simple manual scanner that incorporates a position encoder. The encoder records the position along the weld and enables the assembly of digital images in real time. Other potential benefits of using TOFD for examining seam-welded piping include:

- Ease of application (that is, typically applied using one or more linear scans along the weld axis)
- Complete coverage of the weld if the technique is applied properly
- Speed of operation (that is, scan/display speeds of approximately 24 in./min (61 cm/min) are routinely achieved in the field)
- Reliable detection capabilities and accuracy of sizing
- Ability to store data for subsequent analysis and comparison with future examination data

The results of EPRI research on the TOFD technique indicate the importance of using the methodology in a way that is capable of achieving adequate coverage of the seam weld. This includes a method of determining the optimum probe separation distance for the specific TOFD application. Although sizing accuracy varied somewhat for different setups, the best overall setup on each specimen resulted in a variance of less than 2% in the difference between measured sizes of flaw length and depth versus the actual sizes.

The TOFD technique is routinely being applied to high-energy seam welds and has been found to be effective for the detection and sizing of flaws of various types and orientations in welds and base materials. The major benefits are speed of operation, ease of application, and reliable detection and sizing capabilities.

The automated ultrasonic system used for an TOFD application should be a multichannel data acquisition and imaging system that generates, as a minimum, two-dimensional grayscale images of the ultrasonic TOFD data in real time. The system should include the motion controls, supporting pulser/receiver channels and digitizers, and ultrasonic signal preamplifiers and peripherals including a hard disc drive, graphics display, and external disc drive for data archival storage. The multichannel ultrasonic TOFD system should provide ultrasonic display mode views of B-scan (parallel) and D-scan (nonparallel) in real time, and an A-scan (unrectified as a minimum) display for use during the setup/calibration and evaluation/analysis processes.

The ultrasonic TOFD system should have a software modeling program to assist in determining the approximate beam coverage on flat and curved surfaces using various search unit frequencies, wedge angles, and probe separation distance.

The system should have routines to aid in analysis of the acquired data. As a minimum, the following routines should be included in the analysis program:

- Linearization
- Zoom control
- A-scan view
- Cursors (calibrated as a minimum)
- Lateral wave or back wall—straightening and removal
- SAFT
- Echodynamics
- Multiple scans mode
- Profiling

Scanners/manipulators should be automated or handheld, semiautomated, and of various sizes to accommodate a variety of weld configurations. The scanner/manipulator system should be equipped with devices to correlate positional references along the weld(s) to be examined (for example, optical encoders).

Preamplifiers providing approximately 30–60 dB amplification gain should be used to maintain adequate signal-to-noise ratio and to return the collected ultrasonic data to the acquisition and imaging system for digitization and analysis.

The search units should be longitudinal wave probes having bandwidth, dampening, center frequencies and element sizes designed for the ultrasonic TOFD technique. Piezoelectric or composite elements may be used. Frequencies should range from 1 to 15 MHz, as appropriate for the material acoustical properties and geometrical shapes under examination. In general, high-frequency and small-diameter search units apply to thin materials, whereas low-frequency and larger-diameter search units are used for thicker materials. Similar to search unit selection, wedges specifically designed for ultrasonic TOFD applications should be used. Various angles, such as 35°, 45°, 60°, or 70°, may be used to establish full examination coverage.

An approved couplant should be used and documented on the appropriate examination records.

Coaxial cables consisting of the minimum number of intermediate cables/connectors not exceeding a total of 250 ft (76.2 m) may be used for examinations unless signal degradation requires shorter distances.

Most utilities rely on consultants and equipment vendors to perform TOFD because of the specialized and expensive equipment required. Utilities can arrange for insulation removal or surface preparation to permit equipment access to the longitudinal piping welds, allowing one or more passes along the weld length necessary to provide the desired coverage when performing ultrasonic TOFD examinations.

8.1.10.7 Electromagnetic Acoustic Transducers

EMATs are essentially a variation of the ultrasonic method. In conventional ultrasonic examination, the ultrasonic wave in the component is generated by a form of electromechanical conversion, usually piezoelectricity. This is a highly efficient method of generating ultrasound, but it requires a fluid couplant to mechanically transfer ultrasound into and out of the component. The EMAT technique uses electromagnetic acoustic interaction for elastic wave generation. An inductive element close to the metal surface induces a mechanical disturbance in the metal, which produces the ultrasonic wave. In electromagnetic acoustic generation, the electromagnetic conversion takes place directly within the eddy current skin depth; therefore, no mechanical coupling with the component is needed. The metal surface of the component is its own transducer and the reception of the reflected signal is accomplished in a reciprocal way.

The advantages of the EMAT technique are:

- It is a nondestructive method.
- The speed is very high, and automated systems are possible.
- It is well suited for large area scans.
- It is good for limited access areas, where couplant application would be difficult.
- Errors due to couplant variation are eliminated.
- No surface contact is required; therefore, minimal surface preparation is required. Uniform scale layers do not have to be removed.
- The degree of reproducibility is high.
- Available special wave modes include surface waves, vertically polarized shear waves, and horizontally polarized shear waves.
- It is the only feasible ultrasonic examination method in areas where fluid couplant is prohibited to prevent component contamination.

The disadvantages of the EMAT technique are:

- There is a very high insertion loss (as much as 50 dB) compared to conventional ultrasonic examination.
- The high insertion loss makes instrumentation design critical—EMATs receivers are specially designed, expensive units.
- A substantial power supply is required and the cabling from the power supply to the probe defines the limits of the inspection area.

The EMATs technique has been used to map boiler tube thickness in areas subjected to corrosion and/or erosion.

Equipment for performing an EMAT examination includes:

- A probe containing an electromagnet, separate transmit and receive radio frequency (RF) coils, and an integral RF pulser and receiver preamp
- A sophisticated data acquisition module containing the display, keyboard input, and signal processing electronics
- A powerful power supply linked to the probe via cables

Most utilities rely on consultants and equipment vendors to perform EMAT examinations because of the specialized and expensive equipment required. Utilities can arrange for insulation removal or opening of the unit before the examination. It is also important that sufficient power be supplied to the nearest opening adjacent to the area to be examined.

8.1.11 Related Literature for Ultrasonic Examination

Guidelines for Advanced Ultrasonic Examination of Seam-Welded High Energy Piping. EPRI, Palo Alto, CA: 2000. 1000564.

J. Landrum and M. Dennis, "Ultrasonic Examination of Seam-Welded High Energy Piping Using Linear Phased Array Techniques," *Proceedings*, 2nd International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, New Orleans, LA (October 2000).

AEA Technology Engineering Services, Inc., *Technical Specification AEAT-TS-003 - High Energy Piping Examinations*, Revision 2, July 1999.

Evaluation of Phased Array Techniques for Application to Seam-Welded High Energy Piping Examinations. EPRI, Palo Alto, CA: 1998. GC-110142.

Guidelines for the Evaluation of Seam-Welded High Energy Piping: An Executive Summary of Current Approaches. EPRI, Palo Alto, CA: 1998. TR-111380.

G. Selby, "Development of Phased Array Ultrasonic Examination Applications at the EPRI NDE Center," *Proceedings*, 6th International Conference on Nuclear Engineering, San Diego, CA (May 1998).

AEA Sonomatic, *MINUTOFD Time-of-Flight Diffraction (TOFD) Ultrasonic Inspection of Welds – Operational and Software License Manual*, Version 1, Issue 1, April 1998.

AEA Technology, *TOFD Course for Level I and II Personnel*, Revision 03, March 1998.

NDE Guidelines for Fossil Power Plants. EPRI, Palo Alto, CA: 1997. TR-108450.

Procedure for Phased Array Ultrasonic Examination of Boiling Water Reactor Core Shroud Welds. EPRI, Palo Alto, CA: 1997. GC-108070.

Guidelines for the Evaluation of Seam-Welded High Energy Piping. EPRI, Palo Alto, CA: 1996. TR-104631.

G. Nakoneczny, D. Schlader, D. Stevens, and R. Tilley. "Field Experience and Performance Summary Using the EPRI EMAT-Based Gaging System for Boiler Tubing," *Proceedings of 1996 Fossil Plant Maintenance Conference*, Baltimore, MD (July 1996). EPRI, Palo Alto, CA. TR-106753.

AEA Sonomatic, *Microplus Operational and Software License Manual*, Version 2, Issue 2, September 1996.

"Standard Practice for Ultrasonic Examination using Electromagnetic Acoustic Transducer (EMAT) Techniques," ASTM Standard E1816-96, July 1996.

"Standard Guide for Electromagnetic Acoustic Transducers (EMATs)," ASTM Standard E1774-95, February 1996.

D. M. Schlader, D. T. Maclauchlan, R. M. Tilley, G. Blais, and P. S. Chang, "EPRI Portable EMATs Wall Thickness Measurement System," in *4th Conference on Fossil Plant Inspections*, San Antonio, TX, January 18–20, 1994, EPRI, Palo Alto, CA: 1994.

British Standard BS 7706, "Guide to Calibration and Setting-up of the Ultrasonic Time-of-Flight Diffraction (TOFD) Technique for the Detection, Location, and Sizing of Flaws." 1993.

European Standard prEN 583-6, "TOFD Technique as a Method for Defect Detection and Sizing."

8.2 Radiography

8.2.1 Introduction

Radiography (X ray or gamma ray) has been a primary weld examination technique for many years. This technique passes gamma radiation through the component and records the exiting backside radiation by either photographic or electronic means. The radiation may be produced either by a radioactive source (gamma) or by an X-ray machine. Radioactive sources commonly use the radioisotope iridium-192 for activity up to 100 curies (3.7×10^{12} disintegrations per second), and cobalt-60 for higher activity levels. X-ray machines produce radiation by

bombarding a metallic target with fast electrons in a vacuum. Whether an X-ray machine or a radioactive source is appropriate for a particular examination depends on a number of factors:

- X-ray machines produce a directional radiation field that is concentrated in a smaller area. This may reduce the peripheral shielding and safety requirements associated with the examination, as well as limiting the size of the area that is examined.
- X-ray machines of sufficient power to examine large, thick-walled components are usually stationary or are often expensive to transport. Normally, material handling equipment associated with the X-ray machine is used to rotate or otherwise move the component to allow a complete examination. A common example is a circumferential weld in a header during fabrication. To examine this weld using an X-ray machine, the header would be rotated. The stationary X-ray machine makes successive readings through the rotating weld until the entire weld has been examined.
- Radioactive sources (iridium-192, cobalt-60) produce an omnidirectional radiation field that must be limited by careful design of the source container and/or the use of auxiliary shielding. Generally, safety requirements such as area evacuation during the examination may be more restrictive for use of isotopes versus X-ray machines.
- The omnidirectional radiation field provided by a radioactive source can be used to examine large areas quickly. A common example is examining a circumferential weld in a header. The source can be placed at the center of the header, and the outside of the circumferential weld can be wrapped with radiographic film or a digital detector can be rotated around the header. If the source is then triggered, the entire weld is examined at the same time.

The advantages of radiography are:

- It is a nondestructive method.
- A permanent film or digital record of each examination is available for archiving and later review.
- Radiography is the ASME Code-approved method for examining numerous types of welds.

The disadvantages of radiography are:

- There are significant safety requirements. The test procedure must protect personnel from radiation exposure, and radioactive sources must be handled properly by qualified personnel.
- It is nonquantitative; flaws cannot be located (depth) or sized precisely.
- Results for components with complicated, nonuniform section thickness can be difficult to interpret.

8.2.2 Applications

Generally, radiography is used to examine welds. The most common use in power plants is for examining original construction or repair welds. It is ideal for detecting rounded or cylindrically shaped flaws, such as porosity or slag inclusion, common to welds. The resolution of radiography is determined by use of a penetrometer or quality indicator, which is an object usually taped to the area to be radiographed and which contains manufactured indications of varying depths and diameters. When the radiographic film is developed (or the digital image viewed), the penetrometer indications are visible, indicating the resolution.

8.2.3 Equipment

Equipment for performing radiography includes either an X-ray machine or a radioactive source that is of sufficient strength to penetrate the object to be radiographed. Flaws are revealed by differences in density of the developed film. Lighter areas are indicative of internal flaws, such as tungsten inclusions, that absorb more of the source energy, and darker areas are indicative of porosity or other flaws that do not absorb as much energy as the surrounding metal.

8.2.4 Examination

Radiography usually requires no special surface preparation and creates a permanent record of the examination—two reasons why it is still popular. Many ASME Code welds require radiography, even if other techniques are used in conjunction with it. The utility must provide access to both sides of the component to be examined so that film can be taped to the back side of the component or a digital detector can be positioned, and sufficient space is required for the radiographic source on the opposite side. The special requirements for radiography pertain mostly to safety requirements because personnel must be excluded from the area where the radiographic exposure is taking place.

Radiography may also be required for detection of weld flaws that have a planar or cracklike shape, such as incomplete penetration, incomplete fusion, or cracking. Unless these planar flaws have significant width and the source and film are oriented across and parallel to the height of the flaw, radiographic images may not detect them. If planar flaws are anticipated to be an issue, the use of angle-beam ultrasonic examination is often preferable to radiography.

8.2.5 Recent Advances

Recent advances in radiographic examination methods have included development of high-energy portable X-ray machines, direct digital detectors, and techniques for reduced personnel exclusion zones. These advances have provided the ability to examine complex geometries that were previously considered to be not examinable, and have reduced the impact on plant outage schedules. They also have provided a more economical alternative to either mitigating damage or performing advanced ultrasonic examination.

8.2.5.1 High-Energy Portable X-Ray Machines

New X-ray machines are available that are powered by batteries, creating a system that is easily transportable to remote locations. The new devices also produce smaller focal spot size and allow examination of a greater thickness range with only one setup than do radioactive isotopes. Additionally, the strength of the X-ray machines can result in shorter exposure times for many applications.

8.2.5.2 Direct Digital Detectors

Historically, radiographic film was used for radiography. In recent years, the advent of phosphor plates eliminated the need for film, removing the need for chemicals used during the development process and allowing for digital storage of the images of examined components. More recently, direct digital detectors have evolved that provide a real-time or near-real-time image of the component being examined. Advantages realized via digital detectors include real-time viewing of the data, a significant increase in examination latitude, the ability to interrogate or confirm component geometry without the need for additional radiographic exposures, and the ability to manipulate the detector during the examination, eliminating the need for multiple setups.

8.2.5.3 Techniques for Reduced Exclusion Zones

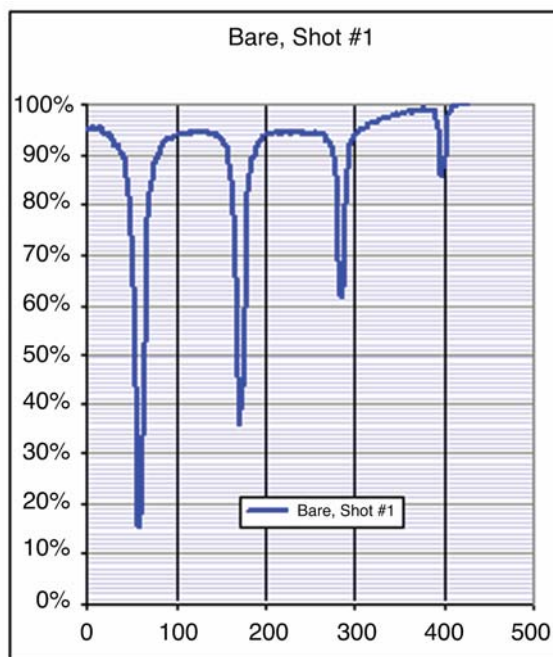
With digital detectors providing up to 10 times the sensitivity of radiographic film and the ability to collimate the radiation beam, personnel exclusion zones are being reduced to an area of only 10–20 feet (3–6 meters) rather than large areas that could include entire buildings.

8.2.5.4 Advances in Crack Depth Sizing

Technology now exists whereby the gray-scale data from either digital radiography, phosphor plate radiography, or digitized radiographic film can be used to make a plot of the resulting remaining ligament beneath a crack along with measurements of crack depth. Figure 8-34 shows such data for a bare tube calibration standard.

Thickness 0.255 in.
Notch Depth 80% (0.204 in.)
60% (0.153 in.)
40% (0.102 in.)
20% (0.051 in.)

V-Shaped EDM Notches
0.063 in. Electrode
With 6-Degree Taper Each Side



1 in. = 25.4 mm

Figure 8-34
Graph Showing Measured Ligament Beneath Calibration Notches

Note that the graph in Figure 8-34 shows the deepest notch (80%) on the left, and the measured remaining ligament is about 16%. It was found that the accuracy of this technology is on the order of 5% of the wall thickness for these tubes.

8.2.6 Related Literature for Radiography

ASME Boiler and Pressure Vessel Code, Section V, Current Edition.

NDE Guidelines for Fossil Power Plants. EPRI, Palo Alto, CA: 1997. TR-108450.

Radiographic Image Storage and Restoration. EPRI, Palo Alto, CA: 1995. TR-104044.

Improvement of a Portable High-Energy Radiographic Inspection System. EPRI, Palo Alto, CA: 1987. NP-4848.

Assessment of Thick Section Radiography. EPRI, Palo Alto, CA: 1977. NP-461.

8.3 Low-Frequency Electromagnetic Technique

8.3.1 Background

The low-frequency electromagnetic technique (LFET) for conductive tubing is beginning to receive recognition as an examination technique for ferrous tubing. LFET was originally applied to storage tank and pipe wall thickness evaluations. The technique has been adapted for use from the outside surface of HRSG finned tubing for detection of both outside surface and inside surface flaws. Prior to the application of LFET, traditional eddy current examination was unable to achieve adequate sensitivity and penetration to satisfy most ferrous tubing through-wall examinations.

8.3.2 Concept

In its original form, LFET involves exciting a transmitter coil or driver with a relatively low frequency of 10–100 Hz while monitoring the magnetic field with a detached receiver coil or sensor, as shown in Figure 8-35. The sensor is placed directly underneath the driver in such a way that the sensor is within the magnetic field induced by the driver.

