ELECTRIC POWER RESEARCH INSTITUTE

Deaerator Tank Assessment Guideline

Current Industry Technology and Approaches

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THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

M&M Engineering Associates, Inc.

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NOTE

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M&M Engineering Associates, Inc.
4616 W. Howard Lane, Bldg. 2, Suite 500
Austin, TX 78728

Principal Investigators
M. Moskal
C. Noble

Contributing Engineers
R. Munson
D. Daniels
G. M. Tanner
B. Bruscato

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Todd Kuntz	Arizona Public Service (APS)
Steven Worrell	CMS Energy/Consumers
Alex Bonnington	Constellation Energy
Richard Lynch	DTE Energy
	Ecodyne Limited
Charlie Farnham	FM Global
Mel Esmacher	GE Water & Process Technologies
James Robinson	GE Water & Process Technologies
Justin Voss	Global Risk Consultants
Sandy Babka	HSB-CT
Mindy Grinnan	JEA
Frank Moore	Kansas City Power & Light
Tony Hardin	Luminant
Frank Sosnin	Mechanical Consulting Services
George Galanes	Midwest Generation/Commonwealth
Tary Hanson	PPL Montana
Bruce Manson	Smurfit-Stone Container Corporation
Marty Sims	Southern Company
Scott Ross	Sterling Deaerator
Mark Koss	TVA
Tim Bacha	WE-Energies
Jack Dickerson	WE-Energies

ABSTRACT

The leaking and rupture of deaerator (DA) vessels has been an issue in industrial plants since the early 1970s. Three catastrophic failures of DA vessels that occurred in North American plants in 1983 prompted an industry-wide effort to understand and prevent these failures. The National Association of Corrosion Engineers (NACE) first published their *Standard Practice: Prevention, Detection, and Correction of Deaerator Cracking SP0590* in April 1990 (the latest version is 2007). Inspection of DA systems across all industry segments has identified high percentages of these vessels with cracking (greater than 30%). The most recent NACE document reports 38% of the vessels inspected at utilities have cracks requiring repair. Unfortunately, unit cycling and lower maintenance frequencies dictated by current economic conditions will likely intensify the severity of the DA cracking problems.

The goal of this project was to revise and update the Electric Power Research Institute (EPRI) report *Deaerator Vessel Assessment Guideline* (DVAG) to reflect current industry technology and approaches. This updated guideline incorporates technical input from the NACE *Standard Practice Document* SP0590-*2007*, but is focused on utility applications. This document provides a comprehensive guideline of today's "best practices," including information and guidance on the following:

- Design and materials of construction.
- Advanced understanding of damage: description and explanation of damage mechanisms, including examples of failure.
- Operational conditions that promote failure.
- Inspection and evaluation.
- Repair options.
- Technical criteria for the mitigation of damage including recommendations of repair-run-or-replace. This includes references to current fitness-for-service best practices such as ASME FFS-001 and API 579.

Overall, this document allows plant engineers, plant chemists, and operators/owners to identify the risk in their DA systems and provides sound engineering evaluation practices for running vessels with damage, repairing them if necessary, or replacing them with vessels with greater integrity.

Keywords
Corrosion fatigue
Deaerator vessel
Fitness-for-service
Flow-accelerated corrosion
Pressure vessel
Steam impingement

ACRONYMS

Below is a list of the commonly used acronyms within this document:

API – American Petroleum Institute

ASME – American Society of Mechanical Engineers

ASNT – American Society for Non-destructive Testing

B&PV Code – Boiler and Pressure Vessel Code

CET – critical exposure temperature

CF – corrosion fatigue

DA – deaerator

DSS – duplex stainless steel

ET – electromagnetic testing

FAC – flow-accelerated corrosion

FFS – fitness-for-service

GMAW – gas metal arc welding

HAZ – heat-affected zone (of a weld)

HEI – Heat Exchange Institute

HRSGs – heat recovery steam generators

LP – low pressure

MAT – minimum allowable temperature

MAWP – maximum allowable working pressure

MT – magnetic particle testing

NACE – National Association of Corrosion Engineers

NCGs – non-condensable gases

NBIC – National Board Inspection Code

NDT – nondestructive testing

ORP – oxidation reduction potential

OT – oxygenated treatment

PED – pressure equipment directive

PPB – parts per billion

PPH – pounds per hour

PT – liquid penetrant testing

PWHT – post-weld heat treatment

QC – quality control

RT – radiography (NDT inspection method)

SA – Society of Automotive Engineers (SAE) alloy grade designation

SCC – stress corrosion cracking

UISCC – under insulation stress corrosion cracking

UNS – unified numbering system (for alloy designations)

UT – ultrasonic testing

VT – visual inspection

WFMT – wet fluorescent magnetic particle testing

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1 INTRODUCTION/BACKGROUND

Deaerators are an essential piece of equipment in most sub-critical boilers and are used for oxygen removal as well as storage of boiler feedwater. This section gives background information on the operation and types of deaerators.[1]

1.1 Principals of Operation

In a general sense, a deaerator is nothing more than a direct contact feedwater heater with the added benefit of removing non-condensable gases (NCGs). To accomplish this, the inlet water (makeup and/or condensate) is mixed with the heating steam. Since the heating steam is assumed to be free from NCGs, the gases move from the water to the steam space because the partial pressure of the NCGs in the steam space is essentially zero. A portion of the steam and the NCGs are then vented out of the unit (typically to atmosphere) to maintain the low partial pressure of the NCGs.

Note that for the most efficient transfer of the NCGs from the inlet water to the steam space, the water is heated to the saturation temperature corresponding to the operating pressure. In addition, the surface area of the water is maximized by spraying it into fine droplets and using mechanical means to continuously break up the water.

Finally, there is a certain amount of residence time during which the water droplets must be exposed to the NCG-free steam so that the NCGs can “migrate” out of the water. This residence time is a function of the inlet temperature, operating pressure, and droplet size (as determined by the type of internals in the deaerator).

1.2 Types of Deaerators

There are essentially two types of deaerators in use today—spray (or spray-scrubber) units and tray (or spray-tray) units. Spray units utilize an atomizing spray section to break up the water for initial heating and deaeration. This spray stage is then followed with a scrubber section which uses fixed baffles and/or orifices to promote vigorous mixing of the heating steam and inlet water to scrub out the remaining traces of NCGs.

[1] This introductory section is repeated (with a few edits) from the EPRI Repair of Deaerators document, ID #1008069, June 2004.

Tray units utilize a similar spray section for initial heating and deaeration, but follow this with a tray section (in place of the scrubber) which cascades the inlet water over a series of trays while heating steam flows through the tray stack to scrub out the remaining NCGs.

Both types of units are capable of removing oxygen down to 7 ppb or less, but the tray design has better performance as loads vary, and typically a longer life due to containment of NCGs within a stainless steel tray enclosure. The vast majority of deaerators in utility power plants are tray units and the information in this document is biased toward them; however many of the principles also apply to spray units.

1.3 EPRI Licensed Material

1.3.1 Design Basis

Most deaerators in the US are designed and constructed to ASME Section VIII, Division 1. This Code explains how to calculate minimum wall thickness of pressure vessels for a given operating temperature and pressure. The minimum wall thickness accounts for the extra wall thickness needed for corrosion allowance. It also sets forth requirements for construction including materials, inspection, and fabrication, which includes welding, preheating, and post weld heat treatment (PWHT). Section 3 of this document covers Code details for deaerators.

1.3.2 Components of Deaerators

1.3.2.1 General

Most utility deaerators in the United States are two tank designs, though some single tank designs are used domestically. Single tank designs are common overseas. The typical two-tank design (see Figure 1-1) consists of a deaerating heater vessel, where the steam and water are mixed, and a storage tank. The storage tank serves several purposes:

1. To provide a surge tank to allow varying plant loads

2. To provide reserve and measurement of the NPSH available to the boiler feedwater pumps.

3. To provide reaction time for water treatment chemical injected into the feedwater

4. To act as a catch-all for various drains and return streams.

Although the storage tank is typically just a large tank, its duty can be severe and it should be subjected to the same rigorous inspection as the heater vessel. In fact, numerous deaerator failures have been due to problems with the storage tank.

Figure 1-1
Deaerator in operation

1.3.2.2 Internals

The remaining components are known collectively as the internals (see Figure 1-2 for typical arrangement.). Water enters the unit through a spray header or waterbox, is sprayed through spray valves, and cascades over the trays which are contained in the tray enclosure (see Figure 1-3 and Figure 1-4 for tray and spray valve photographs.). The primary purpose of the internals is to provide sufficient contact and residence time to heat and deaerate the feedwater. In addition, the internals serve to contain the non-condensable gases and prevent them from attacking the pressure shell of the unit.

Although outdated, external vent condensers are occasionally used to minimize the vent plume and associated steam loss from the unit. These are typically an external shell and tube heat exchanger utilizing the inlet makeup stream to condense a significant amount of the vent steam. The drains from the exchanger are then gravity fed back to the heating area over the trays. Most modern deaerators feature an internal vent condenser to minimize the required vent rate. This is an area inside the unit where the vent stream passes in close proximity to the inlet header or waterbox. The cooling effect of the inlet water serves to condense some of the vent stream for a lesser overall vent rate.

Figure 1-2
Deaerator internals

Figure 1-3
Deaerator trays

Figure 1-4
Deaerator spray valve

1.4 Current Trends

Deaerators have come under increasing scrutiny since the late 1980s when there were a few instances of the pressure vessel failing catastrophically with some loss of life. The failures were examined by NACE and their findings formed the basis of NACE Standard RP0590-90 (the current version is SP0590-2007) [1]. The final result for most plants is that their insurance carrier requires more frequent and thorough inspection of the deaerator to evaluate its integrity as a pressure vessel.

Deaerators have also been included in the recent research into flow-accelerated corrosion (FAC). While originally researched as a pipeline issue in nuclear plants, FAC has been observed in numerous deaerators and has caused at least one through-wall leak in a utility deaerator. FAC will be discussed in more detail in Section 4 of this document titled “Damage Mechanisms.”

Finally, the utility of deaeration as a whole has come into question as some utility plants have switched to oxygenated treatment. Oxygenated treatment has been in extensive use overseas for some years but has only recently come into play in the U.S. Essentially, plants with all ferrous feedwater systems have had some success in allowing dissolved oxygen levels to run considerably higher than traditional all-volatile treatments allow. The intent is to form an oxide layer on the feedwater components which protects them from further attacks.

Oxygenated treatment will reduce the amount of oxygen removal that a deaerator must achieve, but it will not make the deaerator obsolete. Even base loaded plants will need a deaerator for start-up use and obviously any existing plant will still need the thermal duty of the deaerator as a feedwater heater. In addition, many of the plants in the U.S. do not have the appropriate metallurgy to use oxygenated treatment and will have to continue to rely upon the deaerator to minimize oxygen attack.

1.5 EPRI Licensed Material

1.5.1 Failure History

In 1984, a NACE task group was formed to study the high incidence of cracking problems in deaerators. The result of this study is the aforementioned NACE Standard RP0590-90. Considered in this study were three storage vessel ruptures, one of which resulted in fatalities. Also noted is a TAPPI “Deaerator Advisory” that reports cracks found in approximately 50% of the vessels inspected in 1983. The noted cracking occurred in welds and their heat-affected zones.

The NACE standard notes data that out of more than 700 vessels inspected, 30 to 40% contained cracks and needed repairs. The cracking, found primarily through wet fluorescent magnetic particle testing, is an environmentally assisted form described as corrosion fatigue that can occur in either the deaerator or storage tank. The standard also reports that cracking is not a function of vessel age. Cracking was found in the vapor zone of the deaerator, at the liquid/vapor interface in the storage tank, and in the liquid zone of the storage tank. The NACE standard concludes that, for horizontal vessels, the most prevalent area for cracking is in the liquid zone between the 4 o’clock and 8 o’clock positions.

It is important to note that one of the factors contributing to crack growth is residual tensile stress from welding. As discussed in the design section of this document (Section 2), all deaerators and deaerator storage tanks should be post weld heat treated to minimize residual stresses. It should also be noted that PWHT does not eliminate the tendency towards fatigue cracking; some vessels with PWHT have been found to be cracked.

1.5.2 New Construction Recommendations

As a result of deaerator failure studies by TAPPI and NACE, HEI and NACE have published guidelines and recommendations for the construction of new deaerators, intended to reduce the incidence of cracking and subsequent failure [1, 2]. The following is a summary of the recommendations. Where the two standards differ, the more conservative of the two is given.

- Corrosion allowance – Vessel head and shell components are to be designed to include 1/8-inch corrosion allowance. Nozzles are to be designed to include 1/16-inch corrosion allowance.
- Welding – Pressure retaining welds are to be full penetration and full fusion.
- Weld seam profile – Internal and external weld seams are to be smooth, and free from abrupt changes. Welds are to blend ground as required.
- NDE of nozzle welds – Internal nozzle-to-shell welds are to be MT or PT examined as applicable.
- Radiography – Shell and head seams are to be inspected by radiography to obtain a 1.0 joint efficiency (i.e., RT-2 as per ASME Section VIII, Div. 1.)

- Post weld heat treatment (PWHT) – Vessels are to receive PWHT in accordance with ASME code (normally 1100°F minimum for one hour per inch thickness).
- Trays – Trays are to be stamped or riveted, stainless steel construction.
- Materials – Materials are to be such that non-deaerated (or partially deaerated) water and NCGs do not come into contact with any carbon steel vessel components.

1.6 References

1.6.1 References Cited in Text

1. *Prevention, Detection, and Correction of Deaerator Cracking,* NACE SP0590-2007, NACE International, Houston, TX, 2007.
2. *Standards and Typical Specifications for Tray Type Deaerators, 8th Ed.,* Heat Exchange Institute, Inc., Cleveland, OH, 2008.

1.6.2 Other Sources

Repair of Deaerators, EPRI, Palo Alto, CA, 2004, 1008069.

2
DA CONSTRUCTION, MECHANICAL DESIGN, AND MATERIALS

2.1 Deaerator Function

Deaerators remove dissolved oxygen and carbon dioxide by thermo-mechanical means. Under pressure or vacuum, the water temperature is raised with steam, reducing the solubility of the dissolved gases. Dissolved gases are removed from the deaerator by venting with steam. There is a time associated with this reaction so residence time or dwell time is an important consideration. Typical deaerator performance standards require that the temperature of the influent water shall be within 2ºF (1.1ºC) of the saturation temperature at the specific operating pressure of the deaerator, and to achieve 0.005 mL/L (7 PPB) outlet dissolved oxygen content. The design of spray-tray type deaerators normally requires the above performance while operating from 10% to 100% of design capacity, which are typical requirements for utility applications.

2.2 Design

Experience shows that deaerator design has evolved to meet changing output performance requirements and to provide equipment that will run year after year with little maintenance. Deaerator equipment is available from many suppliers, though only a few typically supply the needs for electric power utilities in North America. The deaerator designer is challenged to: (1) achieve the required deaeration performance and output, typically specified as pounds per hour (PPH) of water; (2) fit the equipment within the available space, sometimes a problem when replacing existing equipment; (3) address known damage mechanisms of deaerators; (4) address non-steady state operations such as turbine trips, cold water inlet surges, and deaerator pressure loss; and (5) provide the equipment at a competitive price.

For example, deaerators with large diameter to length ratios provide the needed capacity and water residence time for sufficient deaeration, but these larger vessels require heavier wall thickness to meet pressure vessel code standards. Conversely, deaerators with small diameter to length ratios, while lower in cost to manufacture, may be problematic with excessive steam flow rates, sometimes leading to rapid vessel damage from flow-assisted corrosion (see Section 4 for details.). Large storage tanks, up to 150 ft. (45.7 m) in length, can be disproportionally costly to fabricate, require very large furnaces for post weld heat treatment and sometimes require extensive field weld assembly. These are but a few of the challenges to producers of deaerator equipment.

Deaerator systems for power generation utilities are designed and built as either spray-tray (sometimes referred to as simply "tray") or spray-scrubber units. Although both systems can achieve the above performance requirements, utility systems require the high capacity provided by spray-tray deaerators. Spray-tray deaerators may be designed with varying orientations with respect to the storage tank (Figure 2-1). In high capacity utility systems it is most common to have a horizontal or vertical water deaerator vessel positioned over the storage tank, connected by a short length of water downcomer and equalizing piping. A typical vertical deaerator and storage tank with connections and names of parts is shown in Figure 2-2.

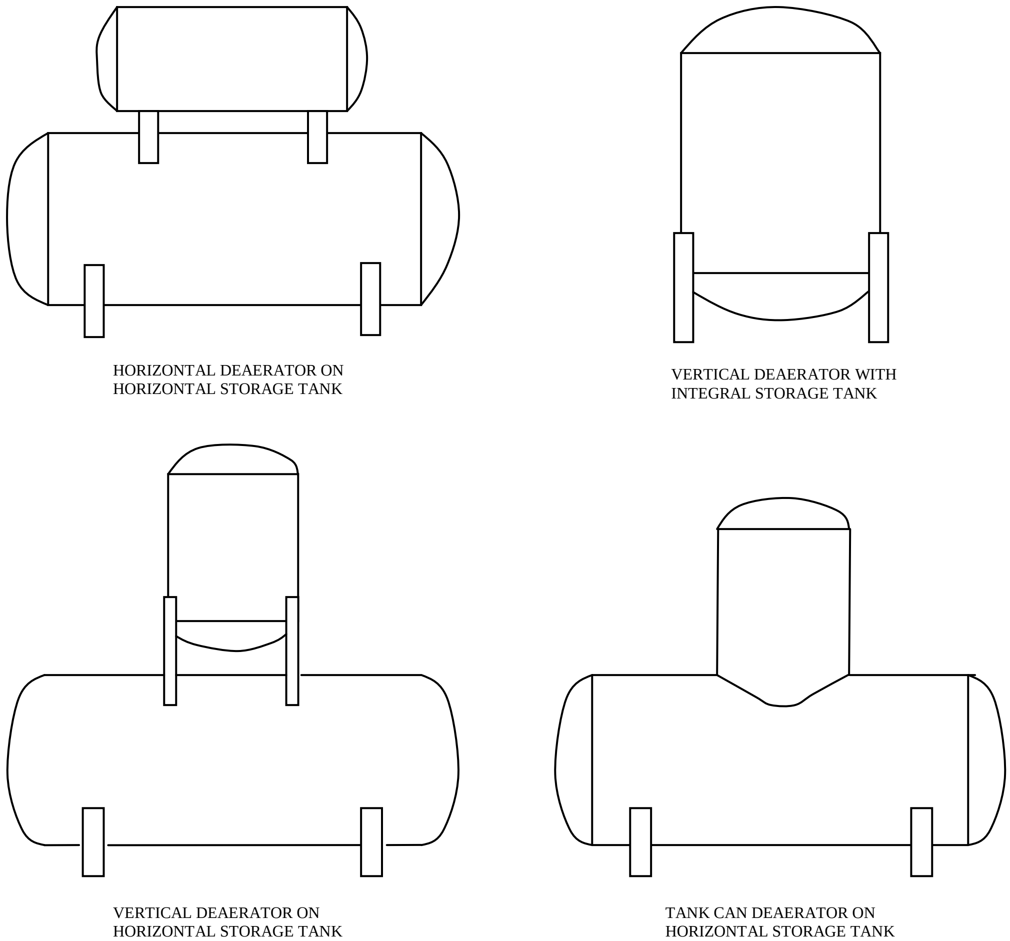
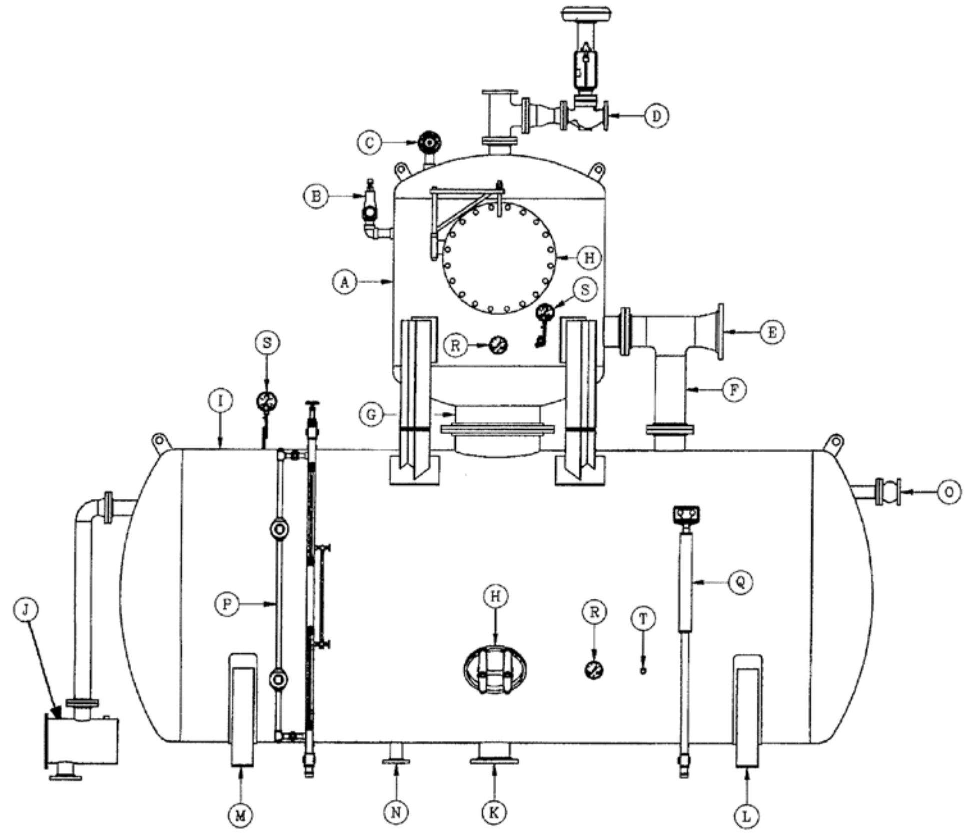


Figure 2-1
Orientation and combinations of deaerators and storage tanks. Source: Heat Exchange Institute standards and typical specifications for tray-type deaerators.



