SG-93-10-012

Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates - Database for Alternate Repair Criteria, Volume 2: 3/4 Inch Diameter Tubing

NP-7480-L, Volume 2

EPRI Project S404-29

EPRI Project Manager:
C. L. Williams

October, 1993

NON-PROPRIETARY VERSION

A. J. Baum
J. A. Begley
T. M. Frick
J. L. Houtman
W. R. Junker
R. F. Keating
P. J. Kuchirka
D. D. Malinowski
T. A. Pitterle
P. J. Prabhu
A. Sagar
R. A. Taylor
R. M. Wepfer

REPORT SUMMARY

The database required to support the alternate repair criteria for outside diameter stress corrosion cracking (ODSCC) of steam generator tubes at support plate elevations has been developed from pulled tube examination results and tests of specimens produced in model boilers. Leak rate and burst pressure correlations with bobbin coil voltage have been developed from the overall data. Volume 2 of this report provides an extended database and updated correlations for 3/4 inch diameter (OD) tubes.

BACKGROUND Outside diameter stress corrosion cracking (ODSCC) has been observed in PWR (pressurized water reactor) steam generators in the U.S. and abroad. The existing criteria governing the need for tube repair in the U.S. are too conservative and result in unnecessary repair with associated repair costs, radiation exposure, and reduced operating efficiency.

OBJECTIVES To develop the database which can be used to establish alternate repair limits for ODSCC in PWR steam generator tubes at support plate intersections.

APPROACH Data from operating experience (eddy current data and normal operating leakage or lack there of) and data from pulled tubes (eddy current data, leak rate, burst pressure and destructive examination results) are collected and included in the database. In addition, ODSCC specimens were fabricated in the laboratory using model boilers and tested to supplement the pulled tube database.

RESULTS Eddy current tests on model boiler specimens were conducted using bobbin coil and rotating pancake coil (RPC) probes. Leak rate tests were performed on the specimens at typical normal operating conditions and at primary to secondary pressure differential following a postulated secondary side pipe break (steam line or feed water line break). The specimens were then subjected to burst pressure testing and destructive examination. The crack morphology of model boiler samples was similar to that of pulled tubes from operating steam generators (stress corrosion cracks with minor to negligible intergranular attack - IGA). Using bobbin coil voltage as the independent parameter, correlations were developed for leak rate and burst pressure.

EPRI PERSPECTIVE Degradation of tubes at support plate intersections and at eggcrate intersections is becoming one of the dominant tube degradation mechanisms in PWR steam generators. The existing repair criteria (based upon percent through-wall penetration as the extent of degradation) applied in the U.S. results in the unnecessary repair of structurally sound tubes. Therefore, development of alternate repair limits based upon eddy current signal amplitude could reduce repair costs and radiation exposure without affecting plant safety. The report TR-100407 outlines the EPRI recommended methodology for the development of alternate repair limits. The database needed to support the methods described therein is provided in this report.

ABSTRACT

Feasibility of alternate repair criteria (ARC) for outside diameter stress corrosion cracking (ODSCC) observed at support plate locations of alloy 600 tubes in PWR steam generators was assessed. The database required to support the alternate repair limits was developed from available data from operating plants and from ODSCC specimens fabricated in the laboratory. Non-destructive (eddy current) examination, leak rate testing, burst testing and destructive examination of the test specimens were performed. Leak rate and burst pressure data, including those of tubes pulled from operating steam generators, were correlated with bobbin coil signal amplitude. This report (Volume 2) documents the database developed for 3/4 inch diameter (OD) tubes to support the repair limits, while Volume 1 documents the database developed for 7/8 inch diameter tubes. Bobbin coil voltage normalization inspection requirements needed to support the ARC.

Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates - Database for Alternate Repair Limits, Volume 2: 3/4 Inch Diameter Tubing

TABLE OF CONTENTS

TABLE OF CONTENTS (Continuation)

ILLUSTRATIONS

ILLUSTRATIONS (Continuation)

ILLUSTRATIONS

TABLES

1.0 INTRODUCTION

This report describes the development of the database and correlations that support the technical bases for alternate repair criteria (ARC) for outside diameter stress corrosion cracking (ODSCC) at tube support plates (TSPs) in PWR steam generators (S/Gs). This program was conducted in two phases. Volume 2, this report, is directed toward 3/4 inch diameter (OD) tubing, whereas the Volume 1 report provides the supporting data for 7/8 inch diameter tubing.

The database is derived from: 1) testing of laboratory induced ODSCC specimens, 2) examination of pulled tubes from operating S/Gs and 3) field experience for operating leakage due to indications at TSPs. Specimen fabrication and testing was performed to develop the database required to support the ARC. The development activities were focused on a bobbin coil voltage based repair limit which integrates eddy current (EC) inspection results with tube integrity requirements. The ARC focus on directly relating bobbin coil voltage to the burst strength of tubes and the potential for tube leakage under normal operating and steam line break (SLB) pressure differentials as the applicable measures for tube integrity.

Regulatory Guide 1.121 (R.G. 1.121), which defines the NRC guidelines for the maintenance of S/G tube integrity, specifies acceptance guidelines to be satisfied to minimize the potential for a tube rupture. Utilizing correlations of bobbin coil voltage with burst pressure, the repair limits are developed to provide large margins against tube burst such that the R.G. 1.121 burst strength requirements are satisfied. Leak rates under accident conditions such as a postulated SLB event can be maintained within acceptable values by limiting the number of tubes left in service which could potentially leak during an SLB event and projecting the end of cycle leak rate for these tubes. A correlation of leak rate with bobbin coil voltage can be used for these assessments. Thus, the ARC based upon relating eddy current (EC) measurements to the burst strength and the potential for tube leakage are appropriate criteria for demonstrating satisfaction of regulatory requirements for ODSCC within TSPs. This report emphasizes the development of the database to support burst pressure and leak rate correlations with bobbin coil voltage. Example correlations are developed based on the data given in this report.

The data described in this report are from 3/4 inch diameter tubing with 0.043 inch nominal wall thickness. Correlations developed using this data are semi-empirical in that bobbin coil voltage is correlated with burst strength and the potential for tube leakage and, as such, there is no purely theoretical basis to adjust the criteria to other tube sizes.

To develop the database needed in support of an ARC for ODSCC at TSPs and to provide the technical basis for an ARC development, the following activities have been performed as documented in this report:

- o Background review of pulled tube examinations - Section 2.
- o Non-destructive examination (NDE) of 3/4 inch diameter tubing - Section 3.

- Review and evaluation of pulled tube data to develop the current pulled tube database supporting ARC correlations - Section 4.

- Preparation of test specimens in a model boiler and testing (eddy current, leak rate and burst testing, and destructive examination) of cracked specimens to develop a laboratory database supplementing the pulled tube data for ARC correlations - Section 5.

- Systematic development of the burst pressure correlation from the burst pressure database (pulled tube and model boiler specimens) and eddy current results - Section 6.

- Systematic development of correlations for leak rates during a steam line break (SLB) and for probability of leakage during an SLB, as functions of bobbin coil voltage - Section 7.

- Destructive examination results for 3/4" model boiler specimens - Appendix A.

- Leak rate adjustments for 3/4" tubing - Appendix B.

2.0 TUBE SUPPORT PLATE REGION PULLED TUBE CRACK MORPHOLOGY

2.1 Introduction & Definitions

The following provides summary information regarding OD originated corrosion at support plate crevice regions of Alloy 600 tubing pulled from steam generators at various plants. The data is presented in support of the development of the alternate repair criteria (ARC). All significant available tube pull data at tube support plate locations from plants with 3/4 inch diameter tubing are summarized.

The type of intergranular corrosion with regard to crack morphology and density (number, length, depth) of cracks can influence the structural integrity of the tube and the eddy current response of the indications. To support the tube repair criteria, the emphasis for destructive examination is placed upon characterizing the morphology (SCC, IGA involvement), the number of cracks, and characterization of the largest crack networks with regard to length, depth and remaining ligaments between cracks. These crack details support interpretation of structural parameters such as leak rates and burst pressure, crack length and depth, and of eddy current parameters such as measured voltage with the goal of enhancing structural and eddy current evaluations of tube degradation. In selective cases, the pulled tube evaluations included leak rate measurements, in addition to the more standard burst pressure measurements, for further support of the integrity and plugging limit evaluations.

Before the support plate region corrosion degradation can be adequately described, some key corrosion morphology terms need to be defined. Intergranular corrosion morphology can vary from IGA to SCC to combinations of the two. IGA (Intergranular Attack) is defined as a three dimensional corrosion degradation which occurs along grain boundaries. The radial dimension has a relatively constant value when viewed from different axial and circumferential coordinates. IGA can occur in isolated patches or as extensive networks which may encompass the entire circumferential dimension within the concentrating crevice. Figure 2-1 provides a sketch of these IGA morphologies. As defined in this report, the width of the corrosion should be equal to or greater than the depth of the corrosion for the degradation to be classified as IGA. The growth of IGA is relatively stress independent. IGSCC (Intergranular Stress Corrosion Cracking) is defined as a two-dimensional corrosion degradation of grain boundaries that is strongly stress dependent. IGSCC is typically observed in the axial-radial plane in steam generator tubing, but can occur in the circumferential-radial plane or in combinations of the two planes. The IGSCC can occur as a single two dimensional crack, or it can occur with branches coming off the main plane. Figure 2-2 provides a sketch of these IGSCC morphologies. Both of the IGSCC variations can occur with minor to major components of IGA. The IGA component can occur simply as an IGA base with SCC protruding through the IGA base or the SCC plane may have a semi-three dimensional characteristic. Figure 2-3 provides a sketch of some of the morphologies possible with combinations of IGSCC and IGA. When IGSCC and IGA are both present, the IGSCC will penetrate throughwall first and provide the leak path.

To provide a semi-quantitative way of characterizing the amount of IGA associated with a given crack, the depth of the crack is divided by the width of the IGA as measured at the mid-depth of the crack, creating a ratio D/W. Depth is the linear dimension measured from the OD surface of the tube through the tube wall, i.e., along the tube radius. Width (for an axial crack) is measured along tube circumference, i.e. perpendicular to the depth. In the current context (for D/W ratio), the width is measured at the mid-depth of the crack, i.e., half the distance between the tube OD and the deepest point of the crack. Three D/W categories were created: minor (D/W greater than), moderate (D/W between), and significant (D/W less than) where for a given crack with a D/W of or less, the morphology is that of patch IGA.

The density of cracking can vary from one single large crack (usually a macrocrack composed of many microcracks which nucleated along a line that has only a very small width and which then grew together by intergranular corrosion) to hundreds of very short microcracks that may have partially linked together to form dozens of larger macrocracks. Note that in cases where a very high density of cracks are present (usually axial cracks) and where these cracks also have significant IGA components, then the outer surface of the tube (crack origin surface) can form regions with effective three dimensional IGA. Axial deformations of the tube may then cause circumferential openings on the outer surface of the tube within the three dimensional network of IGA; these networks are sometimes mistakenly referred to as circumferential cracks. The axial cracks, however, will still be the deeper and the dominant degradation, as compared to IGA.

Recognizing all of the gradations between IGA and IGSCC can be difficult. In addition to observing patch IGA, cellular IGA/SCC has been recognized. In intergranular cellular corrosion (ICC), the cell walls have IGSCC to IGA characteristics while the interiors of the cells have nondegraded metal. The cells are usually equiaxial and are typically in diameter. The cell walls (with intergranular corrosion) are typically mils) thick. The thickness and shape of the cell walls do not change substantially with radial depth. Visual examinations or limited combinations of axial and transverse metallography will not readily distinguish ICC from extensive and closely spaced axial IGSCC with circumferential ledges linking axial microcracks, especially if moderate to significant IGA components exist in association with the cracking. Radial metallography is required to definitively recognize cellular IGA/SCC. Cellular IGA/SCC can cover relatively large regions of a support plate crevice (a large fraction of a tube quadrant within the crevice region). Figure 2-4 shows an example of ICC from Plant L (7/8 inch diameter tubing).

A given support plate region can have intergranular corrosion that ranges from IGA through individual IGSCC without IGA components and IGSCC with or without ICC.

2.2 Plant R-1 Corrosion Degradation

For Plant R-1, three tubes with six intersections were pulled in 1992 and five tubes with nine intersections were removed in 1991 or earlier. This paragraph describes the results of the destructive examinations for these tubes.

2.2.1 Plant R-1 1992 Pulled Tubes

Three hot leg steam generator tube segments from Plant R-1 (tubes R7-C71 and R9-C76 from S/G C and tube R9-C91 from S/G D) were examined by Westinghouse in 1992 to provide supporting data for the development of alternate plugging criteria specific to support plate crevice corrosion. The first, second and third support plate crevice regions of each tube were nondestructively examined. Subsequently, elevated temperature leak testing and room temperature burst testing were conducted on the second and third support plate crevice regions of each tube. Consistent with past experience, no indications were detected at the first plate (actually the first plate is the flow distribution baffle), and destructive examination of the first plate crevices was not performed. The burst tested specimens were then destructively examined using metallographic and scanning electron microscope (SEM) fractographic techniques. The following provides a brief summary of the more significant observations.

NDE Results. A summary of the field and laboratory NDE results is given in Section 4. Field bobbin voltage calls ranged from . Throughwall depth estimates as deep as were identified. The indications in tube R9-C91 (for the second and third crevice regions, respectively) were not assigned depth calls in the field. Reevaluation of the field data applied depth estimates of , respectively, for these indications. All intersections destructively examined exhibited confirming RPC calls. While OD origin indications were observed at the second and third support plate crevice regions of each tube by the various eddy current examinations performed, none were found within the first support plate (flow distribution baffle location) crevice region. There was good agreement between the field and laboratory eddy current results, but a significant increase in the bobbin probe signal voltage was noted in three instances in going from the field to the laboratory data. These increases are probably related to the effects of the tube pulling stresses on the corrosion crack networks. The eddy current data suggested that corrosion was present in the form of axial cracks within the crevice regions. Laboratory UT data suggested that a larger number of axial indications were present.

Leak and Burst Testing. The second and third support plate crevice region of each tube was leak tested at elevated temperature and pressure. This test is capable of accurately measuring very low levels of leakage. None of the crevice regions of tubes R7-C71 or R9-C76 leaked at normal operating conditions (differential pressure) or at steam line break conditions (differential pressure). The third support plate crevice region (SP3) of tube R9-C91 did not leak at normal operating conditions, but did develop a very small leak ( ) at steam line break conditions. Post-leak inspection verified that the leak occurred within the crevice region and not at a fitting. SP2 of tube R9-C91 developed a leak at normal operating conditions and a leak at steam line break conditions. Post-leak test inspection, found that the crevice region had two leak locations. Both leak locations had very small (inch) throughwall corrosion.

Extensive destructive examination was required to locate throughwall corrosion at SP3 of R9-C91. Neither the burst crack nor the next largest macrocrack had throughwall corrosion. The only throughwall corrosion (in length) was located in a crack network adjacent to the second largest macrocrack.

Results of the burst tests are presented in Section 4. All burst tests resulted in bulging or fishmouthing and tearing of the crack opening, as shown by the ductility, burst length and burst width measurements. All but SP2 of tube R9-C91 developed simple axial burst openings which were centered within the crevice regions. SP2 of tube R9-C91 also had an axial burst opening centered within the crevice region, but it was complex in shape. It appeared to have formed from   closely spaced and interconnected axial openings. Another interesting observation was that the burst opening of SP3 of tube R9-C91 occurred at a different location than the leak location. All   burst specimens had similar burst pressures that ranged from   SP3 of tube R7-C71 had data recorder problems that prevented knowing the true burst pressure. It is known that its burst pressure exceeded

The upper figure of Figure 2-5 shows the recording of burst pressure versus time for R9-C76, SP2 as an example of a normal and successful burst test. It is seen that the recorder responds quickly to the pressure changes. The water pressure is controlled to follow the drawn target line. However, due to the small volume of the overall system, the initial water pump strokes produce spikes in the pressure, although these spikes are negligible at moderate pressures. The recorder follows these spikes closely. It is also seen that the recorder immediately follows the complete drop in pressure following the burst test.

The burst history of SP3 of tube R7-C71 is complex; it was burst tested twice. The first time, a Swagelok fitting leak produced a small leak that prevented the internal pressure from exceeding   The middle part of Figure 2-5 shows the pressure versus time curve for this run. Note that the recorder normally followed the initial pressure spikes, but with no tube burst there was no rapid drop in pressure. Instead, there was gradual drop-off in pressure as the pump tried to maintain pressure with the small fitting leak. After the initial attempt at bursting the tube, it was noted that the tube appeared normal and that a few drops of water were leaking from the lower Swagelok fitting when several hundred psi of water pressure was applied. The Swagelok fitting was tightened and the test was repeated. During the second run, the recorder was malfunctioning such that the recorder was moving in a sluggish, nonresponsive manner in the vertical (pressure) axis. The bottom figure of Figure 2-5 shows the pressure curve. First, note that no initial pressure spikes were recorded. Second, note that the post-burst test pressure drop-off was slow, even though a large burst opening was subsequently observed. Finally, note that the maximum pressure recorded was lower than the initial burst run, but the tube only had plastic deformation during the second run. After adjustment, no subsequent recorder malfunction occurred. It is suspected that the recorder was set at the calibration setting (filter in recorder to facilitate calibration) and not returned to the record setting for the final burst test. It is concluded that the burst test results for SP3 of tube R7-C71 are low and should be excluded in any final data base of burst test results.

Free span portions of the three tubes had room temperature burst pressures that ranged from Room temperature tensile properties of free span sections are also presented in Section 4

Destructive Examination Results. The leak and burst fracture faces were opened for SEM fractographic examinations. Table 2-1 presents a summary of the fractographic data. The burst openings occurred in axial macrocracks that were composed of numerous axially oriented microcracks that were confined to a relatively narrow axial band. Most of the microcracks had interconnected during plant operation since most of the microcrack ledges, separating the individual microcracks, had only intergranular features. However, the macrocracks also had ledges with dimple rupture features, indicating that the metal between these microcracks tore during burst testing. The thickness of these torn ledges ranged from Most of these torn ledges occurred nearer the macrocrack tips than the mid-macrocrack regions. The macrocracks were confined to the crevice regions and were typically long with a maximum length of The maximum crack depths ranged from throughwall while the average macrocrack depths ranged from throughwall.

Figures 2-6 through 2-11 present sketches of the crack distribution found by visual (30X stereoscope) examinations of the post-burst tested specimens and by subsequent destructive examinations. The sketches show the locations where cracks were found and their overall appearance, not the exact number of cracks or their detailed morphology. Due to the complexities of the observed crack networks, radial metallography, in addition to the more standard transverse and axial metallography, was frequently used to provide an overall understanding of the intergranular corrosion morphology. From the metallographic examinations, it was concluded that the dominant corrosion morphology was axial intergranular stress corrosion cracking (IGSCC) with various amounts of intergranular cellular corrosion (ICC) being associated with the axial IGSCC. In some instances only axial IGSCC was present. In other instances, ICC appeared to dominate locally. However, with progressive grinding, it was shown that axial IGSCC was always found to be deeper than the associated ICC. ICC depths were typically or less. At the locations where ICC had been present, only axial IGSCC remained after grinding. This feature of cellular corrosion with partial depth cellular patterns and deeper penetration by axial IGSCC has been found in all pulled tubes with cellular corrosion, including Plant E-4 indications with more extensive cellular corrosion than found in domestic pulled tubes.

Figure 2-12 provides an example of both axial IGSCC and ICC as revealed by radial metallography. The low magnification (16X) photomicrographic montage is from a portion of the mid-crevice region of SP3 of tube R9-C76 at a depth of throughwall. Predominantly axial IGSCC is seen to the left of the photo and predominantly ICC is observed to the right of the section. Figure 2-13 provides higher magnification (100X) photomicrographs of the ICC region.All of the support plate crevice regions examined were remarkably similar in the types of corrosion found and in the corrosion distribution.

Overall crack densities were low to moderate (typical crack densities ranged from cracks over at a given elevation) However, the cracks were not uniformly distributed and local crack densities were significantly higher Crack densities would range from if local area data were incorrectly extrapolated over the tube circumference All of the individual corrosion cracks found had only minor to moderate IGA components (D/W ratios ranged from) No surface IGA, i.e., that independent of corrosion cracks, was observed

For SP2 of R9-C91, the leak locations were comprised of very short throughwall corrosion penetrations at the burst crack and at a secondary crack For SP3 of R9-C91, which showed no leakage at normal operating conditions and a very small leak at SLB conditions, neither the burst crack nor the largest secondary macrocrack (Table 2-1) were found to have throughwall corrosion The cellular pattern at the edges of the secondary crack at about of Figure 2-11 was also examined and found to have no throughwall corrosion Throughwall corrosion of very short length was found in the cracking pattern adjacent to the secondary crack Following leak and burst testing, the throughwall penetration at the tube ID was about long Figure 2-14 shows fractography and a sketch for the associated crack The short length of deep corrosion accounts for the very small leak rate, as well as the modest bobbin coil voltage for this intersection

From Table 2-1 for the 3rd TSP of R9-C91, it can be noted that the burst crack has a shorter length and smaller average depth than the largest secondary crack This occurs as patches of cellular SCC at the ends of the secondary crack are included in the total crack length measurement It is expected that the tortuous nature of the crack path for the secondary crack made it somewhat stronger than the burst location

Conclusions. The examined second and third support plate crevice regions of the pulled tubes had combinations of axially oriented IGSCC and ICC The corrosion was of OD origin and was always confined to within the crevice region Usually, the corrosion was centered within the crevice region and did not extend to the support plate crevice edge locations Overall crack densities were low to moderate, but with the non-uniform nature of the crack distributions, local crack densities were high Only minor to moderate IGA components were found in association with the IGSCC and no surface IGA was observed The field and laboratory eddy current inspections accurately described the presence of axial cracking Destructive examinations showed that the most significant cracking occurred where the eddy current indications were located Laboratory UT inspection results suggested the presence of an even larger number of axial cracks Destructive examinations showed that the UT call of a larger number of axial cracks than the eddy current data suggested was correct

Crack networks in of the crevice regions developed small leaks during the leak testing that was conducted prior to burst testing The maximum leak rate at elevated temperature and pressure was liters per hour at normal operating conditions and liters per hour at steam line break conditions

The presence of intergranular stress corrosion cracking at the support plate locations did not reduce the burst pressures of these corroded regions by more than a factor of compared to the undegraded, freespan burst pressures. This is well above the safety limitations. The burst pressures ranged from at locations where corrosion macrocracks ranged from inch long. The maximum depth of corrosion ranged from throughwall.

2.2.2 Plant R-1 1991 Pulled Tubes

This paragraph describes the crack morphology and burst/leak rate measurements for tubes pulled from Plant R-1 in 1991. Five hot leg tube segments (R5C112, R10C69, R7C47, R20C46 and R10C6) were removed and included the first, second and third TSP regions. The burst test data are described to assess whether the measured pressures are representative of a burst or a more limited crack opening causing leakage. A completed burst test is characterized by fishmouth opening of the crack, bulging of the tube and/or tearing at the edges of the corrosion crack as found for the 1992 pulled tubes (Table 2-1). In general, the burst test opens up the entire macrocrack length or a very large fraction of the corrosion crack. It is shown that the 1991 burst tests resulted in either minor crack opening (not representative of a complete burst) or moderate openings still less than expected for a complete burst. The minor crack opening exhibited in these tests would not have resulted in coolant release rates consistent with the U.S. NRC definition of a steam generator tube rupture as exceeding the makeup capacity of the plant. For essentially undegraded tube sections which had fishmouthed and bulged ruptures, the resulting burst pressures were or more lower than found for other tests of the same or typical 3/4 inch diameter tubing. Upon review of the data, the EPRI ARC Committee concluded that the burst data are not reliable and should not be included in the ARC database.

