ELECTRIC POWER
RESEARCH INSTITUTE

Examination of Heat Recovery Steam Generator Plants

Case Studies of Remote Visual Inspection Techniques

1014197

Examination of Heat Recovery Steam Generator Plants

Case Studies of Remote Visual Inspection Techniques

1014197

Technical Update, March 2008

EPRI Project Manager

S. Walker

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

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

GE Inspection Technologies

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

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

CITATIONS

This document was prepared by

GE Inspection Technologies
721 Visions Dr.
Skaneateles, NY 13152

Principal Investigator
M. J. Nugent

This document describes research sponsored by the Electric Power Research Institute (EPRI).

This publication is a corporate document that should be cited in the literature in the following manner:

Examination of Heat Recovery Steam Generator Plants: Case Studies of Remote Visual Inspection Techniques. EPRI, Palo Alto, CA: 2008. 1014197.

PRODUCT DESCRIPTION

The following EPRI reports have documented problems associated with the operation and maintenance of complex heat recovery steam generators (HRSGs):

- *Heat Recovery Steam Generator Tube Failure Manual* (1004503) provides information about known HRSG tube failures and necessary steps that can be taken to diagnose and prevent similar problems.
- *Delivering High Reliability Heat Recovery Steam Generators* (1004240) provides guidance for the continued and reliable operation of HRSGs from initial design, fabrication, and operation through lessons-learned experience.

As HRSGs age, components begin to fail, regardless of the care taken to ensure the use of suitable materials, optimal heater design, and applicable water chemistry guidelines. Therefore, it becomes necessary to apply nondestructive evaluation (NDE) techniques to inspect, monitor, and help mitigate HRSG failures, as described in the following reports:

- *Interim Guidelines for the Nondestructive Examination of Heat Recovery Steam Generators* (1004506) provides information on various NDE techniques available and their possible applications to detect and characterize location-specific forms of damage in HRSGs.
- *Electromagnetic Nondestructive Evaluation (NDE) for Heat Recovery Steam Generators* (1008093) provides additional information concerning electromagnetic NDE for HRSGs.
- *Examination of Heat Recovery Steam Generator (HRSG) Plants – Assessment of Fiber-Optic Techniques* (1008092) provides recommendations of the use of fiber optics and suggests that this may be a good way to perform inspection on HRSGs.

Access to tubes from both the outer and inner surfaces and tube-to-header welds has been a major limitation in applying suitable NDE techniques. Consequently, this report focuses on the introduction of various visual NDE techniques for field implementation. Specific visual NDE techniques covered in this report include the use of fiberscopes, borescopes, and lecturescopes. Each of these can be applied from the inside of finned and nonfinned tubing and piping that might be subject to various forms of corrosion, pitting, hydrogen damage, and cracking.

Results and Findings

This report provides an overview of suitable visual examination techniques that use fiber optics to perform flaw detection in tubing and piping materials that are encountered in HRSGs. The described NDE techniques have been shown to be applicable from the internal surfaces of HRSG components if access to the components is either available or made available. Applying the appropriate NDE methods to each of the components and damage mechanisms is key to maintaining safe continued operation.

Challenges and Objectives

Because of access limitations, the most prevalent NDE method currently used for HRSGs is visual examination of tubes and headers from either the inside or outside of the tube. Unfortunately, if indications are found that do not penetrate completely through the wall, no quantitative information can be obtained by the visual method to assist with run, repair, or replace decisions.

Applications, Values, and Use

This report reviews visual examination equipment that is commercially available and suitable for HRSG applications by providing information on tube wall loss caused by corrosion and fatigue damage. With available access, these techniques are easy to implement and require no surface preparation before examination.

The specific visual examination techniques presented in this report are applicable from the inside surface of finned and nonfinned tubing and piping that might be experiencing various forms of corrosion, pitting, hydrogen damage, or cracking.

The case studies provide details of what has been found in operating plants with the use of fiber-optic equipment.

EPRI Perspective

This report enhances and affirms the previous NDE guidance provided in the EPRI report *Examination of Heat Recovery Steam Generator (HRSG) Plants – Assessment of Fiber-Optic Techniques* (1008092). The goal of this activity was to acquire case studies affirming the capability of existing visual examination technology, primarily using fiber optics, for application to HRSG components—in particular, for finned tubing and header-to-tubing junctures.

Approach

As part of this project, the use of fiberscopes, borescopes, and lecturescopes as remote visual inspection (RVI) techniques was investigated. In addition, their potential applications for HRSG inspection was studied, and specific case studies were gathered to serve as examples of the use of RVI for component examination.

Keywords

Combined-cycle power plants
Corrosion
Failure reduction
Heat recovery steam generators (HRSGs)
Nondestructive evaluation (NDE)
Visual examination

CONTENTS

1 **INTRODUCTION 1-1**

2 **REMOTE VISUAL INSPECTION OVERVIEW 2-1**

Remote Visual Inspection Overview 2-1

Remote Visual Inspection Equipment 2-2

Remote Visual Inspection Data Management 2-8

3 **CASE STUDY: HEADER 3-1**

4 **CASE STUDY: DESUPERHEATERS (ATTEMPERATOR) 4-1**

5 **CASE STUDY: BOILER TUBE THERMAL FATIGUE 5-1**

6 **CASE STUDY: BOILER TUBE HYDROGEN DAMAGE 6-1**

7 **CASE STUDY: BOILER TUBE CLEANLINESS AND PRE-COMMISSIONING 7-1**

8 **CASE STUDY: BOILER TUBE LEAKS 8-1**

9 **CASE STUDY: BOILER TUBE FLOW-ASSISTED CORROSION 9-1**

10 **CASE STUDY: CORROSION FATIGUE 10-1**

11 **CASE STUDY: FOREIGN OBJECT AND LOOSE PART RETRIEVAL 11-1**

12 **CONCLUSION 12-1**

1
INTRODUCTION

Heat recovery steam generators (HRSGs) have been used for many years in both process (oil/petrochemical) and electric utility applications. Some process applications are carbon monoxide (CO) boilers in fluidized catalytic cracking units (FCCUs) or waste heat recovery boilers in sulfur recovery units. The fundamental purpose of an HRSG is to combust either a low-value fuel (such as CO and sulfur oxides) in a process plant application or the exhaust from steel mill blast furnaces or gas turbines for use in power generation applications.

In the late 1980s and early 1990s, new high-efficiency gas turbines— with many technological advantages over the gas turbines of previous generations—were introduced. The firing temperatures of these combustion turbines exceeded 2400°F (1316°C) for maximum efficiency, with some simple cycle thermal efficiencies approaching 60%.[1]

Utility applications of HRSGs have often been used on the back end of land-based combustion turbines. Many of the original HRSGs in utility applications were designed for qualifying facilities under the Public Utility Regulatory Policies Act of 1978 (PURPA). Many of these plants went into service with long-term service agreements that nearly assured utilities of base-loaded operation. These agreements were made at a time of uncertain long-term operation of aged utility power plants due to life extension considerations of the late 1970s to early 1980s.[2]

Newer HRSGs that were constructed as merchant facilities in the late 1980s to early 1990s typically experienced rigorous cycling duty because of the absence of long-term purchase agreements. Many of the HRSG designs were not originally designed for cyclic duties, however, and with increasing cycles came increasing mechanical problems. As mechanical problems increase and components start to fail, more inspection is required to help mitigate these failures because they are not only an asset reliability issue but a significant safety issue as well.

Because of potentially catastrophic failures, power plant safety has always been of paramount importance—and HRSGs are no exception. For example, gas-fired stations that suffered catastrophic explosions in the 1990s include Ford Motor Co.'s Rouge plant, Tampa Electric Co.'s F. J. Gannon station, KCP&L's Hawthorn station, and Kansas City Board of Public Utilities' Nearman Creek plant. All of these incidents were natural gas explosions that occurred at conventional power stations. HRSGs experienced significant incidents that injured or killed workers in 2003, 2004, and 2005.[3]

---

[1] Robert C. Swanekamp, *HRSG Users Handbook.* PSI Media Inc., Las Vegas, NV 2006. pp. 2.1-1, 2.

[2] Robert C. Swanekamp, *HRSG Users Handbook.* PSI Media Inc., Las Vegas, NV 2006. p. 2.1-5.

[3] Robert C. Swanekamp, *HRSG Users Handbook.* PSI Media Inc., Las Vegas, NV 2006. p. 1-2.

Even without a catastrophic explosion, boiler tube failures can be fatal, as evidenced by this most recent incident. The following excerpt was taken from a November 8, 2007, article in the Salem, Massachusetts, newspaper, *Salem News*:[4]

> SALEM - Salem Harbor Station has been shut down in the wake of the deadly steam explosion that killed three workers earlier this week. The power plant, which has 145 employees, could remain closed a week or more, an official said. . . .
>
> The company said the employees who were killed were working on a fan a few feet from the boiler and were not working on the boiler itself.
>
> [A] veteran steam operator was making sure the fan was turned off and safe before [a] mechanic began to work on it, the company said. [The mechanic], who had been on the job only two days, was watching [the veteran steam operator] to learn about the work of a steam operator, according to company and union officials.
>
> The men were working on the ground floor of the plant when the tube ruptured, blowing steam down on them from 20 feet above, the company said.
>
> A fourth worker had left the area only moments earlier to use the men's room, an official said.
>
> There was no warning that the water tube inside the boiler was about to explode, the company said. No alarms or other warnings sounded in the control room that monitors plant activity.
>
> "There was nothing to indicate there was a problem up until the actual rupture," [a company official said].
>
> The boiler that failed was installed in 1958, the company said. Parts are regularly replaced, but the company did not know the age of the steel tube that ruptured.
>
> At the same time, however, he acknowledged that work conditions at a power plant that uses hot steam under high pressure are much different than the average workplace.
>
> "This is a very dangerous industry," said Simpson, who used to work at the Salem plant. "This is an extremely dangerous industry."

A robust inspection program can help moderate the risk of these potentially catastrophic failures. This report enhances the previous nondestructive evaluation (NDE) guidelines provided in the Electric Power Research Institute (EPRI) report *Examination of Heat Recovery Steam Generator (HRSG) Plants: Assessment of Fiber-Optic Techniques* (1008092). The report focuses on the introduction of the use of fiberscopes, borescopes, and lecturescopes, which can be applied from the inside of finned and nonfinned tubing and piping that might be subject to various forms of corrosion, pitting, hydrogen damage, and cracking. The current report covers the few major types of remote visual inspection (RVI) and their potential applications for HRSG inspection and provides specific case studies as examples of the use of RVI for component examination.

---

[4] Tom Dalton, "Salem plant shuts down in wake of deaths," *Salem News*, November 8, 2007, http://www.salemnews.com/archivesearch/local_story_312120203 (accessed February 18, 2008).

2
REMOTE VISUAL INSPECTION OVERVIEW

Remote Visual Inspection Overview

Because of complex geometry, confined space safety concerns, and the need to access component internals, direct visual inspection of HRSG component internals is often not feasible. In these instances, RVI has proven to be a valuable asset for HRSG examination.

RVI has been around since before the 1950s and has evolved steadily since then with the consumer and commercial video recording industries. Figure 2-1 provides an overview of RVI's history along with its corresponding recording media.

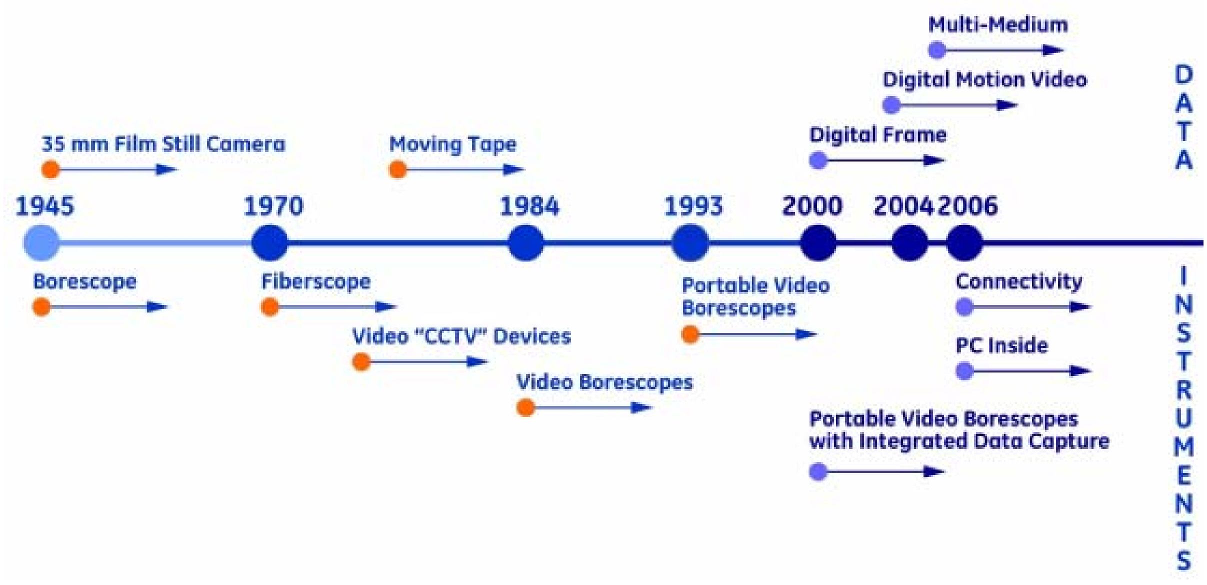

Figure 2-1
History of RVI

RVI is the use of a remote visual imaging instrument to view and capture images from otherwise inaccessible locations. RVI is generally considered a subset of visual examination within the engineering discipline of NDE. NDE also includes ultrasonic, eddy current, acoustic emission, magnetic particle, dye penetrant, and radiographic examination technologies. RVI can serve as a stand-alone technique, or it can be used as a complement to conventional test data (such as vibration, pressure, and flow) or NDE techniques (such as ultrasonic, eddy current, and radiographic). RVI is often used for root-cause failure analysis or as a key support technology for visual trend monitoring in various components. It can also perform as a vision system for remote tooling, *in situ* welding, blade blending, loose-parts retrieval, or other remote operations.