Typical Deaerator Connections and Accessories

K. Deaerator Section
L. Relief Valve
M. Vent
N. Water Inlet
O. Steam Inlet
P. Equalizer
Q. Downcomer
R. Access Manway
S. Storage Section
T. Overflow Control

A. Outlet
B. Fixed Support Saddle
C. Sliding Support Saddle
D. Drain
E. Vacuum Breaker
F. Level Gauge/Level Alarm Column
G. Level Controller
H. Thermometer
I. Pressure Gauge
J. Sampling Connection

Figure 2-2
Typical vertical deaerator and storage tank with names of components and accessories. Source: Heat Exchange Institute standards and typical specifications for tray-type deaerators.

The components of a typical horizontal spray-tray system are shown in Figure 2-3. During operation, most of the dissolved oxygen is released in the spray chamber when droplets contact the non-condensable, free steam, but final oxygen is stripped when water droplets cascade though the series of trays at the bottom of the deaerator vessel. The direction of steam flow through the deaerator is typically countercurrent from the water direction (from the bottom up through the trays), but designs may be concurrent or even cross-current with water flow. The major components within the tray enclosure are the water distribution system, the tray supports and the trays.

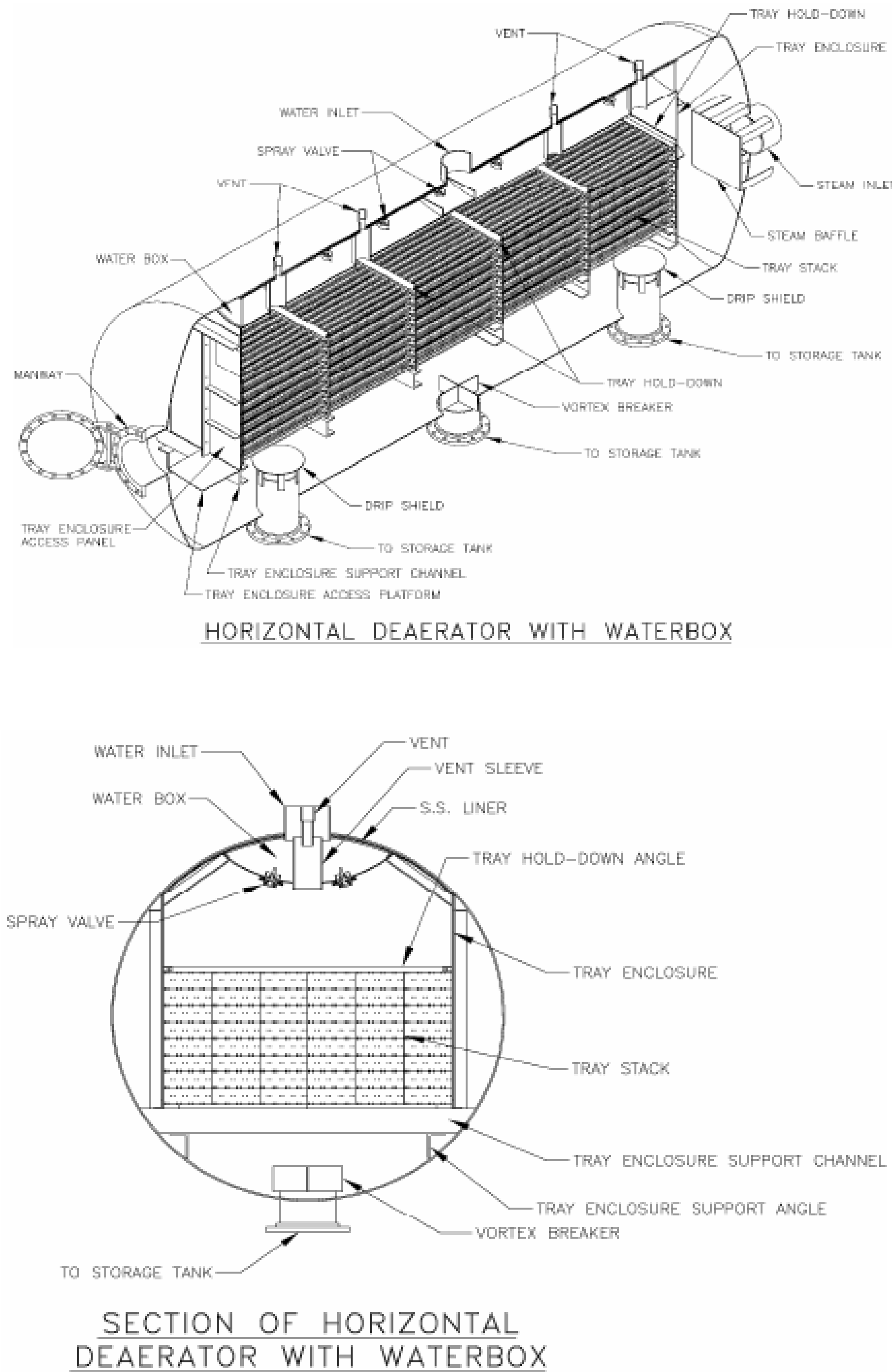
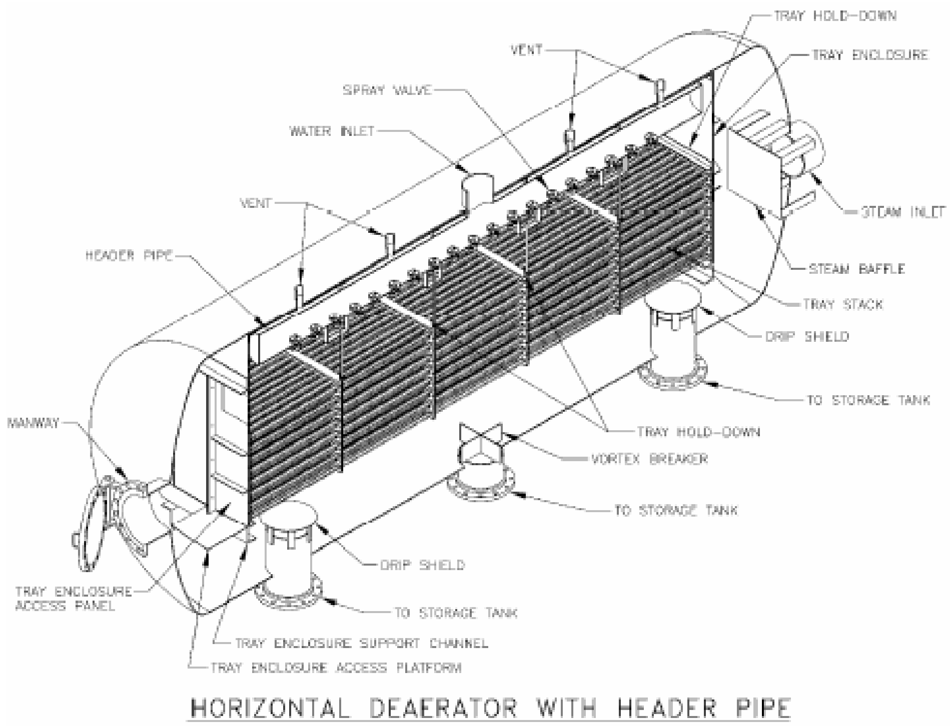


Figure 2-3
Typical arrangement of horizontal deaerator with a waterbox (Courtesy of Kansas City Deaerator Company, Inc.)



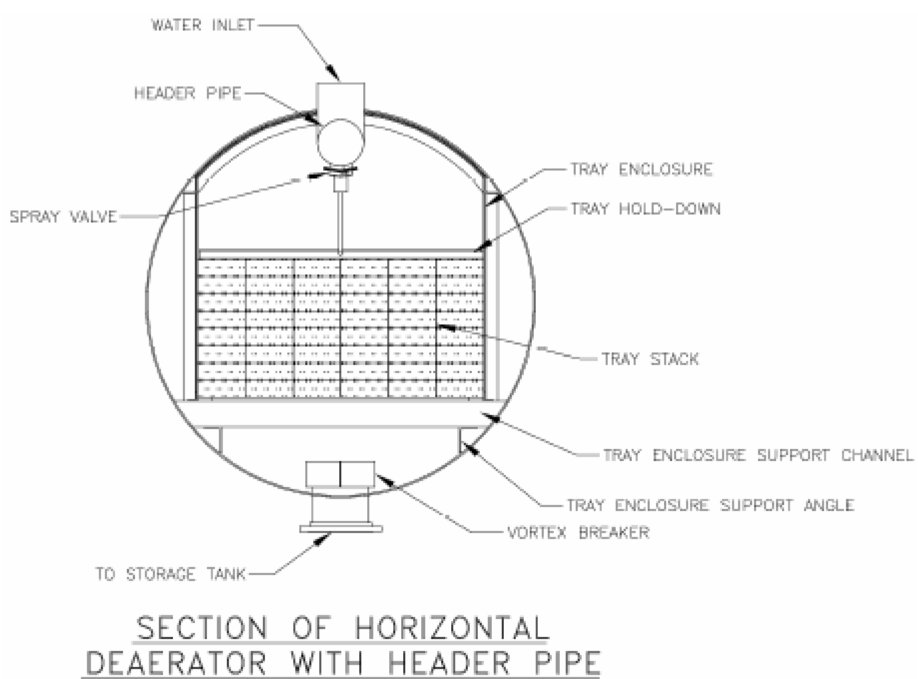


Figure 2-4
Horizontal deaerator with a header pipe distribution system (Courtesy of Kansas City Deaerator Company, Inc.)

Water distribution systems, fabricated entirely from austenitic stainless steel, have improved in the past two decades in attempts to avoid cracking problems associated with differential thermal expansion. Most horizontal deaerators built prior to the 1990's were designed with a "football" shaped waterbox (Figure 2-3). The upper portion of the waterbox is comprised of sheet stainless steel lining welded to the carbon steel shell; the lower half is fabricated from stainless steel plate and contains the water spray valves. Depending on the particular design, this type of waterbox arrangement may be prone to cracking at the long weld seam between the box and the shell. Rapid temperature excursions also can result in distortion and cracking in the waterbox at the vents and the spray valve locations. Later designs, shown in Figure 2-4, with the water pipe header separated from the deaerator shell avoid many of the thermal expansion problems associated with the contiguously welded stainless steel box and carbon steel shell.

At the top of the deaerator, non-condensable gases and steam collect and are vented through or above the water distribution system. Because the environment is very corrosive, vents and vent condensers must necessarily be made from stainless steel.

The tray stack, housed below the waterbox or pipe header, is supported by and contained within the tray enclosure. The enclosure and its supports must be sturdily designed to hold the weight of the tray stack. Hold-down clips and attachments must also be sufficiently rugged to restrain the trays should an upset from water flashing occur in the storage section. All of the above components, water distribution system, tray enclosure, and trays are typically fabricated from stainless steel to resist corrosion from oxygenated water. (Industrial deaerators often bring process condensate and makeup water directly into the deaerator. These streams are often saturated with oxygen, and therefore, stainless steel components are required. Deaerator manufacturers design for these more rugged conditions.)

In a typical utility boiler, the turbine condensate is pumped forward from the hotwell to the DA with very little potential for dissolved oxygen to contaminate the feedwater. The current EPRI guideline for dissolved oxygen at the condensate pump discharge, 10 ppb, is far too low to cause oxygen pitting. For units that cycle frequently, particularly from a cold start, the stainless steel spray headers and trays are still important as they will often see high dissolved oxygen levels until the boiler is generating sufficient steam to provide steam to the deaerator.

Following the cascade through the trays, the fully deaerated water collects in the sump portion of the deaerator vessel and proceeds through a vortex breaker and downcomer piping to the storage tank. One or more equalizing pipe connections between the deaerator and the storage tank are required to maintain equal pressure between the vessels.

The storage tank is simply a large tank to provide a stable net positive suction head for the feedwater pumps. It also stores water and serves as a surge capacity for varying plant loads. Finally, a system is provided for feedwater chemical additions, typically reducing agents such as hydrazine, which are typically added downstream of the condensate pump discharge. However, the storage tank is the first area in the feedwater system with sufficient temperature and residence time to complete the chemical reaction.

Consideration should be given in design of deaerator systems to provide auxiliary equipment to warm stored water prior to start-up. Mixing hot and cold water within the deaerator can cause water hammer, upsets, and excessive thermal stresses in the vessel, conditions which lead to mechanical damage and low-cycle corrosion fatigue (CF) damage.

Finally, the deaerator and storage tank should be designed for good internal accessibility which is needed for proper visual and nondestructive test inspections. Not all of the deaerator vessel can normally be accessed for inspection, but consideration for needed inspections of known damage mechanisms is vital to safe and long-term operation of the equipment.

2.3 Materials of Construction

Deaerator materials have not changed much for several decades, with pressure vessel grade carbon steel being used for the shell, heads, and nozzles. Austenitic stainless steel has invariably been specified for all components contacting un-deaerated or partially deaerated water: inlet nozzle, waterbox/ header pipe, waterbox lining, vent condenser, valve plate, vent and spray valves. Tray enclosures and trays are also specified to be stainless steel. A summary of current materials of construction is shown in Table 2.1.

Table 2-1
Materials of construction for deaerators

Component	Subcomponent	Material	Strength (ksi) Tensile	Strength (ksi) Yield, min.	Comments
Deaerator and Storage Vessels	Shell and Heads	SA 212, Grade B	70-90	38	Withdrawn in 1967; replaced by SA515, Gr. 70 (coarse-grained practice) and SA516, Gr. 70 (fine-grained practice).
		SA 285, Grade B	50-70	27	Intermediate strength steel. May be ordered as copper-bearing.
		SA 285, Grade C	55-75	30	Intermediate strength steel. May be ordered as copper-bearing.
		SA 515, Grade 70	70-90	38	Steelmaking practice is coarse austenitic grain unless fine grain is specified.
		SA 516, Grade 70	70-90	38	Fine grained practice.
	Nozzles – Carbon Steel	SA 106, Grade B	60 min.	35	Seamless pipe.
		SA 105	70 min.	36	Forgings.
	Nozzles – Stainless Steel	SA 312, Grade TP304L	70 min.	25	Seamless pipe.
		SA 182, Grade F 304L			Forgings.
Deaerator Internal Components	Tray Enclosure and Hardware	SA 240, Type 304L or 316L	70 min.	25	Stainless steel plate, sheet, and strip. Sometimes 400 series stainless steel is specified.
	Water Distribution System	SA 240, Type 304L or 316L			Stainless steel plate, sheet, and strip.
		SA 312, Grade TP304L or TP316L			Stainless steel seamless pipe.
	Target Plate	Carbon steel or TP304L/TP316L stainless steel			Stainless steel plate.
	Trays	SA 240, Type 430	65 min.	30	Ferritic stainless steel sheet. Also Type 304L
	Spray Valves	CF3M	-	-	Stainless steel. Cast alloy equivalent to Type 316L stainless steel.

2.3.1 Shell Materials

Knowledge of the shell materials used in deaerators is important when repairs are contemplated or required. Welding repair procedures vary for different carbon and low-alloy steels. Further, the strength and toughness properties are necessary when Fitness-For-Service (FFS) assessments must be made on damaged equipment.

Historically, almost all deaerator shells have been fabricated using one of several available carbon steels. The specific grade of carbon steel plate varies according to grades and steel mill practices at the time of manufacture. Deaerators manufactured prior to 1967 were largely fabricated from SA 212, Grade B, which was superseded by SA 285, Grades B and C. About 1970, SA 515, Grade 70 was the material of choice; in 1980, SA 516, Grade 70, a plate material manufactured using fine-grain steel practice, provided a superior combination of toughness and strength. The latter material, SA 516, Grade 70 is used today for most deaerators and deaerator storage vessels. Since about 2005, a few deaerator shells and heads have been fabricated from Type 304L stainless steel in efforts to mitigate CF and FAC corrosion damage. Even small amounts of chromium in the carbon steel can produce significant immunity to FAC. Please refer to more information on stainless steels for deaerator shells and components in the following *Discussion* section of this report.

2.4 Purchasing Standards

Most deaerators purchased by utilities are specified according to the Heat Exchange Institute (HEI) Standard and Typical Specifications for Tray-Type Deaerators [1]. The standard covers minimum requirements for design and fabrication Codes (ASME), pressure/vacuum design, pump section design, nozzle sizes/loads and required accessories. Also covered in the standard are:

- Minimum corrosion allowance for the deaerator head, shell and nozzles
- Requirements for post weld heat treatment (PWHT; not required by ASME, but considered necessary to resist in-service CF)
- Nondestructive examination requirements, such as radiographic testing of welds (in addition to ASME Code)
- Storage tank requirements
- Requirements for accessory equipment such as relief valves, regulating valves/controls and gauges

Although the Eighth Edition of the HEI Standard was revised in 2008, it does not address some issues that can improve deaerator longevity. The purchaser of new deaerators should consider the following additional requirements:

- Require that PWHT of carbon steel vessels be performed at the highest specified temperature of 1100ºF to 1200ºF (593ºC to 649ºC) in lieu of using ASME approved alternate PWHT time-temperature cycles (see PWHT in Section 3 of this report).
- Require a baseline WFMT inspection at the fabrication shop to avoid misinterpretation of weld defects at the first in-service inspection.
- Consider the use of duplex stainless steels in lieu of austenitic stainless steels for improved resistance to thermal cracking and corrosion fatigue (details below).
- Increasing the tray thickness from 20-gauge to 16-gauge to better withstand upsets and incidental damage.