The following describes the destructive examination results for the 1991 Plant R-1 pulled tubes:

Tube R5C112, TSP3. Plant R-1 pulled tube R5C112, TSP-3 had a field bobbin voltage indication of and a post-pull bobbin voltage of By destructive exam, the maximum corrosion depth (at axial grinds) was In the laboratory, the indication was found to leak at about while pressurizing for a burst test. The tube section was then leak tested at prototypic conditions before further burst testing and found to have leak rates of at normal operating and SLB pressure differential, respectively. A bladder was then inserted to continue burst testing. The "burst" pressure measured was

Figures 2-15 to 2-17 show, respectively, the post-burst test crack, a map of OD crack indications and the crack depth vs length of the macrocracks that opened during leak and burst testing. Figure 2-15 also shows the location and length of throughwall crack opening following the burst test. From Figure 2-15, it is seen that two post-burst crack openings are separated by a ligament. The lengths of the two throughwall penetrations are about These lengths are typical of individual microcracks. Even the end to end opened crack length of about is much less than the throughwall crack expected for a burst pressure of A completed burst test is characterized by fishmouth opening of the crack and/or tearing at the edges of the corrosion crack. This burst test shows neither of these burst features and did not open up either of the macrocracks. It is concluded that the "burst" test is an incomplete test. It is postulated that a slow pressurization rate permitted the bladder to enter the microcracks as they opened and caused the bladder to tear which terminated the test. As a consequence, the "burst" test is not considered reliable and is not included in the voltage/burst correlation data base.

A increase in eddy current bobbin voltage and the appearance of leakage at a pressure of in a post-pull test raises questions of damage to tube R5C112 prior to leak rate testing and the suitability of including this leakage data in leak rate - bobbin voltage correlations. The measured crack depth profile of Figure 2-17, as obtained from the metallography of the successive axial grinds of the OD surface depicted in Figure 2-16, was used to estimate the pressure at which fracture of the remaining crack depth ligaments would be expected. The estimated pressure at which ligament fracture and thus leakage would be expected is about or many times higher than the observed pressure of . This indicates the tube was damaged prior to leak rate testing and should not be included in the general leak rate database. The measured SLB leak rate for this indication of would be expected to have a throughwall crack length of about or larger.

R10C69, TSP 3. This indication had a bobbin voltage of which increased to volts in the post-pull inspection. Figure 2-18 shows the burst crack opening after the burst test and after cutting and bending of the tube to open the macrocrack. It is seen that only minor crack opening has occurred and the opened length is very short . After bending to open the macrocrack, a large part of the macrocrack is not throughwall. Figure 2-19 shows that the burst opening represents only part of the approximately macrocrack length which had a maximum depth of . The measured burst pressure of is approximately the expected burst pressure for a throughwall crack and much less than expected for an average depth equal to the maximum depth. It is concluded that the burst test did not result in a complete burst. Therefore, this indication is not included in the burst pressure data base.

R7C47, TSP 3. The 3rd TSP intersection of R7C47 had a indication that increased to in the post-pull inspection. Figure 2-20 shows the burst crack opening for this indication and Figure 2-21 shows the crack map. The macrocrack associated with the burst opening is about long with a maximum depth of about . Figure 2-22 shows the crack depth vs. length profile, which indicates an average depth of about . The crack length having depths greater than . The burst pressure for a long crack with an average depth of would be expected to be at least compared to the measured . From Figure 2-20, it is seen that the burst test resulted in only a minor crack opening of about which again indicates an incomplete burst test, and the data point was excluded from the database.

R20C46, TSPs 2 and 3. Both intersections of tube R20C46 burst just above the TSP elevation at hand held grinding tool marks. These marks were applied in the laboratory for location purposes. Since the burst pressures are associated with the grinding marks outside the TSP rather than the degradation within the TSP, these indications are not included in the database.

R10C69, TSP 2. No detectable bobbin indication was found in either the field or post-pull inspection for the 2nd TSP intersection of R10C69. The destructive exam also shows no measurable degradation at this TSP intersection. The burst opening is centered at the TSP indication and shows a ductile, fishmouth rupture typical of bursts for indications with modest degradation. The measured burst pressure was

To evaluate the potential need to adjust the measured burst pressure for this type of indication, an undegraded freespan piece of tube R7C47 was burst by Westinghouse for comparison with burst of the Plant R-1 freespan tubing as part of the destructive examination program. The Westinghouse test yielded a burst pressure of which is similar to that found for undegraded model boiler tubing. The freespan burst pressures during the destructive exam program were in the range of or about lower than the Westinghouse tests. Historically, burst pressures for undegraded 3/4 inch tubing have been in the range of The low burst pressures obtained during the destructive exam tests tend to indicate a potential systematic problem in the time frame of these tests. Based on these results, the burst test is not considered reliable and is not included in the database.

R5C112, TSP 2. The 2nd TSP of R5C112 was called NDD in the field evaluation, by reevaluation of the field data and for the post-pull evaluation. The tube burst at above the TSP location and thus should correspond to an undegraded tube burst pressure. The expected range of burst pressures for undegraded tubing is The low measured burst pressure indicates an unreliable data point.

R10C6, TSP 2. The 2nd TSP of R10C6 had a bobbin indication which increased to in the post-pull inspection. The burst crack opening is shown in the upper part of Figure 2-23 at two magnifications. The crack opening is about long with minor bulging or tearing. Figure 2-24 shows the OD crack map and associated depths. The macrocrack that opened in the burst test is about long with a maximum depth of The expected burst pressure for a long crack conservatively assuming an average depth of would be about or significantly in excess of the measured It is concluded that the reported burst pressure underestimates a complete burst by at least and the data point has too many uncertainties for including in the ARC database.

R10C6, TSP 3. The 3rd TSP of R10C6 had a bobbin indication which increased to in the post-pull examination. Figure 2-23 shows the burst crack opening for this indication. The burst opening length is about with a maximum depth of Similar to the 2nd TSP for this tube, a minimum increase of in the measured burst pressure of would be appropriate for this indication and the data point is not included in the ARC database.

Crack Morphology. Figures 2-16, 2-19, 2-21 and 2-24 show available OD crack maps and associated maximum depths found in the tube examination. These figures also show regions on the tube which were characterized in the destructive examination as IGA. The IGA depth was generally negligible However, the 3rd TSP of R7C47 was identified as having very local IGA depths up to the range as shown in Figure 2-21. The IGA characterization used to define the OD crack maps is believed to have identified ICC as IGA. A review of the metallography data indicates negligible volumetric IGA involvement. The Plant R-1 pulled tube crack morphology can be classified as axial IGSCC with a lesser extent of ICC associated with the IGSCC, with minor surface IGA.

2.3 Plant E-4 Corrosion Degradation

A total of 18 steam generator tubes comprising 27 tube support plate crevice regions have been removed and destructively examined from European Plant E-4. The dominant corrosion morphology is that of axial IGSCC with cellular IGA/SCC. The cellular IGA/SCC is localized in the crevice region such that most of the crevice region is free of corrosion. The crevice regions had moderate crack densities, moderate IGA components associated with individual major cracks, and no significant IGA independent cracking. Burst tests conducted produced the expected axial opening through complex mixtures of axial, circumferential and oblique cracks. For the more strongly affected areas, while the cracking remained multi-directional, there was a predominance of axial cracking. Figures 2-25 and 2-26 provide radial section photomicrographs through two of the more strongly affected areas showing cellular IGA/SCC at Plant E-4.

Leak testing was also performed on a number of intersections from Plant E-4. The voltage ranges leak tested were from The minimum voltage indication which leaked had a signal. This intersection had an adjusted (for temperature effects) leak rate of at normal plant conditions and a leak rate of at SLB conditions. The minimum burst pressure of was recorded for an indication. Other indications with higher voltages had higher burst pressures. The burst and leak test results are given in Section 4.

Limited destructive examination data is available on the Plant E-4 pulled tubes. Due to the large recorded voltages for these indications with rather long throughwall lengths, the average crack depths are heavily biased due to this throughwall length.

Axially oriented sketches of the burst openings are available for several of the tubes pulled in 1992, in addition to width and depth of penetration data for the IGSCC patch (ICC) areas. For tube R16-C31 the length of throughwall corrosion was listed as inch) while the length of the overall macrocrack was Burst pressure was The deepest ICC patch, throughwall, was approximately wide. All but one of the intersections listed (total intersections with available data) had ICC widths less than A total of separate ICC patch areas were located. The widest ICC patch width was identified on tube R47-C66, and was approximately wide with a depth of about The maximum single microcrack depth an R47-C66, TSP 3 was about and the total length of OD involvement of the burst crack was Another separate patch area was wide and about deep. The 550/130 kHz mix voltage of this indication was , with an associated burst pressure of The macrocrack did not progress throughwall so no leakage was detected. These tubes were also circumferentially separated by axial loading until failure, after the internal pressurization burst testing was performed. This was done to assess the impact of the ICC upon axial strength of the tube. Tube R47-C66 exhibited the lowest ratio of axial rupture force to expected strength of an unflawed section (cross sectional area times ultimate tensile strength) in order to assess the amount of affected cross sectional area. The ratios for the other intersections of the other tubes were from

Of the 1992 pulled tubes, R26-C47 TSP region 2 had the largest SLB leak rate, adjusted to , or approximately This indication had a throughwall length of about and total burst macrocrack length of about Somewhat larger leak rates were found in the 1993 pulled tubes. The Plant E-4 burst and leak rate data are given in Section 4 for all pulled tubes.

2.4 Plant B-1 Corrosion Degradation

A description of the corrosion found at TSP 5 of Plant B-1 is provided below. This region is singled-out for two reasons. First of all, it has through wall corrosion. Secondly, the tube had a small region believed to have cellular IGA/SCC.

OD origin, axially orientated, intergranular stress corrosion cracks were observed confined entirely within the fifth support plate crevice region on the hot leg side of tube R4-C61 from steam generator C of Plant B-1. axial macrocracks were observed around the circumference. The largest of these was examined by SEM fractography without any metallography. The macrocrack was long and through wall for However, the crack was nearly (effectively) through wall for The macrocrack was composed of individual microcracks that had mostly grown together by intergranular corrosion (the separating ledges had intergranular features that ranged from of the length of the ledges). Since no metallography was performed on the axial cracks, it is not possible to definitively describe the axial crack morphology at this location. At the eighth support plate region of the same tube, metallography showed that the morphology was that of SCC with a crack depth to IGA width ratio (D/W) of . Figure 2-27 summarizes the crack distribution and morphology data for the fifth support plate crevice region.

In addition to the OD origin axial macrocracks observed at the fifth support plate region, one location adjacent to the burst crack had intergranular circumferential cracks. The maximum penetration observed for the circumferential cracking was through wall. The morphology of the circumferential cracking was more that of IGA patches than of SCC. In addition to the main circumferential cracks, the region had numerous smaller cracks aligned in both the axial and circumferential directions providing a crazed appearance. See Figure 2-28. This crazed degradation is now recognized as probably being cellular IGA/SCC. Previously the crazed pattern was thought to represent only shallow IGA type degradation that completely disappeared a short distance below the surface. Figure 2-29 provides micrographs of relevant cracks showing the morphology of axial and circumferential cracks. As stated above, the axial cracks had a morphology of IGSCC with a moderate D/W ratio of while the circumferential cracking had a morphology more like that of IGA, with a D/W ratio of

Field eddy current bobbin probe inspection (in June 1989, just prior to the tube pull) of the fifth support plate crevice region produced a deep indication in the kHz differential mix.

2.5 Plant S Corrosion Degradation

Three hot leg tube segments were removed from Plant S in 1993 for destructive examination. The tubes included R33-C20, R28-C41, and R42-C43, S/G B. The removed sections included only the first TSP crevice region, the flow distribution baffle (FDB). The Plant S eddy current indications are somewhat different than the rest of the pulled tube population in that not only are the degradation indications located at the flow distribution baffle, but the apparent indication growth was unprecedented in domestic plants for indications at TSP intersections. Bobbin coil voltage calls for these indications were These locations had only low voltage signals present at the end of the previous cycle,

NDE Results. A summary of the field and laboratory NDE results is given in Section 4. Post-pull bobbin voltages ranged from , and represented increases of over the field calls. The increase in voltage is believed to have been caused by the tube pulling operation tearing ductile ligaments that separate individual microcracks within the overall crack networks. Field and Laboratory RPC inspection identified axial cracking within the crevice. Laboratory UT suggested a degradation morphology of intergranular cellular corrosion (ICC) in addition to the dominant axial cracking. Both the RPC and UT suggested throughwall corrosion of

Leak and Burst Testing. The FDB region of each tube was leak tested at elevated temperature and pressure. All three developed leaks. The leak rates for test conditions considered valid ranged from for R33-C20 at normal and SLB pressure differentials, from for R42-C43 at normal and SLB conditions, and for R28-C41 at normal conditions.

Tube R28-C41 was initially leak tested to Post test evaluation of the data indicated that the leak rates exceeded the capability of about for the leak measurement facility. Subsequent leak testing in a new facility with increased capacity showed that the later leak tests were affected by prior opening of the cracks (hysteresis) in the initial leak test and the test results above normal operating conditions are not reliable. Tube R33-C20 and R42-C43 were tested in the larger leak rate capacity facility and the measurements are considered valid. Tube R33-C20 was also tested to in the initial leak test facility so that SLB measurements of in the new facility are considered valid measurements.

Room temperature burst testing resulted in axial burst openings in all specimens. The openings were centered in the crevice regions. The circumferential position of the crevice region specimens burst openings were the same as the location of the deepest UT indications. The burst pressures were for R28-C41, for R33-C20 and for R42-C43. The burst pressure of R28-C41 was believed to have been influenced by the above noted repeated leak testing at SLB conditions and significant tube deformation during removal (bobbin voltage increased from following tube pulling operations). These effects caused a premature opening of the burst crack. No crack tip tearing was associated with the burst and the length of the burst opening was less than the macrocrack length. For these reasons, the burst data for R28-C41 is considered unreliable. The burst test values for R33-C20 and R42-C43 are consistent with the mean regression of the voltage-burst relationship, while the actual burst test data for R28-C41 is below the mean but above the lower prediction interval. Burst and leak test results for the Plant S indications are given in Section 4.

Destructive Examination Results. The burst fracture faces of the FDB crevice region specimens were opened for SEM fractographic examinations. The burst openings occurred in axial macrocracks that were composed of numerous axially oriented intergranular microcracks of OD origin. In the case of the FDB region of tubes R28-C41 and R33-C20, the burst fracture occurred in a single axial macrocrack composed of microcracks confined to a narrow axial band. In the case of the FDB region of R42-C43, the burst fracture was composed of parallel axial macrocracks apart. The centers of these macrocracks were connected near the centers of the macrocracks by a "V-shaped" throughwall macrocrack. The length of each side of the "V-shaped" macrocrack was approximately

All of the axial, burst related macrocracks were throughwall for an unusually long fraction of the macrocracks, resulting in very high calculated average depth values. The macrocrack length and average depths were deep and , for tubes R28-C41 and R33-C20, respectively. Tube R42-C43 had cracks forming the burst opening with lengths and averaged depths of

Most of the burst fracture microcracks had interconnected during operation, however, a small number of ledges exhibited dimple rupture features, indicating they had torn during the burst test. Figures 2-30, 2-31, and 2-32 are sketches of the cracks distributions around the tube OD, post-burst testing. The sketches show the locations where cracks were found and their overall appearance, not the exact number of cracks or their morphology.

Radial metallography was used to provide insight as to the corrosion morphology in tube R28-C41 and R42-C43. It was concluded that the dominant corrosion morphology was axial IGSCC with significant ICC found in association with the IGSCC. The ICC occurred in elongated patches (about wide by up to high). The IGSCC was shown by progressive grinding to dominate the morphology. The maximum depth of ICC were for R28-C41 and for R42-C43. The cellular ICC morphology is shown by the radial metallography photomicrograph of Figure 2-33. The morphology of R33-C20 differed from the others in that only minor ICC in association with the IGSCC was detected.

The density of axial cracks in the crevice regions was typically high in the local areas of deposits for the partially packed crevice and where there was tube-to-FDB contact or near contact. Little cracking was identified in the remaining portions of the tube OD surface (see Figures 2-30, 2-31, and 2-32). Little or no surface IGA was detected. D/W ratios for the FDB cracking indicated only a minor association as typical D/W ratios ranged from

Summary of Plant S Degradation Morphology. The tube degradation identified at the FDB region in Plant S is best categorized as dominant IGSCC with ICC in association with the IGSCC, but to a lesser extent. The causative mechanism for the rapid and unprecedented apparent growth identified in Plant S has been best described by a combination of caustic crevice chemistry conditions accentuated by partially packed FDB crevices. The tube-to-FDB gap is about diametrally, compared to the diametral gap at the TSPs. The increased surface area (large partially packed crevice) is believed to have permitted more rapid contaminant absorption due to the increased surface area of the corrosion product buildup exposed to the bulk water in the presence of an oxidant (available oxygen). Exceptionally high copper levels were detected in the tube OD and crack face oxide layers. It is believed that the copper entered the steam generator as copper-oxide and was reduced due to the caustic crevice chemistry, creating locally elevated oxygen concentrations in the crevice regions, and thereby leading to rapid corrosion rates.

Table 2-1

SEM Fractography Data on Corrosion Present on Plant R-1 SG Tubes

Figure 2-1. Patch and uniform IGA morphology as observed in a transverse tube section. (A similar observation would be made from a longitudinal section.)

Figure 2-2. Schematic of simple IGSCC and branch IGSCC. Note that branch and simple IGSCC are not distinghuishable from a longitudinal metallographic section. From a longitudinal section, they also look similar to IGA (see Figure 2-3).

Figure 2-3. Schematic of IGA with IGSCC fingers and IGA with IGA fingers. Note that neither of the above variations can be distinguished from a longitudinal section.

Figure 2-4. Photomicrographs of radial metallography performed on a region with axial and circumferential degradation on Plant L tube R16C74, TSP 1. Cellular IGA was found with little change in the cell shape and cell wall thickness at depths of below the OD surface. Note that the cut section was flattened, preferentially opening the circumferential wall of the cells

Figure 2-5. Normal burst pressure curve and R7C71, TSP2 with fitting leak and with recorder malfunction.

Figure 2-6. Sketch of the crack distribution found at the second support plate crevice region of tube R7-C71 from Plant R-1. Included is the location of the burst test fracture opening. The OD origin intergranular corrosion was confined to the support plate crevice region, including that found on the burst fracture face.

Figure 2-7. Sketch of the crack distribution found at the third support plate crevice region of tube R7-C71 from Plant R-1. Included is the location of the burst test fracture opening. The OD origin intergranular corrosion was confined to the support plate crevice region, including that found on the burst fracture face.

Figure 2-8. Sketch of the crack distribution found at the second support plate crevice region of tube R9-C76 from Plant R-1. Included is the location of the burst test fracture opening. The OD origin intergranular corrosion was confined to the support plate crevice region, including that found on the burst fracture face.

Figure 2-9. Sketch of the crack distribution found at the third support plate crevice region of tube R9-C76 from Plant R-1. Included is the location of the burst test fracture opening. The OD origin intergranular corrosion was confined to the support plate crevice region, including that found on the burst fracture face.

Figure 2-10. Sketch of the crack distribution found at the second support plate crevice region of tube R9-C91 from Plant R-1. Included is the location of the burst test fracture opening. The OD origin intergranular corrosion was confined to the support plate crevice region, including that found on the burst fracture face.

Figure 2-11. Sketch of the crack distribution found at the third support plate crevice region of tube R9-C91 from Plant R-1. Included is the location of the burst test fracture opening. The OD orgin intergranular corrosion was confined to the support plate crevice region, including that found on the burst fracture face

Figure 2 - 12. Radial metallography of the mid-crevice region of SP3 of tube R9-C76 from Plant R-1, near . The low magnification (16X) montage shows predominantly axial IGSCC to the left from and predominantly ICC to the right from .

Figure 2 - 13. Higher magnification (100X) photomicrographs of the ICC shown in Figure 2 - 12.

Figure 2 - 14. Through Wall Corrosion for SP3 of R9-C91 from Plant R-1.

Figure 2 -15. Plant R-1 Pulled Tube R5-C112, TSP 3: Crack Before and After Burst Test

Figure 2 - 16. Plant R-1 Pulled Tube R5-C112, SP3: Incremental Grind and Polish Results.

Figure 2 - 17. Plant R-1 Pulled Tube R5-C112 SP 3: Crack Depth Profile

Figure 2 -18. Plant R-1 Pulled Tube R10-C69, TSP 3: Crack After Burst Test

Figure 2 9. Plant R-1 Pulled Tube R10-C69, SP3: Incremental Grind and Polish Results.

Figure 2 - 20. Plant R-1 Pulled Tube R7-C47, TSP 3: Crack After Burst Test

Figure 2 - 21. Plant R-1 Pulled Tube R7-C47, SP3: Incremental Grind and Polish Results.

Figure 2 - 22. Plant R-1 Tube R7C47, SP 3: Crack Depth Profile

Figure 2 - 23. Plant R-1 Pulled Tube R10-C6, TSP 3: Crack After Burst Test

Figure 2 - 24. Plant R-1 Pulled Tube R10-C6, SP2: Incremental Grind and Polish Results.

Figure 2 - 25. Radial metallographic section through a portion of the third support plate crevice region of tube R19C35 from Plant E-4. A cellular IGA/SCC structure is observed. The depth of the section was not specified.

Figure 2 - 26 Radial metallographic section through a portion of the fourth support plate crevice region of tube R19C35 from Plant E-4. A cellular IGA/SCC structure is observed. The depth of the section was not specified.

Figure 2-27. Description of OD corrosion at the fifth support plate crevice region of tube R4-C61 from Plant B-1.

Figure 2-28. Network of small, mostly circumferentially oriented OD surface cracks observed in the fifth support plate region of tube R4-C61 from Plant B-1.

Figure 2 -29. Photomicrographs of tube R4-C61 corrosion degradation. Top photo shows axial cra mophology (transverse section) at the eighth support plate location (no transverse metallography was performed at the fifth support plate region). Bottom photo shows circumferential crack morphology (axial section) at fifth support plate region

Figure 2 - 30 Sketch of the crack distribution found at the flow distribution baffle plate crevice region of Tube R28-C41. Included is the location of the burst test fracture opening.

Figure 2-31. Sketch of the crack distribution found at the flow distribution baffle plate crevice region of Tube R33-C20. Included is the location of the burst test fracture opening.

Figure 2-32. Sketch of the crack distribution found at the flow distribution baffle plate crevice region of Tube R42-C43. Included is the location of the burst test fracture opening.

Figure 2 - 33. Low magnification (16x) montage of a radial metallographic section deep obtained at the FDB region of Tube R28-C41 showing intergranular cellular corrosion (ICC) and axial IGSCC.

3.0 NON-DESTRUCTIVE EXAMINATION

An extension NDE program was implemented to characterize the laboratory cracked specimens and to assess the sensitivity associated with application of bobbin coil voltage as the basis for tube repair limits. This program is described in Volume 1 (7/8" data) of this report and is not repeated in this report. This section defines the voltage normalization for ARC applications with 3/4 inch diameter tubing, voltage renormalization for alternate calibrations such as the Belgian data, and provides the general voltage trends obtained for EDM slots.

3.1 Voltage Normalization for ARC

To provide for repeatability of the voltage measurements, a common voltage calibration is used for ARC applications. Bobbin probe voltages are calibrated to the holes on an ASME standard. The ASME standard includes flat bottom holes of depth and diameter. The dimensions on the holes should be manufactured to a tolerance of . For 3/4 inch diameter tubing with 0.043 inch nominal wall thickness, the bobbin voltages for the ASME holes should be normalized to and/or mix. The for the mix results are obtained when the reference EPRI laboratory standard is setup to . If the particular probe and standard being applied for a voltage measurement does not yield the same voltage ratio for to within about , voltages should be normalized to for the mix.

