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Item No. 21046

Standard
Recommended Practice

Recommended Practice for Prevention, Detection, and Correction of Deaerator Cracking

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Foreword

NACE Task Group T-7H-7 on Deaerator Cracking was formed in 1984 to conduct an organized, in-depth study into the cause of the high incidence of serious deaerator cracking problems in steam generating plants. The task group had previously sponsored technical symposia in which several papers were published on deaerator cracking.[1-8]

This standard is intended to be the primary source of information on deaerator cracking and is directed toward operators and designers of deaerator equipment used in steam generation. Information presented in this standard reflects the work of the many individuals involved in documenting the deaerator cracking problem and is based on studies of carbon steel units.

In developing this standard, the task group considered the case of a southeastern U.S. paper mill that had experienced a ruptured deaerator storage tank with loss of life. The catastrophic failure resulted in an increase in deaerator inspections and widespread concern for vessel reliability and personal safety. A "Deaerator Advisory," published by the Engineering Division of TAPPI,[(1)] reported that 68 vessels (approximately 50% of the vessels inspected in 1983) showed cracking in welds and adjacent heat-affected zones resulting from corrosion fatigue.[9] Of the three reported storage vessel ruptures, one resulted in fatalities and considerable plant downtime.

Other literature on deterioration of deaerators noted that investigations of various systems indicated that cracks in the welds and heat-affected zones of longitudinal and circumferential seams were the cause of some of the problems.[10] Corrosion, another major cause, had occurred at a more rapid rate in the weld heat-affected zone in some instances, and problems had reportedly occurred in both the welds and the base metal caused by shell thinning to levels that could not support the load. Periodic internal inspections combined with nondestructive examinations were recommended to detect deaerator deterioration. Other reports of the seriousness of deaerator weld cracking also were published at this time.[11-15]

T-7H-7 has continued to actively collect data and information on reinspections. However, continued efforts will focus on surveillance of the cracking problem and updates relative to the committee's findings.

This standard recommended practice was originally prepared in 1990 by T-7H-7 under the guidance of NACE Unit Committee T-7H on Corrosion and Its Control in Steam Generating Systems and issued by NACE International under the auspices of NACE Group Committee T-7 on Corrosion by Waters. It was revised by T-7H-7 in 1996.

(1) Technical Association of the Pulp and Paper Industry (TAPPI), Box 105113, Technology Park, Atlanta, GA 30348.

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Contents

Section 1: General

1.1 The objective of this section is to identify important factors influencing boiler feedwater (BFW) deaerator cracking based on literature references and case history analyses.

1.2 Function of Deaerators

1.2.1 The function of the deaerator in the steam plant cycle is to reduce oxygen and other dissolved gases in the feedwater to acceptable levels. Usually, oxygen content can be reduced to less than 10 µg/L (ppb) as illustrated in Table 1 (see Paragraph 1.5.1).

Two typical designs of mechanical feedwater deaerators are shown in Figures 1a and 1c. Figures 1b and 1d show the weld areas associated with each type of unit. The steam used in these systems raises feedwater temperature, which lowers the solubility of oxygen. With proper venting, the steam also serves as the "stripping gas," removing the oxygen from the system, and with the system shown, provides feedwater storage and proper mechanical conditions for the feedwater pump.

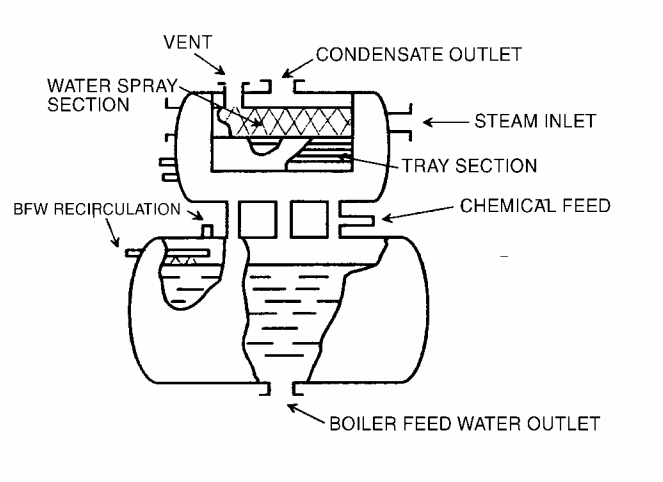


FIGURE 1a
Typical Mechanical Feedwater Deaerator

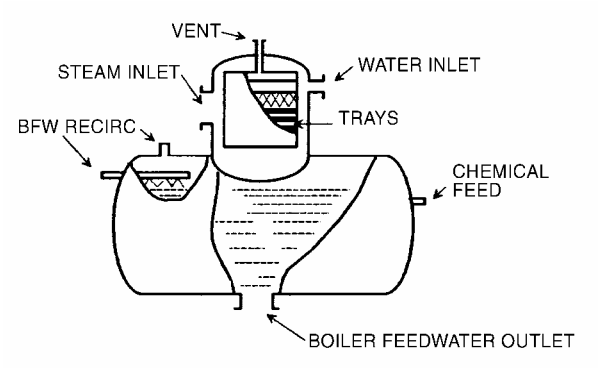


FIGURE 1c
Saddle-Type Mechanical Deaerator

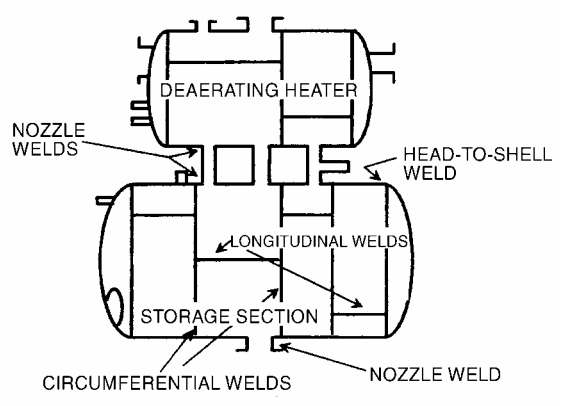
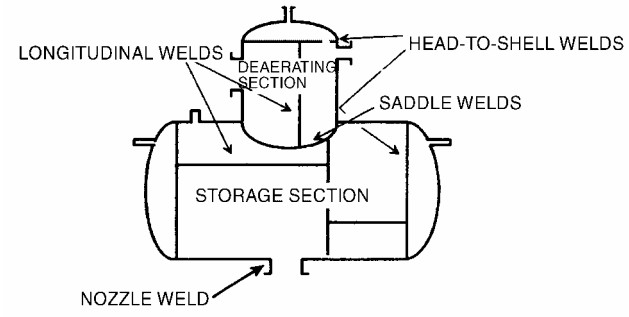


FIGURE 1b
Weld Areas Associated with Typical Unit



Where a vertical heater is welded directly to the storage vessel, the saddle weld is of particular interest because of the fabrication stresses possible.

FIGURE 1d
Weld Areas Associated with Saddle-Type Unit

1.3 Oxygen Contamination

1.3.1 Severe oxygen contamination occurs in boiler feedwater when mechanical problems occur with deaerators, feedwater pumps, turbine gland seals, and systems operating under vacuum. Incomplete deaeration can be caused by many factors, including improper venting, operational changes that cause an influx of cold make-up water, improperly aligned trays, plugged or broken water spray nozzles, and operation with a temperature differential between the dome and storage sections that deviates from specifications.

1.4 Deaerator Failures

1.4.1 Internal structural and component failures related to equipment design, system design, and operation have occurred in deaerators. The deaerator is a relatively simple device when compared with typical boilers and/or turbines in a system. As such, it has often been neglected when unusual operating conditions are considered.

1.4.2 Deaerator design for utility systems has evolved as a result of several problems with utility deaerators that have been reported because of load rejection, thermal steady state or shock stresses, vibration, or component shortcomings. For example, data from field reports obtained between 1969 and 1979 showed that damage to trays in utility deaerators was common prior to 1976.[16]

1.4.2.1 Of the 80 installations surveyed, 18 (22.5%) reported damage to trays or related hardware. Trays were dislodged and rattled about inside the unit and, in some cases, were bent and broken beyond repair.

1.4.2.2 Tray pans, end clips, fasteners, and distribution troughs were also damaged.

1.4.2.3 Shrouding around the tray enclosure was damaged in some cases as a result of plant upsets and, in particular, following full-load rejection, which occurs when the turbine trips and turbine extraction steam is lost. This may cause flooding of the downcomers, resulting in water being blown upward against the tray bank.