2.5 Fabrication and Quality Control

Today, all the major deaerator producers for utilities subcontract the fabrication work to outside tank and pressure vessel shops. Some producers contract to only two or three trusted weld fabricators, while others contract many shops for fabrication work. Deaerator equipment is complicated in that many combinations of materials and welding procedures are involved, including the need for attention to final surface finishes, nondestructive testing, and good control of PWHT. Quality control becomes more difficult when several fabrication shops are located at remote distances, or if quality checks are infrequent. All shops holding an ASME stamp must have a designated quality control (QC) person and QC plan. However, the quality of work in all ASME shops can vary and in-plant QC programs covering fabrication to ASME requirements may still be insufficient to ensure the needed quality of deaerators. When purchasing new deaerator equipment, the utility (end user) should enquire with both the producer and fabricator as to quality assurance procedures to ensure all requirements are met. Prior to any work being done it is good practice to visit the fabricator along with the designer/producer to emphasize QC issues. The end user may also benefit by scheduling his own quality control oversight visits to the fabricator to emphasize the need for high quality workmanship and to verify that needed requirements are met.

2.6 Discussion on Stainless Steel

2.6.1 Austenitic Stainless Steel

As noted above, within the past decade or so, a few Type 304L stainless steel deaerator shells have been manufactured. The intention is to provide better resistance to CF and FAC damage. There is little doubt that Type 304L stainless steel provides excellent resistance to FAC damage, but it is questionable as to whether good resistance to CF can be obtained. Austenitic stainless steels have relatively poor CF resistance and are not commonly used in applications requiring high corrosion fatigue resistance [2]. Further, it is not practical to post weld heat treat stainless steel, and residual stresses further reduce the material's resistance to cyclic fatigue cracking in water. It should be noted that CF damage occurs more in storage tanks than in deaerators. So far as is known, no large deaerator storage tanks have been made from stainless steel.

A common corrosion problem with austenitic stainless steel pressure vessels is under-insulation stress corrosion cracking (UISCC). At least one instance has been reported of under-insulation stress corrosion cracking of a Type 304L stainless steel deaerator shell [3]. This condition occurred when chloride contaminated water penetrated the exterior insulation, allowing for concentration of chlorides and subsequent corrosion cracking. For resistance to UISCC damage, stainless steel vessels should be painted on exterior surfaces under the insulation.

2.6.2 Duplex Stainless Steel

Duplex stainless steels (DSS) have existed for sixty years. However, the "first generation" of DSS alloys was not readily welded without loss of toughness and corrosion resistance. Consequently, their practical use in process applications such as deaerators was severely limited. Within the last two decades a "second generation" of DSS alloys has come into commercial production. These grades are characterized by a composition balance, particularly the use of nitrogen as an alloying element, allowing practical welding without loss of desirable properties.

The most common DSS alloy in use has been Alloy 2205 (UNS S32205), which has corrosion resistance properties exceeding 316L austenitic stainless steel. However, for use in deaerators, Alloy 2205 is overqualified—too costly and unnecessarily over-alloyed to simply resist corrosion from water. More recently, a family of so-called "lean" DSS alloys has been produced having a better cost advantage for use in mild corrosion-resisting applications such as for deaerators. Other advantages of DSS (and lean DSS in particular) compared to austenitic alloys are higher strength, a favorable thermal coefficient of expansion when welded to carbon steel, and good resistance to UISCC. Not all lean DSS alloys are ASME Code approved for Section VIII, Division 1 construction. ASME Code Case 2418 qualifies Alloy 2101 (Outokumpu) for Section VIII construction, and code cases are pending for other manufacturers' lean DSS alloys.

Deaerator designers and fabricators should be aware that DSS alloys are readily welded, but must be welded with specific heat input criteria to achieve proper ductility and corrosion properties. As with any weld fabrication, procedures must be developed and carefully followed to consistently achieve the intended results. As of the time of this writing, it is unknown as to whether any deaerator shells or internal components have been built from DSS alloys.

2.7 Deaeration in Heat Recovery Steam Generators (HRSGs)

Industrial Heat Recovery Steam Generators have been used to recover heat from a variety of chemical processes. These units often had stand alone deaerators, and some early versions of HRSGs used strictly for power generation also used deaerators. However, nearly all the combined cycle plants built since do not. Rarely there may be a small deaerator section (spray header and trays) located directly on top of the LP Drum.

In a typical modern combined cycle plant, condensate and makeup water travels from the condenser, through a heating element close to the stack (often referred to as a feedwater heater or LP Economizer, then into an LP Drum. The LP drum typically provides head pressure for boiler feed pumps that feed the IP and HP drums.

Without a standalone deaerator, the HRSG typically relies on deaeration in the hotwell for the small amounts of makeup water the unit requires. Makeup water often is sprayed high in the condenser to facilitate the removal of dissolved oxygen in the condenser.

Dissolved oxygen at the condensate pump discharge during operation is typically less than 10 ppb due primarily to the very small amount of makeup required on these units. However, these units often are called into cycling service. When starting up, the amount of makeup water (and therefore the amount of dissolved oxygen in the water going to the LP drum) can be much higher than the desired limit. Corrosion fatigue in the LP drum and associated piping is a significant corrosion mechanism in some HRSGs.

Reducing agents are not recommended in modern combined cycle plant as they typically contain no copper alloys in the steam cycle.

2.8 References

2.8.1 References Cited in Text

1. *Standards and Typical Specifications for Tray Type Deaerators, 8th Ed.*, Heat Exchange Institute, Inc., Cleveland, OH: 2008.
2. Jonas, O., Mancini, J., "Corrosion of Deaerators," ASM Handbook, Vol. 13C, p. 452, 2006.
3. Twigg, R. J., "Reality Check: The Reinspection of Deaerators," Paper #525, proc. Corrosion 96, NACE, Houston, TX: 1996.
4. Kansas City Deaerator Company, Inc.

2.8.2 Other Sources

Repair of Deaerators, EPRI, Palo Alto, CA: 2004. 1008069.

Prevention, Detection, and Correction of Deaerator Cracking, NACE SP0590-2007, NACE International, Houston, TX: 2007.

3
CONFORMANCE TO CODES AND STANDARDS

Several codes and standards are applicable to the safe construction and operation of deaerators. They provide simple, convenient provisions for the design, fabrication, inspection and repair of deaerators. A brief discussion of some of these provisions (and limitations) is provided below.

3.1 Codes

3.1.1 ASME Section VIII Division 1: Provisions

A new deaerator should be constructed and stamped in accordance with American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code Section VIII, Division 1, entitled *Rules for the Construction of Pressure Vessels*.

3.1.1.1 Design

Design provisions establish minimum wall thicknesses throughout the deaerator based on the maximum allowable working pressure (MAWP) and the maximum operating temperature that will be imposed on the deaerator.

3.1.1.2 Allowable Design Stresses

The Code designates allowable design stresses for the design of the vessel. They are contained in the ASME B&PV Code Section II, Part D, entitled Properties. Appropriate safety factors are incorporated into the allowable design stress values (See Appendix 1, Part D: Basis for Establishing Stress Values.).

3.1.1.3 Approved Materials

Only approved materials listed in Section II and having maximum use temperatures for Section VIII of the Code can be used in Code construction. Deaerators are almost always constructed with carbon steels as the pressure boundary material although many utilities have switched to low alloy steels with low levels of Chromium to minimize flow accelerated corrosion issues. Using approved materials establishes a controlled weldability for the material of construction.

3.1.1.4 Fabrication

Provisions include material identification, repair options if defects are present in the materials, and manufacturing tolerances. Specialized requirements for welded and forged construction are included in the Code.

3.1.1.5 Welding

Requirements include full penetration, full fusion welding of butt joints and qualification testing of weld procedures and welders.

1. Post Weld Heat Treatment (PWHT) - Temperature ranges, time and thickness requirements are delineated. Note: for carbon steels, PWHT is mandatory only for thicknesses over 1½-inches. For lesser thicknesses, PWHT is optional, usually at the specification of the purchaser.
2. Inspection - For butt welds, three levels of radiographic inspection (X-ray; RT) of butt welds are possible—Full (100%), Spot, or No X-ray. RT defines the joint efficiency utilized in the vessel design with 100%, 85%, and 70% joint efficiency.

3.1.1.6 Hydrostatic Testing

The Code requires a hydrostatic test at 1.3 x MAWP (maximum allowable working pressure) after the completion of the vessel.

3.1.1.7 Documentation and Stamping

The Code requires a U-1 Form to be filled out by the fabricator of the vessel and signed by the authorized inspector. This provides verification that the vessel was constructed in accordance with Code requirements. A name plate or impression stamping is affixed on the vessel showing the manufacturer, MAWP, minimum design temperature, serial number and year built.

3.1.2 National Board Inspection Code (NBIC)

In-service boilers and pressure vessels are inspected and repaired according to the rules and provisions in the NBIC. In many cases, NBIC refers back to the provisions in the ASME original Code of Construction. The application of the NBIC is determined on a state-by-state basis by local jurisdictional rules.

3.1.3 Limitations of Code when Applied to Deaerators

ASME and NBIC codes are generic codes that apply to all pressure vessels (and boilers). It is not possible to include all the special requirements found necessary to ensure the safety of a specific application, site, product, or application such as a deaerator. For example, except for a specific provision for establishing a corrosion allowance to be added to the material thickness to allow for thinning from corrosion, the codes do not contain provisions to mitigate most corrosion mechanisms. Thus corrosion mechanisms such as stress corrosion cracking, corrosion fatigue, and hydrogen induced cracking are not addressed nor are they mitigated specifically via Code provisions.

Some damage mechanisms have been found to be mitigated by PWHT which significantly reduces the hardness of the weld metal and weld heat affected zone (HAZ), as well as reducing residual welding stresses. For carbon steels (and certain alloy steels) the ASME Code contains provisions for reduced PWHT temperatures using extended times at temperatures.

To illustrate, PWHT of carbon steels is usually specified at 1100°F to 1200°F at one hour per inch of maximum thickness. But the Code allows PWHT at 1050°F to 1150°F at two hours per inch; 1000°F to 1100°F at four hours per inch; 950°F to 1050°F at ten hours per inch; or 900°F to 1000°F at twenty hours per inch.

For deaerators, it has been found that cracking of the welds can be mitigated (but not eliminated) by PWHT. Thus all deaerator vessels should be given a final PWHT irrespective of whether PWHT is mandatory under Code provisions (see NACE SP0590-2007). Furthermore, it would seem prudent to also require PWHT at the highest PWHT temperature (1100°F to 1200°F) to minimize hardness levels and residual stresses in the deaerator.

3.2 Standards

Two standards, specifically applicable to deaerator construction and operation have been developed. An additional standard, API 579-2/ASME FFS-2, 2009, refers to evaluation methodology for operation of pressurized equipment with cracking.

3.2.1 National Association of Corrosion Engineers (NACE) Standard Practice SP0590-2007, Prevention Detection and Correction of Deaerator Cracking.

NACE SP0590, as the title implies, deals primarily with describing deaerator cracking, inspection methods to detect that cracking, evaluation methods to assess the significance of the cracking and possible repair methods.

3.2.2 Heat Exchange Institute, Inc., Standards for Typical Specifications for Tray Type Deaerators, 8th Edition.

The HEI Standard deals primarily with order requirements for new deaerators which can mitigate deaerator cracking.

3.2.3 The Major Provisions in These Standards Can Be Listed as Follows:

- New vessels shall be constructed in accordance with ASME Section VIII, Division 1.
- Repairs of in-service deaerators shall be in accordance with the National Board Inspection Code.
- A corrosion allowance of ⅛-inches (3mm) shall be included in the deaerator shell and head. A minimum corrosion allowance of 1/16-inches (1.5mm) shall be included in nozzles, internal nozzle reinforcing pads, nozzle necks, and manway covers. No corrosion allowance is specified for stainless steel nozzles.
- Longitudinal and circumferential head and shell weld seams shall be 100 % RT inspected.
- The deaerator vessels shall be PWHT in accordance with ASME Section VIII, Division 1. Note: a requirement added herein requires that PWHT must be conducted at 1100°F to 1200°F.
- Additional magnetic and dye penetrant inspection procedures, other design material requirements, and many other items are described in these standards.

3.2.4 American Petroleum Institute API 579-2/ASME FFS-2, 2009

This Standard contains methods for conducting engineering analysis to demonstrate the structural integrity of an in-service component found to contain a flaw or damage. There are methodologies specifically prepared for pressurized equipment. The guidelines in this Standard may be used to make run-repair-replace decisions to help determine if pressurized equipment containing a flaw can continue to operate safely for some period of time.

The possible application of API 579 to evaluate in-service deaerators found to contain cracking is discussed in Section 8 of this document.

3.2.5 International Regulations

Many newly manufactured deaerators are built for countries outside of North America, therefore several of the relevant international regulations and their relevant websites are listed below.

3.2.5.1 European Union

The Pressure Equipment Directive (PED) is the main regulation used, and deaerators could be built to any Code accepted by the Notified Body. The most relevant codes in Europe are EN 13445 (EU), AD Merkblatt (Germany), CODAP (France), and PD 5500 (UK).

3.2.5.2 Australia

Most of the States will accept the ASME code if the user also agrees with it, but the design will be verified against AS1210 (Pressure vessels) per State Regulations.

http://infostore.saiglobal.com/store/

3.2.5.3 New Zealand

OSH Accepts ASME, AS1210, PD 5500 and several other Codes as long as the design is verified by an approved Design Verification organization and the fabrication is done by and approved Fabrication Inspection Body.

http://www.osh.dol.govt.nz/

3.2.5.4 Japan

Deaerator construction falls under Ministry of Health Labour and Welfare (MHLW) Rules/Regulations. Review of the design is performed by an accredited design reviewer. Japan has its own boiler/pressure vessel standards which ASME usually meets.

3.2.5.5 Malaysia

The Department of Safety and Health (DOSH) accepts the ASME Code, provided fabrication inspections are performed by an approved (by DOSH) agency and design review is also performed by that agency or DOSH.

http://www.dosh.gov.my/doshV2/

3.2.5.6 Singapore

The Ministry of Manpower (MOM) accepts the ASME Code with design review and inspection by an approved agency (by MOM).

http://www.mom.gov.sg/Pages/default.aspx

3.2.5.7 India

Any steam touched vessel or vessel that is a part of the boiler system needs to meet the Indian Boiler Regulations.

http://dipp.nic.in/boilerrules/index1.htm
http://dipp.nic.in/boiler_rules_updated/contentsregulation.htm

4
DAMAGE MODES IN DA SYSTEMS

Mechanical equipment has a finite life. It can and will deteriorate in service and can fail. Fitness-for-service (FFS) determination (covered in Section 8 of this document) is a quantitative method to evaluate the expected rate of deterioration and operating safety of deaerator heater and storage vessels. The first step in FFS assessment is to identify damage mechanisms or flaw types that are likely to cause deterioration. In general, the following types of deterioration modes can be expected in utility deaerator equipment:

- Surface cracking, which may be on the inside or outside
- General loss of metal thickness on the waterside due to corrosion and/or erosion
- Surface pitting on the waterside
- Gradual deterioration of manufacturing flaws by corrosion or cracking
- General metal loss and/or cracking on the outside due to under-insulation corrosion or general atmospheric corrosion

Knowledge of the damage mechanism(s) present may be obtained by visual examination of the area of distress in the equipment and comparing the appearance with known exemplar examples of damage modes. The examination may often be supplemented and verified by performing metallurgical tests, either by using in-place metallography or by removing samples for laboratory testing.

Since the failure of several large deaerator storage tanks occurred in the1970s and 1980s many publications relating to types of vessel damage have been cited. By far the most common types of damage reported were (1) cracking, and (2) metal loss by erosion-corrosion (now called flow-accelerated corrosion or FAC). Despite efforts to reduce deaerator and storage tank deterioration problems, both cracking and metal loss in the vessels are by far the most common problems that persist today. Yet, many different types of damage, still generally classified as cracking or metal loss by corrosion, have been reported in conference proceedings, technical journals, and by deaerator manufacturers. One problem in identifying specific damage mechanisms is that no systematic studies have yet been specifically directed toward deaerator deterioration and cracking.

EPRI has published a number of reports on corrosion fatigue both in deaerators and in boiler tubing [1], [2], [3]. The mechanism is the same whether in the deaerator or boiler, though thermal stresses are higher in boiler tubing. A comprehensive laboratory research on corrosion fatigue was conducted regarding the understanding of crack initiation and propagation in boiler tubes [4], [5].

The following discussions on the various types of damage should help to focus on those most important to the utility industry. For completeness, the less common types of damage, often more associated with industrial boilers and deaerator vessels, are also discussed. The various damage mechanisms are summarized in Table 4.1, and the locations of prevalent damage are shown in Figure 4.1 and Figure 4.2. General industry terms were used for clarification.

Table 4-1
Deaerator damage mechanisms

DM Reference Number	Damage Mechanisms
1	Corrosion Fatigue (CF)
2	Flow-Accelerated Corrosion (FAC)
3	Corrosion Pitting
4	Steam Impingement
5	Mechanical Damage
6	Stress Corrosion Cracking (SCC)
7	Thermal Fatigue
8	Down-Time Corrosion
9	Corrosion Grooving
10	Mechanical Fatigue (vibration fatigue)
11	Galling
12	Preferential Corrosion
13a	Stress-induced Pitting
13b	Cavitation
13c	CO2 Pitting
13d	Chloride Pitting
13e	Erosion
13f	Intergranular Corrosion
13g	Hydrogen Cracking
13h	Caustic Cracking