RPC probe voltages should be normalized to for the long, throughwall notch at The calibration must be established at the frequency used for reporting the RPC amplitudes.

Alternate voltage normalizations based on throughwall holes or slots were also evaluated for ARC applications as described in Section 3.10 of Volume 1 (7/8" data) of this report. No advantages were found for these alternate normalizations and the hole normalization is required for bobbin voltages.

3.2 Voltage Renormalization for Alternate Calibrations

In Belgium, differential inspections are applied for TSP intersections with 3/4 inch diameter tubing. The Belgian normalization is for throughwall, diameter holes. The 3/4" tube database is significantly expanded by inclusion of tube pull and burst test data produced by Laborelec from Plant E-4 in Belgium. In support of the industry effort to develop alternate repair criteria for support plate ODSCC, Laborelec has collected field data using both Belgian and ARC voltage calibrations on U.S. testing equipment (MIZ-18) as well as Belgian equipment; this data has included several pulled tubes among ~57 indications evaluated. For the ARC data, Zetec equipment was used to obtain the data.

For the Belgian data, both Zetec and Belgian equipment were used to obtain the data. In addition, the Belgian ASME calibration standards were cross-calibrated to the reference laboratory standard.

The Zetec bobbin coil data tapes for were independently evaluated by Westinghouse for 53 TSP intersections. Figure 3-1 shows the correlation between the Westinghouse and Belgian (Laborelec) voltage evaluations. It is seen that both evaluations are in excellent agreement so that either Westinghouse or Belgian data analyses may be used for ARC applications. Where Westinghouse evaluations are available, they are used as the reference voltage amplitudes to enhance general consistency with the other ARC data. Where not available, the Laborelec evaluations are used.

Evaluations of the Belgian ASME calibration data were performed to assess potential differences between Belgian and domestic ASME calibration standards and probes. Table 3-1 summarizes results of a Westinghouse assessment of the Belgian field data for the Belgian ASME standard and compares the results with values obtained using domestic standards and probes. For results normalized to for the ASME hole, it is seen that the Belgian standard/probe leads to lower voltages for the remaining holes including the Belgian throughwall holes. This leads to a ratio of about for the Echoram probe versus about for the Belgian standard/probe when the ARC normalization is compared to the Belgian normalization. To further evaluate this difference, a domestic ASME calibration standard and an Echoram probe were provided to Laborelec for both 3/4 inch and 7/8 inch tubing. Cross-calibration results for the 3/4 inch U.S. transfer standard are shown in Table 3-1, for which the transfer standard yielded for the hole corresponding to for the laboratory standard.

Laborelec evaluated the differences between Belgian and U.S. standards/probes using the Belgian manufactured laboratory ASME standard, the U.S. manufactured transfer standard cross calibrated to the reference laboratory standard, a Belgian probe and an Echoram probe. Holes in the Belgian ASME standard were obtained by EDM while the U. S. standards are drilled. Holes sized for the ASME and holes were measured and found to be in close agreement such as to minimize tolerance effects on the measurements. The manufacturing process for the standards and the influence of probe design were separately evaluated. Results of the Laborelec evaluation are given in Table 3-2. Results for the manufacturing process compare measurements for the domestic drilled hole standards with the Belgian EDM hole standards. Voltages were normalized using the Belgian standard as applied for field measurements and then compared to voltage measurements for the U. S. drilled standard. From Table 4-2, it is seen that ratios of EDM to drilled hole voltages for throughwall holes (holes) are approximately for 3/4 inch tubing and for 7/8 inch tubing. However, for the ASME holes, the EDM/drilled ratio is for 3/4 tubing and for 7/8 inch tubing The ratio factor of represents a direct adjustment factor to the Plant E-4 pulled tube voltage measurements obtained at this mix with a Belgian ASME standard.

To further check this ratio, additional Belgian standards were cross-calibrated against each other and found to be in excellent agreement (within tight EDM tolerances). For example, the field ASME standard used for the Plant E-4 measurements was cross calibrated against the Belgian laboratory standard and found to have a cross calibration factor of .

Laborelec also evaluated the influence of probe design on ratios between the same simulated defect and between frequencies using the U. S. calibration standard. Results are also given in Table 3-2. For 3/4 inch tubing, the differences between probes are small for holes and even smaller for throughwall holes. These differences are typical of probe to probe variations of the same manufacturer or between domestic manufactures and can be ignored as a correction for ARC data. These variations are included in the ARC database for model boiler and pulled tube data for which the small probe to probe differences contribute to the spread of the burst and leak rate data. For 7/8 inch tubing, the differences between Echoram and Laborelec probes at are more significant , while small at .

Based on the above results, the net adjustment factor of the Plant E-4 data for cross-calibration of ASME standards are obtained as follows:

Cross-calibration of Laborelec laboratory standard to U. S. transfer standard.

Cross-calibration of Plant E-4 standard to Belgian laboratory standard.

Cross-calibration of U. S. transfer standard to reference ARC laboratory standard.

Net cross-calibration factor

Thus, the Plant E-4 pulled tube voltages measured at with the Belgian ASME standard need to be increased by a factor of

The Plant E-4 field measurements at (ARC normalization) and at (Belgian normalization) can be applied to obtain a general correlation for renormalization of Belgian data (3/4 inch tubing) to the ARC normalization. Figure 3-2 shows the correlation obtained for the voltage renormalization based on Zetec equipment for the data (adjusted for cross calibration of ASME standards) and Belgian equipment for the data. When Zetec equipment is used for both measurements, the correlation has less spread than that of Figure 3-2. The slope of for large voltages is similar to the ratio obtained for throughwall defects in Table 3-1, while the low voltage slope of was feathered into the correlation based on consistency with the ASME hole data of Table 3-1. The renormalization factors thus increase with increasing voltage. The correlation of Figure 3-2 is to be applied for incorporating Belgian data at into the ARC database.

Data have been obtained for renormalizing other voltage calibrations to the ARC calibration. Post-pull laboratory data were obtained on Plant R-1 pulled tubes (8 data points) at both mixes with voltage normalization at on the ASME mix for each frequency mix. The data have been correlated as shown in Figure 3-3 for renormalizing data to the ARC normalization. For Plant R-1 applications, it was also found necessary to convert data to . Field data for both mixes were obtained for 96 indications to develop the correlation shown in Figure 3-4. These renormalization correlations based on field flaws were substantiated independently by data obtained on an ASME standard using the three mixes as given in Table 3-3. The results show the renormalizations increase with depth and increasing voltage amplitudes for the mixes, in that order.

3.3 Voltage Trends for EDM Slots

In order to anticipate the behavior (bobbin amplitude response) of cracks, EDM slots of varying depth and length were prepared for 3/4 inch tubing. As with the 7/8 inch data for EDM slots, the NDE measurements were made according to the EPRI guidelines. For 3/4 inch tubing, the support plate mix data obtained using a bobbin probe were evaluated to determine the peak-to-peak voltage values for each notch. These data are displayed in Figure 3-5. The trends apparent in these data are virtually identical to those collected with a probe from the mix channel for 7/8 inch tubing (Figure 3-6). At partial depths up to about , bobbin voltage saturates or does not increase significantly for crack lengths greater than about long. For throughwall indications, voltage does not saturate up to about length although the rate of increase falls off with length such that voltages increase only about between indications.

Table 3-1

Ratio of U. S. 550/130 kHz to Belgian

Table 3-2

Laborelec Results for Renormalization of Belgian to U. S. Volts

Table 3-3

Voltage Normalization Trends Between Frequency Mixes [1]

Figure 3-1 Comparison of Bobbin Voltages at between Westinghouse and Belgian Evaluations

Figure 3-2. Belgian (3/4" Tubing) Voltage Renormalization to U. S. ARC Calibration for Plant E-4 1992 Voltages indications at Tube Support Plates

Figure 3-3. Correlation Between Bobbin Voltages at
from Plant R-1 Pulled Tube Data

Figure 3-4 Signal Amplitudes at for Plant R-1 TSP Indications

Figure 3-5. Bobbin Coil Voltage Dependence on Slot Length and Depth - 0.75" Tubing

Figure 3-6. Bobbin Coil Voltage Dependence on Slot Length and Depth - 0.875" Tubing

This page
intentionally blank

4.0 PULLED TUBE DATA EVALUATION

This section identifies the field experience data from operating steam generators that are utilized in the development of alternate repair criteria (ARC) for ODSCC at TSPs. The field data utilized for 3/4 inch diameter tubing include pulled tube examination results from both domestic and European plants and occurrences of tube leakage for ODSCC indications at support plates. Emphasis for the pulled tube data are placed on bobbin coil voltages, burst pressures and leak rate measurements.

4.1 Pulled Tube Data Base Summary

The available pulled tube data base for ODSCC at TSPs in Westinghouse steam generators is summarized in Table 4-1 for both 3/4 and 7/8 inch diameter tubing. The number of 7/8 inch pulled tubes is provided as a general comparison with the 3/4 inch data and is not utilized in the 3/4 inch evaluation of this report. Both tubing sizes have a comparable number of pulled tube intersections, although the 7/8 inch tubing has more tube burst data. The 3/4 inch pulled tube data cover a much wider voltage range than the 7/8 inch data . In addition, there is a much larger leak rate database for 3/4 inch tubing. None of the pulled tubes have been reported as leakers during plant operation. The field eddy current data for all pulled tubes were reviewed for voltage normalization consistent with the standard adopted (see Section 3.1) for the plugging criteria development.

Table 4-2 summarizes the available information on three suspected tube leaks (3/4 inch tubing) attributable to ODSCC at TSPs in operating steam generators. These leakers occurred in European plants, with two of the suspected leakers occurring at one plant in the same operating cycle. In the latter case, (Plant E-4), five tubes including the two with indications at TSPs were suspected of contributing to the operating leakage. Leakage for the two indications at TSPs was obtained by a fluorescein leak test as no dripping was detected at secondary side pressure. For the Plant B-1 leakage indication, other tubes also contributed to the approximately total leak rate. Helium leak tests identified other tubes leaking due to PWSCC indications. Using relative helium leak rates as a guide, it was judged that the leak rate for the ODSCC indication was less than . These leakage events indicate that limited operating leakage can occur for indications above about

Evaluations of the 3/4 inch diameter, pulled tube burst and leak rate data are given in Sections 4.3 to 4.6. The results support ODSCC as the dominant degradation mechanism, although the indications were not burst tested and are too small for tube leakage considerations. The most extensive leak rate and burst test data for 3/4 inch diameter pulled tubes are from Plant R-1 and Plant E-4, as described in Sections 4.3 and 4.4. Plant S (Section 4.5) provides the largest pulled tube voltage indication at with burst and leak rate measurements.

4.2 Tensile Properties for Pulled Tube and Model Boiler Specimens

The 3/4 inch diameter model boiler specimens have above average tensile properties while the pulled tube data have both higher and lower tensile properties than average values. The tensile property differences between model boiler and pulled tube data are greater for 3/4 inch tubing than found for 7/8 inch tubing. The 3/4 inch model boiler tubing had above average material properties, while the 7/8 inch model boiler tubing had properties slightly below average. For both the 3/4 and 7/8 inch tubing ARC development, all model boiler and pulled tube burst pressure data are renormalized to approximate average tensile properties (for Sy+Su) for Westinghouse tubing as described in this section.

Tubing manufacturing data have been utilized to develop mean tensile properties together with the standard deviation and lower tolerance limit at room temperature and . These data are given in Table 4-3. Also given in the table are the values for (Sy + Su). An Sy+Su value of at room temperature is used to normalize the measured burst pressures for the model boiler and pulled tube data. The ratio of the Lower Tolerance Limit (LTL) flow stress at flow stress at room temperature is utilized to adjust the voltage/burst correlation obtained at room temperature to obtain the operating temperature LTL correlation.

Table 4-3 also includes the tensile properties for the 3/4 inch model boiler specimens and for each of the available pulled tubes. Since burst pressures are proportional to the flow stress, the measured burst pressures are normalized to approximate mean properties by the ratio of the tubing mean (Sy + Su) of (flow stress of) at room temperature to the tube specific (Sy + Su) given in Table 4-3.

4.3 Evaluation of Plant R-1 Pulled Tubes

This paragraph describes the evaluation of Plant R-1 tubes pulled in 1992 and in 1991. The burst and leak rate measurements are evaluated and summarized below.

4.3.1 Tubes Pulled from Plant R-1 in 1992

Three tubes with six intersections were pulled from Plant R-1 in 1992. All intersections were burst tested at room temperature and leak tested at operating conditions as described in this paragraph. Destructive examination morphologies and an evaluation of the R7C71, TSP 3 burst test are given in paragraph 2.2. Bobbin coil voltages were measured using the ARC normalization at and ASME standards were cross calibrated to the reference laboratory standard. The field and laboratory re-evaluation of the field NDE data are given in Table 4-4. The bobbin voltages between both evaluations are in good agreement except for R9C91, TSP 2 for which the re-evaluation is about higher. The field and laboratory bobbin evaluations for this indication are shown in Figure 4-1. The laboratory evaluation is based on maximum peak to peak voltage utilizing guidelines for ARC voltage analysis. The field evaluation utilized the maximum depth flaw indication for the voltage, which results in a somewhat smaller voltage. For consistency with the overall ARC database, the laboratory re-evaluations of the field data are used for the voltage amplitudes. The cross calibration corrections were applied to the evaluated data to obtain the final voltages as given in Table 4-4.

Table 4-4 summarizes the 1992 pulled tube data. Burst pressures were obtained for 5 intersections. As described in paragraph 2.2, the burst pressure for TSP 3 of R7C71 was not reliably obtained due to a malfunction of the pressure recorder during the burst test. All six intersections were leak tested at operating temperature conditions and the two intersections of R9C91 were found to have small leaks at SLB conditions. The 3rd TSP intersection had a very small leak rate. The only throughwall corrosion found through extensive destructive examination of this intersection had a throughwall length which had opened to about following leak and burst testing. This indication had a bobbin voltage of and represents the lowest voltage found to date for a throughwall crack, as well as the lowest voltage indication with measurable leakage, although the leak rate is negligibly small.

The laboratory bobbin data show that R9C76 at TSP 3 and R9C91 at TSPs 2 and 3 had post-pull voltages a factor of higher than pre-pull voltages. The tube spans between TSP 2 and TSP 3 of R9C76 and between TSP 1 and TSP 2 of R9C91 had significant (, respectively) tube elongation resulting from tube pulling operations. The tube pull report shows the highest pull force of occurred as the second TSP intersection of R9C91 entered the secondary face of the tubesheet. A maximum pull force of was applied to the other tubes. These results support an expectation that the increases in post-pull voltages are a consequence of damage (ligament tearing) from the tube pulling operations. Ligament tearing would likely have the greatest influence on measured leak rates at normal operating conditions. Influence on SLB leakage is also possible but less conclusive since the related ligament tearing could have occurred at the SLB pressure differentials. For R9C76 with measurable SLB leakage, throughwall corrosion was found by destructive examination and the leak rates are included in the database, although tube pulling damage may have influenced the leak rates.

The crack morphology was found to be principally axial ODSCC with some local patches of cellular corrosion. Based on progressive radial (into tube wall) grinding, the cellular corrosion was found to about depth, with deeper penetrations showing only axial cracks. This pattern of partial depth cellular cracking with deeper axial cracks has been found at all cellular indications examined by radial metallography, including the Plant E-4 indications with greater cellular involvement. All indications were located entirely within the TSP intersections.

4.3.2 Tubes Pulled from Plant R-1 in 1991

Five tubes were pulled in 1991 and earlier, with 9 TSP intersections destructively examined. An assessment of the burst and leak rate measurements is given in paragraph 2.2. Upon review by the EPRI ARC Committee, it was concluded that the data should not be included in the burst database and the R5C112, TSP intersection should not be included in the leak rate data. The burst tests resulted in incomplete burst tests and lower than expected values for undegraded tubes. No throughwall corrosion was found for R5C112, although leakage was found at and it is expected that damage during tube pulling operations resulted in throughwall penetration. The NDE and destructive exam data are summarized in this paragraph for use in probability of leakage assessments and overall data summaries.

Tubes which were pulled from Plant R-1 steam generators in 1991 and in earlier inspections were field examined using the mix with the bobbin probe, calibrated on the basis of a carbon steel support simulator (ring) on an ASME standard tube yielding at To include this information in the 3/4 inch tubing database, the field EC data were re-calibrated to the ARC normalization for the hole on the ASME standard.

In addition, the post-pull data on Plant R-1 tubes were used to develop renormalization ratios from the field to the ARC normalization. Post-pull laboratory data were obtained for mix with the ARC normalization at The post-pull voltages are much higher than pre-pull voltages and thus are not used to support the ARC development. However, the post-pull data were used to develop the conversion factors for renormalizing the field data to the normalization when both evaluations are independently normalized to for the ASME hole as given in Section 3.2 and Figure 3-3. The pre-pull Plant R-1 voltages were converted to the ARC normalization using Figure 3-3.

For this voltage normalization, the standard TSP volts at were also obtained to permit adjustment of the field data to a normalization of for the mix. Division of these TSP voltage measurements by the field normalization of yields the voltage adjustment factor for obtaining the ASME hole normalization (for mix). This adjustment factor is applied to the field evaluation with TSP normalization as shown in the field evaluation columns of Table 4-5 to obtain the field voltages for the mix normalized to for the ASME hole. The Westinghouse evaluation for the mix is also shown in Table 4-5. The agreement is generally better than between the field and Westinghouse evaluations.

The voltage renormalization factors of Figure 3-3 were then applied to the pre-pull voltages of Table 4-5 to obtain the ARC normalization voltages also given in Table 4-5. The Westinghouse evaluated voltages are used for the ARC development although differences from the field evaluation are small.

Also shown in Table 4-5 are the Westinghouse evaluated RPC voltages based on evaluation of the available field data at with normalization to for a long EDM notch. The field RPC voltages were normalized to for the ASME holes and are not directly comparable to the ARC voltages normalization.

Table 4-4 summarizes the Plant R-1, 1991 pulled tube results. Four of the intersections had increases in bobbin voltages by a factor of between pre-pull and post-pull inspections. None of the intersections had throughwall corrosion. Eight of the nine intersections showed no leakage during room temperature pressurization tests, which is consistent with the maximum corrosion depths ranging from insignificant to depth. The crack morphology was found to be multiple axial ODSCC with negligible volumetric IGA involvement. The destructive exam did not include radial metallography to examine for potential patches of cellular corrosion. All indications were entirely within the TSP intersection and nearly centered within the TSP.

4.4 Evaluation of Plant E-4 Pulled Tube Data

Recent (1992, 1993) tube pulls from Plant E-4 provide a major contribution to the 3/4 inch tubing burst pressure and leak rate data base. Burst and/or leak rate data were obtained for 17 tubes and 25 TSP intersections with bobbin indications. NDE data for 10 of the intersections on 6 tubes were obtained at the ARC voltage normalization. The eddy current data were obtained to the Belgian and ARC voltage normalizations to provide the basis, as described in paragraph 3.2, to convert prior and future Belgian data to the ARC data base. The results of cross calibration of Belgian (EDM holes) and domestic (drilled holes) ASME calibration standards are discussed in paragraph 3.2.

For five of the 1992 pulled tubes leak and/or burst tested, the Plant E-4 eddy current data were collected for the ARC voltage normalization as well as the Belgian normalization. For the ARC data, both Zetec and Belgian equipment were used to obtain the data. In addition, the Belgian ASME calibration standards were cross-calibrated to the reference laboratory standard, which resulted in a factor on the Belgian data as described in Section 3.2. Table 4-6 summarizes the NDE results for the five pulled tubes. The bobbin data were evaluated by both Laborelec and Westinghouse with the results shown in the table. Voltages between the two evaluations are in excellent agreement. The last column of Table 4-6 shows the ARC voltages for these indications, which include the factor for cross-calibration of ASME standards. As given in Section 3.2, the more complete Laborelec field measurements obtaining ARC and Belgian voltage normalizations were used to obtain the correlation of Figure 3-2 for renormalizing the Belgian voltages to the ARC mix and ASME hole calibration. This correlation has been applied to obtain the ARC voltages for Belgian pulled tubes, except for the six tubes in Table 4-6.

Leak rate and burst test measurements were performed on the Plant E-4 pulled tubes as summarized in Table 4-7. These data include free span burst and leak rate measurements for bobbin voltages up to , and provide an extensive pulled tube database over a wide voltage range.The Plant E-4 burst tests were performed with a plastic bladder and no foil reinforcement. The burst test results showed tearing, except for tube R26C47, and are considered to require no adjustments to burst pressures other than the adjustment for material properties. Tube R26C47 is included as a minimum burst pressure since no tearing occurred.

The leak rate measurements are also given in Table 4-7. This table includes tubes R19C35 and R26C47, which had been previously (1991) pulled and examined. Leak rates were measured at room temperature. The Plant E-4 leak rate measurements were made at room temperature at and for normal operating and SLB differential pressures, respectively. Laborelec has defined an analytical procedure using measured leak rate dependence on pressure differentials to adjust the room temperature test results to prototypic temperatures and pressure differentials. The adjustment procedure is described in Appendix B and confirmed against more detailed crack models (in the computer code named CRACKFLO). The adjustment procedure is applied to the measured leak rates given in Table 4-7 (various ΔPs) to obtain the adjusted leak rates given in Appendix B and Section 6.2.

The Plant E-4 pulled tubes have been found to have axial ODSCC and cellular SCC crack morphologies. The cellular morphology involves larger areas than found for the Plant R-1 pulled tubes. Similar to the Plant R-1 morphology, the cellular SCC depth is limited; deep or throughwall indications have axial orientation.

4.5 Evaluation of Plant S Pulled Tube Data

Three tubes with flow distribution baffle (FDB) intersections were pulled from Plant S in 1993. These indications are the three largest voltage indications removed from domestic plants and the indication is the largest pulled tube voltage in the 3/4 inch tubing ARC database. The pulled tube results are given in Table 4-8.

Bobbin voltages from the field and laboratory re-evaluation of the field data are in good agreement. The voltages include cross-calibration of the field ASME standard to the reference laboratory standard.

The leak rates for R33C20 and R42C43 were measured at three pressure differentials above . The three measurements are used in Appendix B to interpolate or extrapolate the leak rates to reference pressure differentials for which the values at are given in Table 4-8. As noted in Section 2, the leakage for R28C41 exceeded the capability of the facility and the SLB leak rates are not reliable; hence, the data can only be used in the probability of leakage correlation. The measurements for R33C20 and R42C43 were obtained in a new, large capacity facility and are valid measurements. Tube R42C43 has two significant throughwall cracks contributing to the leak rate.

The burst test for R28C41 did not result in crack tearing and the opened crack length was less than the macrocrack length as discussed in Section 2. The burst pressure does not represent a complete burst and the test data are not reliable. The burst tests for R42C43 and R33C20 are considered to be reliable measurements as described in Section 2.

The crack morphologics for R42C43 and R28C41 have significant cellular corrosion, to depths of respectively, in association with the deeper SCC indications. Only a small ICC patch was found on R33C20, which had a single dominant axial indication.

4.6 Evaluation of Plant B Pulled Tubes

Bobbin and destructive examination data are available from four tubes and 17 pulled tube intersections from Plant B Units 1 and 2 as given in Table 4-9. However, only the 5th TSP intersection of Unit 1 tube R4C61 was burst tested. The bobbin data were obtained at a mix normalized to for the mix at the ASME hole. The mix is sufficiently close to the mix of the ARC normalization such that no voltage adjustment is necessary. The pre-pull field bobbin voltage for this indication was and the maximum depth was The post-pull bobbin data was and depth.