Similar to many NDE disciplines, the relative success or failure of RVI can depend on choosing the proper RVI equipment. Factors such as resolution, lighting, and image processing combine to make the entire picture that is displayed to an inspector. All of these factors can affect image quality and therefore an inspector's probability of detection. The video borescope and the push camera are typically the most widely used RVI tools in HRSG applications.

Finally, a key element in any RVI program is the choice of storage medium. In today's digital world, there are many choices of storage media and formats. It is important to ensure that the data files can be easily shared for review and, because resolution can significantly impact the probability of detection, to maintain image resolution.

Remote Visual Inspection Equipment

There are four basic types of visual imaging instruments. The device with the most basic technology, which also provides the highest resolution, is the borescope. Rigid borescopes are rigid optical devices similar to telescopes that use lenses to transmit an optical image from a remote location to a human eye or camera. Fiber optics or distal lighting provides illumination at the remote target. The optical lens train is a set of precision-cut lenses placed in the shaft to carry the image in sharp focus back to the eyepiece. This lens train accounts for the rigid borescope's excellent resolution. Because the image is never broken into a finite number of optical fibers or video camera pixels, the image remains unpixelated all the way to the operator's eye. Rigid borescope diameters run from approximately 0.08 in. (2 mm) to 0.39 in. (10 mm) with commonly available lengths to approximately 1.97 ft (60 cm). They are manufactured with either a fixed-forward or side-viewing optics design or use a movable prism at the distal end of the scope to allow user control of the direction of view. Borescopes with variable direction of view are commonly referred to as *swing-prism borescopes*. The rigidity and comparatively short lengths of all borescopes, however, can limit their applications in HRSGs. A diagram of a typical rigid borescope is shown in Figure 2-2.

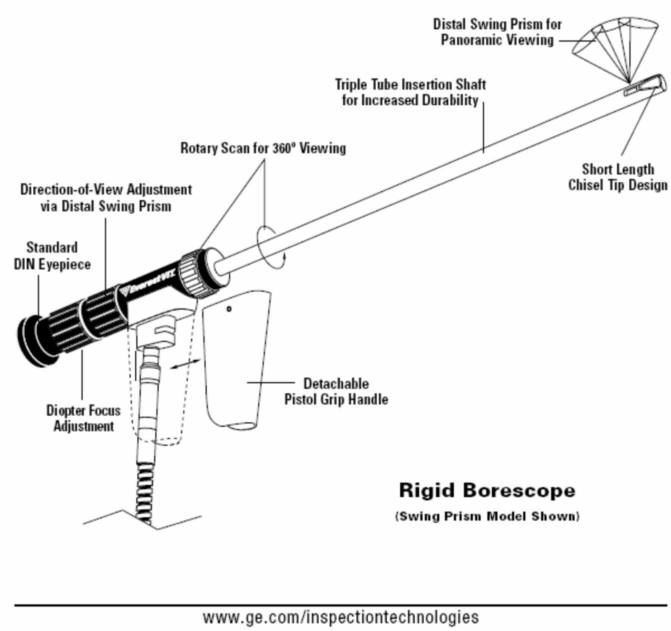

Figure 2-2
Rigid Borescope

The second type of RVI instrument is the flexible fiberscope. Fiberscopes are flexible fiber-optic devices that use a coherent fiber-optic bundle (that is, image bundle) for image transfer and a second noncoherent fiber-optic bundle (that is, illumination bundle) for illumination. Imaging performance depends primarily on the quality of these fibers and lens sets. The eyepiece magnifies the image carried back by the imaging bundle for viewing by the human eye. High-resolution fiberscopes have extremely small diameter and high light-transfer efficiency imaging fibers. The number of imaging fibers in an image bundle determines the fiberscope's effective resolution. Some fiberscope models are equipped with distal tips that accept an additional lens to change the direction of view from forward to side. This side-view tip adapter enables the same scope to be used as either a forward or side-viewing scope. Fiberscopes with illumination bundles that use a single, continuous fiber-optic bundle—extending from the distal tip through the insertion tube and out to a light source—have the highest light transfer efficiency and are therefore the preferred instrument for HRSG inspections.

Tip articulation is an additional feature of fiberscopes that can be extremely beneficial for inspecting the diverse types of equipment found in an HRSG. *Articulation* refers to the ability of the operator to "steer" the fiberscope tip. Fiberscopes are designed to be four-way, two-way, or non-articulating. Articulation is accomplished by a set of steering cables that push and pull collars together or apart in order to steer the viewing tip. The fiberscope's flexible insertion tubes allow it to be "snaked" through equipment bends and enable it to reach areas that are not accessible by rigid borescopes, making it better suited for most HRSG applications. Articulating fiberscopes typically come in diameter ranges from approximately 0.16 in. (4 mm) to 0.31 in. (8 mm) and typical lengths to approximately 9.84 ft (3 m). A diagram of a typical fiberscope is shown in Figure 2-3.

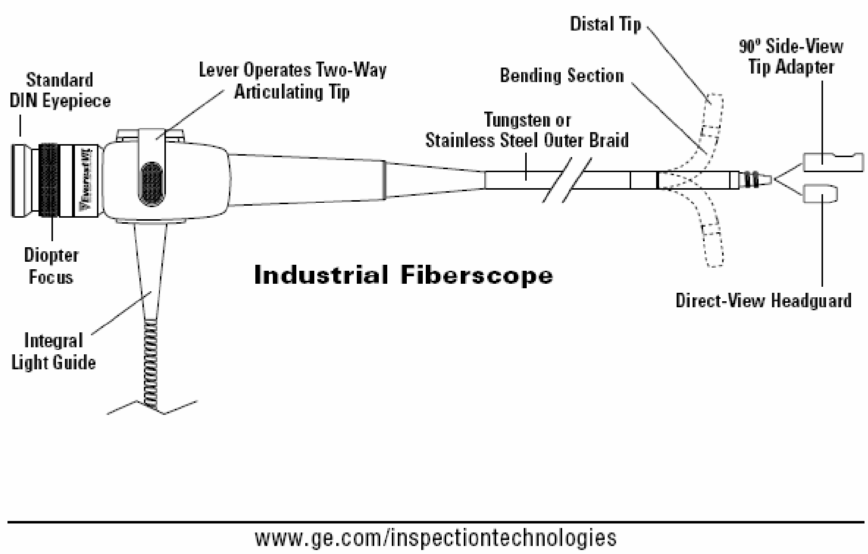

Figure 2-3
Flexible Fiberscope

Both borescopes and fiberscopes can be used with an adapter called a *C-mount* that allows video cameras, 35-mm single lens reflex (SLR) cameras, or digital cameras to be coupled to their eyepiece to capture inspection images onto videotape, 35-mm film, or digital storage media (see Figure 2-4).

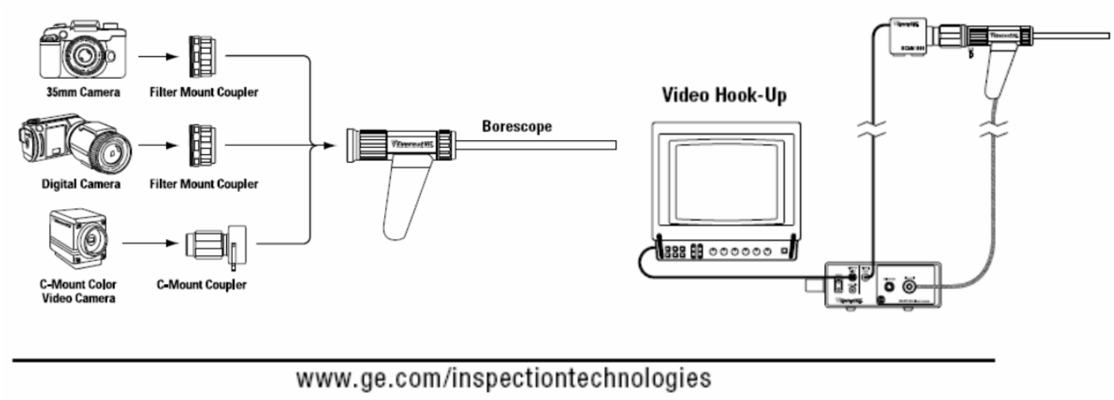

Figure 2-4
Borescope with C-Mount Adapter and Camera

Borescopes and fiberscopes are optical instruments that require the C-mount adapter to convert their images into an electronic display. The most widely used types of RVI equipment today use *charged coupled devices* (CCDs), which are solid-state devices that hold an array of light-sensitive elements known as *pixels* or *picture elements*. Figure 2-5 shows an example of a pixel in a digital image. The amount of detail that can be captured in a CCD imager is called the *resolution* and is measured in pixels. The more pixels there are, the more detail can be captured; the more detail there is, the more a picture can be enlarged before it becomes "grainy" and starts to look out of focus.

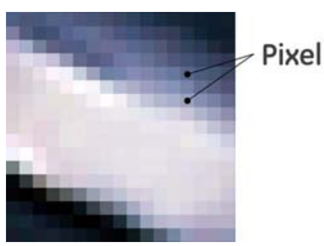

Figure 2-5
Example of a Pixel in a Digital Image

A CCD camera system consists of a lens system, a CCD imager, and processing electronics and produces a brighter, higher resolution image than do conventional fiberscopes. Its advanced micro-electronic technology enables the CCD to function as a miniature television camera that is capable of electronically capturing and sending both still and motion-video images with great clarity to a video monitor or image capture device. Because of the CCD's diminutive size, (see Figure 2-6), the silicon chip can be placed within the tip of small-diameter probes that are on the scale of most fiberscopes.

Figure 2-6
Charged Coupled Device Imager

The most popular, versatile, and widely used CCD-based RVI instrument is the video borescope. Video borescopes were introduced in the early 1980s; these flexible devices have a small (1/10–1/4 in. [2.54–6.35 mm] diagonal) CCD imager at their tip. With the imager at the distal tip as opposed to the ocular end of a fiberscope, much greater clarity, depth of field, and color quality are possible. These devices use noncoherent fiber optics for illumination and use specialized split-head video camera technology to minimize their diameter size. See Figure 2-7 for an example of video borescope construction.

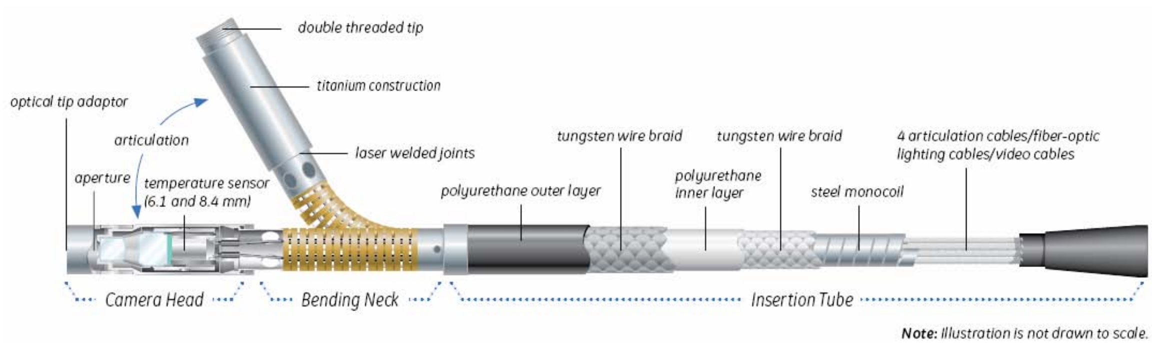

Figure 2-7
Flexible Video Borescope

The electronic imaging of video borescopes makes longer lengths more practical. They come in articulating diameters from approximately 0.15 in. (3.9 mm) up to 0.33 in. (8.4 mm) and in lengths up to 100 ft (30.48 m). One model of video borescope uses a unique form of air articulation to allow tip movement at this 100-ft (30.48-m) distance. This can be particularly useful when access may be more difficult but when long distances are needed for inspection, such as large headers. The electronic control of articulation allows for systems to articulate in every direction, as shown in Figure 2-8.

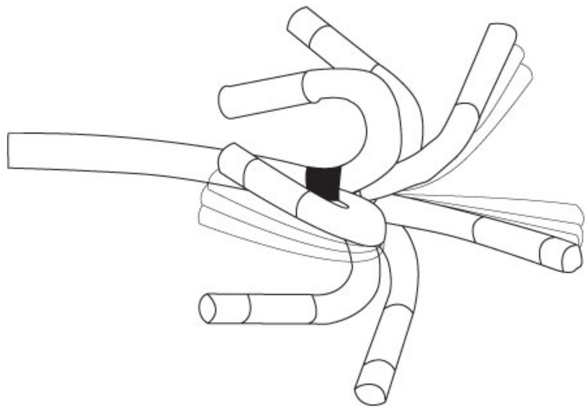

Figure 2-8
Video Borescope Articulation

Video borescopes typically have interchanging tips that modify the depth of field and field of view of the image and allow for different angles of view. There are also multiple tip technologies available that enable accurate surface measurements of the remote target. Three common video borescope measurement techniques are stereo, shadow, and comparison measurement.

Stereo measurement technology uses prisms or other methods to split an image. This allows the camera to capture left and right views with a precise angle of separation. The video borescope's computer algorithm then analyzes the position of user-placed cursors, applies a triangulation geometry calculation and returns the most accurate measurement (see Figure 2-9).

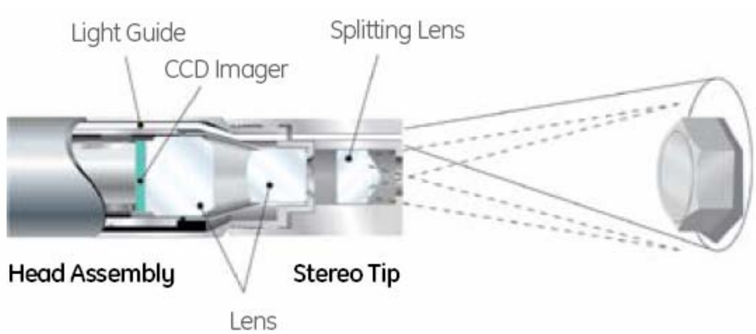

Figure 2-9
Stereo Measurement Optics

Shadow measurement technology is also based on triangulation of tip-to-target distance. The system projects a shadow across an inspection image. The position of the shadow in the image indicates the distance to the object. With this information, the system can calculate the size of user-selected features or defects, providing an accurate measurement value (see Figure 2-10).