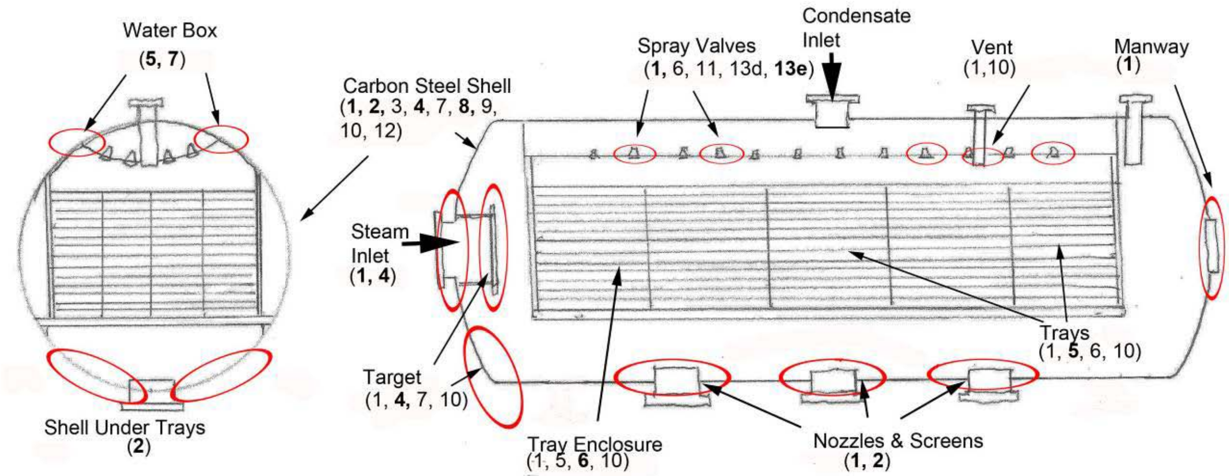


Figure 4-1
Damage mechanism locations within the deaerator heater

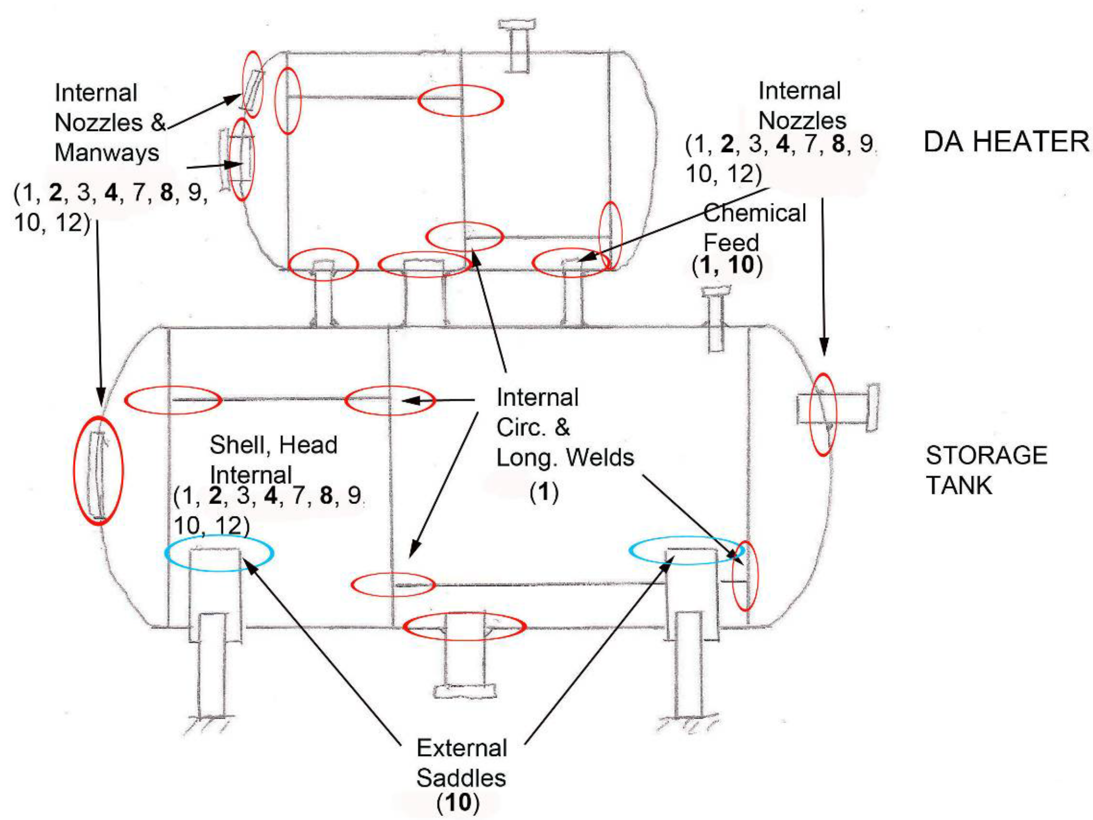


Figure 4-2
Damage mechanism locations on the inside and outside, including the deaerator storage tank

4.1 Corrosion Fatigue (CF)

4.1.1 General

The consensus of opinion amongst failure analysts in the NACE Committee T7H-7 studying cracking and rupture of boiler feedwater deaerators is that the main damage mechanism is corrosion fatigue [6]. This damage mechanism involves formation of protective oxide films during operation (usually magnetite). The films can rupture if subjected to strain in excess of 0.2% in tension [7]. When an oxide film ruptures, bare metal is exposed to feedwater, and thus a small anode is formed in the presence of a large cathode (magnetite layer). In the presence of water, the nascent anode region is immediately converted to more iron oxide. Additional stress cycles repeat the process until a crack is produced. An important condition for corrosion fatigue to occur is to have significant and repeated tensile stresses. These stresses have both a mean and cyclic component. The presence of a high mean stress, such as residual stress from welding, allows cracking to initiate and propagate with a lower applied tensile stress from operational loads. Therefore, post weld-heat-treatment (PWHT) may be utilized in new construction to reduce the vessel's propensity to CF damage. The cyclic stresses can be from piping vibration, pressure fluctuations, loads induced by flow (water-hammers), or structural vibratory loads.

4.1.2 Description

Failure analysis studies on deaerators and storage tanks show the following characteristics of corrosion fatigue [8]:

- Cracks occur in welds and heat affected zones (HAZ).
- Cracks are generally transverse to the welds and HAZ, and occur both parallel and perpendicular to the hoop stress direction.
- Where cracks occur in base metal, they are opposite external welds or other areas of high localized stress.
- The worst cracks are located in circumferential and head-to-shell welds in horizontal vessels.
- Cracks are concentrated, but not solely located, below the liquid level in the storage tank. Cracks are normal to the plate surface and may be very tight.
- Multiple cracks propagate parallel to one another with little branching.
- Cracks are filled with iron oxide corrosion product and only rarely contain trace quantities of other species such as Al, Si, Ca, Mg, Cl, and S.
- Welds and adjacent base metal, including and extending up to about one inch (25 mm) beyond the HAZ, have a higher incidence of corrosion pits than the base plate. Pits are often deeper than they are wide.
- Cracks initiate from corrosion pits.
- Crack tips are blunt.
- Cracks are not limited to any particular material specification.

4.1.3 Where Cracking Is Found

Most cracking is observed on the waterside of the deaerator storage tank, but cracking in the deaerator heater is also common. The deepest and greatest number of cracks occur in large diameter horizontal storage tanks and are generally observed below the water line in the head-to-shell and circumferential welds. Cracking may be observed adjacent to nozzles, usually on the waterside but may also be on the outside of nozzles connected to poorly supported piping. Cracking may be associated on the waterside in regions where attachments or vacuum rings are welded to the outside surface. Cracking has also been observed on the outside of the vessel adjacent to saddle welds and similar areas of restraint.

4.1.4 CF Remedies

There is no known means to completely eliminate CF in deaerator equipment. Mitigation of new equipment may include PWHT of vessels to minimize residual welding stresses, whether or not the process is required by the ASME Boiler and Pressure Vessel Code. Studies have shown that water/steam hammer is a likely contributor to deaerator cracking [9]. Water hammer in the inlet system to the deaerator can result in vibration. It is usually caused by mixing a superheated condensate stream which is above the saturation temperature with a cold makeup stream. The hammer may be eliminated by using separate entry systems for each stream. Likewise, base loading deaerator equipment where possible with minimal load fluctuations and pressure swings will reduce the propensity to cracking. Reducing thermal stresses in start-up is also important. Corrosion fatigue initiates at corrosion pits, so the pH and dissolved oxygen content of the water particularly during periods of lay-up, is critical. Prevention of excess oxygen in the carbon steel portions of the vessel during operation or layup is significant.

4.2 Flow-Accelerated Corrosion (FAC)

4.2.1 General

Flow-accelerated corrosion is a form of corrosion that has plagued nuclear and fossil power plants for many years [10]. (In the United States, flow-accelerated corrosion is commonly known as erosion-corrosion, where an erosion component is present. However, the term flow-accelerated corrosion has become more common and is the preferred damage mechanism term.)The damage mechanism is promoted on the waterside of vessels and piping when the right combination of liquid flow and environmental conditions exist. FAC damage can occur in many different metals, but is most prevalent in the carbon steel portion of high temperature piping and equipment found in power plants. Alloy steels, including low-alloy steel containing chromium, are resistant to FAC. If the steel can be specified as having a minimum of 0.1% chromium, the equipment can be expected to have much improved FAC resistance compared to carbon steel with no chromium [10]. Because water is necessary to remove the oxide layer, FAC does not occur in equipment or piping transmitting dry or superheated steam.

FAC may occur in single-phase (water) or two-phase (water-steam) environments. However, in deaerator equipment, FAC is almost always single-phase FAC. In some cases, steam and water mixtures may be involved in a drain return line, but it is the condition at the metal surface that determines the nature of the FAC damage. In two-phase FAC, the water droplets must be entrained in steam and applied with sufficient force to create cavitation erosion or by droplet impacts where the oxide film is continuously removed and high metal losses occur.

4.2.2 Description

Flow-accelerated corrosion may show the following characteristics:

- The damaged surface has a variable appearance with a locally thinned vessel (or piping) wall.
- Affected areas usually show regions with a “metallic” appearance, as opposed to an oxide-covered or dull appearance.
- The surface may be scalloped or show orange-peel topography (single phase FAC).
- The appearance may suggest water droplet impingement.
- Sharp changes in water-steam flow direction at nozzles or connections may exhibit excavations and tiger striping (two phase FAC).

4.2.3 Where FAC is Found

FAC is almost entirely confined to the shell and nozzle areas of the deaerator heater, as opposed to the storage tank. Any place where there is a penetration into the deaerator is an area where FAC can be found. This includes heater drain returns and recirculation lines. In addition, areas where there is a higher velocity of water and water/steam mixtures are susceptible. This includes areas under the belly of horizontal spray-tray heaters under the tray stack or around the vortex breaker on the connections between the deaerator and deaerator storage tank. These areas are susceptible because of high steam and water flow rates that propel water droplets against the vessel shell and support components. Problems with water distribution, say from multiple broken feedwater inlet nozzles, can create an area of FAC where one had not been seen previously. This is one reason why routine visual inspection of the deaerator and deaerator storage tank is important.

Other susceptible regions are on the shell at recirculation tees and at the nozzle vortex breaker. Steam impingement on the inlet target plate of the deaerator is a special case of FAC and is discussed in the section on steam impingement below.

4.2.4 FAC Remedies

Unfortunately, some of the conditions that promote FAC in deaerators are defined by the manufacturer’s design. Horizontal heaters with a relatively small shell-diameter-to-tray-length ratio will have high velocity steam flows under and through the tray stack, leading to high impingement conditions. Likewise, recirculation tees, return lines, or nozzles positioned close to the deaerator shell may promote FAC damage to the shell. Weld overlaying the deaerator shell with filler metal has been a common method to protect against FAC damage (see Section 9, Repair Options). Currently, weld overlays using ER70S-B2L consumables have been cited as best to restore shell thickness and protect against FAC damage [1].

4.3 Corrosion Pitting (Downtime Corrosion)

4.3.1 General

Pitting corrosion is a form of localized attack that results in holes in the metal. Pitting may be described as a cavity with the surface diameter about the same or less than the pit depth. The pit is most often filled with corrosion product. Pitting in deaerators occurs in the carbon steel and may be difficult to detect because it is usually covered with layers of oxide. One must remove the oxide to discover whether pitting has occurred. Oxygen is necessary for pitting to occur in deaerators. Therefore, deaerators do not experience pitting when operated properly (i.e., dissolved oxygen has been removed). Rather, pitting usually occurs when the deaerator system is shut down for an extended period, allowing oxygen to be absorbed in residual water. Pitting can occur in all carbon steel areas of the deaerator but is most often found in the storage tank [1].

CF is a damage mechanism that is promoted by pitting [11]. Pitting is not necessary for CF to occur, but pits serve as potent stress concentrators and reduce the nominal (applied) stress needed to initiate CF. Pitting is more often experienced in industrial deaerators, but many instances of utility deaerator pitting have been reported, including the inspection of approximately 300 utility deaerators/storage tanks, of which 225 were reported to have pitting corrosion and 170 were cracked [12]. Another report of eighty-four deaerators inspected revealed that twenty had significant pitting, and cracks were found in nine of them (30% of pitted deaerator vessels were cracked) [13].

4.3.2 Where Pitting Corrosion is Found

Pitting corrosion may be found in any carbon steel part of the deaerator and storage tank, but is most prevalent in low regions where water may not drain completely during shutdown or layup periods. Metal oxide and mineral scale, which is often thicker around welds, can concentrate impurities and accelerate pitting [14].

4.3.3 Pitting Remedies

As noted above, pitting should not occur during operation if the unit is running properly. Pitting may be controlled to acceptable levels by maintaining feedwater chemistry within recommended guidelines and using proper layup procedures [14, 15]. If improper layup occurs, considerable oxygen pitting damage can occur even if the period of oxygen contamination is short [16]. Oxygen contamination occurs in feedwater systems when mechanical problems exist with deaerators, feedwater pumps, turbine gland seals, and systems operating under vacuum. Oxygen intrusion can be caused by improper venting, operational changes that cause cold make-up water, tray misalignment, malfunction of water spray valves, and operation with an excessive temperature differential between the deaerator and storage section.

4.4 Steam Impingement

4.4.1 General

Steam Impingement (steam cutting) is a special form of erosion-corrosion, and is closely related to FAC. Attacked surfaces are locally thinned, usually producing unevenly eroded regions associated with the steam inlet target to the deaerator. Entrainment of some condensed water is necessary for impingement attack to occur. As with FAC, affected areas usually show eroded regions displaying a "metallic" appearance free of oxides, as opposed to iron oxide-covered and a dull appearance.

4.4.2 Where Steam Impingement is Found

The steam target and target support steel are areas of primary metal loss. Associated erosion and thinning may occur in the deaerator shell adjacent to, and below, the steam inlet target.

4.4.3 Steam Impingement Remedies

Metal loss in the target region is best resolved by constructing the target and supports from Type 304L austenitic, or Type 2205 duplex stainless steel. Positioning of the target plate too close to the steam inlet nozzle accelerates metal loss on both the target and shell. Mitigation of shell thinning by steam impingement has been accomplished by welding sacrificial plates over the affected areas. However, this method involves welding directly to the shell, requiring special procedures. Subsequent inspection of the shell area under the sacrificial also requires periodic removal and re-welding of the sacrificial plate.

4.5 Mechanical Damage

4.5.1 General

Deaerator vessels and storage tanks are susceptible to mechanical damage. Obvious mechanical damages are impacts from plant equipment, forklifts, and hoists. These are easily identified and remediation can be addressed using the NBIC, API 579, or in many cases good engineering judgments. The most common cause for damage to trays in a spray-tray deaerator is tray upset when pressure is lost due to turbine load-rejection, control valve failure, or any condition resulting in flashing of the water in the storage section. Full load trips and loss of turbine extraction steam may cause flooding of the downcomers, resulting in water being blown upward against the tray bank. Tray damage can occur if hold-down supports are insufficient or inadequate.

More subtle forms of mechanical damage occur due to poor design of support structures, water hammer, or inoperable or poorly maintained expansion plates that result in buckling or high operational stresses that contribute to other damage mechanisms such as corrosion fatigue.

4.5.2 Identification

Tray position should be verified after flow upsets to check for dislodged trays. Frequent systematic inspection of the vessels and attached and supporting structures are the best detection method. Comparison to photographic references is a simple method. More complete surveys using fixed reference points and comparative to historical trends are also possible if damage is suspected. One major issue is the ability of the vessels to freely expand and contract. Periodic inspection and maintenance of the slide plates are very important.

4.5.3 Mechanical Damage Remedies

Once mechanical damage is identified, there are two steps for remediation. First, the cause of the damage must be identified and eliminated. There are various pipe stress analysis programs that can aid in this evaluation if needed. Generally, a comparison of the current configuration to the as-built drawings is a good starting point. The second step is to evaluate any secondary damage such as a contribution to fatigue or SCC and inspect the vessel to detect this damage. The best protection against damage from tray upsets is to provide operational protection to avoid sudden pressure loss to the deaerator. Once trays are dislodged, they should be repositioned as soon as possible to avoid further damage, which can occur even during normal operation.

4.6 Less Common Damage Mechanisms

4.6.1 General

Many other types of damage to deaerators have been reported in technical journals, at conferences, and in other publications, mostly in non-utility applications. Most of the less common damage types have been either unsubstantiated by laboratory examination, or were simply repeated from other publications. These less common damage mechanisms are listed, with reference to prior sources.

4.6.2 Stress Corrosion Cracking (SCC)

Stress Corrosion Cracking (SCC) has frequently been co-incident with CF damage of carbon steel deaerator and storage tank shells [6, 17]. The association was cited due to appearance of crack morphology. Corrosion fatigue is usually characterized by transgranular cracking; cracks are often wedge shaped or necklaced, with oxides present in the cracks. By contrast, the morphology of stress corrosion cracking in carbon steel is usually intergranular and branching with sharp features and tight cracks. Many instances of cracking in carbon steel deaerators and storage tanks showed mixed intergranular and transgranular cracking, with the cracks branching toward the tips. Thus, a combination of CF and SCC was suspected. McIntyre [6] reported that some of the NACE Committee T7H-7D case histories of deaerator cracking were “clearly anodic stress corrosion cracking due to the carryover of caustic salts from boiler water return.” SCC has also been attributed to cracking of stainless steel trays and spray valve springs [14]. While both caustic SCC of carbon steel and chloride SCC of austenitic stainless steel are common damage modes, they require a concentration mechanism of ions for cracking to occur; thus SCC within the deaerator is unlikely unless pitting is prevalent. Twigg [18] reported an instance of under-insulation SCC of a solid 304L stainless steel deaerator heater shell. However, chloride under-insulation SCC of the exterior of austenitic stainless steel pressure vessels is a well understood failure mechanism. Chlorides readily concentrate by contaminated water entering through the insulation and concentrating by flashing on the metal surface. During operation, cracking is prevalent in regions of high stress such as the weld HAZ.

4.6.3 Thermal Fatigue Cracking

Thermal fatigue cracking has been cited as a cause for cracking of stainless steel vent piping, tray enclosures and trays [1]. Thermal stresses result in combined carbon steel-stainless steel fabrication due a 50% greater coefficient of thermal expansion of stainless compared to carbon steel. Thermal stresses also result from excessive rates of heating and cooling.

4.6.4 Down Time Corrosion

Down-time corrosion can result in general corrosion and pitting on carbon steel surfaces and should be controlled whenever extended shutdown periods are planned. It is preferred to maintain a steam blanket on the equipment as this ensures some hot deaerated water for the subsequent startup [20]. Deaerators and storage tanks should be protected from corrosion during long periods of down-time or lay-up by blanketing with nitrogen or filling to the vent with water containing a volatile oxygen scavenger and either ammonia or amine. Units may also be protected by draining when hot and maintained dry with dehumidified air or desiccant.

4.6.5 Corrosion Grooving

Corrosion grooving was described by Twigg [12], where it was observed in storage tanks below chemical feed inlets.

4.6.6 Mechanical Fatigue (Vibration Fatigue)

Mechanical fatigue (vibration fatigue) of DA systems is typically found on external attachments on the exterior surfaces of the vessels. Fatigue on the interior surfaces will almost certainly be corrosion fatigue and classified as such. External fatigue can be either low cycle, generally caused by thermally induced stresses from cycling, or high cycle induced by vibratory forces such as chattering safety valves or induced by flow. It is important to identify the mechanism as high cycle or low cycle fatigue to appropriately deal with the causes.

4.6.7 Galling

Galling damage can be observed on DA systems at the attachment points or on the thermal expansion plates or pads. Austenitic stainless steel bolts, nuts and studs commonly experience galling damage

4.6.8 Preferential Corrosion

Preferential corrosion can occur along the heat affected zone of welds. Boiler feedwater preferentially attacks large ferrite grains adjacent to the weld, resulting in ditching [14, 5].

4.6.9 Other

Numerous other damage mechanisms have been cited in deaerator literature, most of which have not been confirmed by laboratory examination. Those include:

- Stress-Induced Pitting: Localized pitting corrosion that is concentrated in areas of high residual stress. The higher stress provides energy which accelerates the corrosion process, thus making the pitting more prone to occur.
- Cavitation: Cavitation has been reported in DA tanks, but it is rare. Cavitation is the pitting of a metal surface caused by the implosion of vapor bubbles or pockets in a two-phase system, such as water/steam. Generally the conditions for this to occur in a DA vessel are rarely seen, unless in an extreme upset condition. Cases reported in the literature are likely misrepresented as FAC damage.
- CO_2 Pitting: Steel vessels can be corrosively attacked by carbonic acid formed from excessive carbon dioxide in a water-rich system. The attack is a form of undercut pitting. Pits will generally be deposit free or at best have a small deposit of hematite oxide.
- Chloride Pitting: Chloride pitting is rarely seen in DA tanks unless a severe contamination event occurs. The pits are severely undercut and energy dispersive analysis of the pit deposit will show chloride residuals. Stainless steel components in the system can also sustain pitting or more likely stress corrosion cracking.
- Erosion: Erosion of a DA system is likely FAC or steam impingement, which are discussed elsewhere in this section.
- Intergranular Corrosion: Intergranular corrosion is generally not seen on DA systems. SCC can be mistaken for intergranular corrosion.
- Hydrogen Cracking: Hydrogen Cracking of DA systems is usually associated with welding defects. Poor quality welds, especially those made with consumables that have not been dried, is the largest cause for hydrogen cracking in welds. In-service hydrogen damage is not possible given the operational environment of a DA system.
- Caustic Cracking: Caustic cracking is a form of stress corrosion cracking and is discussed in the above sections.