Tube R4C61 at the 5th TSP was burst tested with no bladder and inside a TSP simulant (diametral gap). No leakage was detected (by loss of pressure) until the crack opened to a large leak rate and loss of pressure at . The initial crack was found by destructive exam to be long with a long throughwall penetration. Given the throughwall penetration and that leak rates were not measured with significant accuracy, this indication is not used in the ARC leak rate database. The post-burst crack had minor opening of the crack faces, with negligible tearing at the edges of the crack. The maximum change in tube diameter as a result of the burst test was OD or about , which is less than the diametral clearance in the simulated TSP. Thus, there is no apparent influence of the TSP on the leak/burst test such that the data point can be used as a lower bound to the burst pressure.

No metallography was performed on the axial indications at the 5th TSP. A mapping of the OD indications was obtained visually following the burst test. The axial indications are typical ODSCC with negligible IGA involvement. Short circumferential branch indications show more IGA involvement at the faces of the cracks. The largest axial macrocrack was examined by SEM fractography and found to be long with throughwall penetration. The crack was nearly throughwall for a length. individual microcracks comprising the macrocrack had mostly grown together by corrosion with only partially uncorroded ligaments remaining. The maximum depth in the circumferential branching cracks was throughwall.

The other Plant B pulled tube data given in Table 4-9 are used only in the probability of leak correlation. All bobbin voltages given in the table are based on re-evaluation of the field data tapes to the ARC guidelines.

4.7 Evaluations of Plant C Pulled Tubes

Bobbin voltages and destructive examination data are available from two tubes and four intersections from Plant C-2 as summarized in Table 4-10. None of the indications were burst or leak tested. Bobbin voltages are based on re-evaluation of the field data tapes to ARC guidelines. Crack morphologies were typical of ODSCC with minor IGA involvement. These data are used only in the ARC probability of leakage correlation.

4.8 Summary of Pulled Tube Test Results

Based on the above evaluations, the 3/4 inch diameter pulled tube data for application in tube burst and leak rate correlations is summarized in Table 4-11. The Plant R-1 data includes 5 burst values and 5 SLB leak rate values (two with leakage). The Belgian Plant E-4 data provides 22 burst data points and 17 SLB leak rate data points (11 points with leakage). Leak rates and burst pressures given in Table 4-11 are as measured and do not include any adjustments to reference pressure differentials or tensile properties. Bobbin voltages for ARC applications are based on laboratory re-evaluation of the field eddy current tapes. Data not considered reliable based on the evaluations of Sections 4.3 to 4.7 are indicated as NR (not reliable) in Table 4-11 and are not included in the burst or leak rate correlations, but are included in the probability of leak correlation when leakage is known to be zero or greater than zero. Table 4-11 does not include all data for the probability of leakage correlation. Additional data for leakage probability are given in Tables 4-4 to 4-11 for indications having leakage inferred from the crack morphology.

The overall pulled tube database having bobbin voltages and destructive examination depths for 3/4 inch tubing is shown in Figure 4-2. The data indicated a broad trend for voltage to increase with depth. The smallest voltage found for a throughwall crack in the current 3/4 inch diameter data is

Table 4-1

Number of Pulled Tubes with NDE and Destructive Exam Data

Table 4-2

Field Experience: Suspected Tube Leakage (3/4" Tubing) for ODSCC at TSPs[1]

Table 4-3

Tensile Strength Properties for 3/4 Inch Diameter Tubing

Table 4-3

Tensile Strength Properties for 3/4 Inch Diameter Tubing

Table 4-4
Plant R-1 Pulled Tube Results

Table 4-5

Field and Westinghouse Evaluations of Plant R-1 1991 Pre-pull Voltages

Table 4-6

Belgian and Westinghouse Evaluations of Plant E-4 Eddy Current Data

Table 4-7
Plant E-4 Pulled Tube Results

Table 4-7 (Continuation)

Plant E-4 Pulled Tube Results

Notes:

1. Belgian measurements and voltage normalization.
2. ARC voltage normalization and U. S. equipment with data evaluated by Westinghouse (negligible differences from Laborelec analysis) except as noted by note 3. Voltages include cross-calibration of Belgian ASME standards to reference laboratory standards as discussed in Section 3.2.
3. ARC voltage normalization obtained from Belgian measurements using correlation given in Section 3.2.
4. Total length of crack in inches, with throughwall crack length given in parentheses.
5. Leak rate tests performed for free span at room temperature and various pressures as given in Appendix B.
6. Burst tests performed with TSP constraint and not used in ARC correlations.
7. Indication was NDD by analysis. Voltage obtained from per note 3.

Table 4-8

Plant S Pulled Tube Results

Table 4-9

Plant B Pulled Tube Results

Table 4-10

Plant C-2 Pulled Tube Results

Table 4-11

3/4-Inch Diameter Pulled Tube Leak Rate and Burst Pressure Measurements

Table 4-11 (Continuation)
3/4-Inch Diameter Pulled Tube Leak Rate and Burst Pressure Measurements

Figure 4-1. Field and Laboratory Bobbin Coil Evaluations for R9C91, TSP 2

Figure 4-2: Bobbin Coil Voltage vs. Maximum Examination Depth

3/4" Pulled Tubes Data, Destructive Examination

5.0 LABORATORY SPECIMEN PREPARATION AND TESTING

5.1 Preparation of Specimens

Cracked tube specimens were produced in the Westinghouse Single Tube Model Boiler test facility. The facilities, environments and test procedures used for the preparation of 7/8 inch diameter specimens (described in Volume 1 of this report) were also utilized for the 3/4 inch diameter model boiler specimens. The only difference between the 7/8 and 3/4 inch programs was an increased emphasis on obtaining lower voltage specimens by performing interim (prior to any leakage) eddy current inspections to remove the non-leaking indications and to shut the facility down upon the first indication of detectable leakage.

The model boiler facility consisted of thirteen pressure vessels in which a forced flow primary system transferred heat to a natural circulation secondary system. Appropriate test specimens were placed around a single heat transfer tube to simulate steam generator tube support plates. The tests were conducted in two boiler configurations, shown schematically in Figures 5-1 and 5-2. The majority of the tests were conducted in the vertically oriented boilers shown in Figure 5-1, in which four support plates were typically mounted on the tube. A few tests were conducted in horizontally mounted boilers, shown in Figure 5-2. Because there was no steam space in the horizontal boilers, seven support plates could be mounted on the heat transfer tube. Since capillary forces, rather than gravity forces, dictate the flow pattern in packed tube support plate crevices, the tube orientation should have little effect on the kinetics of the corrosion processes.

The thermal-hydraulic specifications utilized in the test are presented in Table 5-1. As indicated, the temperatures are representative of those found in PWR steam generators, and the heat flux is typical of that found on the hot leg side of the steam generator. The tests utilized 3/4 inch O.D. mill annealed alloy 600 tubing from heat NX7368. The tubing was manufactured by the Plymouth Tubing Co. to Westinghouse specifications. The chemical and physical properties of the tubing are presented in Table 5-2.

The cracks were produced in what is termed the reference cracking chemistry, consisting of either or sodium as sodium carbonate in the makeup tank. Typically a test was initiated with the chemistry, and if a through wall leak was not identified after of operation, the chemistry was applied. The occurrence of primary to secondary leakage was determined by monitoring the boilers for lithium, which would ordinarily only be present in the primary system. Because of hideout in the crevices, the boiler sodium concentration was typically between of the makeup tank concentration. Hydrazine and ammonia were also added to the makeup tanks for oxygen and pH control, respectively.

A summary of the test pieces which were subsequently leak and burst tested is presented in Table 5-3. Two groups of tests are listed; the EPRI test pieces were prepared under this program, while the Spanish test pieces were fabricated for a group of Spanish utilities. The only difference between the two groups of tests is that the crevices were packed with different sludge formulations. As in most previous model boiler test programs, the EPRI tests used what is termed simulated plant sludge while the Spanish tests used a formulation more representative of that typically found in steam generators in Spanish plants. As indicated in Table 5-4, the only difference between the two formulations is that magnetite has replaced the metallic copper content in the simulated plant sludge.

As outlined in Table 5-3, three means of packing the tube support plate crevices were utilized. In the fritted configuration, loose sludge was vibratorily packed into the crevice and then held in place with alloy 600 porous frits placed over both ends of the crevice. In this configuration, cracks were typically produced near the interface between the sludge and the frits. In some cases, multiple cracks were produced at both ends of the crevice.

The dual consolidated configuration consisted of two sludge regions, in which the outer region contained chromic oxide, while the inner region contained either simulated plant or Spanish sludge. The regions had the following dimensions, with the distances given in millimeters:

The two-region sludge configuration was specified in order to limit cracking to the small inner region, containing an oxidizing sludge. Chromic oxide is nonoxidizing, and previous testing had found that accelerated corrosion is less likely to occur in its presence. The outer region provided thermal insulation for the inner region, so that the temperature in the inner region was sufficiently high to produce accelerated corrosion. The two sludge regions were baked onto the tube using a mixture consisting of sodium hydroxide, sodium sulfate, and sodium silicate. The support plates were then mounted on the tube over the sludge and held in place with externally mounted set screws. Since corrosion should be confined to the inner region, this configuration was intended to produce short, individual cracks.

The mechanically consolidated sludge configuration was fabricated by mechanically compacting sludge within a tube support plate simulant, drilling a hole in the sludge for the tube, and then sliding the tube through the hole until positioned properly. This configuration was used because relatively low voltage indications had been produced in previous tests using this configuration.

As indicated in Table 5-3, there was considerable variation in the time taken for a crack to be produced in a given test piece. In general, cracking was produced in shorter time spans with this heat of material (NX7368) than for the heats used in similar tests performed with 7/8 inch diameter tubes. Cracks were typically produced most rapidly with the fritted configuration and most slowly with the dual consolidated configuration, although a few cracks were produced very quickly with the dual consolidated configuration. Details of crack networks produced in the model boiler specimens are presented in Appendix A.

5.2 Non-destructive Examination (NDE) Results

The model boiler specimens were eddy current tested in the laboratory using both the bobbin coil probe and the RPC probe. The bobbin coil voltages were measured in accordance with the analysis guidelines used for the EPRI ARC program. Most of the bobbin measurements were obtained using a diameter Zetec probe; some specimens were also tested with an Echoram probe. In the case of the 3/4 inch diameter tubing, the bobbin coil results reported here are for the mix frequency. The reference calibration was performed with the holes in the ASME standard set to in the differential mix channel. The RPC test results are for the frequency with the voltage normalization of for the long through-wall EDM (electric discharge machining) slot in the ASME calibration standard. Table 5-5 presents a summary of the NDE data for the model boiler specimens. All eddy current measurements were obtained as received from the model boilers with the TSPs and packed crevices present on the tube.

5.3 Leak Rate Testing

The objective of the leak rate tests is to determine the relationship between eddy current characteristics and the leak rates of tubes with stress corrosion cracks. Leak rates at normal operating pressure differentials and under steam line break conditions are both of interest, since leakage limits are imposed under both circumstances. The SLB leak rate data are used to develop a formulation between leak rate and bobbin coil voltage.

Crevice condition is an important factor. Tightly packed or dented crevices are expected to significantly impede leakage through cracked tubes. Since denting is readily detectable by non-destructive means while crevice gaps cannot be readily assessed, the emphasis is placed upon open crevices and dented crevices as the limiting cases. All leak rate testing with 3/4 inch diameter tubing was performed with open crevices. Leak testing of 7/8 inch diameter tubing with denting is discussed in Volume 1 of this report.

Leak testing of cracked tubes is accomplished as follows. The ends of the tube are plug welded. One end has a fitting for a supply of lithiated (Li), borated (B) and hydrogenated ( ) water to the tube inner diameter. The specimen is placed in an autoclave and brought to a temperature of and a pressure of . The pressure on the outer diameter is brought to to obtain a normal operating pressure of . A back pressure regulator on the secondary side maintains the pressure. Any leakage from the primary side of the tube tends to increase the secondary pressure because of the superheated conditions. The back pressure regulator then opens, the fluid is released, condensed, collected and measured as a function of time. This provides the measured leak rate. The cooling coil is located prior to the back pressure regulator to prevent overheating and to provide good pressure control. Typical leakage duration is one hour unless leak rate is excessive and overheating of the back pressure regulator occurs. Pressure is controlled on the primary side of the tube by continuous pumping against another back pressure regulator set at . The bypass fluid from this regulator is returned to the makeup tank.

To simulate steam line break conditions, the primary pressure is increased to by a simple adjustment of the back pressure regulator and secondary side is vented within one to three minutes to a pressure of . The pressure differential across the tube is thus psi. Temperature fluctuations settle out in several minutes and the leakage test period lasts for approximately .

A summary of leak test results is provided in Table 5-6. Leak rates at normal operating pressure differential and at steam line break conditions were obtained for all specimens. The steam line break conditions increased the leak rates by about a factor of ten compared to normal operating conditions. However, there was significant variation in this ratio from specimen to specimen with larger leak rates tending toward a ratio of about It is believed that the larger ratios are due to breaks in ligaments between microcracks at increased pressure differential. Hence large variation in this factor was expected. Prolonged leak rate testing under operating conditions is expected to lead to lower rates for small leak rates. The increase in the leak rate upon transition to accident conditions then becomes more variable.

5.4 Burst Testing

Given the assumption that significant support plate displacements cannot be excluded under accident conditions, burst tests of tubes with stress corrosion cracks are conducted in the free span condition.

Burst tests were conducted using an air driven differential piston water pump at room temperature. Pressures were increased at a rate of about for the burst tests. Pressure was recorded as a function of time on an X-Y plotter. Sealing was accomplished by use of a soft plastic bladder. Burst tests of tubes with stress corrosion cracks were done in the free span condition. No foil reenforcement of the sealing bladders was used since the crack location which was to dominate the burst behavior was not always readily apparent. Some of the maximum openings developed during burst testing were not sufficient to cause extensive crack tearing and thus represent lower bounds to the burst pressures. The openings were large enough in all cases to lead to large leakage. Burst test results are summarized in Table 5-6.

5.5 Destructive Examination

Destructive examinations of the model boiler specimens were performed to characterize the size, shape, and morphology of the specimens which were leak rate and burst tested. The crack morphology was also compared generally to the corrosion morphology observed in tubes pulled from operating power plant steam generators. A summary of the available results for 3/4 inch OD specimens is presented in Appendix A. The throughwall crack lengths are used in Section 7 to aid in assessments of the threshold voltage for SLB leakage, development of a correlation of bobbin voltage to throughwall crack length, and an estimated correlation of voltage with leak rate utilizing analytical relations of leak rate with throughwall crack length.

5.6 Review of Model Boiler Data for Acceptability

Based on potential "outlier" behavior in the burst and leak rate correlations, specimen voltage, leak rate and burst test data were reviewed to assess acceptability of the measurements. The results of the review of potential "outliers" are described below.

Specimen 591-3 Bobbin Voltage. Specimen 591-3 had the simulated TSP supported by a Teflon spacer in the model boiler preparation of the specimen. In some cases with this type of TSP support, cracking has been found in the Teflon spacer and/or the simulated TSP. Figure 5-3 shows the RPC trace for this specimen. A total of indications can be seen with of the indications extending below the bottom of the TSP. Attempts were made to separate the bobbin voltages for the indications within the TSP from the indications below the TSP .

However, it is doubtful that the peak to peak bobbin voltage for the indications within the TSP does not include some response from the indications below the TSP. Therefore, the bobbin voltage for this indication should not be included in the database. Since the individual indications are apparently resolved by RPC, it is expected that the RPC voltage is reasonable.

Specimen 598-1 Bobbin Voltage. Specimen 598-1 has a bobbin amplitude of and is the only model boiler specimen . Figure 5-4 shows the RPC trace for this specimen. The high bobbin voltage results from the large crack indications which individually have RPC voltages of . Integration of the indications by the bobbin coil results in the large bobbin amplitude.

This type of indication is not prototypic of field indications. Unlike the 7/8" model boiler data for which 10 specimens have been prepared in model boilers, specimen 598-1 is a single data point for 3/4" tubing. Since the indication appears to be non-prototypic and the single high voltage data point could unjustifiably influence correlations with voltage, the bobbin voltage should not be used in correlations. RPC voltages should be reasonable.

Specimen 598-3 Leak Rates. By destructive examination, specimen 598-3 was found to have a . throughwall crack. However, there was no measured leakage at normal operating pressure differentials and only at SLB pressure differentials of psi. A throughwall crack of would be expected to leak on the order of at SLB test conditions as found for other specimens (590-3, 600-1, 601-4). It is therefore concluded that the crack became plugged by deposits or a measurement error was made. Thus the leakage data is considered not reliable and is not included in the database for correlations.

Specimen 604-2 Leak Rate. Specimen 604-2 has a bobbin voltage of , a total crack length of , with a throughwall length of and a SLB leak rate of with no operating leakage. This specimen is a potential low leak rate outlier in the SLB leak rate correlation. This indication had no remaining uncorroded ligaments such that the leak rate is unexpectedly low for a throughwall crack. However, no problems were identified with the leak rate measurement. The throughwall length is on the border between no leakage, such as 595-2 with a throughwall length of , and significant leakage such as 591-1 with a throughwall length of . Thus there is not a sufficient basis to exclude the measured leak rate from the database. The bobbin voltage is associated with dominantly a single axial crack and is consistent with expected values for the throughwall crack length. Consequently, this specimen is retained in the data base for the leak rate correlation.

Specimen 600-3 Bobbin Voltage and Leak Rate. Specimen 600-3 has a bobbin voltage of with a measured leak rate of and represents a high leakage potential outlier in the leak rate correlation. This indication has a throughwall crack length of . The RPC voltage was and represents the only specimen having an RPC voltage larger than the bobbin voltage. Multiple bobbin voltage measurements were made due to the unexpectedly low bobbin voltage compared to the RPC volts, but no significant differences were found between the repeat measurements. Since the leak rate is consistent with the throughwall crack length, the low bobbin voltage is the principal contributor to the high outlier behavior. This specimen tends to be low on the burst pressure correlation, which is also consistent with an unexpectedly low voltage. The voltage is very low for a throughwall crack (see voltage/length correlation of Section 7). The voltage is dominated by a single RPC indication. The destructive examination indicated that uncorroded ligaments remained in the burst crack face, which is unusual for a crack with the given throughwall length and voltage. It is expected that the remaining ligaments caused a significant reduction in the bobbin voltage. To obtain the measured leak rates, the uncorreded ligaments must have torn during the leak testing. This specimen was prepared in the model boiler with a pressure differential of about . The pressure differential for the normal operation leak rate test was . Based on the associated leak rate of , it is expected that some ligaments had already torn at . If the specimen had been developed in the model boiler at a typical S/G differential pressure of about , it is likely that more ligaments would have corroded or torn and the post-model boiler voltage would have been higher.

In summary, the low bobbin voltage is attributable to remaining uncorroded ligaments which tore during the leak tests to result in high leak rates for the associated voltage and high outlier behavior in the leak rate correlation. This behavior, while a low probability combination, is the anticipated cause of outlier behavior in the leakage and burst correlations. Thus there is no basis to exclude this specimen from the ARC database.

Specimen 601-6 Bobbin Voltage and Burst Pressure. Specimen 601-6 had a bobbin voltage of , a throughwall length of , a SLB leak rate of and a low burst pressure of . The specimen would be a potential outlier for the burst correlation. The RPC response for this indication is shown in Figure 5-5. The single crack response is seen to have a low voltage dip at about the middle of the crack. From destructive examination, it was found that the dip was associated with a relatively thick uncorroded ligament which separated two throughwall cracks with no other uncorroded ligaments. It is expected that the single remaining ligament reduced the bobbin voltage but tore during the leak and burst tests and did not add significantly to the burst pressure. This is the only specimen found in both the 3/4 and 7/8 inch model boiler programs to have a single ligament separating throughwall cracks. This type of crack morphology can be expected to result in outlier behavior in the leak and burst correlation while representing a low probability occurrence as found in the model boiler test program. Thus this specimen provides appropriate outlier behavior in the correlations and is retained in the ARC database.

Based on the above assessments for potential outlier behavior, the bobbin voltages for 591-3 and 598-1 and the SLB leak rate for 598-3 are unacceptable data and are excluded from the ARC database. Specimens 600-3 and 601-6 have crack morphologies expected to result in outlier behavior and are retained in the database. Specimen 604-2 is also retained in the database.

5.7 Model Boiler Data Base Summary

As described in the above subsections, model boiler specimens have been fabricated and tested to augment the pulled tube database at support plate intersections. Forty-seven (47) laboratory specimens have been prepared using 3/4 inch OD tubing. The specimens were subjected to eddy current examination. Degradation at simulated tube support plate intersections have ranged from NDD to [illegible] in bobbin coil amplitude. All of these specimens have been burst tested, with the results displayed in Table 5-6. Specimens with significant degradation (41) have also been leak tested. Further, many of the samples were destructively examined to determine degradation characteristics and crack morphology. The available maximum and through wall crack length data obtained for many of these specimens from the destructive examinations are listed in Table 5-6. The model boiler database is combined with the pulled tube database and the combined database used for determining burst and leak rate correlations as described in Sections 6 and 7.

Table 5-1

Model Boiler Thermal and Hydraulic Specifications

Table 5-2

Chemical and Physical Properties of Tubing Material (NX7368)

Table 5-3

Model Boiler Test Specimen Summary
3/4" Diameter Tubing

Table 5-3 (Continued)

Model Boiler Test Specimen Summary
3/4" Diameter Tubing

Table 5-4

Composition of Sludge Used for Crevice Packing

Table 5-5

Laboratory Specimen NDE Summary

Table 5-5

Laboratory Specimen NDE Summary

Table 5-5

Laboratory Specimen NDE Summary

Table 5-5

Laboratory Specimen NDE Summary

Table 5-6
Leak Rate & Burst Test Results for 3/4 Inch OD Laboratory Specimens

Table 5-6
Leak Rate & Burst Test Results for 3/4 Inch OD Laboratory Specimens

Figure 5 - 1. Schematic of Vertically Mounted Single Tube Model Boiler

Figure 5 - 2. Schematic of Horizontally Mounted Single Tube Model Boiler

Figure 5-3. RPC trace for Specimen 591-3.

Figure 5-4 RPC trace for Specimen 598-1.

Figure 5-5. Rotating Pancake Coil Response of Sample 601-6.

6.0 BURST PRESSURE CORRELATION

6.1 Introduction

This section utilizes the model boiler (Section 5) and pulled tube (Section 4) data to develop a correlation of burst pressure versus bobbin voltage. Similar to Revision 1 of Volume 1 of this report (for 7/8 inch diameter tubing), a systematic methodology has been applied for the development of the burst (and leak rate) correlation. A thorough statistical procedure was implemented as described below. All normalization of eddy current data has been reviewed in detail and resolved by the EPRI ARC Committee. The 1991 pulled tube data from Plant R-1[1] were not included due to the large uncertainty in the burst test results, as discussed in Section 2. However, the 1992 pulled to be data from Plant R-1 are included. Thus the data, methodology, and correlation provided in this section provide a high degree of confidence in the results.

6.2 Data Base for Burst Pressure Correlation (3/4 Inch Tubing)

The database used for the development of the burst correlation (burst strength versus bobbin coil voltage amplitude) for 3/4 inch diameter tubing is derived from model boiler specimens and pulled tubes. All of the data were derived from Alloy 600 tubing with 3/4 inch OD and 0.043 inch nominal wall thickness. The model boiler test results for 3/4 inch tubing are described in detail in section 5. All reported bobbin coil measurements on model boiler specimens are for mix frequency with the holes in the reference ASME standard normalized to .