1.4.2.4 Flashing of steam from the storage section to the deaerator section causes damage and is related to excessive pressure drop in the equalizers or excessive pressure drop across the tray bank; this problem was alleviated by adequately sizing the equalizers and providing sufficient height above the bottom of the deaerator.

1.4.2.5 Since 1976, the reported incidence of tray damage has decreased significantly.

1.4.3 Other problems also were reported when units were operated without regard to design limitations.[16] Severe thermal stresses occur, for example, when a deaerator is alternately subjected to hot steam and cold water; this can cause rapid failure of the unit. In one peaking unit, extensive failure occurred after a few months of operation because superheated steam had been fed at reduced pressures during offload periods and cold condensate was fed in slugs to maintain level. In another situation, condensate was near steam temperatures between batches, resulting in severe damage.

1.4.4 Water hammer or steam hammer can also occur in the steam plant. At the deaerator, steam hammer is usually caused by water entering a steam line or steam-filled space. In one installation, the water level was being held 75 cm (30 in.) above the recommended level when a load rejection occurred. This resulted in severe water/steam hammer, which damaged equipment supports. Other operational concerns are prolonged low-load operation, flows beyond design, operation at less than design temperature, steam temperature above design level, and localized stress intensities.

1.5 Inspection Statistics

1.5.1 Statistics have been compiled by Work Group T-7H-7a using information supplied by independent testing laboratories, insurance companies, and in-house maintenance inspection teams from the chemical and power industries. Table 1 shows typical performance of oxygen removal equipment in an attempt to define operating parameters of most units. The oxygen levels are based on operation under design conditions. The statistics in Table 2 were developed by the task group and relate to all types of deaerators.

TABLE 1
Typical Performance of Oxygen Removal Equipment

Type	Pressure kPa (psig)	Temperature °C (°F)	Dissolved Oxygen µg/L (ppb)
Open Heater	Atmospheric	70 to 99 (160 to 210)	500 to 1,000 (500 to 1,000)
Deaerating Heater	7 to 100 (1 to 15)	102 to 120 (215 to 250)	40 (40)
Deaerator	7 to 100 (1 to 15)	102 to 120 (215 to 250)	7 (7 or less)

TABLE 2
Inspection Statistics by Industry

Industry	Number Inspected	Number Cracked[(A)]	% Cracked
Pulp and Paper	315	120	38
Chemical and Refining Processing	218	99	45
Utility	47	18	38
British Columbia Dept. of Labor	70	32	46

[(A)] Vessels were considered cracked if crack depth required repair.

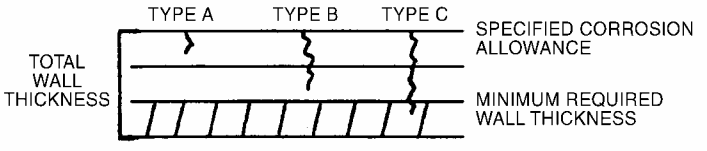
1.5.2 Current statistics show that of more than 700 vessels inspected, 30 to 40% were cracked and required repair. Documented inspections have totalled 467. Wet fluorescent magnetic particle inspection (WFMT) results were used to compile these statistics.

1.5.3 Analysis of inspection data has shown no apparent statistical correlation between or among cracking and manufacturer, operating pressure, size, age, materials, water treatment, or other variables. A survey conducted by T-7H-7, however, found that water/steam hammer was a likely contributor to the problem.

1.5.4 A mini-survey of 174 vessels was conducted to clarify the scope of the deaerator cracking problem. No differentiation was attempted relative to industry segment. Table 3 lists the definitions and provides an illustration of the terms used to describe the discontinuity types reported. Three categories were used to define the severity of cracks detected, with the most severe being Type C, which usually required repair by welding. Figure 2 shows the sample distribution as a function of unit age; Figure 3 illustrates the number of vessels in the total sample set that had incurred various degrees of cracking; Figure 4 shows the percent distribution of Type C discontinuities as a function of deaerator vessel age; and Figure 5 illustrates the total number of vessels with discontinuities as a function of vessel age. Overall, this survey supports initial observations that the deaerator cracking problem is not a function of vessel age, especially in the area of total cracks detected.

TABLE 3
Discontinuity Terms Used in Statistical Study Only

Type A	The discontinuity depth found is less than the specified corrosion allowance of the vessel.
Type B	The discontinuity depth found is greater than the specified corrosion allowance but does not enter the minimum wall thickness. Sound metal remaining is more than the minimum required wall thickness.
Type C	The discontinuity depth found enters the minimum required wall thickness, usually requiring repair by welding.



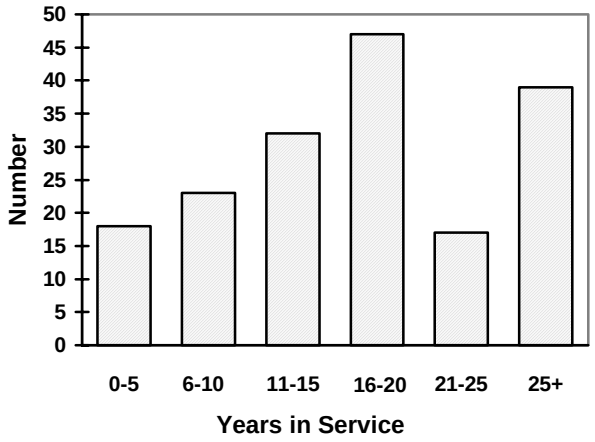


FIGURE 2
Deaerator Cracking Mini-Survey Sample Distribution by Years in Service

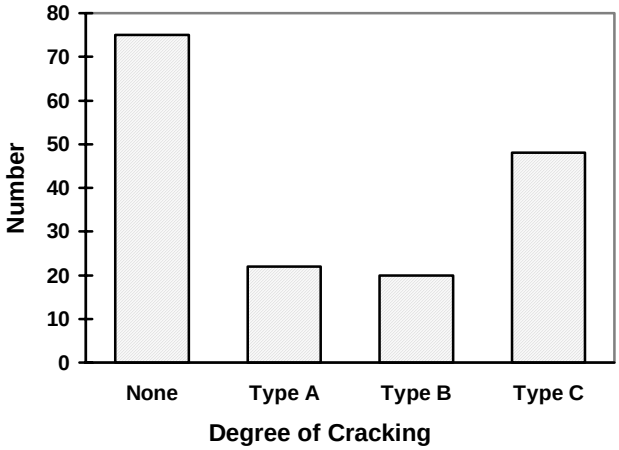


FIGURE 3
Cracking Distribution in Mini-Survey by Degree

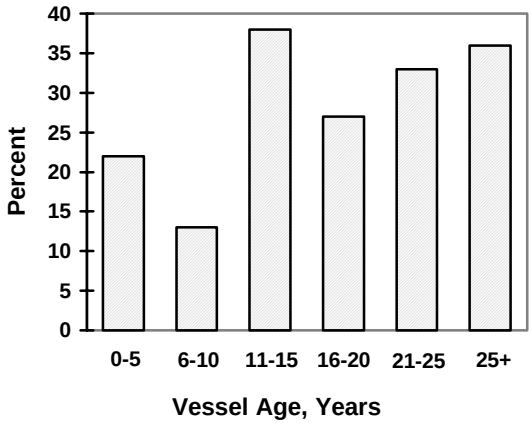


FIGURE 4
Type C Cracks Detected in Mini-Survey as a Percentage by Vessel Age

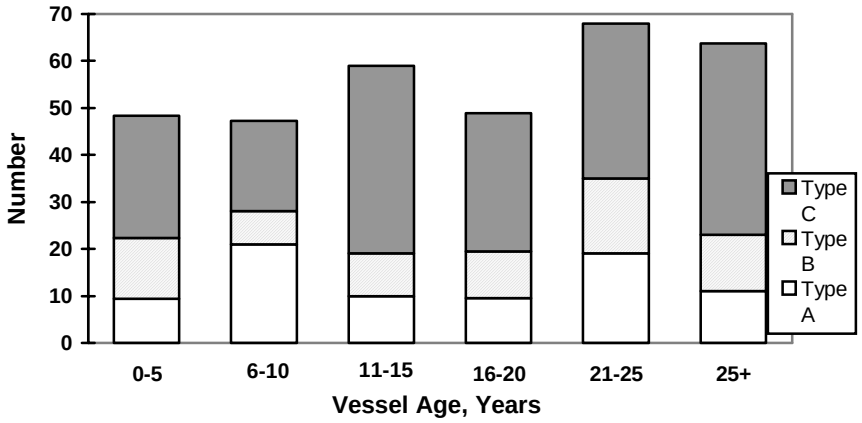


FIGURE 5
Total Cracks Detected in Mini-Survey by Vessel Age

1.6 Conclusions

1.6.1 The cracking reported in the case histories is predominantly a form of environmentally assisted cracking that can best be described as corrosion fatigue.