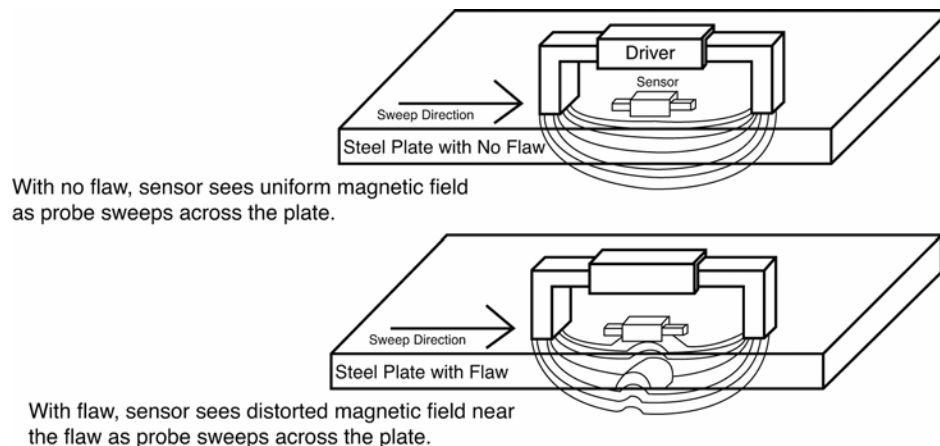


Figure 8-35
Principles of LFET

8.3.3 Application and Limitations

LFET has an emerging presence in the HRSG examination industry and has proven to be a valuable NDE technology for detection of inside and outside surface cracks and pits in finned HRSG tubing. Currently, the primary application is for detection of both circumferential and axial cracks, as well as pitting, in carbon steel heat exchanger tubing examinations. Figures 8-36 and 8-37 show an LFET sensor being used for HRSG finned tubing examination.

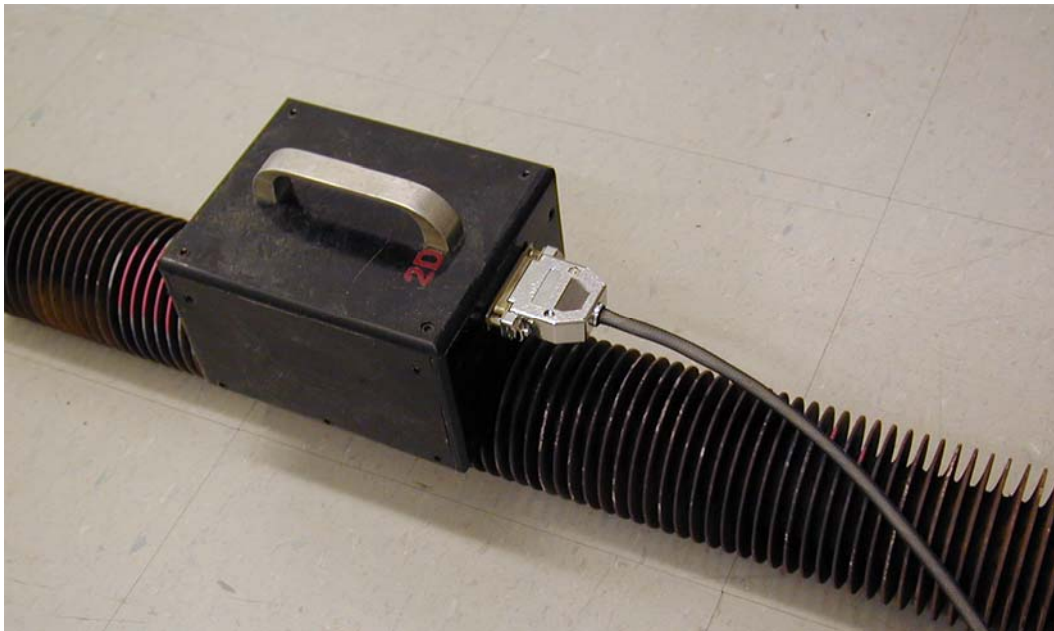


Figure 8-36
LFET Sensor Applied for HRSG Tubing

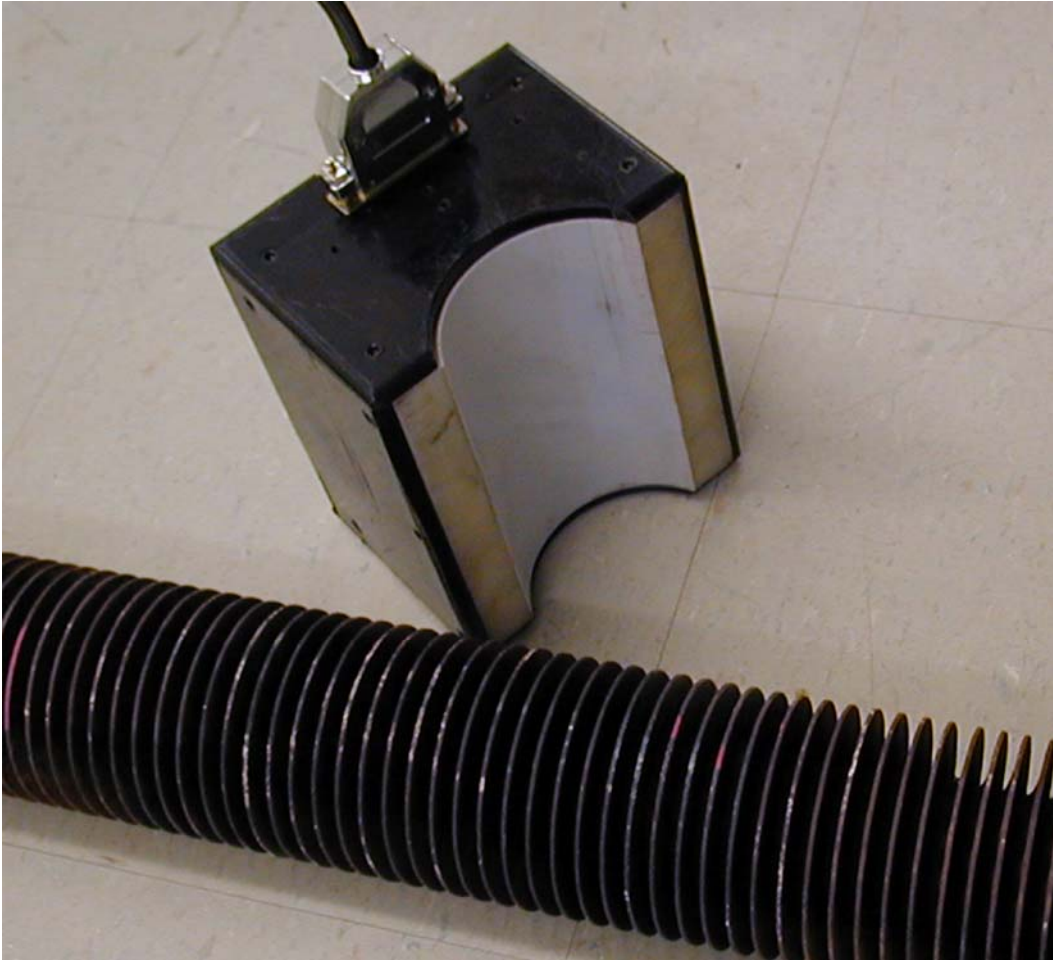
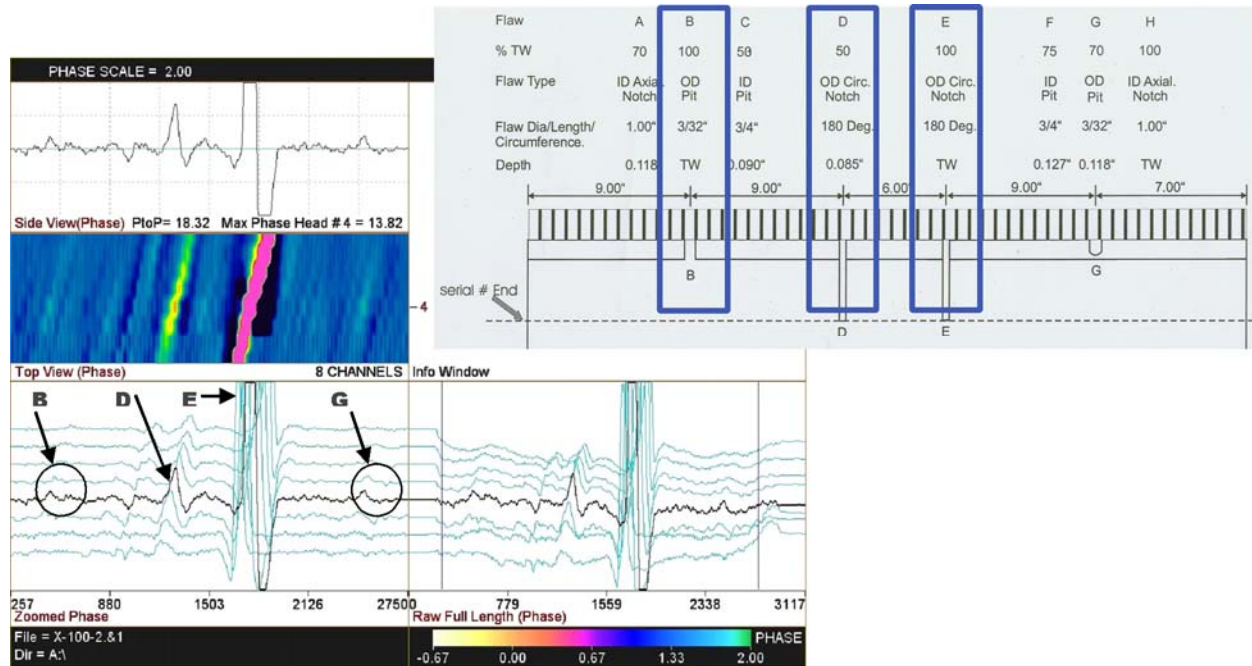


Figure 8-37
LFET Sensor for HRSG Tubing

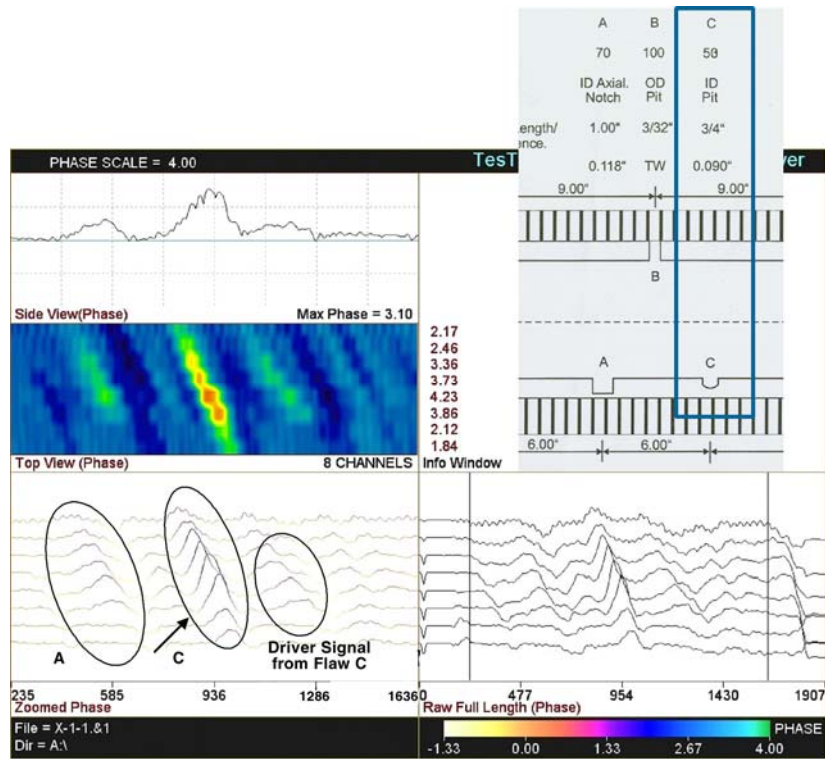
LFET is a good screening tool. When appropriately applied, it is sensitive to both horizontal and vertical flaw orientations. Flaw detection is dependent upon the wall loss volume, rather than flaw depth, so flaw sizing is not currently performed with this technology. Scanning allows for a C-scan plot of the examined areas by indicating the presence or absence of tubing flaws. Figure 8-38 shows an example involving detection of flaws (labeled B, D, E, and G) consisting of outside surface pits and circumferential notches. Each flaw was readily detected.



1 in. = 25.4 mm

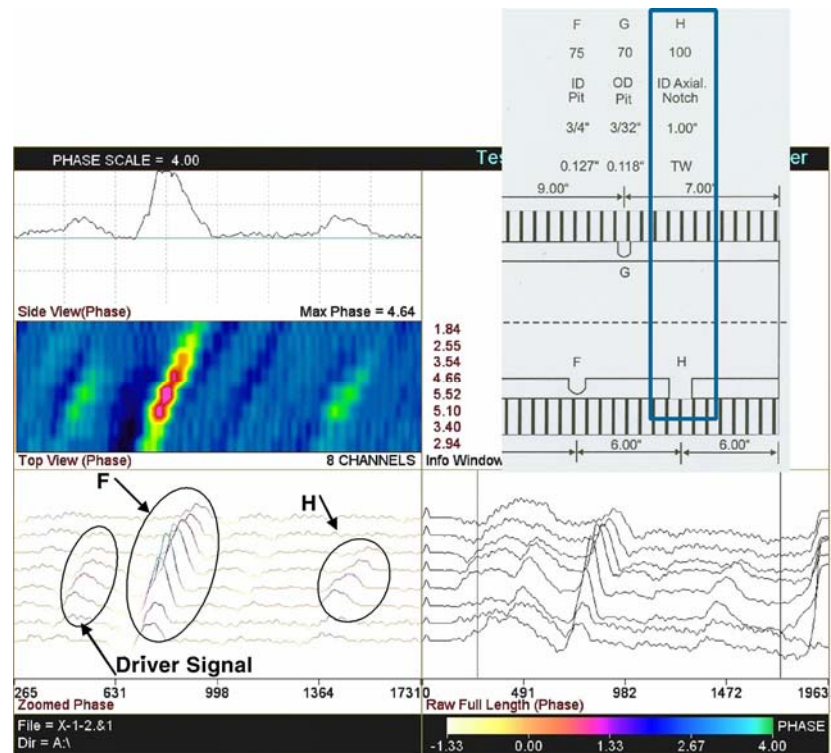
Figure 8-38
Example LFET Application—Detection of Outside Surface Flaws

Figures 8-39 and 8-40 show the LFET being applied for detection of inside surface pits and axial notches (flaws labeled A, C, F, and H). Again, both types of flaws were readily detected.



1 in. = 25.4 mm

Figure 8-39
Example LFET Application—Detection of Inside Surface Flaws



1 in. = 25.4 mm

Figure 8-40
Additional Example LFET Application—Detection of Inside Surface Flaws

8.3.4 Related Literature for Low-Frequency Electromagnetic Technique

K. Krzywosz, “Electromagnetic NDE Techniques for Condition Assessment of HRSG,” Boiler Tube and HRSG Tube Failures and Inspections International Conference. San Diego, CA (November 2004).

9

MATERIAL CHARACTERIZATION

This section discusses methods for material characterization. Covered topics include alloy identification, replication, portable hardness testing, etchants, miniature sampling, small punch testing, and stress measurement.

9.1 Alloy Identification

9.1.1 Introduction

The practice of alloy identification is important to many aspects of HRSG assessment programs. With time, documentation of materials of construction may be lost, necessitating alloy identification for use in engineering analyses, development of repair procedures, or planning for component upgrades and replacements. In addition, accidental substitution of materials occurs and can have catastrophic results in critical applications if a lower grade of material is mistakenly substituted for the specified material. The field identification and/or verification of the materials of construction for HRSG components consists of various techniques that can be used *in situ*.

The three primary identification methods are:

- Manufacturer's identification
- Qualitative alloy identification
- Quantitative alloy identification

The manufacturer's identification method relies on the use of documentation and physical markings on components to identify or verify the materials of construction. Qualitative techniques include analysis of materials through tests other than chemical analysis. Quantitative identification is performed through the use of *in situ* chemical analysis. Most field methods are nondestructive so that the removal of a material sample is unnecessary; however, a minimum amount of surface preparation is required.

9.1.2 Manufacturer's Identification

Manufacturer's identification relies on the use of documentation and/or physical markings on the actual components. In general, manufacturers provide material certifications with critical components. These certifications include Certificates of Heat Analysis (or *mill certs*), which provide a chemical analysis of an ingot or billet that was used as the starting point in the

fabrication of a component, and Certificates of Product Analysis, which provide a chemical analysis of the actual component after fabrication. It must be noted that material specifications contained in material lists, design drawings, owner's manuals, and so on should not be used interchangeably with certificates of analysis. Furthermore, the use of manufacturer's identification necessitates an absolute correlation of the analysis certificate with the actual component. This correlation is typically carried out through the use of physical markings.

The physical identification of materials includes the use of symbols or markings that provide a code to the material identification of a component. These symbols or markings include foundry marks embossed on the exterior of castings, color coding or stenciling of new materials, and stampings or embossing on forged components. Foundry markings on castings can provide information on:

- American Society for Testing and Materials (ASTM) grade
- Foundry name or logo
- Heat number
- Alloy type

Additional information such as design pressure and temperature rating may also be included. Similar information on ASTM grade, forge shop name, heat number, and design pressure and temperature ratings may be found in the stampings on forged components.

When foundry or forging markings are not identifiable or are questionable, *in situ* alloy identification using qualitative or quantitative methods is used.

9.1.3 Qualitative Alloy Identification

As previously mentioned, qualitative techniques include analysis of materials through tests other than chemical analysis. These methods use the physical properties of the material in the identification process and include the following:

- Metal color
- Magnetic behavior
- Density measurements
- Spark testing
- Chemical spot testing
- Thermoelectric testing
- Metallographic examinations
- Optical emission spectroscopy

The use of metal color is a method to sort different alloy groups that exhibit unique color differences (such as dark yellow bronzes, reddish coppers, or silvery white aluminums), but not to sort alloys within a group.

Magnetic behavior can be used in the simple test of separating magnetic materials from nonmagnetic materials or through more sophisticated eddy current-based alloy identification techniques.

9.1.4 Quantitative Alloy Identification

Quantitative field techniques sort and identify material by actual chemical analysis of the component at one or more locations. Although *in situ* chemical analysis techniques do not typically analyze for all elements present in a material, they are usually comprehensive enough to identify unknown materials and provide certain compositional data with a high degree of accuracy. These techniques are based on X-ray fluorescence spectroscopy (XRF).