The pulled tube data included in the database are obtained from Plants R-1, E-4, S and B-1. The bobbin data from Plant E-4 pulled tubes were partially (8 of 22 burst data points) measured at mix with the ARC voltage normalization, and 14 indications were measured at using the Belgian NDE procedures. This data has been normalized to correspond to the ARC database. The principal adjustment to the direct field measurements resulted from cross-calibration of the Belgian ASME standard to the reference laboratory standard. Conversion of the Belgian data to the ARC mix is obtained from direct field measurements obtained with both voltage normalizations as described in Section 3.2. This process involved significant and detailed efforts by two independent parties (Laborelec and Westinghouse) and thorough review by the EPRI ARC Committee such that there is negligible uncertainty in the normalization procedure. The bobbin data from the 1992 pulled tubes from Plant R-1 and the Plant S pulled tubes were obtained using a procedure equivalent to that used for the model boiler database (field ASME standards were calibrated against the reference standard). The 1991 pulled tube data from Plant R-1 were not included due to the large uncertainty in the burst test results. The bobbin voltages from Plant B-1 were measured at a frequency mix essentially the same as the model boiler specimens.The pulled tube results are described in Paragraphs 4.3, 4.4, 4.5 and 4.6.

---

[1] Actual plant names are on file at EPRI.

The burst pressures of all the room temperature data are normalized to a reference flow stress of . This value is close to the mean flow stress for the mill annealed Alloy 600 tubing at room temperature. The resulting burst pressure database is summarized in Table 6-1 for both the model boiler specimens and the pulled tubes. The database includes 45 model boiler specimens and 30 pulled tube intersections.

6.3 Burst Pressure versus Voltage Correlation

The bobbin coil voltage amplitude and burst pressure data of Table 6-1 were used to determine a correlation between burst pressure and bobbin voltage amplitude. This is not to say that a "formal" functional relationship, in the sense of one variable being dependent on the other, exists between the variables since the burst pressure is not caused by the bobbin voltage and vice versa. The burst pressure and bobbin voltage variables considered are mainly functions of a third variable, i.e., the crack morphology. While the variation in crack morphologies is essentially infinite, suitable descriptions can be effected based on the depth, average depth, profile description, etc. However, the characterization of the morphology is not essential to this analysis since a relationship is being independently established between two offspring variables. Although the correlation analysis does not establish a causal relationship between the variables, it does, however, establish a "working" relationship that can be employed for the prediction of one variable from the other. The data considered are shown on Figure 6-1 along with the results of three correlation analyses which will be discussed in later paragraphs.

The analysis performed considered the scale factors for the coordinate system to be employed, i.e., logarithmic versus linear, the detection and treatment of outliers, the order of the regression equation, the potential for measurement errors in the variables, and the evaluation of the residuals following the development of a relation by least squares regression analysis.

In summary, it was concluded that the optimum linear, first order relation could be achieved by considering the burst pressure relative to the common logarithm (base 10) of the bobbin amplitude voltage. For this relationship it was determined that a bobbin voltage value of volt could be ascribed to the burst data where degradation was not detected, i.e., no detectable degradation (NDD). This is necessary to include NDD specimens in the database since the burst pressure should be a continuous function to the point of no existing degradation. A linear, first order equation relating the burst pressure to the logarithm of the bobbin amplitude was developed. The correlation coefficient from the regression analysis was found to be significant at a level. Analysis of the residuals from the regression analysis indicated that they are normally distributed, thus verifying the assumption of normality inherent in the use of least squares regression.

6.3.1 Selection of Coordinate System

In order to establish a correlation between the pairs of variables, but expected to have independent variances, the method of least squares (LS) curve fitting was employed.

The simplest functional form is a linear relationship of the type

(6.1)

where the variables x and y may be linear or logarithmic independently, and the coefficients of the relation, a_0 and a_1 are to be determined from the analysis. In addition, the choice of the regressor variable is not pre-determined. Both variables are assumed to be subject to random fluctuations which are normally distributed about the mean of the variable or the logarithm of the variable with a mean of zero and some unknown, but reasonable variance. It is also assumed that this variance is constant, or uniform, over the range of interest of the variables. In practice this may not be the case; however, any non-uniformity present would not be expected to significantly affect the analysis outcome.

Analyses were performed to determine the optimum nature of the variable scales, i.e., linear versus logarithmic, and the appropriate selection of the regressor variable. It was concluded that the most meaningful correlation could be achieved by considering the log of the voltage as the regressor and the burst pressure as the response. Thus, the functional form of the correlation is

(6.2)

where P_B is the burst pressure and V is the bobbin voltage amplitude. The basis for selection of the form of the variables was based on performing least squares regression analysis on each possible combination and examining the square of the correlation coefficient (the index of

Index of Determination, r^2, for Various Selections of Coordinate Scales		
	Pressure	Log(*Pressure*)
Volts		
Log(*Volts*)		

determination) for each case. The selection of the regressor variable does not affect the calculation of the index if the calculations are performed on the transformed data. The results of the calculations are shown above. Similar to the results found for 7/8" diameter tubes, Volume 1, the results clearly indicate an advantage of treating the voltage on a logarithmic scale.

It is noted that the data contain some results for specimens in which there was no detectable degradation (NDD) from the non-destructive examination. The inclusion of this data is necessary in order to predict burst pressures for indications with very low bobbin amplitudes. Two methods were considered for inclusion of the NDD data in the analysis. The first method consists simply of assigning a low bobbin voltage amplitude to the data. This was done for the determination of the best choice of scales for the coordinates of the plot. The value assigned was for the NDD specimens. The second method consists of modifying the prediction model to include a voltage offset variable to be determined from the data, i.e., the prediction equation becomes

(6.3)

where V_0 is the additional parameter to be determined from the data. V_0 represents a voltage offset at which the NDD data are included in the regression at V=0. Since the equation is now non-linear in the parameters, the application of least squares techniques is not appropriate. However, if an assumed value is assigned to the offset term, the equation is once again linear and least squares can be applied to find the values for the other two coefficients. Analysis was performed for a variety of offset values with the result that the index of determination was a maximum of . This is slightly greater than the value reported above for determining the best selection of the coordinate scales. Since the improvement is slight, it was concluded that the complication of including a voltage offset in the prediction model is not necessary to account for the NDD specimens. Additional analysis was performed to determine if a value less than would be appropriate for NDD specimens. It was found that the index of determination becomes a maximum, , if the NDD specimens are assigned a voltage level of . However, the improvement was significant only in the third decimal place. Since this level of amplitude was present in the data for a confirmed indication, it was judged to be inappropriate as an assigned value for NDD specimens. Likewise, reduction of the assigned value was considered inappropriate since it would reduce the fit of the regression burst curve artificially.

An additional consideration for the analysis of the data was to increase the order of the prediction equation. This would allow for the assignment of a lower value for the NDD specimens. Under this consideration the model would be

(6.4)

The regression analysis resulted in an index of determination of . This result is judged to be no significant improvement in the index of determination, and the introduction of a second order term provides no improvement in the model. This is consistent with the results found in Volume 1 for nominal 7/8" diameter tubes. Thus, a linear (first order) model was retained for the analysis.

6.3.2 Regression Analysis for the Identification of Outliers

The burst pressure data were analyzed to identify any potential outlying data points. The analysis was performed using the robust regression technique based on minimizing the median of the squares of the residuals. The method, known as the least median of squares method, is described in Appendix D of Volume 1.

The potential outlier analyses were performed in two steps. An initial evaluation was performed to identify potential outliers for further evaluation of the test data. This process led to the identification of unreliable and atypical data as described in the evaluations reported in Sections 4 and 5. After exclusion of the unreliable data from the database, the analysis for potential outliers was repeated. None of the data points used in the analysis were identified as potential outliers.

6.3.3 Error-in-Variables Analysis

A general assumption in performing a least squares regression analysis to establish a correlating relationship is that both of the variables, burst pressure and bobbin voltage in this case, are subject to random fluctuations about their respective mean values (or their respective log mean values). If there are significant uncertainties in the measurement of one or both of the variables the slope of the LS correlation line will be biased. A discussion of regression when errors are present in the independent variable is provided in Appendix D of Volume 1. In essence, the regression performed always underestimates the absolute value of the slope of the true relation, if one exists. A Wald-Bartlett type evaluation of the data was performed, and it was concluded that the presence of measurement error would not have a significant effect on the slope of the correlation line. It is noted that the Wald-Bartlett technique relies on being able to sort the data in the order of the real x variable. The application here is based on sorting on the observed, i.e., X, variable. Thus, the application is for the purposes of determining whether or not gross measurement errors are likely to be present, not for the determination of an improved estimate of the slope. The later analysis of the residuals demonstrates that the conventional regression curve is adequate for this evaluation.

Since the omission of correction for measurement error results in an under prediction of the magnitude of the slope of the correlation and the slope is negative, predicted burst pressures for voltages below the centroid of the data will be slightly less than predictions based on consideration of the measurement error. For voltage values greater than the centroid of the data the correlation slightly over predicts the burst pressure.

6.3.4 Burst Pressure Correlation for 3/4 Inch Diameter Tubing

The final fit of the data is shown in Figure 6-1. The correlation line is given by

(6.5)

where the burst pressure is measured in ksi and the bobbin amplitude is in volts. As noted in Paragraph 6.3.1, the index of determination for this regression was ; thus, the correlation coefficient is . The estimated standard deviation of the residuals, i.e., the error of the estimate, σ_p, of the burst pressure was . A one-sided simultaneous confidence bound, corresponding to a two-sided band, was calculated for the mean burst pressure,

(6.6)

where n is the total number of data points used, and is the F-distribution value corresponding to an upper tail area of . In addition, a one-sided prediction band for individual values of burst pressure, P_i, as a function of voltage was also calculated per the following equation:

(6.7)

where is the t-distribution value corresponding to an upper tail area of The lower prediction bound is also shown on Figure 6-1.

Since the burst tests were performed at room temperature (RT) conditions, the prediction bound was further reduced to a level corresponding to the lower tolerance limit (LTL) for the material properties of the tubes. This was done by multiplying the predicted burst pressure by the ratio of the LTL limit of flow stress at to the reference, or normalized, value of the RT flow stress used in the analysis. A second order fit of bobbin amplitude to differential pressure for the prediction curve as adjusted by the LTL material flow stress was performed for the purpose of determining lower bound voltage amplitudes as a function of the applied pressure differential.

(6.8)

Using this result the voltage amplitude corresponding to a differential pressure of would be , and the amplitude corresponding to a differential pressure of would be . The pressure differential corresponds to the structural limit of $1.43 \times \Delta P_{SLB}$ for ΔP_{SLB} = . The lower prediction bound for LTL material properties is also shown on Figure 6-1.

6.3.5 Analysis of Residuals

Verification of the regression analysis was performed based on testing the correlation coefficient for significance. For the analysis with degrees of freedom, a correlation coefficient in excess of would be significant at a level of . Given the calculated correlation coefficient of , it is very reasonable to accept the hypothesis that the burst pressure and bobbin amplitude are correlated. The ratio of the mean square regression to the mean square error was found to be . The random occurrence of an F-distribution value of this magnitude has a probability on the order of .

In order to verify conformance with the assumptions inherent in performing the LS analysis, the residual values were plotted against the predicted burst pressures. The results, shown on Figure 6-2, indicate acceptable scatter, i.e., nondescript, of the residuals about a mean of zero. Finally, a cumulative probability plot of the ordered residuals as described in Appendix D of Volume 1 was prepared. The results are shown on Figure 6-3. Since the data form an approximate straight line, the distribution of the residuals is normal. Outliers in the data would be expected to lie to the right of the cumulative probability line in the upper half of the plot, and to the left of the line in the lower half of the plot. The cumulative distribution of the residuals support the finding from the least median of squares analysis that the are no outliers in the data.

Table 6-1

Burst Pressure and Leak Rate Data Base for 3/4 Inch Tubing

Table 6-1
(continued)
Burst Pressure and Leak Rate Data Base for 3/4 Inch Tubing

Figure 6-1: Burst Pressure vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 6-2: Burst Pressure vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 6-3: Burst Pressure vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 6-4: Burst Pressure vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

This page
intentionally blank

7.0 SLB LEAK RATE CORRELATION

7.1 Introduction

This section utilizes the model boiler (Section 5) and pulled tube (Section 4) data to develop a correlation of steam line break (SLB) leak rate (primary to secondary leak rate under SLB conditions) vs. bobbin voltage. Consistent with Revision 1 of Volume 1 of this report (for 7/8 inch diameter tubing), significant progress has been made in the application of systematic methodology for the development of the leak rate (and burst) correlation. A thorough statistical procedure was implemented as described below. All normalization of eddy current data has been reviewed in detail and resolved by the EPRI ARC Committee. Data from non-leakers are not included in the leak rate correlation developed in Section 7.6. However, a separate correlation has been developed for probability of leakage using all availabile data from 3/4 inch tubing, as described below in Paragraph 7.4. Thus, the data, methodology, and correlations included in this section provide a high degree of confidence in the results.

The developed probability of leakage (Paragraph 7.4) as a function of voltage provides a statistically based estimate of the leakage threshold. Alternate leakage threshold assessments are given in Paragraph 7.3 to estimate a threshold for significant leakage. To assess trends expected for leak rate vs. voltage correlation, a combination of analytical calculations of leakage as a function of crack length and regression fits to crack length vs. voltage data are presented in Paragraph 7.5.

7.2 Data Base for SLB Leak Rate Correlation (3/4 Inch Tubing)

The database used for the development of the SLB leak rate correlation (primary to secondary leak rate under SLB conditions vs. bobbin coil voltage amplitude) for 3/4 inch diameter tubing is derived from model boiler specimens and pulled tubes. All of the data were derived from alloy 600 tubing with 3/4 inch OD and 0.043 inch nominal wall thickness. The model boiler test results for 3/4 inch tubing are described in Section 5. All reported bobbin coil measurements on model boiler specimens are for mix frequency with the holes in the reference ASME standard normalized to 2.75 volts.

The pulled tube data included in the database are obtained from Plants E-4, R-1 and S[1]. Leak rate measurements (11 indications with leakage) on the Plant E-4 pulled tubes were performed at room temperature. These have been adjusted to provide leak rates under operating temperature using procedures described in Appendix B. The bobbin data from the 1992 pulled tubes (2 indications with leakage) from Plant R-1 were obtained using procedures equivalent to those used for the model boiler database (field ASME standards were calibrated against the reference standard). Two indications with leakage including the highest voltage pulled tube were obtained from Plant S. The pulled tube results are described in Paragraphs 4.3, 4.4 and 4.5.

---

[1] Actual Plant names are on file at EPRI.

The SLB leak rate data are normalized to primary pressures of and to the secondary side pressure of at operating temperature. Renormalization from the measured leak rate conditions for SLB leak rates (as described in Paragraph 7.4) is developed in Appendix B. The resulting SLB leak rate database is summarized in Table 6-1 for both the model boiler specimens and the pulled tubes. Data from non-leakers are not included in the leak rate correlation.

7.3 Leak Rate Threshold Assessment

As a crack is initiated and grows to a certain size (in depth and length), it becomes detectable through eddy current inspection. Such a crack indication would have a signal amplitude associated with it. As the crack grows, so does its signal amplitude. When the crack becomes throughwall, it would have a significant voltage amplitude signal. Although extremely short cracks may be construed to have small amplitudes, in practice, a throughwall corrosion crack will have some minimum signal amplitude. It is not known explicitly what minimum voltage amplitude may be associated with such a crack.

In order for a crack to result in leakage across the tube wall, the crack must be throughwall. Further, for an OD initiated throughwall crack to leak, it must have some minimum length at the tube ID. The estimated bobbin voltage threshold for leakage based on throughwall crack length considerations is discussed in Section 7.3.4. A voltage threshold for leakage is also supported by the scarcity of leak rate test results for bobbin coil amplitudes below Thus it may be concluded that there would be an eddy current voltage threshold below which corrosion cracks would not cause leakage. A voltage threshold for SLB leakage is assessed below from the body of available data.

7.3.1 Threshold Based on Destructive Exam Depth of Pulled Tubes

Figure 7-1 is a plot of bobbin voltage versus maximum depth of cracks in pulled tubes from operating steam generators with 3/4 inch diameter Alloy 600 tubing. Due to the differences in crack morphology among the various pulled tube specimens, the plotted data is scattered as expected. However, an increasing trend between bobbin voltage and maximum throughwall depth from destructive examination is visible. On the semi-log plot, a linear relationship between the voltage and destructive examination depth is broadly indicated. Figure 7-1 shows a regression fit to the data for depths This regression fit can then be extrapolated to depth to estimate the expected voltage for a crack just penetrating throughwall. The best estimate voltage for a throughwall indication is about and the lower confidence on the mean regression line is about All of the data for throughwall cracks fall above as may be noted in Figure 7-1. Since a crack must be throughwall to cause leakage, it follows that the minimum bobbin voltage threshold for leakage in 3/4 inch tubing is expected to be nominally about and above confidence.

7.3.2 Threshold Based on Leakage Data

A considerable amount of data exists on the leak rate of ODSCC flaws in pulled tubes and model boiler specimens. In the 7/8 inch data report (Volume 1), the 7/8 inch and 3/4 inch data were combined to assess potential thresholds for leakage. For 3/4 inch tubing, 100 data points are used in this section to assess the threshold based on leakage data.

The data were classified into leaking and nonleaking specimens. A frequency distribution of voltage amplitudes in each classification was determined. This is shown in Figure 7-2 as a stacked bar chart. The number of leaking specimens in each voltage range out of the total number in that range is also shown at the top of each bar in the figure. The ratio of the number of leaking specimens in a voltage range (bin) to the total number of specimens in the bin was calculated from the above frequency distribution of voltage amplitudes. This result, probability of leakage, within each voltage range is plotted as a bar chart in Figure 7-3.

The probability of SLB leakage data of Figure 7-3 indicates a threshold for leakage in the range and that leakage approaches probability in the range. A statistical analysis of the data for probability of leakage is given in Section 7.4. A low probability of leakage between is indicated by the data, with only one leaker at below the more frequent leakage data at . The pulled tube indication had a very small leak rate of about , which indicates that the threshold for leakage is very sensitive to a definition of any leakage above zero or a small leak rate as the threshold. For the present assessment, the indication can be applied as the leakage threshold based on measured leakage data.

7.3.3 Threshold Based on Bobbin Voltages of Non-leaking Specimens

A voltage threshold for SLB leakage is derived using data from non-leaking specimens. All available data for corrosion cracks with throughwall or near throughwall indications are used in this evaluation. Specimens with crack depths greater than (from destructive examination) which exhibited no leakage during the leak test are listed in Table 7-1. It may be noted that, in the case of 3/4 inch tubing, these flaws had signal amplitudes in the range of volts. These data suggest an SLB leakage threshold of about , although the standard deviation is large which indicates that this estimate may not be reliable.

7.3.4 Threshold Based on Throughwall Crack Length

The threshold for SLB leakage can also be assessed by evaluating the lowest bobbin voltages resulting in leakage at SLB conditions and by evaluating the throughwall crack length generally required for measurable leakage. If the throughwall crack length associated with measurable leakage can be defined, the voltage versus crack length relationship developed for 3/4 inch tubes in Section 7.5 can be used to assess the voltage threshold for leakage. The crack length method for estimating a voltage threshold for leakage provides a more physical insight into the threshold estimate.

The leakage threshold can be assessed by examining crack length data Table 7-2 shows specimen throughwall crack lengths for no leakage, leakage and leakage between . In the case of 3/4 inch diameter tubing, no leakage was found for throughwall cracks up to Two indications with bathtub flaws and very short throughwall corrosion lengths are expected to have experienced OD ligament tearing to result in leakage at SLB conditions These indications are 601-1 and R9C91, TSP-3 It is expected that these indications would not have leaked without ligament tearing at increased pressure differentials. No leakage was found for either of those indications at normal operating conditions The smallest throughwall, non-bathtub flaw with leakage is in the range of , from Table 7-2. Overall, the data of Table 7-2 indicate that throughwall crack lengths are generally required for SLB leakage. The bobbin voltage associated with a throughwall crack length of is expected to be , based on the correlation of Section 7.5.

7.3.5 Voltage Threshold Considerations for SLB Leakage (3/4 Inch Tubing)

In the above sections, the SLB leakage threshold was evaluated from different perspectives: voltage indications required for throughwall cracks , voltage threshold from leak rate data , voltages of non-leaking tubes with throughwall and near throughwall degradation , and crack lengths required for leakage In all cases, the data show that the bobbin amplitude threshold for zero leakage is expected to exceed about whereas the threshold for significant leakage in a 3/4 inch diameter tube, based on Table 7-2, is about

Based on the above, leakage rates (bobbin volts) should be related to a threshold leak rate. The threshold for zero leakage is expected to exceed about , while the threshold for meaningful leakage is expected to exceed about The SLB leak rate methodology and analysis for units with 3/4" OD tubes is intended to be conservatively applied. Therefore, a leakage threshold of about 1.0 volt is applied for units with 3/4" OD tubes. That is, all indications above have a probability of leakage as developed in Section 7.4 and a conservative leak rate (Section 7.6) for indications in the range of ARC applications.

The best fit or maximum likelihood estimate for probability of leakage, developed below in Section 7.4, supports a leakage threshold The upper bound shows a low probability of leakage of less than below the limit. This lower voltage estimate is consistent with the threshold estimates developed above. Both the probability of leakage at confidence and the SLB leak rate at confidence are very low such that the threshold could be applied with negligible error in the SLB leak rate.

7.4 Probability of SLB Leakage Versus Bobbin Voltage

The above discussion and the supporting data indicate that even when the voltage amplitude of a corrosion crack exceeds the leakage threshold, there is a likelihood of no leakage. In order to quantify this fact, the probability of SLB leakage as a function voltage is derived in this paragraph.

7.4.1 Database for Probability of Leakage

The current evaluation of probability of SLB leakage is limited to 3/4 inch diameter tubing. Hence, the database used here is limited to the 3/4 inch specimen results given in Table 7-3 and Figure 7-1. Figure 7-1 includes pulled tube results for which leak or burst tests were not performed. The data set for this analysis consists of a total of 100 pairs of test results for which leak test results are available, or for which it could be verified from destructive exam results that leakage would not occur at a pressure less than or equal to the postulated SLB differential pressure. When pulled tube leak tests were not performed, the maximum crack depths were evaluated to define the indications as non-leakers or leakers as discussed in Section 4.0. The database consists of 39 model boiler specimens and 33 pulled tube intersections for which SLB leak rates are known from direct measurement. In addition, there are 28 pulled tube specimens for which leak rate tests were not performed and whether or not they would leak was assessed on the basis of the crack morphology from destructive examination.

Statistical Evaluation for Leakage Probability

An analysis was performed to establish an algebraic relationship that could be used to predict the probability of leakage during a postulated SLB as a function of bobbin amplitude voltage. Two approaches were considered for the analysis. The procedure for the first approach would be to segregate the results into a series of discrete bobbin amplitude ranges, called bins, based either on the actual voltage observed or based on the logarithm of the bobbin voltage. This would be followed by the preparation of a cumulative histogram of the results, e.g. Figure 7-3, and the fitting of a smooth polynomial, or a cumulative normal distribution type curve through the results. There are, however, two significant drawbacks associated with this type of an approach. The first drawback is that the shape of the plotted histogram is dependant on the number of subdivisions used to segregate the data range. The second drawback is that there would be no direct way of establishing confidence bounds on the model, although binomial limits could be calculated for each bin.

To consider the second drawback further, we note that the probability of leakage must be limited to a range of 0 to 1. A correlating equation to fit the data could be achieved by employing the method of least squares (LS) or maximum likelihood (ML) to estimate the parameters of the equation. If the expression was based on correlating probability as a function of leakage, the upper confidence band for the resulting expression would exceed unity for some voltages. Likewise, for lower voltages the lower confidence band would yield probabilities less than zero.

In general, the criteria for a good estimator are that it be unbiased, consistent, efficient, and sufficient. The parameters of a correlation curve from either LS or MLE analysis will satisfy the above requirements if the requirements for performing the analysis are met. However, for the probability of leak data, the estimating curve will not be strictly consistent for a sample size less than infinitely large due to variability inherent in establishing the subdivision size. It is noted that although the objections of the second drawback might be overcome by correlating voltage to probability, the requirement for a consistent estimator might not be met. It was therefore decided, that the first analysis approach would not be pursued.