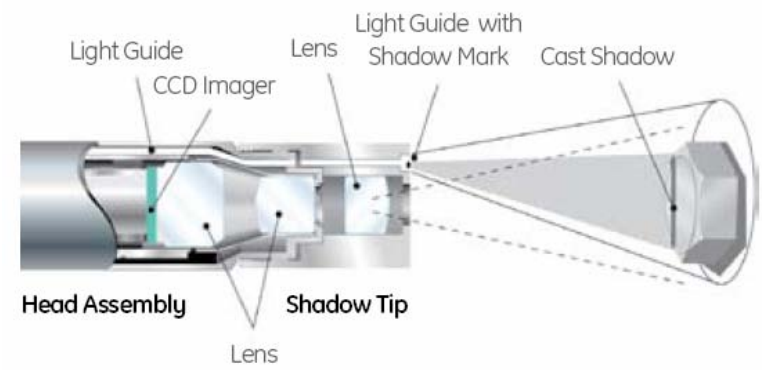

Figure 2-10
Shadow Measurement Optics

Finally, comparison measurement uses a known reference dimension in the inspection image to measure other objects in the same view and plane (see Figure 2-11).

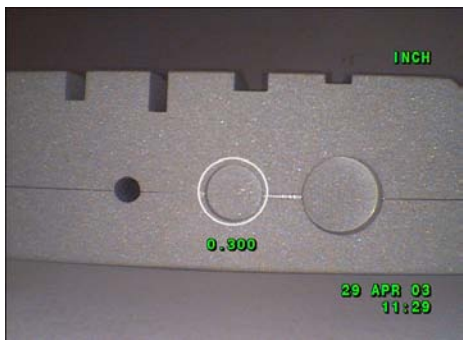

Figure 2-11
Comparison Measurement

CCD technology has also enabled the design of many different types of closed-circuit television (CCTV) camera systems that use unit-head video camera technologies along with motorized, remote focus, zoom, iris, pan, tilt, and locomotion to achieve remote imaging. These systems make up the fourth type of RVI technology and generally use light-emitting diodes (LEDs) or filament lamps for illumination. This diverse group of equipment comes in a variety of packages. The most basic and widely used of these systems for HRSG applications is the push camera for long-length boiler tube inspections. See Figure 2-12 for examples of different types of CCTV systems. These systems can inspect areas from 1 in. to 30 ft (25.4 mm to 9.14 m) in diameter and can reach lengths up to 2000 ft (610 m).

Pan Tilt Zoom Camera Push Camera Robotic Crawler

Figure 2-12
Typical RVI Equipment

Remote Visual Inspection Data Management

As RVI moves forward in today’s digital environment, it is enabling new strides in RVI data management, analysis, and archiving. Images of interest continue to be viewed and saved for documentation, but the process no longer has to end at the inspection step, disconnected from the information workflow. By leveraging software, RVI can now be an integral data capturing and management tool. Today the inspector can use integral image management software to create folders, organize and delete files, and even create reports. With the newest video borescopes, these reports or isolated images can be exported directly from the video borescope using e-mail or uploaded to a company network or World Wide Web for remote viewing. In short, today’s computing power and network connectivity are harnessed within video borescopes and greatly increase inspection productivity by driving workflow from the borescope workstation through software. Functions of embedded video borescope application-specific software can include organization of the images with meaningful names, standardization of the inspection process (so that comparable information is generated with less dependence on the expertise of the inspector), standardization and error mitigation of the inspection, and creation of a file structure for information recall to provide a way to categorize data for analysis.

Modern technology has truly ushered the RVI industry into the digital data management era. Fully digital data streams and improved optical and illumination technology provide better overall imaging quality, which translates to higher probability of flaw detection. Supporting this, enhanced data acquisition methods yield higher quality inspections. The video borescope functioning as a workstation provides networked inspection that can vastly improve the ability to share data and facilitate the use of remote expert analysis. This, in turn, improves decision making and enables archiving methods to increase inspection efficiency and planning. All of these advancements in RVI technology provide measurable improvements in inspection productivity and the quality of the visual inspection.

3
CASE STUDY: HEADER

Header ligament cracking has been identified as a reliability issue in a variety of steam system headers, from economizer to superheater headers. The problem of ligament cracking in high-temperature boiler headers was first identified in the early to mid-1980s when investigation of a header showing large creep deformation also revealed cracks in and around tube bore holes. In this particular header, it was determined that all of the inspected areas had ligament cracks extending from tube hole to tube hole. The cracks originated from inside the header, extending axially in the tube-hole penetrations and radially from these holes into the ligaments.

Since these initial findings, numerous high-temperature headers have been examined. Of the secondary superheater outlet headers inspected, approximately one-third were found to contain ligament cracking. Of the remaining headers surveyed, only a small percentage was found to have been damaged by this phenomenon, indicating that secondary superheater outlet headers are more susceptible to this form of cracking. Headers made of Cr-Mo steels have been found to be equally prone to cracking. No unique correlation could be found between the age of the header and its susceptibility to cracking. The cycling history, on the other hand, seems to be a major contributing factor to cracking.

The occurrence of ligament cracking has often been found in conjunction with stub-tube weld cracking (a form of damage related to creep deformation of the header), implying that creep deformation may be significant for ligament cracking. There is also a similarity between the appearance of ligament cracking in high-temperature headers and that in economizer inlet headers (that is, low-temperature headers); however, the economizer inlet header cracking is known to be caused by fatigue. The metallographic evidence obtained from the cracks in high-temperature headers indicates a fatigue-like propagation mode. Therefore, a controversy exists with regard to the mode of propagation of the cracking.

RVI is uniquely conducive to conducting header inspections. Detection of ligament cracks requires inspection of the tube-hole penetrations after some tubes have been cut off in order to allow access. The RVI equipment can be inserted through a cut tube or a hand-hole removed for repair or clean-out purposes. A photograph of the initial entrance into a header and subsequent discovery of ligament cracks is shown in Figure 3-1. This image shows a typical entry into a superheater header that is clean and free of debris. Ligament cracks generally initiate in the tube bore holes and are oriented parallel with the axis of the tube hole as seen in Figures 3-2 and 3-3. The initial cracks usually are numerous and may extend to the inside surface of the header, exhibiting a characteristic “starburst” pattern when the hole is viewed from inside the header as in Figure 3-4.

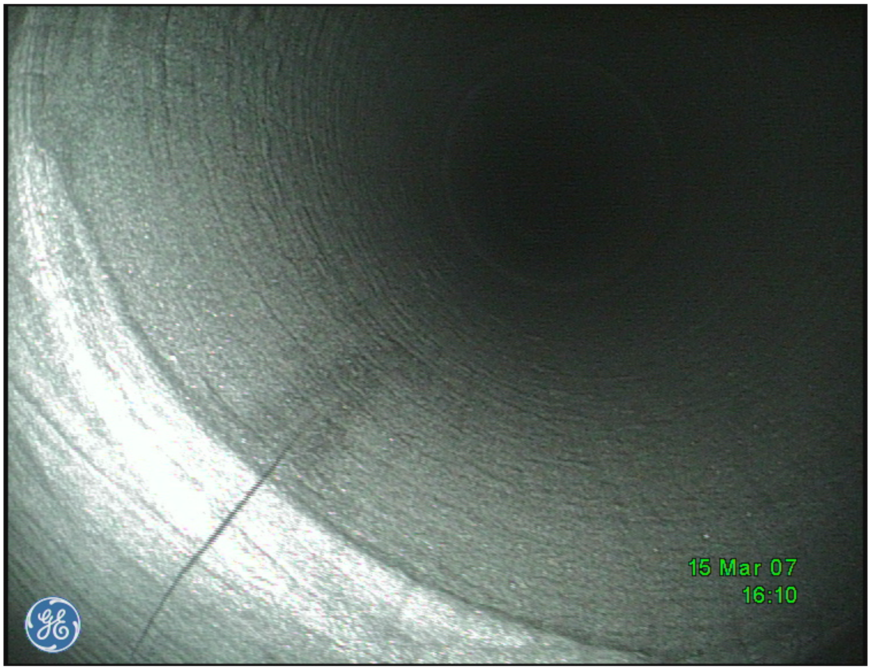

Figure 3-1
Initial Entry into a Cleaned Header
(The header surface shows signs of service but has been recently cleaned and is free of debris.)

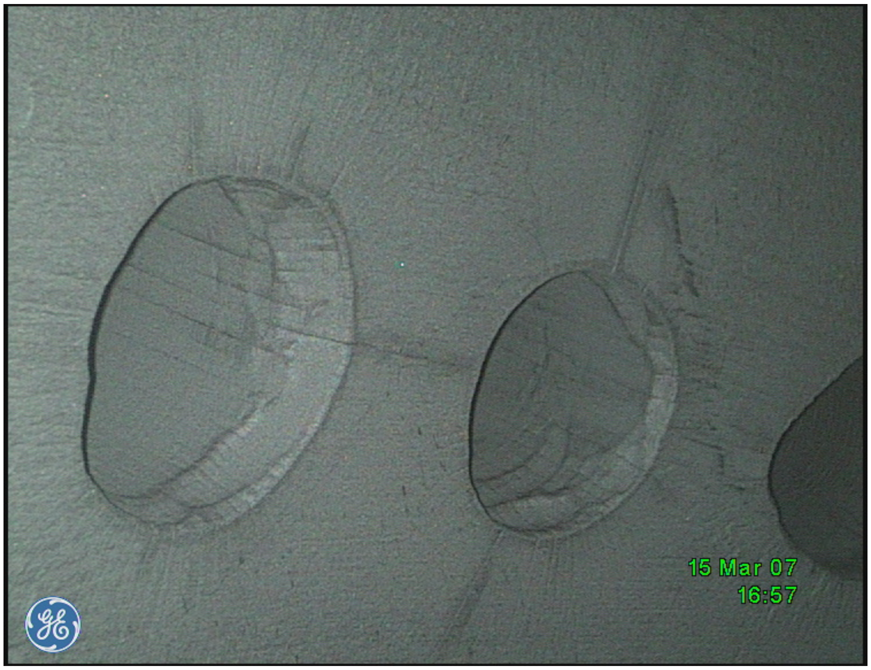

Figure 3-2
Cracks on Surface of Tubes and Header Ligaments
(Ligament cracks initiate on tube bore holes and are parallel with the tube axis.)

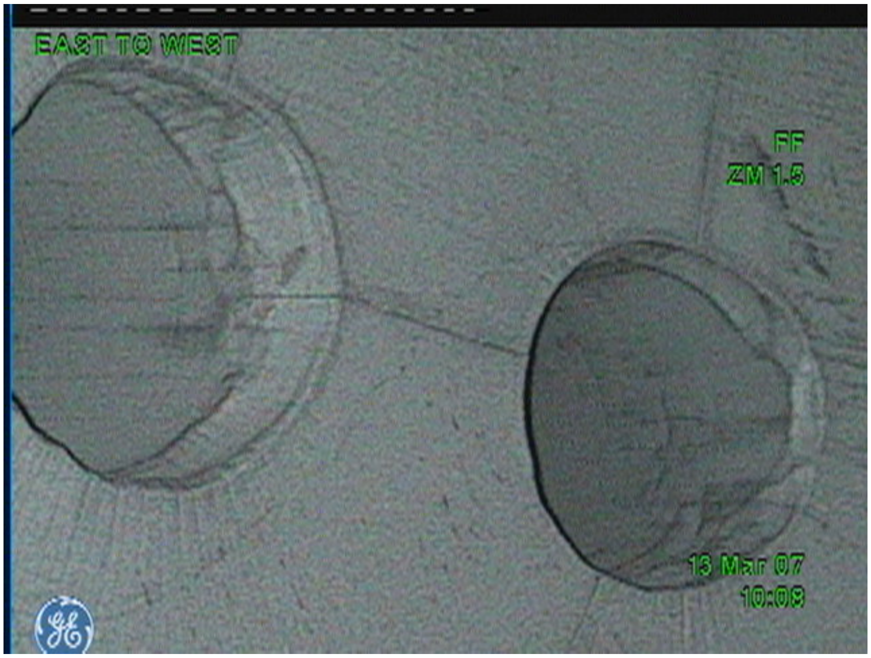

Figure 3-3
More Direct View of the Image from Figure 3-2 Showing the Indications in More Detail

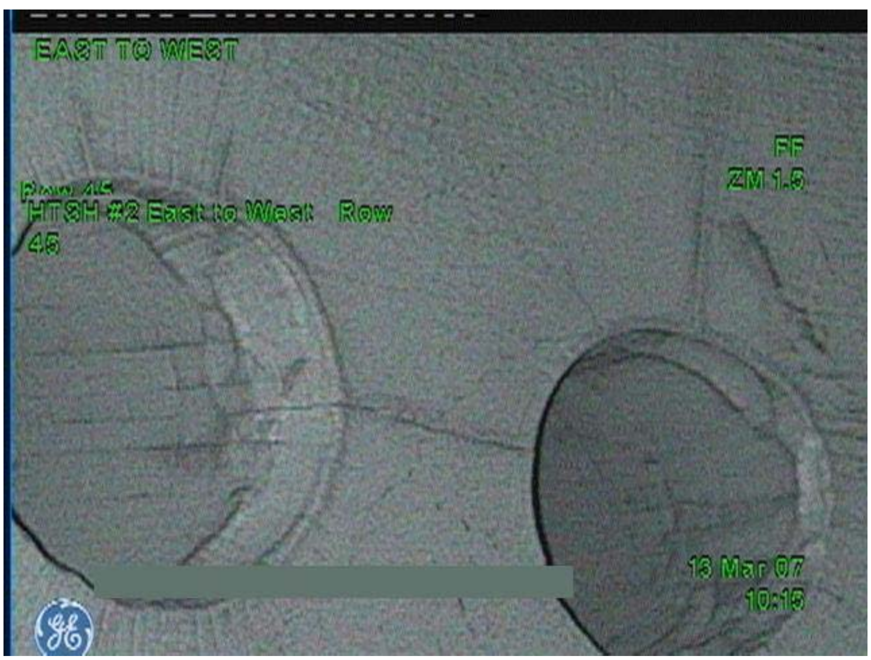

Figure 3-4
Close-Up of the Image from Figure 3-3

In most cases, these initial cracks are not visible unless the oxide layer is removed. The oxide layer usually is thickest at the location where ligament cracking is observed, implying that this type of cracking is associated with high temperature. Some RVI images from a more oxide-coated header can be seen in Figures 3-5 through 3-7.