1.6.2 The preferred method of inspection for carbon steel deaerators and deaerator storage tanks is the WFMT. Ultrasonic testing (UT) and radiography testing (RT) can be successfully used to supplement WFMT.

1.6.3 Residual tensile stress from welding is one of the primary factors promoting crack growth.

1.6.4 Differential thermal stresses were identified as causative agents in three of the deaerator or storage tank ruptures studied.

1.6.5 In some cases, deaerator vessels are externally insulated and leaks may not be observable. On this basis application of classical leak-before-break and through-thickness yielding fracture criteria, based on linear elastic fracture mechanics, may not ensure against the catastrophic rupture of BFW deaerators.

1.6.6 Because the operating environment of the deaerator is a likely contributor to the cracking, the following information must be generated in order to develop rational deaerator inspection intervals and cracking prevention measures:

1.6.6.1 Characterize the deaerator environment

1.6.6.1.1 Chemically

(a) Oxygen, carbon dioxide (CO_2) content

(b) Other species

(c) pH range and average since the last inspection (or start-up)

1.6.6.1.2 Mechanically

(a) Qualitative estimate of thermal stresses on start-up, shut-down

(b) Vibrational stress range that may be caused by water/steam hammer or level control upsets as well as other factors

Section 2: Failure Analysis

2.1 The objectives of this section are as follows:

(a) To standardize the nomenclature of deaerator vessel welds and cracking (see Appendix A).

(b) To standardize the failure analysis information required in order to compile reliable data (see Appendix B).

(c) To define the mode of failure and cause(s), when possible, on a cracked and failed deaerator tank.

(d) To develop a failure analysis atlas and correlate any cracking trends and sources.

2.2 Conclusions

2.2.1 The cracking reported in the deaerator case histories (see Appendix C) is predominantly a form of environmentally assisted cracking that can best be described as corrosion fatigue. Evaluation of the failure analyses on more than 30 cracked units indicates that there is little or no difference in crack morphology in deaerators, deaerator storage tanks, or other similar vessels. This observation is valid, even though there are wide variations in industries, deaerator and storage tank designs, manufacturers, materials of construction, welding processes, sizes, ages, operating conditions, and crack locations (liquid, interface, vapor zone). Based on case histories submitted to NACE International and a literature search,[(2)] the following observations and conclusions can be made:

2.2.1.1 Cracking occurs in both the weld and heat-affected zones of the weld (within approximately 10 cm [4 in.] of either side of the weld) (see Appendix E).

2.2.1.2 Cracking is most frequently transverse to the weld and heat-affected zones, but cracking parallel to the weld, especially at the toe, is also common.

2.2.1.3 In many vessels, the most serious cracking has been found to be parallel to the head-to-shell circumferential weld; catastrophic failures have occurred at this location.

2.2.1.4 Cracking has been found in the vapor zone, at the vapor/liquid interface, and in the liquid zone. The most prevalent area for cracking on horizontal vessels has been the liquid zone between the 4 and 8 o'clock positions.

2.2.1.5 Internal surfaces, in areas where attachments are welded to the exterior surfaces of the vessel, have also shown cracking.

2.2.1.6 Cracking is perpendicular to the surface and primarily straight-line, although some cases have shown limited branching.

2.2.1.7 Cracking may initiate from corrosion pits and weld surface defects.

2.2.1.8 Metallographic examination has shown that most of the cracks are funnel-mouthed, are filled with corrosion product, and have blunt tips.

2.2.1.9 The cracking is transgranular in almost all cases. In some instances, there has been very shallow intergranular or branched transgranular attack at the tip or on side cracks.

[(2)] See Appendix D for photographic representations of various types of cracks.

Section 3: Inspection Methods

3.1 The objective of this section is to provide standard procedures for the inspection of deaerator heater and water storage vessel welds. The procedures are intended to detect original and service-related discontinuities located on the inner surface of the vessel in welds and the adjacent base metal. Results of all nondestructive examinations (NDE) shall be reviewed by engineers or inspectors who are competent to evaluate the results to determine the vessel's serviceability.

3.2 The scope of these guidelines includes qualifications of personnel, NDE equipment, weld layout of vessel, areas of inspection, methods of inspection, and method of reporting results.

3.2.1 Inspection Personnel Qualifications

All third-party inspection personnel shall be trained and certified in accordance with ASNT[3] SNT-TC-1A or equivalent to a minimum of Level I. Interpretation of the test results shall be made by personnel certified to a minimum of Level II. If in-house inspection personnel are used, they shall be qualified to use and interpret results from the tests to the levels equivalent to those indicated above.

3.2.2 NDE Equipment

All NDE equipment shall be as described in ASME[4] Boiler and Pressure Vessel Code, Section V,[17] Article 2 for RT, Article 4 for UT, and Article 7 for magnetic particle testing (MT).

3.2.3 Weld Layout of Vessel

A simple, clearly labeled vessel layout sketch identifying all welds should be made to ensure repeatability of the inspection. ASME Boiler and Pressure Vessel Code, Section VIII,[18] Division 1, Figure UW3 typifies a pressure vessel layout format.

3.2.4 Areas of Inspection

All internal welds should be inspected. Close attention should be paid to (a) nozzle, head-to-shell, longitudinal, and circumferential welds, (b) plug welds in the centers of spun heads, and (c) internal surfaces corresponding to external attachment welds.

3.2.5 Methods of Inspection

3.2.5.1 A visual inspection shall be conducted to assess the general condition of the internal welds and internal surfaces corresponding to external welds.

3.2.5.2 WFMT, utilizing the AC/DC yoke method in accordance with ASME Boiler and Pressure Vessel Code requirements, is the most effective test technique. (The AC mode is preferred for smooth surfaces; the DC mode is preferred for irregular surfaces.) The weld surface must be adequately prepared (see Paragraph 3.3.4.1) to ensure that any potential discontinuities are revealed.

3.2.5.3 If discontinuities are found, inspection should be expanded to detect the extent of the discontinuities. Other NDE methods such as RT or UT may be used to complement the examination. Exploratory grinding should be considered to confirm the depth of discontinuities.

3.2.6 Method of Reporting

For long-range maintenance planning, it is desirable to establish a database in which trend analysis can be performed. Every deaerator inspection report should include the date of inspection, the name and certification level of the inspector, the minimum required thickness, and the corrosion allowance. Additionally, a drawing that depicts the vessel diameter and length, the number of nozzles, and the circumferential and longitudinal welds should be provided along with vessel specifications such as the manufacturer, date of fabrication, shell thickness, joint efficiency percentage, type of material, design pressure, postweld heat treatment (PWHT), operating pressure, operating temperature, operating history, and a description of surface preparation and NDE methods employed. The inspection results should describe the locations, orientation, and length and depth of the indications that were found.

3.3 Nondestructive Examination

3.3.1 Vessel Condition Classifications: Each inspected vessel should be classified based on discontinuities or cracks found.

[3] American Society for Nondestructive Testing (ASNT), 4153 Arlingate Plaza, Columbus, OH 43228.
[4] American Society of Mechanical Engineers (ASME), 345 East 47th St., New York, NY 10017-2392.

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

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

3.3.1.3 Category III: Discontinuities were detected and weld repairs required.

3.3.2 Reinspection Criteria

Limited information is currently available on recurrence of cracks, initiation of cracks after repair, and crack growth. T-7H-7 is currently considering criteria for reinspection. Substantiation and modifications will be based on information presented to the task group in future meetings and symposia. Interested parties with information pertinent to this evaluation are invited to participate or supply information to the committee.

The time interval between inspections should be based on conditions found during prior inspection and the severity of operating conditions. Those vessels that have required repair or have shown prior indication of cracking should be considered for more frequent inspections (at intervals not exceeding approximately three years) than those with no history of cracking. Future inspection intervals may be increased or decreased based on inspection history. Future inspections are necessary even if prior inspections revealed no problems.

3.3.3 Test Methods Other Than WFMT

3.3.3.1 Internal WFMT is by far the most comprehensive and sensitive inspection method and therefore is recommended. It is the most practical and effective method for locating the types of defects with which the industry is concerned. However, the time necessary for internal access that requires shutting down the vessels and probable removal of some internals has been a concern of owners and operators.