The second approach to the analysis stems from the observation that the data may be considered as samples from a dichotomous population. This means that the data are categorical, and that the number of categories is two, i.e., either no leak or leak. However, for an analysis treating the data in this manner a normal linear correlation model of the type

(7.1)

where a_0 and a_1 are coefficients to be determined from the data, and f(*volts*) is either volts or log(volts), is not appropriate since normal distribution errors, ε, do not correspond to a zero (no leak) and one (leak) response.

It is appropriate to analyze the data in this situation by non-linear regression analysis, and, logistic regression in particular, since the data is dichotomous. Letting P be the probability of leak, and considering a logarithmic scale for volts, V, the logistic expression is

(7.2)

This can be rearranged as

(7.3)

where the logit transform is defined to be

(7.4)

The model considers that there is a binomial probability of leak for each value of voltage. The objective of the analysis was to find the values of the coefficients, a_0 and a_1, that best fit the test data. Since the outcomes of the leakage tests are dichotomous, the binomial distribution, not the normal distribution, describes the distribution of model errors. It would, therefore, be inappropriate to attempt an unweighted LS regression analysis based on equation (7.3). The appropriate method of analysis is based on the principle of maximum likelihood. The application of ML leads to estimates of the equation parameters, i.e., a_0 and a_1, that are such that the probability of obtaining the observed set of data is a maximum. The results of applying ML to the dichotomous outcomes are the likelihood equations,

(7.5)

and

(7.6)

Here, P_i is a test outcome and $P(v_i)$ is an expected outcome based on the input value of the voltage using equation (7.2), where $v_i = \log(V_i)$. Since these equations are non-linear in the coefficients a_0 and a_1, an iterative solution must be determined.

Two evaluations of the parameters were performed, one using a commercially available statistics program with logit fitting capability, and a second based on manually trying to iterate to a solution based on weighted least squares. The purpose was to provide an independent verification of the results from the commercial program. The accepted measure of the goodness of the solution is the deviance,

(7.7)

The deviance is used similar to the residual, or error, sum of squares in linear regression analysis, and is equal to the error sum of squares (SSE) for linear regression. For the probability of leak evaluation, P_i is either zero or one, so equation (7.7) may be written

(7.8)

Both evaluations provided similar deviance values and the final solution obtained was

(7.9)

Asymptotic confidence limits for each individual logit(P_i) are found as

(7.10)

where is the associated probability for a two-sided confidence band. The standard error of logit(P_i) is found for each voltage level as

(7.11)

where V_a is the estimated variance-covariance matrix of the parameter estimates. Letting

(7.12)

the upper and lower one-sided confidence limits are

(7.13)

The upper bound values were calculated for each voltage/leak pair. The results are shown graphically in Figure 7-4.

7.5 General Trends for SLB Leak Rate Correlation

To provide guidance for a statistically based SLB leakage versus voltage correlation, it is desirable to establish the expected trends for the correlation based more on the physics of leakage. The regression analysis of the leak rate and voltage data should produce a correlation consistent with the expected or physical trends. This comparison is particularly useful for the low voltage range where there are few data points on leaking tubes (due to low probability of leakage as shown in previous section) and the regression analysis results must be extrapolated to the low voltage range. This section develops these trends on leakage for both 3/4 and 7/8 inch diameter tubing. The database on leakage and throughwall crack lengths at low voltages is more extensive for 3/4 inch than 7/8 inch tubing. This permits both the trend and regression analysis to be better characterized for 3/4 inch tubing. The 3/4 inch tubing results provide additional guidance for the 7/8 inch correlations.

The trend analyses utilize a correlation of voltage versus throughwall crack length (from destructive examination) and calculated leak rates vs. crack length using an analytical model (CRACKFLO) qualified against corrosion (principally PWSCC) and fatigue cracks. A general form for the relation of voltage vs. throughwall crack length is developed from first principals of eddy current and a more arbitrary form based on fitting EDM notch data is also used in the analysis. The evaluation then establishes leak rate versus voltage trends from:

1) Formulation of a throughwall (TW) crack length (L) versus voltage (v) correlation from available data using regression analysis $\{L=f_1(v)\}$

2) Calculation of leak rate (Q) as a function of L using the CRACKFLO computer code. Formulate a simplified relationship of Q as a function of L through regression analysis of CRACKFLO predictions $\{Q=f_2(L)\}$

3) Development of a correlation between Q and v from the above. Substitute the formulation $L=f_1(v)$ into $Q=f_2(L)$ to get $Q=f_3(v)$. Compare $Q=f_3(v)$ to the direct correlations.

7.5.1 Functional Form for Dependence of voltage on Crack Length

Figure 7-5 shows bobbin voltage data for deep slots as a function of slot length ℓ for the 7/8" and the 3/4" diameter tubes. The voltage increases as ℓ increases and V is proportional to ℓ^2 for small values of ℓ. This dependence of V on ℓ becomes weaker as ℓ becomes large; for very long slots, the voltage is almost independent of ℓ. This type of dependence is expected since the presence of an axial slot interrupts the current flow and the current has to go around the length of the slot, at least for short slots. However, as the slot length increases, some of the current would go around the tube circumference. For very long slots (for ℓ approaching the tube circumference), the current path around the slot length offers higher resistance than the path around the tube circumference. Thus for large ℓ, almost all the current goes around the circumference and the signal voltage becomes independent of the slot length.

The observation that for small slot lengths, $V \propto \ell^2$ is not unexpected since as the slot interrupts the high frequency alternating current, it acts as a radiation source. When the slot length is small compared to the wave length, it can be treated as a Hertzian oscillator. The radiation resistance for the Hertzian oscillator is given by[2]

(7.14)

---

[2] E. C. Jordan and K. G. Balman, Electromagnetic Waves and Radiating Systems (p. 325) Prentice Hall Inc. 1968

where ℓ is the oscillator length and λ is the wave length. Thus for short slot lengths, $V \propto \ell^2$ is theoretically acceptable. The value of λ would be in the range of about For the mixes and the , the wave length can not be defined rigorously but it could be expected to exceed . The ℓ^2 dependence of voltage is not expected to be rigidly valid for slot lengths beyond , although it may be able to be used up to approximately . The situation can be treated as the case of two resistors, R_1 and R_2, in parallel (R_1 representing the slot and R_2 representing the path around the tube circumference).

(7.15)

From the above discussion for ℓ^2 dependence of the slot resistance,

(7.16)

The circumferential resistance, R_2, is a constant and characteristic of the tube dimensions and the eddy current test frequency. Thus R_2 can be represented as:

(7.17)

where λ_c may be defined as the characteristic length for the tube dimension and test frequency. Then the total resistance offered to current can be represented as:

(7.18)

The bobbin voltage for the case of a slot can be represented as:

(7.19)

where V_∞ represents the asymptotic voltage as ℓ becomes very large.

For real cracks, the voltage would not approach zero for a throughwall length approaching zero. The above functional form can be modified for actual cracks to account for the finite voltage, V_0 expected for ℓ (throughwall) = 0. Then

(7.20)

The value for λ_c can best be obtained by regression analysis of the crack data. V_0 can be estimated as the voltage obtained as the crack approaches throughwall. From Section 7.3 and Figure 7-1, V_0 would be expected to be about for 3/4 inch tubing and about for 7/8 inch tubing. The correlation efforts of this section were performed for V_0 = , which was the best estimate for V_0 at the time this effort was performed. For throughwall holes and the ARC voltage normalizations, the ratio for 7/8 to 3/4 inch tubing voltages is . As developed later in this section, V_0 = leads to an acceptable regression fit to the 3/4 inch crack data and is applied in this analysis. The throughwall hole ratio of is applied in the later analysis to utilize V_0 = for 7/8 inch tubing.

There are no corrosion throughwall crack length data large enough to readily estimate V_∞. The available data is limited to throughwall crack lengths. Therefore, V_∞ for 3/4 inch tubing is obtained by regression analysis of the crack data together with λ_c. For 7/8 inch tubing, the crack database is not adequate to obtain both V_∞ and λ_c by regression analysis. Laborelec has performed extensive bobbin measurements of EDM slots. The Laborelec data indicate that the 7/8 to 3/4 inch voltage ratio decreases as the throughwall slot length increases and approaches for long slots. Therefore, V_∞ is assumed to be equal for both tubing sizes and the value obtained by regression analyses of 3/4 inch crack data is also applied as a fixed parameter for regression analysis of the 7/8 inch data. Thus, only λ_c is obtained by regression analysis for the 7/8 inch correlation.

The functional form of equation (7.20) for the voltage dependence on crack length can be tested for adequacy by fitting voltage data for throughwall EDM slots. The result of the regression analyses with all three parameters adjusted to fit the data is shown in Figure 7-5. It is seen that equation (7.20) provides a good fit to the EDM slot data. Thus, the EDM slot data supports the theoretical functional dependence of voltage on crack length given by equation (7.20). The V_∞ value of is unique to slots and cannot be assumed (other than as an upper bound) for cracks due to potential contact or ligaments at actual crack faces. Thus, equation (7.20) provides an acceptably sound theoretical basis for fitting actual crack data for which variability in voltage vs. crack length can be expected to be much greater than for EDM slots.

To test the sensitivity of leak rate vs. voltage to the functional form of crack length vs. voltage, an arbitrary form was developed by obtaining a functional dependence that gives a good fit to the EDM slot data. This fit, functional form and constants for the slot fit are shown in the lower part of Figure 7-5. This functional form is carried through the trend analysis for 3/4 inch tubing for which there is adequate crack data to determine the coefficients (a,b,c) by regression analysis.

7.5.2 Voltage vs. Crack Length for ODSCC Data

Throughwall crack lengths have been obtained for a significant number of 3/4 and 7/8 inch model boiler specimens. A more limited set of data is available from pulled tube examinations. The 3/4 inch data are given in Table 6-1. The 7/8 inch data have been reported in Volume 1 of this report. For some specimens with more extreme complexities in the crack morphology, it cannot be expected that voltage would be reasonably related to crack length. For example, specimens with multiple, large voltage cracks have excessively large voltages compared to the voltage for a single throughwall crack. The specimen crack morphologies were examined to eliminate the more extreme cases from the regression analysis. Table 7-4 identifies the basis for not including particular specimens in the regression analyses. More specimens were not included for 7/8 inch tubing (8 specimens) than for 3/4 inch tubing (4 specimens). The regression analyses include 24 specimens for 3/4 inch tubing and 15 specimens for 7/8 inch tubing. No very short throughwall cracks have been found for 7/8 inch tubing except for R31C46, and it is therefore difficult to fit a multivariable regression curve to the data. For this reason, V_0 and V_∞ of equation (7.20) were predefined, as described above, for the 7/8 inch regression analysis.

Figure 7-6 shows the correlation obtained by applying equation (7.20) to the 3/4 inch data with all coefficients obtained by the regression analysis. Although the fit is reasonable, V_0 = volts is unacceptably high for the expected voltage for a very short throughwall crack. Therefore, V_0 was fixed at the more reasonable estimate of discussed above and the regression analysis was repeated. The resulting correlation is shown in Figure 7-7. The resulting λ of is consistent with expectations. V_∞ of is reasonable although judged to be toward the low end of expected values. Figure 7-7 also shows the correlation obtained for 7/8 inch data with V_0 and V_∞ set at predefined values as previously discussed. The resulting 7/8 inch correlation appears reasonable, although the limited data precludes high confidence in the results.

The Plant S pulled tube data with throughwall indications were obtained after the regression analyses described in this section. The three Plant S data points have been added to Figure 7-6 for comparisons with the regression database. It is seen that the Plant S data are in very good agreement with the other pulled tube and model boiler data. Thus, the regression fits would be minimally influenced by including the Plant S data. Figure 7-8 shows the regression fit to the 3/4 inch data using the more arbitrary formulation obtained by fitting the 3/4 inch EDM slot data.

7.5.3 Leak Rate Versus TW Crack Length

An analytical model (CRACKFLO code) is used to predict leak rate as a function of axial TW crack length at SLB conditions (ΔP= used in analysis). For simplicity, regression analysis was used to fit a subset of CRACKFLO solutions to obtain SLB leak rate vs. crack length for the present application.

The adequacy of CRACKFLO for predicting leak rates can be assessed by comparing predicted leak rates with measured leak rates for the ARC data base. Figure 7-9 shows this comparison of CRACKFLO predictions with measured data as a function of throughwall crack length. The predictions are good for 3/4 inch tubing and somewhat high for 7/8 inch tubing. An analytical model using throughwall corrosion lengths can be expected to underpredict leakage when ligaments are torn by the SLB pressure differential. This is an expected condition for the two 3/4 inch points with crack lengths which had bathtub flaws (thin OD ligaments) and the Belgian pulled tubes (above length) which had a significant level of cellular corrosion. The analytical model can be expected to overestimate leakage when ligaments are present and do not tear at SLB pressure differentials. This is the expected cause for the high predictions for 7/8 inch tubing. Overall, the comparisons of Figure 7-9 support the use of CRACKFLO predictions for the present application.

7.5.4 SLB Leak Rate Versus Bobbin Voltage

The above correlations of voltage to crack length and CRACKFLO analyses for leak rate vs. crack length can be combined to obtain the trend for SLB leak rate vs. voltage as shown in Figure 7-10 for a pressure differential of . The volt-slot theory curves in Figure 7-10 are based on Equation (7.20) and Figure 7-7 while the slot fit basis utilizes the relation given on Figure 7-8. For leak rate vs. voltage, it is seen that both the theoretical formulation of Equation (7.20) yields essentially the same trends as the arbitrary formulation obtained by fitting the EDM slot data. Thus, the leak rate relation is not particularly sensitive to the form of the leak rate vs. crack length relation provided both forms are fit to the same database. The 7/8 inch trend of Figure 7-10 shows lower leak rates than found for 3/4 inch tubing. This difference between tubing sizes would be even greater if the 7/8 inch CRACKFLO predictions shown in Figure 7-9 was lowered to improve agreement with test data comparable to that for 3/4 inch tubing. Figure 7-17 compares the Equation (7.20) formulation (volt-slot theory curves of Figure 7-10) with the measured leak rate and voltage data for 3/4" tubing. The agreement between the semi-theoretical formulations and the measured data is generally good.

The results of Figure 7-10 shows three dominant trends - a steep increase in leakage at the voltage threshold, a modest slope from about and a steep slop above These general trends can be used as guidance for defining the trends in the leak rate correlation as extrapolated to lower voltages than the dominant database.

7.6 SLB Leak Rate Versus Voltage Correlation

The bobbin coil and leakage data of Table 6-1 were used to determine a correlation between SLB leak rate and bobbin voltage amplitude. This is not to say that a "formal" functional relationship, in the sense of one variable being dependent on the other, exists between the variables since the amount of leakage is not caused by the bobbin voltage and vice versa. Both of the variables considered are really mainly functions of a third variable, namely the crack morphology. While the variation in crack morphologies is essentially infinite, suitable descriptions can be effected based on the length, average depth, profile description, etc. However, the characterization of the morphology is not essential to this analysis since a relationship can be independently established for two offspring variables. Since both bobbin voltage and leakage are offspring variables the results of the correlation analysis do not establish a formal relationship between the variables, however, the results do establish a "working" relationship that can be employed for the prediction of one variable from the other.

7.6.1 Selection of Coordinate System

In order to establish a correlation between the two variables, which are paired, but expected to have independent variances, the method of least squares (LS) curve fitting was employed. The simplest functional form is a linear relationship of the type

(7.21)

where the variables x and y may each be considered to be linear or logarithmic. In addition, the choice of the regressor variable is not pre-determined. Both variables are assumed to be subject to random fluctuations which are normally distributed about the mean of the variable or the logarithm of the variable with a mean of zero and some unknown, but reasonable variance. It is also assumed that this variance is constant, or uniform, over the range of interest of the variables. In practice this may not be the case, however, any non-uniformity present would not be expected to significantly affect the analysis outcome, and can be tested at the conclusion of the analysis.

Analyses were performed to determine the optimum nature of the variable scales, i.e., linear versus logarithmic, and the appropriate selection of the regressor variable. It was initially concluded that the most meaningful correlation could be achieved by considering the log of the leak rate as the regressor and the log of the voltage as the predicted variable. Thus, the functional form of the correlation is

(7.22)

where Q is the leak rate and V is the bobbin voltage. The final selection of the form of the variable scales was based on performing least squares regression analysis on each possible combination and examining the square of the correlation coefficient for each case. A summary of the results of the calculations is provided in the following table. Given the results, it is clear that the appropriate choice of axes scales should be log-log.

Index of determination, r^2, for Various Selections of Coordinate Scales ΔP_{SLB}=		
Bobbin Amplitude	Leak Rate	
	Linear	Logarithmic
Linear		
Logarithmic		

These results strongly suggest that the appropriate choice of axes scales is log-log. The number of data points used for the above evaluations was 39. The corresponding critical value of r^2 for significance at a level of is approximately. Thus, the log-log regression with an r^2 value of is significant at a level greater than. (The actual value is for the log-log regression.) This is also true for the linear-log set of axes, however, the coefficient is significantly better for the log-log set.

Guidance on the appropriate choice of the regressor variable can be based on the knowledge of the approximate value of the slope of the relationship from CRACKFLO analysis results. Comparisons showed that the slope of a log (Q) on log (V) regression line more closely matched the CRACKFLO results bobbin amplitudes with an inverse regression matching better for amplitudes. The CRACKFLO results indicated the potential for a slope change between about. It was initially concluded, therefore, that both regression lines would be calculated, giving the option of selecting the higher of the two for any voltage level as a candidate for the upper bound leakage. Graphical results verified the selection of the regressor and regressed variables as being appropriate in the range of interest. Subsequent discussions with the EPRI Committee for Alternate Repair Limits for ODSCC at TSPs concluded that the voltage range of interest was limited and that only the regression of log (Q) on log (V) needed to be considered. The CRACKFLO results are shown on Figure 7-17 associated with the analysis of confidence and prediction bounds (discussed later).

It is noted that the CRACKFLO results also indicated that the leak rate would be expeted to decrease dramatically for indications with amplitudes below. This is in agreement with the results of the probability of leak analysis.

7.6.2 *Correlation Analysis and Identification of Outliers*

In order to determine if the parameters of the relationships were being biased by the presence of unduly influential data points, a least median of squares regression analysis was performed on the data set for the log(Q) versus log(V) regression. One point was identified as a potential outlier for a ΔP of An examination of the testing program information revealed no basis for rejecting the data, thus it was retained for the analysis.

7.6.3 *Error-in-Variables Analysis*

The potential effect of measurement errors in the regressor variable are discussed in Appendix D of Volume 1 of this report. The variance, σ_X, of a variable, say X, with measurement error, as estimated from the data, consists of two parts, the intrinsic variation, σ_x, of the actual value of the variable, x, and the variation, σ_m, due to measurement error, m, i.e.,

(7.23)

A Wald-Bartlett type of analysis was performed for each direction of regression. Considering the log(Q) as the regressor resulted in a line indistinguishable from the standard regression line. Considering log(V) as the regressor resulted in a line with a slightly larger slope than the standard fit. This was to be expected since the previous use of the technique for the burst pressure correlation indicated that measurement errors for the bobbin amplitude were not significant. It is recognized that the use of the Wald-Bartlett technique has met with some controversy with some members of the EPRI Committee for Alternate Repair Limits for ODSCC, however, it is generally accepted as a viable technique for determining if errors in the variables are significantly affecting the regression line. Since no accepted quantitative values for the variance of the errors exists, a rigorous errors-in-variables analysis cannot be performed. The results obtained here imply that errors in the independent variable are not significantly biasing the analysis.

7.6.4 *SLB Leak Rate Correlation for 3/4 Inch Diameter Tubing*

The final fits of the data are shown in Figures 7-11 through 7-13 for SLB pressure differences (ΔP's) of , respectively. The correlation lines are given by

(7.24)

The coefficients for the above equation are provided in the following table for the three ΔP_{SLB} levels. In addition to the least squares regression line, the upper one-sided simultaneous confidence bound, the upper prediction bound, and the arithmetic average of the regression line were determined. These are depicted on Figures 7-14 through 7-16 for the regression of log(Q) on log(V) for the three respective pressure differentials. Figure 7-17 provides a comparison of the regression results to those obtained using CRACKFLO for a pressure differential of

Regression Coefficients for SLB Leak Rate to Bobbin Amplitude Correlation			
	SLB @	SLB @	SLB @
a_0			
a_1			

Since the regression was performed as log(Q) on log(V) the regression line represents the mean of log(Q) as a function of bobbin amplitude. This is not the mean of Q as a function of V. The residuals of log(Q) are expected to be normally distributed about the regression line. Thus, the median and mode of the log(Q) residuals are also estimated by the regression line. However, Q is then expected to be distributed about the regression line as a log-normal distribution. The regression line still estimates the median of Q, but the mode and mean are displaced. As a uniform example, the values, 0.1 and 10 have a numerical average of 5.05, while the average of their logarithms is 0 with an anti-logarithm of the average of 1. The corresponding adjustment to the normal distribution to obtain the arithmetic average, i.e., mean, for a log-normal distribution results in

(7.25)

for the expected AA of Q for a given V, where σ^2 is the estimated variance of log(Q) about the regression line. where σ^2 is the estimate variance of log(Q) about the regression line. Examination of the Figure 7-14 indicates that below a voltage level of , the upper confidence band on log(Q) is conservative relative to the expected mean leak rate.

7.6.5 Analysis of Residuals

Analysis of the regression residuals was performed per the descriptions given in Appendix D of Volume 1. As previously noted, the correlation coefficients obtained from the analyses indicate that the log-log regressions at the various SLB ΔP's are significant at a level greater than . Additional verification of the appropriateness of the regression was obtained by analyzing the regression residuals, i.e., the actual variable value minus the predicted variable value from the regression equation.

Figures 7-18 through 7-20 show the scatter plot of the log(Q) residuals as a function of predicted log(Q) for the three SLB differential pressures of interest. For each, the arrangement of the data points is non-descript, indicating no apparent correlation between the residuals and the predicted values.

Cumulative normal probability plots were prepared for each of the steam line break differential pressures, see Figures 7-21 and 7-23. For each of these cases a straight line is approximated, typical of the behavior of normally distributed residuals.

Given the results of the residuals scatter plots and the normal probability plots, it is considered that the regression curve and statistics can be used for the prediction of leak rate as a function of bobbin amplitude, and for the establishment of statistical inference bounds.

Table 7-1. **Non-Leaking 3/4 inch Specimens with Throughwall or Near Throughwall Cracks**[1]

Table 7-2. **Dependence of SLB Leakage on Throughwall (TW) Crack Length**

Table 7-3: Database for Probability of Leak for 3/4" Diameter Tubes

Table 7-4

Destructive Examination Data Not Used in Crack Length Correlation

Figure 7-1: Bobbin Coil Voltage vs. Maximum Examination Depth

3/4" Pulled Tubes Data, Destructive Examination

Figure 7-2: Distribution of Leaking and Non-Leaking 3/4" OD, Alloy 600 SG Tubes @ SLB Conditions versus Bobbin Amplitude

Figure 7-3: Probability Distribution of SLB Leakage versus Bobbin Amplitude for 3/4" OD, Alloy 600 SG Tubes

Figure 7-4: Probability of Leak > 0 l/hr vs. Bobbin Amplitude

3/4" Tubes, Model Boiler & Field Data

Figure 7-5

Voltage Vs EDM Slot Length

Figure 7-6

Bobbin Voltage Vs TW Crk Length - 3/4"

Figure 7-7

Bobbin Voltage Vs TW Crk Length – 3/4"

Figure 7-8

TW Crack Length Vs Voltage – 3/4" Tubing

Figure 7-9

Comparison Of CRACKFLO To ODSCC Leakage

3/4" Tubing Data

Figure 7-10

Trend Analysis For Predicting
SLB Leak Rate Vs Bobbin Voltage

Figure 7-11: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-12: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-13: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-14: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-15: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-16: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-17: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-18: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-19: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-20: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-21: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-22: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

Figure 7-23: SLB Leak Rate vs. Bobbin Amplitude

3/4" x 0.043" Alloy 600 SG Tubes, Model Boiler & Field Data

This page
intentionally blank

APPENDIX A

DESTRUCTIVE EXAMINATION

A.1 Objectives

The objective of this task is to characterize the size, shape, and morphology of the laboratory created corrosion in alloy 600 tube specimens which have been leak rate and burst tested. The crack morphology is also to be compared generally to the corrosion morphology observed in tubes pulled from operating power plant steam generators. A summary of the available results for 3/4 inch OD specimens is presented in this section.