Figure 3-5
Oxide Layer on the Header Wall Is Indicative of High-Temperature Service

Figure 3-6
Oxide Layer on the Header Wall, with Some Isolated Spalling, Is Indicative of High-Temperature Service

Figure 3-7
Oxide Layer on the Header Wall with a Darker Image from a Different Angle

Some of the initial cracks subsequently grow deeper into the ligaments between the holes, both inside the bore and on the inside surface of the header. Link-up of cracks between holes on the inside surface then leads to crack propagation from the inside of the header to the outside. Steam leakage can occur when these cracks link up with those cracks associated with the outside surface stub-tube welds.

Some debris can be found in headers as shown in Figure 3-8. This type of debris can be composed of loose scale or foreign objects that can lead to localized flow disruption and the subsequent short- or long-term overheating failures of tubes. The general overall cleanliness of a header can also be assessed by RVI as seen in the economizer inlet header in Figure 3-9. A typical starburst pattern as described earlier in a header stub can be seen in Figure 3-10.

Figure 3-8
Debris in a Header May Lead to Localized Flow Disruption in the Tube and Subsequent Overheating

Figure 3-9
Clean Header Condition Can Be Documented with RVI

Figure 3-10
Starburst Pattern Can Be Seen with Increased Definition

Other RVI images from header inspections can be found in Figures 3-11 to 3-15. Figure 3-11 shows a circumferential crack that runs through the tube penetration in the header, and Figure 3-12 shows a tube with a crack. Figure 3-13 shows an overall view of the penetrations into the header, and Figure 3-14 shows some header ligaments with no cracking. Finally, Figure 3-15 shows some low-temperature rust (hematite) that may have formed on recent cracks during an extended shutdown.

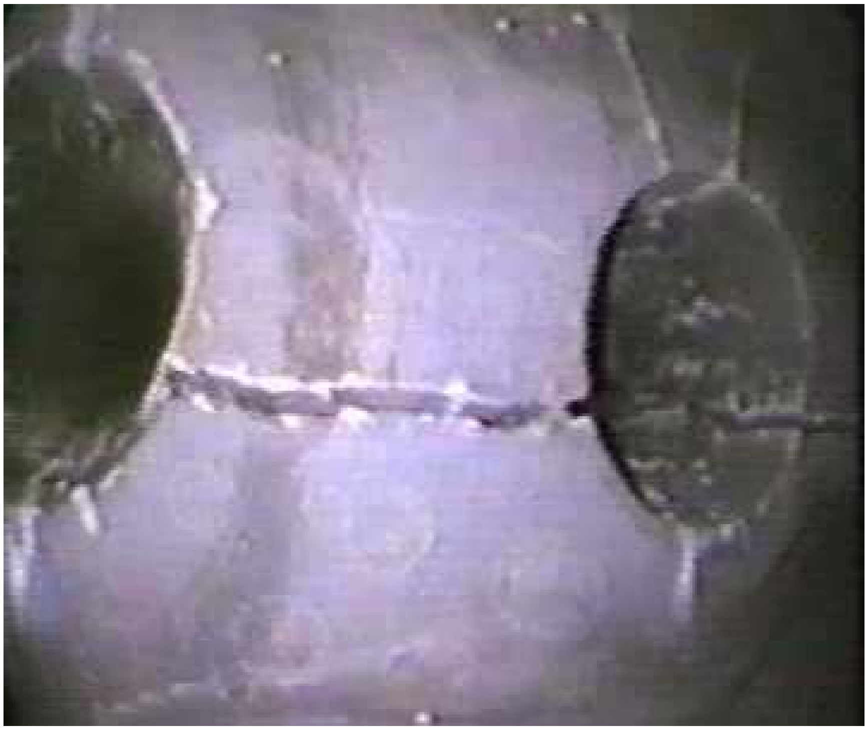

Figure 3-11
Circumferential Crack Running Through the Tube Penetration in the Header
(The relative width of the crack can be used to prioritize crack severity.)

Figure 3-12
Crack in the Tube Wall as Documented with RVI

Figure 3-13
Overview of Header Penetrations with Some Spalling of High-Temperature Oxide

Figure 3-14
Header Penetrations with No Cracking as Documented by RVI

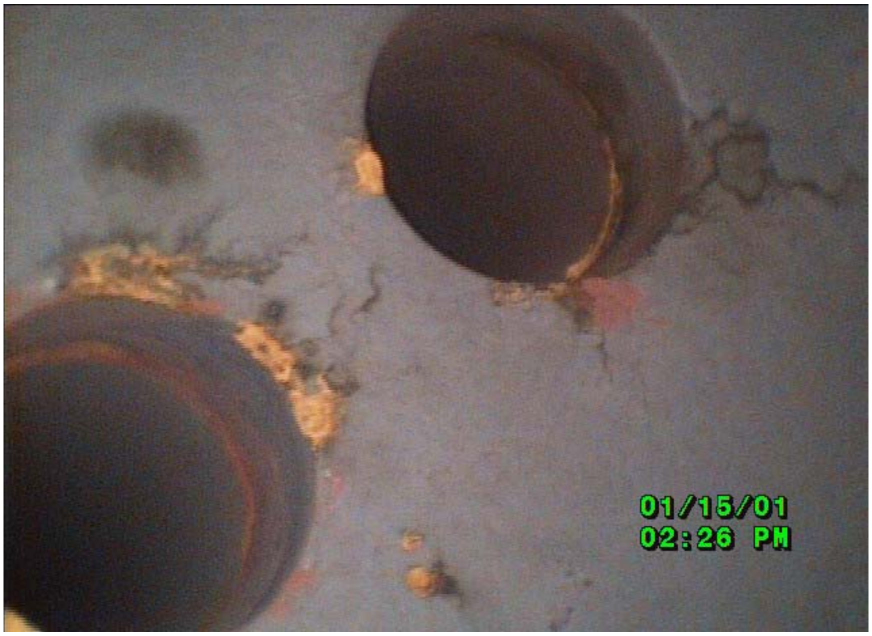

Figure 3-15
Lower Temperature Rust on Potential Cracks Can Be Identified by a Characteristic Reddish Color Using RVI

In addition to the RVI inspection, the oxide on the inside surface may be carefully removed to avoid the smearing over of any shallow cracks. A high-sensitivity dye penetrant is then applied and examined with a fiberscope. If any cracks are detected, knowledge of the length-to-width ratio of these defects provides a qualitative measure of the degree of damage.

Cracks seem to radiate from the bore of the tube holes or other openings. They develop from a combination of design, thermal cycles, surface finish, and age of material and stress loadings. In some cases, they develop and relieve the stress and arrest. In some cases, they reach a critical size and will grow with additional thermal cycles.

For large cracks, volumetric ultrasonic examination of the header with pulse-echo techniques can be used to determine the crack depth. A crack-growth analysis can then be performed to determine the remaining life or the effects of changes in operating conditions to extend header life. Findings from several recent investigations are helpful in identifying the "suspect" locations that need evaluation. It has been observed that the susceptibility to cracking could be related to locally high metal temperatures on the inside walls of the headers at the tube intersections and to the type of tube penetration design. Ultrasonic examination of tubes to characterize the oxide-scale thickness (and therefore temperature) and design drawings can be used to pinpoint locations in the header that need further evaluation.

Investigations into the ligament cracking problem have been undertaken by a number of organizations. Definition of the key parameters causing initiation and propagation has been attempted by the following:

- Installation of thermocouples in previously analyzed headers
- Metallographic examination of cracked material
- Measurement of the residual mechanical properties of ligament material
- Study of the formation and fracture properties of the steam-side oxide layer
- Stress analysis of various header configurations under transient conditions

Specialized ultrasonic examination techniques can be used to detect and determine crack depth, echo-dynamics, and other characteristics of the crack that will be available for follow-up inspections. The key is to have a proven NDE technique, automated digitally recorded data for follow-up comparison, and competent technicians to conduct these examinations. This information can then be used in a finite-element analysis (FEA) or fitness-for-service analysis performed by the NDE firm or other qualified engineering organization to provide a suitable level of confidence in the remaining-life results. In most cases, a detailed engineering analysis using risk assessment, FEA, and a comprehensive inspection program is required.

4
CASE STUDY: DESUPERHEATERS (ATTEMPERATOR)

In order to desuperheat superheated steam, water is injected into the stream. A specific type of desuperheater is chosen based on several system parameters, including desired inlet and outlet steam temperatures and pressures, the ratio of minimum to maximum flow (that is, turndown) in the affected steam line, the steam velocity, position, allowable residual superheat, and water supply. Based on these conditions, various desuperheater options exist. The simplest and least expensive type of desuperheater uses a standard nozzle to inject water into the steam flow. Attemperator-type desuperheaters are a step up from mechanical atomization units. The attemperator is basically a tube-shaped water diffuser surrounded by a water-filled chamber. The desuperheating water is preheated in the outside chamber before it is mixed with the steam in a central diffuser assembly. After leaving the diffuser's throat area, the steam/water mixture enters the main steam flow in a fog-like condition. Final heat transfer is achieved before the mixture contacts the steam-pipe's sidewalls. Water pressure into the attemperator is approximately equal to that of the steam flow. Attemperators are best suited for higher temperatures and pressures where atomizing steam is not available. RVI images of a desuperheated nozzle with a damaged liner can be seen in Figures 4-1 and 4-2.

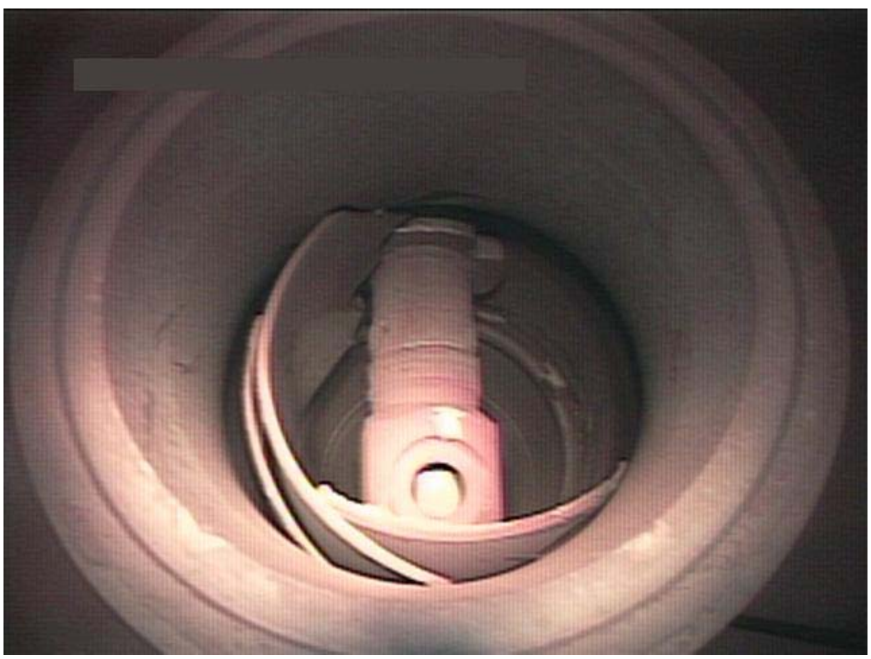

Figure 4-1
Desuperheater Nozzle with a Damaged Liner as Seen by RVI

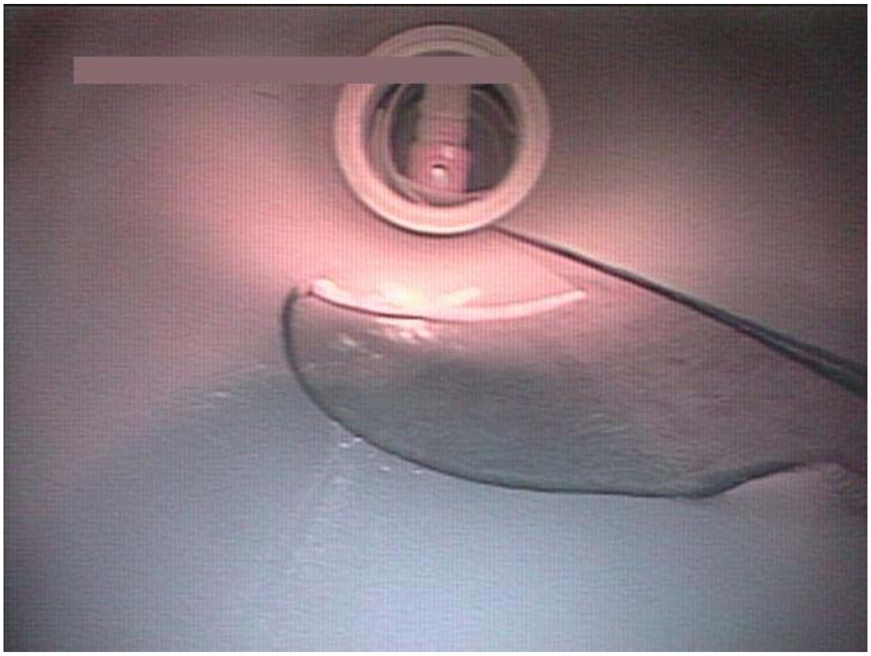

Figure 4-2
Missing Liner Section in a Desuperheater
(Fragments from this liner can be seen in Figure 4-1.)

Adding a venturi section to either a mechanically atomized or attemperator-type desuperheater can increase its performance by boosting the steam's velocity in the zone where it absorbs cooling water. Annular venturi desuperheaters consist of a cone-shaped device that can suffer from cracking as seen in the RVI image of an attemperator nozzle crack in Figures 4-3, a liner crack at a stop block in Figure 4-4, and a crack in the liner near a nozzle in Figure 4-5. Damage can be seen in the liner in these images that may lead to decreased superheater performance and possible foreign object damage to equipment downstream.