In XRF an X-ray beam impinging on the surface of an unknown material causes the surface atoms of specific chemical elements in the material to emit fluorescent X-rays. The fluorescent X-rays have unique energy levels and wavelengths that are characteristic of the specific chemical elements in the unknown material. These characteristic X-rays are passed through detectors to measure either the energy level or the wavelengths. Typically, the measurements are analyzed by a microprocessor that compares the percentages of the chemical elements present in the unknown material to preprogrammed compositions of specific alloys. The instrument then identifies the alloy if the measured composition matches a preprogrammed alloy and displays the percentages of the measured elements.

Many instruments used in this method of alloy identification are very portable for field applications and provide quantitative analysis results in an efficient and timely manner. In addition, a range of instruments exists. The selection of which one to use depends on time constraints, number of elements to be analyzed, and precision required from the measurements. In general, the accuracy of measurements is dependent on the specific instrument and the surface conditions at the test location.

Typically, some degree of surface preparation is required for the effective use of these instruments. Specifically, a test location must be selected that is representative of the bulk of the component, because the fluorescent X-rays are obtained from only a comparatively thin layer of the material. Also, the test area should be sufficiently large for the particular instrument. Surface curvature and irregularities should be minimized, and all extraneous surface materials (scale, oxide, deposits, coatings, paints, oils, or greases) must be removed. In addition, the surface finish must be controlled through the use of grinding unless the test location is a finished or machined surface.

9.2 Replication

9.2.1 Introduction

Replication is an NDE method for the reproduction of surface topography from a component. The examination of replicas using either an optical microscope or a scanning electron microscope (SEM) is useful in the evaluation and characterization of surface features. Replication can be performed using a wide range of materials and procedures, depending on the features to be reproduced and evaluated. The replication method that is most commonly referred to is the reproduction of microstructural features using metallurgical replication; however, casting replicas are also commonly used in the assessment of component condition.

9.2.2 Casting Replication

Quantitative assessment of surface features is a necessary step in the evaluation of numerous damage mechanisms. Silicon rubber or acetate castings (replicas) can be taken from surfaces for the laboratory examination of features associated with erosion, corrosion, dimensional changes, and cracking. In addition, castings can be sectioned to provide direct measurements of feature dimensions. However, it must be realized that the dimensional accuracy retained in a casting replica is highly dependent on the replication material used, on the curing times and temperatures, and on local environmental factors.

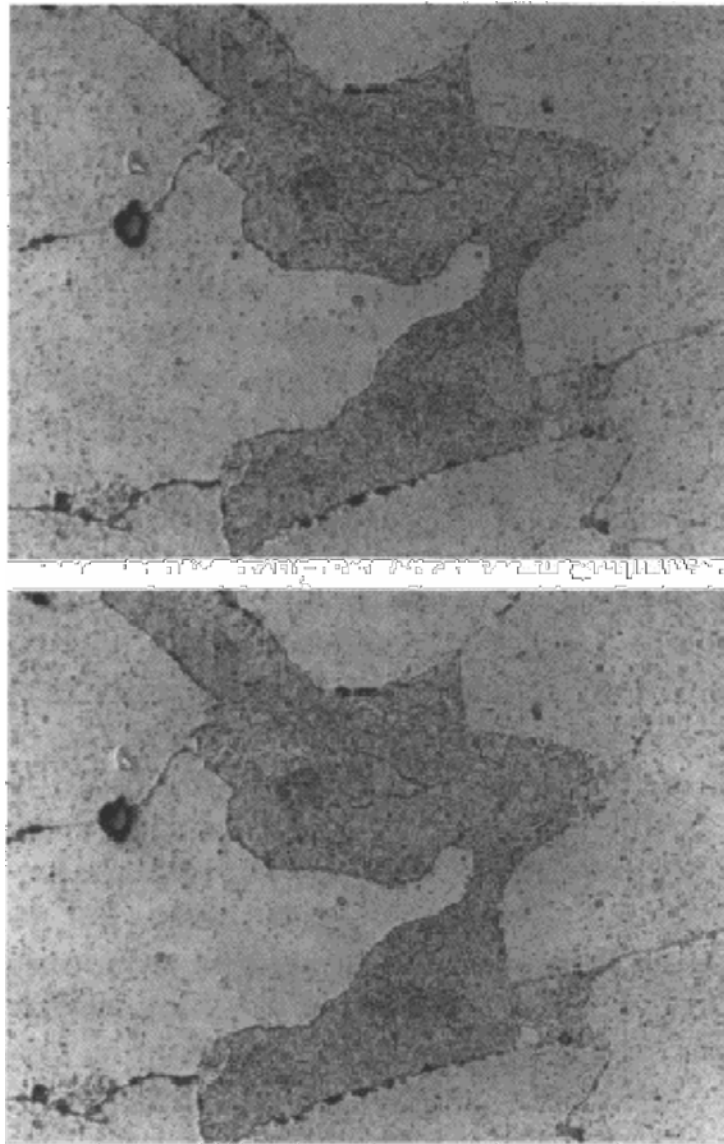
Casting replication is also routinely used as an effective method for the removal and preservation of surface deposits and/or contaminants for subsequent chemical analysis and identification. In addition, these replicas provide archival evidence of the dimensions and morphology of a surface condition or feature against which future results can be compared to establish specific rates of change.

9.2.3 Metallurgical Replication

Metallurgical replication is a field-implemented technique that allows for NDE of material microstructure and metallurgical condition and is the most commonly used form of replication in the condition assessment of fossil power plant components. In lieu of replicas, a metallurgical evaluation of material condition or identification of a damage mechanism requires the removal of material samples from a component, submittal of the samples to a metallurgical laboratory, preparation and analysis of the sample, and repair of the sampled location, all tasks that require significant time and expense to complete. Metallurgical replication allows for the metallurgical analysis of large numbers of locations in a timely manner without the requirement for repair, provided that the examination surface is accessible.

Metallurgical replication is performed following standard metallographic techniques used in a laboratory; however, replication is performed *in situ* on the component under examination. Specifically, portable equipment is used for the grinding stages to prepare the surface for subsequent polishing. As with grinding, polishing is carried out in progressively finer steps to remove scratches and the deformed surface layer that can interfere with detailed microstructural

interpretation. After polishing is completed, the surface is etched with a suitable etchant solution to reveal the microstructural features of interest. When the preparations are complete, a thin piece of acetate film is moistened in acetone and applied to the prepared surface. The acetate will conform to the surface, “duplicating” the surface features (although in reverse), as shown schematically in Figure 9-1. When the acetate film is dry, it is removed from the component and placed on a slide for analysis using a standard metallograph or portable microscope. If proper procedures are followed, replicas can be produced that can be interpreted using optical microscopes with up to 1000X magnification or SEMs with up to 5000X magnification.



Creep-cavitation damage in a cracked tee section of a desuperheater inlet header, shown by conventional metallography (above) and plastic replication (below).

Figure 9-1
Examples of Conventional Metallography and Plastic Replication

The characterization of microstructures, with emphasis on identifying fabrication history (forging, casting, welded construction), heat treatment (annealed, as-fabricated), and typical structures (decarburization, quenched structures, spheroidization, graphitization) can be carried out on-site with the use of replication. Characterization can also include the separation and identification of benign fabrication-induced flaws (laminations, forging laps, slag, porosity, liquation cracking) from deleterious service-induced damage.

Service-induced damage mechanisms include:

- Spheroidization
- Graphitization
- Creep
- Fatigue (mechanical or thermal)
- Hydrogen cracking
- Stress corrosion cracking
- Corrosion

Each mechanism can be identified so that only the appropriate remedial actions are undertaken, to minimize unnecessary maintenance efforts.

Metallurgical replication is used extensively for the evaluation of microstructural degradation (such as thermal softening, spheroidization, precipitation, graphitization, and decarburization) that occurs due to long-term exposure to elevated temperatures. It must be realized that these changes can affect critical properties (such as creep ductility and strength) of the material and thus affect the service life. These microstructural changes, once observed, can affect the material properties selected in subsequent analytical assessments. Therefore, replication can provide assistance in the selection of critical material properties in the analytical prediction of crack growth or remaining life.

An example of microstructural degradation (graphitization) detected by replication in a C-1/2 Mo steel component is shown in Figure 9-2. This replica was subsequently evaluated using quantitative image analysis to determine the volume fraction of graphite nodules in the material, as well as key shape factors. These quantitative measurements became the baseline against which future replica results could be compared to establish component-specific degradation rates.

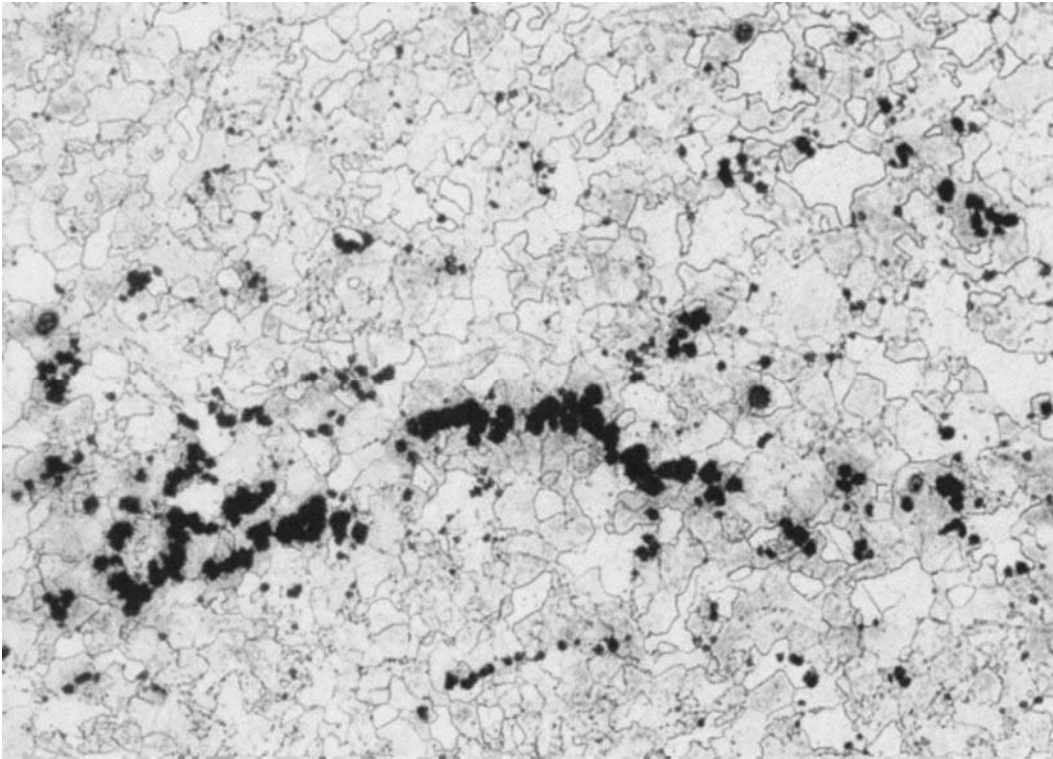


Figure 9-2
Graphitization in C-Mo Steel [9-1]

Historically, the most important use for metallurgical replication in the fossil power industry has been in the assessment and prediction of useful life for components subject to creep damage. Specifically, creep is a progressive damage mechanism that begins as isolated grain boundary cavities. As damage progresses, the density of cavities increases until microcracks form. Microcrack development is then followed by macrocrack formation and propagation. Creep damage detected through replication can be described using qualitative or quantitative approaches.

9.3 Portable Hardness Testing

Hardness is defined as the resistance of a metal to indentation, scratching, cutting, and so on. When hardness is measured by pressing a very hard ball or diamond point into the metal under restrained conditions, the depth of penetration can be correlated with the material tensile strength. This process is conducted with hardness testing machines or equipment, such as Equotip, Rockwell, or Brinell testers.

Portable hardness testers come in many varieties and are very useful as NDE tools because they can indicate hard or soft spots in components, which can be indicative of component damage. Estimates of the hardness of boiler tubes can be of assistance in remaining life calculations.

Hardness traverses across welds and can indicate whether the weld has been stress relieved. Due to its low cost, simplicity, and rapid data acquisition, this technique has many applications in a plant NDE program.

Some of the portable testers are sensitive to the orientation and mass of the component being evaluated. These factors must be carefully considered during the calibration phase of hardness testing. Measurements made on thin-walled tubing may be difficult to make using rebound-type hardness testers.

9.4 Etchants

9.4.1 Introduction

Chemical etchants, typically acidic, are used to reveal metallurgical features of metallic components. The use of etchants permits the examination of the metal microscopic features (grain boundaries, phases, carbide structure, and so on) and the identification of macroscopic features such as weld, defect, and repair locations.

9.4.2 Component Application

Metallurgical etching can be used to detect weld seam locations on piping, and to detect locations of weld repairs in turbine casings or valve castings, if they have been ground smooth. Etching is also applied when characterizing metallurgical properties, such as assessing the effects of elevated-temperature service. Etching can be performed in the field or laboratory and under a wide variety of conditions.

9.4.3 Application Methods

To reveal microscopic features, the area of interest is polished using sequentially finer grits until a mirror-like surface results. Final polish is achieved using 1 micron paste. Generally, only rough polishing (240 or 320 grit) is required to effectively reveal macroscopic features. Following polishing, a specific etchant is applied for a short period of time, during which the surface dulls in appearance. Dwell times can range from a few seconds to several minutes, and become increasingly shorter with higher component temperatures. Etchant selection and concentration is based on the alloy composition and microstructural feature to be examined. For carbon and low-alloy steels, such as 2 1/4 Cr -1 Mo, solutions of nitric acid (Nital) and picric acid (Picral) are commonly used for microscopic work, whereas high-concentration solutions (50%) of hydrochloric acid are used for macroscopic examination. Most stainless steels can be etched using hydrochloric and picric acids (Vilella's reagent) or hydrochloric acid and copper chloride (Kalling's reagent).

9.4.4 Implementation

Studying the microstructural characteristics of a component requires that direct access be gained in the field, or that a sample be delivered for laboratory examination. Good lighting is essential, and electrical connections should be available to operate polishing equipment or microscopes, if required. Etching does not require power hookups, unless an electrolytic etching technique is used. Ideally, component temperature should be at or near ambient during the etching procedure. The small quantities of chemicals used during the procedure generally do not require any special safety requirements, although safety should be considered during planning phases. The mixing and handling of chemicals should be performed only by experienced personnel.

9.5 Miniature Sampling and Small Punch Testing

9.5.1 Introduction

The safe and economical continued operation of HRSGs requires assessment of critical operating components. Typically, these assessments are performed through NDE for the detection and characterization of damage. Engineering analyses are carried out subsequent to the examinations, to evaluate the effects of damage on the future operation of the component. In addition to information about the type and degree of damage, provided by NDE and operating conditions, these analyses often require key material properties as inputs to the analyses for refinement of the life predictions.

Although approaches exist that can alleviate the need for material testing (that is, probabilistic risk-based analysis) the most reliable method involves determining component specific properties. Numerous material properties may be required for the evaluation of operating plant components that can only be quantified from material testing programs. Conventional physical testing programs require representative material to be removed from the subject component and subjected to testing. Historically, a significant amount of material would have to be removed for the production of test specimens to determine many of the properties of interest (such as yield, tensile, and creep strength or fracture properties). The removal of large sections from critical components is not always technically or economically feasible because of the extent of postsampling repair or restoration required. Therefore, techniques have been developed for the testing of miniature samples that are provided from “nondestructive” miniature sampling systems.

9.5.2 Miniature Sampling

The metallurgical evaluation of critical components can be performed in a number of ways, including direct evaluation with portable microscopes or metallurgical replication; examination by electromagnetic, ultrasonic, or hardness methods; and removal of material samples and subsequent laboratory testing. This last method not only allows for the metallurgical evaluation of the material condition, but also for determination of properties to be used in analytical analyses. Material removal to obtain samples can be performed by “boat” sampling, plug

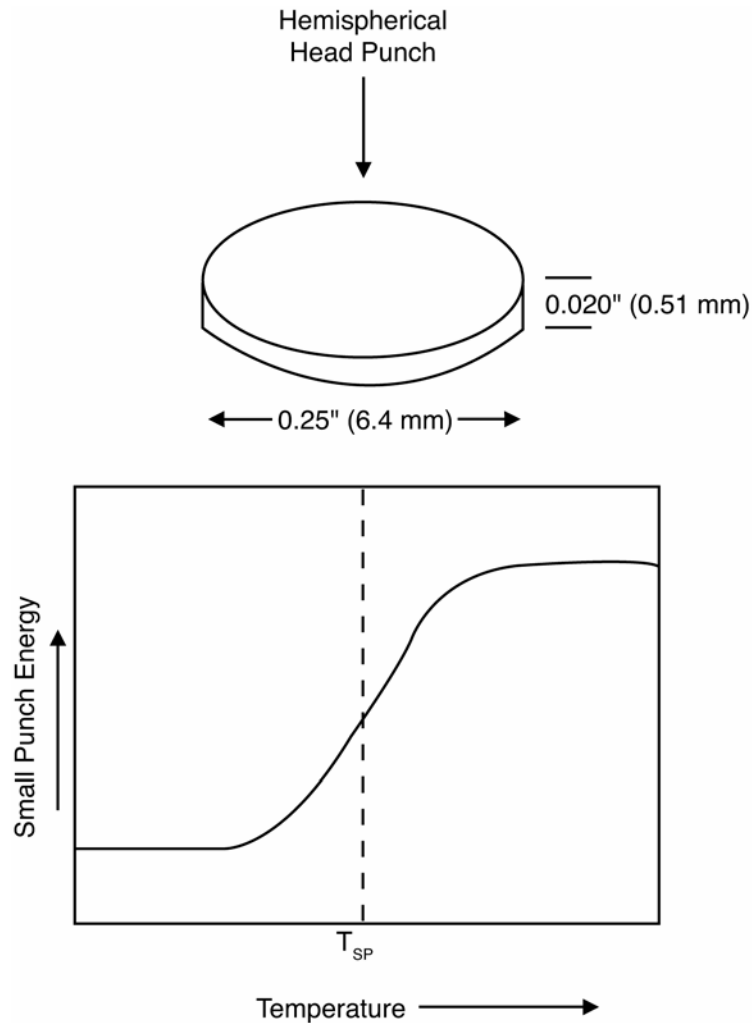
removal, component sectioning, and/or miniature sampling. Boat sampling, plug removal, and component sectioning can all produce a significant amount of material for testing; however, each method can also require significant repair or restoration efforts. In addition, some component configurations are not easily sampled by conventional methods. Therefore, miniature sampling methods have been developed for the removal of small material specimens without requiring postsampling repair.