3.3.3.1.1 Dye penetrant testing (PT), shear wave ultrasonic testing (UTS), and RT may be used to supplement, but not in lieu of, WFMT; however, these test methods are not always sensitive enough to discern tight fatigue cracking, particularly if it is located in areas where weld undercut or overlap exists.

3.3.3.1.2 PT in accordance with the ASME Boiler and Pressure Vessel Code, Section VIII requirements is considered to be a suitable alternative examination method to WFMT when the areas to be examined are stainless steel. Although surface preparation is necessary, the risk of metal "smear" or overlap as a result of grinding, wire brushing, and abrasive blasting can eliminate the effectiveness of PT because defects must be open to the surface.

3.3.4 Surface Preparation for WFMT

3.3.4.1 Industry recognizes the potential problem of improperly performed surface preparation for WFMT. Improper surface grinding resulting in the overheating of the area can create additional cracking. Abrasive blasting has been used for initial surface preparation in many installations. During initial inspection, proper surface preparation to remove weld overlap, undercut, or rough weld surface must include light grinding (0.8-mm [0.03-in.] maximum depth). Removal of these conditions is essential before performing a proper WFMT. During subsequent inspections, abrasive blasting or disk sanding should be used prior to grinding to determine whether any additional preparation is required. When required, the proper technique is light grinding at an approximate 45° angle to the direction of the weld and a gradual 3:1 taper of the ground area.

Section 4: Repair, Design, and Fabrication

4.1 The objective of this section is to provide guidelines for materials, design, fabrication, inspection, and acceptance criteria for new deaerator vessels (including both heater and storage sections). This section also provides guidelines for repair of existing deaerator vessels.

4.2 Adherence to these guidelines should reduce the residual stresses and improve the overall integrity of the weld. Relief of tensile stress, shot peening, full-penetration welding, weld and base metal compatibility, joint configuration, and improved surface contour are all addressed in these guidelines to reduce residual stresses and stress concentrations. Construction in accordance with the ASME Boiler and Pressure Vessel Code, spot RT, corrosion allowance, and inspection by qualified personnel are also discussed in these guidelines to improve deaerator vessel design.

4.3 Repair of Deaerator Heater and Storage Tank—After any repairs are completed, the vessel should be reinspected using WFMT that initially indicated the need for repair.

4.3.1 In general, all repairs and alterations of deaerators shall be carried out in accordance with a recognized repair code such as the National Board of Boiler and Pressure Vessel Inspectors[5] National Board Inspection Code (NBIC)[19] or API[6] 510.[20]

4.3.2 The severity (i.e., length and depth) and type of all indications should be determined.

4.3.3 The cost of replacement as opposed to the cost of repair, including the cost of equipment down-time for each, should be evaluated. An alternative to removal and/or repair of cracks may be based on an engineering assessment.

4.3.4 Treatment of Cracks with Depths not Entering Minimum Required Wall Thickness

4.3.4.1 The cracks should be removed and the equipment reinspected to ensure that the cracks have, in fact, been removed.

4.3.4.2 The surfaces of the cavities formed by removing the cracks should be contoured to eliminate notches. A 3:1 taper is recommended to avoid sharp edges that could lead to further cracking.

4.3.4.3 The vessel should be inspected periodically to determine whether any of the cracks reappear or whether new ones are forming.

4.3.4.4 PWHT (at 600 to 650°C [1100 to 1200°F] with holding time in accordance with the ASME Boiler and Pressure Vessel Code),[7] followed by WFMT of the heat-treated weld areas, should be considered. Other means of reducing residual tensile stresses, such as controlled shot peening, may be considered as an alternative.

4.3.5 Treatment of Cracks with Depths Entering Minimum Required Wall Thickness

4.3.5.1 All cracks should be removed (by grinding, air arc gouging, or removal of a cracked section), then the area should be reinspected with WFMT to ensure that the cracks have been removed. Air arc gouging may result in crack propagation.

4.3.5.2 Weld filler metal and base metal with the same minimum specified tensile strength as the parent metal shall be specified.

4.3.5.3 Arc strikes should be removed and the area should be repaired by blend grinding. Internal weld reinforcement and undercut at the weld toe should be minimized. All regions shall be blend ground to assure a smooth transition with the base material. Abrupt changes in surface contour are not acceptable.

4.3.5.4 Spot RT should be considered as a minimum (procedures according to the ASME Boiler and Pressure Vessel Code) for major weld repairs.

4.3.5.5 PWHT (at 600 to 650°C [1100 to 1200°F]) with holding time in accordance with the ASME Boiler and Pressure Vessel Code,[7] followed by a WFMT reinspection of the heat-treated area, should be considered. Alternative means of reducing residual tensile stresses, such as controlled shot peening, may be considered.

4.3.5.6 A record of repairs shall be completed and submitted to the owner.

4.3.6 Operating conditions should be reviewed to ensure that the deaerator is operating within its design limits.

4.3.7 The deaerator internals and accessories should be inspected and reviewed to ensure that the system is operating correctly. Adequate overflow and overpressure protection is important (see Section 5).

4.4 Guidelines for Manufacture of New Deaerator Heaters and Storage Tanks

4.4.1 Design and construction should comply with Section VIII, Division 1 (or Division 2 when appropriate) of the ASME Boiler and Pressure Vessel Code, regardless of design pressure. Registering the vessel(s) with appropriate jurisdictional authorities, if needed, to ensure long-term availability of documentation, should be considered.

4.4.2 Spot RT in accordance with the ASME Boiler and Pressure Vessel Code as a minimum should be considered.

4.4.3 Longitudinal and circumferential seams shall be full-penetration butt welds. All nozzle welds shall be full-penetration welds.

4.4.4 Weld filler metal and base metal[8] with minimum specified tensile strength not to exceed 500 MPa (70 ksi) shall be specified.

[5] The National Board of Boiler and Pressure Vessel Inspectors, 1055 Crupper Ave., Columbus, OH 43229.
[6] American Petroleum Institute (API), 1220 L St. NW, Washington, DC 20005.
[7] 1 h minimum hold time is recommended.
[8] Equivalent to ASME/AWS classification E70XX, ER7XX-X.

4.4.5 Adjusting the detailed design to minimize the discontinuity stress concentration effect at the head-to-shell joints should be considered. The normal minimum ASME Boiler and Pressure Vessel Code requirement of a 3:1 taper may not be adequate.

4.4.6 PWHT (at 600 to 650°C [1100 to 1200°F]) with holding time in accordance with the ASME Boiler and Pressure Vessel Code is recommended.[7] Alternative means of reducing residual tensile stresses, such as controlled shot peening, may be considered. Shot peening may not be effective for long terms if improper operation results in significant internal corrosion or if grinding or surface preparation for inspections removes the critically peened layer.

4.4.7 Vessels shall be inspected by a qualified representative of the purchaser and/or owner/operator.

4.4.8 Prior to PWHT, arc strikes should be removed and the area repaired by blend grinding. Internal weld reinforcement and undercut at the weld toe should be minimized. All regions shall be blend ground to ensure a smooth transition with the base materials; abrupt changes in surface contour are not acceptable.

4.4.9 A minimum corrosion allowance of 1.6 mm (0.063 in.) should be considered in the design.

4.4.10 The use of accessory items, plant system design, and operating procedures to minimize stresses on and corrosion of the deaerator should be considered. Adequate overflow and over-pressure protection is important (see Section 5).

4.4.11 WFMT in the shop should be considered as part of vessel acceptance criteria. This will serve as a benchmark for future inspections.

Section 5: Operation and Water Chemistry

5.1 The objective of this section is to describe the operational and water chemistry parameters that may influence deaerator deterioration. These guidelines represent input from many manufacturers, water treatment companies, and users of deaerators, and represent good general operating practices. Specific installations may have conditions not addressed by this section for which operating conditions must be individually developed.

5.2 Background

5.2.1 Deaerators frequently produce consistently good results year after year. Because of this, good deaerator performance has been taken for granted in many plants, at times causing regular monitoring and inspection programs to be neglected. However, numerous problems can result from misoperation and neglect. The January 1983 catastrophic failure of a deaerator in the southeastern United States, the subsequent detection of cracks in numerous deaerators throughout the United States and Canada, and the identification of corrosion fatigue as the likely cause of the cracking highlighted the need to address this problem and identify the operating and water chemistry parameters that may influence deaerator deterioration.

5.2.2 A survey conducted by the task group revealed that water/steam hammer is a likely contributor to deaerator cracking. However, other operating conditions that cause thermal and mechanical stresses or corrosive attack can also contribute to deaerator deterioration.