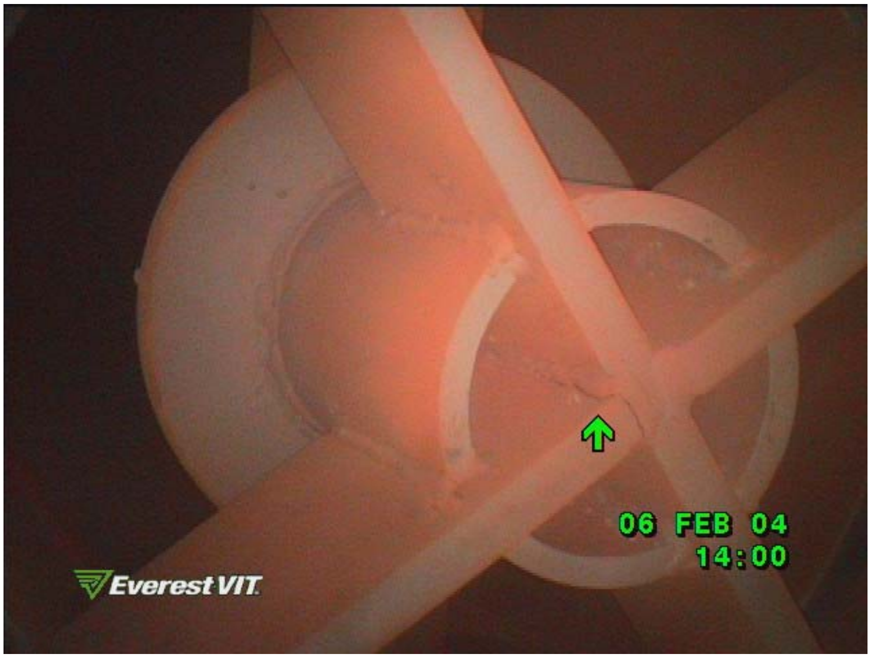

Figure 4-3
RVI Image of Cracking in an Attemperator Nozzle
(Cracking may progress and lead to failure of the nozzle.)

Figure 4-4
Crack in a Liner Attachment near the Stop Block
(Cracks may progress and cause additional damage.)

Figure 4-5
Crack in a Liner near the Nozzle
(Cracks may progress by vibration and cause additional damage downstream.)

5
CASE STUDY: BOILER TUBE THERMAL FATIGUE

Boiler tube failures have been the leading cause of unit unavailability, and RVI can be used to diagnose numerous root causes of these failures.

Thermal fatigue involves the variation of stress caused by fluctuating temperatures. Room-temperature fatigue results from the variation of stress caused by changing loads, but environmental effects are considered constant. At elevated temperatures, crack propagation is enhanced by the formation of oxides or other corrosion deposits. In the simplest case of cyclic stress at elevated temperatures, the protective oxide will crack and expose fresh metal to further oxidation. A surface crack is “wedged” open by the formation of these scales because the oxide occupies a greater volume than the metal from which it forms. The oxide “wedge” imposes higher stresses at the crack tip, and the crack propagation rate increases.

Boiler tube failures can result from cracks that initiate and grow through thermal fatigue. Thermal fatigue cracks develop from excessive strain of the tube steel by rapid cycling of the tube metal temperature. Conditions for thermal fatigue crack initiation and propagation are produced through large and sudden changes in tube surface temperature that cause a differential temperature across the tube wall thickness. If the change in temperature is severe and rapid, thermal shock of the tube occurs, and failure can be experienced within 10 or fewer thermal cycles. Wetting of a tube surface at high temperature by water having a considerably lower temperature can produce high tensile stresses on the wetted surface until the water evaporates. When the surface is cooled, the metal will want to contract but will be prevented from doing so by the metal that remains at the higher temperature. The restriction of the metal’s contraction results in high tensile stresses on the surface and produces multiple cracks. This sudden cooling of the tube surface is called *quenching*.

RVI of boiler tubes is typically performed with video probes or push cameras. Access into the tubes can be gained from steam drums or headers or by cutting the tubes that need to be examined. An RVI image of a “good” boiler tube is shown in Figure 5-1. This is the typical appearance of an economizer tube after a two-week shutdown. Figure 5-2 shows a linear crack in the same economizer tube as that shown in Figure 5-1. The crack is longitudinal and discontinuous. Figure 5-3 shows signs of “mud-cracking” on the inner surface of the economizer tube. This cracking may be because of cracking in the oxide layer/deposit on the inner surface or to actual thermal fatigue.

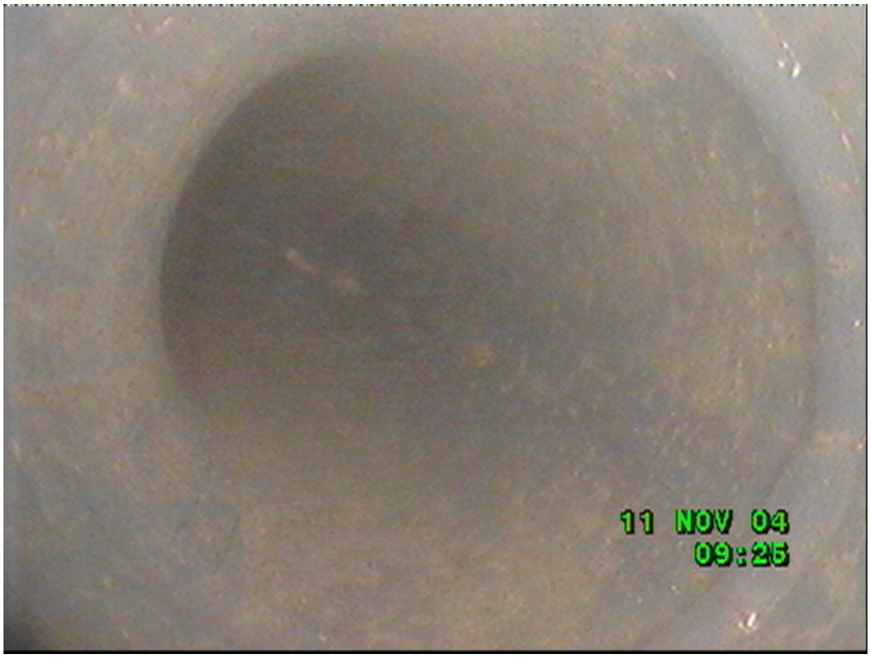

Figure 5-1
RVI Image of a "Good" Economizer Tube Two Weeks After Shutdown
(The tube has a "normal" coating of high-temperature oxide.)

Figure 5-2
Longitudinal Crack in an Economizer Tube
(Cracks are noted by dark linear indications on the remote visual inspection image.)

Figure 5-3
Crazed “Mud-Cracking” Type of Damage Found on the Inner Surface of an Economizer Tube

Figure 5-4 shows an RVI image of a more pronounced linear crack in a tube. Although depth measurement is not quantifiable with RVI only, this crack is more pronounced than the one shown in Figure 5-2. Also in Figure 5-4 are reddish colored “blooms” of magnetite. This is indicative of low-temperature hematite that has formed on the fresh iron surface of the cracks and has occurred during the two-week shutdown. The darker black color of the more pronounced linear crack is an indication that this crack was present during the service of the boiler and has a higher temperature black iron oxide known as *magnetite*. A similar image is also shown in Figure 5-5.

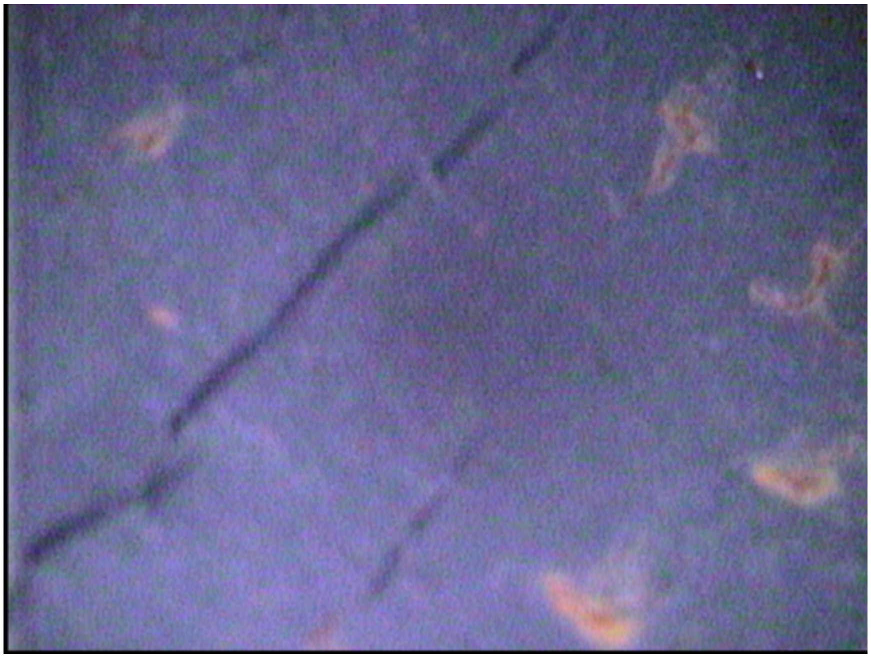

Figure 5-4
Reddish Color Rust "Blooms" of Hematite in the Magnetite Scale
(Longitudinal cracks are also present in the image.)

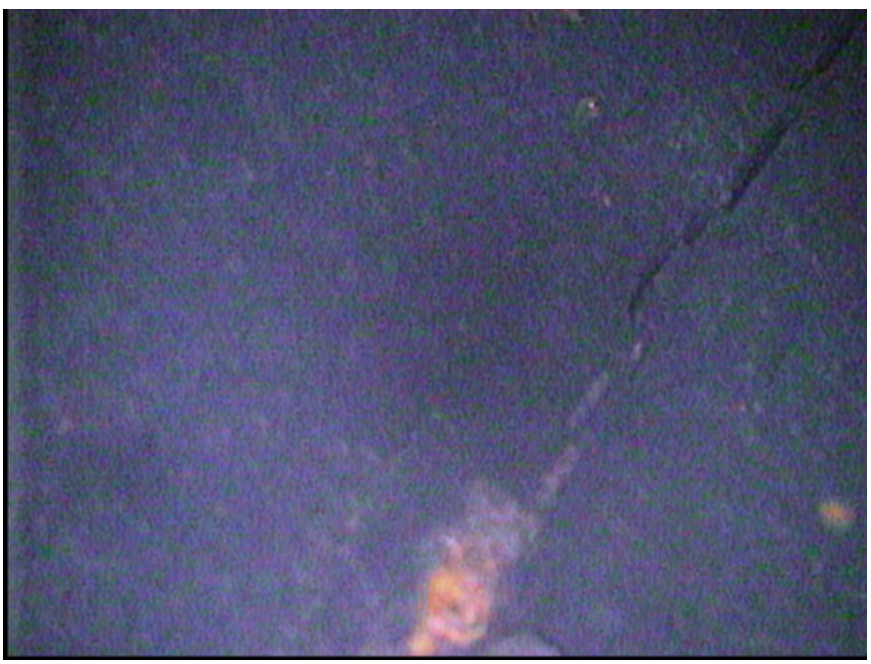

Figure 5-5
Close-Up Image of Red Rust from a Longitudinal Crack Found in the Tube
(Cracks may have been present or opened more during a recent shutdown.)

A tube with multiple linear cracks that were formed during high-temperature exposure is shown in Figure 5-6. Again, depth estimation is only qualitative, but the absence of low-temperature hematite on the crack surfaces suggests that these cracks were present during higher temperature operation.

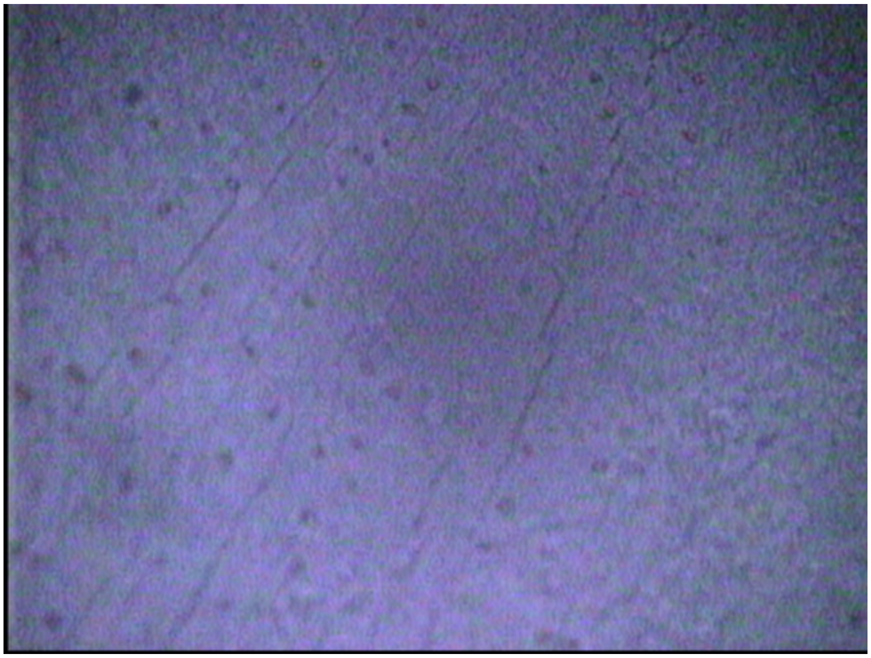

Figure 5-6
Multiple Longitudinal Cracks Found in an Economizer Tube
(This type of cracking is indicative of thermal fatigue from hot/cool or wet/dry cycles.)

Figures 5-7 and 5-8 show areas of an economizer tube with more severe mud-cracking. In these areas, the nonlinear “craze” pattern is present. In addition to the red rust (hematite) in the cracks, hematite is also present on the uncracked tube surfaces where the black high-temperature magnetite had spalled as a result of the mud-cracking.

Figure 5-7
More Severe Crazed Cracking Than That Seen in Figure 5-3
(Some of the oxide layer has spalled in this region.)