4.7 References

4.7.1 References Cited in Text

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5 EFFECTS OF WATER CHEMISTRY ON DAMAGE INITIATION/PROPAGATION

5.1 Introduction

The feedwater chemistry is critical to controlling and reducing corrosion in the deaerator and deaerator storage tank. Equally or even more important is the chemistry of any water left in the deaerator or deaerator storage tank during the time when the unit is off line and the DA is at atmospheric pressure and exposed to air. Conversely, the proper operation of the deaerator in removing dissolved oxygen is critical to the control and minimization of corrosion in all downstream equipment such as feedwater heaters, the economizer, and the boiler.

In utility boilers, the feedwater chemistry program uses only volatile chemicals, typically ammonia or a neutralizing amine for pH control and a reducing agent such as hydrazine, to establish a reducing environment for the control of copper alloy corrosion. Reducing agents such as hydrazine are recommended when copper alloys are present in the feedwater heaters.

Reducing agents are not a substitute for a properly functioning deaerator and should never be used as such. Although mistakenly referred to as oxygen scavengers, the application of reducing agents increases the rate of flow-accelerated corrosion in feedwater equipment including the deaerator and deaerator storage tank.

Nearly all supercritical units in the US, many of the high pressure (> 2600 psig (17.93 MPa)) drum units with full-flow condensate polishing, and all ferrous feedwater heaters operate with oxygenated treatment (OT). Proper operation of oxygenated treatment provides that once the unit chemistry is established the deaerator vents are closed, and the deaerator vessel ceases to function as a deaerator and only serves as a head tank for the boiler feed pumps.

Controlled amounts of oxygen added at the condensate pump discharge minimize flow accelerated corrosion in the feedwater piping and deaerator during operation. Units on oxygenated treatment will start up under all volatile treatment guidelines (with no oxygen addition; also no reducing agent) until the unit is up and running and other chemistry parameters are close to normal. At this point, the thermal stresses required for corrosion fatigue should have been relieved, so the addition of oxygen does not increase the propensity of corrosion fatigue in these units. EPRI recommendations for unit startup and shutdown are that oxygen levels be maintained below 100 ppb during these transient periods and if possible before firing the boiler on startups.

Combined cycle power plants generally do not have an independent deaerator. Some HRSGs do have a small deaerator built into the top of the LP drum. Generally these units depend on the small amount of makeup water deaeration that occurs in the condenser to maintain the desired dissolved oxygen limit of < 10 ppb at the condensate pump discharge. In multi-pressure units the low pressure (LP) evaporator section performs as an efficient deaerator.

5.2 Feedwater Chemistry Limits

This is a very brief overview of feedwater chemistry as it affects the water and steam chemistry in the deaerator and deaerator storage tank. The EPRI Cycle Chemistry Guidelines for Fossil Plants [see references on EPRI Chemistry Guidelines at the end of this chapter] provide the criteria to establish a proper feedwater chemistry program and normal operating limits for their unit.

The feedwater chemistry of steam cycles operating on All Volatile Treatment and phosphate or caustic programs are generally the same. The specific limits are dependent on the presence or absence of copper alloys in the feedwater heaters. If there are copper alloy feedwater heaters, the pH of the feedwater must be slightly lower to prevent the acceleration of copper corrosion by excessive amounts of ammonia. The recommended pH limits for mixed metallurgy (copper and carbon steel in the feedwater section) are 9.0 - 9.3. The pH limits for all ferrous metallurgy (no copper alloy feedwater heaters) are 9.2 - 9.6.

Ammonia in the feedwater is responsible for maintaining the pH in this range in most fossil-fired units and HRSGs used primarily for power production. Ammonia addition to the cycle may be derived from a number of sources, including the direct addition of ammonium hydroxide solutions to the condensate/feedwater, the breakdown products of neutralizing amines, and the breakdown product of hydrazine or any other nitrogen-containing reducing agent.

Some ammonia is lost via the deaerator vents, but more leaves with the vacuum pump steam jet air ejector vent and condensate (if it is not returned to the condenser). Carbon dioxide enters the feedwater with any makeup water or comes in with air in-leakage. Some carbon dioxide may also be generated from the degradation of organic (carbon-based) chemical treatments. Carbon dioxide neutralizes ammonia in the condensate, requiring the addition of more ammonia (or amine) to bring the pH back up into the control range. The relationship between carbon dioxide and ammonia concentration can be seen in Figure 5.1. Excessive air in-leakage increases both the carbon dioxide and ammonia concentrations in the feedwater if the feedwater pH is maintained.

Deaerator design should be capable of reducing dissolved oxygen in the feedwater coming into the DA to a level of less than 7 ppb. This is generally the design guarantee point. In practice, far lower levels of dissolved oxygen are achieved in a properly performing deaerator, typically less than 2 ppb.

Condensate entering the DA should contain less than 10 ppb dissolved oxygen. Higher levels than 10 ppb typically indicate air in-leakage problems upstream of the condensate pump and should be addressed at that level. During unit startup condition, large amounts of oxygenated makeup water are frequently added either directly to the deaerator or indirectly through the condensate. During part of this time, there may be no steam to the deaerator. Even if steam is flowing to the DA, the amount of cold makeup water or condensate being fed to the DA is significant and the quantity of steam is often minimal. Low temperature water can cause the deaerator to behave more like a water heater. Under these conditions excessive amounts of oxygen can enter the feedwater.

If there is not a significant decrease in dissolved oxygen across the deaerator (dissolved oxygen at the deaerator outlet should be less than 7 ppb) and the DA is operating at temperature, it can be assumed that there are mechanical issues (vents closed, damaged sprays) that are preventing the deaerator from functioning properly. In this case the deaerator must be taken out of service and inspected as soon as possible and any mechanical issues corrected.

5.3 Feedwater Chemistry and Flow-Accelerated Corrosion

Corrosion fatigue and flow-accelerated corrosion (both single phase and two-phase) are functions of the feedwater chemistry. Improving the feedwater chemistry control and startup chemistry can markedly minimize the conditions contributing to the mechanisms and subsequent failures.

EPRI has published numerous reports on flow-accelerated corrosion (FAC).references], which prove details for a complete understanding of the FAC mechanism. In brief, the rate of FAC is a function of metallurgy, design (flow, piping configuration), temperature, and the feedwater chemistry (primarily the pH and oxidation-reduction potential or oxygen content of the water).

The phenomenon of FAC is a process in which the normally protective magnetite (Fe_3O_4) layer on carbon steel dissolves in a stream of flow water (single phase) or wet steam (two-phase) The process reduces or eliminates the protective oxide (magnetite) layer and promotes rapid removal of the base material until the component fails due to excessive wall loss.

When this iron oxide layer is composed nearly exclusively of magnetite (Fe_3O_4) the porosity of the magnetite layer and the mobility of the ferrous ion (Fe^{+2}) make it susceptible to removal in areas of turbulent flow. Chemicals such as hydrazine provide a strongly reducing environment which promotes the exclusive formation of magnetite. In areas susceptible to FAC, the effect of the hydrazine is to promote a highly reducing potential which increases the solubitility of magnetite in solution and accelerates the FAC mechanism.

Small amounts of dissolved oxygen (5-10 ppb) in the water increase the free corrosion potential by several hundred millivolts and promote the formation of iron oxide hydrate (FeOOH) and ferric oxide (Fe_2O_3) particles that form within the porous magnetite layer and inhibit the diffusion of the Fe^{2+} ions from the steel surface. In addition, the hematite structure markedly reduces the solubility of the protective oxide layer, stabilizing it. Increasing the pH of the feedwater increases the stability of magnetite by increasing the precipitation of the soluble Fe^{+2} ions, resulting in greater stability of the protective iron oxide layer.

Small amounts of chromium (> 0.3%) in the carbon steel reduce the dissolution rate of the protective oxide and lower, if not eliminate, the potential for FAC. As iron oxide is removed, the chromium oxide becomes more concentrated in the passivation layer increasing the stability of the layer. Studies and experience have shown that even small amounts of chromium make a significant difference in the rate of FAC in a given area of piping. Typically, when specifying piping for areas that are susceptible to FAC, 1.25-Cr alloys are favored. When making repairs to areas of FAC in deaerator shells, chromium-containing weld metal is used for the same reason.

Flow-accelerated corrosion occurs in both single-phase water and in two-phase wet steam (a mixture of water and steam). In the two-phase fluid the suspended or condensing droplets of moisture (water) are responsible for the iron oxide dissolution and subsequent FAC mechanism. The turbulence and motive conditions are typically provided by the rapidly expanding or collapsing steam. Two-phase FAC is most prominent in areas of pressure or temperature transients where rapid flashing of superheated liquid or condensing of sub-cooled steam occurs, resulting in a highly turbulent or high velocity two-phase fluid.

Areas just below feedwater heater drain returns or re-circulating line penetrations are susceptible to single phase FAC. Excessive flow rates underneath the spray box can cause FAC in an area. This may be a design issue or can be caused by one or more broken spray nozzles in the feedwater inlet header. Single phase FAC has a smooth shiny appearance with small divots, scallops, or chevrons in the metal. Depending on the orientation of flow away from the area, the chevrons may be more or less circular. The overlapping of the scalloped areas results in a surface texture has an “orange peel” appearance.

Two-phase FAC is produced when water droplets are entrained in a saturated steam flow and impinge on a metal surface. They can produce rough patches or very specific areas of corrosion bordered on both sides by areas where there is no corrosion. This results in a striped or “tiger striped” appearance. Steam and water mixtures are generally considered more aggressive to carbon steel than water alone. The area where two-phase corrosion can be found in deaerators is often at the steam inlet where wet steam may be introduced into the deaerator.

The pH of the feedwater is critical to reducing the rate of FAC in the deaerator. The purpose of a deaerator is to remove gases from solution by contacting small droplets of the water with steam. This contact not only removes the dissolved oxygen, but also some ammonia lowering the pH of the feedwater and increasing the rate of FAC in that area. To counteract this effect, additional efforts may be required to increase the pH of the feedwater upstream of the deaerator. This will reduce the potential for FAC in the deaerator.

Unless there are copper-alloy feedwater heaters, EPRI does not recommend the use of any reducing agent such as hydrazine. Hydrazine has been shown to increase the rate of FAC by lowering the oxidation-reduction potential and increasing the formation and solubility of ferrous iron in the protective oxide layer.

When there are copper-alloy feedwater heaters, the plant must balance the potential for copper corrosion versus the increased risk of FAC. In its most recent guidelines, EPRI recommends controlling the level of hydrazine such that the oxidation reduction potential (ORP) of the feedwater is between -300 and -350 mV. To prevent overfeed or underfeed of the reducing agent in units that cycle or vary load, an on-line ORP or hydrazine analyzer may be needed.

5.4 Feedwater Chemistry and Corrosion Fatigue (Stress Assisted Cracking)

Since deaerators are used in a number of industrial boilers, there are a significant number of publications in the literature regarding this failure mechanism. Outside the utility industry this mechanism is also referred to as stress assisted cracking or more generally as environmentally assisted cracking.

As its name implies, corrosion fatigue is a combination of two separate mechanisms. There is a corrosion component and a stress-related fatigue component. Stress may be in the form of residual stresses in the material associated with either formation or welding compounded with thermal stresses. Severe corrosion fatigue is most often associated with excessive strain (stress) within the component resulting from restraint of movement of the component, such as differential thermal expansion restrained by an external attachment, change in component thickness or component orientation. When the internal strain becomes excessive, a break in the protective oxide film will result in exposing non-passivated steel to the chemical environment. Once the oxide layer is cracked, the presence of dissolved oxygen, carbon dioxide, low pH conditions, and any contamination products or impurities such as chlorides in the water can attack the underlying metal resulting in the initiation and formation of a pit. The pit induces a localized stress riser and the site of subsequent attack. The pit growth proceeds with repetitive stress and corrosion cycles, and cracks develop at the base of the pit in the orientation of the strain. Dissolved oxygen, low pH conditions, chlorides and other contaminants including corrosion products migrate to the tips of the cracks continuing the corrosion process and weakening the metal. Even when the crack becomes filled with iron oxides, the presence of these oxides can produce stresses within the metal. Repeated stress and corrosion cycles drive the crack deeper in to the metal. Low pH feedwater, typically driven by the amount of carbon dioxide or impurities dissolved in the water, as well as conditions of ammonia loss and phosphate return contributes to the corrosion. The pH at various carbon dioxide and ammonia concentrations can be seen in Figure 5.2.

Metallographically, corrosion fatigue cracks are transgranular and oxide filled. Areas of corrosion appear as wide spots in the cracks. These often alternate with straight thin oxide filled cracks that occur during high stress conditions.

In utility boilers, corrosion fatigue failures more commonly occur in economizers and boiler tubes, particularly near constraints such as buckstays. In deaerators, corrosion fatigue damage is primarily located in stressed areas in or near the longitudinal or circumferential welds in the deaerator and particularly in the deaerator storage tank. Corrosion fatigue may appear as a pinhole leak or multiple cracks that run axially along a weld or constraint. The mechanical constraint may be on the inside or outside of the vessel. Regular inspection of the deaerator welds normally finds corrosion fatigue cracking before it has had a chance to reach deep enough into the metal to cause a failure.

Removing dissolved oxygen from the feedwater prior to startup reduces the risk of corrosion fatigue. In Figure 5.3 the Pourbaix diagram on the right shows that the risk of corrosion fatigue is greater when the oxidation reduction potential is greater than - 0.5 mV with a pH (at 250ºC (482ºF)) between 6 and 8. (Neutral pH at 250ºC (482ºF) is 5.6) These graphs are at temperatures higher than typical DA operation, but similar principles apply. In the industry, maintaining feedwater dissolved oxygen levels below 100 ppb during the entire startup process is considered good practice.

Achieving low levels of dissolved oxygen during startup often requires purging of condensate storage tanks with nitrogen, flooding the deaerator with nitrogen prior to filling, or a nitrogen purge of the deaerator and deaerator storage tank prior to firing. Proper startup technique can reduce the risk of corrosion fatigue and the prevalence of cracks in the deaerator welds.

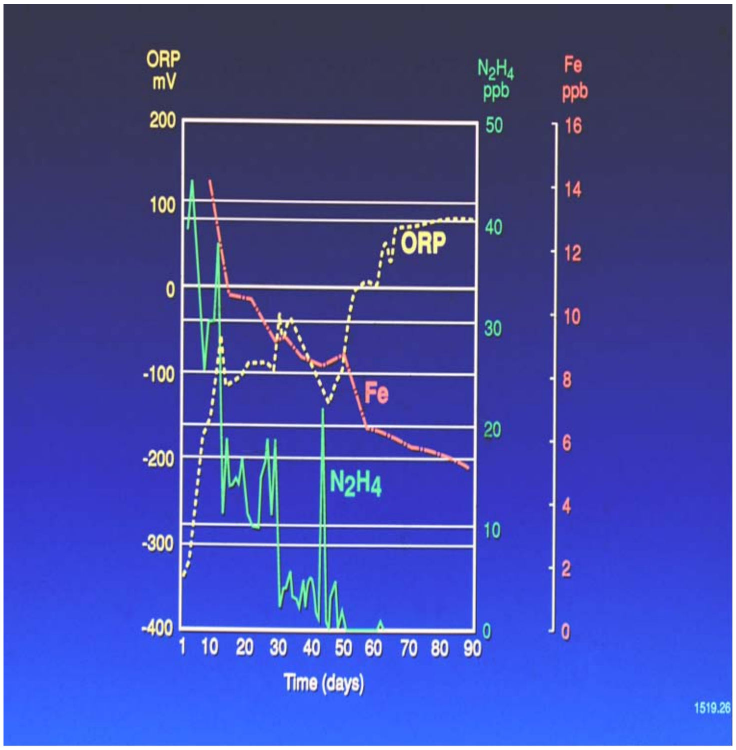

Figure 5-1
Change in oxidizing-reducing potential (ORP) and feedwater iron levels (Fe) at the economizer inlet when Hydrazine (N2H4) is gradually reduced on a 600MW drum rnit with an all-ferrous feedwater system (Source: R.B. Dooley, J. Mathews, R. Pate and J. Taylor, "Optimum Chemistry for 'All-Ferrous' Feedwater Systems: Why Use an Oxygen Scavenger," Proc. 55th International Water Conference, Pittsburgh, PA, Oct. 1–Nov. 2, 1994.)

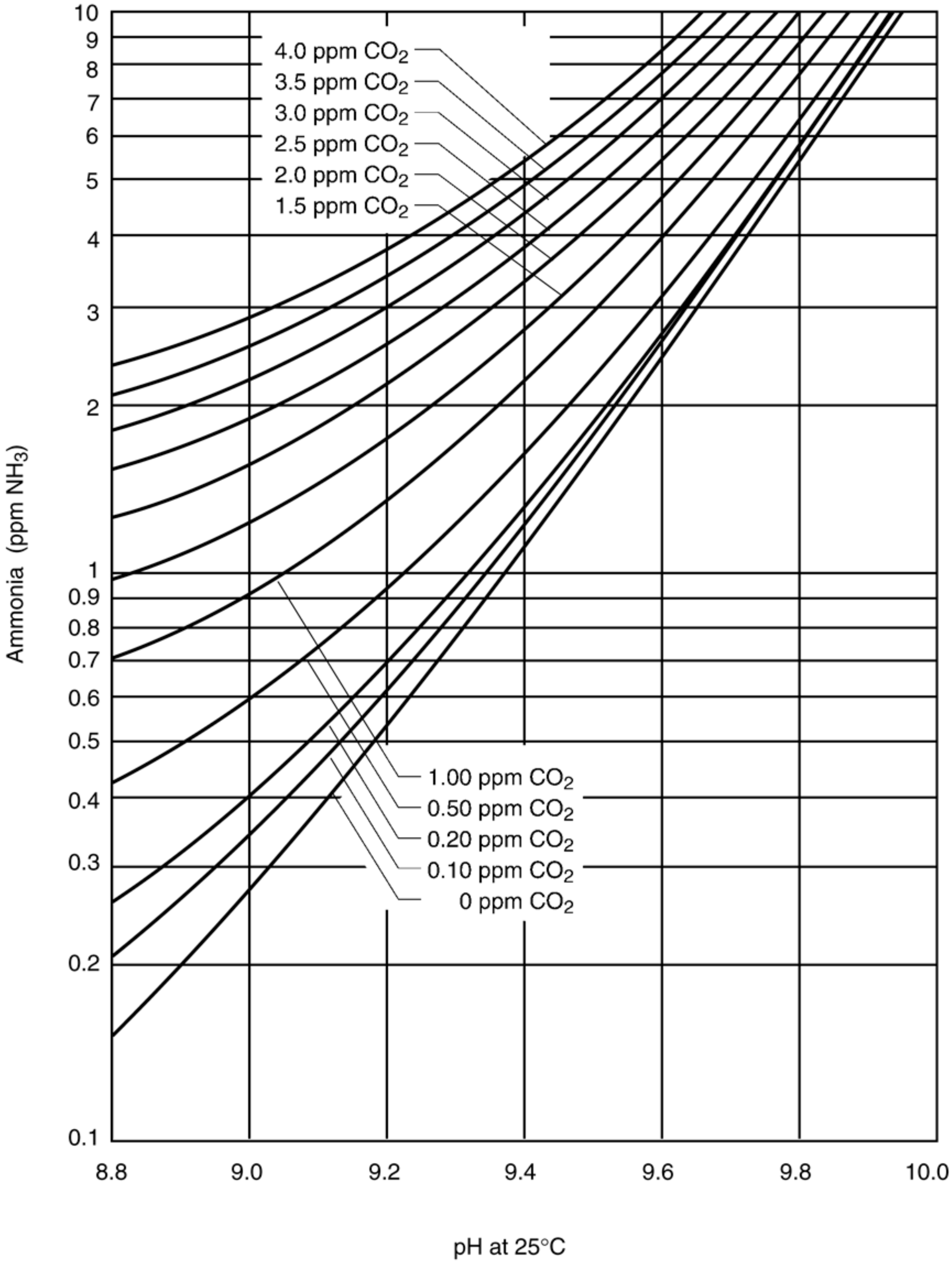

Figure 5-2
The pH relationship between carbon dioxide and ammonia in feedwater (Source: Cycle Chemistry Guidelines for Fossil Plants: Phosphate Continuum and Caustic Treatment, EPRI, Palo Alto, CA: 2004. 1004188)