5.3 Recommended Operating Practices to Reduce Deterioration

5.3.1 Minimize Stress During Start-Up

5.3.1.1 Rapid start-up after cold layup can produce stresses very conducive to corrosion fatigue. Regardless of the start-up procedures used, emphasis should be placed on making sure an appropriately gradual, steady, and monitored start-up is followed. An adequate steam supply for start-up, as well as operation, should be available. Start-up stresses can be reduced by avoiding procedures resulting in pressure fluctuations, sudden pressure loss, and excessive water/steam hammer. Also, a vessel warm-up period can be included as part of the start-up when high operating temperatures or hot super-heated steam is used.

5.3.2 Minimize Temperature and Pressure Fluctuations

5.3.2.1 Temperature and pressure fluctuations add stress to the metal and are common in many deaerators. To minimize these fluctuations, it is essential for the deaerator inlet steam to have adequate pressure, pipe size, and supply. If the adequacy of the normal steam supply is questionable, an alternate source that makes up any deficiencies should be provided.

5.3.2.2 When needed, the steam supply should be controlled by a pressure-reducing valve (PRV) to help maintain constant deaerator pressure. The pressure-sensing pickup for the PRV should be located to minimize pressure fluctuations in response to changes in operating conditions. If changes in operating conditions produce significant pressure fluctuations, the effects of relocating the pressure-sensing pickup on controlling these fluctuations should be investigated.

5.2.3.3 Deaerator load should be as constant as possible because large influxes of cold water can deplete deaerator pressure, causing flashing of water in the storage tank. To help reduce the severity of load swings, the deaerator storage tank level control should be tuned to respond slowly to minor level variations and progressively to larger variations.

5.3.3 Control of Water/Steam Hammer

5.3.3.1 In addition to minimizing water/steam hammer with controlled start-up and operating procedures, the proper handling of condensate is also important to protect the deaerator. If condensate at a higher temperature than the saturation temperature of the deaerator is returned to the entry that also contains cold make-up, water/steam hammer may occur unless precautions are taken. The necessary precautions include maintaining back pressure on the high-temperature condensate line and cooling the returning condensate either through the direct injection of cool make-up water or through a make-up heat exchanger. Even with these precautions, water/steam hammer may occur in the return line whenever the condensate temperature exceeds 100°C (212°F) because the hot condensate is often a two-phase steam and water mixture. Resizing of the line to avoid hammer may be required. Condensate that exceeds the temperature of the deaerator can many times be returned independently to the deaerator through a properly located and designed nozzle that allows separation of the water and flash steam.

5.3.4 Control of Water Chemistry

5.3.4.1 The dissolved oxygen content of the deaerated water should be regularly monitored to ensure effective deaerator performance. The presence of oxygen levels beyond the manufacturer's specifications is an indication of equipment or operating problems that may increase deaerator corrosion. Possible problems indicated by poor oxygen removal are operation outside design, inadequate venting, insufficient steam supply, poor steam regulation, broken water sprays, and improperly installed or damaged trays.

5.3.4.2 An oxygen scavenger should be injected into the deaerator drop leg or storage compartment as required to maintain less than 10 µg/L (ppb) dissolved oxygen content in the boiler feedwater. This should provide maximum protection against oxygen corrosion.

5.3.4.3 The corrosion rate of carbon steel used for deaerator and storage compartment construction increases as the pH decreases. The deaerated water pH should be maintained between 7.5 and 10.0 at all times. To increase corrosion protection, it is desirable to maintain the deaerated water pH at 9.0 or above, if practical.

5.3.5 Monitor Operation Regularly

5.3.5.1 The deaerator operation should be monitored at least daily and preferably once per shift. Items that should be monitored include:

5.3.5.1.1 Pressure and Temperature—The temperature should be within 1 to 2°C (2 to 4°F) of the saturation temperature and the pressure should be within 3 kPa (0.5 psi) of the set pressure at all times. Temperature differential between the deaerator and storage sections should also be within 1 to 2°C (2 to 4°F) of each other. Deviations warrant prompt investigation and corrective action.

5.3.5.1.2 Deaerator Venting—There should be a plume of steam issuing from the deaerator vent at all times. In many cases, the plume should be 0.6 to 0.9 m (2 to 3 ft) out of the top and consist of 15 to 45 cm (6 to 18 in.) of clear space next to the deaerator vent. No entrained water should be present in the vent.

5.3.5.1.3 Storage Tank Level Control—The storage tank level should be recorded and alarms maintained to be sure it is modulating within the normal range. Deviations from the norm should be investigated.

5.3.5.1.4 Oxygen Content—The deaerator oxygen content should be checked at least once per shift and maintained below the recommended maximum content (see Paragraph 5.3.4.2). Corrective actions should be initiated if significant deviations occur.

5.3.5.1.5 Deaerator Water pH—The deaerated water pH should be monitored at least once per week. If it varies from the recommended control range (see Paragraph 5.3.4.3), corrective action should be taken immediately.

5.3.6 Out-of-Service Inspection

5.3.6.1 The deaerator should be given a thorough inspection on a regular basis. Items that should be inspected include:

5.3.6.1.1 Inlet Sprays—Inlet spray valves should be checked to be sure they are free from deposits, they are intact, springs are not broken, spring tension is correct, guide stems are not worn, and retaining nuts are not loose. If a spray pipe is used, it should be checked to ensure that the orifices are not worn and the spray pipe is level.

5.3.6.1.2 Vent Condenser—The vent condenser baffling should be checked to be sure it has not been damaged so that the vent will not entrain water. If the unit is equipped with a shell-and-tube condenser, it should be checked for deposits, corrosion, and integrity.

5.3.6.1.3 Tray Section—The trays should be inspected to be sure they are properly secured and in place when installed and are not upside down. The spray compartment should be examined for cracking or other damage.

5.3.6.1.4 Steam Inlet—The steam inlet should be checked to be sure it is not damaged or eroded and impingement baffles are secure and properly placed.

5.3.6.1.5 Regulating and Safety Valves—All regulating and safety valves must be in proper working order and worn seats and discs should be repaired or replaced.

5.3.6.1.6 Pressure Gauges and Temperature-Indicating Devices—All pressure gauges and temperature-indicating devices should be checked to be sure that they read correctly, are in proper working order, and are easily visible to the operator.

5.3.6.1.7 Deaerator and Storage Vessels—The deaerator and storage vessels should be carefully inspected for signs of corrosion, deposition, and cracking at welds (see Section 1 and Appendices B, C, and D for general information and use).

5.3.7 Corrosion can seriously damage an out-of-service deaerator. Therefore, when a deaerator is removed from service, it should be protected as conscientiously as the boiler.

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Appendix A: Standardized Nomenclature

The following is the standardized nomenclature for deaerators and deaerator storage tank welds and cracking:

I. Weld Description
- A—Longitudinal
- B—Circumferential
- C—Nozzle
- D—Support
- E—Attachment

II. Crack Orientation
- A—Longitudinal (parallel)
- B—Transverse to weld
- C—"Spider" pattern

III. Crack Location
- A—Weld deposit or toe of weld
- B—Heat-affected zone (HAZ)
- C—Parent metal
  - 1—Head
  - 2—Shell
  - 3—Nozzle, support structures, etc. (which require a specific description)
  - 4—Deaerator or deaerator storage vessel
  - 5—Above or below the normal liquid level

Appendix B: Standardized Failure Analysis Format for Deaerator Heaters and Storage Vessels

I. Information on vessel
   A. Industry
   B. Manufacturer
   C. Date of manufacture
   D. Date of service
   E. Dimensions of vessel
      1. Length (m or ft)
      2. Diameter (m or ft)
      3. Shell thickness (mm or in.)
      4. Head thickness (mm or in.)
   F. Description or drawing of vessel showing whether vertical or horizontal and spray or tray tube
   G. Welding process used in manufacture if known and PWHT (if any)
   H. Code designed vessel

II. Operating parameters and history of vessel
   A. Pressure (kPa [psig])—design and operating
   B. Temperatures (°C [°F])—design and operating
   C. Chemical additives and where added
   D. Type of water source (softening, ion exchange, etc.)
   E. Percentage condensate and make-up
   F. Oxygen content of boiler feedwater should be measured after deaeration and, if possible, without the addition of the oxygen scavenger.
   G. pH of boiler feedwater
   H. History of and operational problems since start- up (internal damage, water/steam hammer, pressure variation, etc.)
   I. History of any repairs since start-up
   J. Normal elevation of water line
   K. Results of any NDE on vessel and crack locations
   L. Internal surface appearance

III. Description of metallurgical sample
   A. Description of sample location in vessel
   B. As-received photograph with close-ups or schematic showing location of cracks
   C. Macrophotographs and photomicrographs of crack cross-sections

IV. Analysis of the base metal and weld metal chemical compositions, ASTM[9] or ASME specifications. Elements suggested are C, Mn, Si, S, P, Cr, Ni, Mo, and Cu. If microhardness readings higher than expected are found, additional elements that may contribute include V, B, Nb, and Ti. In common steels used for deaerators, these elements should be in trace quantities only. Steels containing elements such as V, B, Nb, and Ti increase stress relief times at a given temperature and hence necessitate longer PWHT or higher PWHT temperatures to reduce hardness and decrease residual stresses.