Several miniature sampling methods exist, including specially designed abrasive cutters, saws, and electrical discharge machining. Regardless of the method, the process must remove the required amount of material from a specific location without introducing thermal or mechanical damage into the component remaining in service or into the material sample, as the damage could affect subsequent testing results. In addition, these methods should not alter the sampled component to the extent that repair welding or additional restoration is required.

Miniature samples removed from critical components can be evaluated by chemical analysis, metallurgical evaluation, and physical testing. Chemical analysis can be performed to identify the material of construction, to quantitatively evaluate composition, or to identify contaminants. Metallurgical analyses are carried out to assess fabrication history, to assess microstructural condition, or to identify damage mechanisms in root cause evaluations. Physical testing is performed to determine current properties or to assess degradation of the material. Due to the limited size of samples, small punch testing techniques have been developed and applied to the determination of tensile, yield, and fracture toughness properties.

9.5.3 Small Punch Testing

Information regarding tensile, yield, and fracture toughness properties is required for fracture mechanics-based component assessment. Direct measurement of these properties allows for component-specific estimates without the conservative dependency on published databases or probabilistic treatments. However, large sample removal can have a significant economic impact; therefore, small punch testing techniques have been developed for the determination of tensile, yield, and fracture toughness properties using samples removed by miniature sampling methods. Specifically, small punch testing (as shown in Figure 9-3) has been demonstrated and routinely used for estimation of uniaxial stress-strain behavior, fracture appearance transition temperature (FATT), and fracture toughness (J_{IC} or K_{IC}). Most notably, the method has been applied to components susceptible to in-service temper embrittlement.

**Figure 9-3****Small Punch Testing**

Source: R. Viswanathan, *Damage Mechanisms and Life Assessment of High Temperature Components*, ASM International, Metals Park, Ohio 44073.

9.6 Stress Measurement

9.6.1 Introduction

The need to measure stresses in metallic components is well recognized, because the rate of growth of flaws, and hence the lifetime of the component, depends on the internal stress levels. Many defect assessment codes now take stresses into account when evaluating tolerable flaw sizes.

There are several traditional methods of measuring stresses, but they are either expensive, slow, or partially destructive to the component being measured. Hole drilling and ring coring are the standard methods used on site because of their portability and ease of application. However, the

spatial resolution is low and the effort required to perform a full stress survey is prohibitive in most cases. X-ray diffraction is a direct and quick method but only measures the stresses in the surface itself, to a depth of approximately 0.01 mm (0.4 mil), whereas neutron diffraction can probe up to 50 mm (2 in.) into steel but requires the component to be brought to the neutron source.

It is possible to infer stress indirectly by measuring material properties that depend on stress. These include ultrasonic and magnetic methods. Their advantage lies in the fact that the probes and sensors can be made to be relatively small so that most parts of a plant are accessible. Furthermore, the techniques are truly nondestructive.

9.6.2 The Ultrasonic Method for Stress Measurement

Stress causes the average bond length between iron atoms to either compress or extend, therefore changing the macroscopic elastic constants, and hence affecting the ultrasonic velocities. Consequently, a measurement of the transit time of a pulse of ultrasonic energy through a defined region of a component can be used to calculate the stress in that part. The disadvantage of the ultrasonic method of stress measurement is its inaccuracy, even when standards are available, unless the standards are of the same size and shape as the components.

9.6.3 The Magnetic Method for Stress Measurement

Introduction. For structural steels and a wide range of other ferromagnetic materials, the presence of stress in the material changes its magnetic domain structure through the effect known as magnetostriction. This causes the domains to expand, contract or reorient themselves along their magnetization axis under the effect of an external applied stress. For materials with a positive magnetostriction such as steel, a tensile stress will cause the domains that are magnetized in directions closest to that of the applied stress to grow at the expense of their neighbors that are magnetized in other directions. This rearrangement reduces the elastic energy, and the lost energy can, in principle, be detected by an appropriate probe. Magnetic properties such as permeability, coercivity, remanence, and hysteresis are intimately related to domain sizes and orientations, so a measurement of such properties can be used to infer the stress state.

The total stress may consist of both applied and residual components. Applied stress refers to elastic stress caused by in-service loads. Residual stress may result from manufacturing processes (such as rolling, forging, welding, cutting, or finishing), from heat treatments (such as quenching, carburizing, or nitriding), from repair procedures such as grinding, or from in-service loads that exceed the elastic limit of the material. For nonisotropic stress fields, there is an angular variation in magnetic properties that can be used to further refine the results.

A variety of examination methods are based on the relationship between stress in a component and the corresponding change in magnetic properties. Generally, an alternating magnetic field is applied and the magnetic response of the component is recorded. Variations of the magnetic hysteresis technique use the shape of the function curve of the component magnetic response,

and/or the time delay between the applied field and the component response, to determine stress. Three main techniques can be used to infer the stress state: Barkhausen emission, magnetoacoustic emission, and stress-induced magnetic anisotropy.

Barkhausen Emission. The Barkhausen emission (BE) technique uses small jumps in the function curve of the magnetic response in an alternating magnetic field to determine residual stress in the component. These jumps result from the magnetic domains in the material realigning themselves, and they can be detected by a small pancake coil located between the poles of a C-core magnet. The AC excitation means that measurements are limited to a depth of penetration typically 0.25 mm (10 mils) below the surface—that is, only surface stress states are measured. Material properties other than stress, for example microstructure such as the presence of inclusions, can also influence the BE signal, so this technique requires well-characterized calibration samples. BE has been used in HRSGs to identify “high stress” locations in piping, headers, and tubing. This comparative method is far less reliant on detailed calibrations.

Magnetoacoustic Emission. Magnetoacoustic emission (MAE) signals originate when domain walls move through 90 degrees, causing an ultrasonic shear wave to be generated. This ultrasonic wave is detected by a small piezoelectric transducer to produce the output signal. However, as the stress increases, the signal reduces. This is because domain walls that have a magnetization parallel to the stress axis are energetically favored over those perpendicular to it, so fewer domains are available to rotate and produce a signal. An advantage of MAE is that the depth of measurement can be around 12 mm (0.5 in.), making this technique potentially more useful if deeper stresses are of concern.

Stress-Induced Magnetic Anisotropy. The stress-induced magnetic anisotropy (SMA) technique goes a step further by measuring the angular variation in magnetic properties and using it to calculate the principle stresses in the component. An SMA probe consists of two C-cores at right angles to each other and an inducing magnet. The whole assembly is rotated to perform a series of angular measurements.

All three techniques can give the directions of the principal stress axes of a biaxial stress field. BE and MAE can give the directions to about 10 degrees and SMA can give the directions to within a few degrees.

BE and SMA signals are related to the differences in the magnitudes of the two principal stresses—that is, they give relative stress levels, not absolute magnitudes. MAE signals, on the other hand, depend on the squared magnitude of the orthogonal stresses, and therefore the technique does not say whether they are compressive or tensile. In other words, MAE measures the absolute magnitude of the stress in the applied field direction. Absolute stress can be measured to around 1.5 ksi (10 MPa) in low-alloy steels, and to around 3 ksi (20 MPa) for a full range of biaxial stresses.

As a result of the individual limitations described above, two techniques are required to measure the sign, magnitude, and orientation of a general biaxial stress field. Commercial magnetic stress measuring systems have been available since the early 1990s and are gaining industry acceptance.

9.6.4 Applications

Stresses due to manufacturing processes can be evaluated before components are installed. This may help prevent premature failure by serving to screen out components that have high levels of residual stress from improper manufacturing procedures. BE has been used in HRSGs during commissioning for this purpose. It is also useful for confirming that desired compressive residual stresses are achieved by processes such as shot-peening, carburizing, and quenching.

Installation procedures may be monitored by determining the stresses in the component after installation. If excessive stress is indicated after installation (welding, and so on) then the installation procedure can be modified, and/or stress relief can be applied to the component.

Service stresses can be determined for pipelines and power plant components. These can be used to validate the original design analysis, or they can be used in root cause investigations to determine the mechanism for premature failures.

9.6.5 Advantages and Disadvantages

The advantages of magnetic stress measuring methods are:

- They are a nondestructive method; there is no need to drill holes or mount rosettes.
- Minimal or no surface preparation is required.
- They are quick to apply—typically, less than a minute is required for each stress measurement.
- The equipment is portable, and the probe is handheld, permitting access to most areas of a power plant.
- Stress monitoring is possible *in situ* under plant operational conditions.
- They are applicable to a wide range of ferromagnetic materials (including ferritic steels and nickel alloys).

The disadvantages of magnetic stress measuring methods are:

- They are generally surface or slightly subsurface techniques (however, this is the critical stress location for most components).
- Multiple readings are needed to achieve quantitative results.
- Most magnetic techniques have a limited range of applicability (they are not good for very low or very high stress levels).
- They cannot be used on nonferromagnetic materials.

9.6.6 Required Equipment

Equipment for conducting a magnetic stress measurement includes:

- A probe that contains a small magnetic yoke to apply an alternating magnetic field to the component, and a coil (or coils) to measure inductance, flux linkage, coercivity, and various other magnetic properties. A magnetoacoustic emission probe also contains a piezoelectric crystal.
- A computer and associated software to record the probe output, analyze the signal, and display usable results.

9.7 Reference and Related Literature

Reference

- 9-1. *Steam: Its Generation and Use*. Babcock & Wilcox, Barberton, OH. Most recent edition published in 2005.

Related Literature

NDE Guidelines for Fossil Power Plants. EPRI, Palo Alto, CA: 1997. TR-108450.

D. J. Buttle, C. B. Scruby, G. A. D. Briggs, and J. P. Jakubovics, "The Measurement of Stress in Steels of Varying Microstructure by Magnetoacoustic and Barkhausen Emission," *Proc. R. Soc. Lond.* A414, 1987, pp. 469–497.

D. J. Buttle, G. A. D. Briggs, J. P. Jakubovics, E. A. Little, and C. B. Scruby. "Magnetoacoustic and Barkhausen Emission in Ferromagnetic Materials," *Phil. Trans. R. Soc. Lond.* A320, 1986, pp. 363–378.

10

OXIDE AND WALL THICKNESS MEASUREMENT TECHNIQUES

NDE techniques for measuring oxide and wall thickness are covered in this section. The discussion includes ultrasonic techniques and pulsed eddy current testing.

10.1 Ultrasonic Oxide Measurements

Ultrasonic-based NDE techniques have been used for more than 25 years to measure the steam-side scale and thickness of tubes and headers in conventional boilers and are equally effective on HRSG plants when access is not a problem. Steam-side oxides form on common (ferritic) boiler pressure parts at a very predictable rate. Two-layered steam-side scales are expected for all ferritic materials. The dividing line between the two layers is approximately at the original metal surface. The rate of growth is usually a linear function of the temperature at the interface between the inner vessel wall and the passing steam. As the steam temperature changes, the oxide growth rate also changes and remains essentially linear up to the wustite (FeO) formation temperature (1058°F [570°C] for carbon steel). The addition of chromium and molybdenum to carbon steel suppresses the penetrating diffusion of oxygen and reduces the steam-side scale formation rate. This behavior has been summarized for 1–3% chromium steels using relationships such as:

$$\text{Log OX} = 0.00022 \text{ LMP} - 7.25$$

Where:

OX = the oxide thickness in mils

LMP = the Larson-Miller Parameter = $T(20 + \log t)$

T = temperature in degrees R ($F + 460$)

t = time of exposure

When the steam-side scale thickness has been determined, the tube metal temperature can be calculated. Continued scale growth, wall thinning, and increasing tube metal temperature can then be forecast into the future and combined with the operating pressure-induced stress and the material stress rupture properties to predict remaining creep life.

10.1.1 Applications

Ultrasonic examination techniques have been perfected to allow for the nondestructive measurement of steam-side oxides as thin as 0.002 in. (0.051 mm) to an accuracy of ± 0.001 in. (0.025 mm) or better. If we consider an HRSG tube that has operated at 1000°F (538°C) for 10,000 operating hours, the expected internal oxide thickness is 2.9 mils (0.074 mm). Similarly, an adjacent tube operating for the same 10,000 hours in a steam environment at 1050°F (566°C) will have grown an internal oxide 5.3 mils (0.135 mm) thick.

Internal oxide thickness becomes important because long-term overheating, internal scale exfoliation, and constrained thermal growth are all mechanisms that can cause deterioration of HRSG tubes. Variations in scale thickness across a tube bundle can also occur due to differences in flue gas and steam flow characteristics, which make certain rows or elements hotter or cooler than others. For example, steam entering a header through tubes directly below the transfer pipe finds an easier flow path than steam in tubes located between pipes. As a result, less steam can be expected to flow in tubes located farther from the nozzles, which causes these tubes to operate at a higher temperature.

The best way to determine the significance of these temperature variations would be by nondestructive measurement of the internal oxide thickness contained in each tube at a location upstream of the header after a period of operation of at least 10,000–20,000 operating hours. This can be used to calculate the average temperature of each of the individual tube circuits and help to identify regions of concern. The variation of calculated temperatures can also be used to estimate the magnitude of constrained thermal stresses at tube-to-header welds and to help in fatigue life predictions.

After the hot tube circuits have been identified, additional measurements can be made along the circuit length. These additional measurements may require the removal of tube fins at selected locations so that measurements can be made. Alternatively, techniques exist whereby the results of measurements made on bare tubing can be extrapolated into the finned tubing at various locations within the bundle.

10.1.2 Ultrasonic Equipment for Oxide Measurements

Recent ultrasonic methodology uses sophisticated equipment to determine the metal/oxide interface in addition to the oxide/air interface determined by more traditional ultrasonic equipment. Standard ultrasonic thickness measurements send the ultrasonic signal into the contact surface and measure the time required for the signal to reflect back to the origin. The resultant time of flight is converted to the tube wall thickness by multiplying by the ultrasonic velocity of the tube material. The measurement of internal scale thickness, in addition to tube wall thickness, is an improvement over the standard measurement in that it locates the tube metal/oxide interface. The speed of sound through the steam-side scale multiplied by the time it takes the signal to pass through the scale yields the internal oxide thickness. The combined measures of internal oxide and tube wall thickness provide temperature and stress inputs, which are then used in creep life calculations to predict the tube remaining life.

10.2 Pulsed Eddy Current Technology

Pulsed eddy current technology is showing promise for measuring pipe wall thicknesses without the need to remove the thermal insulation first. This provides the opportunity to perform examinations while the plant is on load when it may be more convenient logistically, and also reduces or eliminates the costs of insulation removal and reinstatement.

Conventional eddy current testing generally uses a single high-frequency excitation to examine the near surface of a component. Pulsed eddy current, on the other hand, uses a burst of low-frequency excitation. The progress of the generated currents, and their reciprocal effect on the probe coil, are measured as a function of time. In this way, changes in the decay of the interaction can be converted into measurements of the thickness of the component.

10.2.1 Implementation

A handheld probe containing the generating and receiving coils is held over the spot to be measured, as shown in Figure 10-1, which shows that there is insulation between the probe and the pipe being examined. This probe may be quite large compared to typical ultrasonic or eddy current probes, measuring several inches in each dimension (100–200 mm per side), so only sections of pipe that are relatively unobstructed can be measured.



Figure 10-1
Pulsed Eddy Current Examination Through Insulation

The size of the area that is being examined depends primarily on the distance between the probe and the outside surface of the pipe, that is, on the stand-off due to the insulation. Different probes have been designed for different thicknesses of insulation, but each results in an examination area that is 1–2 in. (25–50 mm) in diameter. The measurement is therefore a composite reading of all the thicknesses in this area. Consequently, the technique can find general thinning but not isolated effects such as pits. With advanced signal interpretation, an estimate of the minimum wall thickness within the evaluated volume is also provided, although its precise location within the region will be determined using conventional or high-temperature ultrasonic methods.

Each measurement takes 5–10 seconds to acquire, so the probe cannot cover large lengths of pipe quickly. Therefore, the approach is used selectively and systematically. It can be applied in zones where wastage is expected either because of similarities with zones in other parts of the plant where wastage has been identified or because of wastage found in units that operate identically. It can also be applied to specific zones in response to predictions from computer codes such as EPRI's CHECUP™ that ranks components relative to their susceptibility to flow-accelerated corrosion.

Trials to date have shown that the technique is capable of measuring wall thicknesses through as much as 4 in. (100 mm) of insulation and 25 mils (0.6 mm) of aluminum cladding.

10.2.2 Applications

The prime use for the pulsed eddy current technique is to measure wall thickness reductions due to flow-accelerated corrosion. In this case, the metal loss is on the inner surface of the pipe, but the technique works equally well when the wastage is on the outer surface. The technique can therefore also be used to find corrosion under insulation.

10.2.3 Related Literature for Pulsed Eddy Current Examination

NDE Guidelines for Fossil Power Plants. EPRI, Palo Alto, CA: 1997. TR-108450.

C. R. Brett and J. A. de Radd, "Validation of a pulsed eddy current system for measuring wall thinning through insulation." *Proceedings of Nondestructive Evaluation of Utilities and Pipelines*, Scottsdale, AZ (December 1996), SPIE, Volume 2947, pp. 211–222.

11

REMOTE NDE TECHNIQUES

This section provides an overview of infrared thermography (IRT) fundamentals and applications. Transient infrared thermography, in which a temporary temperature change is induced in the component being inspected, is also discussed.

11.1 Remote Methods: Infrared Thermography

11.1.1 Introduction

Infrared thermography is a technology that has been extremely useful in power plant preventive maintenance programs for the detection of specific abnormal conditions that manifest themselves through a temperature change at a viewable surface. This temperature change may be due to a change in the amount of heat produced in the component, due to a change in the amount of heat being conducted through the component, or due to the amount of heat reflected from the component. Infrared thermography instruments detect infrared radiation (IR) and convert the information to a visual presentation that can be easily interpreted by a trained operator.

11.1.2 Fundamentals

Any object at a temperature above absolute zero emits radiation in the infrared band of the electromagnetic spectrum. The amount of IR emitted is a function of the temperature of the object, with increased temperature producing increased IR emission. In simple terms, an IR detector is a device that detects IR and produces an output voltage that varies as a function of the IR energy. By scanning a component, an equivalent voltage can be produced for each resolution area of the scanned region.

Modern IR cameras for-real time imaging of IR data operate according to one of two principles. Both utilize special camera lenses that are similar (in terms of lens optics) to normal photographic lenses, except they pass radiation in the IR bandwidth rather than visible light. These lenses are made of exotic materials such as germanium.