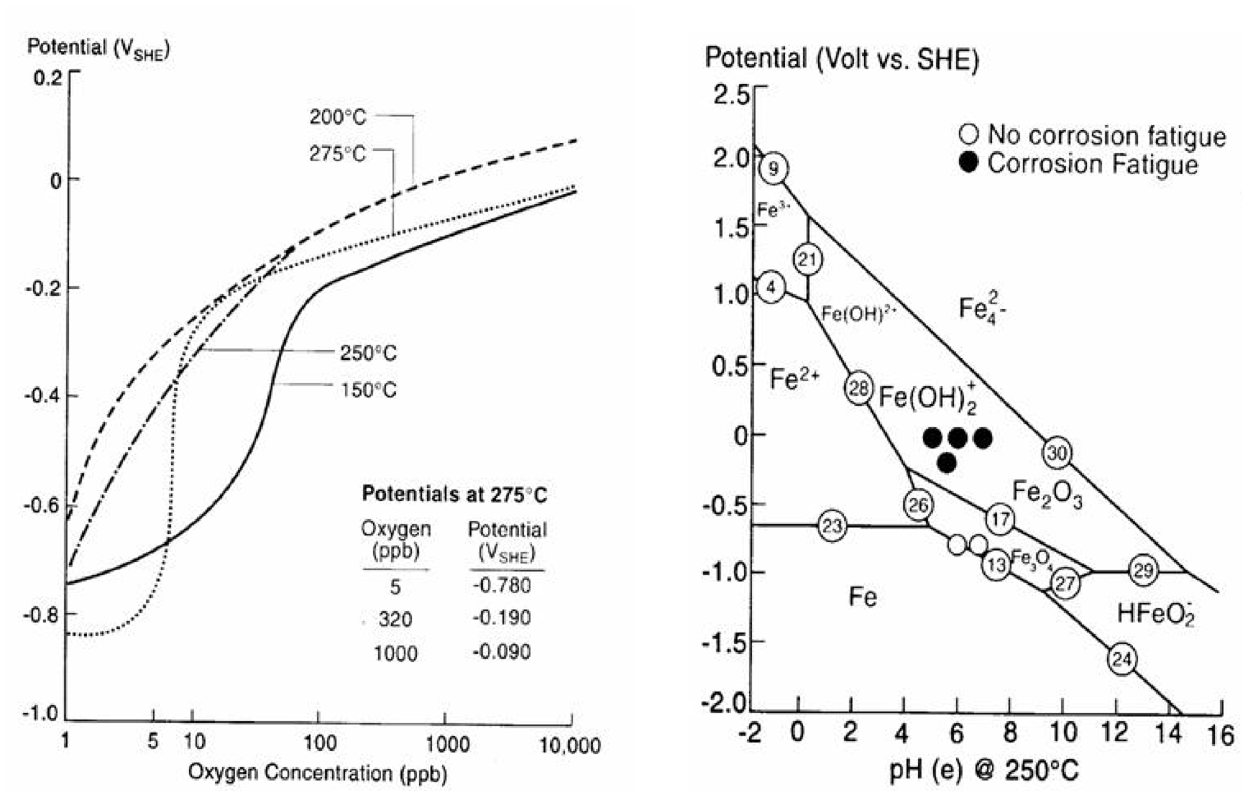

Figure 5-3
Corrosion fatigue and dissolved oxygen concentrations (Source "Corrosion Fatigue Boiler Tube Failures in Waterwalls and Economizers Volume 2: Laboratory Corrosion Studies EPRI, Palo Alto, CA 1992, TR-100455)

5.5 EPRI References for Water Chemistry

5.5.1 EPRI Documents on FAC

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5.5.2 EPRI Documents on Corrosion Fatigue

1. *Corrosion Fatigue Boiler Tube Failures in Waterwalls and Economizers Volume 2: Laboratory Corrosion Studies*, EPRI, Palo Alto, CA 1992, TR-100455

5.5.3 EPRI Chemistry Guidelines for Fossil Fired Power Plants

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6
OPERATIONAL FACTORS IN DAMAGE INITIATION AND PROPAGATION

6.1 General

The objective of this section is to provide guidance to plant engineering and operations as to the operational factors contributing to deaerator damage. In general, systems that are thermally stable and operate base loaded are less likely to encounter damage. When upset conditions (steam hammer, pressure fluctuation, low outlet temperature, high oxygen, and water out of the vent) become frequent, the root cause(s) of the upsets must be found and corrected. The following paragraphs cover factors that are believed to contribute to a few of the most serious damage types in deaerators and deaerator storage tanks.

6.2 Corrosion Fatigue (CF) Cracking

NACE and others indicate that corrosion fatigue (CF) cracking is most experienced when frequent load changes occur or the deaerator is alternately subjected to hot steam and cold water [1, 2, 3]. Operational conditions contributing to water or steam hammer are most likely to produce severe alternating tensile stresses in the vessel shell, both deaerator and storage tank, that may lead to fatigue crack initiation and propagation. At the deaerator, steam hammer may be caused by water entering a steam line or steam-filled space. One case was cited where the water level in a deaerator was held at an excessively high level during a turbine trip resulting in severe water hammer and damage to the deaerator supports. Other operational concerns are prolonged low-load operation, flows beyond design, operation colder than design, and steam temperature in excess of design. These factors and others that result in repeated pressure surges are most likely to contribute to CF damage. Copeland [4] reviewed plant operating data and record charts to find significant stress cycles, especially during start-up. Although deaerator operating pressures are relatively low, the material thickness in deaerators and storage tanks are such that slightly increased stresses can be significant, especially when combined with residual stresses inherent in some non-heat treated vessels. Copeland also monitored operating stresses with strain gages in vessel areas that were cracked, but did not measure significant stress aberrations.

6.3 Flow-Accelerated Corrosion (FAC)

As noted in Section 4 of this guideline, conditions influencing FAC in deaerators are mostly defined by the manufacturer’s design, and operating conditions cannot normally be changed to reduce the problem. An exception is that FAC can occur if the deaerator is operated above design limits or with damaged spray valves and/or trays, resulting in excessive water impingement on lower carbon steel tray enclosure supports. FAC may also be minimized by relocating recirculation tees or elbows to minimize direct impingement of water onto the carbon steel shell or attachments.

6.4 Corrosion Pitting

Corrosion pitting is most likely to occur during shutdown periods and can be minimized by ensuring the deaerator and storage tank are thoroughly drained and dry. During periods of long layup the vessels should be protected by using proper layup procedures [2, 5].

Pitting cannot occur during operation if the deaerator is operating normally, but excess oxygen during operation can be present due to other conditions. One example is high oxygen during non-steady state operation (startup and shutdown). The length of a stabilization period is system-specific, but three days of boiler operation to reach steady state may be used as a guideline. If there is a down-ward trend in oxygen content measurements, steady state condition has not yet been attained. Other factors contributing to excessive oxygen during operation are improper design of air inlet, spray valves not installed correctly, water inlet temperature too low and improper venting.

6.5 Steam Impingement

As noted in Section 4 of this guideline, steam impingement is a special case of FAC. Damage from steam impingement is confined to the steam inlet region of the deaerator, especially the target plate and structural attachments. There is little that can be done in operation of the deaerator to reduce erosion by steam impingement. Rather, the longevity of the target is dependent on position from the steam inlet (less wear as the distance is increased) and the use of erosion resistant alloys such as 304L stainless steel for the target plate and attachments.

6.6 Mechanical Damage

Many of the operational factors influencing CF also apply to deaerator mechanical damage. As noted above, full-load rejection from turbine trips may cause flooding of the downcomers resulting in water being blown upward against the tray bank. Likewise, steam flashing from the storage tank to the deaerator causes mechanical damage to trays and enclosures, and is related to excessive pressure drop in the equalizers or excessive pressure drop across the tray bank. This problem is minimized in the design stage by adequately sizing the equalizers and providing sufficient height between the bottom of the deaerator and tray stack.

NACE reported in surveys that mechanical damage to trays in utility deaerators was very common prior to about 1976. Of the 80 installations surveyed, approximately 22% reported damage to trays or enclosure hardware. Since 1976, the reported incidence of tray damage has decreased significantly. Damage occurred as a result of plant upsets, especially full-load rejections. Trays were reported to be dislodged, bent, and broken. Tray end clips, fasteners, and distribution troughs were also damaged, as well as tray enclosures. More recent design improvements in tray and hold-down hardware have reduced the incidence of this damage.

6.7 References

1. *Standards and Typical Specifications for Tray Type Deaerators*, *8th Ed.*, Heat Exchange Institute, Inc., Cleveland, OH: 2008.
2. Jonas, O., Mancini, J., "Corrosion of Deaerators," ASM Handbook, Vol. 13C, p. 452, 2006.
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4. Copeland, J. F., Eastman, A. D., Schmidt, C. G., "Fatigue an Stress Corrosion Cracking Evaluations in Deaerators," Paper #216, proc. Corrosion87, NACE, San Francisco, CA: 1987.
5. "Consensus for the Lay-up of Boilers, Turbines, Turbine Condensers, and Auxiliary Equipment," ASME Research Report, CRTD- Vol. 66, 2002.

7
INSPECTION ISSUES/RE-INSPECTION GUIDELINES

7.1 General

The objective of this section is to provide guidance to the plant engineer or corporate team responsible for ensuring that the deaerator equipment is performing well and evaluating its physical condition. A written plan for periodic inspection of the deaerator equipment, both internal and external, is an essential element to accomplish these goals. Fortunately, there is a wealth of information published to provide insight on what type of damage to look for and the methods to detect the damage modes. As shown in Section 4 of this report, the most prevalent damage mechanisms in deaerators occur on the waterside. Therefore, periodic internal inspections are mandatory. The interval of such inspections varies from unit to unit, and guidelines to determine inspection intervals are discussed below. Deterioration of deaerators and storage tanks can also occur on the outside and should not be overlooked in the inspection plan. Ultimately, the goal of the inspection is to ensure that the equipment is fit for continued operation until at least the next regularly scheduled shutdown.

The data obtained from the inspection must be reviewed by engineers or inspectors who are competent to evaluate the results and to determine the equipment serviceability. The data should also be presented in a form that can be used to assess fitness-for-service (FFS); refer to Section 8 of this document entitled "Fitness-For-Service." If the inspection reveals conditions that require repair, the data should be sufficiently complete to assist in decision making in the needed repairs.

Experience in deaerator heater and storage tank failures of the 1980's focused primarily on cracking in these vessels. Data by NACE on cracking was presented in the document *Standard Practice – Prevention, Detection and Correction of Deaerator Cracking*, 1990 [1]. Updates to the publication were made in 1996, and again in 2007. The NACE document should be used as the guide to identify cracking in deaerators and storage tanks. The document covers:

- Personnel qualifications
- NDT equipment
- Weld layout of vessels
- Required surface preparation
- Areas of initial inspection for cracking
- Areas of re-inspection for cracking

- Methods of inspection for cracking
- Method of reporting
- Vessel classification

The last item on this list of cracking, vessel classification, is critical in assessing the interval of re-inspection and FFS category:

Category I: No relevant discontinuities as defined by the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 criteria were detected.

Category II: Discontinuities were detected but weld repairs not required.

Category III: Discontinuities were detected and weld repairs required.

The NACE method for categorizing deaerators and tanks is extended in this document to include damage mechanisms other than cracking, e.g., general metal loss by FAC or steam impingement.

7.2 Safety Precautions

Personal safety for inspectors should be ensured by complying with jurisdictional and plant procedures for lockout-tagout and safe entry of a confined space. The equipment must be cool enough and adequately ventilated. Inspectors and nondestructive testing personnel must use the specified personal protective equipment.

7.3 Inspection Planning

Key tasks in planning deaerator equipment inspections are as follows:

1. Establish inspection guidelines including:

    a. In-service and out-of-service modes
    b. Equipment items to inspect
    c. Inspection coverage, inside and outside
    d. Nondestructive testing (NDT) methods (visual, WFMT, UT, etc.)
    e. Inspection interval
    f. Data review and responsible personnel

2. Review past inspection and condition information.

3. Ensure inspection personnel are qualified for the required tasks. Walk-down inspections when the equipment is running should be carried out by plant employees who are trained to inspect for problem symptoms and operating conditions. Detailed visual and nondestructive test inspections for internal deterioration, thinning, and vessel cracks should be performed by properly trained and experienced inspectors. Written NDT procedures should be used. Plant personnel may be qualified to perform these inspections, including the necessary nondestructive testing. However, most plants contract with inspection service companies to do out-of-service deaerator inspections. NDT technicians should be trained and certified in each inspection method used to inspect deaerators in accordance with the recognized governing jurisdiction or with either:

   a. SNT-TC-1A of the ASNT (American Society for Non-destructive Testing);
   b. Standard 48.9712 of the CGSB Canadian General Standards Board;
   c. Non-destructive testing – Qualification and certification of NDT personnel – General principles, EN 473, CEN rue de Stassart, 36, B-1050 Brussels.

4. All inspections except routine daily or weekly walk-down inspections in running mode by operators should be formally documented. Documentation should be sufficient so that a person not familiar with the particular inspection can use it to locate all deficiencies and repeat the inspection and/or test results.

7.4 Inspection Practices

7.4.1 Running Mode

Visually examine the exterior of the heater and storage vessels, looking and listening for steam or water leakage, moist insulation, hammering in the water inlet piping, water in the vent steam, and proper steam plume. The NBIC recommends that operators examine for conditions that should be avoided, including: (a) restricted steam flow, especially with cold feedwater; (b) operation above maximum capacity; (c) operation below minimum effective capacity; (d) operating with blended water temperature too high; (e) any significant pressure or temperature fluctuation; (f) water hammer; and (g) high oxygen in the boiler feedwater from the deaerator.

7.4.2 Out-Of-Service Mode

A comprehensive “out-of-service” deaerator system inspection starts with a well-lit, detailed visual inspection (VT) of the interior and, to the extent possible, the exterior of the vessels. The inspection should include a suitable means for crack detection: wet fluorescent magnetic particle testing (WFMT); liquid penetrant testing (PT); electromagnetic testing (ET). Ultrasonic testing (UT) should be used for thickness measurements, depending on the results of the visual inspection and insurance/jurisdictional requirements. Use of past reports when inspecting deaerator vessels is important to ensure that areas are not overlooked, as well as determine rates of deterioration of problem components. Below is a description of each step in the inspection process. Additional inspection discussion is available in the EPRI document *Repair of Deaerators* [2].

7.4.2.1 Visual Inspection

Visual inspection is the most important inspection and detects a majority of problems except most very tight cracking. Carbon steel component surfaces will usually require additional cleaning by wire brushing. Almost all problems will be found on the interior of the deaerator heater and storage tank, and exterior inspection necessitates removal of insulation. Yet, periodic inspection of the exterior of both the heater and storage tank should be included in the inspection plan, as cracking can be experienced at supports and unsupported nozzle penetrations. Periodic exterior inspection that includes removal of insulation should be factored into the overall inspection plan. Components of the deaerator that should be visually inspected include:

- Vessel Shell: All accessible shell and head surfaces should be inspected for disruption of the oxide film, looking especially for streaks, pitting, and eroded surfaces (signs of FAC or steam impingement erosion). Any surface where steam or water enters is a possible region for deterioration by these damage mechanisms. FAC damage is especially prevalent in the "underbelly" portion under the tray section, or at the downcomer to the storage tank. Areas of erosion should be measured for thickness using the UT method. Cracking may be visible, especially at weld junctures of carbon steel-to-stainless steel, such as the water box or vent penetrations, but will require additional testing by an appropriate NDT method (discussed below). Use of low angle illumination parallel to the shell surface increases the effectiveness of the visual inspection, especially in determination of possible distortion due to weld overlays.
- Water Distribution System: Water boxes, usually constructed from austenitic stainless steel, are prone to longitudinal cracking at the juncture to the shell. Repairs are difficult and re-cracking is almost inevitable. Cracking at the juncture to the shell should be closely examined and tested for possible crack penetration into the shell. Cracking may also occur at the vent and spray valve penetrations. The water box stainless steel liner to the shell can be inspected by removing one or more spray valves. Water distribution header pipes, in lieu of the older style water boxes, are not rigidly welded to the shell and are normally less affected by distortion and cracking from differential thermal expansion.
- Vents: The seal welds from vents to the water box may experience cracking, resulting in water short circuiting the spray valves. Cracking can usually be observed visually, but the weld should be checked with PT.
- Tray Enclosure: Examine the tray enclosure for distortion, cracking, and signs of water short circuits.
- Trays: Examine for damage of severely warped trays. Trays should be firmly held in place by hold-down fixtures. Check for tray displacement and signs of corrosion and cracking.
- Tray Enclosure Supports: Visually inspect welds for cracking, although these components should also be examined using WFMT or PT.

- Steam Baffle: The steam baffle and target plate are subject to deterioration from steam impingement and can be examined visually. Regions of the vessel head and shell should be visually examined for local thinning, supplemented by UT thickness inspection.
- Storage Tank: The storage tank is prone to cracking that is usually not detected by visual inspection. Yet, a 100% visual inspection of the storage tank should be performed looking for surface discontinuities or visual disturbance of oxides which may indicate local corrosion, especially at nozzle inlets and outlets. Screen covers on outlet nozzles should be removed for visual and MT inspection.

7.4.2.2 Inspection for Cracking

As noted above, the reader should consult the NACE Standard [1] for detailed guidelines on crack detection in deaerator vessels. Supplementary crack test information is provided in this document:

- Weld Layout: A layout drawing showing all welds must be prepared to ensure accurate recording during crack detection. It is important to note whether the vessel welds are viewed from inside or outside if “roll-out” drawings are prepared.
- Surface Preparation: A critical step in the process is surface preparation, which is normally performed by grit blasting or blend grinding welds for the first inspection, and only power wire brushing or flap wheel sanding is usually required for re-inspections. A survey by NACE in 2005 indicated that for internal re-inspections, the majority of respondents used either abrasive blasting or power brushing. When detected, cracking is usually perpendicular or longitudinal to the weld. To avoid masking of fine cracks, final grinding should be performed at a 45 degree angle to the weld cap.
- NDE Equipment: WFMT is almost universally used for crack detection of carbon steel, and liquid penetrant (PT) is normally used for stainless steel. Both of these methods require good surface preparation for proper interpretation of surface indications. More recently, users have found using electromagnetic testing (ET) to be faster and require little or no surface preparation to detect cracks. The ET method may be used to quickly screen welds for cracking with suspect crack areas tested more thoroughly with WFMT or PT.

7.4.2.3 Thickness Testing

Many insurance and jurisdictional agencies require periodic thickness testing for corrosion thinning. *Thickness testing scans along the shell should never be a substitute for internal visual inspection*. Conditions found by visual inspection should be investigated by UT inspection. Straight beam UT can provide acceptably accurate results within about +/- 1% when performed by an experienced technician. Surface preparation by flap wheel sanding is usually required. UT line scans such as described in API 653 are a way to determine the cross-section thickness profile for detailed FFS integrity evaluations.