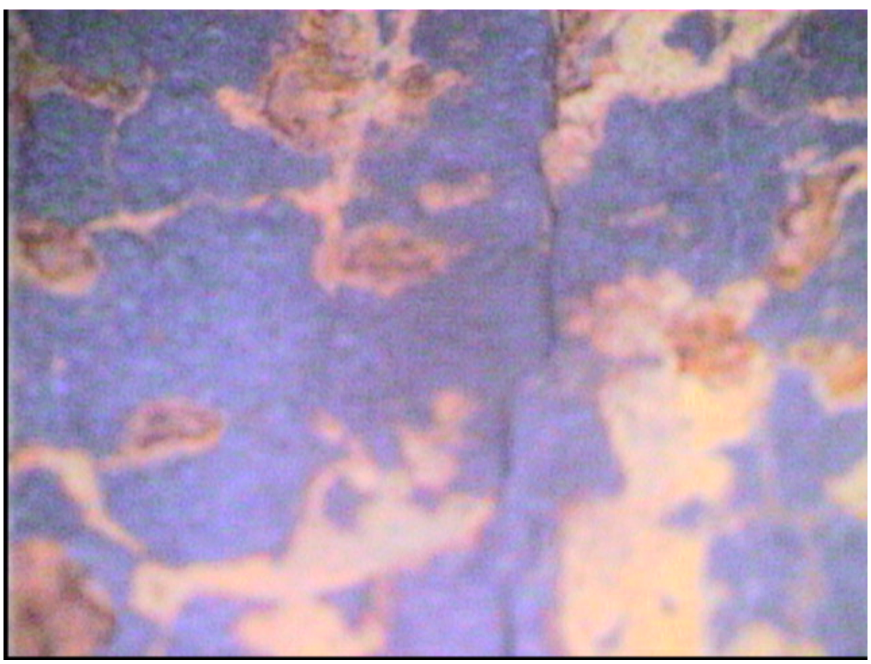

Figure 5-8
Close-Up of the Area with the Spalled High-Temperature Black Magnetite Oxide Layer and Cracks in the Tube Surface

6
CASE STUDY: BOILER TUBE HYDROGEN DAMAGE

Boiler tube failures caused by hydrogen damage result from fouled heat-transfer surfaces and an acidic (that is, low pH) condition of the boiler water. Hydrogen damage is sometimes incorrectly referred to as *hydrogen attack* or *hydrogen embrittlement* in which carbon steel will become brittle from the combination of hydrogen and carbon, which forms gaseous methane (CH_4) at the grain boundaries in the tube steel. Hydrogen damage develops from the generation of hydrogen during the rapid corrosion of the internal surface of the tube. The hydrogen atoms migrate through the tube steel where they can react with the iron carbide (Fe_3C) to form the methane. The larger methane gas molecules become trapped between the grain boundaries and cause a network of discontinuous internal cracks to be produced. These cracks grow, and some will link up to cause a through-wall failure.

Hydrogen may be generated during operation of the boiler with low pH water chemistry from the ingress of acidic salts through condenser leakage, contamination from chemical cleaning, or malfunction of the chemical control subsystem. Also, hydrogen may be generated in the concentration of the corrosive contaminants within the deposits on the internal tube wall, especially in crevices, shallow pits, and under weld backing rings.

Hydrogen damage usually produces a blowout of a rectangular section of the tube in a manner described as a *window*. The edges of the fracture are thick because the tube steel has been weakened by the decarburization of the iron carbide (cementite) and by the formation of the methane-filled micro-fissures. Hydrogen-damaged tube steel will crack if tensile stress is applied because the metal fails in a brittle manner.

Hydrogen damage can occur with little or no apparent wall thinning from the corrosion process; however, in most cases, localized metal wastage will occur. In these cases, RVI is particularly useful in detecting the problem because the corrosion process will produce a large, deep pit or gouge that is covered by a dense multi-laminated oxide deposit as seen in the RVI images shown in Figures 6-1 and 6-2.

Figure 6-1
Inner Surface Deposit with a Pit as Found by RVI
(This type of deposit and subsequent pitting may be indicative of hydrogen damage in waterwall tubes.)

Figure 6-2
Layered Deposit on a Pitted Area in a Waterwall Tube as Seen in Figure 6-1

The localized metal loss on the inner surface of this waterwall tube can more clearly be seen in the RVI images in Figures 6-3 and 6-4. Most times after failure, the deposit (as seen in Figure 6-5) may be blown or flushed off by the failure event.

Figure 6-3
Localized Wall Loss in the Pit Seen in Figure 6-1
(Removal of the tube section would confirm the presence of hydrogen damage.)

Figure 6-4
Additional RVI Image of the Pitted Region Seen in Figure 6-1
(Actual penetration depth can be confirmed by ultrasonic examination.)

Figure 6-5
Layered Deposit on a Pitted Region
(Such deposit may confirm external ultrasonic examination or identify areas for external ultrasonic examination.)

NDE techniques can be applied to determine the extent of the hydrogen-damage corrosion. One such case study involved automated ultrasonic thickness measurement techniques using dual-element transducers and a multiplexing data acquisition system to detect where tube metal wastage had been experienced. When automated ultrasonic nondestructive testing methods have been applied, tube damage verification can be conducted using RVI to confirm corrosion locations. This was the situation in the previous RVI images and also in the RVI image shown in Figure 6-6.

Figure 6-6
RVI Image of a Pitted Region with Hydrogen Damage
(This region was subsequently removed for laboratory examination.)

7

CASE STUDY: BOILER TUBE CLEANLINESS AND PRE-COMMISSIONING

Initial cleaning of HRSGs (that is, pre-cleaning or commissioning) or post-service chemical cleaning of HRSGs is a critical task for long-term corrosion protection and HSRG life. There have been a number of cases in which pre-commissioning or initial cleaning had not been performed or was inadequately conducted, which led to major equipment damage within weeks or months of initial operation. RVI is a proven method to determine pre-service cleanliness and confirm the effectiveness of cleaning processes.

In some more recent designs, the HSRG engineering, procurement, and construction contractor and the equipment manufacturer have worked together to develop a method that would leave no mill scale or lubricants on the inner diameter of the tubes, thus eliminating the need for an alkaline boil-out or chemical cleaning. This can significantly reduce the cost and time at the end of a project when critical resources are generally at a premium. This type of pre-commissioning procedure calls for a high-velocity flush followed by steam blows.

Equipment must be pre-commission cleaned to remove dirt, mill scale, and other contaminants that are present on metal surfaces after fabrication. If not removed, these particles can dislodge and damage or plug critical sections of the equipment.

Boiler feedwater piping downstream of the deaerator is cleaned to remove scale or dirt, which could later dislodge and foul boiler tubes. The heat transfer sections of boilers are cleaned to obtain clean metal surfaces for efficient heat transfer. Most industrial boilers operate on water that has been given some kind of external treatment such as hot lime-zeolite or demineralization. In addition, chemicals are added to the boiler water in order to further condition the water and thereby minimize corrosion and fouling in the boiler. Eventually, however, almost all boilers require cleaning to remove accumulated deposits. The types of deposits present are directly related to the quality of water and the treatment being used.

Deposits in boilers are usually the result of impurities in the water such as hardness, silica, and corrosion products. In most low-pressure boilers, some hardness is present in the feed; various phosphate compounds are added to form sludge with the calcium and magnesium ions, which can then be blown down from the bottom drum.

High-pressure boilers operate on essentially pure water in a closed system. Steel construction is used for the boiler, lines, and so on, and copper alloys are used in main condensers and heaters. Fouling and scaling are due to interaction between water and the metal during many long hours of exposure at operating conditions and the much lesser exposure to water or water and air during downtime. Fouling may be influenced by very small amounts of chemicals added for pH control and oxygen scavenging.

The black magnetic iron oxide, which is the stable oxide phase under operating conditions, is partly formed *in situ* on tube surfaces, where it provides a protective coating that stifles further reaction, and partly by the deposition of iron oxide carried into the boiler by the feedwater. Even though this may be only a few parts per billion in the water, the cumulative amount can become significant when water is delivered to the boiler in large quantities. For example, one 224,000 lb/hr (approximately102,000 kg/hr) boiler with 0.1 ppm iron in the feedwater takes in 250 lb (approximately 115 kg) per year of iron oxide.

The copper originates from outside the boiler and is present in the feedwater in concentrations in the low parts per billion range. Normally the copper phase is very finely divided and may be mixed with particles of Fe_30_4 in a manner that escapes detection by the naked eye. In some cases, if there has been excessive accumulation of deposits in local areas, masses of copper crystals may be visible. Instead of being intimately mixed together, the Fe_30_4 and Cu may form separate masses.

Calcium and magnesium may be present due to an in-leakage of water into a condenser or to the small quantities present in the demineralized plant effluent. When phosphates are used for internal treatment, calcium phosphates will form and may deposit on tube surfaces—especially if intermittent blowdown is inadequate. Magnesium is usually precipitated as the oxide if sufficient alkalinity is present in the boiler water. Silica is normally reduced to a very low level in the demineralization plant in order to minimize the potential for turbine fouling but may be present in some boilers.

RVI may be used to assess the initial or ex-service cleanliness of HRSG components. An RVI examination of an economizer upper header in a CO boiler revealed significant deposition as shown in the overview in Figures 7-1 and 7-2. A closer RVI image shows some of the spalled deposit in Figures 7-3 and 7-4.

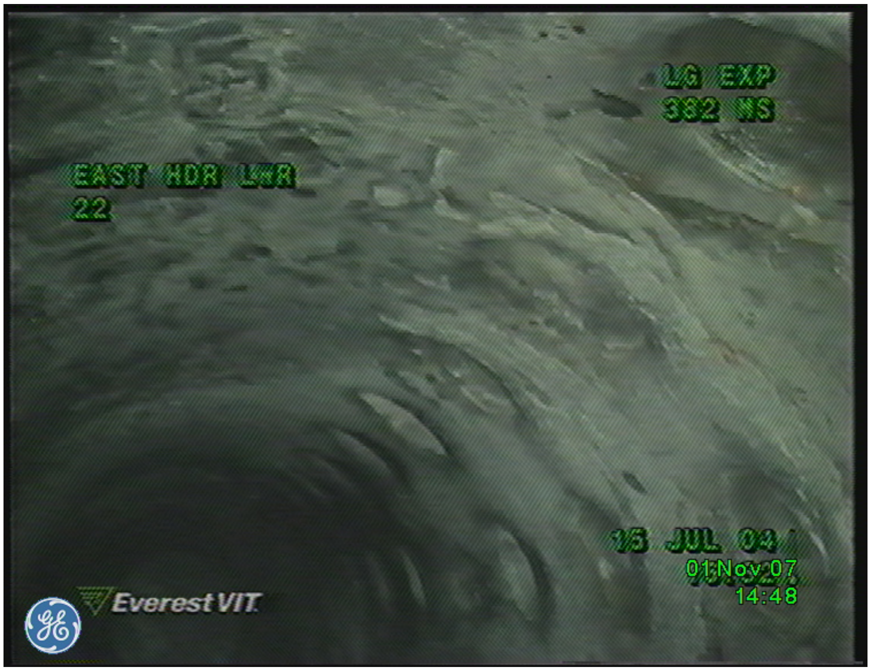

Figure 7-1
Upper Economizer Header with Significant Surface Deposit as Identified by RVI

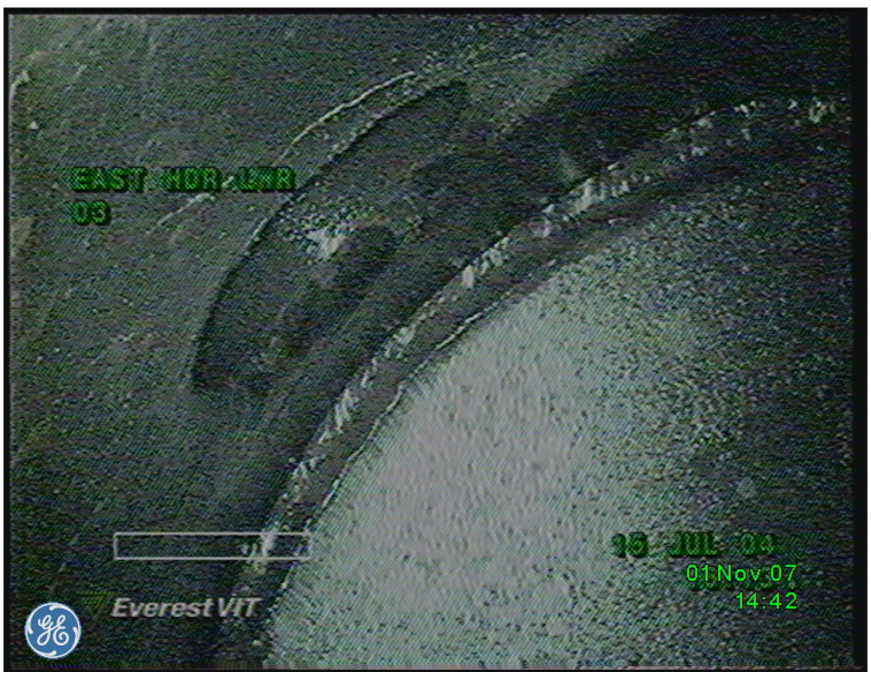

Figure 7-2
Additional RVI Image of the Upper Economizer with Significant Surface Deposit
(Deposit is more than what would be expected from normal properly treated service.)

Figure 7-3
Close-Up Image of the Upper Economizer with Significant Surface Deposit
(RVI should be reviewed with a water treatment specialist for additional evaluation.)

Figure 7-4
Layered Spalling in the Upper Economizer with Surface Deposit
(This amount of deposit could be considered excessive and should be further evaluated.)

The lower header was also examined, and debris and low-temperature rust are shown in Figures 7-5 and 7-6. Some loose and layered accumulation of higher temperature oxide was also found in the lower header as seen in the RVI images shown in Figures 7-7 and 7-8. Additional destructive samples will quantify the amount and composition of deposit present, and a competent chemical cleaner should be contracted for the safe, environmentally compliant removal of these deposits.

Figure 7-5
Lower Economizer Header with Some Accumulation of Low-Temperature Rust
(This may be a result of inadequate blowdown practices.)