V. Hardness of weld metal, heat-affected zones, and parent metal
   A. Microhardness as needed

VI. Fractography of opened cracks
   A. Visual light fractograph
   B. Scanning electron microscopy (SEM)

VII. Scale analysis
   A. Energy dispersive x-ray spectroscopy (EDS) as minimum
   B. Other techniques if possible

[9] American Society for Testing and Materials (ASTM), 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959.

Appendix C: Deaerator Failure Analyses

Note: These case histories are compiled only from cracked vessels on which a metallographic failure analysis has been performed.

No.	Vessel	Size (Length and Dia.)	Head Thickness	Shell Thickness	Material	Year Built	Industry	Summary of Findings
1	Feedwater Storage Vessel	10 m (33 ft) x 3 m (10 ft)	22.2 mm (0.875 in.)	19.1 mm (0.750 in.)	SA 285 Grade C	1968	Pulp and Paper	520 kPa (75 psig) operating pressure. Extensive corrosion fatigue cracks transverse to all five circumferential welds; several through-wall cracks. Temporary repair with OD bands welded to vessel until replacement.
2	Feedwater Storage Vessel	8.0 m (26 ft 4 in.) x 3.7 m (12 ft)	12.7 mm (0.500 in.)	9.53 mm (0.375 in.)	SA 285 Grade C	1973	Pulp and Paper	240 kPa (35 psig) operating pressure. Hundreds of corrosion fatigue cracks transverse to all four circumferential welds with no through-wall cracks. All cracks and circumferential welds ground out and weld repaired with a modified PWHT. No recracking in two years.
3	Feedwater Storage Vessel	7.7 m (25 ft 2 in.) x 3.4 m (11 ft)	20.6 mm (0.813 in.)	17.5 mm (0.688 in.)	SA 285 Grade C	1959	Utility	340 to 410 kPa (50 to 60 psig) operating pressure. Deep directional pits and corrosion fatigue cracks transverse to circumferential welds; maximum crack depth 3.3 mm (0.13 inch). Cracks and pits ground out and weld repaired.
4	Vertical Storage Vessel	2.9 m (9 ft 6 in.) x 1.4 m (4 ft 6 in.)	12.7 m (0.500 in.)	9.53 mm (0.375 in.)	ASTM Grade Unspecified	1952	Chemical Plant	70 to 140 kPa (10 to 20 psig) operating pressure. Numerous corrosion fatigue cracks parallel and transverse to circumferential welds and in all nozzle welds. Cracks more concentrated below water level. Several through-wall cracks. Vessel abandoned.

No.	Vessel	Size (Length and Dia.)	Head Thickness	Shell Thickness	Material	Year Built	Industry	Summary of Findings
5	Horizontal Storage Vessel	13.9 m (45 ft 8 in.) x 3.7 m (12 ft)	7.94 mm (0.313 in.)	7.94 mm (0.313 in.)	ASTM A 515 Grade 70	1971	Pulp and Paper	410 kPa (60 psig) operating pressure. Many corrosion fatigue cracks transverse and parallel to circumferential and longitudinal welds. Cracks found in liquid level. Vessel repaired and welds shot peened; recracking found after two more years of service.
6	Vertical Direct Contact DA and Storage	3.4 m (11 ft) x 1.8 m (6 ft)	9.53 mm (0.375 in.)	9.53 mm (0.375 in.)	BS 13 (Similar to BS 4360 Grade 43C)	1956	Oil Refinery (U.K.)	140 kPa (20 psig) operating pressure. Directional pits and cracks transverse to circumferential, longitudinal, and nozzle welds. Maximum crack depth 6.4 mm (0.25 in.). Vessel weld repaired and returned to service.
7	Horizontal Storage Vessel	2.4 m (8 ft) x 2.1 m (7 ft)	9.53 mm (0.375 in.)	9.53 mm (0.375 in.)	Shell: A 516-70 Heads: A 285-C	1974	Oil Pro-duction	150 to 220 kPa (22 to 32 psig) operating pressure. Corrosion fatigue cracks transverse to longitudinal seam welds and nozzle welds. Cracks penetrated 33% of wall thickness and mostly below the water level. Vessel scrapped.
8	Horizontal Storage Vessel	16.7 m (54 ft 9 in) x 4.4 m (14 ft 6 in.)	20.6 mm (0.813 in.)	20.6 mm (0.813 in.)	ASTM A 516 Grade 70	1974	Synthetic Crude Oil Plant	280 kPa (40 psig) operating pressure. Water hammer history in early operation. Corrosion fatigue cracks transverse to all circumferential welds below the water line; 4.76-mm (0.188-in.) maximum depth. Cracks also parallel and transverse to manway and to vacuum stiffener fillet welds. Cracks ground out and weld repaired; no cracking after one year of service.

No.	Vessel	Size (Length and Dia.)	Head Thickness	Shell Thickness	Material	Year Built	Industry	Summary of Findings
9	Horizontal Storage Horizontal Deaerator	16.7 m (54 ft 9 in. x 4.4 m (14 ft 6 in.) 9.2 m (30 ft 2 in.) x 3 m (10 ft)	20.6 mm (0.813 in.) 15.9 mm (0.625 in.)	20.6 mm (0.813 in.) 15.9 mm (0.625 in.)	ASTM A 516 Grade 70	1974	Synthetic Crude Oil	280 kPa (40 psig) operating pressure. Water hammer history in early operation. Storage section: Corrosion fatigue cracks transverse to four of six circumferential welds located below the water line; cracks to 3.18 mm (0.125 in.) deep. Also cracks transverse to two vacuum stiffener fillet welds below the water line. Parallel and transverse cracks to the manway fillet weld and to two nozzle welds. Deaerator section: 6.4-mm (0.25-in.) deep cracks transverse to all four circumferential welds and parallel cracks in tray support fillet welds. Cracks in both vessels ground and weld repaired with no PWHT. Recracking found in one year.
10	Horizontal Single Drum Cascading Tray	2.4 m (8 ft) x 2.1 m (7 ft)	9.53 mm (0.375 in.)	7.94 mm (0.313 in.)	Carbon Steel Grade Unknown	1958	Office Complex	21 to 34 kPa (3 to 5 psig) operating pressure. Unit shut down in summer; pronounced water hammering from 1958-1982. Condensate preheat exchanger installed in 1982 to eliminate water hammering; first inspected in 1984. Bottom of vessel perforated by O_2 pits. Corrosion fatigue cracks in attachment weld of pressure gauge nozzle in vapor space and internal tray baffle weld.

No.	Vessel	Size (Length and Dia.)	Head Thickness	Shell Thickness	Material	Year Built	Industry	Summary of Findings
11	Vertical Deaerator Horizontal Storage	3.5 m (11 ft 7 in.) x 2.9 m (9 ft 6 in.) 11.2 m (36 ft 10 in.) x 3.9 m (12 ft 8 in.)	9.53 mm (0.375 in.) 12.7 mm (0.500 in.)	9.53 mm (0.375 in.) 12.7 mm (0.500 in.)	BS 4360 Grade 43C	1968	Oil Refinery (U.K.)	100 kPa (15 psig) operating pressure with minimal fluctuations and upsets. Storage section: Corrosion fatigue cracks transverse to all seven circumferential welds and all longitudinal seam welds; most severe below water level; crack depth to 50% of wall. Cracks also in support webs and bottom water outlet nozzle welds. Deaerator section: transverse and radial cracks to 3.18 mm (0.125 in.) in tray support welds, spray nozzle welds, and downcomer weld. Storage section replaced and PWHT done; deaerator repaired and PWHT done.
12	Horizontal Vessel Storage	11 m (36 ft) x 3.4 m (11 ft)	12.7 mm (0.500 in.)	11.1 mm (0.438 in.)	SA 212 Grade B	1968	Pulp and Paper	280 kPa (40 psig) operating pressure. 150 cracks transverse to all six circumferential welds with one through-wall crack. All cracks below the water line and identified as corrosion fatigue. All cracks were ground out and weld repaired. New through-wall crack within five weeks' service. Vessel was then replaced.
13	Horizontal Deaerator	2.8 m (9 ft 3 in.) x 2.4 m (8 ft)	9.53 mm (0.375 in.)	9.53 mm (0.375 in.)	SA 515 Grade 70	1981	Pulp and Paper	410 kPa (60 psig) operating pressure with severe pressure fluctuations. Seven through-wall corrosion fatigue cracks in circumferential head-to-shell weld where backing bars had been used in original fabrications. Very poor weld quality throughout. Backing bars removed and cracked sections of vessel cut out and replaced; all welds shot peened.