One of the two IR operating principles involves the use of rotating prisms and/or oscillating mirrors to focus the IR detected from each resolution area within the field of the lens onto a single detector. The converted voltage is then color-coded and displayed on a television monitor such that its position in the display is correlated to its position within the field of the lens. The scan is performed at high speed, with each resolution area sequentially displayed, to produce a television quality image.

In the second means of imaging, the single detector is replaced with a two-dimensional detector array, and the mechanical scanning prisms and mirrors are eliminated. In this case, each detector detects and displays a unique resolution area within the field of the lens.

In either case, the image may be produced in colors, where color is representative of IR level, or in gray tones (black and white). In the former, the colors are generally assigned using a spectral palette in which low IR values are assigned “cool” colors starting with deep blue, and high IR values are assigned the “hot” colors, progressing through green, orange, red, and magenta to white. In black and white displays, white is used for high IR value and black is used for low values, with gray tones used for intermediate values. Normally, the instrument can be adjusted to maximize resolution, that is, to use the entire palette over the range of IR values presented.

To some degree, IR value can be correlated to temperature, although the accuracy of temperature measurement is affected by other variables in addition to component temperature. The IR value detected for a specific point within the field is a function of the IR that is emitted, any IR that is reflected from that point from other components, and any IR that is transmitted through the component at that point. Consequently, transmitted and reflected IR can lead to significant error. In addition, emitted IR is a function of the emittance of the surface, which is further a function of the material and surface conditions, including surface finish, color, and so on.

As a result, accurate absolute temperature measurements can be difficult to achieve. However, relative readings from one point to another on the same component or on similar components can be reasonably accurate, as can measurements made on the same component at different points in time. For this reason, IRT can be very useful for sorting similar or identical components viewed under similar conditions and for time-dependent changes (trend analysis) on a given component.

One simple means of improving absolute temperature measurement accuracy is to apply a nonreflective coating to the various surfaces. This minimizes the reflected component of measured IR and provides a more uniform emittance. Flat black paint is ideal; however, application of paint is often not practical. The developer used for liquid penetrant examination, which is a dull, powdery material that can be purchased in aerosol cans and which can be removed easily, has proven effective.

11.1.3 Applications

IRT surveys of numerous components in the power station can be conducted quickly and conveniently by merely working through the plant systematically and viewing the various components. This method of implementing IRT can be extremely effective for the detection of general conditions that produce characteristic IR profiles and that exhibit steady-state change when a change occurs.

In general, however, such techniques are not adequate for the detection of many innocuous “flaws” that are not obvious under steady-state conditions. In such cases, it may be necessary to introduce a thermal transient and observe the component under transient conditions. Examples include the detection of wall thinning in tubes and pipes. If observed during a transient event—

such as the introduction of heated fluid into the tubing or piping—small faults can often be detected. Once steady-state conditions are reached, the local effects of small faults can be overcome by general heating, therefore making them undetectable.

11.2 Remote Methods: Transient Infrared Thermography

11.2.1 Introduction

Transient infrared thermography is used to detect subsurface flaws and conditions. The technique uses much the same equipment as passive IRT (IRT that does not induce a heat change), but the key difference is that with transient IRT a temperature change is temporarily induced in the component being inspected. The applied disturbance will cause heat to flow in order to restore thermal equilibrium. However, the presence of a flaw will change the heat flow patterns when compared to an unflawed region of the component. Consequently a thermal imaging camera can be used to observe the different heat flow patterns and hence detect the flaw.

The component can be either heated or cooled, and the heating or cooling can be applied by the examiner or by changing the plant conditions. Flaws generally appear as isolated hot or cold spots in the thermal image. They last for a short period of time after the transient pulse before they fade away as equilibrium is restored.

This technique has also been used as a rapid way to find thin regions in tubing.

11.2.2 Advantages and Disadvantages

Thermal imaging cameras are supplied with a range of lenses having different fields of view so the area in the image can be quite large. If the camera is pointed at any object, then all points are imaged simultaneously. Consequently, when a transient thermal event is applied to the entire imaged area, then the whole area is being examined at the same time. This parallel property means that a transient IRT examination can examine large areas in a short time, rather than requiring a slow, point-by-point, process.

The main disadvantage of transient IRT is that the cost of thermal imaging equipment is still relatively high and each new type of inspection configuration needs to be appraised to determine the minimum detectable flaw prior to application.

11.2.3 Basic Theory

When a component is in a steady state condition, the surface temperature distribution is constant (by definition) so if it is viewed with a thermal imaging camera, only the surface is observed. Major subsurface features can have an effect on this surface distribution if they conduct heat to another region (for example, external supports can sometimes be observed when thermally imaging the inside walls of a duct), but in general, smaller subsurface features and flaws will be undetectable.

If, however, the thermal equilibrium is disturbed, then heat flows will be produced to set up a new temperature distribution. It is these heat flows that provide information on subsurface defects, because the heat flow in a defective region is quite different from that in a good region. If the surface of a component is viewed using a thermal imaging camera and a heating source is applied to the surface, then removed, the thermal image will change, and defective regions will show up as a difference in the rate at which equilibrium is restored. In other words, local hot or cold spots will appear at the location of a defect, then fade away. This concept is sketched in Figure 11-1.

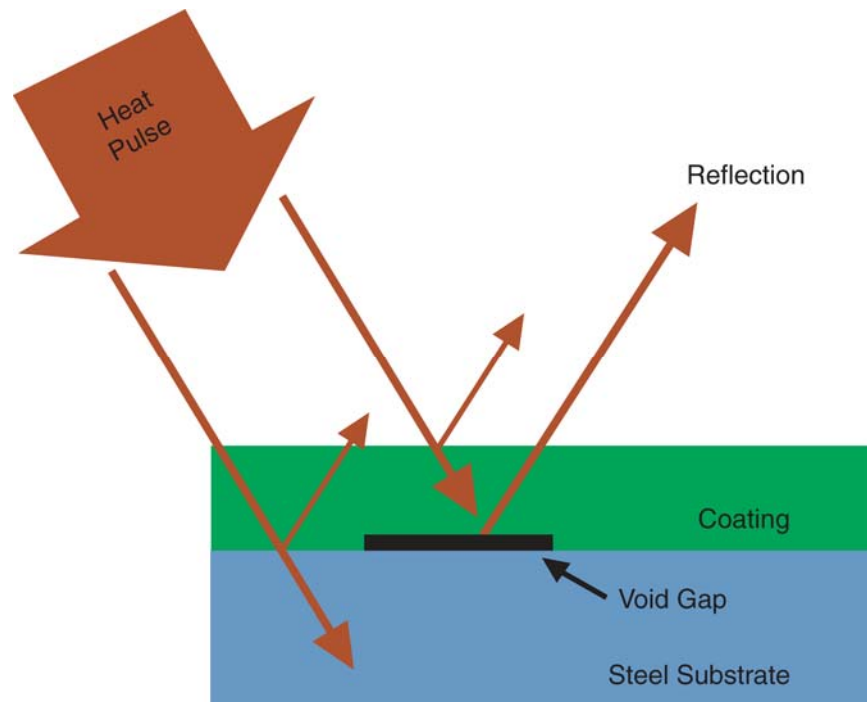


Figure 11-1
The Concept of Transient Thermography

The overall time for the transient process is dependent on the thermal diffusivity (a quantity involving heat capacity, thermal conductivity, and density).

11.2.4 Implementation

Transient conditions most often involve a heat cycle, although they can involve a cooling cycle in certain instances. Transients can be deliberately imposed, as in the case of flushing heated liquid through pipes and tubes during maintenance outages. Transients can also occur naturally, during startup or shutdown of certain systems that can be observed safely during the transient events. In certain instances, this form of transient thermography can be effective for the detection of material discontinuities such as cracks, pits, internal voids, and so on, or the detection of gross fluid flow imbalances or blockages.

A photographer's flashlamp produces a very intense and brief pulse of energy. This source has been used to examine plasma spray coatings that are applied to the crowns of waterwall tubes in conventional fossil-fueled units to protect them from excessive wastage. In this case, the coating is usually a nickel-chrome alloy about 0.6 mm (25 mils) thick, and the thermal transient lasts a few tenths of a second. Flaws are predominantly found at areas of overlap between one run and the next, when spray equipment has been changed, and in cases where the pipe has not been sufficiently grit-blasted and degreased. Obviously, the heat input achievable with a remote flash source is very minimal; consequently, the infrared equipment must be sensitive to very minor changes in terms of its sensitivity and resolution.

For nonmetallic coatings and linings the process is slower, so some crude heating methods are possible—for example, a hot air blower such as a heat-shrink gun or hair drier. More uniform heating can be achieved using a large resistive heating element, and in plants where there are huge coated areas, this is a very effective means to examine complete ducts and towers. Despite its apparent crudity, the technique has successfully found small flaws, such as 40-mil (1-mm) diameter gas pores in the coating and trapped grit at the interface, as well as disbonds and holes. The effectiveness of an examination is determined primarily by the resolution of the thermal camera, not by the sophistication of the heat source. The duration of the thermal transient is several tens of seconds, allowing the examiner plenty of time to make camera adjustments while the examination is in progress. Examination rates of 10 m²/min (100 ft²/min) can be achieved.

One system that is still in the developmental stage uses a scanning infrared laser to produce the thermal input and an infrared detector to measure the response. The laser spot and detector are scanned over the curved surface of the blade under computer control.

11.2.5 Equipment

A high-resolution thermal imaging camera is required, along with some means of storing thermal images for later playback and analysis (usually a video cassette recorder although PC systems are taking over this role), and a means of producing the transient heating or cooling event.

11.2.6 Applications

A number of components in conventional fossil-fueled units have been examined using transient IRT. Successful applications to date include the following:

- Metallic
 - Examination of thermal barrier coatings on turbine blades
 - Examination of plasma spray coatings on tubes
 - Identification of underdeposit corrosion of tubes
 - Locating of fluid flow blockages

- Nonmetallic
 - Examination of epoxy resin and glass flake vinyl ester (GFVE) coatings used in flue gas desulfurization (FGD) plants
 - Examination of rubber linings such as those used in FGD towers
 - Examination of GFVE coatings on impeller blades
 - Examination of GFVE and other plastic coatings in water treatment plants
 - Examination of ceramic coatings on hydroelectric (Pelton) blades

To date, IRT has not been used for the examination of HRSG pressure parts. The presence of tube fins and tight tube spacings will undoubtedly be one of the challenges that make this technique difficult to apply.

11.2.7 Related Literature for Infrared Thermography

NDE Guidelines for Fossil Power Plants. EPRI, Palo Alto, CA: 1997. TR-108450.

“PowerGen Demonstrates Infrared Imaging for FGD Coating Inspection,” *EPRI Journal*, Sep/Oct 1996, p. 37.

Infrared Thermography: Predictive Maintenance Guidelines. EPRI, Palo Alto, CA. NP-6973.

Thermography Leak Detection Techniques Development. EPRI M&D Center Project RP 3485-15.

12

NDE CONSIDERATIONS DURING DESIGN, PREFABRICATION, AND SHOP FABRICATION

This section contains an overview of QC/QA to be performed during design review, prefabrication, and shop fabrication. (Section 2 of this report also contains some significant information about prefabrication and shop fabrication NDE requirements.)

12.1 Prevention of Potential Problems by Design Review

During the design process, many decisions are made that will have a bearing on the eventual development of damage to HRSG pressure parts. Many of these considerations have been detailed in the EPRI reports *Heat Recovery Steam Generator Tube Failure Manual* and *Delivering High Reliability Heat Recovery Steam Generators* [12-1, 12-2]. These considerations were based on failures and problems observed during operation. It should be emphasized that much can be done during design to reduce the incidence and extent of damage (that will need to be monitored and eventually repaired) and to ease the execution of future examination processes. Some summary comments are made here to indicate the types of issues that might be usefully considered during a design review in order to have a positive impact on how NDE is conducted:

- It is imperative that the design engineering be done by an experienced, knowledgeable organization.
- The purchaser must have, or must hire, personnel who are experienced and knowledgeable in HRSG design to review the proposed design for adequacy.
- Practical consideration should also be given to the fact that there is more than one way to accomplish a task and that just because something is different from prior designs it does not mean it is inferior.
- Design features that facilitate fabrication without compromise of requirements are good design.
- HRSGs are “boilers,” but because of the service in which they are used and the way in which they are cycled, traditional boiler design will often be insufficient. For example, consideration of the thermal stresses on the structure and joints due to heating and cooling must be included in the design.
- Fabrication considered during the design process may need to incorporate some more robust considerations. For example, some partial penetration welds may need to be made into full penetration; exceptions to post-weld heat treatment (PWHT), normally allowed in the applicable Code and generally adequate, may not be acceptable.

12.2 Prevention of Potential Flaws and Deficiencies Prior to Starting Fabrication

Another opportunity to lessen the burden on subsequent NDE programs occurs when the raw materials are accumulated prior to start of fabrication. Depending on the component, various flaws and deficiencies can be present in the raw material as received. The following remarks indicate some of the steps to be taken in this regard:

- A common problem can be the receipt of materials that are incorrectly labeled or marked, or material on which the identity is illegible—shops can mix material. Because of conservatism in the fabrication codes, a piece of 1 1/4 Cr or 2 1/4 Cr tubing used where 9 Cr is specified may very well last for a number of years of operation, but it is unlikely to achieve the life anticipated by the designer. This problem is usually detected through good receipt inspection and review of shipping documents and Certified Mill Test Reports (CMTRs). For critical materials (alloy steels), positive material identification (PMI) by use of equipment such as XRF is deemed necessary or prudent. Purchasing only from reliable vendors who have a demonstrated material identification and control program is the best preventive action.
- All dimensions/items delineated by the material specification should be checked. The minimum wall thickness is probably the most important to verify. The vendor, as part of ultrasonic flaw detection scanning, usually performs NDE thickness checks. Additional spot-checking with a micrometer during receipt inspection is prudent.
- Electric resistance welded tubing has unique potential problems. The weld seam should be examined with ultrasonic or eddy current testing for soundness in lieu of, or in addition to, hydrostatic testing. Another problem with electric resistance welded tubing is if the inside scarf that is trimmed at the point of welding is not removed as it should be and if the tubing is delivered with the scarf still inside of the tube, this can initiate in-service deposition and corrosion.
- For most fabricators, spiral finned tube is considered a raw material—a material that can yield product with various conditions that will affect performance. The most obvious example is lack of adequate bonding of the fin to the tube by the high-frequency resistance welding process. In June 1990, a consortium of manufacturers drafted a document titled International Standard for Dimensions, Tolerances, and Tests of High Frequency Resistance Welded Fins [12-3]. This standard includes requirements for the bare tube, weld fin dimension, and discoloration and rust. After the international specification was issued, some manufacturers have since issued in-house standards [12-4], which provide further clarification and modifications of selected items, such as supplementary (rather than mandatory) fin bond tensile strength testing. The international specification requires that the fins be bonded to the tube over 90% of its specified nominal width. This is usually determined by visual examination of a section of fin stripped from the tube. If there are differences of opinion on the amount of bond, the international specification requires that a tensile test be used to define the acceptability of the bond. The international standard requires that the bond have a fracture strength of a minimum of 25 ksi (172 MPa). Many users and fabricators have instituted higher strength levels, particularly for alloy tubing. Prior to developing a QC/QA plan, if it is important to review the purchase specification contract to determine which standard was required.

- Other spiral fin items that should be verified are fin height, fin thickness, fin pitch, twist, inclination, and corrugation at the root. These will all affect heat transfer and draft loss. According to the international standard and ASME B&PV Code Section I, this product, although made with alloy tubes (P4, P5A, or P5B), does not require post-weld heat treatment (PWHT) if certain criteria are met. The primary requirement is that the HAZ depth under the fin not infringe on the minimum wall thickness of the tube. Vendors must be able to give documented evidence of their testing program to verify this.

12.3 Prevention of Potential Flaws and Deficiencies During Fabrication (Construction)

12.3.1 Overview of Fabrication Issues and General Considerations

The fabrication operations that occur in manufacturing of an HRSG consist of:

1. Machining, burning, and grinding
2. Bending
3. Welding
4. Heat treating

Most fabrication nonconformances can be prevented by careful preparation, good execution, and timely visual and dimensional inspection.

Some general considerations for preventing nonconformances during fabrication are:

- Prior to the start of fabrication, a careful review of the manufacturer's system for control and its implementation is prudent.
- The first system to be reviewed should be the QC/QA system to be put in place. As part of the review of QC, the qualification of NDE technicians should be examined. Conformance to the applicable Code should be confirmed. Evaluation of tests and test procedures to be followed should be checked for adequacy and conformance to the applicable Code.

Additional specific guidance is contained in the sections that follow.

12.3.2 Machining, Flame Cutting, and Grinding

Most of the machining required in HRSG manufacture is in the preparation of components, mainly pipe or tube for welding. Oxyfuel, plasma, or other flame cutting methods and grinding are also used for weld preparation. The weld preparation dimensions must be met in these operations. A weld groove that has insufficient depth will not comply with the applicable Code or design requirement. A groove preparation that creates a knife-edge in lieu of the land specified

may cause the welder to produce weld nonconformances during the welding process. If the preparation is not of proper dimensions, the fit-up may result in gaps or root openings that are larger than good welding practice allows.

When flame cutting is used to create the weld preparation, the burned surface must be removed by grinding prior to welding. Inadequate cleanup will result in incomplete fusion and slag inclusions.

Deficiencies in these initial weld preparation operations can be found by good dimensional and visual inspection. Nonconformances cannot be practically (economically) remedied, and the part may have to be replaced. Adjustment of the process or the equipment and training of personnel will prevent the same problems from recurring on future components.

12.3.3 Bending

The bending that is used in HRSGs consists of tube and pipe bending and the straightening of pipe after warpage from welding.

Tube bending is not really addressed by the ASME Code, but it is generally controlled by the fabricator's practice developed over years of experience. The practice includes the minimum radius of cold bends, the minimum radius of hot bends, the minimum wall thickness that can be bent, and the roundness and wall thinning allowed.

Of greatest importance for the operational life of the component is the heat treatment, if any, that is required post-bending. Most materials and non-tight radius bends will not require heat treatment. Other materials, such as high alloys, will require a normalize-and-temper treatment after any degree of bending or a solution anneal in tightly bent stainless steel tubing to be used in the creep range. The bending parameters and subsequent heat treatment need to be carefully evaluated.