7.4.2.4 Reporting:

Accuracy of data recording and reporting is a must and is often overlooked. The function is simple, yet this mundane task is necessary for the purpose of locating exact test locations in the future, and to provide guidance for necessary repairs. A complete description of flaws or thin regions is also necessary should FFS analysis be required. Quality reporting is one reason to use professional testing services for nondestructive testing; these companies invariably provide superior report and test documentary services.

7.4.2.5 Review and Use of Inspection Results:

Plant or corporate engineering and maintenance personnel should carefully review the inspection results and, if necessary, perform a more detailed analysis using FFS methods described in Section 8 of this report. Comparing inspection results from current inspection activities with those from previous inspections can help to determine if detrimental processes are underway (e.g. thinning or crack growth) that may compromise the reliability of the deaerator equipment. The latest inspection results should be the basis for planning the scope and timing of future inspections. Updated inspection reports for the vessels should be kept in an easily accessible file.

7.5 Interval of Inspection

Interval of inspection in this report generally follows the guidelines provided by the NACE Standard. Closer intervals between inspections may be dictated by insurance or jurisdictional requirements, which must be followed if they are more stringent than suggestions provided by NACE or in this report.

Many factors influence deaerator and storage tank deterioration. Included are original design and fabrication factors, including quality of construction, residual stresses (PWHT), and materials of construction. Operating conditions must be considered, which include number of pressure cycles, whether base loaded, and operational upsets. Other factors are past inspection findings, repair history, and quality of repairs.

Detailed baseline inspection of new vessels should be performed when new, or within three years of initial operation, to establish an inspection history based on the design, fabrication and operating factors for that period of operation.

For operating vessels, the NACE Standard recommends inspection intervals not exceeding three years unless a risk-based FFS approach indicates with confidence that a longer period is acceptable. Once cracking or wall thinning is found, a more frequent interval (compared to the most recent inspection interval) should be considered. Vessels classified as Category I in accordance with the NACE system may be inspected at intervals of up to ten years. In the Category I condition, annual reviews of operating factors and mechanical/inspection history should be performed to ensure that changes do not occur that could influence cracking or corrosion thinning susceptibility. Inspection intervals of vessels in Category II or III should be performed at one or two-year intervals depending on the severity of deterioration.

Other NACE recommendations on interval of inspection follow:

Category II – the interval should be no greater than three years.

Category III – the interval should be no greater than one year.

If a vessel has been found cracked and subsequently repaired, and it has been inspected for two consecutive intervals with no further cracking (i.e., last two inspections resulted in vessel Category I), the inspection interval may be extended. For any vessel that is on extended intervals (not inspected since vessel placed into service – greater than three years; Category I – greater than ten years; Category II – greater than three years; Category III – greater than one year), annual reviews of operating factors and mechanical/inspection history shall validate that operating conditions are consistent with past performance. If operating conditions are significantly changed or the mechanical/inspection history indicates a change in conditions that would increase the susceptibility to cracking, consideration should be given to reducing the corresponding re-inspection interval.

7.6 References

7.6.1 References Cited in Text

1. Prevention, Detection, and Correction of Deaerator Cracking, NACE SP0590-2007, NACE International, Houston, TX: 2007.
2. *Repair of Deaerators*, EPRI, Palo Alto, CA: 2004. 1008069.

7.6.2 Other Sources

Vormelker, P. R., "Deaerator Inspection and Analysis," Paper #214, *proc. Corrosion87*, NACE, San Francisco, CA: 1987.

Perdomo, J. J., Spry, T. D., "Deaerator Inspection: What to Look For," *Materials Performance*, pp. 52-55, July 2005.

Twigg, R. J., "Reality Check: The Reinspection of Deaerators," Paper #525, *proc. Corrosion 96*, NACE, Houston, TX: 1996.

Thielsch, H., Knarr, N., "Fitness-for-Purpose Evaluation of a Deaerator with Cracking," *Materials Evaluation*, pp. 561-563, May 1992.

8
FITNESS-FOR-SERVICE METHODS AND PROCEDURES

8.1 Introduction

Once the inspection of the deaerator has been completed, the data acquired will need to be reviewed and assessed. If crack-like flaws, thinning of walls, or significant pitting were found, then assessment of the damage is required to determine the suitability for continued service as well as help make run-repair-replace decisions. Both ASME and API, have a common standard to perform fitness-for-service (FFS) assessments to address the structural integrity of the pressure containing equipment that was identified through inspection to contain flaws or damage. The standard is known as API 579-1/ASME FFS-1. Three levels of assessment are provided in the standard. The Level 1 assessment is the most conservative, but easiest to perform. The Level 2 assessment would require a more detailed evaluation and the Level 3 assessment would require the most detailed evaluation. Those performing the assessment typically proceed from a Level 1 assessment to Level 3 assessment sequentially until an acceptable result has been determined or clear course of action is identified. The FFS assessments are recognized by API Codes and Standards (510, 570, & 653) and by NBIC-23 as suitable means to evaluate the structural integrity of pressure vessels, piping, and storage tanks. As such, the FFS assessments can be used for equipment designed to the following ASME B&PV Codes: Section VIII, Division 1; Section VIII, Division 2; and Section I, as well as API Standards: API 620 and API 650 (these API standards do not apply to deaerators).

The remainder of this section will provide highlights of the various levels of FFS for typical damage mechanisms found in deaerators and the basics of the process to assess the current state of a component's integrity along with the projected remaining life of the component. For a detailed "how to' on performing a FFS assessment, please use the API 579-1/ASME FFS-1 standard with example problems found in API 579-2/ASME FFS-2.

8.2 Flaw/Damage Identification

Table 4.1 in Section 4 of this document shows the primary damage mechanisms for DA's. There are four primary categories of degradation resulting from the various damage mechanisms: 1) crack-like flaws, 2) thinning - local and general, 3) pitting, and 4) distortion/deformation. A fifth category that is not a degradation mechanism for deaerators, but can occur in other vessels, is brittle fracture. Once a flaw/damage mechanism has been identified, an assessment should be performed to determine suitability for continued operation as well a remaining life assessment. Table 8.1 shows the FFS assessment procedures for various damage mechanisms that could be found in deaerators.

The first step in the process is to gather data on the deaerator being evaluated. Some common data required is the manufacturer's data report, fabrication drawings, material test reports, material properties test data, current operating conditions, past inspection reports, and records of hydro-testing. If some of this information is not available, the analysis accuracy will be degraded. Assumptions or approximations for unknown data should be conservative.

8.2.1 Brittle Failures

Deaerators have been manufactured from a variety of materials previously shown in Table 2-1. Several of these construction materials (SA 212 Grade B, ASTM SA 515 Grade 70, and SA 285 Grade C) have been found to be brittle at room temperature and even higher temperatures, depending on original grain size as well as head/plate forming temperatures. As such, any deaerators that were manufactured from these materials as well as all carbon steels and low alloy steels not listed in the API 579-1/ASME FFS-1 Table 3.2 or ASME Code Section VIII, Division 1, paragraph UCS-66 would need to be evaluated for brittle failure. They may be susceptible to brittle failures both with and without crack-like flaws. Therefore, an FFS will need to be performed for brittle fracture first without any flaws and then with any crack-like flaws found during the inspection. API 579-1/ASME FFS-1 Chapter 3 provides the details needed for the potential brittle evaluation. The critical exposure temperature (CET) and minimum allowable temperature (MAT) will need to be determined. For deaerators, the CET will most likely be the lowest on cold start ups that occur during the winter. The MAT is derived using the API 579-1/ASME FFS-1 Guideline.

8.2.2 General Metal Loss

If the inspection of the deaerator reveals areas of the vessel wall thickness that have thinned as a result of general corrosion or flow-accelerated corrosion (FAC), an FFS assessment per API 579-1/ASME FFS-1 may need to be performed. If the thinning is within the specified corrosion/erosion allowance and sufficient thickness is available to account for future loss before the next scheduled inspection, no FFS assessment is required; otherwise one should be performed. API 579-1/ASME FFS-1 Chapter 4 provides the details needed for the general metal loss evaluation.

8.2.3 Localized Metal Loss

If the inspection of the deaerator reveals localized areas of the vessel wall thickness that have thinned as a result of corrosion/erosion, blend grinding that was needed to remove a flaw or some type of damage, or mechanical damage that created a gouge or dent, an FFS assessment per API 579-1/ASME FFS-1 may need to be performed. If the thickness is within the specified corrosion/erosion allowance and sufficient thickness is available to account for future loss before the next scheduled inspection, no FFS is required. However, if this is not the case then an FFS assessment should be performed. API 579-1/ASME FFS-1 Chapter 5 provides the details needed for the localized metal loss evaluation. There are basically three-types of localized metal loss: local thin areas, grooves, and gouges. Local thin areas have a width and length that are the same order of magnitude, while a groove has a length that is significantly greater than the width. The gouge has a length that is much greater than the width that and was created by mechanical means. The flaws must be characterized by analysis before the FFS assessment should be attempted.

8.2.4 Pitting Corrosion

If the deaerator's inspection reveals pitting corrosion, an FFS assessment per API 579-1/ASME FFS-1 should be performed. There are four types of pitting categories: widespread pitting, localized pitting, a combination of widespread pitting and localized metal loss, and a combination of localized metal loss with pitting confined to the localized metal loss region. API 579-1/ASME FFS-1 Chapter 6 provides the details needed for the pitting corrosion FFS evaluation.

8.2.5 Shell Distortion

If the inspection of the deaerator reveals a bulge, out-of-roundness, or general shell distortion, an FFS assessment per API 579-1/ASME FFS-1 should be performed. API 579-1/ASME FFS-1 Chapter 8 provides the details needed for the shell distortion FFS evaluation.

8.2.6 Crack-Like Flaws

If the inspection of the deaerator reveals crack-like flaws, an FFS assessment per API 579-1/ASME FFS-1 should be performed. The crack-like flaw mechanisms for deaerators were previously shown in Table 4-1 in Section 4. They consist of various types of fatigue (e.g., corrosion, thermal, mechanical, and vibratory) and various forms of stress corrosion cracking (e.g., chloride and caustic). API 579-1/ASME FFS-1 Chapter 9 provides the details needed for the crack-like flaw FFS evaluation. Stress computation will be required for primary stresses, secondary stresses, and residual stresses. Material properties (tensile and yield strength) along with fracture toughness will be required. If the mechanism is fatigue cracking then fatigue data (da/dn) will be required, and if stress corrosion cracking is the mechanism then crack growth rate (da/dt) will be required to assess remaining life. Finally, flaw characterization will be required. For single crack-like flaws, flaw dimensions (length and depth) will be required. For multiple crack-like flaws (e.g., stress corrosion cracks), evaluation of the interaction of flaws in close proximity to each other and their idealized shape will be required.

8.2.7 Dents and Gouges

If the inspection of the deaerator reveals dents, gouges, or dent/gouge combinations as a result of inadvertent damage during repair work or inspection, an FFS assessment per API 579-1/ASME FFS-1 may need to be performed. The effect of the damage can be evaluated for continued operation or for calculating a reduced maximum allowable operating pressure. For the case of deaerators, reducing the pressure would not be an option and thus repairs would be required if under current conditions it is determined not to be suitable for continued operation. API 579-1/ASME FFS-1 Chapter 12 provides the details needed for the dents and gouges evaluation. A dent is the inward or outward mechanical deformation of a cross-section of a shell member's ideal geometry (e.g., shell bulges inward or outward). A gouge is the mechanical removal of an elongated section of the wall thickness with the length much greater than the width. The dents and gouges must be characterized per procedures in Chapter 12.

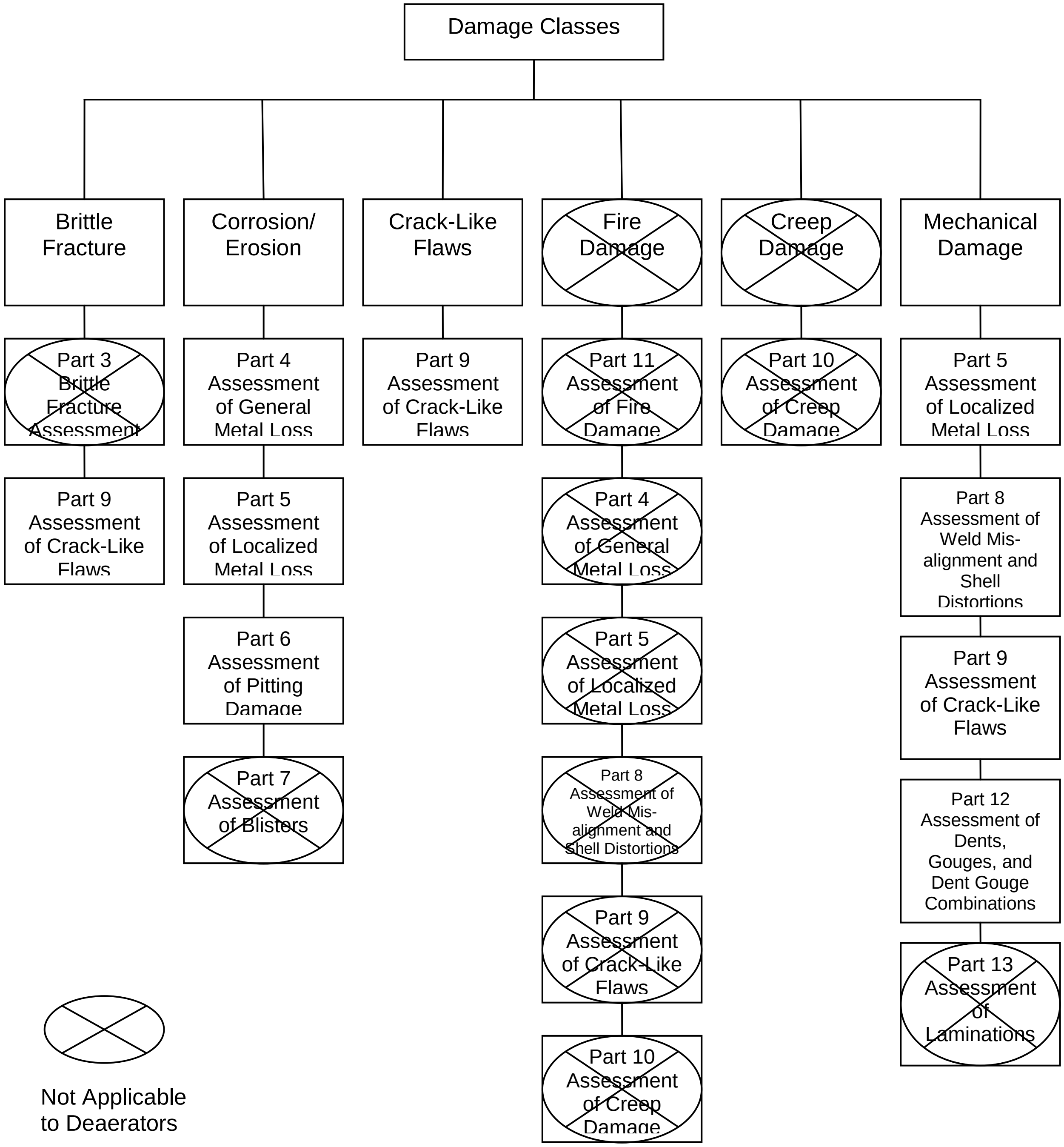

Figure 8-1
FFS assessment procedures for various damage classes, taken from Figure 2.1 in API 579-1/ASME FFS-1 and modified for deaerators.

9
REPAIR OPTIONS/CODE (NBIC) AND INSURANCE CONSIDERATIONS

Deaerators used by utilities will eventually require repairs, with the type and extent of repair being dependent on the damage mechanism(s) incurred. This section covers considerations that are important when damage to the deaerator or deaerator storage vessel must be repaired. The most common repair is in situ welding.

By far the most costly and time consuming repairs encountered will involve correction of damage by corrosion fatigue (CF) or flow-accelerated corrosion (FAC). CF damage is most often repaired by welding within the pressure boundary components of the deaerator and deaerator storage vessels. FAC damage is most often encountered only in the deaerator, and is of most concern when the pressure boundary (shell) becomes thinned. Other frequent damage may be cracking of stainless steel components in the deaerator, especially long seams in the waterbox or stainless steel vent piping. Such repairs must be carefully performed because the cracking damage can extend into the pressure boundary of the carbon steel shell. Stainless steel to carbon steel weld joint repairs are complicated. The largest consideration is the formation of residual stresses developing from differential thermal expansion coefficients between the alloys. Another consideration is the dilution of the welds and the local degradation of corrosion resistance properties.

Several matters are important to review in advance of performing deaerator and storage vessel repairs:

- Welding on an ASME Code vessel requires repair according to the National Board Inspection Code (NBIC). The NBIC usually references the welding requirements of the original construction (most often Section XIII, Div. 1).
- The original ASME U-1 form for the vessel must be used to identify materials of construction, corrosion allowances, post weld heat treatment (PWHT), and weld joint efficiencies. The absence of the U-1 form requires extensive metallurgical studies to characterize the materials and assure the success of the repair. Local code authorities must be consulted for guidelines in repairing these vessels.
- Previous weld repairs made on the vessel and the materials used, including welding consumables, must be known.
- Past and current nondestructive testing (NDT) thickness test and crack test results should be known. It is notable that future damage often originates at locations of past weld repairs because of the introduction of residual stresses from welding, and sometimes because prior

weld repairs were not performed to good standards. Thickness test results are often needed to decide on the type of repairs needed due to FAC or other corrosion thinning; for example, whether the repair must be made using a flush insert patch or by weld overlay.

The reader is encouraged to consult the document *Repair of Deaerators*, #1008069, EPRI, Palo Alto, CA, 2004 for details on repairs. The 2004 document refers to methods of repair of wasted areas, selection of filler metals, welding processes used, partial shell replacement/flush patches, and factors in design, fabrication, PWHT, nondestructive examination, and testing. Additional commentary not covered in the above EPRI document follows in this document.

9.1 Deferring Weld Repairs

Repair by removing cracks or original weld flaws found in the vessel by subsequent nondestructive testing warrant careful consideration. Many repairs in deaerators and deaerator storage tanks, especially when the vessels are relatively new, can be made by grinding only, omitting or deferring weld repairs. This is especially important if the vessel was stress-relieved (PWHT) during original construction. Owners should not be too quick to make weld repairs without first performing a Fitness-For-Service (FFS) assessment of the vessel. *Refer to **Section 8** of this document for details on FFS*. The problem with welding on a vessel that received PWHT during original construction is that field welding methods, even temper-bead welding or welding followed by PWHT, seldom restore the vessel to the low level of residual stresses that was achieved in original construction. Temper-bead welding will refine microstructure, but does not reduce residual stresses from welding. Consequently, after weld repair the vessel may be in a state more vulnerable to future cracking. Thus, the first step in deciding whether or not to perform weld repairs is to make a run-repair-replace decision based on the damage mechanism and extent of damage. This consideration emphasizes the need to perform a base-line nondestructive test on new deaerator vessels, detecting flaws that resulted from original fabrication, as opposed to waiting until a later NDT examination and the need to assess whether a weld flaw is original or a propagating crack.

9.2 CF Damage Repair

CF damage almost always occurs at welds. When it is determined that CF damage is present and that it must be removed, the usual repair method is to grind, re-weld, and re-inspect the weld. This is frequently very time consuming as the cracked region must be inspected using the liquid penetrant (PT) or magnetic particle test (WFMT or MT) method to ensure the crack is completely removed. When cracking is extensive, for example at circumferential weld seams joining the vessel shell to the head, consideration should be given to completely removing the head and shell, trimming the damaged regions and re-welding the head to the shell. Finished welds should be blend ground for good evaluation by NDT. A full circumferential weld seam may be effectively treated with a PWHT following the weld repair, which may defer or eliminate future cracking (see also the section following on PWHT).