No.	Vessel	Size (Length and Dia.)	Head Thickness	Shell Thickness	Material	Year Built	Industry	Summary of Findings
14	Horizontal Storage Vessel	17.3 m (56 ft 8 in.) x 3.7 m (12 ft)	15.9 mm (0.625 in.)	14.3 mm (0.563 in.)	SA 515 Grade 70	1971	Pulp and Paper	340 to 410 kPa (50 to 60 psig) operating pressure with frequent pressure cycling 40 leaking corrosion fatigue cracks transverse and parallel to the circumferential welds in the bottom half of the vessel. Vessel replaced and welds shot peened. No cracking after four years.
15	Com-bination Deaerator Storage Vessel	4.6 m (15 ft) x 1.2 m (4 ft)	?	?	SA 285 Grade A	1947	Pulp Mill	Severe cracks transverse to circumferential welds adjacent to feedwater recirculating pipe. One crack penetrated the wall. Cracks were intergranular, appearing more like SCC than corrosion fatigue. Shell segments were cut out and replaced; vessel returned to service.
16	2 Vertical Deaerator Vessels	?	9.53 mm (0.375 in.)	9.53 mm (0.375 in.)	SA 515 Grade 70	1969	Pulp and Paper	Frequent water hammering. Extensive cracks transverse to circumferential welds, nozzle welds, and manway welds. Several through-wall cracks typical of corrosion fatigue. One vessel repaired, one scrapped.
17	Horizontal Storage Vessel	6.2 m (20 ft 6 in.) x 3 m (10 ft)	14.3 mm (0.563 in.)	11.1 mm (0.438 in.)	ASTM A 212 Grade B	1964	Utility	520 kPa (75 psig) operating pressure. About 60 corrosion fatigue cracks transverse to the center circumferential weld. Maximum crack depth to 50% of the shell thickness with all cracks below the water level. All cracks ground out and weld repaired.
18	Horizontal Storage Vessel	6 m (20 ft) x 2.3 m (7 ft 7 in.)	12.7 mm (0.500 in.)	9.53 mm (0.375 in.)	Carbon Steel Grade Unspecified	1973	Oil Refinery	100 kPa (15 psig) operating pressure. Numerous cracks transverse and one crack parallel to circumferential welds, all below the water level. Maximum crack depth 3.18 mm (0.125 in.); appear to be corrosion fatigue cracks under heavy oxide scale that was also cracked.

No.	Vessel	Size (Length and Dia.)	Head Thickness	Shell Thickness	Material	Year Built	Industry	Summary of Findings
19	Horizontal Feedwater Storage Vessel	9.2 m (30 ft 4 in.) x 3.7 m (12 ft)	15.9 mm (0.625 in.)	11.1 mm (0.438 in.)	ASTM A 212 Grade B	1967	Pulp and Paper	450 kPa (65 psig). Corrosion fatigue cracking inside vessel below water level, associated with all internal welds and external saddle welds. Vessel failed at a 7.3-m (24-ft) circumferential crack on the shell side of a poorly profiled head weld. Average depth of this crack was 3.18 mm (0.125 in.) extending to 9.53 mm (0.375 in.) over a 0.6-m (2-ft) span. Replacement vessel used smooth-profiled welds and PWHT was done.

Appendix D: Photographic Representations of Various Types of Cracks

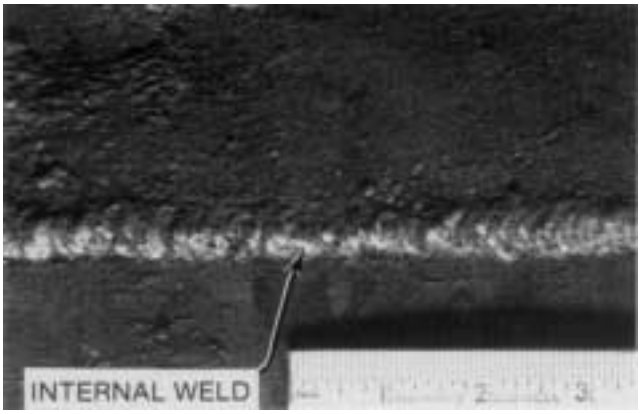

FIGURE D1
A Deaerator Head-to-Shell Internal Weld

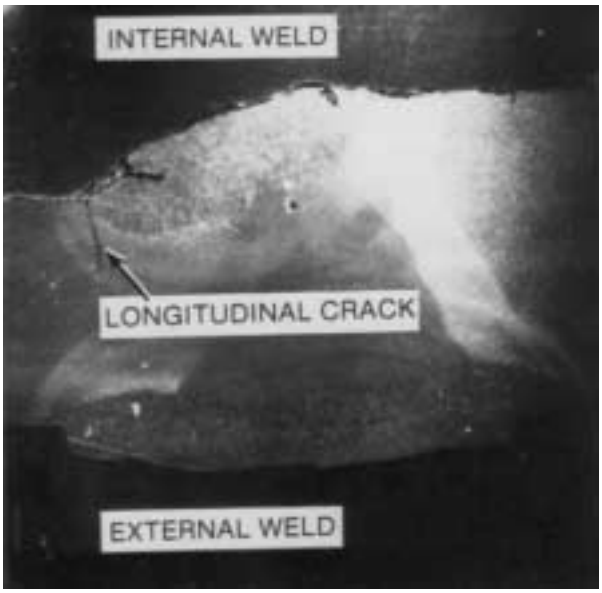

FIGURE D1a
A cross-section at a right angle to the weld section shown in Figure D1, showing both internal and external vessel welds and a longitudinal crack at the toe of the internal weld. 3X

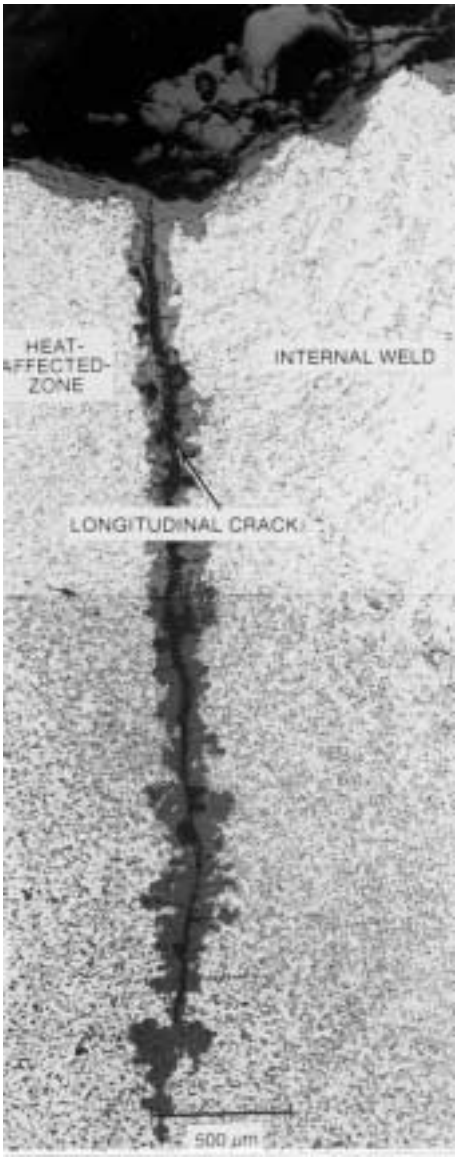

FIGURE D1a-1
Photomicrograph of the crack at the toe of the internal weld (unground) shown in Figure D1a.