During bending, some bends are made "hot," which means that a band of tube on the inner radius of the bend is heated prior to bending. This allows the inside to compress during bending and minimizes the thinning on the outer radius of the bend. This type of bending can produce much tighter radius bends than cold bending. The temperature used for this bend is normally in the 1400–1700°F (760–927°C) range. In carbon and low-alloy steels, there is usually no detrimental effect on material. However, in high-alloy steels (such as 9 Cr material), the resulting structure can be very detrimental, and further heat treatments are often required. These usually consist of a full normalize-and-temper treatment prior to further processing. These treatments are also required after cold bending. During heat treatment, it is likely that heavy scaling of components will occur, which will reduce the wall thickness but usually not sufficiently to be a concern. Of greater concern is the removal of loose scale from the internal surfaces of components to prevent subsequent oxide exfoliation, resulting in solid particle erosion or pluggage of downstream components.

If the fabricator's bending parameters are followed, no nonconformances should result. Deviation from the approved bending parameters can result in:

- Cracked or failed tubes
- Bends that are too thin on the back side
- Bends that are unacceptably out of round
- Bends that have too little cross-sectional flow area

All of these potential problems can be found by examination of the bending process and dimensional inspection of the completed parts. As with machining, remediation is not usually possible, and the components must be scrapped. Adjustment of the process or the equipment and the training of personnel will prevent the same problems from recurring on future components.

Unique bending problems can occur with bending of seam-welded ferritic steel tubing. If the seam is bent on the tension (versus the compression) side of the bend, it may crack. Heating the bend area prior to bending can also prevent the cracking. The phenomenon is not necessarily caused by defective material but is inherent to some extent with this product form.

Straightening a warped or bowed tube by heat adjusting is a proven standard fabrication process. Procedures dictate the temperatures to be used and the type of equipment to be used. It does require a high level of skill and experience. In the hands of a novice and with the wrong kind of heating torch, melting or severe microstructural damage can occur; however, not allowing its use is impractical.

Straightening warpage in pipe is usually accomplished by three-point pressing and is performed cold. This is a very straightforward manufacturing process and almost never causes problems. The problems that can occur are flattening of the component, overstraightening, and (on high-alloy materials) cracking. Care in operation will prevent the first two of these potential problems. High alloys may require stress relief prior to any straightening operation.

Stress relief of components for straightening may be required. This is usually performed at or below the temperature of final PWHT and is no problem as long as it is of sufficient time and temperature to accomplish the softening required. The acceptable minimum and maximum temperature limits for stress relief will depend on the component alloy.

12.3.4 Welding

Fabrication of HRSGs will require the development, qualification, and execution of proper weld procedures. As a result, even though extensive references to the basics of weld procedures are available, a brief discussion of the following key issues is provided here:

- General welding issues
- Welder performance qualification and training
- Welding process controls

- Weld preparation
- Weld processes to be used
- Welding filler materials, shielding, and purging gases
- Preheat, maintenance of preheat, maximum interpass temperature, and interstage heat treatment
- Post-weld heat treatment (PWHT)

12.3.4.1 General Welding Issues

A written, qualified welding procedure is required for pressure boundary welding. For example, ASME Code Section IX covers procedure requirements. The welding procedure includes a welding procedure specification (WPS) and a procedure qualification record (PQR). The WPS provides a “recipe” to the welder or welding operator about both essential and nonessential weld parameters. The PQR lists the actual weld parameters used to weld appropriate test coupons and the results of required acceptance tests. More than one PQR may be required to qualify a single WPS.

Competent design and welding engineers should perform a thorough review of the weld detail design drawings. The WPSs and the PQRs that support them should be carefully reviewed for conformance to the Code to which they are qualified and for acceptability for the particular work in question. Procedures can easily conform to Code but not be acceptable for work.

12.3.4.2 Welder Performance Qualification and Training

Another area to be evaluated is the qualification of welders/welding operators. Their qualifications to the applicable Code should be verified. For critical welds or materials, special weld testing over and above the applicable Code, pertinent to the weld to be made, may be required and prudent.

12.3.4.3 Welding Process Controls

During the actual welding, auditing or checking of the welder’s progress is imperative. The welder’s qualifications should be rechecked, or at least audited, as the work progresses. Even with special testing and review of welder qualification lists, an unqualified welder may be inadvertently assigned. In most welds, the first pass is the most critical. Its size and appearance must be checked. The filler metals, the flux/gas being used, the preheat and maintenance of it, the amperage and voltage, and the adequacy of back purging are among the items that can easily and routinely be monitored. Additionally, the weld consumable control needs to be continuously monitored to prevent mixed consumables or damp rods from being used.

12.4.4.4 Weld Preparation

The weld preparations should be examined for depth, size, profile, and the correctness of the fit-up. Joints must conform to alignment and mismatch tolerances. If the parts are not in proper position dimensionally, they may pose a problem for later fitting and welding operations. If alignment or mismatch tolerances are not adhered to, the joint may not meet Code requirements and will not be acceptable. Nonconformances found (such as misalignment, excessive root gap, and/or the location and dimension of parts) should be corrected prior to the start of welding. In certain situations, proper fit-up may be impossible to achieve due to an error in the design drawings. If this is the case, the nonconformance should be reported and corrected by the design engineer.

12.3.4.5 Welding Processes

Welding processes to be used will be specified in the WPSs and the supporting PQRs. Common processes include gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), submerged arc weld (SAW) and flux cored arc welding (FCAW).

12.3.4.6 Welding Filler Materials, Shielding, and Purging Gases

Weld consumable control procedures must be evaluated. The use of incorrect filler metals may not be detected until a problem occurs in service. For example, low hydrogen electrodes that are not controlled can lead to hydrogen entrapment and its resulting embrittlement.

Purging or back purging means the creation of an inert atmosphere around the joint to be welded to prevent excessive oxidation or atmospheric contamination of the root pass. Back or root purging is accomplished by plugging the component close to the joint to minimize the amount of inert gas required and the time needed to achieve an acceptable purge. Methods of plugging vary widely; two in common use are “purge paper” (water soluble paper) and purge dams or seals. However the purge is implemented, it is critical that it is adequate prior to and throughout the first two or three passes of weld. An adequate purge must produce an oxygen content of less than 1%. This can be measured with an oxygen detector (“sniffer”). The time required to purge a large component may be measured in hours. The proof of the adequacy of a purge can be seen by visual and touch examination of the weld root after welding. If surface oxidation and contamination (“sugaring”) have occurred, they can generally be remedied by grinding.

12.3.4.7 Preheat, Interpass Temperature, and Interstage Temperature Requirements

After proper fit-up, the specified preheat temperature and the level of back purging on high-alloy materials must be implemented. The welder or welding operator is responsible for these operations; however, QC and/or supervisory checks for conformance are mandatory. Inadequacies in preheat and back purging must be corrected prior to the start of welding.

Preheat is given to weld joints to drive off any moisture and to give the material sufficient heat as necessary to slow down the cooling rate during welding in order to prevent or minimize the formation of undesirable microstructures and cracking in the HAZ. Preheating will also minimize hydrogen cracking. Required preheat and interpass temperatures should be included in the WPS.

Maintenance of preheat from the start until the completion of the joint can also be critical. On thin components of carbon or low-alloy steel, preheat maintenance is not usually necessary. On high-alloy steels and thicker components of low-alloy steel, it is the only prudent practice. This means that even if welding is not completed at the end of a shift and will not restart immediately, the preheat must be maintained. If the time gap in welding is to be extended, an “extended preheat” may be allowed. Another aspect of preheat maintenance is that the minimum preheat and maximum interpass temperature range should be kept narrow and allowed to fluctuate as little as possible when welding large-diameter thick nozzles into drums or other comparable components.

Immediately following the completion of welding, a post-weld bake-out may be utilized on alloy steel, particularly thick sections and high-alloy materials, prior to cooling from preheat temperature. It usually consists of raising the weld and surrounding area to temperature in the 600–700°F (315–371°C) range for 1 to 4 hours. Its primary purpose is to allow any hydrogen that may be trapped in the weldment to dissipate.

12.3.5 Post-Weld Heat Treatment

Most heat treatment required during fabrication and erection are those of the PWHT type described in this section. Other types that will be required will be those in, or necessitated by, bending (discussed in Section 12.4.3) and intermediate heat treatments (discussed in Section 12.4.4.7) given welds prior to final PWHT.

The PWHT procedures to be used should be reviewed for conformance to the applicable WPS and for adequacy of heating rates, temperature gradients, soak temperature range, and time. Assuming that the procedures for this operation have been reviewed and are deemed adequate, there are potential deficiencies in implementation that have to be dealt with. Other areas of concern in PWHT are:

- The arrangement of monitoring thermocouples or other devices.
- Ensuring that the weldment is properly supported so that no dead weight or system loads are present during PWHT.
- The necessity to ensure uniform heat treatment and prevent large temperature differentials in parts of components. For example, in some manufacturers’ PWHT of tube-to-header welds, a clamshell furnace is used with the tubes extending out of the furnace. The tubes, particularly finned tubes, can absorb heat along this length to such an extent that the tube-to-header weld may not see adequate PWHT. This can be evaluated by having thermocouples attached to the tubes or welds. It can be minimized by heating or insulating the tubes where they extend from the furnace.

- With high-alloy steels (9 Cr, for example), a proper PWHT is imperative. In the as-welded condition, the weld and HAZ both have extremely high hardness. The component will be susceptible to cracking of welds if moved; it is also susceptible to stress corrosion cracking. If the PWHT temperature is too low, the weld and HAZ will remain brittle. If it is too high, the material will lose the unique properties for which it is being used. In most heat treatments a $\pm 50^{\circ}\text{F}$ ($\pm 28^{\circ}\text{C}$) range is common. On these alloys a $\pm 25^{\circ}\text{F}$ ($\pm 14^{\circ}\text{C}$) range is often required. Also, as these alloys require PWHT of every weld, many local PWHTs will be required. All are critical. To determine the adequacy of PWHT, a hardness test is often imposed on either a sampling basis or a 100% basis. Readings found outside a recommended range indicate an inadequate PWHT and the need for remedial action, that is, re-heat treatment.
- For certain alloys, such as T91/P91, the weld region must be cooled to a prescribed temperature range (for example, below the martensitic transformation temperature and above the dew point) prior to heating to the PWHT temperature range.

12.4 Common Weld Flaws and Nonconformances; Post-Weld NDE

Since it is impossible to “inspect in quality,” the most important quality steps are those that occur prior to or during fabrication. In spite of this, it is also important to evaluate the weld region following welding to provide additional assurance that nothing “slipped through the cracks.”

Common weld flaws and defects can be generally classified into groups with similar features. International Standard ISO 6520-1 [12-5] provides a convenient listing of six main groups:

- **Cracks** – including crack, longitudinal crack, transverse crack, radiating cracks, crater crack, group of disconnected cracks, and branching cracks
- **Cavities** – including gas cavity (gas pore, uniformly distributed porosity, clustered [localized porosity], linear porosity, elongated cavity, worm-hole, surface pore), shrinkage cavity (interdendritic shrinkage, crater pipe, end crater pipe), and microshrinkage
- **Solid inclusions** – including slag inclusion, flux inclusion, oxide inclusion, and metallic inclusion
- **Lack of fusion and penetration** – including lack of fusion (incomplete fusion) and lack of penetration (incomplete penetration)
- **Imperfect shape and dimensions** – including imperfect shape, undercut, excess weld metal, excessive convexity, excess penetration, incorrect weld toe, overlap, linear misalignment, angular misalignment, sagging, burn-through, incompletely filled groove, excessive asymmetry of fillet weld (excessive unequal leg length), irregular width, irregular surface, root concavity, root porosity, poor restart, excessive distortion, and incorrect weld dimensions (thickness, width, throat)
- **Miscellaneous imperfections** – including stray arc, spatter, torn surface, grinding mark, chipping mark, underflushing, tack weld imperfection, misalignment of opposite runs, temper color (visible oxide film), scaled surface, flux residue, slag residue, incorrect root gap for fillet welds, and swelling

Unacceptable indications (that is, nonconformances) must be removed or adequately dispositioned and weld repairs made where needed, followed by reexamination by the same methodology by which the original nonconformance was found. In critical connections, NDE requirements in excess of those required by the applicable Code are sometimes required. In these cases, the acceptance criteria may be the same as the Code or may be predefined by the owner or design engineer.

12.5 Fabrication Hydrotests

An evaluation test performed on almost all HRSGs during specific stages of fabrication is a hydrostatic or leak test. This test is separate from Code-required hydrotesting that is performed on a completed unit. These tests are done on coils or harps on modules. Many of the welds tested by this means in shop will not be visible later due to further fabrication. Also, these welds are sometimes said to be the most critical in the unit because they are among the most inaccessible after the unit is erected.

For any hydrotest, care should be taken to prevent future damage from the liquid used during the test. Having the hydrotest water treated with a corrosion inhibitor may be sufficient. A further step would be the insertion of a vapor phase inhibitor into the components. Additional recommendations on shop hydrotesting can be found in Section 9.6 of the EPRI report *Delivering High Reliability Heat Recovery Steam Generators* [12-2].

12.6 Post-Fabrication Shipping and Storage

The reliability and performance of HRSGs is strongly dependent on the condition of pressure-part components and their exposure to potentially damaging conditions from the time they leave the shop until the time they are installed. As a result, it is important that the appropriate procedures be established to ensure adequate protection of HRSG components during transportation to the site and storage at the site during construction in order to:

- Prevent the accumulation of contaminants in the cycle
- Prevent corrosion of pressure-part surfaces
- Prevent accumulation of debris in pressure parts that could lead to tube blockages or provide a site for in-service damage on startup

The following list provides some key considerations pertaining to transport and storage:

- The interior of all equipment should be free from all foreign material such as welding rods, waste, loose mill scale, oil, grease, or other deleterious material. All openings should be closed immediately after cleaning. Rust, if any, should consist of no more than a surface film discoloration that can be readily removed by wiping.
- The sections that have been hydrostatically tested in the shop should be drained of all water prior to crating and shipment. If there is any doubt about whether a vessel contains water and if the parts will be shipped or stored where freezing could occur, a suitable antifreeze should be used to prevent component damage.

- The equipment should be suitably crated, boxed, or otherwise prepared for shipment to prevent damage during handling and shipment. Each box, crate, or component should be marked on the outside with the shipping weight.
- Austenitic stainless steel pressure-part materials should be protected during storage, handling, and shipment from seawater, seawater spray, rain, or dew when subject to industrial atmospheres.
- All flange faces, machined surfaces such as tube and header beveled ends, and threads should be clean and coated with a corrosion preventive. Flange faces, couplings, threads, and machined surfaces should be protected with suitable covers or plugs made of wood, metal, or plastic. Exposed finished and machined surfaces, including bolting, should be given a heavy coating of rust-inhibiting compound. Bolt threads should be protected from damage.
- The storage and handling of materials should prevent damage prior to application or installation. Protection should take into account the following:
 - Pressure-part openings should be sealed to prevent entry of moisture.
 - Pressure parts should not be stored in direct contact with the soil.
 - Austenitic pressure parts should not be supported on porous supports in contact with the soil.
 - Lined sections should be protected from water.
- Lifting devices and structural bracing should be provided to permit handling and lifting without damage during shipment and erection.
- Bracing and supports should be provided to prevent damage during shipment. Temporary steel shop attachments not required for field use should be removed prior to shipment. Temporary bracing and supports should be painted yellow to denote that removal is required before operation.
- All equipment and assemblies should be cleaned inside and outside prior to shipment to remove grease, oil, weld spatter, scale, slag, and foreign matter.
- All liquids used for cleaning or hydrostatic testing should be removed prior to shipment.
- Shop-installed insulation should be protected against mechanical damage and degradation from adverse weather conditions and contamination from foreign materials that could pose a corrosion risk.
- Equipment or components that must be stored indoors and kept clean and dry at all times should be identified, including, as a minimum, the items listed here:
 - Burners and accessories
 - Control panels
 - Control equipment—all types
 - Damper drives and interconnecting linkwork
 - Drum internals
 - Electrical devices—all types

- Heat insulation
- Igniters
- Motors—electric and air
- Motor starters
- Pumps
- Refractories
- Safety valves
- Soot blowers
- Spare parts
- Strainers
- Thermocouples
- Valves—all types
- Water columns and gages
- Water level indicators

12.7 References

- 12-1. *Heat Recovery Steam Generator Tube Failure Manual*. EPRI, Palo Alto, CA: 2002. 1004503.
- 12-2. *Delivering High Reliability Heat Recovery Steam Generators*. EPRI, Palo Alto, CA: 2003. 1004240.
- 12-3. “International Standard for Dimensions, Tolerances, and Tests of High Frequency Resistance Welded Fins” (effective June 1990), prepared by the following manufacturers: Aletas y Birlos (Mexico), Biraghi (Canada), Daikure (Japan), Enerfin (Canada), Escoa (United States), Fintube (United States), Kentube (United States), LP S.P.A. (European Union), Mannesmann Camoy (European Union), Shinko Hatsujo Kogyo (Japan), Spiro-Gills (European Union), Tempco (United States), and Taft (United States).
- 12-4. “Standard Specification for High Frequency Electric Resistance Welded Finned Tubes” (effective May 2002), Fintube Technologies, Inc.
- 12-5. International Standard ISO 6520-1, “Welding and Allied Processes—Classifications of Geometric Imperfections (Flaws) in Metallic Materials—Part 1: Fusion Welding. 1998.

13

NDE CONSIDERATIONS AND FLAW PREVENTION DURING ON-SITE CONSTRUCTION

This section discusses issues that pertain specifically to on-site construction of HRSGs. It covers QA/QC concerns, welding, PWHT, and NDE.

13.1 General Issues Pertaining to On-Site Construction QA/QC

The requirements placed on construction sites should be essentially the same as those for fabrication shops. All of the shop operations are used by construction, but with minimal amounts of bending and machining. The construction site will not have to be concerned with raw material other than a few lengths of pipe or tubing that may be required. All of the parts will be fabricated components from a fabrication shop and will have the Code Manufacturer's Data Reports certifying the pedigree.

Qualification of weld procedures and welders must still be handled as in the shop. NDE procedures and personnel qualifications must also be addressed.

While construction sites must deal with fit-up, welding, PWHT, and NDE as in the shop, they have the added challenge of doing everything in much more confining and precarious situations, making fit-up of welds more difficult than in the shop. This is compounded by the fact that a larger portion of pipe butt welds will require conformance to ANSI B31.1, where the fit-up requirements are tight. This makes construction fit-up doubly challenging.