A.2 Examination Methods

Examination methods include visual examinations, macrophotography, light microscopy and/or SEM (scanning electron microscopy) examinations, SEM fractography, and metallography. A number of model boiler test specimens were selected for destructive examinations. Most of these were leak and burst tested.

The specimens were initially examined visually and with a low power microscope. The burst opening and visible cracks around the circumference of the tube within the tube support plate intersection were visually examined and their location in relation to the burst crack noted. (When the crack networks were particularly complex, such as when circumferential components were strongly present, photographs of the crack networks were taken and included in this report for more complete documentation of the data.) The major burst crack was then opened for fractographic observations including crack surface morphology, crack length, and crack depth using SEM. One metallographic cross section of each tube specimen was selected containing the majority of secondary cracks within the tube support plate region. The location of the cracks within this metallographic cross section was noted, the cracks measured as to their depth and a crack was photographed to show the typical crack morphology. Note that the one metallographic section through each specimen will provide the secondary crack distribution at that location. Secondary cracks at other elevations would not be recorded unless the burst test happened to open the secondary cracks sufficiently for visual examination to record their location.

A.3 Destructive Examination Results

Tube 590-1. The crevice region of tube 590-1 showed only axial cracks, of which were through-wall. The longest of the through-wall cracks caused the burst opening. At the tube burst opening, the macrocrack (composed of one microcrack) was long at the OD and long at the ID. The crack morphology was IGSCC. A metallographic cross section capturing the axial cracks is shown by a sketch in Figure A-1. The crack morphology is shown in a photomicrograph in this figure The shape of the burst crack and its morphology is described in Figure A-2 together with the OD crack distribution found in this tube

Tube 590-2 The crevice region of tube 590-2 had large numbers of axial and circumferential cracks The cracking was concentrated on one quadrant of the tube's circumference Photographs of the tube following burst testing are shown in Figures A-3 and A-4 The burst fracture occurred in a highly irregular fashion dictated by the axial and circumferential tube degradation The burst opening was formed by at least small cracks which joined partial circumferential cracks to form the irregular overall crack pattern The macrocrack length due to corrosion measured at the OD surface and it was through-wall for The microcracks and their ligaments had intergranular ligaments and the morphology of the burst crack was that of IGSCC (Figure A-5) A metallographic cross section through the region with the highest crack density showed a crack distribution as sketched in Figure A-6 A photomicrograph of typical secondary cracks is also shown in this figure They suggest that the cracking is primarily IGSCC with some IGA contributions Figure A-7 provides a summary of the overall crack distribution and summary information regarding the burst crack

Tube 590-3. Rupture in tube 590-3 occurred from a single axial OD origin crack confined to the crevice region The macrocrack was long and was through-wall for a length of Only one microcrack could obviously be observed on the macrocrack The morphology was that of IGSCC Figure A-8 provides summary data regarding the corrosion observed on tube 590-3

Tube 591-1 Burst in tube 591-1 occurred from a single, relatively small axial crack which was long on the OD and long on the ID While small axial secondary cracks were observed away from the burst near the bottom of the crevice region, no secondary cracks were observed near the burst opening However, a metallographic cross section through the center of the burst opening revealed additional axial secondary cracks which were located away from the burst The location of these cracks in relationship to the burst opening is indicated by a sketch in Figure A-9 A photomicrograph of one of the secondary cracks is also shown All cracks had a morphology of IGSCC The shape of the main crack and the distribution of cracks are depicted in Figure A-10

Tube 591-2. The burst fracture in tube 591-2 occurred in an area of the crevice region where many small but deep axial cracks were concentrated The burst created a macrocrack which was long on the OD and it was formed by smaller microcracks The crack was through-wall for a length of The ligaments forming the macrocrack all had ductile features and the morphology of the cracking was that of IGSCC Figure A-11 shows the crack distribution observed by metallography in a circumferential cut through the lower region of the crevice where the crack density was highest A photomicrograph of one of the cracks is also shown A sketch describing the shape of the burst macrocrack, as well as the overall distribution of secondary cracks within the crevice region as observed by visual examination, is shown in Figure A-12. Although this indication was through-wall for cracks, no leakage was measured at SLB conditions for this tube. This would indicate that the throughwall corrosion length of did not significantly tear to longer lengths in the leak test, even though the indication has a bathtub shape with a thin OD ligament.

Tube 591-4. A group of small, deep, OD origin, axial cracks, concentrated in one region of tube 591-4 within the crevice region, caused the burst fracture. The irregular shape of the burst opening (Figure A-13) was formed by small microcracks which grew together by intergranular corrosion to form the macrocrack. The morphology of the macrocrack was that of IGSCC. The macrocrack crack was long and through-wall for . A metallographic cross section through the center of the burst crack revealed many secondary cracks of considerable depth. The cracks are depicted by a sketch in Figure A-14 together with a photomicrograph of the cracking. Summary data regarding the burst crack and the overall crack distribution are shown in Figure A-15.

Tube 595-1. OD origin intergranular corrosion cracking was found confined to one area within the crevice region. The burst test opened one relatively large axial macrocrack inch long and throughwall for . The macrocrack was formed by microcracks which joined by intergranular corrosion. A summary of the burst crack data and a sketch of the overall crack distribution within the crevice region is shown in Figure A-16. A metallographic cross section through the center of the crevice region was made. Figure A-17 shows a sketch of the observations (no secondary cracks were found around the circumference) as well two photomicrographs of the burst crack. Its morphology was that of IGSCC with a minor D/W ratio of

Tube 596-2. The burst test revealed one burst opening centered within the crevice region (Figure A-18) with minor secondary cracks present nearby. The axial burst opening consisted of an OD origin macrocrack composed of at least microcracks whose ligaments all had intergranular features. The intergranular macrocrack was long and throughwall for . A summary of the burst crack data and crack distribution found within the crevice region is presented in Figure A-19. A metallographic cross section through the crevice region revealed the crack distribution shown in Figure A-20. Included are two photomicrographs, one of the burst crack and one of a secondary crack nearby. The crack morphology was that of IGSCC with a minor D/W ratio of

Tube 596-3. The burst fracture in tube 596-3 occurred from a group of small axial cracks of OD origin. of the deep microcracks joined together during the burst test to form the burst opening macrocrack. The ligaments between the microcracks had only intergranular features and the crack morphology was that of IGSCC. The macrocrack caused by IGSCC was long on the OD and was throughwall for a length of . A metallographic cross section through the region with the highest density of cracking revealed a crack distribution shown by a sketch in Figure A-21. A photomicrograph in this figure shows the crack morphology of two of the secondary cracks. A summary of the burst crack data and of the overall crack distribution within the crevice region is shown in Figure A-22.

Tube 598-1. Burst testing revealed three major axial crack networks as is sketched in Figure A-23. The main macrocrack formed the burst opening. The OD origin intergranular macrocrack was long and it was throughwall for No obvious ligaments were visible on the crack fracture face and it may have been composed of only a single microcrack. Figure A-23 summarizes these observations. A summary of the crack distribution and photomicrographs of the crack morphology as revealed by mid-crevice transverse metallography are provided in Figure A-24. The morphology of the cracking was IGSCC with a minor D/W ratio of

Tube 598-2. A summary of the crack distribution and data regarding the main burst crack are provided in Figure A-25. major axial crack networks were observed within the crevice region. The burst crack was the longest. It had intergranular features for a l th of and it was throughwall for The burst macrocrack was composed of OD origin microcracks joined together by intergranular corrosion. Figure A-26 provides a sketch of the crack distribution as revealed by a mid-crevice metallographic cross section. secondary cracks were observed in addition to the burst crack. Photomicrographs of the of the burst crack and one of the secondary cracks is also provided. The morphology of the cracking was IGSCC with a minor D/W ratio of

Tube 598-3. OD origin axial cracking in Tube 598-3 was confined to one circumferential position as shown in Figure A-27. The burst crack was the largest crack shown at the bottom of the crevice region. It was intergranular for a length of and throughwall of inch. A metallographic cross section through the lower crevice region revealed the crack distribution sketched in Figure A-28. secondary cracks were found. The included Figure A-28 photomicrographs of the burst crack and of one of the secondary cracks show that the cracking has a morphology of IGSCC with a minor D/W ratio of

Tube 600-2. The crack distribution observed within the crevice region of tube 600-2 is shown schematically in Figure A-29. Numerous axial cracks of OD origin were found concentrated in one quadrant of the crevice region. The largest macrocrack network formed the burst opening. It was formed by microcracks ligaments separating the microcracks had intergranular features while the , a particularly thick ligament, had only ductile features. The intergranular macrocrack was and was throughwall for The morphology of the cracking was that of IGSCC. The D/W ratio was approximately Figure A-30 provides a sketch summarizing the observations obtained from a metallographic transverse cross section of the specimen. The figure also provides a photomicrograph showing the morphology of the burst crack. The morphology of a single, large ligament separating throughwall cracks is one of a few of this type found in the model boiler program. Large leak rates found for this specimen imply that the large ligament tore during the tests to result in essentially a throughwall crack.

Tube 601-3. The tube support plate crevice region of tube 601-3 had more than axial cracks randomly distributed throughout the crevice region. The upper crack network near degrees formed the burst opening. The OD origin intergranular crack was long and was throughwall for The irregularly shaped burst macrocrack was formed from microcracks See Figure A-31 All ligaments separating the microcracks had only intergranular features Figure A-32 provides summary information obtained from a transverse metallographic section Of the secondary cracks observed around the circumference at the elevation of the section, were throughwall The morphology of the cracks was that of IGSCC with typical D/W ratios of approximately Although cracks had short throughwall penetration, leak testing resulted in no leakage at SLB conditions

Tube 601-6 The burst opening in the crevice region of tube 601-6 was large and showed many facets produced by the ligaments separating the numerous parallel axial microcracks that were present in a narrow axial band A photograph of the burst opening is shown in Figure A-33 Visual and SEM fractographic observations of the burst macrocrack indicated that it was formed from microcracks One ligament separating the microcracks near the crack center was relatively wide and had only ductile features This large ligament is expected to have reduced the bobbin voltage lower than that expected for the relatively large macrocrack other ligaments had mostly ductile features The remaining ligaments had only intergranular features The macrocrack length due to corrosion was long, of which was throughwall The shape of the burst crack as well as the distribution of cracks found within the crevice region of the tube is shown in Figure A-34 The crack morphology was that of IGSCC Examples of the crack morphology and a sketch of the crack distribution found at one elevation (observed) from a transverse metallographic mount are shown in Figure A-35 The crack D/W ratio was approximately

Tube 604-2 The cracking found in tube 604-2 was limited and local The crack distribution observed within the crevice region is presented as a sketch in Figure A-36 The burst crack was formed from a single microcrack that was long The burst crack was throughwall for Figure A-37 presents the cracking distribution found near the upper crevice region by transverse metallography A total of cracks were observed They had an IGSCC morphology with a D/W ratio of approximately

A.4 Destructive Examination of Spanish Test Pieces

The following paragraphs present results of destructive examinations performed on six model boiler specimens fabricated by Westinghouse for a group of Spanish utilities Section 5.1 contains a discussion of the differences in the preparation of the EPRI and Spanish test pieces Table A-1 summarizes the sizes of the principal cracks in the Spanish specimens Figure A-38 shows photos of the burst crack openings prior to destructive examination Destructive examination results are provided below

Tube 600-1. Figure A-39 shows a photo and diagram of the crack surface, showing the presence of cracks Crack "a" is very short, but reaches a depth of Crack "b" is comprised of multiple cracks which begin on various planes and have various depths, some of which are throughwall and others which are not Table A-1 shows the crack lengths For crack "b", the grain boundary crack length times the tube ID is considered to be the sum of the lengths of the throughwall cracks. Examination of the external surface of the specimen was conducted to detect the existence of other possible cracks, in addition to the principal crack. Figure A-40 shows a sketch of the cracks on the external surface of tube 600-1. The existence of small axial cracks may be seen only around the principal crack. None of these cracks passes throughwall, and the maximum crack length observed is

Tube 600-3. The grain boundary crack surface of tube 600-3 is shown in Figure A-41; crack lengths are summarized in Table A-1. staggering and ductile ligaments may be seen, since the cracks begin in different planes. Examination of the external surface of the sample showed no cracking other than the principal crack.

Tube 601-1. Figure A-42 shows a photo and diagram of the grain boundary crack surface on specimen 601-1. The crack extended approximately throughwall over a length of about Examination of the external surface of the specimen showed no other cracking other than the principal crack. This indication has a bathtub flaw shape (thin OD ligaments) and experienced leakage at SLB conditions, indicating some tearing of the OD ligaments may have occured during the tests.

Tube 601-2. The crack surface and diagram of the principal crack are shown in Figure A-43. In this case, there is a rather uniform grain boundary crack surface which passes through the piece almost uniformly without staggered ligaments - unlike tube 601-1. The length of the crack through the primary side is similar to that on the secondary side, as may be seen in Table A-1. Examination of the external surface detected small axial cracks near the crack surface, as may be seen in Figure A-44. The longest of these axial cracks extended over a length of about on the OD and on the ID.

Tube 601-4. Figure A-45 shows the crack surface of tube 601-4. Table A-1 summarizes the lengths of the two grain boundaries, "a" and "b", which are separated by a ligament of approximately Crack "a" passes throughwall and has many ductile ligaments due to its beginning on different planes. Crack "b", formed by the union of many small cracks, has a maximum depth of . Multiple axial cracks were detected around the OD crack surface, as shown in Figures A-46 and A-47. Of the more than axial cracks observed in addition to the burst crack, only the crack labeled "g-2" in Figure A-46 passed throughwall, with an OD length of and an ID length of . The ID surface of this crack "g-2" is shown in Figure A-48. In order to determine the depths of the rest of the cracks on tube 601-4, a metallographic study was performed on the various sections shown in the sketch in Figure A-49. The cracks ranged from deep. Figures A-49 also shows three photographs from the metallography.

Tube 601-5. Figure A-50 shows the crack surface on sample 601-5. The crack is formed by grain boundary cracks, none of which pass throughwall, joined by different lengths of ligaments. The lengths of the grain boundary cracks are shown in Table A-1. The cracks sizes range from long on the OD and deep to long and deep. Figure A-51 shows the position of more than cracks recorded on the OD of this specimen, these cracks are not limited to the area around the principal crack surface. Of these cracks, the maximum length recorded was , with no crack passing throughwall. Metallographic cuts were made in the areas of most interest due to their degree of cracking, as shown in the sketch in Figure A-52. The resulting depths varied from Figure A-52 also shows two photographs from the metallography.

A.4 Comparison with Pulled Tube Crack Morphology

Most of the support plate cracking on pulled steam generator tubes was OD origin, intergranular stress corrosion cracking that was axially orientated. Large macrocracks were frequently present and were composed of numerous short microcracks (typically long) separated by ledges or ligaments. The ledges could have either intergranular or dimple rupture features depending on whether or not the microcracks had grown together during plant operation. Most cracks had minimal to moderate IGA features (minor to moderate D/W ratios) in addition to the overall stress corrosion features. Even when the IGA was present in association with the cracks in significant amounts, it did not dominate over the overall SCC morphology. The numbers of cracks distributed around the circumference at a given elevation within the crevice region varied from a few cracks to typically less than In some cases, the number of cracks was significantly larger than this, in one case possibly approaching For this situation, patches of IGA formed where the cracks were particularly close and the individual cracks had some IGA characteristics. Even for this situation, the axial SCC was still the dominant corrosion morphology as the IGA was typically one third to one half the depth of the IGSCC. In addition, intergranular cellular corrosion (ICC) has been increasingly observed confined to areas within the crevice region. Finally, IGA, separate and independent of SCC, has been occasionally observed. It is usually present as small isolated patches of IGA. In the few cases where more uniform IGA has been observed, it is typically shallow and intermittently distributed within support plate crevice regions.

The model boiler corrosion observed in this investigation on 0.75 inch specimens appeared similar to that observed on 0.875 inch diameter model boiler specimens and was similar to that observed within typical pulled tube support plate crevice locations. Most model boiler corrosion was axially orientated IGSCC with negligible to moderate IGA aspects (minor to moderate D/W ratios) in association with the cracking. Some of the model boiler specimens had cracking with almost pure IGSCC, i.e., with no obvious IGA aspects (D/W ratios of or higher), more similar to PWSCC than to the typical OD IGSCC observed within support plate crevice corrosion on pulled tubes. IGA independent of the cracking was not observed in the model boiler specimens. The numbers of cracks at a given elevation were typically less than , similar to that observed in many of the pulled tubes. However, only one model boiler specimen had a moderate crack density and none had high crack densities as have been occasionally observed in plants. A number of the model boiler specimens from the second set of tests conducted in 1991, however, did have very complex crack networks that frequently had circumferential cracking in association with the predominant axial cracking. Some of the complex crack networks may have had cellular IGA/SCC components similar to that occasionally observed in pulled tubes.

It is concluded that the laboratory generated corrosion cracks have the same basic features as support plate crevice corrosion from pulled tubes. The laboratory created specimens frequently had somewhat lower crack densities, but individual cracks usually had similar IGA aspects (minor to moderate D/W ratios). IGA independent of IGSCC was not observed in the model boiler specimens as was sometimes observed in pulled tubes. The observed differences in corrosion morphology between the model boiler specimens and the pulled tubes is not believed to be significant.

Table A-1

Size of the Principal Cracks Spanish Tests Pieces

Figure A-1. Sketch of a metallographic cross section through the crevice region of tube 590-1. The burst crack and secondary cracks were observed. A photomicrograph of a secondary crack is also shown. The crack morphology is that of IGSCC. Mag. 100X

Figure A-2. Summary of burst crack observations and the overall crack distribution observed at the crevice region of tube 590-1.

Figure A-3. Photographs of the burst opening in tube 590-2 showing axial and circumferential cracking.

Figure A-4. Photographs away from the burst opening in tube 590-2 showing axial and circumferential cracking.

Figure A-5. Photomicrograph of the burst crack in tube 590-2 showing a morphology of IGSCC.

Figure A-6 Sketch of a metallographic cross section through the crevice region of tube 590-2. The burst crack and a number of secondary cracks on of the circumference were observed. A photomicrograph of secondary cracks is also shown. The crack morphology is that of IGSCC with some IGA contributions. Mag. 100X

Figure A-7. Summary of burst crack observations and the ove[illegible] crack distribution observed at the crevice region of tube 590-2.

Figure A-8. Summary of burst crack observations and the overall crack distribution observed at the crevice region of tube 590-3.

Figure A-9 Sketch of a metallographic cross section through the crevice region of tube 591-1. The burst crack and secondary cracks on of the circumference were observed. A photomicrograph of a secondary crack is also shown. The crack morphology is that of IGSCC. Mag. 100X

Figure A-10. Summary of burst crack observations and the overall crack distribution observed at the crevice region of tube 591-1.

Figure A-11. Sketch of a metallographic cross section through the crevice region of tube 591-2. The burst crack and a number of secondary cracks around the circumference were observed. A photomicrograph of secondary cracks is also shown. The crack morphology is that of IGSCC. Mag. 100X

Figure A-12. Summary of burst crack observations and the overall crack distribution observed at the crevice region of tube 591-2.

Figure A-13. Photographs of the burst opening in tube 591-4.

Figure A-14. Sketch of a metallographic cross section through the crevice region of tube 591-4. The burst crack and a number of secondary cracks around the circumference were observed. A photomicrograph of the burst crack and a secondary crack is also shown. The crack morphology is that of IGSCC. Mag. 100X

Figure A-15. Summary of burst crack observations and the overall crack distribution observed at the crevice region of tube 591-4.

Figure A-16. Summary of crack distribution and crack morphology observed in the support plate crevice region of Tube 595-1.

Figure A-17. Sketch of crack distribution observed in a metallographic cross section of the support plate crevice region of Tube 595-1. Crack morphology of the burst crack (two photomicrographs) is shown below the sketch.

Figure A-18. Photograph of burst opening in crevice region of Tube 596-2.

Figure A-19. Summary of crack distribution and crack morphology observed in the support plate crevice region of Tube 596-2.

Figure A-20. Sketch of crack distribution observed in a metallographic cross section of the support plate crevice region of Tube 596-2. Crack morphologies of the burst crack and of a secondary crack (two photomicrographs) are shown below the sketch.

Figure A-21. Sketch of a metallographic cross section through the crevice region of tube 596-3. The burst crack and a number of secondary cracks on one quadrant of the circumference were observed. A photomicrograph of secondary cracks is also shown. The crack morphology is that of IGSCC. Mag. 100X

Figure A-22. Summary of burst crack observations and the overall crack distribution observed at the crevice region of tube 596-3.

Figure A-23. Summary of crack distribution and crack morphology observed in the support plate crevice region of Tube 598-1.

Figure A-24. Sketch of crack distribution observed in a metallographic cross section of the support plate crevice region of Tube 598-1. Crack morphologies of the burst crack and of a secondary crack (two photomicrographs) are shown below the sketch.

Figure A-25. Summary of crack distribution and crack morphology observed in the support plate crevice region of Tube 598-2.

Figure A-26. Sketch of crack distribution observed in a metallographic cross section of the support plate crevice region of Tube 598-2. Crack morphologies of the burst crack and of a secondary crack (two photomicrographs) are shown below the sketch.

Figure A-27. Summary of crack distribution and crack morphology observed in the support plate crevice region of Tube 598-3.

Figure A-28. Sketch of crack distribution observed in a metallographic cross section of the support plate crevice region of Tube 598-3. Crack morphologies of the burst crack and of a secondary crack (two photomicrographs) are shown below the sketch.

Figure A-29. Summary of crack distribution and crack morphology observed in the support plate crevice region of Tube 600-2.

Figure A-30. Sketch of crack distribution observed in a metallographic cross section of the support plate crevice region of Tube 600-2. Crack morphology of the burst crack (photomicrograph) is shown below the sketch.

Figure A-31 Summary of crack distribution and crack morphology observed in the support plate crevice region of Tube 601-3.

Figure A-32. Sketch of crack distribution observed in a metallographic cross section of the support plate crevice region of Tube 601-3. Crack morphologies of the burst crack and of a secondary crack (two photomicrographs) are shown below the sketch.

Figure A-33. Photograph of burst opening in Tube 601-6.

Figure A-34. Summary of crack distribution and crack morphology observed in the support plate crevice region of Tube 601-6.

Figure A-35. Sketch of crack distribution observed in a metallographic cross section of the support plate crevice region of Tube 601-6. Crack morphologies of secondary cracks (two photomicrographs) are shown below the sketch.

Figure A-36. Summary of crack distribution and crack morphology observed in the support plate crevice region of Tube 604-2.

Figure A-37. Sketch of crack distribution observed in a metallographic cross section of the support plate crevice region of Tube 604-2. Crack morphologies of the burst crack and of a secondary crack (two photomicrographs) are shown below the sketch.

Figure A-38. Burst openings on Spanish test pieces.