Figure 7-6
Low-Temperature Rust and Debris in the Lower Economizer Header Which Should Prompt an Evaluation of the Need for Chemical Cleaning

Figure 7-7
An Additional RVI Image of Low-Temperature Rust and Debris in the Lower Economizer Header That Can Be Used in a Follow-Up Evaluation by a Water Treatment Specialist

Figure 7-8
RVI Image of High-Temperature Scale and Debris in the Lower Economizer Header That Can Be Used for an Evaluation by On-Site or Corporate Specialists

8
CASE STUDY: BOILER TUBE LEAKS

RVI may be used to safely identify leak areas in equipment removed from service because of known leakage. Equipment can be pressurized and examined with RVI where human entry may not be safe or prudent or is not accessible without some significant scaffolding or staging. One such example is provided in Figure 8-1, which shows a leak in an HRSG economizer tube under 100 psi (689 kPa) pressure. The circular serrated external fins on the economizer tube would obscure easy direct visual inspection from a distance, and the exact nature of the leak might not be ascertained until much more time and effort have been spent to gain access.

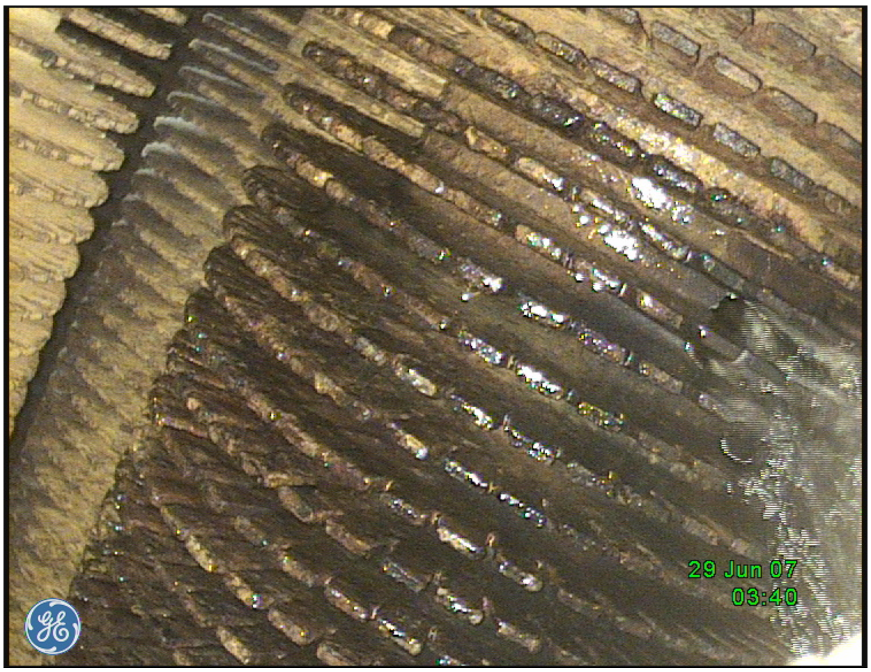

Figure 8-1
External RVI Image of a Leak in an Economizer Tube Can Be Found Before Significant Staging or Personnel Deployment Is Accomplished

Also, due to the “nesting” of tubes in the economizer section, direct access may not be achievable—so RVI may allow for identification of the leak from a remote area, as in the case in Figure 8-1. This image was captured by a small-diameter video probe that was routed through a tight nesting of tubes. In cases such as a location 24 ft (7.3 m) above the actual leak, the most expedient method of repair may be pluggage of that specific tube at the header rather than significant removal of tubes in order to access the leak.

9
CASE STUDY: BOILER TUBE FLOW-ASSISTED CORROSION

Sudden failures of high-pressure, high-temperature feedwater piping by flow-accelerated corrosion (FAC) have been shown to be a problem in HRSGs. The conventional condensate/feedwater treatment of oxygen-scavenging/pH-conditioning, used for many years by utilities throughout the country, has proven to be the culprit. The reducing environment generated by this chemistry will induce FAC, in which gradual thinning of pipe or tube walls is localized and leads to sudden catastrophic failure.[5]

Some RVI images of FAC, as reported by utility operators, are shown in Figures 9-1 through 9-5.

Figure 9-1
Flow-Accelerated Corrosion as Found by RVI in a Boiler Tube: Localized Wall Loss May Compromise Tube Integrity

---

[5] Brad Buecker, “Flow-Accelerated Corrosion: A Critical Issue Revisited,” *Power Engineering,* July 2007, pp. 20–24.

Figure 9-2
Flow-Accelerated Corrosion as Found by RVI in a Boiler Tube: This Damage Has Been the Cause of Tube Failures

Figure 9-3
Flow-Accelerated Corrosion as Found by RVI in a Boiler Tube: This Type of Damage May Be Confirmed by External Ultrasonic Examination

Figure 9-4
Flow-Accelerated Corrosion as Found by RVI in a Boiler Tube: Tube May Require Removal for Additional Laboratory Evaluation

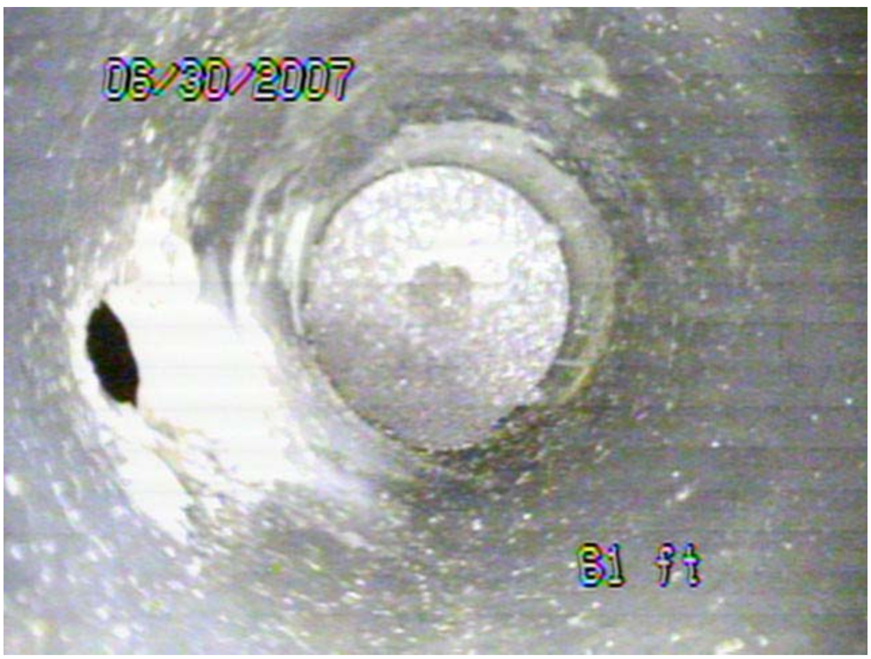

Figure 9-5
Flow-Accelerated Corrosion with a Hole as Found by RVI in a Boiler Tube

10
CASE STUDY: CORROSION FATIGUE

Although most HRSGs are less than 20 years old, corrosion fatigue has been a well-documented mode of boiler tube failure in conventional utility boilers. When boiler equipment is subjected to extensive service lives (more than 20 years of service), many areas of constraint or attachment may develop cracking problems. Boiler tube failures can result from corrosion fatigue, which is a damage mechanism resulting from the combined effects of a corrosive environment and cyclic stresses. Many times, corrosion fatigue failures can develop in locations in transitional areas of boilers such as scallop bars, burner boxes, buckstay attachments, and headers that may not be completely enclosed in the firebox. Failure and venting of the steam external to the firebox or flue gas path can be fatal to personnel in the local area.

Corrosion fatigue cracks develop from the interaction of corrosion processes and fluctuating stresses that are produced through many circumstances. Examples include concentration of stress from the formation of pits, notches, or other surface irregularities due to corrosion on the tube surface or to external welding—which includes temporary attachment of supports during construction or repairs. These processes may initiate cracks that grow as a result of the fluctuation of stress due to cyclic thermal expansion and contraction.

Figure 10-1 shows an RVI image of multiple parallel longitudinal cracks in a waterwall boiler tube after a through-chemical cleaning. This image and the others that follow were captured with a 1-in. (25.4-mm) diameter push camera. The tubes were accessed from a steam drum at the top of the boiler.

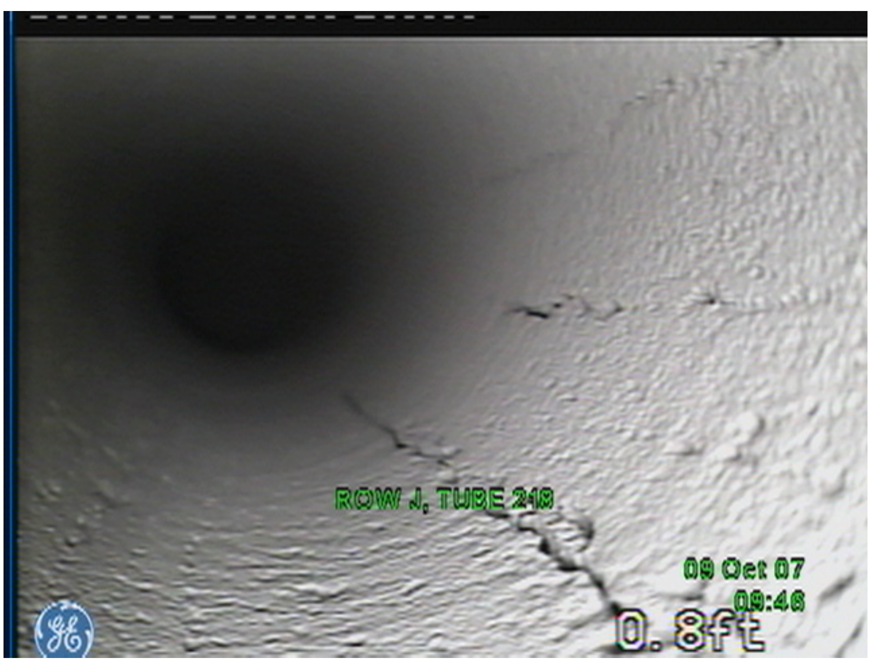

Figure 10-1
Corrosion Fatigue Cracking in a Boiler Tube as Identified with RVI
(There are several longitudinal cracks in this image.)

A corrosion fatigue crack can initiate and propagate to failure in fewer stress cycles and at lower stress levels than would normally be required to produce a fatigue failure in a clean air environment.

The fracture surface of a corrosion fatigue crack will be thick-edged and perpendicular to the maximum tensile stress or opposite the external weld restraint. The fracture surfaces are coated with a tenacious oxide deposit; however, the oxide may be washed away by the water or steam leakage after the failure. Multiple parallel cracks are usually present at the metal surface near the failure. A microscopic examination is required to confirm that a corrosion fatigue failure mechanism was involved in any actual failure incident. Fatigue crack-arrest lines or “beach marks” are not found because these features become undistinguishable due to corrosion on the crack surface. The cracks are straight, relatively wide open, and blunt at the tip. Intergranular cracking or void formation is generally not present.

The oxide deposit can play an important role in crack propagation because the volume occupied by the oxide is greater than the volume of metal from which it formed. The corrosion product oxide deposit prevents the crack from closing during the compression portion of the stress cycle and increases the stress at the crack tip. The crack propagates faster due to the formation of the oxide wedge in the crack.

Corrosion fatigue cracks can initiate from either the external or internal tube surface and are often associated with pitting, welding defects, notches, or other surface irregularities. Internal aligned pits on the inner surface of a tube can lead to a corrosion fatigue failure as seen in a typical RVI image in Figure 10-2.

Figure 10-2
Corrosion Fatigue Cracking in a Boiler Tube
(Numerous aligned cracks in this pattern may indicate external attachment.)

Thermal cycling and expansion constraints are the primary strain loads, and high-temperature oxidation is the primary corrosion process. Cracks that originate on the outside surface are the result of adverse stresses from restricted thermal expansion. Cracks that originate on the inside surface are the result of preferential corrosion from dissolved oxygen or acidic conditions at a location with high stress. An RVI image shown in Figure 10-3 shows a cluster of cracks on the inner surface of an economizer tube, and an additional RVI image of a similar cluster-type accumulation of cracks can be seen in Figure 10-4.

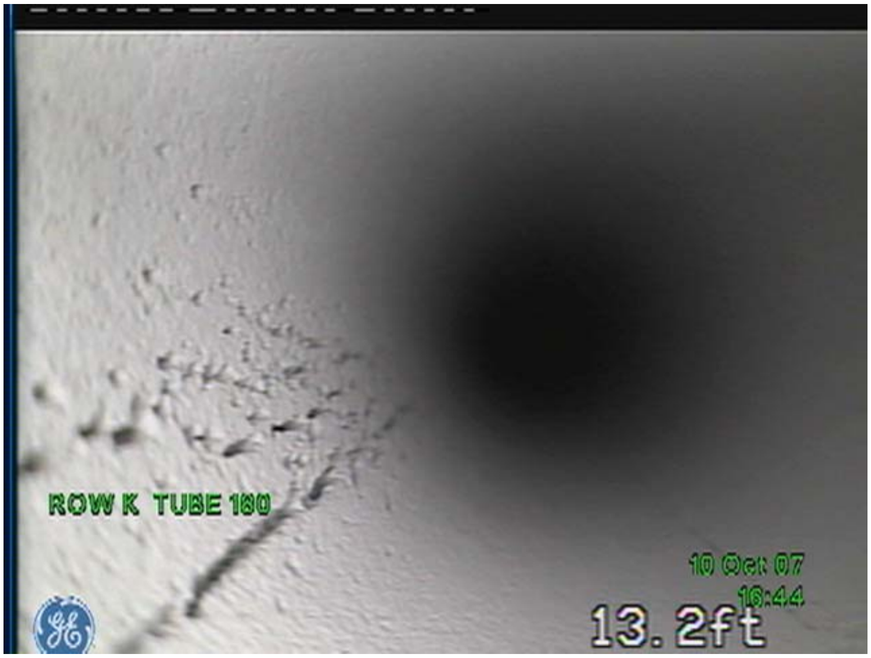

Figure 10-3
Corrosion Fatigue Cracking in a Boiler Tube
(An additional RVI image of similar cluster type accumulation of cracks can be seen in Figure 10-4.)