During erection, components must be assembled in a manner that will allow for expansion or clearance for movement during heating cycles. The remedy for these problems is removal and reinstallation of components or shifting an adjacent component that is being impinged upon.

Weather conditions may make construction challenging. Wind, rain, humidity, and salinity of the ambient air are all factors that can impact an erection site. Joining of critical welds may be rescheduled to a time when weather conditions improve, or temporary shelters, heaters, and so on will be required.

13.2 General Issues Pertaining to On-Site Welding

The weld processes used, and percentage of each, will vary between a fabrication shop and a construction site. The GTAW process will be used on almost every butt joint for the root pass and often for the next fill pass. Totally absent will be the SAW process, which is most common

for girth welds in thick components in the fabrication shop environment. FCAW, which has nearly supplanted SMAW in fabrication shops, will be much reduced in volume on construction sites. On construction sites, the SMAW process is the prominent process for filling grooves and making attachment welds.

Because of this, a good weld rod control procedure must be implemented to prevent moisture pickup in rods. Most construction sites use “hot boxes” for welder use at the point of welding.

As with weld rod control in shops, the construction site must have competent, knowledgeable welding engineers overseeing this vital function. An example of lack of electrode control was a site where an E9018G (low hydrogen, modified 9%Cr, EN 1599:EZCrMo9B42) electrode was used instead of an E9018B3 (low hydrogen, 2.25%Cr 1%Mo, EN1599:1997ECrMo2B32H5) electrode. The welding engineer did not recognize the difference. When the error was detected and an evaluation made, more than 100 pipe butt welds had been produced and heat-treated. All had to be removed and replaced.

As noted previously, many weld joints will be made in accordance with ANSI B31.1, which, in addition to tighter fit-up tolerances, has more NDE required. Additionally, preheat for welding is mandatory. PWHT requirements are essentially the same as in Section I of ASME.

Because fit-up tolerances may be more restrictive on construction sites and also harder to achieve, it is good practice to require a QC check of fit-up, preheat, and back purge quality (if required) prior to releasing welders to initiate welding. As in the shop, using resistance heaters on either side of the joint for preheating is best practice, but depending on the weld being made, the use of rosebud flame heaters is standard practice in the field. This is acceptable if the process is rigorously monitored with temperature indicators or pyrometers. For alloy steels such as modified 9% chromium materials, use of electrical resistance or electrical inductance heaters rather than flame torches is recommended (further guidance on welding these materials can be found in EPRI reports 1004240 and 1006590 [13-1, 13-2]). As in shops, most joints will be on carbon steel components, which, because of their thickness, will not require preheat other than as necessary to drive off moisture from the joint to be welded or when ambient temperatures are low. Heavier thicknesses of carbon steel and alloy steel will have to be preheated as reflected by weld procedures.

On higher-alloy steel components, in addition to preheat, a back purge will be required to prevent oxidation and atmospheric contamination of weld roots. Somewhat different techniques are needed to accomplish this on site, because access to the component internal surface is extremely limited. Many joints are purged by a process of plugging both sides of the joint with purge paper and introducing purge gas from the outside through the root opening. Purging to an oxygen level below about 1% is required. Because the volume to be purged cannot be easily determined, using a “time for a certain volume” method is not reliable. Oxygen detectors or “sniffers” should be used to determine the necessary quality of purge gas prior to and during the welding of roots.

Visual examination of the weld root for adequacy of purge and other weld deficiencies can usually be accomplished by leaving openings or “windows” in the root as it is welded. It is possible to examine 75–85% of weld roots by this method, particularly if three “windows” are left until the end for observation. Often a welder partner will observe the root as it is being put in. Weld root nonconformances can be much more easily corrected at that point than at a later time.

13.3 General Issues Pertaining to On-Site Post-Weld Heat Treatment

PWHT of joints on construction sites is almost always accomplished by use of resistance heating wraps. An adequate distance on each side of the joint must be heated with a smoothly decaying temperature profile to ensure a good stress relief and not put too much thermal stress on the component. EPRI reports 1004240 and 1006590 [13-1, 13-2] provide recommendations on the distance that should be heated and insulated and the temperature gradient that should be maintained during PWHT. If multiple joints are being made simultaneously, which is normal practice, then care must be taken to ensure that adequate thermocoupling and monitoring are performed.

PWHT with handheld gas torches, while the least desirable method, may be acceptable for thin-walled carbon steel welds, but it is not recommended for alloy steel or thick components. This will usually be confined to small joints, and only one or two should be made at a time. For thin-walled joints, monitoring is usually accomplished with temperature indicators or a pyrometer with temperatures being recorded throughout the heat treatment. For more critical joints, a well-spaced group of thermocouples is generally used. Monitoring by QC is advisable.

As in the fabrication shop, it is prudent to require hardness checks on joints made in high-alloy steel (for example, SA-335-P91) components. Trusting a heat treat chart alone, particularly one where PWHT was by resistance heating, can have potential problems. There have been many instances when perfectly acceptable charts were shown for welds whose hardness attested to a less-than-adequate stress relief.

13.4 General Issues Pertaining to On-Site Construction NDE

One of the most effective NDE methods is visual examination. Visual examination should be performed on root passes, including the inside surface if accessible, and on completed welds. Welds that lack the appearance of “good workmanship” are suspect and should be prime candidates for further evaluation using other NDE methods. Besides general appearance, visual examination (with the necessary weld gages) can determine the presence of:

- Undercut
- Excess reinforcement
- Lack of fill
- Fillet size and shape
- Rollover

- Porosity
- Some cracking
- Other nonconformances

A less obvious item to check is the direction of weld progression. Where possible, all pressure boundary welds with all processes should be welded in an upward progression unless the WPS has been developed and qualified for downward progression. This will minimize the chance of trapping slag and/or having lack of fusion in the weld. Examination of “chevrons” formed during solidification of weld metal will indicate the direction of welding.

As a minimum, butt welds must be examined to the extent required by the governing Code. Fillet welds and some butt joints will usually require examination only by visual, liquid penetrant, or magnetic particle techniques. It is strongly suggested that a sample of the joints not requiring examination by Code be examined also. Preferably, this spot checking should be prescribed in the contract and should be performed prior to completion of a large group of welds of a given type.

While there are very complicated sampling plans in existence and available, the following simple one has been found to be most adequate. Ten percent of each welder’s welds should be examined, with two additional welds examined for each weld found to be rejectable. A “weld” is usually defined as a single joint if it is small or a length of weld approximately 1–2 ft (0.5 m) if the weld is of large circumference or is a linear fillet-type weld. If possible, select additional welds in close proximity to the one rejected. If these welds are not readily available, test the welder on current production and do not go backward past the welder’s last acceptable weld. The details of spot-checking NDE should be prescribed in the contract and should emphasize the earliest welds of a specific type made by a specific welder.

Volumetric NDE (ultrasonic or radiography) is used by the Code and in enhanced QA plans to examine butt welds because of the inaccessibility of the joint inside surfaces. In the United States, ASME B&PV Code Section I acceptance criteria are usually applied unless different criteria are agreed to by the customer and the erector. As with magnetic particle and liquid penetrant examinations, a sampling of welds not required by the applicable Code to be examined is strongly endorsed, but preferably should be documented in the construction contract. Although all joints are critical, some are more critical than others due to:

- Damage that could result if a failure occurred
- Their accessibility for repair
- The nature of the materials (that is, their propensity to have flaws or problems)

Such welds might prudently be examined at a 100% level, perhaps using NDE methods and procedures that are more comprehensive and sensitive than the minimum Code requirements.

13.5 References

- 13-1. *Delivering High Reliability Heat Recovery Steam Generators*. EPRI, Palo Alto, CA: 2003. 1004240.
- 13-2. *Guideline for Welding P(T)91 Materials*. EPRI, Palo Alto, CA: 2002. 1006590.

14

NDE DURING COMMISSIONING

14.1 Introduction

Commissioning is the time after manufacture and construction of an HRSG and before the unit enters into commercial operation. Commissioning also signals the time when service-induced damage begins to occur on HRSG pressure parts. Many units are installed on very tight construction schedules that allow minimal time for commissioning of the plant. Combined-cycle units are sometimes accepted for commercial service before commissioning, and often, the performance of major transient tests is not included in the acceptance tests. This is imprudent, even for combined-cycle units that will operate continuously thereafter, and it is unacceptable for units that are expected to be available for cycling service.

Thus, there are unique opportunities during commissioning for “diagnostic NDE” to be used that can forewarn of potential degradation mechanisms and pressure-part failures. The concept of “diagnostic NDE” is proposed here for use in monitoring temperature, stress, and fluid- and gas-side damage influencing factors during and after commissioning that are at the heart of pressure-part degradation.

Commissioning usually includes spot checking to verify that the HRSG has been built to Code, and performance testing to verify that the unit meets the agreed-upon operating and performance criteria as stated in the original contract between the original equipment manufacturer and the potential owner/operator. The phases of the commissioning process where NDE is used include:

- Baseline measurements
- Diagnostic troubleshooting and monitoring
- Pressure testing

EPRI will address the whole commissioning area in a follow-on project. Some basic guidance is provided here as it relates to NDE requirements.

14.2 Baseline NDE Measurements

Baseline NDE measurements should be made on the assembled HRSG components following the HRSG construction and assembly, and prior to insulating the piping and drum components. An example list of baseline NDE measurements to be taken during commissioning follows:

- As-built wall thickness measurements
- Tube spacing and side clearances
- Header clearances and cold setting position
- Alloy verification
- Internal condition of the drums, headers, and tubes
- Residual stress measurements

Measurement of tube spacing and side clearances in the gas path will provide an indication of potential avenues of gas laning and localized overheating. Header clearances and positioning will provide information on transfer piping stresses and support loads. Other baseline data may include thickness measurements, residual stress measurements, and alloy verification. These data should be compiled and archived for comparison with similar data to be taken after some appropriate period of operation, allowing for service-induced changes.

It is advisable that the baseline internal condition of the drums, headers, and tubes be established during commissioning and prior to commercial operation. This may require remote access, visual examination techniques using borescopes, or internal videoscopes. The objective of the internal baseline NDE is to ensure that foreign objects, internal corrosion, or welding imperfections such as burn-through or mismatch are not present prior to unit operation.

14.3 Diagnostic Troubleshooting and Monitoring

14.3.1 Measurements of Environmental Conditions

The refining and optimizing of the cycle chemistry and controls during commissioning is described extensively in EPRI reports 1004240 and TR-110051 [14-1, 14-2].

14.3.2 Temperature Measurements

It is important that a sufficient number of temporary thermocouples be installed during commissioning so that the operation of the HRSG components is verified to be within the predicted temperature ranges. The temporary thermocouples will help determine whether conditions developed in the HRSG are compatible with those assumed for design verification calculations. It is important that the rate of change of the relevant temperatures be measured during all unit transients in order to prevent the accumulation of high thermal stresses that can arise from rapid startup or shutdown.

A list of potentially susceptible locations for confirmation of thermal transients should be developed prior to commissioning. This can be accomplished by summarizing the conclusions from the design verification process in a panel-by-panel list of all susceptible locations in the HP superheaters and reheaters, evaporators, economizers, and preheater. Included should be a list of anticipated, or limiting, tube-to-tube temperature differences for each suspect location. The list of susceptible locations should be rank-ordered by agreed-upon criteria such as:

- The level of confidence assumed for the design verification process
- The level of conservatism in the analytical model used to predict cycles to failure
- The margin between predicted cycles to failure and the design number of startups

When selecting the locations to be investigated, additional importance should be given to the locations where the magnitude of the tube-to-tube temperature differences is significantly influenced by the rate of heating or cooling during startups or shutdowns or by the timing of the opening and closing of drains, vents, bypasses, feedwater valves, and so on. Sample locations are included the following remarks:

- HP superheater and reheater tube rows are always strong candidates for thermocouple installation. Thermocouples should be installed on a selection of the bare part of tubes close to the upper and lower headers. Transient temperatures of tubes directly in line with the pipe branches on inlet headers and/or outlet headers should be compared with adjacent tubes and also with those farthest from an inlet and outlet branch with smaller pressure drops through the tubes. Tubes at the ends of modules are also exposed to hotter gas leaking past upstream rows.
- The temperature of tubes in the rows downstream of attemperators should be measured to identify anomalies between tubes immediately opposite the pipe branch and the inlet header and also to assess whether there is significant variation in steam temperature between tubes in different panels caused by maldistribution of spray water.
- Evaporators can also develop significant transient temperature differences between the gas inlet row and subsequent tube rows and the downcomer. If design analysis of HP, IP, and LP evaporator circuits has demonstrated that the thermal stresses developed by a temperature difference of 212°F (100°C) between the gas inlet row and downcomer ensures a sufficient cyclic life, there is no purpose in installing temporary thermocouples in the evaporator. However, if a temperature difference between front row tubes and downcomer significantly smaller than 212°F (100°C) has been used for determination of the peak thermal stresses in downcomers, pipes, tube banks, and risers, thermocouples should be installed to validate the peak transient temperature differences. Typical locations would be at the top and bottom of a few front and rear row tubes, a downcomer, and pipes.
- Temporary thermocouples should be installed in economizer sections to determine if steaming of the economizer is occurring.

The method used for attaching thermocouples to tubes and headers must ensure that the process used to spot weld the thermocouples to tubes and headers causes no damage to the substrate material and ensures that each thermocouple measures the metal surface temperature. To do so, thermocouples must be welded to the tube/header surface, because thermocouples clamped to the

tubes generally produce inconsistent, unreliable measurements. The thermocouples must be covered with insulation to ensure that they are not influenced by convection from the hotter gas or radiation from duct liners. A procedure for spot welding thermocouples to tubes and headers that has been successfully used on several HRSGs is provided in Appendix B of EPRI report 1004503 [14-3].

Care will be required not to introduce significant damage during commissioning tests, such as when rapid unit ramp rates are introduced as part of fine tuning the unit's operating procedures.

14.3.3 Stress Measurements

Stresses acting on the pressure-part components can be calculated from the pressure sensors installed in the system. Less frequently, direct measurements are used to determine the amount of stress that a component must endure during operation. Such measurements can typically be characterized using high-temperature strain gages positioned at locations that are judged to be susceptible to damage. In addition, a comparison of the residual stresses imparted to the transfer piping and header connections can be obtained by experimental methods for NDE of stresses.

14.3.4 Installation of Diagnostic NDE Equipment

Diagnostic NDE during the commissioning phase can be used to enhance unit operation and diagnose potential problem areas. This may use conventional, permanently installed instrumentation such as thermocouples and cycle chemistry instrumentation. There is growing interest in, and increasing use of, specialized diagnostic instrumentation that may be temporary or permanently installed. Examples include temporary thermocouples, heat flux monitors, or permanently installed acoustic emission waveguides. Acoustic emission can be applied to help identify areas subjected to severe temperature, stress, and/or corrosion during service. Another example is thermography view ports, which can be used to characterize the general pattern of temperature variation in the HRSG. The installation of thermographic "targets" during commissioning should be considered, along with the positioning of a viewing port within the transition duct to be used for the installation of thermography equipment.

Additional information on diagnostic troubleshooting and monitoring can be found in Sections 10.7 and 10.8 of EPRI report 1004240 [14-1] and Section B.4 of EPRI report 1004503 [14-3].

14.4 Pressure Testing and NDE

Stress, temperature, and environment are the key variables that act on HRSG pressure parts and cause deterioration. Sensors are installed during the commissioning phase that will measure the changes that occur during operation, as these key variables come into play.

Transient tests should include, but not be limited to, startup tests after specific shutdown periods following normal shutdowns, including overnight shutdown, 30-hour shutdowns, 56-hour shutdowns, and cold start from ambient conditions. Each transient test should be performed in accordance with the operating procedures developed during the design phase.

When the HRSG has been assembled and prior to performance of the Code-required hydrostatic test, it is good practice to perform a pressurized air test on the system to verify that all components have been installed, welded, and/or tightened properly. This practice may avoid cleanup of hydrostatic test water if valves, pipes, sampling lines, and so on were not installed properly.

The ASME B&PV Code (PG-99) requires that newly constructed pressure-part components be subjected to a hydrostatic test at 1.5 times the normal working pressure in order to establish the maximum allowable working pressure. This test is to be witnessed by an AI. If leaks are found, the test is to be repeated after repairs are made. The hydrostatic test is intended to locate manufacturing and assembly defects present in the pressure parts. After a leak is found, the HRSG may need to be drained before appropriate action is taken to seal the leak.

Hydrostatic testing also offers a unique opportunity to measure early system loads due to the combined effects of manufacturing residual stress and internal pressure. Experimental methods for residual stress measurement usually suffer from the inability to determine the absolute value of stress and the relationship between stress and the measurement parameter. The usefulness of these techniques is therefore limited to comparisons among components. Placement of measurement sensors from these devices on piping systems subjected to internal pressure during hydrostatic testing may provide correlation between calculated values of actual stress from internal pressurization and the measured values of residual stresses among the various components. For any hydrotest, care should be taken to prevent future corrosion or water freeze damage from the hydrotest liquid.

14.5 References

- 14-1. *Delivering High Reliability Heat Recovery Steam Generators*. EPRI, Palo Alto, CA: 2003. 1004240.
- 14-2. *Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)*. EPRI, Palo Alto, CA: 2006. 1010438.
- 14-3. *Heat Recovery Steam Generator Tube Failure Manual*. EPRI, Palo Alto, CA: 2002. 1004503.

A

GENERIC OWNER HRSG BID SPECIFICATION (NDE SECTIONS)

XXX ENERGY GENERATION SERVICES

BID SPECIFICATION

FOR

ENERGY FACILITY

**EMERGENCY RESPONSE NONDESTRUCTIVE EXAMINATION SERVICES for HEAT
RECOVERY STEAM GENERATOR (HRSG) TUBING, PIPING, and ASSOCIATED
COMPONENTS**



Bid Due: July 26, 2002

BID REQUIREMENTS AND INSTRUCTIONS

General

Notice is hereby given that the Owner, XXX ENERGY CORPORATION, will accept bids for Emergency Nondestructive Examination Services (i.e., Magnetic Particle Testing (MT), Liquid Penetrant Testing (PT), Radiograph Testing (RT), Ultrasonic Testing (UT), etc.) at the Energy Facility for the Nondestructive Examination of HRSG tubing, piping, and associated components according to this specification prepared by XXX ENERGY GENERATION SERVICES, TECHNICAL SERVICES DEPARTMENT, and described herein.