Figure A-39 Crack surface of test piece 600-1

Figure A-40 Diagram of defects existing in the external surface of test piece 600-1

Figure A-41. Crack surface of test piece 600-3

Figure A-42   Crack surface of test piece 601-1

Figure A-43. Crack surface of test piece 601-2

Figure A-44 Diagram of defects existing in the external surface of test piece 601-2

Figure A-45   Crack surface of test piece 601-4

Figure A-46 Diagram of defects existing in the external surface of test piece 601-4

Figure A-47 Test piece 601-4 Appearance of the external surface around the crack surface (see Figure A-46) 15X

Figure A-48 Test piece 601-4 Appearance of crack "g-2" on the internal surface (see Figures A-46 and A-47)

Figure A-49 Test piece 601-4 Appearance of the cracks detected in the metallographic cuts of sections "a" and "b"

Figure A-50 Crack surface of test piece 601-5

Figure A-51. Diagram of defects existing in the external surface of test piece 601-5

Figure A-52. Test piece 601-5. Appearance of some of the cracks detected in the metallographic cut of section "a".

This page
intentionally blank

Appendix B

Leak Rate Adjustment For 3/4" Tubes

B.1 Objectives

This appendix summarizes adjustments to leak test results for 3/4" outside diameter tubes with cracks. The tests were conducted under typical pressure differentials corresponding to normal operation (N.O.) and steam line break (SLB) conditions. However, the test conditions may not be identical to specific plant conditions. For instance, measurements at SLB conditions were obtained at a pressure differential, but with a secondary side pressure rather than a prototypic pressure to improve the maintenance of constant test conditions in the measurement facility.

Adjustment procedures have been developed to scale the test conditions to plant specific conditions. The objectives of this appendix are as follows.

1. Adjust the Belgian room temperature measurements of leak rate to operating temperature, and adjust to reference pressure differential from measured pressure differential.
2. Adjust Westinghouse measurements at operating temperature from high primary pressure to a primary pressure consistent with steam line break.
3. Adjust leak rates at temperature between measured and reference pressure differentials.

B.2 Leak Rate Adjustment Procedure

Paul Hernalsteen of Laborelec in Belgium has developed adjustment procedures to scale the Belgian data to operating temperature and pressures different from the measured ones. First, the leak rate is defined as follows.

(1)

where

L = volumetric leak rate
K = discharge coefficient
A = leakage flow area; a function of Δp and temperature T
ρ = water density; a function of temperature T
T = water temperature
Δp = pressure differential; $p_1 - p_2$ if no flashing or $p_1 - p_{1f}$ if flashing at p_{1f}
p_1 = upstream pressure, or primary side pressure
p_2 = downstream pressure, or secondary side pressure
p_{1f} = saturation pressure corresponding to upstream temeperature T_1

The pressure differential is the difference between the upstream and downstream pressures of the cracked passage of the tube. During steam line break, the leakage flow may flash on the secondary side.

Hence, the effective downstream back pressure is equal to the saturation pressure, p_{1f}, if it flashes at the saturation point of the upstream temperature T_1.

B.2.1 Adjustment Under the Same Temperature

Let us consider the measurement conditions of leak rate at a reference temperature T_o. Now we can write

(2)

(3)

where the subscript o indicates the condition at the reference temperature T_o at which the leak rate test is made. The reference temperature T_o may be at room temperature, T_a (say, 70°F), or at operating temperature of about 616°F. The subscript m refers to measurement. In addition,

Δp_o = desired pressure differential at the reference temperature

Δp_{mo} = listed measurement pressure differential at the reference temperature

Both Eqs (2) and (3) describe the leak rate at the reference temperature but at different pressure differentials. We reserve Eq (2) for the test measurements. Eq (3) is for the desired conditions, to which Eq (2) is to be adjusted. We will adjust the leak rate from the measured pressure differential Δp_{mo} to a desired pressure differential Δp_o under the same temperature T_o. To do so, we write the following.

(4)

where the coefficient δ is a function of the pressure differential as follows.

This coefficient δ involves two parameters. The first one is the area of crack flow opening. The second one is the pressure differential. We will rearrange the above expression as follows.

(5)

where we have used the following definition.

$$\Delta p^* = p_1 - p_2$$

The superscript * emphasizes the total difference of the upstream and downstream pressures, regardless of whether water flashing taking place or not. When the Δp is used without the * superscript, it can be $p_1 - p_2$ for non-flashing situations or $p_1 - p_{1f}$ for flashing situations. The explicit function of Eq (5) will be given later. Eqs (4) and (5) adjust the laboratory test data to any Δp_o to be analyzed at the same temperature.

B.2.2 Adjustment Under Different Temperature

Steam generator tube leakage occurs, in general, at the operating temperature T of about 616°F. The Belgian data were measured at the room temperature. One has to scale the laboratory, room temperature data to the operating temperature. For this goal, we write the following equality

(6)

Using Eq (4), Eq (6) becomes

(7)

Using Eq (1), Eq (7) appears as follows.

(8)

The above expression describes the procedure to adjust a measured leak rate at Δp_{mo} and T_o to an equivalent leak rate at Δp^*_o (= Δp^*) and T.

The leak rate $L(\Delta p, T)$ is the volumetric rate at operating temperature T. However, leak rates detected in actual plant monitoring are collected at room temperature T_o. Laboratory tests of leak rate under the operating temperature are generally collected at room temperature, too. An equivalent room temperature, volumetric leak rate, say $L(\Delta p, T)_{Ta}$ can be obtained from

(9)

Using Eqs (8) and (9), we get

(10)

We can write the above equation as follows.

(11)

where

(12)

(13)

(14)

The α factor involves a ratio of flow area of the crack opening as a function of Δp^*_{mo} and Δp^*_o under the same upstream temperature, T_o. The α factor captures the mechanical effect of the total pressure differential on the crack opening area. The β factor adjusts temperature effect on the leak rate through flow area change and upstream water density variation under the same total pressure differential (i.e., $\Delta p^*_o = \Delta p^*$). The γ factor takes care of hydraulic effect of pressure differential on leakage flow rate.

B.2.3 The Mechanical Factor α

As reported by Hernalsteen of Laborelec, significant tearing of crack lengths took place during tube pulling. The measured leak rates in Table B-1 represent the behavior of significant tearing of the crack length. For each of the eleven leaking tubes, the leak rates have been plotted as a function of pressure differential on a semi-logarithmic paper. There are usually 4 data points per test tube and they reasonably align along a straight line. According to the straight line fit of the leak rate, Hernalsteen developed the following correlation for scaling measured leak rates from one pressure differential to another one at same room temperature.

(15)

where the pressure differentials are in psi, and b is a correlation constant. This correlation of the mechanical adjustment factor α fits the Belgian pulled tube data of Table B-1. The behavior of the pressure adjustment factor may vary from one pulled tube to another. For the Plant E-4 data, the constant b in Eq (15) principally varied from , with one indication at about . The larger constants tended to occur when there was increased evidence of damage from tube pulling effects, which would likely lead to higher than expected leak rates at low pressure differentials such as normal operating conditions. Leak rates at higher pressure differentials such as SLB conditions would be less influenced by ligament tearing in tube pulling operations, as some ligaments would likely tear away at the higher pressure differential. For this reason Laborelec has recommended the constant of for all Plant E-4 tube intersections. Thus, it follows that

(16)

Equation (15) is equivalent to the following expression

(17)

or

(18)

(19)

The correlation constants b or b^* can be determined from straight line fit of the test data. Based on Belgian data base, the constant $b =$ is recommended by Hernalsteen. Thus, it follows that

(20)

is appropriate for the Belgian Data. The slopes of leak rate vs. pressure differential for the Belgian data were steeper than generally expected, which is typical of tearing ligaments as the pressure differential is increased. For applications of the adjustment procedure, b^* is obtained as a fit to individual specimen leak rate data when at least two measurements with leakage have been obtained. When only a single leakage measurement is available, $b^* =$ is applied, as further described in Section B.3.2.

B.2.4 The Temperature Factor β

The flow opening area of the crack is approximately (as confirmed by CRACKFLO analyses) inversely proportional to the product of flow stress σ_f and Young's modulus E of the tube metal. Both flow stress and Young's modulus are functions of temperature. Therefore, it follows that

(21)

where ρ is the water density corresponding to upstream temperature $T_l = T$ and pressure p_l. The ρ_o refers to a $T_l = T_o$, and ρ_a to a $T_l = T_a$.

B.2.5 The Hydraulic Factor γ

The γ factor describes the effect of pressure differential on leakage flow rate. When there is no water flashing at T_o and T, $\Delta p = \Delta p^*_o$ and $\Delta p_{mo} = \Delta p^*_{mo}$, so $\gamma = 1$. When there is water flashing, we have to use effective pressure differentials for Δp and Δp_{mo}. We can now write the γ factor as follows.

(22)

where C_p is a parameter used to correlate the effective pressure differential through flashing pressure. For an isentropic process, the flashing takes place at the saturation pressure corresponding to the upstream water temperature, T_I (e.g., T_I, T_{oI}). Thus, C_p = 1 is for an isentropic process. If a real process deviates significantly from an isentropic one, the parameter C_p will be less than unity.

B.3 The Mechanical Factor α

B.3.1 Belgian Factor α and Leak Rate Adjustment for Plant E-4 Data

Table B-1 presents measured leak rates for the pulled tubes from Plant E-4 steam generators. The leak rate tests were done at room temperature (70°F). There were eleven sample pulled tubes tested. These data have been used to establish Eq (15) for the mechanical adjustment factor α. The CRACKFLO model has been developed based on Westinghouse fatigue crack and pulled tube data. The CRACKFLO pressure adjustment factor is different from the Belgian. The difference is believed due to minimal ligament tearing used in the CRACKFLO model compared to significant tearing in the Belgian pulled tubes. The following subsection will discuss the mechanical adjustment factor for minimal ligament tearing.

B.3.2 General Mechanical Factor α and Leak Rate Adjustment for Minimal Ligament Tearing

The applicability of Eq (18) or (15) are verified with the CRACKFLO code. Table B-2 presents the CRACKFLO code results of leak rate at different crack lengths under a variety of pressure differentials during operation. It also includes comparison of the CRACKFLO adjustment factor and the α factor by Eq (15) with b = and Eq (18) with b^* = . Similar to Table B-2, Table B-3 presents the comparison for a variety of pressure differentials under steam line break.

The Belgian α adjustment factor for Plant E decreases faster than the CRACKFLO and exponential adjustment factors having $b^* = b$ for decreases in Δp from the reference point. Use of the exponential adjustment factor is then conservative in estimating the leak rate when the adjustment is toward a lower Δp. Adjustment to Westinghouse measurements in this report are to lower pressure differentials, such that the use of the exponential form of Eq (18) with b^* = leads to higher adjusted leak rates than if Eq (15) with b = were applied.

As shown in Tables B-2 and B-3, Eq (18) with b^* = yields good agreement with crack opening models such as CRACKFLO which do not and cannot account for tearing of ligaments within macrocrack. Smaller values of b^*, such as the Belgian , can be expected when ligament tearing occurs and larger values than about when ligaments do not tear and retard crack opening compared to a uniform crack. The use of $b^* =$ for Eq (18) introduces an arbitrary conservatism. This conservatism yields higher leak rates when adjusting from higher to lower pressure differentials. It can add arbitrary scatter to the adjusted data set.

To assist interpretation of the adjustment procedure, only Eq (18) will be applied where b^* is obtained for a given data set (Belgian data) or for an individual specimen. Determination of b^* by fitting Eq (18) on an individual specimen basis to the measured data is the preferred method. Equation (18) is then applied to interpolate or extrapolate the measurements to the desired pressure differential. Equation (18) with $b^* =$ will be used only for specimens having a single pressure differential with measured leakage. This approach is based on good agreement with the CRACKFLO analytical crack opening model with b^* $=$ as described above.

B.4 Temperature and Flashing Adjustment Factors

Temperature adjustment factor β is defined by Eq (21). Flashing adjustment factor γ is defined by Eq (22).

B.4.1 Temperature Factor β Only and Leak Rate Adjustment (i.e., without Flashing)

For water without flashing at T_o and T and $\Delta p = \Delta p_o = \Delta p_{mo}$, it follows that

We will compare this β factor with the CRACKFLO calculated adjustment factor under non-flashing conditions. Table B-4 presents the comparison for the case without water flashing. Note that the reference temperature T_o is equal to the room temperature T_a. Similar results were obtained for crack lengths of . These results indicate that the approximation of Eq (21) to Eq (13) yields good agreement with the more detailed crack area models in CRACKFLO for leak rate ratios between different temperatures.

B.4.2 Adjustment Factors β and γ from Room to Operating Temperature under SLB Conditions

For water flashing at T and non-flashing at T_o and $\Delta p_o = \Delta p_{mo}$, it follows that

where β is given in Eq (21) and γ by the second expression of Eq (22). Note that the reference temperature T_o is equal to the room temperature T_a. Table B-5 presents the comparison of leak rate adjustment between the CRACKFLO code and the proposed expressions with a pressure coefficient $C_p = 1.0$.

For $C_p = 1.0$, the proposed expressions of β and γ factors yield an adjustment lower than the CRACKFLO calculated factor. The deviation comes from the flashing point. A $C_p = 1.0$ implies that flashing takes place at the saturation pressure corresponding to upstream temperature T_I. For $T_I =$, the saturation pressure $p_{If} =$. However, because of heat transfer and friction along the leakage passage, the water flashing will occur at lower pressure, or a saturation pressure corresponding to a temperature lower than the upstream temperature T_I. In fact, the CRACKFLO code predicts a flow choking at a pressure less than p_{If}.

To bring the proposed equation to yield a result equal to the CRACKFLO calculation, we obtain a C_p for each case. Table B-6 presents the results for C_p. The longer the crack length, the larger the pressure coefficient for a given pressure differential. A longer crack length means a larger crack opening, and thus less friction and smaller heat transfer effect. It approaches the ideal case: an isentropic (i.e., frictionless and adiabatic) process; hence, a situation with less leak rate. We can use C_p = for Δp = , and C_p = for Δp = .

B.4.3 *Adjustment Factors α and γ for Primary Δp Changes at Temperatures with Flashing*

Westinghouse leak rate testing was conducted at a primary pressure higher than the typical pressure during steam line break. The tests were conducted at the operating temperature of . We will adjust the leak rate to the typical primary pressure. The relevant adjustment factors are the mechanical adjustment factor α and the flow flashing adjustment factor γ. It follows that

where the α factor is defined by Eqs (18), and the γ factor by the first expression of Eq (22) or (23). Note that $T_o = T$ = . We would like to convert the leak rate to the equivalent volumetric rate at the room temperature (T_a = 70°F). To do so, we use the following expression.

As an illustration, Table B-7 presents some results of the adjustment factors for scaling from one flashing conditions to another one. We have used Eq (18) with the constant parameter b^* being to calculate the α factor. Table B-7 also lists the comparison between the CRACKFLO code prediction and the proposed expressions with appropriate choice of the pressure coefficient C_p. There are good agreements. These lead to confidence in using the proposed expressions of the adjustment factors α and γ.

The C_p factor was included in the adjustment factor to improve agreement with the CRACKFLO code and is an empirical factor. The CRACKFLO code is a more rigorous solution to the momentum equations than Eq (1) and is felt to be more accurate solution. The use of C_p is slightly more conservative than assuming C_p = 1, as the use of C_p reduces the correction for flashing (increases γ closer to 1.0) and thus leads to slightly higher leak rates. The momentum equation can predict the effect for which the CRACKFLO solution was preferred over Eq (1), which results in the C_p factor being dependent on the pressure differential. C_p is a hydraulic correction which should not be dependent on the pressure differential, and not a leak rate variation with the crack opening leakage area.

The inclusion of C_p is not critical to the adjustment model, since the effect is small and inclusion reduces the generality of the adjustment model. For these reasons, it is fine to drop C_p from the model. Thus, Eq (22) becomes:

(23)

It can be shown that the above expressions are applicable to both isentropic and non-isentropic flashing processes. The effect of the non-isentropic flashing appears in the discharge coefficient K in Eq (1), and it is not necessary to introduce an empirical factor C_p to account for the non-isentropic effect to the saturation pressure p_f.

B.5 Leak Rate Adjustment to Belgian Plant E-4 Data

Table B-1 presents leak rates measured at Laborelec for both normal operating and steam line break conditions. Both conditions simulate the typical pressure differentials across the tube, but tests were conducted at room temperature. We would like to scale these room temperature data to the hot temperature of . First, we scale the normal operating data.

B.5.1 Adjustment for Normal Operating Data

All of normal operating conditions involve no flashing of wate, so the adjustment factors are as follows.

where the factor α is defined by Eq (18) and the factor β by Eq (21). The individual correlation constant b^* is obtained for each specimen. The Δp_{mo} is given in Table B-1; for example, tube R19C35 was tested at , and $T_a = T_o =$. We will scale to $\Delta p_o =$ and $T =$. When there is no water flashing, $\Delta p = \Delta p_o$, so $\gamma = 1$. The properties of flow stress, Young's modulus and water density can be found in Table B-4. Table B-8 presents results of leak rate at the target conditions.

B.5.2 Adjustment for Steam Line Break Data

Table B-1 lists the measured leak rate and pressure differentials Δp_{mo}. We are going to scale them to $T =$ and $\Delta p_o =$, respectively. It follows that where the α and β factors are defined by Eqs (18) and (21), respectively, and the γ factor by the second expression of Eq (23). Individual correlation constants b^* were obtained from Laborelec for each specimen. Table B-8 shows the adjusted leak rate at pressure differentials of psi.

B.6 Adjustment to Leak Rate Data Base for Alternate Δp

Table B-9 lists the model boiler tests and plant data. These tests were conducted at an operating temperature of about and at primary pressures higher than the typical pressure during steam line break. The relevant adjustment factors are the mechanical factor α and flow flashing factor γ. The leak rates were collected and cooled from T_o = to room temperature T_a = . Thus, the β factor is not required in the leak rate adjustment because it was adjusted already by test procedure.

B.6.1 The Correlation Constant b^* for the α Factor

Tubes used for these tests had minimal ligament tearing at cracks. As discussed in Sect. B.3.2, the α factor is defined by Eq (18), which involves a correlation constant b^*. Rather than using b^* = as derived from the Belgian tubes with significant ligament tearing, it is to be estimated on a tube-by-tube basis using test data shown in Table B-9.

We define the following variables for deriving expression for estimating the correlation constant b^*.

where

R = Ratio of volumetric leak rates
L_{SLB} = Volumetric leak rate under SLB conditions
L_{NOP} = Volumetric leak rate under NOP conditions

This ratio R is equal to the product of α and γ factors. We write the α factor as follows.

where

Δp_{SLB} = pressure differential under SLB condition
Δp_{NOP} = pressure differential under NOP condition

Since there is no water flashing under the NOP condition the γ factor appears as follows.

where

p_{SLB} = upstream pressure during SLB

p_f = upstream saturation pressure corresponding to upstream temperature T_o

Equating R to $\alpha\gamma$ and solving for b^* leads to the following equation.

(24)

Some tests yielded no leakage under the NOP conditions. Thus, the ratio R becomes infinite, and the correlation constant b^* approaches zero. A zero constant b^* results in a zero adjusted SLB leak rate when scaling from the measured SLB leak rate at to lower pressure differentials. A meaningful lower bound of the ratio R will lead to a conservative adjustment, and such a ratio is selected to be based on the cases where the NOP leak rate being not zero. Therefore, R = is used for the tests which have zero NOP leak rate. Note that the Belgian constant b^* = corresponds to a R = . The other choice is to take the average over all data, which is R = and b^* = . In addition, we set R = if the measured data yields a value less than unity. Use of R = results in an adjusted leak rate being less than R = when adjusted from higher measured pressure differential to lower differentials. For conservatism, we set R = for the case with zero NOP leak rate.

B.6.2 Results of the Leak Rate Adjustment

Leak rate adjustment for these data was made using both mechanical and hydraulic factors as described above. Table B-10 presents the adjusted leak rate for the normal operating (NOP) and SLB conditions. Two sample tubes result in adjusted leak rates for both differentials under SLB being less than the adjusted leak rate under NOP. For conservatism, we use γ = 1 for these two lower pressure differentials.

B.7 Plant S Leak Rate Adjustment

Leak rate measurements of pulled tubes from Plant S have been conducted under various pressure differentials. Table B-11 lists the test data for pulled tubes Row 33 Column 20 (R33C20) and R42C43. Each tube has four acceptable data points. One point is at a low pressure differential and three at higher ones. The lowest differential represents normal power operation (NOP), and the other three approximate steam line break (SLB) conditions. Figure B-1 shows the measured leak rate vs. pressure differential for R33C20, as an illustration.

A two step procedure was used to adjust the measured leak rate. The first was to adjust the measurement to reference absolute temperature and pressures while keeping the same pressure differential. For normal power operation, the reference pressure is the primary coolant pressure at psia. For steam line break, the reference pressure is the secondary side fluid pressure at . For both normal power operation and steam line break, the reference temperature is the primary coolant temperature at . Thus, the first step involves adjustment of temperature (i.e., β factor) and water flashing (i.e., γ factor) to bring the measurements to nominal NOP or SLB conditions. Table B-12 presents the adjusted measurement. Figure B-2 shows the adjusted measurement data by the first step for the R33C20 tube.

The second step is to convert the adjusted measurement data to target pressure differential and temperature. In the present case, the temperature is also , and thus step two involves the use of the α factor only. For normal power operation, the NOP data point and the lowest pressure differential of the three SLB points are used to develop a correlation constant b^* for adjusting the NOP data point. Such a procedure is similar to the data adjustment for other Westinghouse tests shown in early sections. For SLB, only the three SLB points are used in developing the correlation constant b^* for the α factor.

The procedure using three SLB data points reduces the potential scattering. Therefore, such a procedure offers better adjustment than other tests which had only two data points (one at NOP and the other at SLB condition). Figure B-3 illustrates a straight fit to three data points for the R33C20 tube, and thus a exponential fit of Eq (18) for the correlation constant b^*. Table B-13 lists the a leak rates obtained by this procedure.

Table B-1

Results of Leak Rate Tests under Room Temperature
and Typical Pressure Differentials during Steam Line Break

Table B-2

Comparison of the Pressure Adjustment Factor α between the CRACKFLO Prediction and Proposed Correlation at Temperature --Power Operating Pressure Differentials--

Table B-3

Comparison of the Pressure Adjustment Factor α between the CRACKFLO Prediction and Proposed Correlation at Temperature --Steam Line Break Pressure Differentials--

Table B-4

Comparison of the Temperature Adjustment Factor d between the CRACKFLO prediction and Proposed Expression for the Case without Water Flashing

Table B-5

Comparison of the Temperature and Flashing Adjustment Factors between the CRACKFLO prediction and Proposed Expression for the Case with Water Flashing

Table B-6

Pressure Coefficient C_p

Table B-7

Comparison of the Mechanical and Flashing Adjustment Factors α and γ between the CRACKFLO Prediction and Proposed Correlations at Operating Temperature

Table B-8

Results of Leak Rate Tests and Their Adjustments at and Normal Operating and Steam Line Break Pressure Differentials (Belgian 3/4" Tubing)

Table B-9

Results of Leak Rate Tests at and Normal Operating and Steam Line Break Pressure Differentials

Table B-10

Results of Leak Rate Tests and Their Adjustments at and Normal Operating and Steam Line Break Pressure Differentials

Table B-11

Measurements of Leak Rates

Table B-12

Adjusted Measurements of Leak Rates to Reference Absolute Pressures and Temperature

Table B-13

Leak Rates Adjusted to Reference Temperature and Pressure Differentials

Figure B-1. Leak rate vs. pressure differential for R33C20 pulled tube from Plant S

Figure B-2 Adjusted measurement of leak rate vs. pressure differential for R33C20 pulled tube from Plant S

Figure B-3. Straight line fit to adjusted measurement of SLB leak rate vs. pressure differential for R33C20 pulled tube from Plant S