9.3 FAC Damage Repair

When it is determined that FAC-wasted areas of the deaerator must be repaired, the question is whether repair should be performed by weld build-up (and/or weld overlay[2]) or by installing a flush (inserted) patch to replace the affected section of the shell. Depending on the vessel size, most deaerator and deaerator storage tanks have wall thicknesses well under 1.0-inch and extensive weld build-up is limited due to local distortion of the vessel from welding stresses. Residual stresses in weld metal are always in tension due to shrinkage of the weld, so the vessel walls tend to shrink on the inside. Thus, at the risk of excessive distortion, practical weld buildup or weld overlay may be limited to only a few square feet of the shell.

Weld filler metal for build-up must be selected based on original base metal construction materials, whereas weld consumables for overlays are best selected with chromium additions to resist FAC damage. For build-up, the weld metal must meet or exceed the minimum strength and toughness requirements of the applicable code used for construction of the pressure component.

The weld filler metal used for overlay is less restrictive than for weld build-up since the overlay thickness does not apply as credit toward ASME minimum allowable wall thickness. Theoretically, overlays of any composition accepted by ASME Section II, Part C for welding onto carbon steel may be applied, including low-alloy steels and stainless steels. Studies have shown that alloys containing chromium (as low as 0.1% chromium) significantly reduce deterioration by FAC; alloys with 1.25% to 2.25% chromium are very resistant to FAC, and higher chromium alloy steels are essentially unaffected by FAC [1]. Weld filler metals with 1.25% to 2.25% chromium are crack sensitive and require careful control of preheat and interpass temperatures to avoid cracking problems. Low alloy carbon steel consumables such as ER70S-B2L have been used extensively for overlay protection from FAC damage [2]. The owner should be aware of NBIC restrictions to welding methods that are alternative to PWHT for Cr-Mo low-alloy welding.

Experience has shown that weld build-up and overlays over large areas are best applied using the automatic Gas Metal Arc Welding (GMAW) process as opposed to manual welding. However, not all regions of the deaerator shell around the tray enclosure may be accessible to automatic welding, and some manual welding is usually needed. With automatic welding, good control is obtained in preheat temperature, interpass temperature, weld bead placement and bead finish. Both weld build-up and the finished overlay weld should be tested for welding flaws using WFMT or MT. It is very important that the quality of weld build-up be free of porosity, slag, and incomplete fusion when it is part of the pressure boundary shell. Likewise, the weld build-up quality must be near perfect or the subsequently applied weld overlay will have unacceptable defects.

As noted above, large or heavy weld build-up can produce unacceptable distortion. In cases where the shell FAC area is very large or thinning is severe, consideration should be given to inserting flush patch(es) or replacing a section of the shell. Shell sections are usually replaced

[2] Weld *build-up* is the process of restoring the original shell thickness, whereas weld *overlay* usually pertains to weld application of a corrosion or erosion resistant overlay onto the shell. Severely corroded vessels must first be restored to minimum allowable wall thickness by weld build-up before application of weld overlay.

with matching low-carbon pressure vessel steel (refer to the ASME B&PVC Section II Materials). Some owners have considered replacing shell sections with Cr-Mo low-alloy plate, such as ASME A387, Grade 11 (1.25 Cr-1/2 Mo), and Grade 12 (1 Cr-1/2 Mo). The Cr-Mo steel grades should be very resistant to FAC, but owners should be cautioned that weldability tests must be conducted and precautions taken to ensure the welding procedures are carefully followed. Further, as noted above, the owner should be aware of NBIC restrictions to welding methods that are alternative to PWHT for Cr-Mo low-alloys. It is unknown whether installations with Cr-Mo low-alloy plate have been made.

9.4 Post Weld Heat Treatment (PWHT)

PWHT is a requirement of original construction for ASME vessels fabricated from P-No. 1 carbon steel when the wall thickness exceeds 1.5 in. (38.1 mm) nominal thickness, including corrosion allowance (Ref. ASME Section VIII, Div. 1, UCS-56). Since most deaerator and deaerator storage vessels have lower nominal thicknesses than required by ASME for PWHT, they are therefore not mandated to receive PWHT during original construction. However, it is widely accepted by deaerator specifications and standards that PWHT be applied to reduce susceptibility to CF cracking [3, 4]. Therefore, all new deaerator and deaerator storage vessels should be purchased in the PWHT condition. Refer also to Section 2 of this document on matters pertaining to PWHT specifications for deaerators.

Whenever practical, PWHT should be performed in weld repairs by heating the full vessel circumference. An alternate method is to PWHT the vessel wall, incorporating just the nozzle, attachment, etc., within the area that is heat treated. However, heat treatment of just a portion of the wall requires careful control of temperature gradients to reduce residual stresses to a minimum. Yet, this latter treatment is seldom as effective at reducing residual stresses as heat treatment of the complete vessel circumference. This is usually a simpler matter in the storage tank than in the deaerator because of complications when heating dissimilar stainless steel components within the deaerator.

Use of NBIC alternate post-construction methods (e.g., high preheat and temperbead welding) to avoid PWHT may be necessary in many cases. While these procedures are widely accepted, they do not achieve the degree of residual stress relief that is usually obtained in PWHT.

At least one instance is recorded where a large deaerator storage vessel (12.0 ft. (3.66 m) diameter and 64.0 ft. (19.5 m) long) was PWHT in the field after CF damage was found and repaired. The vessel was supported on the inside to prevent sagging when heated to 1100ºF (593ºC) by internal gas firing. No significant CF was found in the vessel during the 25 years following PWHT.

9.5 Insurance and NBIC Options in Deaerator Repair

Insurance companies have great incentive to require that deaerator vessels are inspected and repaired within best practice guidelines. Further, most insurers (as well as many state and provincial jurisdictions) may require owners to work within the insurer guidelines for inspection and repair. Likewise, the National Board of Boiler and Pressure Vessel Inspectors (NBIC) have guidelines covering deaerator repair. These institutions recommend that deaerator owners maintain a system of deaerator equipment documentation covering data from inspection and repairs including system design drawings, vessel modification records, histories of inspections and findings, drawings or sketches showing areas of cracks and repairs, and ASME Manufacturer's Data Reports.

Prior to inspection and repair, planning meetings should be held involving the owner, the insurance inspector (an authorized inspector who holds a valid National Board Commission), and qualified inspection and repair team representatives. Of particular importance is the insurer's attitude toward Fitness-For-Service options available to the user (refer to Section 8) as to whether the insurer will accept the use of API/ASME FFS-1 procedures to assess the safety of continued operation of the equipment with known flaws. For example, a recent survey conducted of both owners and insurance companies indicated that while one insurer accepted the API/ASME FFS-1 procedures, none of the owners took advantage of this accepted practice. The same insurer requested that deaerator weld repairs be followed by PWHT, even though the vessel may not have been PWHT during original construction.

9.6 References

1. *Flow-Accelerated Corrosion in Power Plants*, TR-106611-R1, Electric Power Research Institute, Inc., Pleasant Hill, CA: 1998.
2. *Repair of Deaerators*, EPRI, Palo Alto, CA: 2004. 1008069.
3. *Prevention, Detection, and Correction of Deaerator Cracking*, NACE SP0590-2007, NACE International, Houston, TX: 2007.
4. *Standards and Typical Specifications for Tray Type Deaerators, 8th Ed.*, Heat Exchange Institute, Inc., Cleveland, OH: 2008.

10 CASE STUDIES

10.1 Case Study 1

Industry:	**Utility**
Deaerator Type:	**Spray-Tray**
Damage Location:	**Storage Tank Circumferential Weld**
Damage Mechanism:	**Corrosion fatigue**
Cracking Orientation:	**Circumferential**
Component Material:	**SA-212, Grade B**
Years in Service:	**Forty-Five Years**
Tank Pressure:	**150 psi Design/132 psi Operation**

A crack was discovered in the center of the vessel on top near a circumferential weld. The crack was ~twelve inches long on the external surface and over twenty-five inches on internal surface. The crack initiated on the internal surface at the weld for a vacuum (stiffening ring). The top 70 degrees of the vacuum ring was removed to allow for repair. The weld was removed by grinding, followed by re-welding.

Figure 10-1
Photograph shows the crack in the circumferential weld of the deaerator storage tank

Figure 10-2
Photograph showing the same crack from inside the storage tank

10.2 Case Study 2

Industry:	**Chemical processing**
Deaerator Type:	**Horizontal DA on Horizontal Storage Tank**
Damage Location:	**Storage Tank Opposite Chemical Feed Inlet**
Damage Mechanism:	**Corrosion/Erosion**
Cracking Orientation:	**General**
Component Material:	**Carbon Steel**
Years in Service:	**Unknown**
Tank Pressure:	**Unknown**

The inlet quill for delivery of water treatment chemicals (sodium sulfite) was improperly installed—the quill was supposed to penetrate thirty-six inches into the vessel but only extended two inches. This deficiency did not allow chemicals to dilute, and therefore led to local erosion/corrosion damage. No leak developed, and the damage was detected via visual inspection. The repair was made by welding in a patch using NBIC Guidelines and given a local PWHT.

10.3 Case Study 3

Industry:	**Chemical Processing**
Deaerator Type:	**Horizontal DA on Horizontal Storage Tank**
Damage Location:	**DA Vessel – Two-Inch ID Inlet Feed Line**
Damage Mechanism:	**Plane Bending Low-Cycle Fatigue**
Cracking Orientation:	**HAZ of Circumferential Weld**
Component Material:	**Type 316L Stainless Steel**
Years in Service:	**Three Years**
Tank Pressure:	**Unknown**

A two-inch diameter feed line made of Type 316L stainless steel was found to be cracked after three years of service. A leak was noted as an indication of the failure. Metallurgical analysis identified fatigue as the failure mode. Mechanical analysis noted high vibratory stresses in the pipe caused by flow turbulence. The pipe was repaired by replacement and reconfiguration of the supports.

10.4 Case Study 4

Industry:	**Utility**
Deaerator Type:	**Horizontal DA on Horizontal Storage Tank**
Damage Location:	**Circumferential Welds Head-to-Shell and Shell Courses in Storage Tank**
Damage Mechanism:	**Corrosion Fatigue**
Cracking Orientation:	**HAZ of Circumferential Weld and Transverse to Circumferential Weld Bead-Indications 360 Degrees Around Circumference at Weld Toe on the Internal Surface**
Component Material:	**Carbon Steel**
Years in Service:	**Unknown**
Tank Pressure:	**Unknown**

The tank was found cracked during a routine scheduled inspection, which was also the first inspection since the storage tank was put into service. Because of the extensive nature of the cracking the tank was replaced.

10.5 Case Study 5

Industry:	**Electric Utility**
Deaerator Type:	**Horizontal DA on Horizontal Storage Tank**
Damage Location:	**Sixteen-Inch Nozzle and Reinforcing Pad Weld HAZ**
Damage Mechanism:	**Corrosion Assisted Cracking, Possible SCC**
Cracking Orientation:	**Crack in Tank Wall in HAZ Adjacent to Flush Patch Repair**
Component Material:	**SA515 Grade 70 (No PWHT)**
Years In Service:	**Thirty-Two Years**
Tank Pressure:	**Unknown**

The tank was found cracked during a routine scheduled inspection. Cracking was at the HAZ or weld toe of a recirculation nozzle attachment and suspected of being caused by inadequate or poorly adjusted piping supports. The repair chosen was to cut out the old nozzle and reinforcement pad and install a flush patch. During welding with a 350ºF preheat, cracks continued to be discovered in the old plate materials adjacent to the new patch. The final solution was to cut out a larger section to avoid cracking in the old HAZ.

10.6 Case Study 6

Industry:	**Utility**
Deaerator Type:	**Horizontal DA on Horizontal Storage Tank**
Damage Location:	**Circumference Welds Head to Shell and Shell Courses in Storage Tank**
Damage Mechanism:	**Corrosion Fatigue**
Cracking Orientation:	**HAZ of Circumferential Weld and Transverse to Circumference. Weld Bead**
Component Material:	**Carbon Steel**
Years in Service:	**Thirty-Two Years**
Tank Pressure:	**Unknown**

Cracking was found on the longitudinal and circumferential welds during routine inspection. Metallurgical analysis identified corrosion fatigue, both transverse and longitudinal. Crack initiation was aided by poor weld workmanship issues, including undercutting and poor fit-up. Crack propagation was driven by support feet that were not free to move. The repair was done by local weld repair. The vessel was not PWHT (stress relieved) after the repair. Repairs were delayed due to the presence of lead paint that had to be remediated.

10.7 Case Study 7

Industry: **Chemical Plant**
Deaerator Type: **Horizontal DA on Horizontal Storage Tank**
Damage Location: **Widespread Corrosion Throughout DA Vessel and Storage Tank**
Damage Mechanism: **Corrosion Pitting- Oxygen Pitting**
Cracking Orientation: **No Cracking**
Component Material: **Carbon Steel**
Years in Service: **Unknown**
Tank Pressure: **Unknown**

The plant shut down two boilers and laid them up properly with wet layup and nitrogen purge; however, the two DA systems were neglected. The tanks were inspected as a precursor to re-commissioning the boilers, and severe internal pitting damage was discovered. The DA tanks were returned to service, and a three-pound block of zinc was added to each storage tank to arrest the corrosion. The zinc blocks were dissolved in one month of operation. The tanks were eventually replaced and the water chemistry was evaluated.

10.8 Case Study 8

Industry: **Chemical Manufacture**
Deaerator Type: **Vertical Can DA on a Horizontal Storage Tank**
Damage Location: **Entire Vessel**
Damage Mechanism: **Over-Pressurization**
Cracking Orientation: **Both Longitudinal and Transverse**
Component Material: **Carbon Steel**
Years in Service: **Unknown**
Tank Pressure: **35-37 PSI**

During a plant startup, seals in the steam extraction line failed allowing 500 psi steam to enter the DA vessel. The vessel catastrophically failed. A low water alarm for the DA occurred immediately before the failure. The safety valve did not lift and was found to be damaged; however, it could not be established if the safety valve damage preceded or resulted from the failure. Steam input would have exceeded the relief valve capacity. Vessel remains were located 400 yards from its original location. Fracture mapping identified the failure origin at the weld joining the integral DA vessel to the horizontal storage tank. No metallurgical defects were found.

10.9 Case Study 9

Industry:	**Pulp and Paper**
Deaerator Type:	**Vertical Spray Scrubber on a Horizontal Storage Tank**
Damage Location:	**Storage Tank**
Damage Mechanism:	**Corrosion Fatigue**
Cracking Orientation:	**Unknown**
Component Material:	**Unknown Carbon Steel**
Years in Service:	**Twenty-Nine Years**
Tank Pressure:	**45 psi**

The storage tank, sixty-four feet overall in length and twelve feet in diameter, was found to have corrosion fatigue cracking at head welds during 1985. Following removal of cracks and re-welding, the storage tank was isolated from the DA heater and subsequently heat treated *in situ*. Before heat treatment it was determined that the original insulation should not be damaged by the heat treatment temperature of 1100ºF. The inside of the tank was supported to prevent sagging at the heat treatment temperature. Heating was performed by gas burners inserted through the manway. Following the heat treatment cycle the insulation was found undamaged. Periodic WFMT inspections since 1985 have not revealed cracking. The tank is still in service; current WFMT inspections are performed at three-year intervals.

10.10 Case Study 10

Industry:	**Pulp and Paper**
Deaerator Type:	**Vertical Spray-Scrubber on A Horizontal Storage Tank**
Damage Location:	**DA Heater**
Damage Mechanism:	**Corrosion Fatigue and Flow Accelerated Corrosion**
Cracking Orientation:	**Unknown**
Component Material:	**SA 516-70**
Years in Service:	**Twenty-Six Years**
Tank Pressure:	**45 psi**

An original tray-spray deaerator heater was installed in 1980 but was replaced due to performance problem with a vertical spray-scrubber heater in 1983. The replacement DA was not post weld heat treated. During the twenty-six years of service, the vessel exhibited corrosion fatigue cracking at welds and significant thinning from flow accelerated corrosion of the shell adjacent to baffle plates (Figure 10.3). An inspection in 2009 revealed thinning at a weld joint, and a region of incomplete penetration of the weld (Figure 10.4). The unit was replaced with a new vertical spray-scrubber during 2009.

Figure 10-3
Flow accelerated corrosion on the ID of the spray-scrubber deaerator. The circumferential weld was previously ground.

Figure 10-4
Flow accelerated corrosion of the DA heater circumferential weld seam revealed a partial penetration weld. The DA heater was replaced.

10.11 Case Study 11

Industry:	**Utility**
Deaerator Type:	**Horizontal Spray-Tray on a Horizontal Storage Tank**
Damage Location:	**DA Heater**
Damage Mechanism:	**Through-Wall Cracking Due to Differential Thermal Expansion**
Cracking Orientation:	**Horizontal at Vessel Sidewall**
Component Material:	**SA 240, Type 304L Stainless Steel**
Years in Service:	**Five Years**
Tank Pressure:	**Unknown**

Two original carbon steel deaerator heaters were replaced during 2005 due to problems with severe flow accelerated corrosion. The new DA shells were fabricated from Type 304L stainless steel—carbon steel tray support channels were welded to the shell. The new units operated satisfactorily for approximately three years when a through-wall crack was discovered in the proximity of a support saddle attachment on one unit. Internal examination revealed cracking adjacent to an internal tray enclosure support channel. Further examination revealed that the carbon steel support channel had been rigidly welded to both sides of the stainless vessel walls (Figure 10.5). The analysis concluded that the difference in coefficient of thermal expansion for the stainless steel shell and carbon steel supports produced high stresses and yielding of the vessel wall, ultimately resulting in cracking. A check of the original vessel design revealed that the support channel was to be welded to one side only, and the channel was to “float” on the opposing wall. Additionally, the proximity of the support to the external saddle attachment increased rigidity and local stresses. A check of the mating stainless steel heater showed cracking in the same location, but the crack had not progressed completely through the vessel wall.

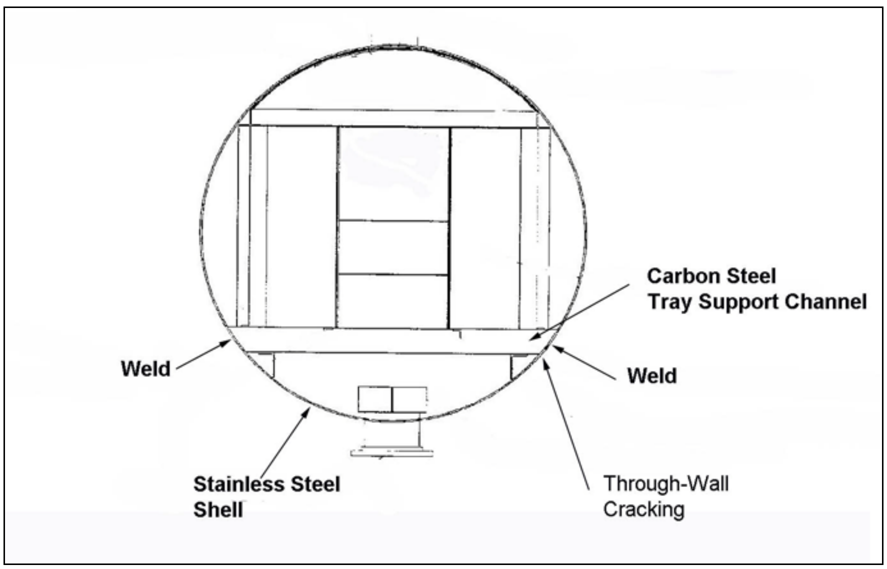

Figure 10-5
Drawing shows the failure location in the deaerator heater

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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