Pricing

1. The bidder is required to provide an all-inclusive hourly crew rate (i.e., Level Technician and assistant) for Radiographic Testing.
2. The bidder is required to provide an all-inclusive hourly technician time and materials rate.
3. XXX Energy reserves the right to accept or reject all or part of these quotations.

Contacts

- A. Technical Contacts
- B. Commercial Contact

Site Visit

Each bidder is required to visit the site on July 16, 2002, at 9:00 a.m. for a meeting to discuss Emergency NDE needs and conditions of contract.

Proposals

- A. Proposals are to be drawn in the name of XXX Energy Company.
- B. Bidder shall describe in writing any possible non-conformance with the requirements of this Specification.
- C. Bidder shall submit with its proposal the procedures/methods it intends to employ in performance of the work. The procedures shall comply at a minimum with the applicable ASME Section V requirements for the inspection method submitted.

- D. Bidder shall submit with their proposal the Resumes/Experience/Certifications and number of the proposed site personnel who will be utilized in the performance of the work. That is, the number of personnel who will be on-site to perform Liquid Penetrant Testing (PT), Magnetic Particle Testing (MT), Radiographic Testing (RT), or Ultrasonic Testing (UT).
- E. Bidder shall submit with its proposal any electrical, water, and space requirements needed.
- F. Bidder shall submit with its proposal the names of any subcontractors it intends to employ in performance of the work.
- G. Bidder shall submit with its proposal a detailed payment schedule.
- H. Bidder shall submit with its proposal the Notice of Intent to Bid form. Proposals will not be accepted for Bidders who submit their pricing on any other form.
- I. **Bid packages are due no later than July 26, 2002 by 5:00 p.m.**

XXX ENERGY COMPANY
NOTICE OF INTENT TO BID

DUE DATE: July 26, 2002

Company Name

Address

Telephone Number

Pricing

Radiographic Testing, (RT) Liquid Penetrant Testing (PT), Magnetic Particle Testing (MT), and Ultrasonic Testing (UT) of HRSG boiler tubing and high energy piping repairs, etc., at the Energy Facility.

All-inclusive hourly Crew Rate for Radiography \$_____

All-inclusive hourly Technician Time and Materials Rate (For on-site additional work, e.g., Magnetic Particle Testing, Penetrant Testing, Ultrasonic Testing, etc.) \$_____Per/Hour

Subcontractors

Name(s)

Address

Name

Title

Date

Signed

XXX ENERGY GENERATION SERVICES SPECIFICATION FOR EMERGENCY NONDESTRUCTIVE EXAMINATION SERVICES

General Information

- Energy Facility
- Phone:

General Description

The Energy Facility is a 1,240-MW nominal capacity, combined-cycle natural gas-fired electric generating facility located at yyyy. The Energy Facility is approximately five (5) miles south of the town of zzz.

The facility consists of the following major components: four (4) Gas-Fired Combustion Turbines, four (4) Heat Recovery Steam Generators (HRSG), and two (2) Steam Turbine Generators.

Owner

XXX Energy LLC

Service Level Expectations for Emergency Nondestructive Examination Services Request

Emergency Response Nondestructive Examination:

Introduction

XXX Energy Generation Services has recognized the necessity and advantages of having emergency response contract relationships and commitments from its Vendor partners. The proposed contract relationship may include all types of emergency requests, such as Radiographic Testing (RT) of HRSG tube leak repairs, performing Ultrasonic Testing (UT), Radiographic Testing (RT), Magnetic Particle Testing (PT), Liquid Penetrant Testing (PT) of high energy piping repairs, performing Magnetic Particle (MT) or Liquid Penetrant testing (PT) of valve replacements, etc. This arrangement includes the ability to be self sufficient, including but not limited to, all necessary management, workforce (large enough to support multiple shifts), and equipment, including personal protective equipment (PPE), personal tools, consumables, etc., to complete the request expediently. XXX Energy Generation Services plans to maintain and utilize emergency response capabilities from Vendors that:

- Communicate to the requester within 1 hour of the request their ability, intent, or commitment to support the request.
- Maintain the ability to be staffed and fully equipped to respond to a request inclusive of being on-site within four (4) hours of their commitment. (XXX Energy Generation Services' intent will be to give the Vendor as much notice as possible to allow adequate and reasonable time to respond, depending on the situation.)
- Will work in a safe, healthful, and efficient manner while maintaining a sense of urgency to complete the assignment and provide a quality product meeting the requisite acceptance standard.

Safety (all work shall be performed in accordance with Federal, State, and OSHA work standards):

- (a) Vendor's work crew shall attend a brief site orientation meeting that may be conducted by either the Owner or a Vendor representative who has met with the Owner and attended a site orientation, on the first day that the Vendor's crew is on-site.
 - (b) All injuries and near misses shall be reported to the Owner or Owners Designee within 24 hours as defined in the site orientation.
 - (c) Failure to follow all station-specific instructions and applicable Federal, State, and OSHA requirements shall cause Vendor employee to be removed from site, and not be allowed to return.
- Will have on-site copies of the Vendor's applicable Nondestructive Examination (NDE) Procedures for the NDE methods utilized and Nondestructive Examination personnel qualifications including current eye exams. Documentation shall be available upon arrival at the site.
 - Will submit all Nondestructive Examination (NDE) reports to the station technical contact before leaving the site.

Based on the nature and location of the HRSG repair needs, the Vendor must be prepared to perform nondestructive examination (NDE) anywhere on the HRSG facility, which may include scaffolding, confined space entry, etc. Based on the nature of the repair, the number of resources and qualifications of those resources may vary.

When the emergency response request is made, XXX Energy Generation Services will inform the Vendor of the potential nature and NDE requirements. A typical NDE service request may include the following: MT, PT, RT, or UT. Again, the Vendor must be prepared to be self sufficient to execute the task.

PURPOSE

To establish a procedure for the radiographic, magnetic particle, liquid penetrant, and ultrasonic examination of the field welds located at the Energy Facility. The radiographic and magnetic particle examination will be performed to determine weld quality acceptance in accordance with the requirements of the applicable American Society of Mechanical Engineers (ASME) Code Section. That is, ASME Section I, Latest Revision, Power Boilers, ASME Section VIII Div. I Unfired Pressure Vessels, ASME B31.1 Power Piping, etc.

SCOPE

This procedure shall be used as an outline to establish the following:

1. References
2. General Procedures/Requirements
3. Safety and Environmental
4. Qualification of Personnel
5. Methods of Inspection
6. Method of Reporting
7. Deviations
8. Equipment and Services Rendered

1.0 REFERENCES

1.1. ASME, Section I, Latest Revision, Power Boilers.

Part PW.

PW-33, Alignment Tolerance.

PW-35, Finished Longitudinal and Circumferential Joints – Reinforcement.

PW-51, Acceptance Standards for Radiography.

Appendix A-260, Acceptance Standard for Magnetic Particle Examination

1.2. ASME, Section V, Latest Revision, Nondestructive Examination.

Subsection A

Article 1, T-170 – Qualification of Personnel.

Article 2 – Radiographic Examination.

Article 4 – Ultrasonic Examination Methods for Inservice Inspection.

Article 5 – Ultrasonic Inspection Methods for Materials and Fabrication.

Article 6 – Liquid Penetrant Examination.

Article 7 – Magnetic Particle Examination.

Article 9 – Visual Examination.

1.3. ASME Code Sections / Standards / NBIC and Jurisdiction Rules

1. ASME Section I, Latest Revision, Power Boilers.
 2. ASME B31.1, Latest Revision, Pressure Piping.
 3. ASME Section IX, Latest Revision, Welder Qualifications.
 4. ASME Section VIII Division I, Latest Revision, Unfired Pressure Vessels.
 5. ASME Section V, Latest Revision, Nondestructive Examination.
 6. ASME Section II, Latest Revision, Part A, Part B, Part C, and Part D.
 7. NBIC, Latest Revision, National Board Inspection Code.
 8. SNT-TC-1A - American Society for Nondestructive Testing, Latest Revision, "Recommended Practice for Nondestructive Testing Personnel Qualification and Certification."
- 1.4. SNT-TC-1A - American Society for Nondestructive Testing, Latest Revision, "Recommended Practice for Nondestructive Testing Personnel Qualification and Certification."

2.0 GENERAL PROCEDURES/REQUIREMENTS

- 2.1 The Contractor is responsible for ensuring that the work performed under this specification shall be performed in a thorough, professional manner and meets all local, state, and federal environmental and safety codes and regulations and the technical requirements of this document.
- 2.2 The Contractor shall be responsible for ensuring that the examinations are performed using approved procedures that comply with the applicable standards and utilizing personnel trained, qualified, and certified in accordance with SNT-TC-1A - Non-Destructive Examination Personnel. If an inspector is observed or found to be deviating from these requirements, the inspector will be warned one time of the deviation. If the inspector is observed or found deviating a second time, the inspector will be removed from site and a random re-inspection will be made of at least five (5) welds previously inspected and accepted by that inspector.

3.0 SAFETY AND ENVIRONMENTAL

3.1 Safety [Goals are No Lost Time and No Recordable Injuries]

- 3.1.1 The Contractor's Project Supervisor is responsible for ensuring that a safe work environment is maintained, with the goals of no lost time or recordable injuries. All safety incidents, e.g., near misses, minor injuries, recordable injuries, etc., are to be reported as soon as possible to the XXX Energy contact.
- 3.1.2 Contractor's work crew shall attend a brief site orientation meeting to be conducted by the Owner on the first day that the Contractor's crew is on-site.
- 3.1.3 All safety incidents, e.g., near misses, minor injuries, recordable injuries, etc., are to be reported to the Owner or Owners Designee within 24 hours as defined in the site orientation.
- 3.1.4 The Contractor shall, in writing or report form, inform the XXX Contract Manager of all ALARA (As Low as Reasonably Achievable) events or reports, radiation safety events, and notifications to regulatory agencies whether the notification is required or is a courtesy, as a result of work performed under this contract.
- 3.1.5 The Contractor Radiation Safety Officer (RSO) shall perform audits on field personnel at a frequency interval to preclude an ALARA event from occurring.
- 3.1.6 Failure to follow station safety rules shall cause employee to be removed from site, and not be allowed to return.
- 3.1.7 Contractor to provide and ensure use of appropriate hard hats, safety glasses, footwear, and other Personal Protection Equipment required by OSHA guidelines and station safety rules.
- 3.1.8 Contractor SPOC shall meet with the Owner for site orientation at the time of the pre-work initiation meeting. The Contractor is then responsible for orienting their crew to the site.
- 3.1.9 **Prior to the commencement and performance of work**, the following shall be coordinated with plant supervision for verification.

3.2 Environmental

- 3.2.1 Material Safety Data Sheets shall be submitted by the Contractor for all hazardous materials being brought on site.
- 3.2.2 If an Owner approved chemical list provides a product suitable for the Contractor's needs, the Owner approved chemical product must be used in lieu of non-approved substitutes. Applicable approved chemicals lists will be provided by the Owner upon request. No substitution will be allowed without prior approval through the Owner's site Hazcom Program Administrator.
- 3.2.3 If any additional chemicals are identified during the course of work, the Contractor must notify the site Hazcom Program Administrator for approval prior to bringing the materials on site.
- 3.2.4 The Contractor shall agree in writing to report any chemical spill to the Owner or site Hazcom Program Administrator promptly. At the Owner's or Hazcom Program Administrator discretion, the Contractor will be required to either clean up any chemical spill(s) caused by the Contractor's actions, or compensate the Owner for any spill cleanup costs. Additionally, the Contractor shall be responsible for proper and legal disposal costs of spill cleanup material, as directed by the Owner's site Hazcom Program Administrator.
- 3.2.5 The Contractor shall provide all training required by law, regulation, or ordinance to their personnel. Documentation must be provided to the Owner upon request.
- 3.2.6 Contractor shall adhere to the Owner's disposal and recycling programs during work on site.
- 3.2.7 Contractors performing work on site shall agree to take all reasonable measures to minimize waste generated. The Contractor will notify the Owner and site Hazcom Program Administrator promptly of any waste created. The **Owner** will be responsible for managing disposal of any hazardous waste generated and **Contractor** will be responsible for costs of same.
- 3.2.8 At completion of the work, the Contractor will remove any chemical products brought on site.

4.0 QUALIFICATION OF PERSONNEL

- 4.1 All inspection personnel performing work shall be trained, qualified, and certified in accordance with SNT-TC-1A - Non-Destructive Examination Personnel Qualifications for performing the Non-Destructive Examination (NDE) methods used.
- 4.2 Personnel qualification verification for all inspection personnel shall be submitted to XXX Energy prior to work commencement for review and acceptance.
- 4.3 Only personnel qualified and certified to a NDE Level II or Level III for the appropriate inspection technique shall perform the examinations.

5.0 METHODS OF INSPECTION

The inspection methods, that is, Visual Inspection (VT), Radiographic Inspection (RT), Visual Inspection (VT), Liquid Penetrant Inspection (PT), or Magnetic Particle Inspection (MT), shall be used in conjunction for the inspection work scopes indicated in Section 1 of this procedure.

- 5.1 **Visual (VT)** - A visual inspection of the welds shall be made to assess their general condition. Misalignment, excessive reinforcement and undercutting at the toes of the welds, visible porosity, arc strikes, etc., are items to be checked for. Any areas with these conditions should be marked for further inspection.
- 5.2 **Radiography (RT)** - A radiographic inspection of the tube welds shall be performed using a single 0° shot, double-wall exposure, double-wall viewing (ellipse), weld reinforcement, without a back-up strip technique, where possible per ASME Section V Article 2 T271.2b. An alternative method if the aforementioned technique cannot be used, is the double-wall exposure, single-wall viewing technique per ASME Section V Article 2 T271.2a. For piping welds, a radiographic inspection shall be performed using the panoramic technique, single wall exposure, single wall viewing, weld reinforcement, without a back-up strip technique per ASME Section V Article 2 T271.1.
 - 5.2.1 The radiographer shall submit technique radiographs to establish acceptable minimum image quality and selection of exposure arrangement. The area that the examinations will be performed in will be accessible prior to the actual examination date so that equipment set-up can be performed/modified to minimize any loss of time when the actual examination does start.
 - 5.2.2 The radiographic weld quality acceptance standard shall be per the applicable ASME Code Section.

- 5.2.3 Weld overlays, if required, shall be made by the radiographer and all indications shall be marked on the applicable weld using a paint marker or equivalent. The weld overlays shall be left with the Owner or Owner's designee.
- 5.2.4 The radiographer shall identify on the film or Reader Sheet, the source side location, for future reference, (e.g., casing side, furnace side, left or right, front or rear side of a panel). All Reader Sheets shall as a minimum meet the requirements of ASME Section V, Article 2 T-291.
- 5.3 **Magnetic Particle (MT)** - A dry powder magnetic particle inspection of the welds shall be performed in accordance with the ASME BP&V Code, Section V, Article 7. The dry powder magnetic particle inspection method shall be performed using two separate examinations of each area and shall be conducted using perpendicular magnetic flux, utilizing the "Continuous Method" of MT. The areas to be tested shall include the weld, fusion lines on either side of the weld, a minimum of two inches (≥ 2 ") on both sides of the weld, and shall have a sufficient examination overlap to assure 100% coverage. Acceptance Standards shall meet the applicable ASME Section.

6.0 METHOD OF REPORTING

- 6.1 A weld data logbook will contain the applicable, that is, visual, radiographic, magnetic particle, liquid penetrant, examination results for each weld. The logbook should contain such information as inspector's name, weld number, accepted, rejected, or not inspected status, and any other applicable information.
- 6.2 Within three (≤ 3) weeks after completion of the fieldwork, the Contractor shall prepare and submit to XXX Energy Company a formal report including one (1) copy. The report shall contain the examination results listed on the applicable radiographic and magnetic particle weld examination sheets and other applicable examination results as needed.

7.0 DEVIATIONS

- 7.1 Any deviation of this specification shall be at the sole discretion and approval of the XXX Energy Company

8.0 EQUIPMENT AND SERVICES RENDERED

8.1 Furnished by the Contractor

The Contractor shall furnish all personnel, supervision, materials, consumables, examination equipment, safety and protective equipment, calibration standards, radiographic film development facilities, fax machines, copiers, office supplies, etc., required to successfully perform the examination and testing work as outlined in this specification. The Contractor shall remove any usable chemical products brought on-site. The Owner will dispose of any wastes generated during this project.

8.1.1 The Contractor shall be responsible for supplying one (1) radiography film viewer that will be located on-site and accessible to both XXX Energy and XXX Energy subcontracted personnel.

8.1.2 The Contractor is responsible for providing and performing an audit (20%) of the film by a Level III qualified in accordance with SNT-TC-1A, Level III, for the appropriate inspection technique to ensure full compliance with the requirements of ASME Section V. XXX Energy Company will not accept any film found during the performance of the work scope or during the audit, which does not meet the requirements of ASME Section V. The Contractor shall re-radiograph at the Contractor's expense any weld that has been radiographed and the film found to not meet the requirements of ASME Section V.

8.1.3 Sub-Contractor Identification:

The Contractor shall identify and the Owner review and approve Sub-Contractors used, if not known prior to the award. The coordination and supervision of any Sub-Contractor used on the work scope is the responsibility of the Contractor.

8.1.4 Damage Control:

The Contractor shall report to the Owner any damages caused by their personnel, and the Contractor shall make repairs at their own expense.

8.1.5 Contractor Single Point of Contact (SPOC)

The Contractor will designate a person to act as the SPOC.

The Contractor shall provide an on-site person for coordination of the associated activities with a defined Owner Contact.

The Contractor shall ensure that a neat, clean work area is maintained on a daily basis.

8.2 Furnished by XXX Energy Company

- 8.2.1 A station representative to act as a liaison between the Contractor and XXX Energy for all work performed.
- 8.2.2 Restroom facilities, electric power, air (100 psig), and water located on the ground floor.
- 8.2.3 Temporary scaffolding.
- 8.2.4 Designated Parking area for the Contractor's personnel vehicles. The Owner will provide to the Contractor and each sub-contractor one (1) vehicle pass allowing the holder inside the gated yard.
- 8.2.5 Vending facilities.

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California; Charlotte, North Carolina; and Knoxville, Tennessee, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

Together...Shaping the Future of Electricity

Program:

Heat Recovery Steam Generator (HRSG) Dependability

© 2007 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

 Printed on recycled paper in the United States of America

1012759

Electric Power Research Institute

3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com