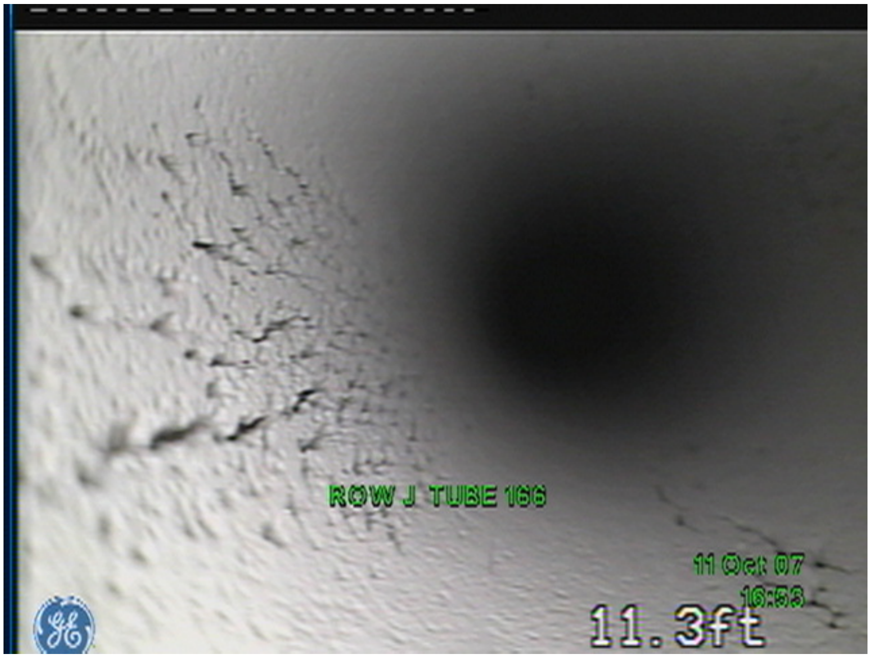

Figure 10-4
Corrosion Fatigue Cracking in a Boiler Tube May Not Be Detectable by External Examination Because of Access Requirements

Corrosion fatigue cracks originating on the external surface result from differences in thermal expansion rates and directions between joining boiler components. Typical failure locations include the following:

- At tubing
  - Penetrations through the walls, roof, or tube sheets
  - At tubing connections to inlet and outlet headers or drums
  - At tubing attachments where binding has occurred or a rigid connection has been made
  - At the end of the membrane of waterwall tubing
- Where tubes are joined by a large plate

Fatigue cracks of this nature have sometimes been referred to as *stress-induced corrosion cracks* or *stress-assisted corrosion cracks*. Failures have been experienced throughout the boiler but have been predominant in the lower half of waterwalls and inlets to economizers. Typical locations are tube attachments where thermal expansion can be restricted during transient conditions. Such locations are the following:

- In tangent tube membrane walls where the tubes are joined by welding on the cold side that results in placing the plane of the neutral axis off the tubing centerline.
- In lower waterwall areas where tubes come off the lower headers to form the lower slope or side walls. Circumferential cracks have been experienced toward the ends of the headers and where the tubes are welded to seal plates.

- In waterwall areas where tubes are attached by clips or welded to tie bars and buckstay attachments.
- In economizer tubing at the feedwater inlet where oxygen levels are the highest.
- In hairpin bends in tubing where high residual stresses are likely to be present from the forming process.

The following NDE methods are used to detect corrosion fatigue cracks:

- RVI through accessible drums and headers
- Dye penetrant and magnetic particle examination for external-surface-originated cracks
- Ultrasonic and radiographic examination for internal-surface-originated cracks

Corrosion fatigue usually develops simultaneously in a multitude of tubes; therefore, when a failure is experienced, it is likely that cracks are present in other tubes at similar locations. NDE of tubes in the vicinity of a failure or at locations throughout the boiler with similar conditions should be conducted to ensure that an incipient crack is not present. The tubes at the ends of the header are most likely to be cracked because the expansion deflection is the greatest at this location.

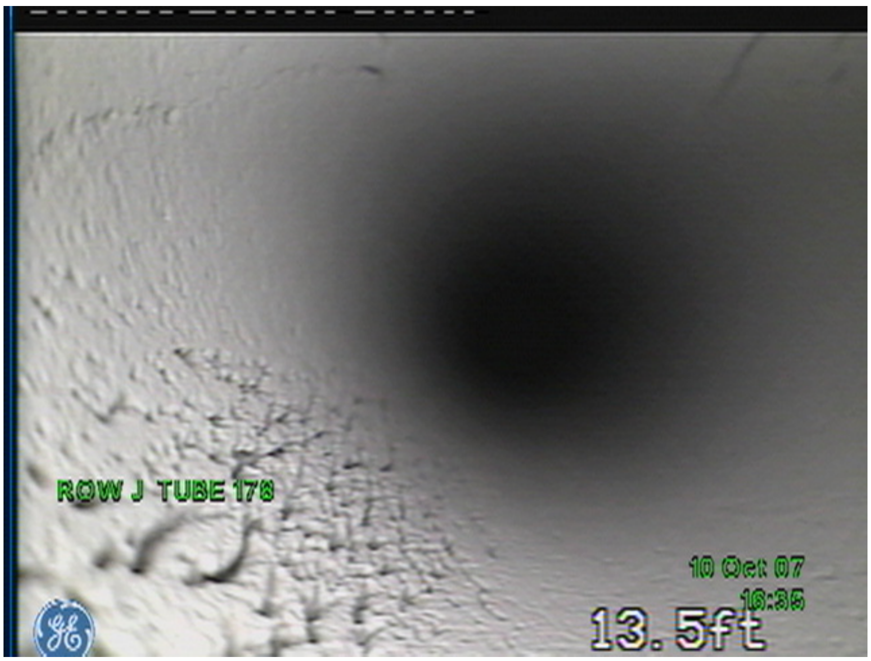

Figure 10-5
Corrosion Fatigue Cracking in a Boiler Tube May Often Require Removal for Diagnosis and Repair

Figure 10-6
Corrosion Fatigue Cracking in a Boiler Tube with Multiple Longitudinal Cracks

11
CASE STUDY: FOREIGN OBJECT AND LOOSE PART RETRIEVAL

Foreign object and loose part retrieval can be a major problem in both utility and process applications. Foreign objects may enter equipment and piping through a number of different sources and may or may not be reported. Prudent foreign object retrieval after an outage or turnaround may save additional downtime, damage, and expense.

One example of a foreign object removed from HRSGs is a blanking plate that had fallen in an 8-in. (203-mm) diameter line. The retrieval involved locating the plate (as seen in the RVI image shown in Figure 11-1) and removing it using a snare as seen in the image in Figure 11-2. Another more typical instance of foreign object retrieval is the removal of a bolt with the use of a claw, as seen in the RVI image shown in Figure 11-3.

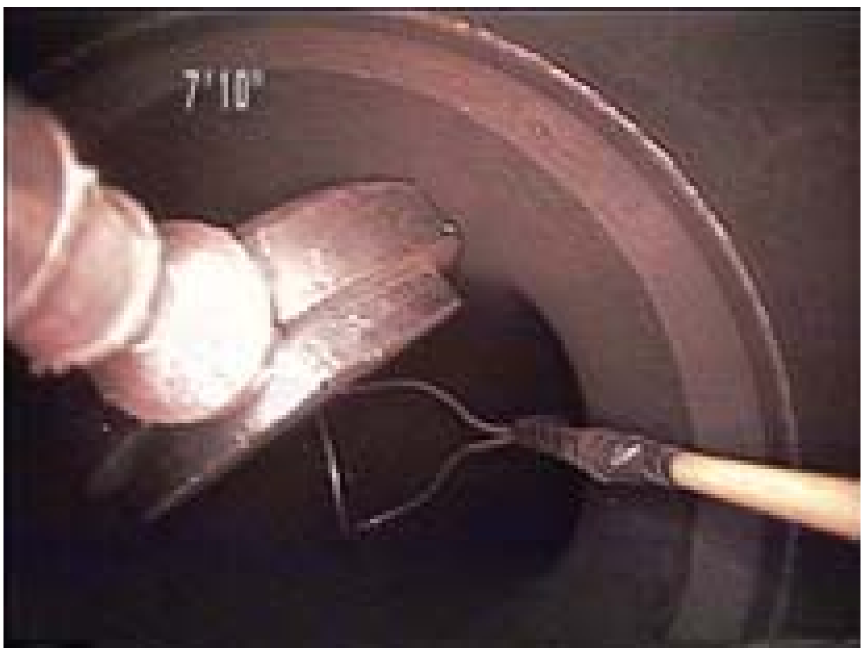

Figure 11-1
Location and Positioning of a Retrieval Tool for a Blanking Plate Using RVI to Assist the Operation

Figure 11-2
Removal of a Blanking Plate with a Snare Using RVI

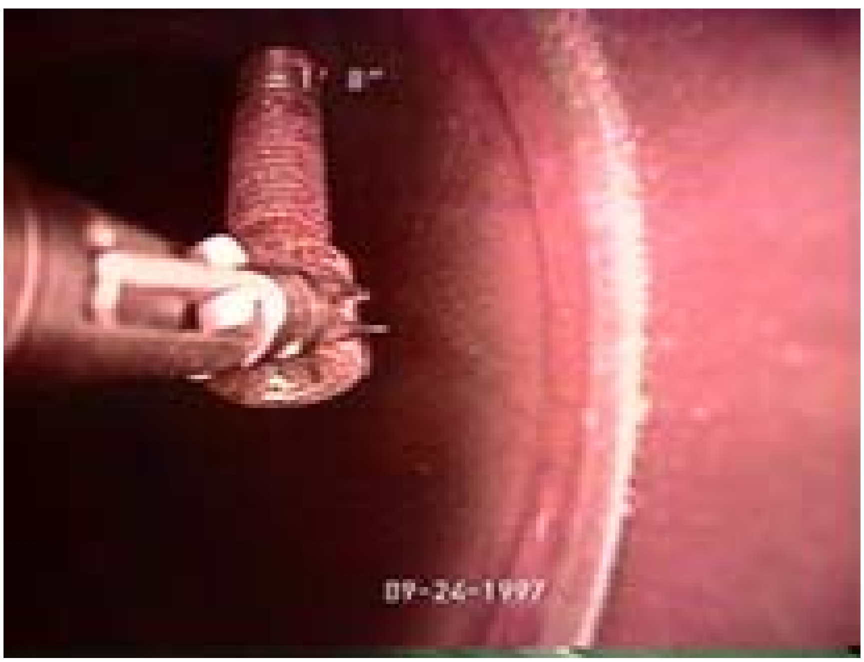

Figure 11-3
Removal of a Bolt with the Use of a Claw
(Loose parts could cause tube obstruction or other impact damage.)

One of the more unusual retrievals was that of a hardhat found in a downcomer line, as seen in the RVI image shown in Figure 11-4. This retrieval was accomplished with the use of a clamp-type device (shown in Figure 11-5). Finally, a more common retrieval application is provided in the RVI image in Figure 11-6, which shows the removal of a piece of metal from a boiler feed pump suction.

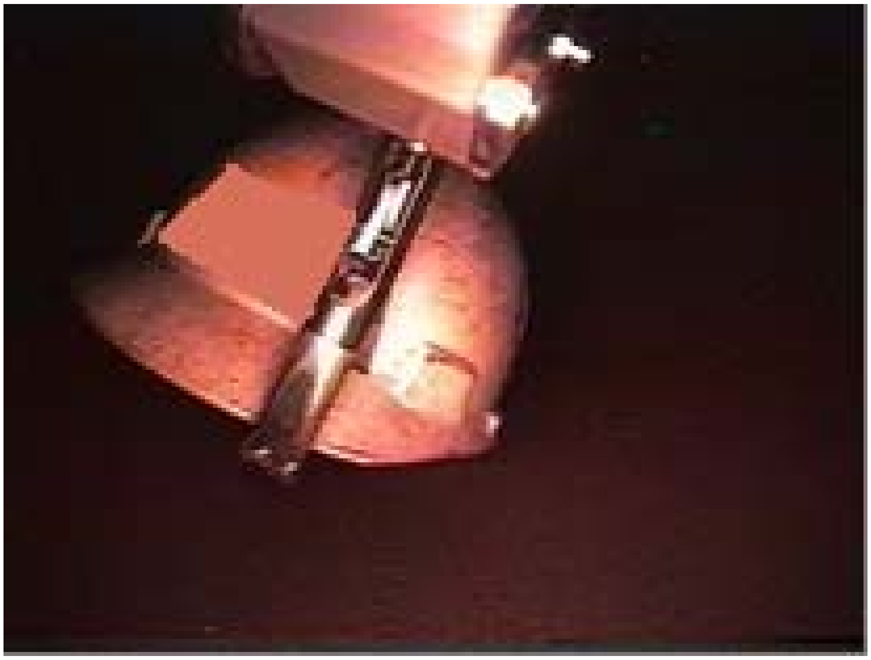

Figure 11-4
Location and Removal of a Hardhat from a Downcomer Line with a Clamp

Figure 11-5
Removal of a Piece of Metal from a Boiler Feed Pump
(Foreign object damage can cause significant damage in rotating equipment.)

12 CONCLUSION

As HRSGs accumulate more service hours and startup and shutdown cycles, some of the damage mechanisms identified in this report may become a reality for many users. An experienced engineering staff using modern complementary NDE techniques can identify precursors to some of these failures. If the precursors are properly diagnosed, corrective actions may be implemented or prudent replacement planning may help to avoid more significant and costly downtime.

Participation in industry users groups often provides a valuable forum for the exchange of information that may highlight specific reliability issues. These issues may be specific to a certain type of equipment or generic problems that have surfaced in the industry. In combination with original equipment manufacturers' recommendations and service bulletins, industry users group exchanges are a valuable tool for developing equipment assessment plans or targeted equipment strategies.

After a problem or strategy has been identified, knowledgeable engineering and inspection resources should be enlisted during the planning stages of the inspection process. Direct visual, enhanced visual, surface examination (such as liquid penetrant or magnetic particle), ultrasonic examination (either manual or automated), and RVI can all be used in a synergistic effort to maximize inspection effectiveness.

As these case studies show, remote visual examination can be a useful tool for assessing the condition of HRSG components. Technological advancements in CCD imagers and RVI data management enable HRSG users to perform better examinations and manage the resulting data in ways that allow them to make better assessments and maintenance decisions. By using advanced remote imaging, HRSG users can perform in-depth examinations of areas not previously accessible. These examinations allow users to uncover defects before catastrophic failure. When used in conjunction with other NDE methods, RVI is extremely helpful in locating and identifying potential problem areas in HRSG units.

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)

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

Printed on recycled paper in the United States of America

1014197

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