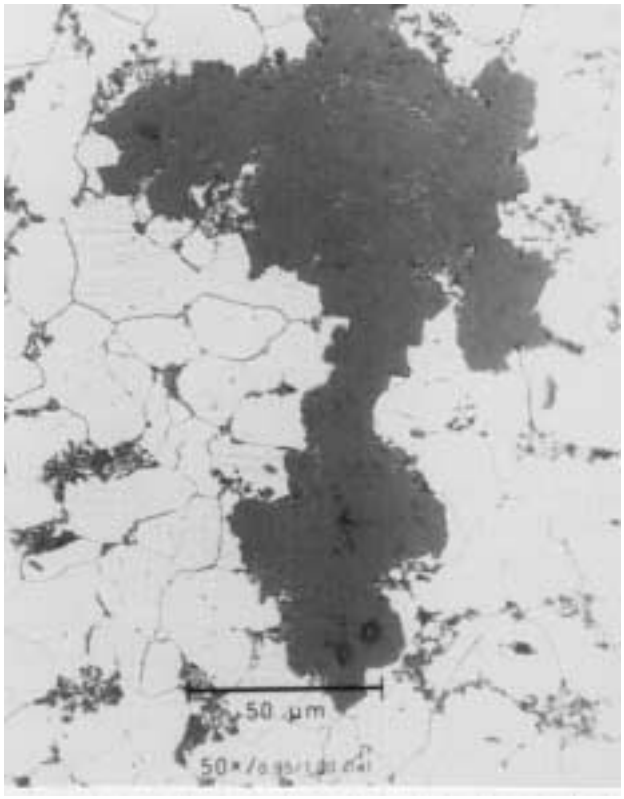

FIGURE D1a-2
The Tip of the Same Crack at Higher Magnification

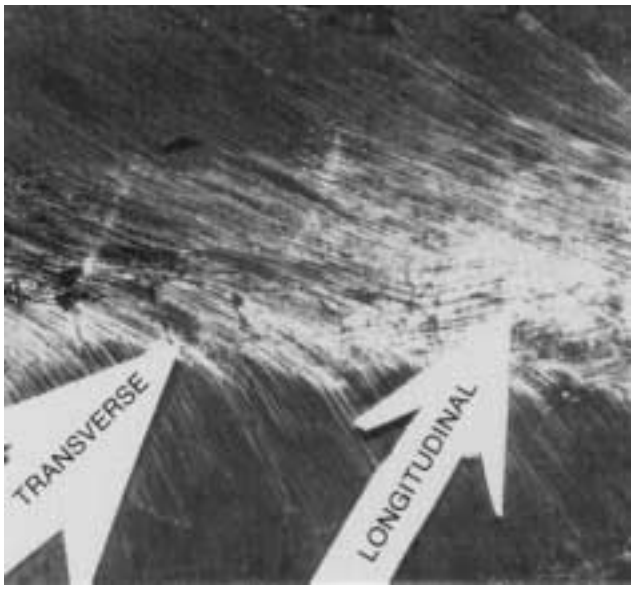

FIGURE D2
Another area of the same weld after grinding flush, shown at higher magnification (1.75X). Intersecting longitudinal and transverse cracks are revealed.

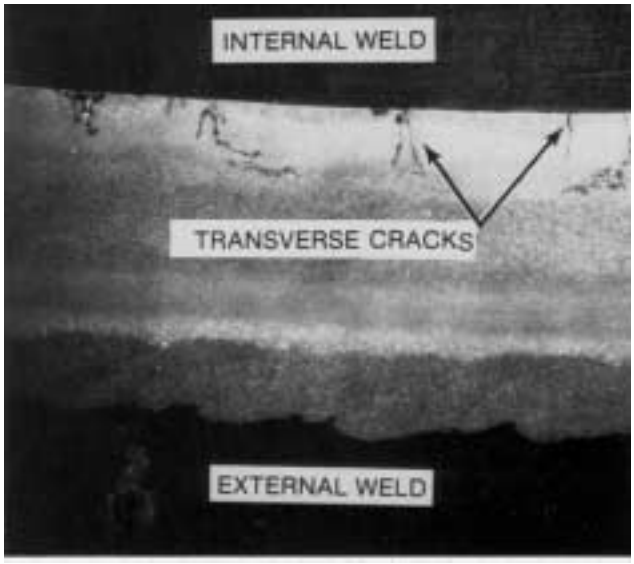

FIGURE D2a
A cross-section at a right angle to the transverse cracks shown in Figure D2. The cracks extend into the weld deposit and the heat-affected zone. 4X.

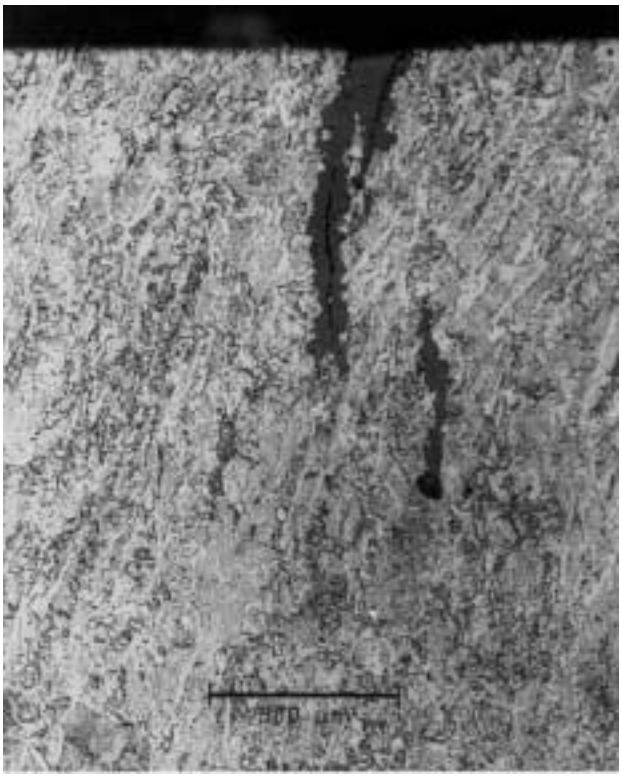

FIGURE D2a-1
Photomicrograph of one of the transverse cracks shown in Figure D2a.

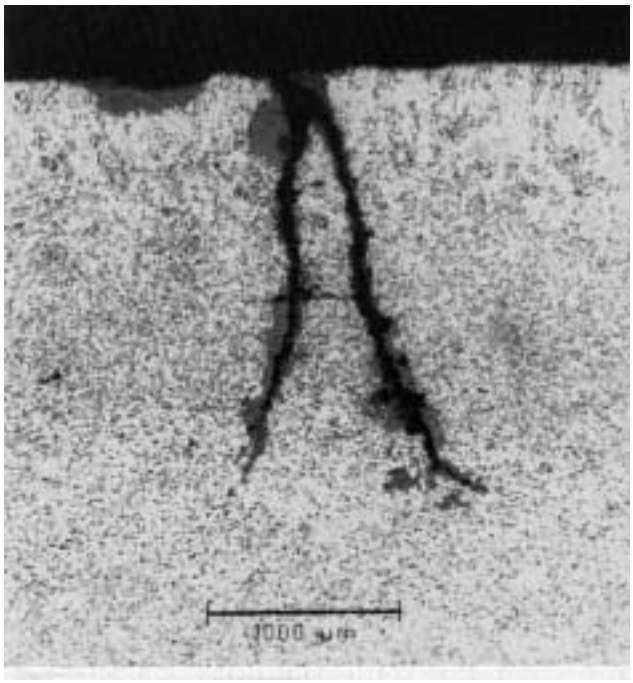

FIGURE D2a-2
Photomicrograph of another transverse crack.

Appendix E: Illustration of Metallographic Cross-Sections at a Right Angle to the Longitudinal and Transverse Cracks

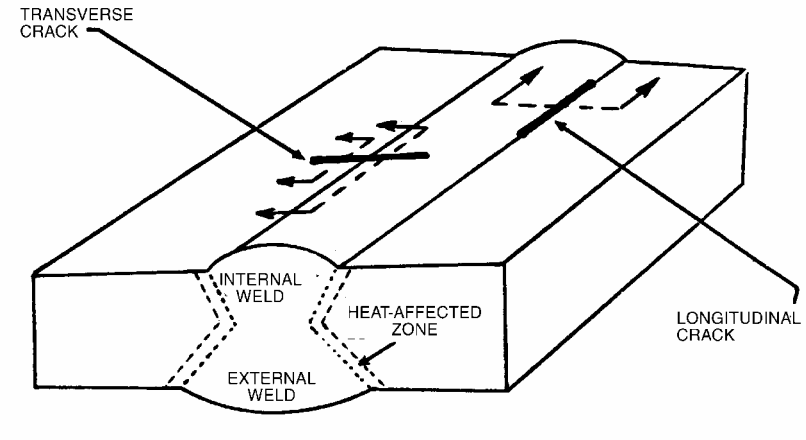

FIGURE E1
Metallographic Cross-Sections